Revisiting the Link between Thunderstorms and Upper Tropospheric Water Vapor

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Abstract

The most important feedback in the climate system is related to changes in atmospheric water vapor or specific humidity (SH), with some of this water vapor transported to the upper troposphere through thunderstorms. This study uses lightning and SH data to show high correlations between the zonal mean lightning activity and the zonal mean SH concentrations in the upper troposphere. The best correlations (r˜0.9) are between lightning activity and UTWV at the 200 mb level (˜12 km altitude). Both lightning and SH at 200mb are 20% higher in July than in January. While the SH increases in concentration above the thunderstorms in the upper troposphere, in the lower stratosphere, a significant drying of the atmosphere is observed due to the "cold trap" region near the tropopause where the atmosphere is "freeze-dried" by the production of ice crystals and cirrus clouds, preventing the further rise of water vapor into the stratosphere.

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Revisiting the Link between Thunderstorms and Upper Tropospheric Water Vapor

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Abstract: As the Earth's temperatures continue to rise due to increasing greenhouse gases in the atmosphere, a large portion of the warming is due to positive feedbacks that amplifies the initial warming from artificial greenhouse gases. The most important positive feedback is from increasing atmospheric water vapor or specific humidity (SH) due to the enhanced ocean evaporation and evapotranspiration from the biosphere. Some of this water vapor is transported via convection to the upper troposphere, where small changes in SH have a significant impact on the Earth's radiation balance. The process of transport to the upper troposphere occurs through deep convective storms and thunderstorms, often accompanied by substantial electrical activity and lightning. This study uses lightning data as a proxy for deep convection, supplied by the World Wide Lightning Location Network (WWLLN). In contrast, the SH data were obtained at different atmospheric pressure levels using the ERA5 reanalysis project. Our findings show high correlations between the zonal mean lightning activity and the zonal mean SH concentrations in the upper troposphere. The best correlations (r~0.9) are between lightning activity and UTWV at the 200 mb level (~12 km altitude). Both lightning and SH at 200mb are 20% higher in July than in January. While the SH increases in concentration above the thunderstorms in the upper troposphere, in the lower stratosphere, a significant drying of the atmosphere is observed due to the "cold trap" region near the tropopause where the atmosphere is "freeze-dried" by the production of ice crystals and cirrus clouds, preventing the further rise of water vapor into the stratosphere.

1. Introduction

As the climate changes and temperatures rise, we are also witnessing an increase in water vapor in the atmosphere (Sherwood et al., 2010). Since water vapor is a natural greenhouse gas, any increases in water vapor in the atmosphere will amplify the initial warming due to anthropogenic greenhouse gases. Such positive feedbacks are hugely important when trying to estimate the changes in the Earth's climate in the future due to future greenhouse warming as a result of anthropogenic pollution. However, the Earth's radiation balance is much more sensitive to small changes in the upper tropospheric water vapor (UTWV) than the same minor changes in water vapor in the lower atmosphere [Rind, 1998]. As global temperatures rise, some climate models predict UTWV to increase by 20% for every 1K increase in surface temperatures [Rind, 1998]. It should be noted that this sensitivity is more significant than that expected from the Clausius-Clapeyron equation (7% increase per degree increase) since UTWV is impacted not only by temperature but also by the transport from the lower atmosphere through deep convective storms. Models also show that while tropical surface temperatures may increase by 2-3° C by 2100, the upper tropical troposphere is expected to warm by 6-7 °C [IPCC, 2021]. This would imply a surface temperature amplification of near 60% due to a doubling of carbon dioxide [IPCC, 1996]. Furthermore, water vapor also has a role in redistributing energy throughout the atmosphere. The change of phase from vapor to liquid or ice results in the release of large amounts of latent heat that accounts for most of the vertical, and about half of the pole-ward, heat transport within Earth's atmosphere.

