Ambient air pollution in the North-China and Indo-Gangetic Plains: role of regional meteorology and emissions

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Abstract

Air pollution is an inevitable global problem, harming both humans and the environment. Where pollution from fine particulate matter leads to more than 7 million premature deaths per year. This research quantifies and contrasts the magnitude, duration, and spatial characteristics of air pollution episodes over the North-China and Indo-Gangetic Plains for one entire year, 2019, and puts them into perspective by relating them to the regional anthropogenic emissions, thereby elucidating the role of meteorology in exacerbating or avoiding air pollution episodes in both regions. It does so by utilizing openly available gridded datasets of emissions and pollution concentrations from the European Centre for Medium-Range Weather Forecasts and involves statistical data analysis and visualization using the NCAR Command Language. Pollution forming efficiency was found to be significantly higher over the Indo-Gangetic Plain, especially in the winter months. Although both regions have similar aerosol concentrations, annual anthropogenic emissions are double over the Noth-China Pain. The accumulation potential is too high over the Indo-Gangetic Plain due to local meteorology, which means the region could never follow a similar pathway for development. It is recommended to further study the influence of local chemistry on gas to particle pollution, especially between the post-monsoon and winter months.

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Introduction

Air pollution from fine particulate matter leads to more than 7 million premature deaths per year according to the World Health Organisation (2019). This number can be expected to rise due to increased indoor and outdoor pollution. Yearly, 4 million people die from outdoor air pollution, of which 91% live in low- and middle-income countries (WHO, 2021a). The other 3.8 million yearly deaths are caused by indoor particle pollution. Fatalities happen through an indoor smoke hazard from people cooking and heating their homes with biomass, kerosene fuels, and coal (WHO, 2021b). Although only 3.8 people die directly from health complications due to pollution, 2.6 billion people are affected by indoor smoke (WHO, 2021b). The most affected regions are South-East Asia and Western Pacific regions.

Two regions in South-East Asia and the Western Pacific are the Indo-Gangetic Plain (IGP) and the North-China Plain (NCP), both home to the world's most polluted cities. IGP, with almost 10% of the global population living here, faces very high levels of air pollution in the form of fine particulate matter (mean diameter < 2.5 µm, PM2.5) (Mogno et al., 2021). This is mainly due to the promiment aggricultural sector, next to inefficient cooking and heating practices (Mogno et al., 2021). NCP, with a population of 400 million, is the home of many industrial cities, including the megacity of Beijing (Kang & Eltahir, 2018). Especially in these megacity clusters, there is heavy air pollution.

This research quantifies and contrasts the magnitude, duration, and spatial characteristics of air pollution episodes of both of these globally significant regions for one entire year, 2019, and puts them into perspective by relating them to the regional anthropogenic emissions, thereby elucidating the role of meteorology in exacerbating or avoiding air pollution episodes in both regions. Therefore, the research question is posed as “How do the frequency and intensity of air pollution episodes in the NCP and IGP depend on the distribution and strength of emissions?” Understanding the persistent characteristics of pollution episodes in these regions in the context of regional meteorology can contribute to effective policy making on emission reduction.

The research utilizes the openly available gridded datasets of emissions and pollution concentrations from the European Centre for Medium-Range Weather Forecasts (ECMWF, n.d.) and involves statistical data analysis and visualization using the NCAR Command Language (NCL).

Literature review

Written accounts prove that air pollution in was already recognized as a threat to human health around 400 BC, which is now approximately 2400 years ago. Hippocrates wrote in his book *'Airs, waters and places'* that air quality could be related to various illnesses, especially in cities. From approximately 65 AD onwards, air pollution was understood in Rome and around 1000 AD also in Central Asia along Silk Road and in the Arab world. Measurements from the 18th century onwards, further establish the relationship between air quality and urban or industrial areas in addition to the composition of gases and particulate matter. This relationship was accelerated through the industrial revolution and reached a peak in 1952 with the Great Smog of London, an event which lead to at least 4000 deaths. Although emissions used to be concentrated in Europe and North America, which now have controls of their emissions, the emissions have increased strongly in East and South Asia which rule the 21st century. Satellite remote sensing in addition to an established network of ground observations give us far more accurate measurements and a broader range of pollutants to study, which brings us to today (Fowler et al., 2020).

Now, air pollution is an inevitable global problem, harming both humans and the environment. It is defined as contamination of the environment by altering the native composition of the atmosphere through the emission of chemical, physical, or biological agents, and leads to more than 7 million premature deaths per year according to the World Health Organisation (2019). "WHO data show that almost all of the global population (99%) breathe air that exceeds WHO guideline limits (10 µg/m3) and contains high levels of pollutants, with low- and middle-income countries suffering from the highest exposures" (WHO, 2019). In addition to this human harm, air pollution drives environmental processes such as haze, eutrophication, ozone depletion, acid rain, climate change, and damage to nature including wildlife (MassDEP, n.d.).

Research on air pollution is in line with the Sustainable Development Goals (SDGs) from the United Nations, as a better understanding of air pollution can contribute to effective policymaking on emission reduction. More specifically, this is in line with SDG 3 "Ensure healthy lives and promote well-being for all at all ages"; with target 3.9 "By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination"; and 3.d "Strengthen the capacity of all countries, in particular developing countries, for early warning, risk reduction and management of national and global health risks" (UN, n.d.-a). As mentioned in the previous paragraph, emission reduction is next to improving human health and also positive for the environment, meaning the research is in line with SDG 13 "Take urgent action to combat climate change and its impacts"; with target 13.1 "Strengthen resilience and adaptive capacity" (UN, n.d.-b).

