An Analysis of Mid-Tropospheric Carbon Monoxide Concentrations Through Climatology, Anomalies, and Transport

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Abstract

This study provides evidence on how anomalously high concentrations of mid-tropospheric carbon monoxide (CO) can be quantified by statistically analyzing 15 years of 500hPa CO volume mixing ratio (VMR) data observed by the Atmospheric Infrared Sounder (AIRS). By creating a linearly regressed CO climatology over the 2003-2017 time period and statistically comparing it to daily observed CO VMR values, both the spatial distribution and the intensity of mid-tropospheric CO anomalies can be visualized, along with their horizontal transport by analyzing ERA-Interim wind data. In addition, for reasons that the linear regression acted to adjust the climatology for anthropogenic changes in CO emissions, it can be stated that wildfire CO emissions are the likely source of these quantified anomalies. Lastly, due to transport issues, the current methodology does not support evidence that these CO anomaly products can automatically detect wildfire point locations. However, these CO anomaly products could still be used to study variations in the distribution of wildfire emissions caused by various large-scale climate processes.

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Secondly, I wanted to express my appreciation for my incredible wife, Katelynn Jeffery, who has withstood the multitude of hardships suffered while earning my MS degree. She has showed kindness, love, and tolerance during times of extremely instability that has characterized my graduate experience. I'm very grateful to be married to such an incredible woman and hope to use the tools I've acquired here to provide for her in the future!

Thirdly, I believe it's important to thank my Grandmother, Elenor Frame, who gave me the love and nurture that allowed me to become the person I am today. Without her support, I would not have been able to overcome the adversity that I experienced during my childhood. Although she is far away, I will always remember her as the one family member who gave me the most encouragement to succeed in life.

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List of Acronyms

AIRS	Atmospheric Infrared Sounder
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EOS	Earth Observing System
hPa	hectopascal
NASA	National Aeronautics and Space Administration
O_3	Ozone
V6	Version 6
VMR	Volume Mixing Ratio

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Chapter 1: Introduction

1.1) What Is Carbon Monoxide?

Very few trace atmospheric gases bring as much reaction from the general public as carbon monoxide (CO). With the ability to gently kill people in their sleep, this odorless and colorless gas is often in the news media due to reports of various injuries and deaths. In short, CO is created during combustion of carbon-based fuels in hypoxic (oxygen-starved) environments. Instead of forming carbon dioxide (CO_2) during the combustion process, carbon monoxide (CO) is formed due to the lack of available oxygen molecules (https://www.epa.gov/).

Among indoor environments, the largest source of CO comes from the operation of hydrocarbon-fueled appliances in poorly ventilated rooms (https://www.epa.gov/). In Outdoor environments, CO pollution comes from a mixture of anthropogenic and natural sources, with the largest emissions coming from transportation, industry, biomass burning, and wildfires. In addition, it is important to note that outdoor CO concentrations generally remain far below the threshold for CO poisoning, except in areas covered in thick smoke from wildfires or heavy urban pollution (https://earthobservatory.nasa.gov/).

1.2) Why study carbon monoxide?

Given that carbon monoxide can highlight various emissions from carbon-based combustion throughout the world, one can clearly envision its usefulness to earth science. In fact, one of CO's best qualities is its lifetime in the atmosphere. Due to its unique physical properties, CO tends to hang around from about one to three months, meaning that the gas can be used as a "tracer" of air pollution. This is important, since the gas

lingers long enough to travel with large-scale circulations around the world (https://earthobservatory.nasa.gov/).

As discussed above, CO has an optimal lifetime to be used as a tracer of air pollution, thus allowing the gas to be used in transport studies. However, CO is also important from a chemical standpoint as well. According to Chin et al. (1994), CO plays an important role in the formation of tropospheric ozone (O_3), a primary air pollutant, which forms due to various photochemical processes. In summary, this mean that higher CO concentrations generally indicate higher amount of air pollution, thus making CO observations very useful to atmospheric scientists.

Now that it's been established that CO is a both important to transport and air pollution studies, it is necessary to specify its importance to studying wildfires. According to Warner et al. (2013), incomplete combustion often leads to CO emissions that are far above the background concentrations, thus making CO an important tracer to sources of fossil-fuel burning, biomass burning, and chemical production by hydrocarbon oxidation processes. Due to this fact, it can now be stated that observations of CO concentrations make a great proxy for detecting the existence of wildfires throughout the world.

1.3) Research objectives for this study

As discussed in the previous section, there are many motivating factors in studying carbon monoxide with regards to earth science. For this research study, a relatively broad approach was taken to analyze 500hPa CO concentrations from a global standpoint. Overall, the main objectives of this research are to create a multiyear

climatology for mid-tropospheric CO, analyze it for trends, and then use it to identify CO anomalies throughout the globe.

Lastly, it is important to specify that the study was completed for the 2003-2017 time period. By statistically analyzing 15 years of data, a climatology can be created to represent expected background values and variability for 500hPa CO VMR across the entire globe. In Sequential order, all research tasks are listed below, along with their respective objectives.

a) Create a multi-year climatology for mid-tropospheric CO concentration levels using statistical analysis of multi-year 500hPa CO VMR observations

b) Quantify mid-tropospheric CO VMR anomalies by statistically comparing daily observed 500hPa CO VMR values to the climatology

c) Analyze the transport of mid-tropospheric CO anomalies throughout the globe using 500hPa reanalysis wind data

d) Investigate applications for the CO climatology, Anomalies, and Transport products developed during the research process.

Chapter 2: Methodology

2.1) Instruments, datasets, and processing tools

To begin the methodology section, it is pertinent to discuss the data, instruments, and processing tools utilized during this research study. In order to study carbon monoxide concentrations throughout the globe, the Atmospheric Infrared Sounder (AIRS) was used, which is an across-track scanning instrument aboard NASA's Aqua

polar-orbiting satellite. As part of the NASA's Earth Observing System (EOS), this satellite is one of the A-train of satellites that began launching in 2002 to study the planet in greater detail. In Figure 1.1, an illustration of the A-Train constellation is shown, where Aqua is the third satellite from the right (https://eospso.nasa.gov/).

