Trends in the incidence of rain height and the effects on global satellite telecommunications

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Abstract

Satellite communications using millimetre waves, in Ka band and above, experience significant fading by rain. Strong attenuation is experienced between the ground station and a level known as the rain height, in ITU-R recommendations assumed to be 360 m above the zero-degree isotherm (ZDI). This paper examines NOAA NCEP/NCAR Reanalysis 1 data to identify changes in the ZDI height over the last 30 years. Near the equator and the poles the ZDI height has been approximately stable over this period. However, in mid-latitudes, different regions show trends of increasing or decreasing ZDI height. Over the economically important regions of North America, China and Western Europe, the ZDI height has shown an increasing trend with peak rates in the range of 8 to 10 metres per year. Given a twenty-year life-time of a satellite system, this could lead to a 10 to 20% increase in fade intensity from a similar rain event. The effect will be compounded by increasing trends in the incidence of heavy rain recently identified in UK data. These trends will need to be considered when designing new systems.

Introduction

In temperate regions, most raindrops start as ice crystals that grow by sublimation at the expense of super-cooled water droplets via the Berganon Process, Yau and Rodgers [1].

As these particles grow, gravity exerts a stronger force and they fall through the atmosphere, growing by collision and accretion. The particles begin to melt as they fall into regions warmer than 0 degrees Celsius. In a stratified atmosphere this leads to a layer, approximately one kilometre thick, containing mixed phase particles, known as the melting layer, or as the bright band by radar meteorologists. Below the melting layer all the ice has melted into raindrops. Depending on the height of the zero degree isotherm (ZDI), an observer on the ground can experience ice, mixed phase or liquid hydrometeors. An atmosphere experiencing strong convection may lead to a column of air with no stratification containing mixed-phase particles throughout.

The atmosphere containing ice crystals above the melting layer has very low specific attenuation at microwave and millimetre-wave frequencies. Below the melting layer, the specific attenuation is due to scattering by raindrops and can be approximated as a power-law of rain intensity e.g. Rec. ITU-R P.837-5 [2]. By contrast, the melting layer has microwave specific attenuations many times that of the equivalent rain intensity due to scattering by the large, water covered, melting particles; see Bråten et al [3].

Models of the average annual distribution of fade experienced by an Earth-space microwave link needs to include attenuation by rain and the melting layer e.g. Rec. ITU-R P.618-10 [4]. The fade due to rain depends upon the length of the Earth-space path passing through the rain. This is generally assumed to be from the ground station to the average annual rain height, h_R , provided by Rec. ITU-R P.839-3 [5] . The average annual rain height is equated to the average annual ZDI height h_0 plus 360 m. Measurements of the difference between ZDI and melting layer height have yielded values between 300 m, Austin and Bemis [6]; and 900 m, Leary and Houze [7]. The difference depends upon latitude, season and geography. The ITU-R provides two models for the average annual distribution of actual rain height relative to the mean. These are both in table form and are in Rec. ITU-R P.530-13 [8] for terrestrial links and Rec. ITU-R P.452-14 [9] for Earth-space links. Both distributions are approximately Gaussian and assumed to apply globally.

Over the last thirty 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 [10], and the Intergovernmental Panel on Climate Change [11]. A recent paper by Paulson [12] examining 20 years of high-resolution rain gauge data from 30 sites in the southern UK, 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. It is also likely that increases in ZDI height are increasing rain fade on Earth-space links. Increasing ZDI height leads to increases the slant-path length affected by rain fading and hence larger rain fades. Recently, Bradley et al [13] have noted 30-year increasing trends in ZDI height in the tropics with gradients up to 6 m/year. General global warming is associated with ZDI height increases. Diaz and Graham [14] noted a strong correlation between ZDI height and tropical sea-surface temperature, while Harris et al [15] states that positive ZDI height anomalies are linked to increasing planetary temperatures.

In this paper we examine global changes in the ZDI height over the last 30 years. NCEP/NCAR Reanalysis data, produced by National Oceanic and Atmospheric Administration (NOAA) is used. Section 2 introduces these data and provides some evidence of its reliability. Section 3 examines global ZDI height trends. Section 4 considers the effects of these trends on Earth-space links.