This literature review covers the health of air pollution, describes different key pollutants, and talks about the most polluted regions in the world. It then gives an in-depth description of the NCP and IGP.

More specifically, this includes a definition of the region, a description of the population, the region's economics, and local meteorology and pollution. The literature ends with a comparison of both regions and points out gaps in the available literature on comparative studies.

Health Effects of Air Pollution

From cities covered in smog to smoke inside our homes, this section elaborates on the different ways air pollution negatively impacts human health. 3.8 people die prematurely from indoor air pollution, and 4.2 million people die prematurely through outdoor air pollution every year (WHO, 2019).

Next to the 3.8 people that die prematurely, around 2.6 billion people are affected by indoor air pollution, which is also known as household air pollution. It is caused by cooking practices with solid fuels and kerosene. Solid fuels include sources such as "wood, crop wastes, charcoal, coal, and dung" (WHO, 2021b). Not only are these practices inefficient, but also generate high levels of household air pollution, sometimes 100 times higher than acceptable. This pollution can penetrate far into the respiratory system. Household air pollution attributes to illnesses such as cardiovascular- and respiratory disease and cancers. Examples of these are pneumonia, stroke, ischaemic heart disease, chronic obstructive pulmonary disease (COPD), lung cancer, and more (WHO, 2021b).

Outdoor air pollution, also known as ambient air pollution, is responsible for the death of approximately 4.2 people per year in 2016. It is mainly caused by transportation, household pollution, power generation, industry, and waste treatment. Just like indoor air pollution, ambient air pollution is linked to cardiovascular- and respiratory diseases, and cancers. "A 2013 assessment by WHO's International Agency for Research on Cancer (IARC) concluded that outdoor air pollution is carcinogenic to humans, with the particulate matter component of air pollution most closely associated with increased cancer incidence, especially lung cancer. An association also has been observed between outdoor air pollution and increase in cancer of the urinary tract/bladder" (WHO, 2021a).

Although health impacts from household and ambient air pollution are somewhat similar in composition, the actual health impact is strongly dependent on the types and concentrations of pollutants to which people are exposed. In addition, health impacts are also dependent on individual health and other characteristics (WHO, n.d.-a). "The children, elderly and pregnant women are more susceptible to air pollution-related diseases. Genetics, comorbidities, nutrition, and sociodemographic factors also impact a person's susceptibility to air pollution" (WHO, n.d.-a). However, there is still a possibility to see some differences between the health impacts of the two different pollution types. "WHO estimates that in 2016, some 58% of outdoor air pollution-related premature deaths were due to ischaemic heart disease and stroke, while 18% of deaths were due to chronic obstructive pulmonary disease and acute lower respiratory infections respectively, and 6% of deaths were due to lung cancer"

(WHO, 2021a). For household air pollution, some 45% of premature deaths were due to ischaemic heart disease and stroke, while 20% of deaths were due to chronic obstructive pulmonary disease, 8% of death were from lung cancer. The main difference in disease comes forward in the amount of pneumonia cases, which accounts 27% of the total share of premature deaths from household air pollution (WHO, 2021b).

Key Pollutants

Air pollution is different everywhere, and pollutants are emitted from a wide range of sources. These sources include industry, transport, agriculture, waste management, natural sources, and households. However, all these pollutants affect air quality in a way, some are emitted anthropogenically and others from natural sources. Air pollution can be categorized into two different classes, primary and secondary air pollution. Primary pollutants are emitted straight into the atmosphere, whereas secondary pollutants are generated within the atmosphere from already emitted gases through chemical reactions and physical processes (EEA, 2021). The following paragraphs will cover key primary and secondary air pollutants.

Key primary pollutants include particulate matter (PM), black carbon (BC), sulfur oxides (SO2), nitrogen oxides (NOx), ammonia (NH3), methane (CH4), non-methane volatile organic compounds (NMVOCs), and a range of metals (EEA, 2021). BC is one of the main components of PM, and a significant driver of global warming. BC contributes to processes such as glacier melting and environmental disruption (WHO, 2021a). It is mainly emitted from combustion (diesel) engines and the burning of solid fuels as well as forest and vegetation fires (Janssen et al., 2012). SO2 is also primarily emitted from fossil fuel burning, in this case for energy generation. The highest concentrations are near industrial facilities, and next to being a precursor for PM, it is also the main component of acid rain. 60% of the total SO2 emissions come from energy production and distribution. NOx is a group of gasses compromising nitrogen monoxide (NO) and nitrogen dioxide (NO2). It's not only emitted through fossil fuel burning just as SO2 and BC, but 40% of emissions come from road transport. NOx contributes to ozone and PM formation (EEA, 2021). NH3 is an industrial chemical which can be produced naturally from the decay of organic matter such as plants and animal waste. It is primarily used in the agricultural sector as fertilizer, but it is also used in the production of refrigerant gas, plastics, textiles, and pesticides (NYS, n.d.). CH4 is a primary component of natural gas and the second most abundant anthropogenic greenhouse gas. Even though CH4 is not the most abundant, it is 25 times more potent in capturing heat compared to carbon dioxide (CO2). CH4 is mainly emitted via the raising of livestock, but also through leaks from natural gas systems (EPA, 2021). Around 90% of total NH3 emissions and 80% of total CH4 emissions come from agricultural activities (EEA, 2021). Finally, there are the NMVOCs, a group of organic chemicals which usually translate to ozone and PM formation (Air Quality Expert Group, 2020).