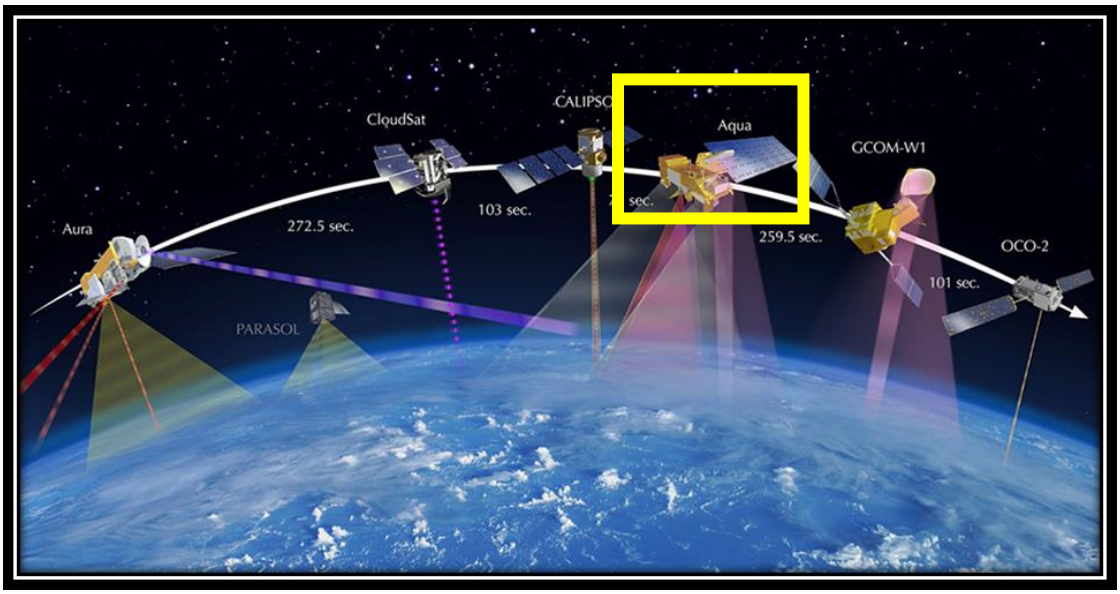

Figure 1.1: A-Train Satellite Constellation (https://atrain.nasa.gov/)

As far as technical specifications, the AIRS instrument has a 13.5 km sensing footprint (at nadir) and a 45 km level-2 resolution due to cloud-clearing techniques (Susskind et al., 2003). Furthermore, the specific dataset used for this study was gridded (level-3) CO volume mixing ratio (VMR), which has a one-degree resolution and uses the V6 retrieval algorithm. Lastly, it is important to note that all CO VMRs were studied at the 500hPa pressure level, for reasons AIRS has the best CO sensitivity in mid-troposphere (Warner et al., 2007).

The second source of data used was ERA-Interim reanalysis data, which was created by the European Centre for Medium-Range Weather Forecasts (ECMWF). In

overview, the ERA-Interim is a recreation of past atmospheric conditions (dating back to 1979) and wields a resolution of 0.75 degrees. Furthermore, the reason for choosing the ERA-interim dataset was to utilize its wind data in the study of CO transport around the world (Dee et al., 2011).

To conclude this section, it is necessary to reveal which data processing tools were utilized to complete the research objectives. For this study, the Python 3.7 ecosystem (https://www.python.org/) was used to complete all programming tasks. As far as data processing, the SciPy python package (https://www.scipy.org/) was used in order to import, manipulate, and export all datasets. In addition, all custom figures were generated using the Cartopy geospatial python package (https://scitools.org.uk/cartopy/) and Matplotlib data visualization python package (https://matplotlib.org/).

2.2) Creating a multi-year climatology

The first and most important stage of this research study was to create a 500hPa CO climatology for the 2003-2017 time period. In quick overview, this dataset was created to accurately estimate 500hPa CO background concentrations and their respective variabilities across the globe. Lastly, this CO climatology was also designed to quantify regional changes in CO concentrations over the multiyear period.

To explain in greater detail, the 500hPa CO VMR climatology was created for each calendar day, ranging from January 1st through December 31st. Furthermore, in order to add reduce temporal noise in the climatology, 30 days of CO VMR data was used centered over each calendar day. In brief, this means that the CO climatology for January 31th was created using the last two weeks of January and the first two weeks of

February. Lastly, it is important to note that all climatology variables are calculated at each grid point, thus reducing spatial noise due to regional differences in CO concentrations observed throughout the globe.

Furthermore, after considering that CO concentrations had changed over the 2003-2017 time period, a linear regression was completed in order to account for variations in anthropogenic CO emissions. From this regression, a grid of slopes, y-intercepts, R-values, and p-values were calculated for the entire planet to give insight on how 500hPa CO VMR changed over the 15-year period. As explained later in this section, these regression variables were then used to calculate a regressed mean, yearly trend, and significance for 500hPa CO VMR on each calendar day.

As a starting point, both the CO VMR slopes and y-intercepts were used to create a regressed 500hPa mean CO VMR for the entire globe. In brief, this climatology product is the best estimation for background CO concentrations while still accounting for yearly trends among the 2003-2017 time period. If a region had persistently high CO VMR observed over the 15-year period, then the regressed 500hPa CO VMR mean values were returned at a maximum. Conversely, in areas with low CO VMR observations over the 15-year period, then the regressed 500hPa mean CO VMR values were returned as a minimum.

To illustrate this quantity, Figure 2.1 shows an example of a regressed 500hPa CO VMR for August 14, 2017, where cool colors indicate lower CO VMR and warm colors indicate higher CO VMR. As expected, the highest mean CO VMR values are seen over the continents due to both natural and anthropogenic sources of CO over land.

Meanwhile, the open oceans are characterized by having the lowest mean CO VMR values thanks to a lack of CO emissions over water.