2 NOAA NCEP/NCAR Reanalysis 1

The motivation for the NOAA NCEP/NCAR Reanalysis project was to address the apparent climate change artefacts introduced by the occasional changes made to numerical weather models, Kalnay et al [16]. Kalnay et al further state: "The basic idea of the Reanalysis Project is to use a frozen state-of-the-art analysis/forecast system and perform data assimilation using past data, ..."

The dataset provides a wide range of meteorological parameters over a global 2.5^{o} grid at 6 hour intervals from 1948 to the present, calculated at 17 pressure levels. The global grid has 73 latitudes and 144 longitudes. This project uses two reanalysis parameters: the air temperature and altitude, both as a function of pressure level, averaged over each grid square and sampled a 6-hour intervals. Diaz et al [17] conclude that the Reanalysis data can reliably predict ZDI height, even over mountainous areas, over the period 1958 to the present. Harris et al [15] found reasonable agreement between Reanalysis derived ZDI height and bright band height measured using TRMM satellite data. Bradley et al [13] identify tropical ZDI heights from Reanalysis data.

3 Temporal Trends in Zero-Degree Isotherm Height

The ZDI height has been calculated from the Reanalysis data by linear interpolation between the lowest temperature-height points that decrease through zero Celsius with increasing altitude. 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 pixel for each 6-hour 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 centred on the 6-hourly sample of interest. Figure 1 illustrates typical time-series of ZDI height for two grid squares: both on the Greenwich meridian, one on the equator and the other on the latitude of Edinburgh (55^{o} North).

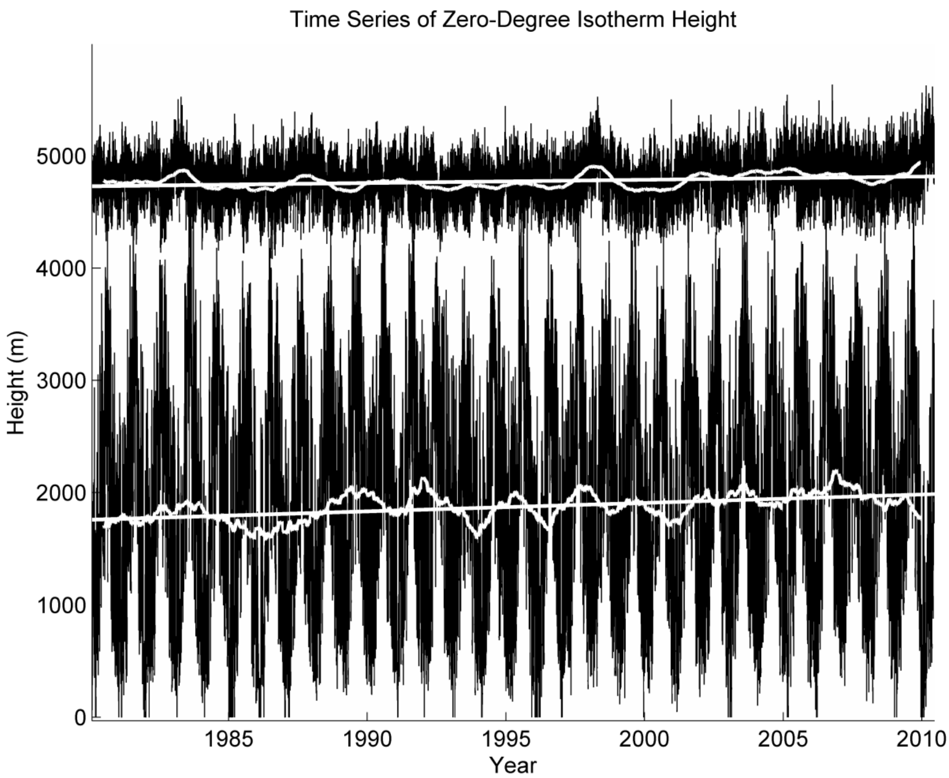

Figure 1: time-series of ZDI height for two grid squares centred on 0^{o} of longitude and 0^{o} latitude (black, upper) and 55^{o} (black, lower). The variable white lines represent the running yearly average while the white straight lines are the least squares fit to the running annual average.