“NMVOCs are mainly emitted from transportation, industrial processes and use of organic solvents” (EEA, n.d.).

Key secondary pollutants are ozone (O3), nitrogen dioxide (NO2), and oxidized volatile organic compounds (VOCs). Ground-level O3, which is different from the ozone of the ozone layer, is formed through a range of chemical reactions through sunlight including NOx, meaning it is most abundant in summer. Ozone is one of the main components of smog and can cause different health problems such as asthma, breathing issues and reduced lung function (WHO, 2021a). NO2 is a form of NOx, and as said before, is one of the main components of PM and O3. The main sources of emissions are also again fossil fuel burning and road transport (WHO, 2021a). Finally, there are the VOCs, which are mainly found through combustion emissions and when building construction materials. However, they are also found in household products such as wax, paint and paint strippers, cleaning products, and more (WHO, n.d.-b). They are similar to NMVOCs, as these are also a group of organic chemicals that usually translate to ozone and PM, but they exclude methane because it is not toxic.

Particulate matter

The previous paragraphs covered a range of pollutants, however, particulate matter (PM) is the most elaborately documented through its wide range of health risks. “Particles with a diameter of 10 microns or less (PM10), including fine particles with a diameter of 2.5 microns (PM2.5), can penetrate deep into lung passageways and enter the bloodstream, causing serious cardiovascular, cerebrovascular and respiratory impacts.” (WHO, n.d.-b). These impacts are do not only develop on the long-term, but short term-exposure is also associated with morbidity and mortality from these diseases. To get a better understanding of PM, it is a mix of different aerosol particles, both solid and liquid with different shapes and sizes. This means PM is not the exact same as aerosols, as aerosols themselves also include gasses in the air whereas PM just refers to the particulates. PM can be categorized as both a primary pollutant through direct emissions from combustion engines and secondary pollutant through chemicals emitted such as SO2, NOx and NH3. Therefore, the origin of PM can vary, but it the main sources of emissions are combustion for both transport and in households for cooking, heating, and lighting (WHO, n.d.-b). PM is separated into three main groupings, which differ in particle sizes, origin and health effects (Smith, 2020). The first one are coarse particles (PM10), which can be defined as all particles with a diameter of 10µm or smaller. Even though they are the largest PM particle, they are still able to creep deep into the lungs which causes irritation of the nose, eyes, and airway. The second group is the fine particles (PM2.5), which can be defined as all particles with a diameter of 2.5µm or smaller. PM2.5 is the most well documented of all, as it is able to penetrate into the lungs and into our bloodstream through its smaller size, making it significantly more unsafe than PM10. Finally, there are ultrafine particles (PM0.1), which have a diameter of 0.1 µm or smaller. There is still little known about PM0.1, however, recent studies indicate that PM0.1 poses an even bigger threat than PM2.5, through enhanced cardiovascular toxicity and greater potential for oxidative stress. Especially considering the fact that the majority, up to 90%, of household PM is PM0.1 (Smith, 2020).

Reducing emissions of air pollutants is in many ways crucial to increasing air quality, as essentially the emission of air pollutants is what drives air pollution and reduced air quality. However, reducing emissions to a certain extent will not lead to the same results of increased air quality everywhere. “There are complex links between air pollutant emissions and air quality. These include emission heights, chemical transformations, reactions to sunlight, additional natural and hemispheric contributions, and the impact of weather and topography” (EEA, 2021). Therefore, it is essential to study the links between air pollutant emissions and air quality to ensure effective policy making on emission reduction.

Most Polluted Regions in the World

Although air pollution affects people in high- middle- and low- income countries, the effects are unequally distributed. “People living in low- and middle-income countries disproportionately experience the burden of outdoor air pollution with 91% (of the 4.2 million premature deaths) occurring in low- and middle-income countries, and the greatest burden in the WHO South-East Asia and Western Pacific regions. The latest burden estimates reflect the very significant role air pollution plays in cardiovascular illness and death” (WHO, 2021a). Figure 1 displays the relationship between national income and pollution levels and clarifies that low- and middle- income countries emit more PM10, PM2.5, and NO2. Air pollution in these countries plays the largest role in the bigger cities.