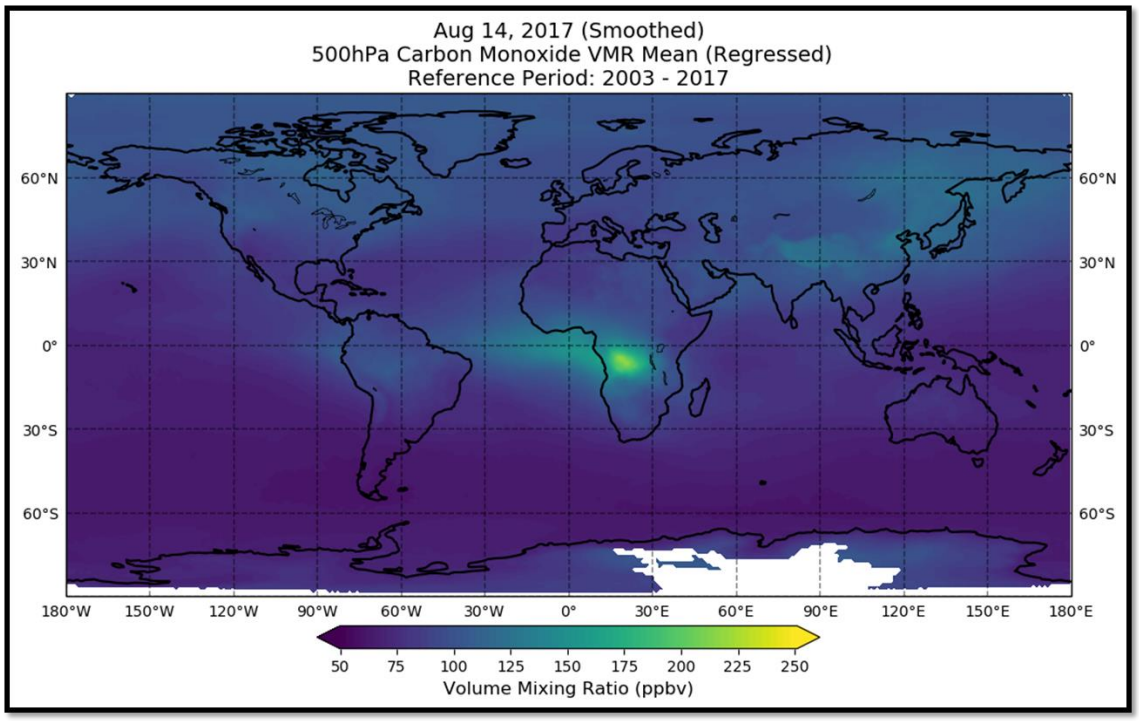

Figure 2.1: Regressed 500hPa mean CO VMR for August 14, 2017

The second major CO climatology product created is the standard deviation of 500hPa CO VMR over the 15-year period. In order to quantify variability in 500hPa CO VMR across the globe, this product was created to represent expected variability in CO concentrations at each grid point for any given time of year. In regions of the world where CO concentrations changed sporadically over the multi-year period, standard deviations were large due to significant variations in year-to-year CO emissions. Conversely, in regions with small year-to-year changes in CO emissions, standard deviations remained low in value.

In Figure 2.2, 500hPa CO VMR standard deviations are shown for August 14th, 2017, where cool colors represent lower CO VMR variability and warm colors represent higher CO VMR variability. As expected, the largest CO VMR standard deviation values occurred over the continents, especially in areas of large biomass burning and regions with large swaths of burned vegetation. Meanwhile, CO VMR standard deviations remained lower over the oceans due to the relatively small amount of CO emissions and transport over open water.

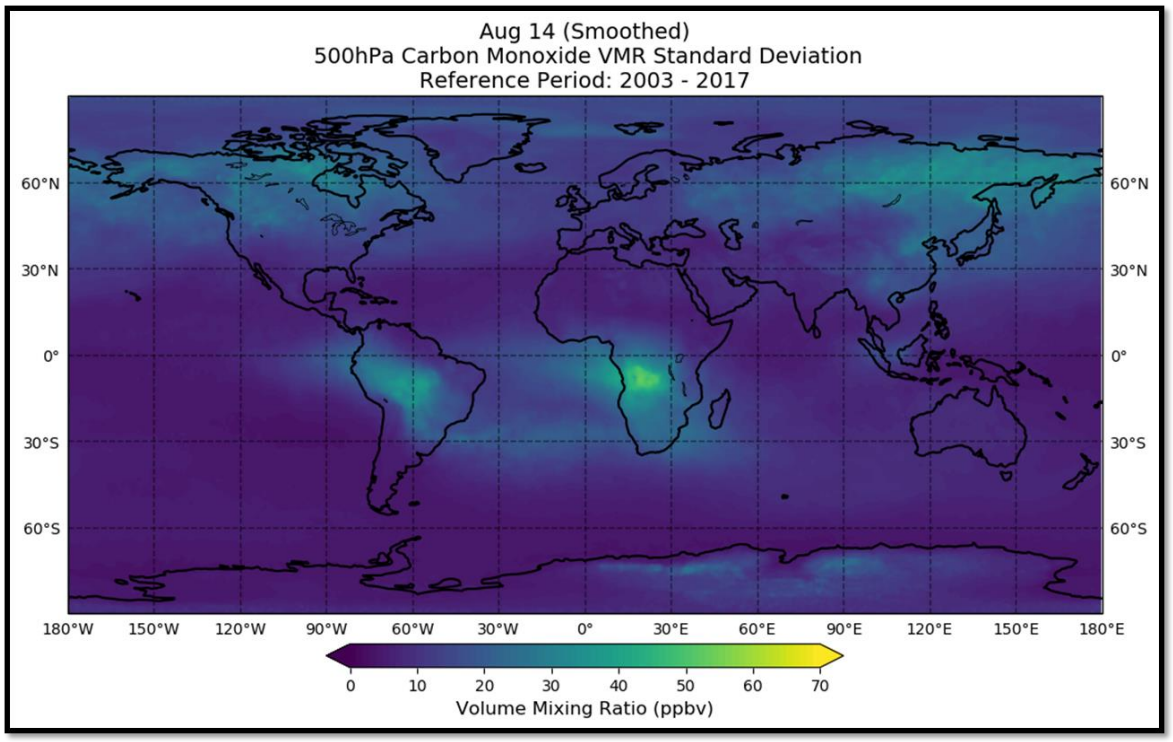

Figure 2.2: 500hPa CO VMR standard deviation for August 14th

In addition to quantifying typical CO concentrations and variability, the last two climatology products that arose from this study are annual CO VMR trends (slope) and their respective significance [(1 – p-value) * 100]. From these yearly trends, both

regional and seasonal changes in CO VMR can be highlighted, thus providing potential insight into multi-year variations in CO emissions throughout the world.