Figure 1 illustrates general features of ZDI height. The ZDI is at its greatest average height in warmer regions near the equator. Over each 12-month period the ZDI height exhibits a near sinusoidal oscillation where it is below the mean during winter and above the mean over summer. This oscillation has low amplitude near the equator where the seasonal temperature variations are small, and the amplitude is larger at mid-latitudes. At high latitudes the ZDI height is constrained by the Earth's surface and the oscillation becomes asymmetric.

The 55^o latitude ZDI height time-series shows a clear increasing trend consistently across the 30-year period spanned by the data. The probability of the apparent trend being due to random variation can be estimated using the Pearson correlation test and the non-parametric Mann-Kendal trend test, see Önöz and Bayazit [18]. Both these tests yield a probability of the observed trend being due to chance less than 10^{-8}. The least squares (LSQ) linear regression line fitted to the running annual mean has a slope of 8 m/year consistent in an increase in mean ZDI height of 240 m over the 30 year analysis period. The yearly running average ZDI height increases from 1764 m in the calendar year 1980 to 1979 m in 2008. Rec. ITU-R P.839-3 provides an estimate of this parameter of 2095 m. The observed trend is an approximate 12% increase in average annual ZDI height, from the 1980 value, that would have produced a similar increase in log rain fade on Earth-space links.

The same analysis was performed on all the grid squares in the dataset. Figure 2 illustrates the slope of the LSQ linear regression to the running annual mean ZDI height for all the grid squares. Close to the equator the trend slopes are small and may be due to random variation. At mid-latitudes i.e. around 40^o north and south, strong increasing trends are observed with a peak value of 10 m/year. A region of strongly increasing ZDI height can be observed spanning the UK and Scandinavia. Extremes of both increasing and decreasing trends occur over the Pacific Ocean. Harris et al [15] notes positive ZDI height anomalies in the Pacific associated with El Niño.

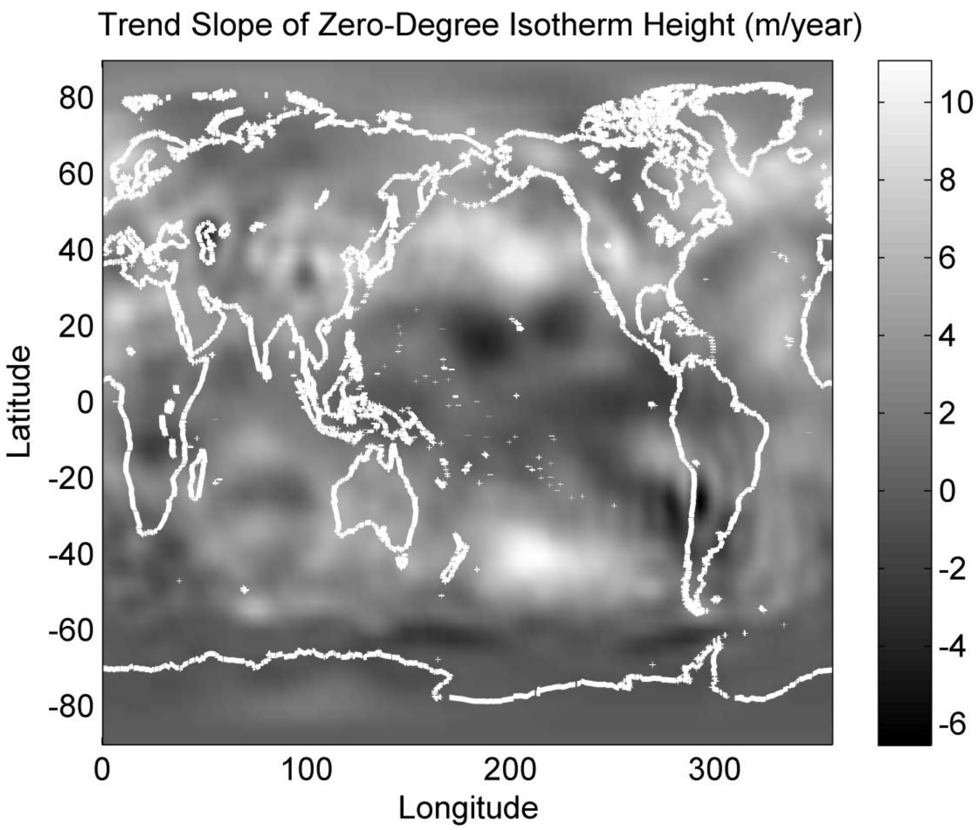

Figure 2: slope of least squares linear regression to the running annual average ZDI height.