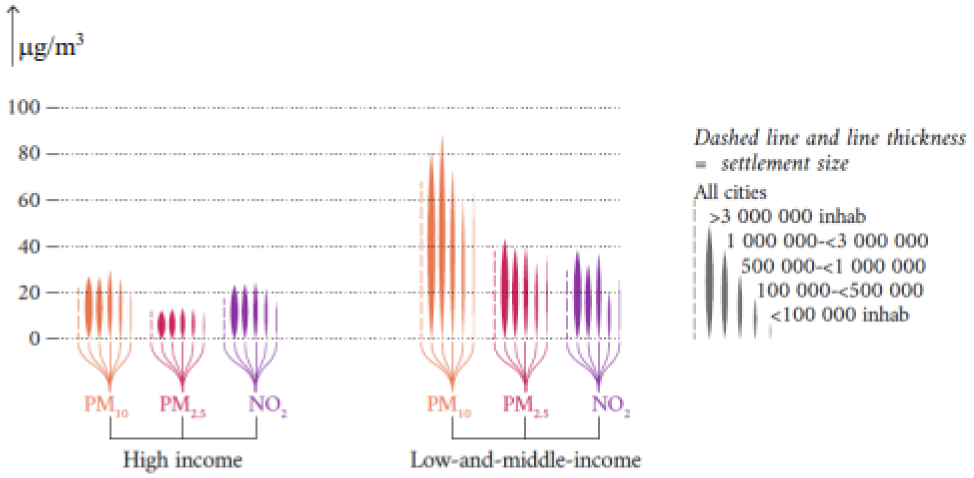

Figure 1: PM10, PM2.5, and NO2 annual means by income level and settlement size, for settlements for which data were available in the latest year between 2010 and 2019. WHO, 2022b

However, high- middle- and low- income countries are quite broad classsifications which require more specification before can be drawn on the distribution of air pollution. Figure 2, displays the relationship between region and pollution levels. Here we can specifically see that PM2.5 pollution levels are by far the greatest in the region WHO defines as South-East Asia. Particulate matter levels are almost double compared to global levels.

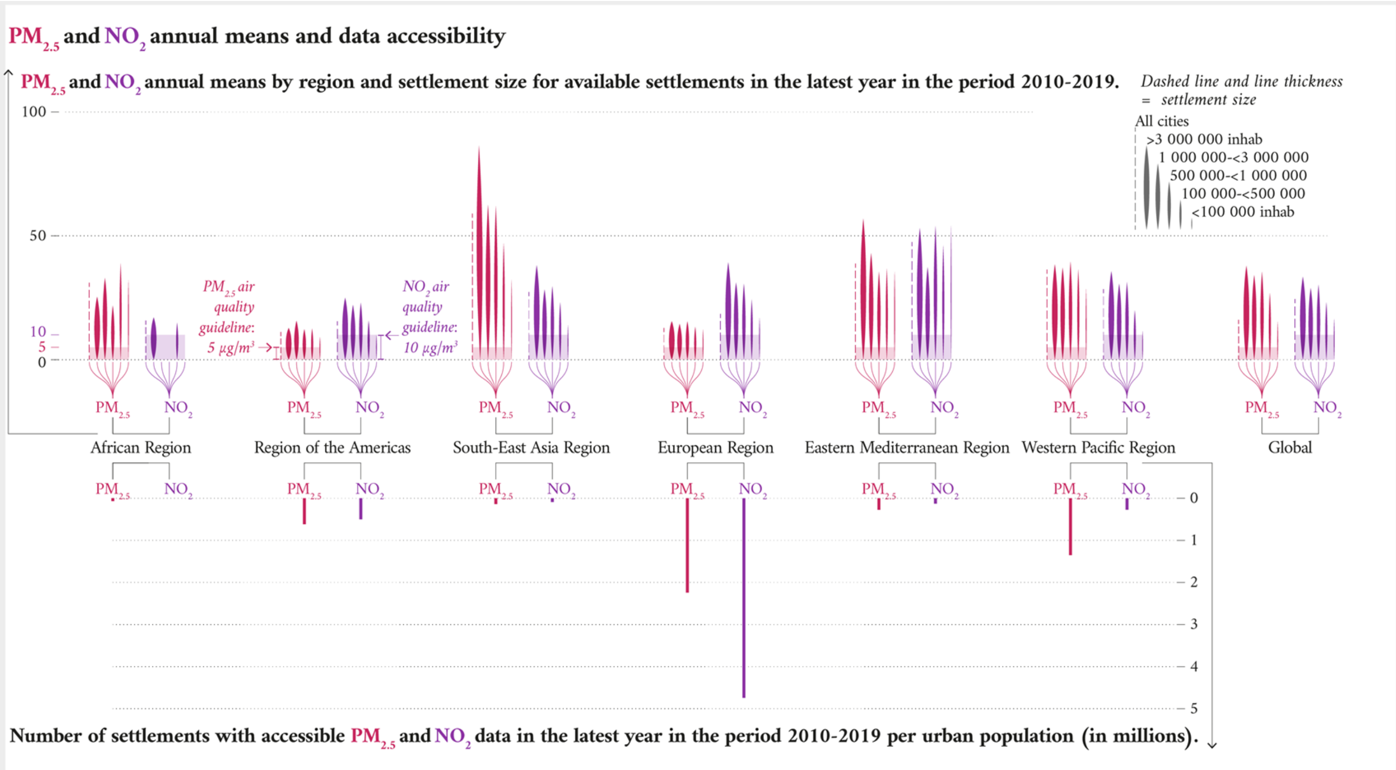

Figure 2: PM2.5 and NO2 annual means and data accessibility, by region and settlement size. WHO, 2022.