Figure 2.3 shows yearly trends for August 14th, where blue colors indicate regions of decreasing 500hPa CO VMR and red colors indicate areas of increasing 500hPa CO VMR values. As expected, the areas of the world with the greatest increase in CO concentrations are seen in developing regions of the world such as Central Africa where biomass burning is still prominent. On the other hand, regions with the largest decrease tend to be rapidly industrializing nations such that have been working to reduce air pollution, such as China.

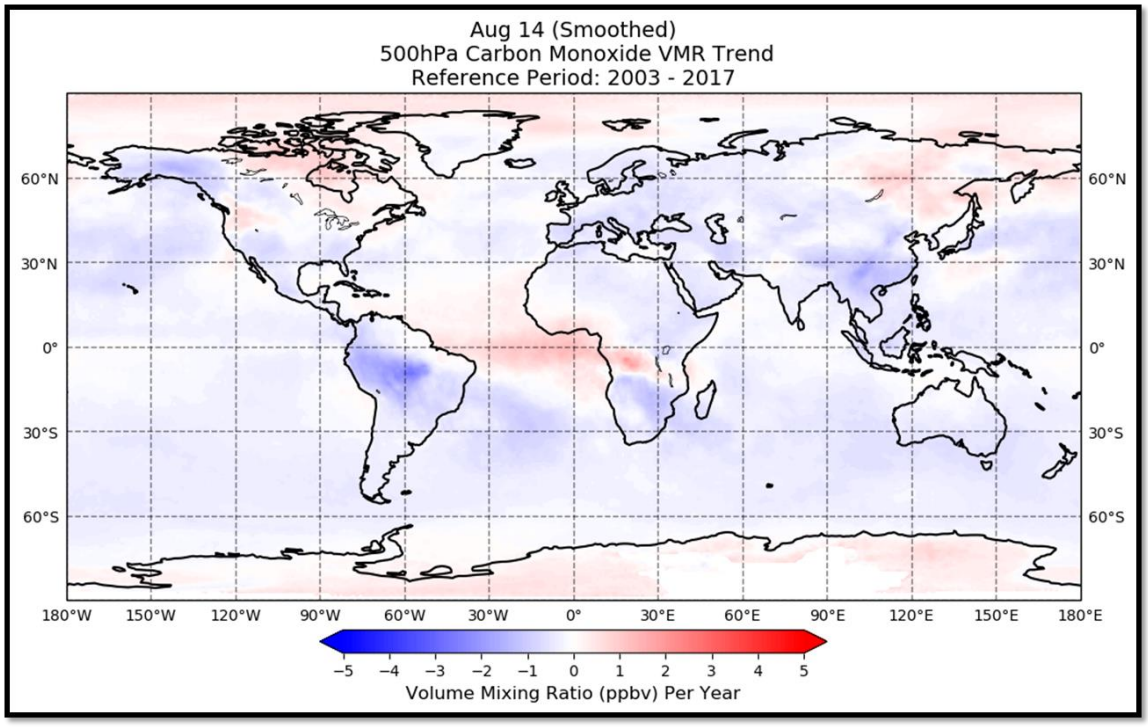

Figure 2.3: 500hPa CO VMR yearly trends for August 14th

In conjunction with 500hPa CO VMR yearly trends, the quantity of "significance" is an essential climatology product that confirms the statistical probability of the CO

VMR trends not occurring at random. Strategically, by using 30 days of CO VMR data centered for each calendar day, the significance was able to remain high in both areas of positive and negative trends. Additionally, after comparing Figure 2.3 to Figure 2.4, it can be seen the high significance (blue) correspond directly to areas of strong trends, while areas of low significance (red) correspond to weak trends. In summary, this means that areas trend maxima and minima confidently indicate changes in both natural and anthropogenic CO emissions.