In addition to trapping in extra heat, water vapor in the atmosphere also plays a significant role in forming clouds, and hence the albedo of the planet. Moreover, water vapor is also essential in atmospheric chemistry [Kley, 1997], assisting in numerous reactions to cleanse the atmosphere from pollutants.

In the upper troposphere, a balance exists between water vapor detrained from deep tropical convective clouds near the tropopause and the drying resulting from the compensatory subsidence associated with the deep convection [Lindzen, 1990]. The detrained moisture from these deep convective storms is the focus of this paper. After the dissipation of the deep convective clouds, the detrained UTWV can be redistributed zonally and meridionally around the globe in the upper atmosphere [Newell et al., 1996]. This source of UTWV can later re-nucleate and sublimate many times to form cirrus clouds in other regions of the globe. Cirrus clouds themselves have a net warming effect on the Earth's climate [Zhou et al., 2014].

The minimum temperatures at the tropical tropopause are so cold (-70 to -80C) that no moisture can exist at those temperatures, with it immediately freezing into ice crystals (cirrus clouds). This cold "trap" prevents water vapor from moving into the stratosphere and higher because the cirrus ice crystals fall through the troposphere until they reach warmer temperature and then melt or sublimate [Holton and Gettleman, 2001]. It is interesting to note that if water vapor would have reached the upper stratosphere (like oxygen) without the cold trap, it would have photo-dissociated into oxygen and hydrogen. The light hydrogen atoms would have left the atmosphere as they continuously do today. Hence, the oceans would have fully evaporated within a short geological period, leaving the Earth without water. Hence, the cold trap at the tropopause has resulted in the Earth retaining its oceans over billions of years. The important role of UTWV and the cold trap region in the Earth's water cycle emphasizes the need to understand more about the link between climate change, deep convection, and changes in UTWV concentrations.

A significant fraction of the water mass transported to the upper troposphere is transported as liquid droplets and ice particles in deep convective clouds [Kent et al., 1995]. We now know that the existence of both supercooled drops and graupel ice in the mixed-phase region of the clouds (between 0 to -40C) are essential in generating large electric fields (and later lightning) in the storms [Takahashi, 1978; Toracinta & Zipser, 2001; Williams, 2005]. Hence, it is logical that the stronger the deep convection, the more water mass will be transported aloft, and the more electrical charging we would expect [Price, 2009]. Previously it has been shown that lightning activity in tropical thunderstorms is well linked to changes in UTWV concentrations [Price, 2000; Price and Asfur, 2006]. On a daily scale, it was shown that the UTVW over Africa lagged by approximately 24 hours relative to the lightning activity. This paper expands on these previous studies using new lightning data sets and new estimates of UTWV, while addressing global zonal mean values on monthly time scales.

The most vigorous convection on Earth occurs in the tropical regions (30N-30S) and primarily during summer. The spatial distributions of lightning from space show that 75% of global lightning occurs in the tropics. Furthermore, 90% appears over the continental landmasses (Baker et al., 1999, Christian et al., 2003), with tropical Africa, SE Asia, and South America being the three "chimneys" of strong deep convection and thunderstorm activity. There are estimated to be between 1000-2000 thunderstorms at any time, with around 50 lightning flashes occurring every second somewhere on the planet.

On the topic of climate change, there are model forecasts that predict global lightning to increase in a warmer climate (Price and Rind, 1994), although recently, a new study claims the opposite could occur (Finney et al., 2018). Some estimates of past changes in thunderstorm activity over Africa show significant increases in the second part of the 20th century (Harel and Price, 2021), while studies of thunder day statistics also show substantial increases in some locations like Alaska [Williams, 2009] and Brazil [Pinto et al., 2013]. In addition, there is evidence for increasing concentrations of water vapor in the upper troposphere (Shi and Bates, 2011) and the lower stratosphere

(Rosenlof et al., 2001; Hurst et al., 2011). These increases in UTWV with time contribute to the positive feedback water vapor exerts on the climate system.