However, in the region of South-East Asia there are also differences in PM2.5 pollution. Figure 3 displays the ambient levels of PM2.5 throughout Asia in 2015. “Lss than 8 percent of the Asian population could breathe air that conforms to the WHO Guideline for PM2.5 of 10 µg/m3. In contrast, more than half of the Asian population, about 2.3 billion people, faced exposure that exceeded even the highest WHO Interim Target of 35 µg/m³” (UNEP, 2019). The World Health Organization & European Centre for Environment and Health (2021) air quality guidelines for annual averages do not only appear to be often exceeded, but also 24-hour averages, also known as air pollution episodes. Their first Interim Target is set at 75 µg/m³. It becomes clear that most PM2.5 pollution is concentrated in the East of China and from the North of India all the way to Iran. Urban air pollution poses to reach the highest levels of PM2.5 in Figure 3, but regional air pollution also shows to be a problem with high levels of pollution all throughout the areas.

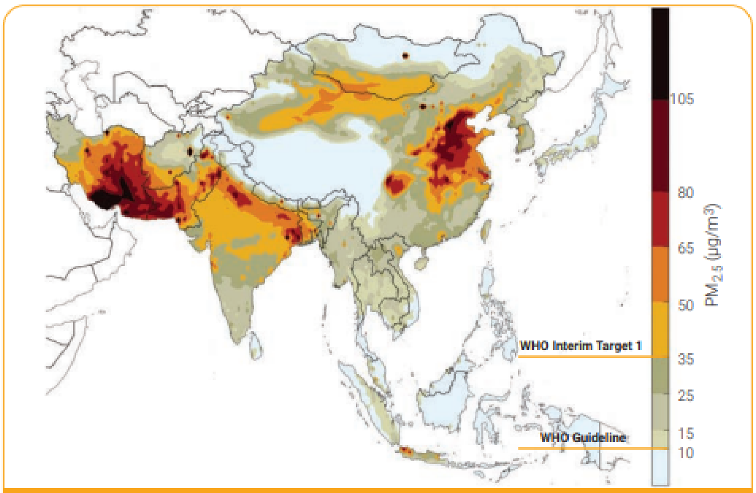

FIGURE 2.5: AMBIENT LEVELS OF PM$_{2.5}$ IN ASIA IN 2015

Figure 3: Ambient Levels of PM2.5 in Asia in 2015. UNEP, 2019.

The research will elaborate on the NCP and IGP specifically, considering these belong to the most polluted areas in the world. Although some parts of the neighboring country Iran might display heavier pollution compared to the IGP, this region is significantly more densely populated making research in this area significantly more relevant.

North China Plain

The North-China Plain (NCP) is located in the eastern coastal region of China between 32°and 40°N latitude, and 100° and 120° E longitude. Mountains surround the NCP in the northwest and in the east. The region includes 7 different provinces (Hebei, Henan, Shandong, Anhui, Jiangsu, Beijing, and Tianjin), which can be seen in Figure 4 (Yang et al., 2018). NCP has a population of around 400 million and is one of the most densely populated in the world (Kang & Eltahir, 2018).

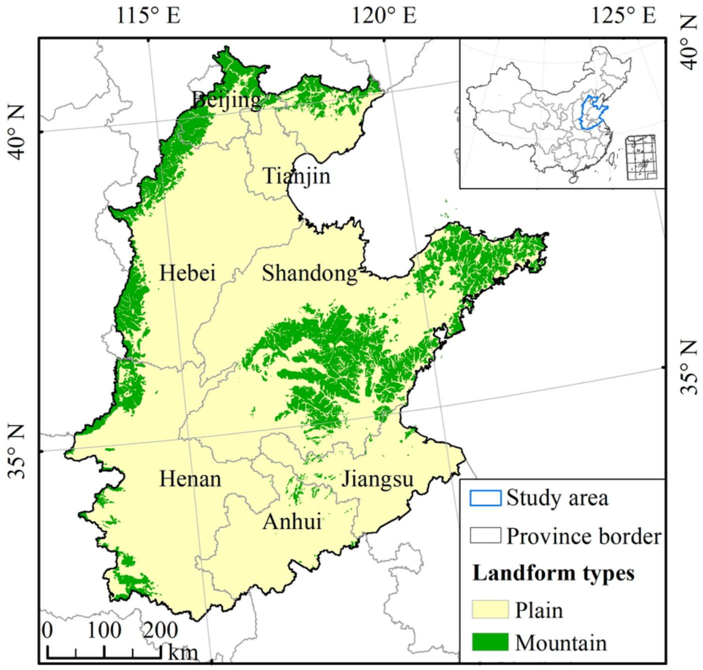

Figure 4: The location and main landform types of the North China Plain (NCP) in China. Yang et al., 2018.

The NCP has a warm temperature and characteristic continental monsoon climate. This type of climate entails there is moderate to little precipitation and the precipitation is concentrated in the warmer months. “Annual precipitation ranges from 550 to 650 mm mostly from July to September accounting for 50–70% of the annual total precipitation” (Yang et al., 2018). The NCP is seen as one of the most important social, economic, and agricultural regions in China. However, this economic development has also led to a rapid increase in anthropogenic emissions. “Average mass concentration of PM2.5 could exceed 250 µg m−3 in the urban areas of Beijing, Tianjin, and Shijiazhuang” (Han et al., 2016). Especially in megacity clusters, there is heavy air pollution. According to Han et al. (2016), the main sources of anthropogenic emissions are the industry sector, power plants, transportation, and the residential sector.