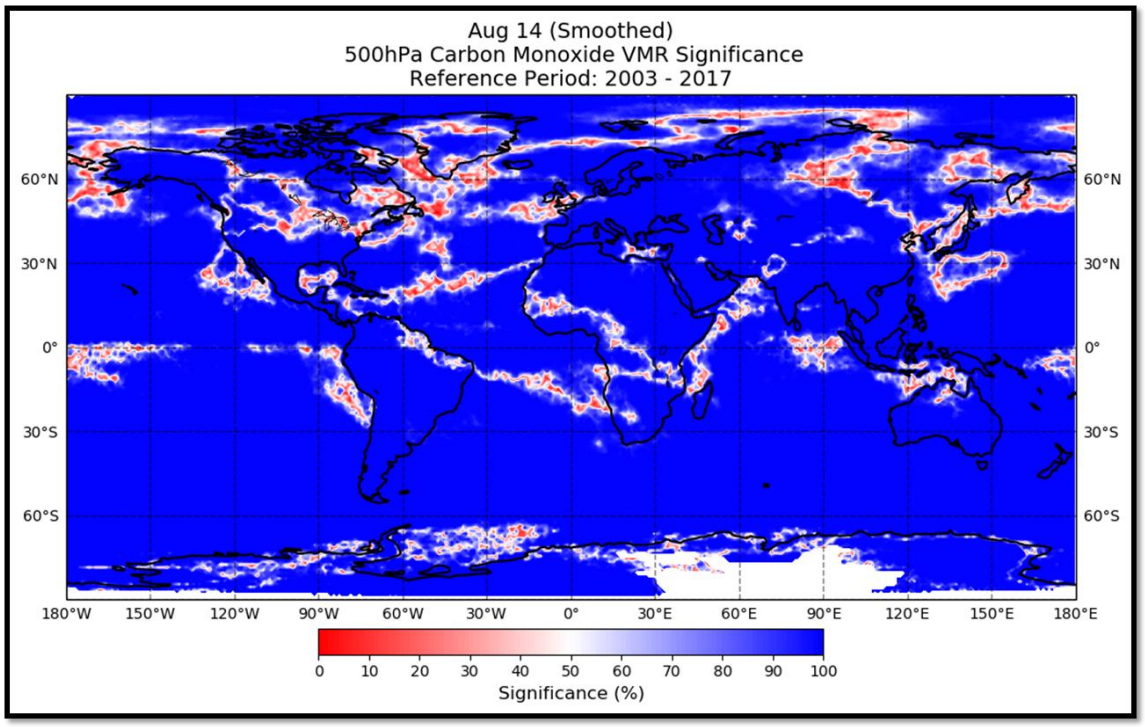

Figure 2.4: 500hPa CO VMR yearly trend significance for August 14th

2.3) Quantifying and tracking CO anomalies

After creation of a CO climatology, the next research objective was to quantify anomalous CO concentrations for each day over the 2003-2017 time period. Furthermore, after considering that the linear regression of CO VMR was completed to adjust for

changes to anthropogenic emissions, it can be stated that anomalous plumes of CO likely indicate emission from wildfires. As a result, these emissions plumes can then be tracked using daily-averaged wind data from the ERA-Interim reanalysis dataset. In summary, by plotting streamlines at the 500hPa pressure level, the transport of anomalous CO concentrations can be visualized, thus giving more insight to the source of those emissions.

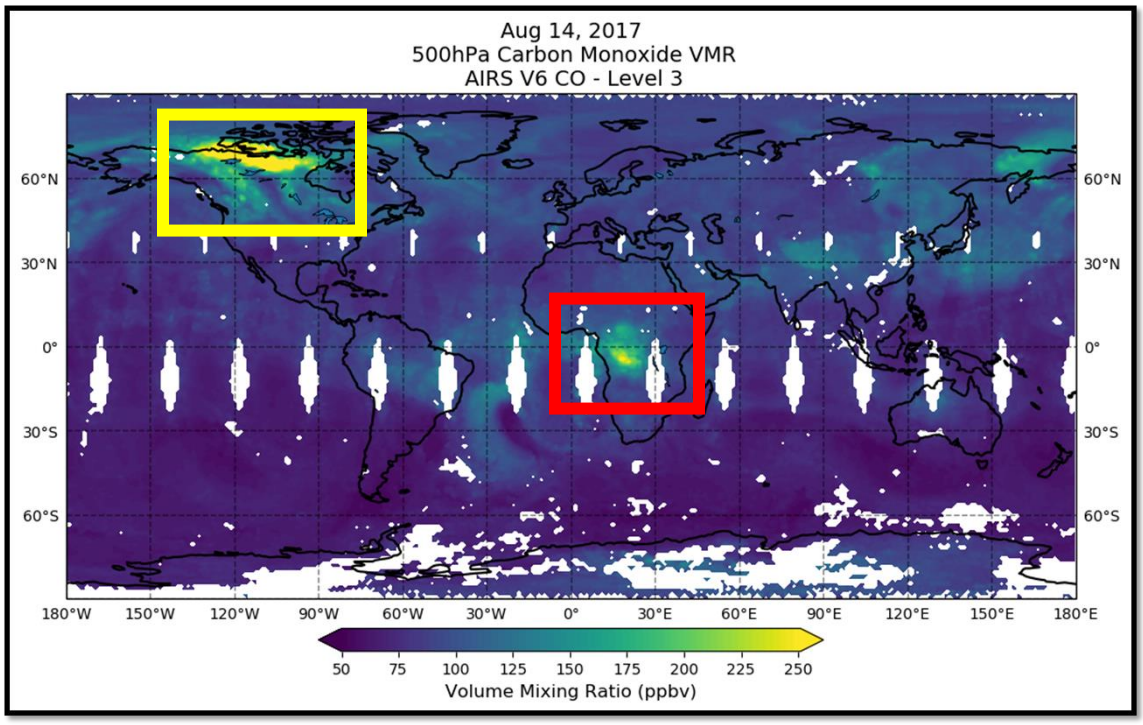

Figure 2.5: 500hPa Observed CO VMR for August 14, 2017

Next, it is essential to justify the motivation for quantifying CO anomalies. In Figure 2.5, which shows the observed 500hPa CO VMR values for August 14th, 2017, a maximum of CO concentrations can be seen in both Africa and North America. However, without any climatological context, there is no way to tell whether these plumes of high

CO VMR are typical. Thus, a comparison between daily-observed CO and its respectively climatology was needed to signify anomalous CO concentrations.

In more detail, CO anomalies were calculated by subtracting the regressed mean CO VMR from the observed CO VMR, then dividing by the standard deviation at each grid point. This numerical method, while simple in nature, was successful in quantifying CO anomalies, where larger values (standard deviations) indicate the anomalously large CO concentrations. In Figure 2.6, both 500hPa CO VMR anomalies and streamlines were plotted for August 14th, 2017, where red colors represent weak anomalies and yellow colors represent strong anomalies. By comparing Figure 2.5 to Figure 2.6, it is shown that the high CO VMR seen over Africa is not anomalous, while the plume of high CO VMR over North America is determined to be significant anomaly that originated over the northwestern part of the continent (based upon streamlines).