In this study, we have revisited the studies of Price (2000) and Price and Asfur (2006), who used a global lightning index (Schumann resonance) to investigate connections with UTWV. The Schumann resonances are obtained from measurements of the extremely low frequency (ELF) radio waves emitted from global lightning and detected at a single location. The present study will use individual lightning discharge data detected utilizing a network of sensors in the very low frequency (VLF) range to provide spatial details of lightning activity, unlike the ELF data.

2. Data

2.1 Lightning data

In this paper, the lightning discharges are detected using the World Wide Lightning Location Network (WWLLN) made up of around 70 VLF sensors distributed around the globe (Rodger et al., 2006). Each station consists of a 1.5-meter whip antenna on top of a tall building, which measures the vertical electric field in the VLF range. In addition, a GPS antenna is connected to the station to keep the station clock to within about 10 μs (Dowden et al. 2002). Each station also includes a VLF receiver and an Internet-connected processing computer.

The reason for using the VLF range is two-fold. First, in the VLF range (6-22 kHz), the waves show very low decay or attenuation as they propagate around the Earth in the Earth-ionosphere waveguide, allowing us to detect the radio waves from an individual lightning discharge from distances of up to 10,000 km. Second, the energy emitted from a lightning discharge is highest in the VLF range due to the physical size of the lightning discharge (radio antenna). However, one disadvantage of using VLF for detecting lightning is the influence of the day-night ionospheric differences on the wave propagation. During the day, the reflection height of the D-region of the ionosphere is around 60km altitude, while at night, it rises to about 100km.
For this reason, there is more absorption of the VLF wave on the daytime side of the Earth, and hence the detection efficiency is lower on the dayside than on the night side of the Earth (Bui et al., 2015).

The WWLLN provides a database for lightning counts and lightning stroke locations worldwide. The network began operating in 2004 with 18 stations and has progressively grown to around 70 stations today. The network is managed by the University of Washington in Seattle (Lay et al., 2004). The WWLLN detects VLF electromagnetic waves generated by individual lightning strokes, although due to the limited number of ground stations, WWLLN is strongly biased towards lightning with higher peak currents (>30kA). The WWLLN algorithm measures the time of group arrival of the radiation from the discharge. The Time of Group Arrival (TOGA) algorithm finds an optimal position for the discharge based on TOGA from at least 5 stations [Dowden et al., 2002; Virts et al., 2013]. The main advantage of the TOGA method is that each station sends to the main computer only a single number (the TOGA) representing the VLF signal time of arrival at the station, rather than sending the entire waveform of the signal for processing. The TOGA time is determined by tracking the phase as a function of frequency over the whole waveform, which can be determined to within a few hundred nanoseconds. As of 2013, the network's detection efficiency (DE) was estimated at 30% of CG strokes of 30kA or greater (Rodger et al., 2017).

The WWLLN detection efficiency is highly dependent on the non-uniform distribution of WWLLN sensors around the world. As mentioned, WWLLN detects mainly CG lightning strokes because CG lightning has, on average, higher currents. However, when comparing CG and IC lightning with the same peak current, it is believed that the DE of the WWLLN is approximately the same for the two types of lightning strikes (Lay et al. 2004, Jacobson et al., 2006). Another reduction in WWLLN DE can happen when a lightning discharge is very close to a sensor (a few hundred kilometers from the station). At this close distance, little dispersion of the VLF wave occurs, while the distribution is needed (for TOGA calculation) to decide whether this VLF signal is due to lightning or not (Rodger et al. 2006).

2.2 Specific Humidity in the Upper Troposphere

The UTWV in this study will be measured using the specific humidity (g/kg) [SH] parameter taken from the European Center for Medium-range Weather Forecasting's (ECMWF) fifth generation reanalysis product (ERA5) [Hersbach et al., 2020]. This reanalysis product provides the most accurate description of the global climate and weather for the past 40 years. The ERA5 reanalysis replaces the ERA-Interim reanalysis.