Figures 3 compare the average annual ZDI height in 2010 with the value provided by Rec. ITU-R P.839-3. The 2010 value was calculated by evaluating the LSQ linear regression at 1/1/2010. Bi-linear interpolation was used to estimate the values of the Rec. P.839 ZDI heights, averaged over 1.5^{o} pixels, at the centres of the 2.5^{o} NOAA grid-squares. The finer model grid used in Rec. P.839 data shows features around the Himalayas not present in the NOAA derived data. Large differences also occur near the poles, in central Asia and central North America. Over latitudes from 40^{o} north to 40^{o} south, the NOAA data are on average 300 m higher than Rec. P.839 values. These differences are due to modelling and assimilated data differences. The consistency imposed on the reanalysis data means that it is very likely that the observed trends are real, despite the altitude offset.

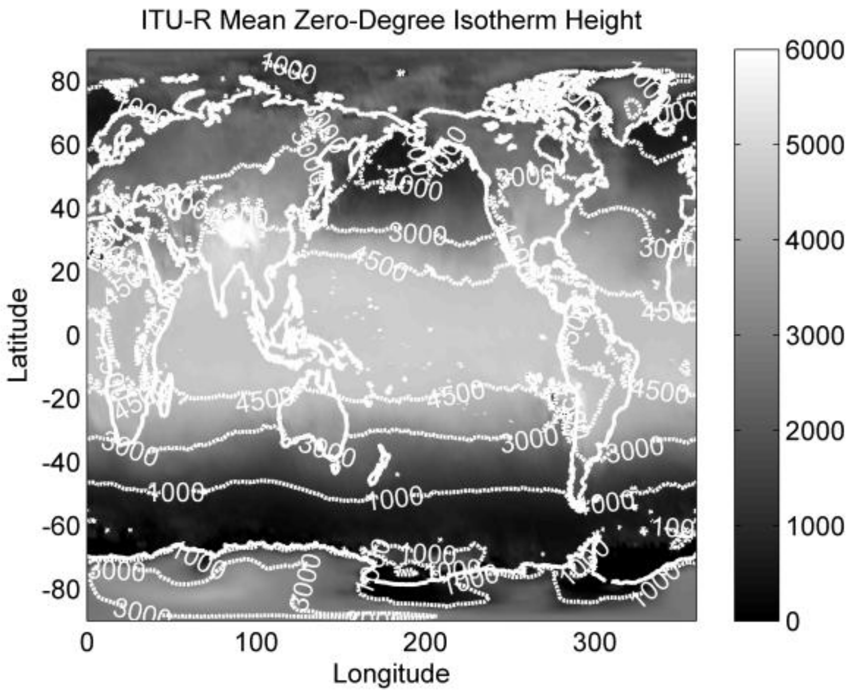
ITU-R Mean Zero-Degree Isotherm Height
Latitude
80
60
40
20
0
-20
-40
-60
-80
Longitude
0
100
200
300
6000
5000
4000
3000
2000
1000
0

Fig. 3(a)