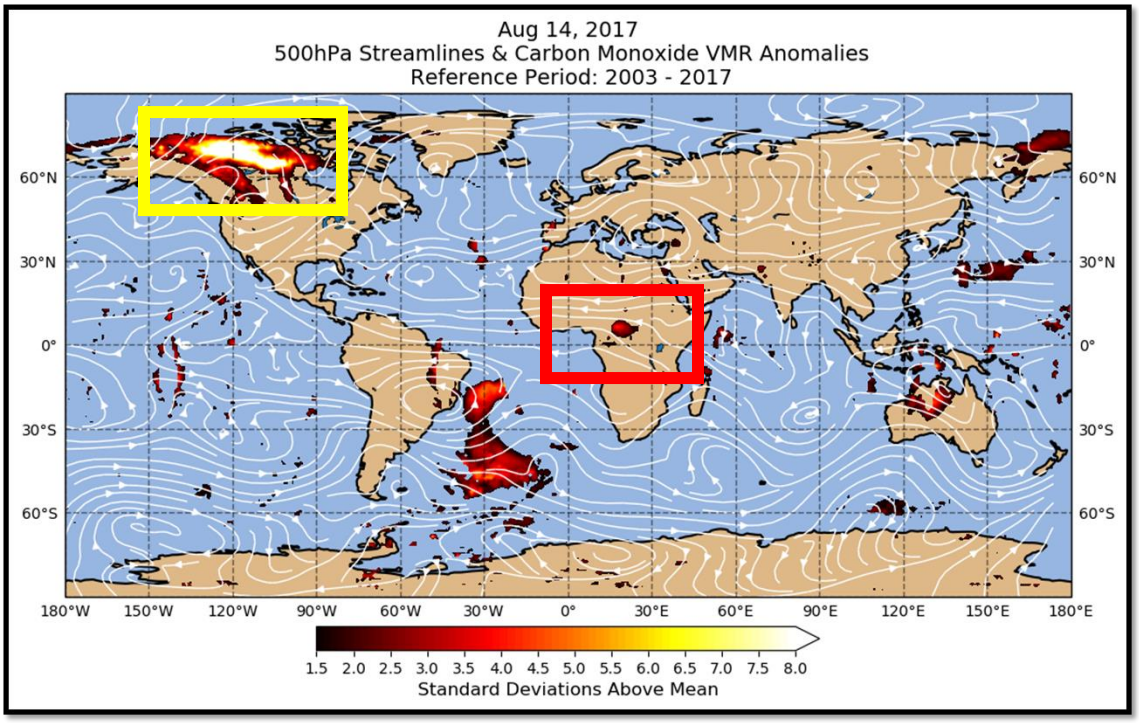

Figure 2.6: 500hPa CO VMR Anomalies and Streamlines for August 14, 2017

Chapter 3: Results

3.1) Analysis of CO climatology

As explained in section 1.3, one of the major objectives for this research was to create a CO climatology that accurately represented CO concentrations and variability throughout the globe. Therefore, an important component of this project was to analyze the CO climatology for accuracy and to investigate regional changes in CO concentrations.

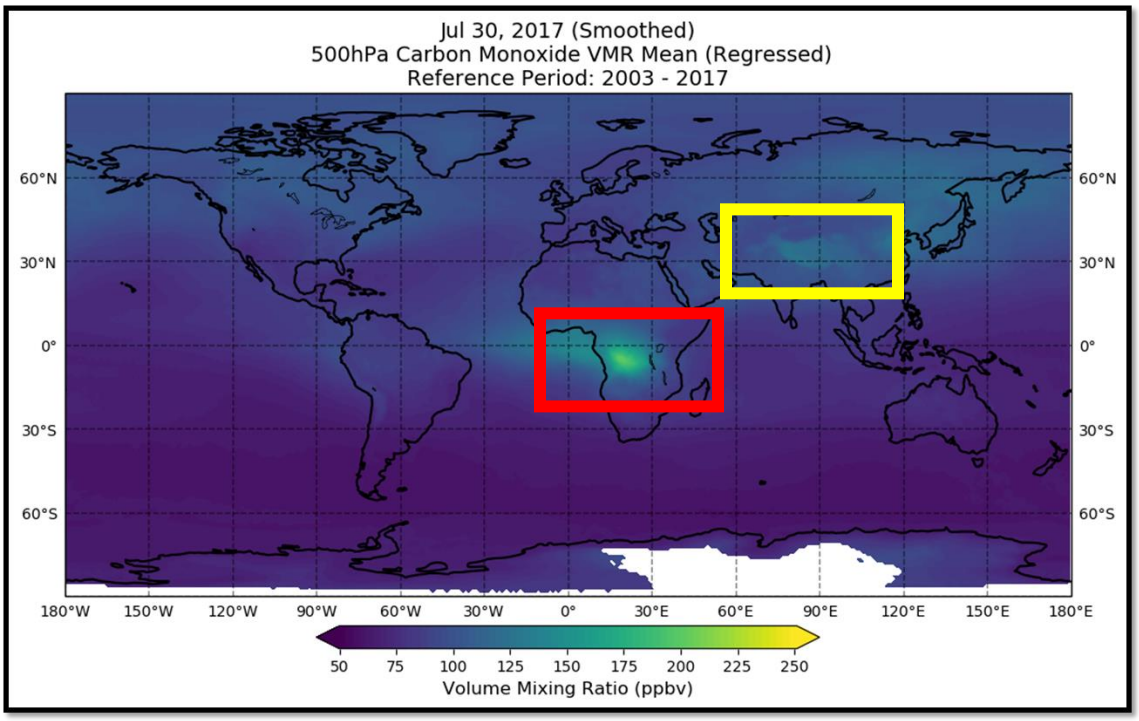

Figure 3.1: Regressed 500hPa mean CO VMR for July 30th, 2017

To begin with this climatological analysis, the first product to be investigated was the regressed 500hPa mean CO VMRs. For reasons that these products were produced from a linear regression and smoothing techniques, some error is expected when estimating historical background CO concentrations. However, after analyzing this

quantity over the 2003-2017 time period, it is fair to say that the regressed 500hPA CO VMR does a fantastic job at picking up on known features in CO emissions.

Figure 3.1 is shown to illustrate regressed 500hPa CO concentrations for July 30th, 2017. In this example, two maxima of 500hPa CO VMR are seen over both Africa and the Himalayan Mountains. As expected, the CO VMR maximum over Africa is known product of large-scale biomass burning that includes both natural (Savannah fires) and anthropogenic (agricultural/biofuel) emissions (Kituyi et al., 2005). Additionally, the maximum of CO VMR over the Himalayan Plateau is a direct result of anthropogenic air pollution getting transported upslope from the sub-continent of India (Yasunari et al., 2010).