Reanalysis products combine model simulations and observations from across the world into a single dataset. The model is used to fill in the gaps, while the observations force the model to agree with reality. This principle is called data assimilation. Every 12 hours, a previous model forecast is combined with newly available observations in an optimal way to produce a new revised best estimate of the state of the atmosphere, called the analysis. Reanalysis is similar, but at reduced spatial resolution allows for the use of datasets spanning several decades. Reanalysis has more time to collect observations. Going further back in time allows for the ingestion of improved versions of the original observations, which all benefit the quality of the reanalysis product. ERA5 provides hourly estimates for many atmospheric quantities.

The ERA5 database covers 1979 until today and continues to be extended forward in time. Generally, the data are available at a sub-daily and monthly frequency and consist of analyses and short (18 hours) forecasts, initialized twice daily from analyses at 06 and 18 UTC. The spatial grid of the climate data from the ERA5 high resolution (HRES) atmospheric reanalysis is 31km, 0.28125 degrees, and the Ensemble of Data Assimilations (EDA) has a resolution of 63km, 0.5625 degrees. The climate data parameters used in this study are primarily the specific humidity at different atmospheric pressure levels. ERA5 data are available from the Copernicus database, which has been pre-interpolated to a regular latitude/longitude grid appropriate for easy access for users (Giusti, 2021).

3. Results

To revisit the link between lightning activity and SH (Price and Asfur, 2006), we have examined the zonal mean distributions of lightning and SH for three years from 2018- to 2020. The data were binned into 5-degree latitudinal bins to reduce the small spatial scale variability. In Figure 1, the data of lightning counts and SH at 200 mb are shown. The left panels are for January, the southern hemisphere summer, while the right panels show the plots for July, the northern hemisphere summer. The top panel shows the data from 2018, the middle panel 2019, and the bottom panels represent 2020. As can be seen in the figures, the lightning and SH data peak at similar latitudes, south of the equator in January and north of the equator in July. There are also clear differences in the lightning and SH distributions in the different years, for the same months. The secondary peak around 30N in January is related to winter storms over the Gulf Stream, the Mediterranean, and the Sea of Japan. In addition, the SH curves are much smoother than the lightning curves since the SH has a long lifetime in the upper troposphere and hence is transported zonally and meridionally away from the thunderstorms regions. In contrast, the lightning counts represent the actual location of the lightning discharges and thunderstorms. Nevertheless, the correlation coefficient between the zonal distributions is high, around r=0.9. This implies the thunderstorm activity (measured via lightning activity) can explain more than 80% of the latitudinal variations in SH at the 200 mb level.

If we take the area under these zonal mean curves for each month of the 3 years, we see that both the lightning amounts and the SH at 200 mb are ~20% higher in July compared with January.