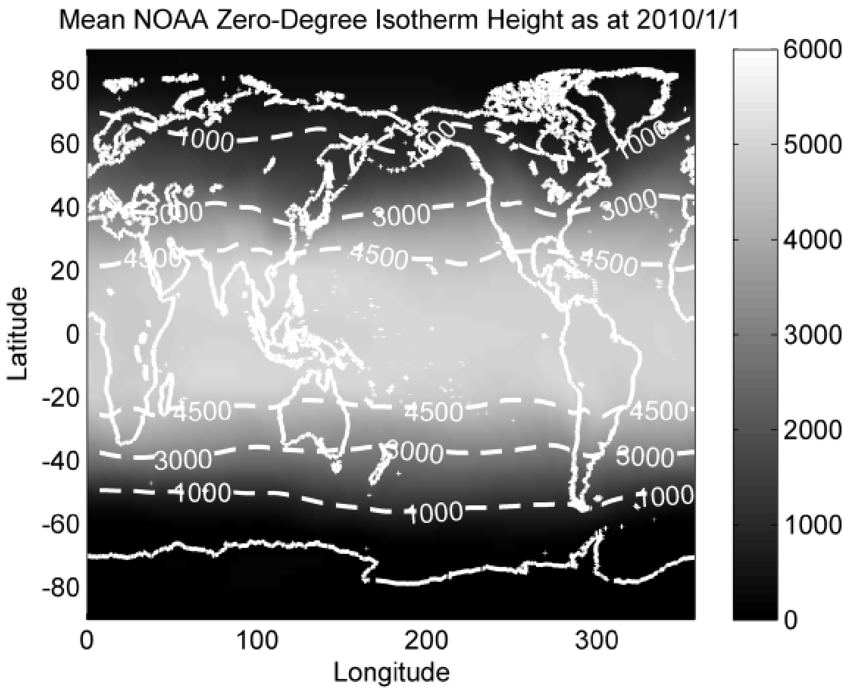
Mean NOAA Zero-Degree Isotherm Height as at 2010/1/1
Latitude
80
60
40
20
0
-20
-40
-60
-80
Longitude
0
100
200
300
6000
5000
4000
3000
2000
1000
0

Fig. 3(b)

Figure 3: Zero-degree isotherm height as provided by (a) Rec. ITU-R P.839-3 and (b) derived from NOAA Reanalysis data. The contour lines correspond to altitudes of 1000, 3000 and 4500 m and are increasing from the poles to the equator.

4 Effects of Zero-Degree Isotherm Height Increase on Satellite Links

The average annual rain fade distribution experienced by an Earth-space microwave link can be estimated using ITU-R Rec. 618-10. The model has a large number of input parameters including average annual rain height and the one-minute rain rate exceeded for 0.01% of an average year. Figure 4 illustrates the predicted one-minute, rain fade distributions for a notional circularly polarised Ka-band uplink operating at 27.5 GHz, between a London ground station and a geostationary satellite at 0^{o} longitude. The calculation used a 0.01% exceeded rain rate of 27.8 mm/hr. This value comes from the Bath Study, Howell and Watson [19] and is the figure 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 annual average ZDI height provided by Rec. ITU-R P.839-3 is 2107 m.

Also illustrated are the distributions using the mean rain height calculated from the linear regression to the London ZDI height, as at 1990 and 2010. During this 20 year period the London annual mean ZDI height increased from 1961 m to 2150 m. The associated rain fade level exceeded 0.01% of time has increased from 15.1 dB to 16.0 dB over this period. At higher latitudes the greater proportionate increase in rain height will yield greater proportionate increase in rain fade.

A recent paper by Paulson [12] shows the 0.01% rain rate averaged over the southern UK has increased by 10 mm/hr from 19 to 29 mm/hr, over the period 1988 to 2008. Any increases in 0.01% exceeded rain rate will exacerbate the trends illustrated in Fig 4. Also plotted is the 1990 distribution using the 0.01% exceeded rain rate of 20 mm/hr. The increasing 0.01% exceeded rain rate and increasing rain height over this period leads to an increase in average annual rain fade, at the 0.01% exceedance level, of 4.3 dB from 11.7 dB to 16.0 dB.