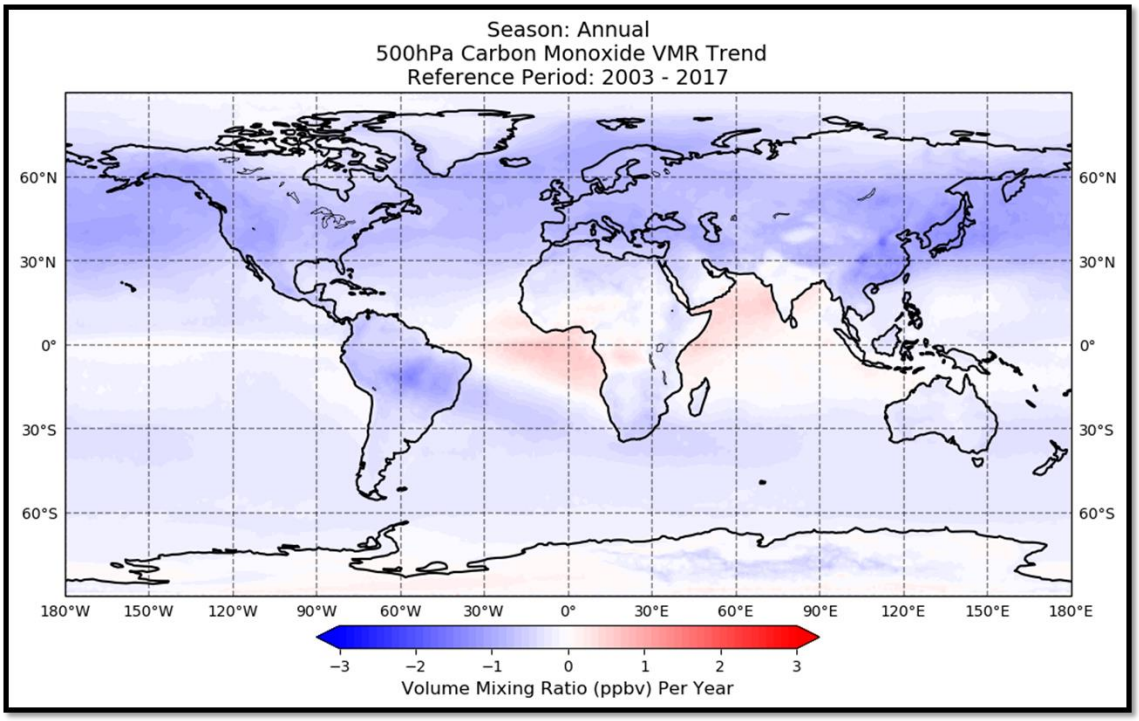

Figure 3.2: 500hPa CO VMR trends for the entire calendar year (2003-2017)

Another important result from analyzing the CO climatology comes from the 500hPa CO VMR trends product. Due to the high significance of trend maxima and minima (as discussed earlier), these 500hPa CO VMR trends can be used to diagnose worldwide changes in CO concentrations over the 2003-2017 time period. In Figure 3.2, which shows CO VMR trends averaged for the entire calendar year, it is shown that CO concentrations are falling throughout most of the world. Conversely, in the developing world, such as Central Africa and India, it appears that CO concentrations may be increasing. In conclusion, it is fair to say that the industrialized world has done an excellent job at cleaning up air quality over the 2003-2017 time period.

3.2) Analysis of CO anomalies

As explained in Section 1.3, the main objective of quantifying CO anomalies was to detect large wildfires and track their emissions throughout the globe. After all, one of the largest motivating factors behind this study is to develop applications based upon these results. Therefore, in order to validate whether wildfires can be detected by the CO anomaly products, a couple recent wildfire events were analyzed as confirmation.

The first event that will be discussed was a June 2017 wildfire that occurred within the European country of Portugal. According to Jones & Narayan (2017), the wildfire began on June 18th and quickly exploded in intensity due to a dangerous combination of warm temperatures, low-humidity, and strong winds. In aftermath, public officials declared this event as the "greatest wildfire tragedy of recent years", after 62 people died in their cars trying to flee the inferno (Jones & Narayan, 2017).

In order to investigate whether this wildfire was detected using the CO anomalies product, Figure 3.3 is given to show 500hPa CO VMR anomalies and streamlines for June 19th, 2017. In this image, an intense (yellow) plume of anomalous CO was located directly over the Portugal, which corresponds to the second day of the deadly event. In conclusion, it can be stated that the anomaly detection appears to work very well for isolated intense wildfires.