Indo-Gangetic Plain

The Indo-Gangetic Plain (IGP) is located in the North of India and a part of Pakistan between 22°and 33°N latitude, and 67° and 92° E longitude, where the north of the region is cut off by the Himalayas. The region includes 7 different states (Sindh, Punjab (PAK), Punjab (IND), Haryana, Delhi NCT, Uttar Pradesh, Bihar, West Bengal, and Bangladesh (BGD)) which can be seen in Figure 5 (Mogno et al., 2021). Similar to the NCP, the IGP has a population of around 400 million, and is one of the most densely populated in the world (Mogno et al., 2021).

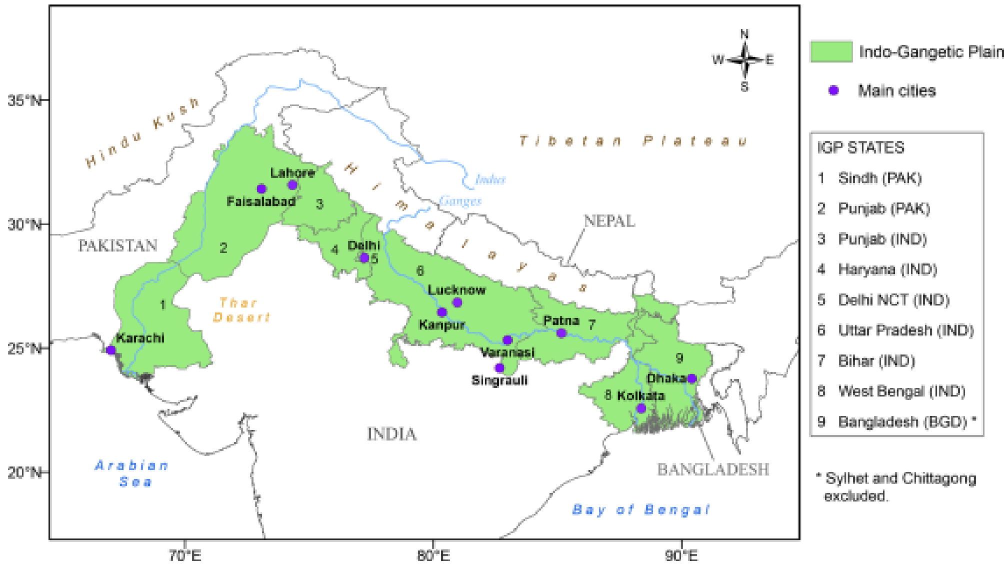

Figure 5: Geographical and administrative features of the Indo-Gangeric Plain (IGP), including Pakistan, India, amd Bangladesh. Numbers denote individual IGP states, and purple dots denote the main cities. Mogno et al., 2021.

The IGP has a sub-tropical climate, which is characterized by hot, humid summers and mild dry winters. “The rainfall is mostly received in summer and is about 65 cm in the west and increases to 250 cm annually to the east and near Himalaya” (Singh & Bhatla, 2019). The monsoon defines the seasons over the IGP. “The pre-monsoon season runs from March to May, the monsoon season is from June to September, the post-monsoon season is from October to December, and winter occurs in January and February” (Mogno et al., 2021). India is dependent on the climate of the IGP, as it causes the region to be a major contributor to the agricultural output, especially for rice and wheat which are planted in a cropping cycle. Residues after a harvest are usually still burned in open fires. “Open burning of these residues across the IGP, particularly during the post-monsoon season, is a large source of gaseous and particulate pollution that has implications for regional air quality and human health” (Mogno et al., 2021). However, next to the agricultural sector, transportation and open solid fuel burning are also significant sources of anthropogenic emissions. The translation of these emissions into aerosols is a complicated process, with strong variations through the monsoon system and high mountain ranges. “The unique geography of the IGP and broader scale meteorological drivers, coupled with the regional diversity of seasonal pollutant emission sources makes this region one of the most challenging places to study the controls of its air pollution and the consequent impact on human health” (Mogno et al., 2021).

Comparative Studies over the NCP and IGP

There is already a range of literature available that compares particle pollution over the NCP and IGP. This section aims to shortly point out what research is already out there when it comes to comparative studies, and where there is still a gap in the available literature. Studies can be divided into two different types, which are comparative studies on the climate effects of particle pollution and comparative studies on the health effects of particle pollution. The full list of comparative studies can be found in Appendix 1.

Comparative studies on health effects illustrate a variety of studies that focus on pollution on different scales. Some studies focus on the countries China and India as a whole, while others focus on particle pollution in different urban areas throughout the IGP and NCP. Examples of these urban areas are Beijing and Delhi. However, there is no comparative literature available that focuses on the specific NCP and IGP regions. Other than scales, there are also differences when it comes to the scope of research on the health effects of particle pollution. Multiple studies analyze air pollution from specific sectors, such as power generation, or during a specific time, for example during the pandemic. On the other hand, most literature addresses general aspects of particle pollution.

Just as for the comparative studies on health effects, comparative studies on climate effects from air pollution illustrate a variety of studies that focus on pollution on different scales. The majotity of the literature focuses on the country level of China and India, however, there is also a significant amount of literature available that focuses on the regional scope of the NCP and IGP. Other than scales, there are also differences when it comes to the scope of research on the climate effects of particle pollution. A significant amount of the literature studies how radiative forcing is influenced by particle pollution. On the other hand, there are also a range of studies on how the monsoon, seasonal cycles and precipitation infleunce aerosol concentrations. Finally, there is also literature on the different characteristics, concentrations and compositionof particle pollution.