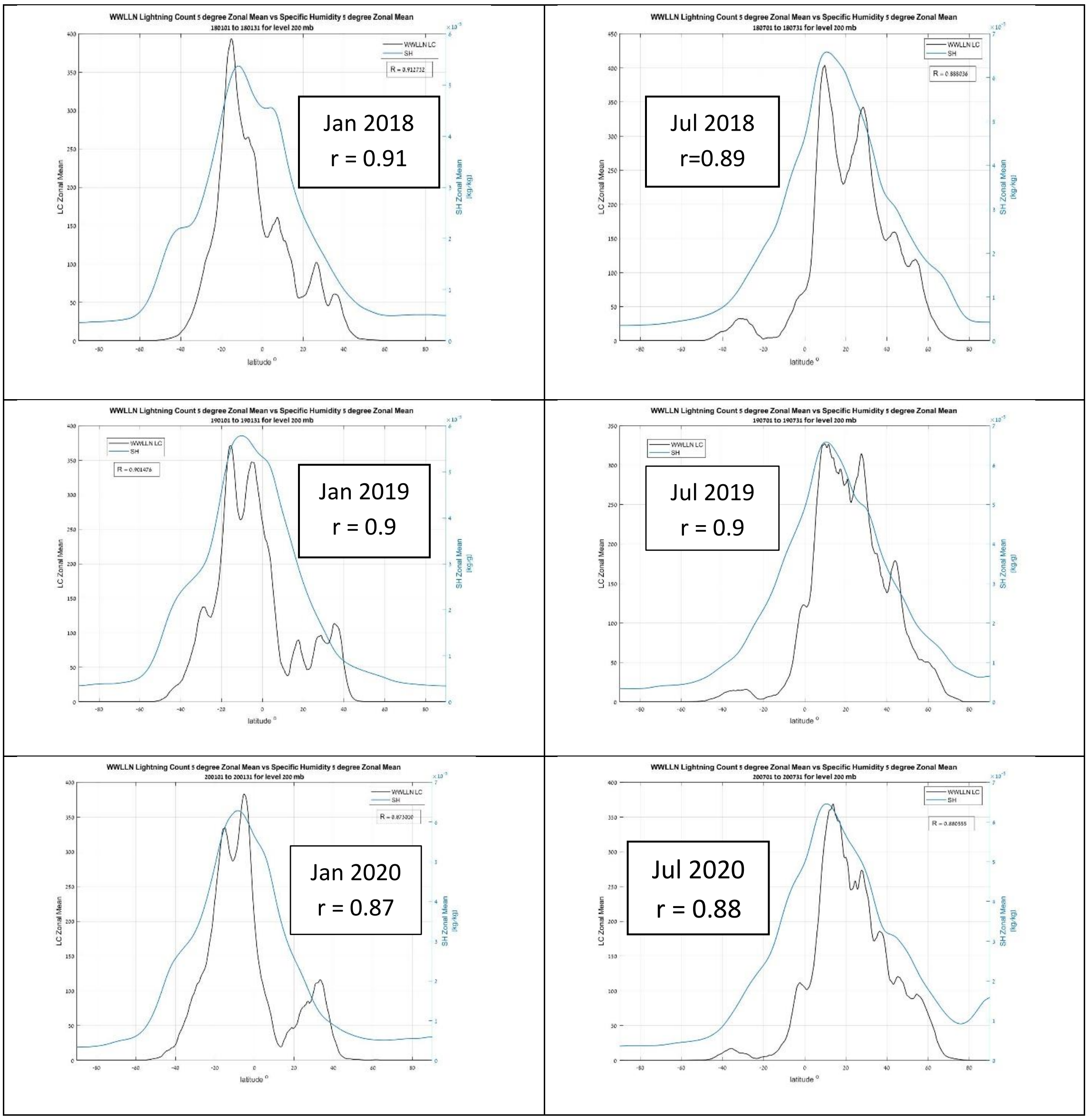

Figure 1: Zonal mean distributions of lightning flashes (WWLLN) (black curves) and specific humidity (SH) (blue curves) from the ERA5 reanalysis. January (left panels) and July (right panels). The rows represent different years, 2018 (top), 2019 (middle) and 2020 (bottom).

As mentioned earlier, the "cold trap" of the atmosphere at the tropopause helps trap in the atmospheric water vapor by freeze-drying the atmosphere at that altitude, producing ice crystals that precipitate back down towards the surface. This can be observed in Figure 2, where we show the zonal distribution of lightning in January 2019 (same in all three panels) together with the SH zonal distribution at 200 mb (bottom panel), 125 mb (middle panel), and 100 mb (top panel).