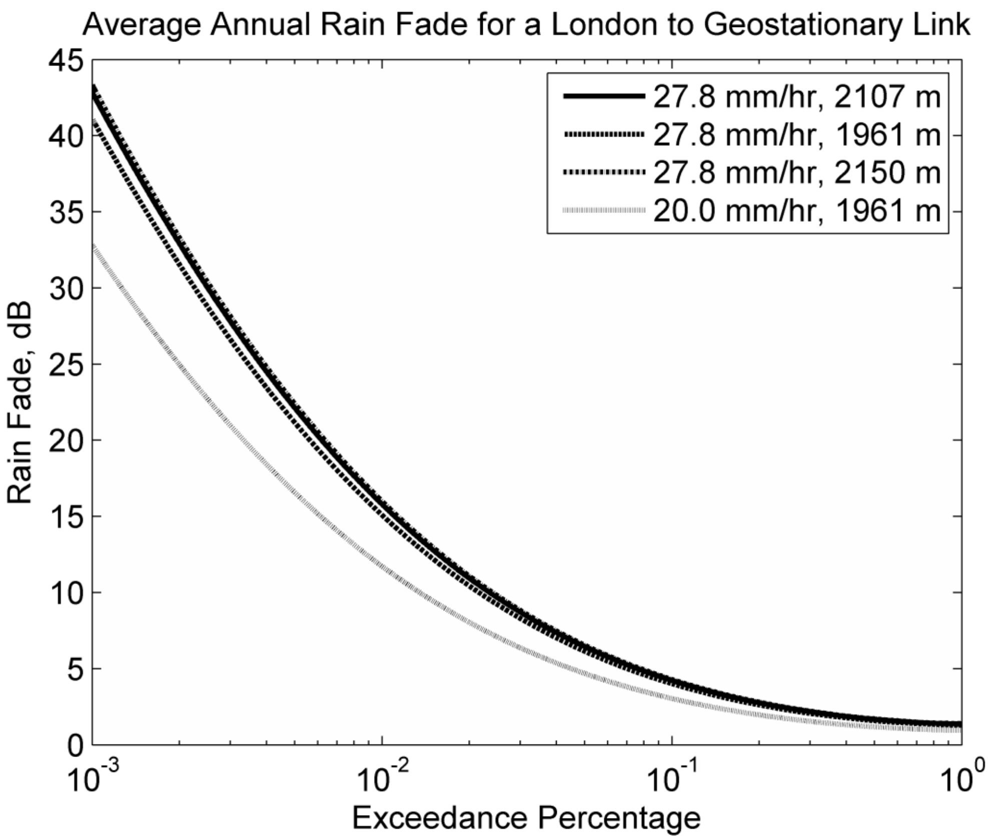

Figure 4: Average annual rain fade distribution for a notional 27.5 GHz, circularly polarised uplink from London to a geostationary satellite at 0^o longitude.

6 Conclusions

Current ITU-R models of rain height assume a time-invariant annual mean level. The rain rate exceeded 0.01% of the time is also assumed to be constant. Both these assumptions may be inadequate for the design of satellite communications systems.

Analysis of NOAA reanalysis data has provided strong evidence of multi-decade trends in ZDI height with increasing gradients as large as 10 m/year. In some regions decreasing trends exist. Over economically important areas such as North America, northern Europe and central Asia, these increasing trends would have increased rain height by 100 m to 200 m over the 20-year life-time and a satellite system, leading to a 10% to 20% increase in rain fade.

Increasing trends in both 0.01% exceeded rain rate and rain height both lead to increasing trends in 0.01% exceeded rain fade and need to be factored in when calculating link budgets and cost-benefits of future satellite systems. The UK is experiencing increases in ZDI height and in the incidence of heavy rain, both leading to increase in rain fade. The increasing incidence of heavy rain is the dominant mechanism. In this extreme case, average annual 0.01% exceeded rain fade could have doubled over the period 1990 to 2010. In practise, this trend would be obscured by large year-to-year and site-to-site variation.

It is likely that the parameters used in many current ITU-R recommendations for the design and coordination of telecommunications networks, are not stationary but are exhibiting multi-decade trends. Even the definition of average annual parameters such as rain height and rain rate distributions, needs to be reconsidered when stationarity is not assumed. Different statistical techniques are required when deriving these parameters from data spanning many years. Many ITU-R recommendations may need to be reframed in terms of time-varying, expected distributions.

The effects of ZDI height increases are likely to be more dramatic on terrestrial fixed links. In latitude and altitude combinations that spend parts of the winter with air temperatures near the ground close to freezing, temperature increases and the associated ZDI height increase could dramatically increase rain fade. Precipitation that was previously frozen and associated with very low specific attenuations will instead be composed of heterogeneous mixtures of ice and water, known as sleet in Europe, with specific attenuations up to four times that of rain with the same accumulation rate.

Acknowledgement

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