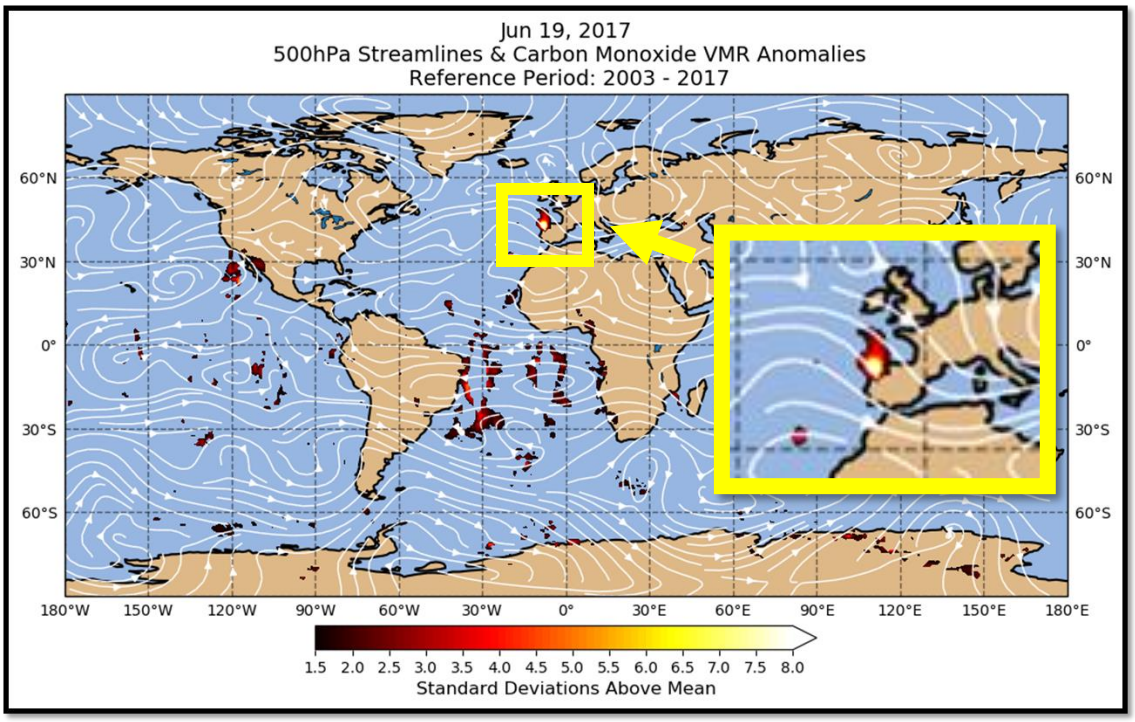

Figure 3.3: 500hPa CO VMR Anomalies and Streamlines for June 19th, 2017

The second major event that will be analyzed is the Summer of 2017 wildfire outbreak that overtook the Northwestern USA. During this extreme event, around 35 wildfires had flared up by the end of August 2017, leading to an ash cloud that covered the large areas of the Pacific Northwest. According to Stevens (2017), the infernos were so massive that Washington State had to declare a state of emergency from the poor air

quality alone. Overall, these series of large wildfires originated from an unusually dry summer, where the entire region went over 50 days without rainfall. This ultimately set the stage for uncontrollable fires given any source of ignition (Stevens, 2017).

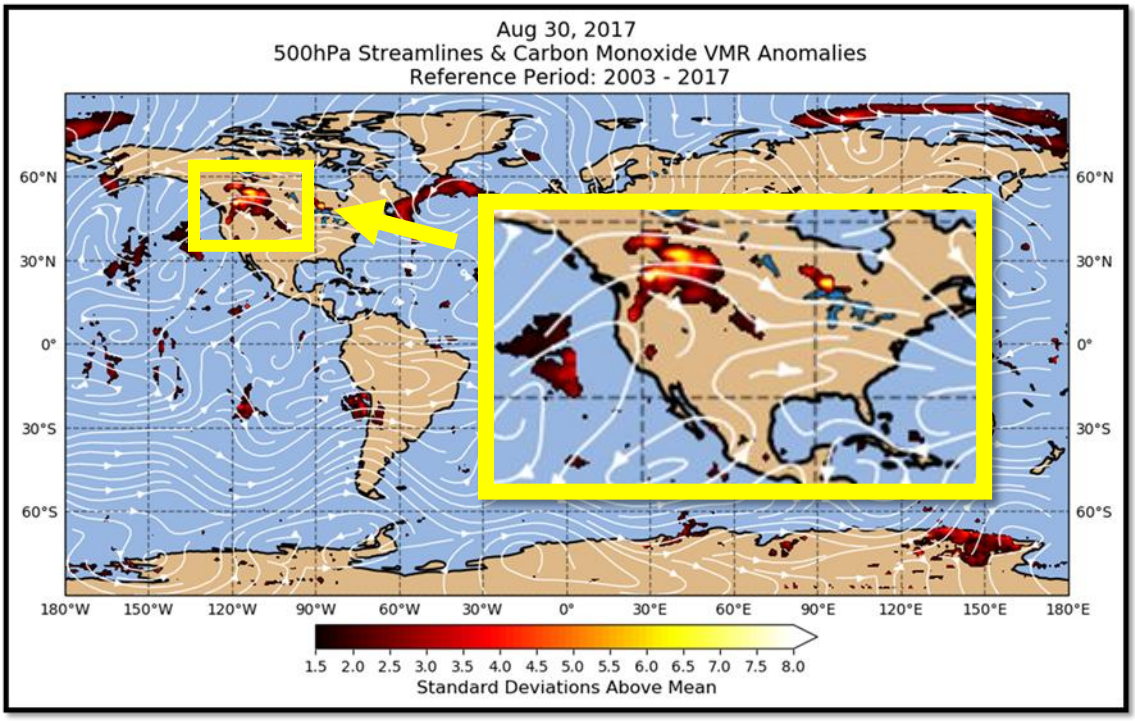

Figure 3.4: 500hPa CO VMR Anomalies and Streamlines for August 30th, 2017

In order to investigate this multi-fire event, Figure 3.3 is shown to illustrate 500hPa CO VMR anomalies and streamlines for August 30th, 2017. However, unlike the smaller Portugal wildfire, this event was much larger and widespread. This means that the massive CO plume is comprised of emissions from multiple wildfires at once. Therefore, even with the streamlines, it is difficult to determine the origin of any one of those wildfires. In conclusion, these CO anomaly detection products can successfully detect wildfire emissions, yet still cannot accurately display their location at the surface due to vertical and horizontal transport of CO downstream.

Chapter 4: Conclusions

Given the results discussed in section 3.2, it can be concluded that the CO anomaly products were successful in both quantifying and tracking wildfire emissions around the world. However, due to horizontal transport of CO by synoptic flow, these anomalies rarely persist over the point source of the fire. Therefore, it is not possible to make an automated wildfire detection system without a proper thresholding method.

As an alternative, the CO anomalies products could instead be used for climate research. Given that wildfire distributions often correlate to the arrangement of large-scale patterns, then it can be stated that spatial coverage of these CO anomaly plumes could be correlated with certain climate processes. By linking variables such as temperature, humidity, and winds to spatial distributions of anomalous CO levels, wildfire emissions could be matched to patterns such as El Nino, which largely affects the amount of biomass burned worldwide.

In conclusion, this research study was successful at creating an accurate CO climatology, discovering multiyear trends, and quantifying anomalies. Future research will likely focus on correlating climate indices alongside CO anomaly distributions. If wildfires are getting worse due to climate change, then these products can give additional insight to where and why those variations are occurring!

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