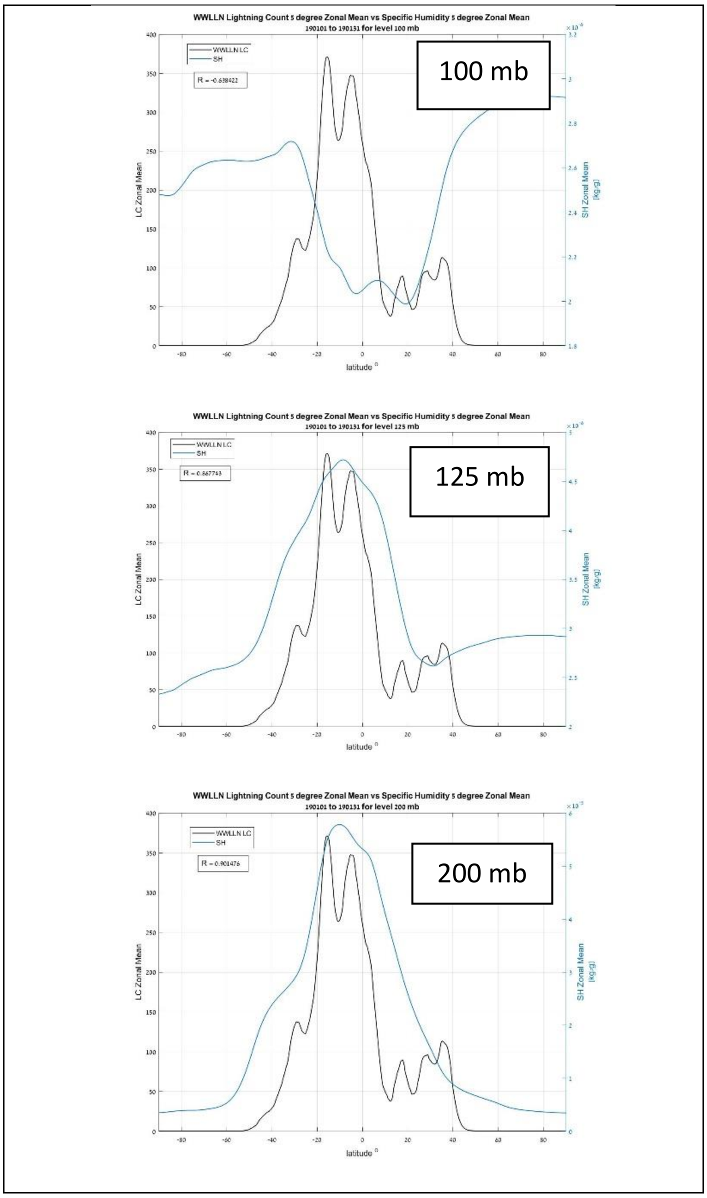

Figure 2. January 2019 lightning counts and SH at 200 (bottom), 125 (middle), and 100mb (top) pressure levels.

The water vapor distributions at 200 mb and 125 mb show the expected maxima in SH in the tropics, matching the location of the thunderstorm activity. However, as we move into the stratosphere (100 mb) there is a sudden drop in the SH concentrations due to the water vapor being converted to ice crystals and precipitating out of the atmosphere. In Figure 3 (top panel), a minimum in SH is observed in the tropics, with the concentrations of SH in the extra-tropics much larger than the SH in the tropics, opposite to what is observed in the upper troposphere.

This cold trap can also be seen in Figure 3, where we see similar zonal profiles in SH and the temperature at 100 mb. The temperatures in the tropics reach -80C, more than 30 degrees colder than midlatitude temperatures at the same pressure level. These extreme temperatures result in the freeze-drying of the tropical atmosphere, shown by the minimum SH concentrations in the tropics at 100 mb (Figure 3).

These observations of decreases in UTWV and temperature at the tropopause level were first mentioned by Brewer (1949). Holton and Gettelman (2001) gave theoretical explanations for this phenomenon. Higher SH air moves up in the tropopause region during the upward-displacement phase in deep convection. However, this upward motion causes adiabatic cooling of the air that limits the water vapor amount entering the stratosphere.