As stated earlier in this literature review, it is essential to study the links between air pollutant emissions and air quality to ensure effective policy making on emission reduction. Although there are studies which analyze links between air pollutant emissions and air quality, these are are focused on specific regions and do not take the form of a comparative study. There are also comparative studies on how the monsoon, seasonal cycles and precipitation infleunce aerosol concentrations, these do not include the relation to regional anthropogenic emissions. Therefore, a comparative research which quantifies and contrasts the magnitude, duration, and spatial characteristics of air pollution episodes and puts them into perspective by relating them to the regional anthropogenic emissions builds upon current available knowledge and is able to contribute to effective policy making.

Methodology

Aim

The aim of this research is to further clear out the role of meteorology in exacerbating or avoiding air pollution episodes over the IGP and the NCP regions. It wants to do this by quantifying and contrasting the magnitude, duration, and spatial characteristics of air pollution episodes of both of these globally significant regions for one entire year, 2019 and puts them into perspective by relating them to the regional anthropogenic emissions. The main objective of the research is to understand the relationship between the cause and the effect in two contrasting regions. In this case, the cause includes the anthropogenic emissions which might translate into the effect of pollution levels in different ways over the contrasting regions of the NCP and the IGP. Therefore, the research question of this paper is: “How do the frequency and intensity of air pollution episodes in IGP and NCP depend on the distribution and strength of emissions?” As a relationship between different variables is determined using statistical data, this is quantitative correlational research. First, the theoretical framework and relevant variables have been explored in the literature review. The results are visualizations of the available variables within our datasets in the form of maps and graphs. The structure of the result section was not pre-determined, as it was the goal to base the next steps on discoveries from the maps and graphs.

Dataset & Variables

This research utilized two different datasets belonging to Copernicus which are both part of the Copernicus Atmosphere Monitoring Service (CAMS), which is the European Union’s Earth observation program (Copernicus, n.d.). The datasets are provided by the ECMWF as part of their collaboration with Copernicus. Datasets are named ‘CAMS global reanalysis of aerosol concentrations’ and ‘CAMS global anthropogenic emissions.

‘CAMS global reanalysis of aerosol concentrations’ provides consistent information on a range of aerosols and reactive gases, including PM1, sea-salt concentration, organic carbon concentration, PM10, dust concentration, PM2.5, black carbon concentration, and sulfates concentration. However, for the scope of this research, only PM2.5 has been analyzed as this species is the most well-documented of all. The name reveals this is a reanalysis dataset. Reanalysis means that Copernicus has assembled the data with observations in combination with satellite instruments and computer models to create a consistent data set (Copernicus, n.d.). Other characteristics of the dataset are a horizontal resolution of 80 kilometers and a temporal resolution of 3 hours (Copernicus, n.d.-b).

‘CAMS global anthropogenic emissions’ provides consistent information on a range of anthropogenically emitted pollutants, including ammonia, black carbon, nitrogen oxides, nonmethane VOCs, organic carbon, and sulfur dioxide. All the different emissions have been used for this research, as emissions can translate into aerosols or particle pollution in different ways. The dataset also provided information on the same emissions for each of the different sectors, including agriculture livestock, agriculture soils, agricultural waste burning, power generation, fugitives, industry, residential, commercial and other combustion, ships, solvents, solid and wastewater, off-road transportation and road transportation. However, for the scope of the research, the decision has been made to sum the emissions from the different sectors. This means only the general translation of pollutants into aerosols is studied and not the difference in translation per sector. Other characteristics of the dataset are a horizontal resolution of 10 kilometers and a temporal resolution of 1 month (Granier et al., 2019).

Timeframe

The aim of the research is to understand and elucidate the relationship between anthropogenic emissions and pollution levels. For this, a representative year of recent trends between these different variables had to be selected. Considering the COVID-19 pandemic has influenced emissions and pollution levels in 2020 and 2021, data for the year 2019 was used since it was the most recent year and without any lockdowns.

Programming Tools

The NCAR Command Language (NCL) has been used to conduct this research, as the language is "designed specifically for the analysis and visualization of data" (NCAR Command Language, n.d.) Data is stored in a NetCDF file format. This is a format that stores multidimensional data. Examples of multidimensional data variables are temperature, wind speed, or in this case air pollution and emissions. Variables can be visualized through different dimensions such as space or time (ArcGIS Pro, n.d.). Simple integration of NetCDF using NCL files made it easy to visualize three-dimensional data, and therefore most suitable for our project.

Ethicalities

Considering this is a quantitative research that utilized openly available gridded datasets of pollution concentrations from the ECMWF and did not require primary data collection, ethicalities are limited. Especially considering our results are openly available. We did not conduct interviews or work with sensitive, personal data. as our research is solely about climate data. However, it has to be explicitly pointed out that any deception or exaggeration about aims and objectives will be avoided, just like any type of misleading information to make sure bias is avoided. It also has to be explicitly mentioned that this research did not cross-validate the datasets with ground observations, which has to be done in further research to ensure the reliability of the results.

Results

This result section is divided into two respective parts. The first section is dedicated to describing graphs and plots made from the aerosol concentrations dataset. The second part will go into describing graphs and plots made from the anthropogenic emissions dataset or both. All of the graphs and plots use the aerosol concentrations and anthropogenic emissions data sets.