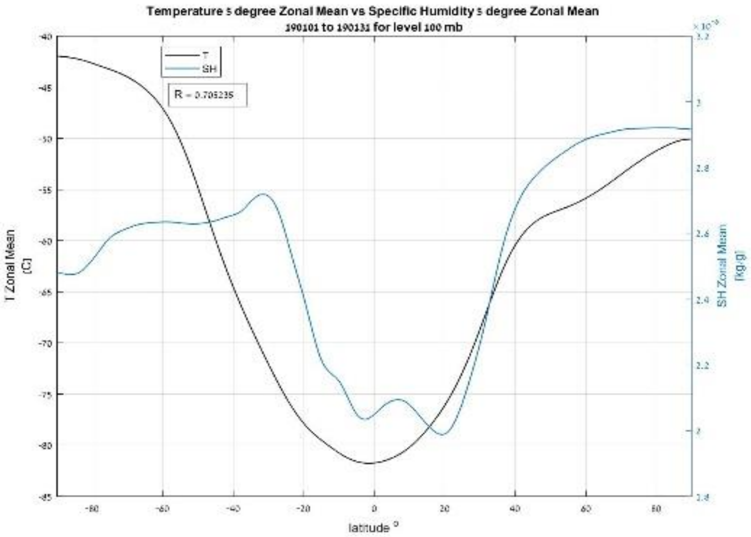

Figure 3. Zonal mean temperature and SH at 100 mb in January 2019 from the ERA5 dataset.

4. Discussion and Conclusions

In this study, we revisit the topic of the moistening of the upper troposphere due to deep convection and thunderstorms. We have used the global lightning data set from the WWLLN network as a proxy of thunderstorm activity around the globe. At the same time, the UTWV is obtained from the specific humidity estimated from the ERA5 reanalysis. Changes in UTWV can result in important climate feedbacks and is an important research topic.

We have looked at the zonal mean distributions of lightning activity and SH in the upper troposphere and lower stratosphere. We observe a very close relationship between the monthly lightning (thunderstorm) and the spatial and temporal changes in SH in the upper troposphere. The best agreement occurs for SH at 200 mb (~12km), with a correlation coefficient between the zonal mean distributions being around 0.9. On a monthly mean, the SH is advected away from the source regions, and hence the SH shows a smoother zonal distribution than the lightning data. The analysis shows that both lightning and SH increase between January and July, with July values of both parameters 20% greater during July as compared with January.

As we move past the tropopause into the stratosphere (100 mb), we see a significant drop in tropical SH due to the extremely cold temperatures (-80C) at those altitudes. The cold temperatures result in a "cold trap" that dries the air from moisture, producing ice crystals and cirrus clouds. These ice crystals can precipitate to lower levels and hence do not enter the stratosphere. Both water vapor and cirrus clouds act to trap infrared radiation emitted at the Earth's surface, and hence both act to reduce the outgoing longwave radiation (OLR) from the Earth. Hence, any future increase in thunderstorm activity (Price and Rind, 1994) would imply more UTWV and cirrus clouds in the tropical tropopause region, with implications for positive feedbacks on the climate system.

One of the critical mechanisms for understanding global climate change is the development of tools and techniques that allow continuous and long-term monitoring of processes affecting and being affected by the global climate. The ability to monitor small changes in UTWV and sub-visible cirrus clouds is not easy given the difficulty of continuous global measurements of both parameters. However, global lightning networks (ground or satellite) are becoming more available to the scientific community (Figure 5a). Given the results in this study, we propose using lightning data as a proxy for tracking the variability and trends in UTWV (Figure 5b) and maybe even global cirrus clouds. In previous studies (Price, 2000; Price and Asfur, 2006), the global lightning data used was from ELF networks that cannot provide spatial resolution of thunderstorms around the globe. In recent years, numerous VLF networks have been developed (WWLLN, ENTLN, GLD360) to supply valuable real-time data on lightning activity around the world. In addition, in recent years, we have started to see lightning sensors on geostationary satellites (Rudolsky et al., 2019). In the coming years, more geostationary satellites with lightning sensors will appear.

Recently, lightning has also been assigned by the World Meteorological Organisation (WMO) as an essential climate variable (ECV) (Aich et al., 2018) due to its importance in climate science. In conclusion, we propose that lightning data can be used in studying changes in upper tropospheric water vapor, cirrus cloud formation, and the drying of the stratosphere, all of which are significant for climate change and climate feedbacks.

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Data availability statement: No new data were used in this paper. All data have been previously published. The lightning data (wwlln.net) have been published before by many others (Dowden et al., 2002; Lay et al., 2004; Virts et al., 2013). The authors wish to thank the members of WWLLN for generously contributing their data to this network. The specific humidity and temperature data have also been published before as part of the ECMWF Copernicus Climate Data (https://cds.climate.copernicus.eu) (Hersbach et al., 2020).

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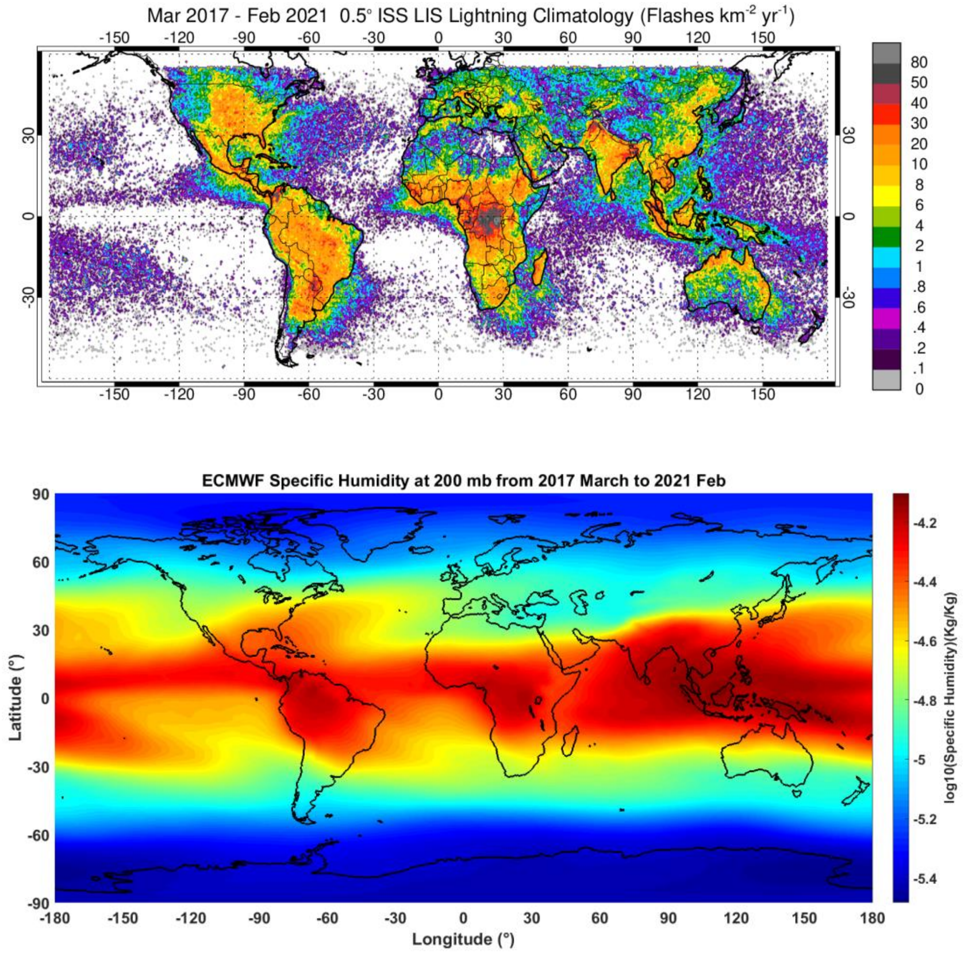

Figure 4: Four years (Mar 2018 – Feb 2021) of a) satellite lightning data from the LIS-ISS sensor (Blakeslee et al., 2020), and b) SH at 200mb for the same period. Note that the color bars are presented on a log scale.

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