Investigating changes in polluted area of IGP and NCP

Temporal changes in polluted area of IGP and NCP

As a first step in analyzing the spatial patterns of pollution over the NCP and IGP, two respective graphs displaying the percentage of polluted grids over the year 2019 have been created (Figure 1). This is to gain a deeper insight into the regional pollution of the areas and to find if there is a difference in parcentage of polluted grids on days where an air pollution threshold is exceeded. Two different thresholds for when a grid was specified as 'polluted' were selected. The red plot has a threshold for a concentration of 75 $\mu g/m^{-3}$, and a blue threshold for a concentration of 60 $\mu g/m^{-3}$. The X-axis depicts the months, however, the three-hourly data has been transformed into daily averages meaning each plot consists of 365 data points. When a daily average of a gridpoint exceeds a threshold, it will be categorized as polluted. The total of polluted grids will then be divided by the total number of grids times 100, meaning you get the percentage of polluted grids for each day. This is depicted on the Y-axis. Getting a percentage is more useful, as the IGP and NCP regions differ in size.

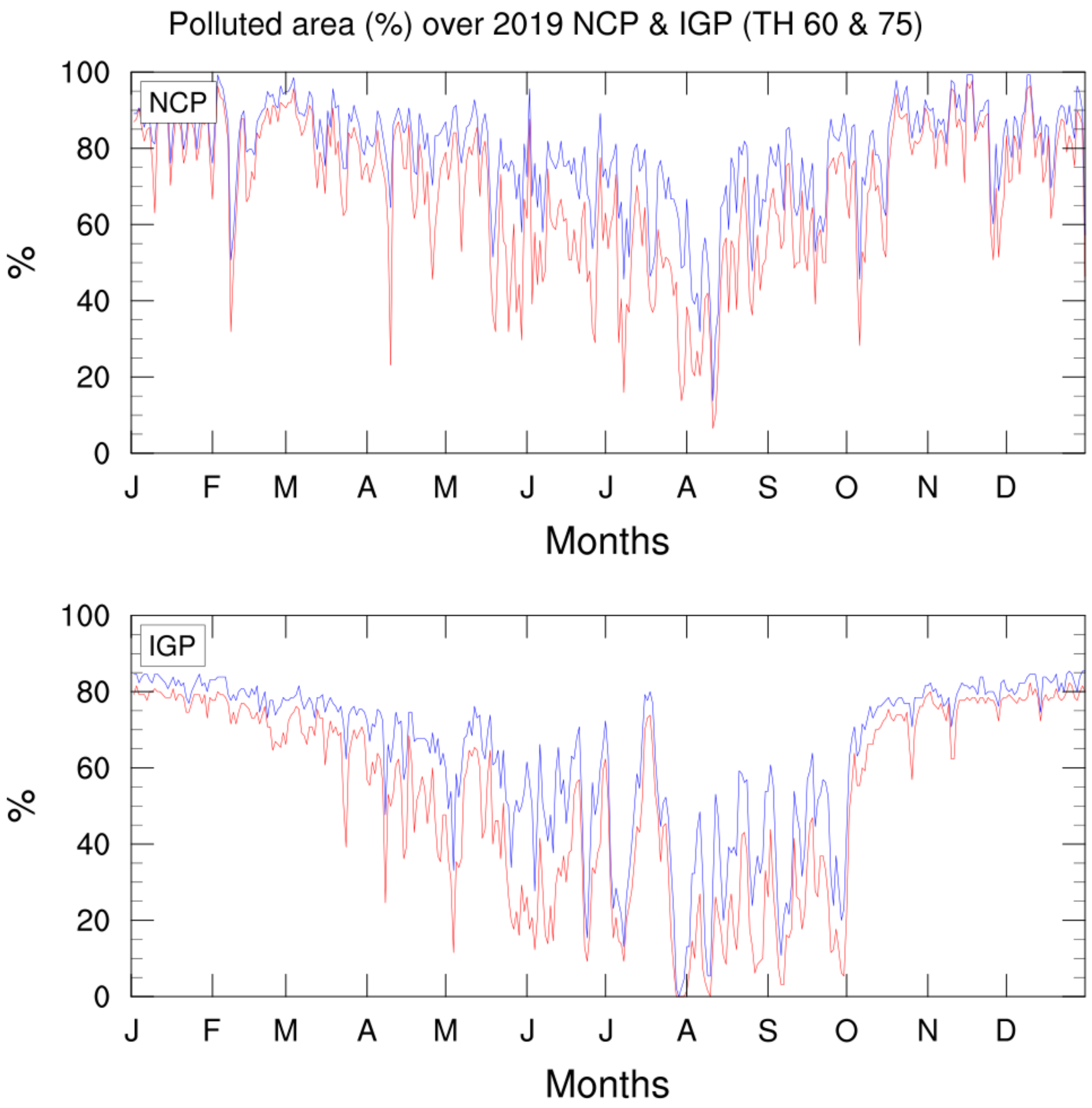

Figure 1: Polluted Area (%) Graph in 2019 over the NCP and IGP (TH 60 & 75)

When analyzing Figure 1, over the year 2019, there is a clear divide in the polluted area over both regions in the months of the southwest monsoon, June to September, compared to the rest of the year. Here, the monsoon months show the percentage of polluted grids is smaller. However, this trend is much more pronounced over the IGP compared to the NCP, where the polluted area appears to float around 80% throughout the entire year, and multiple times even reaches 100%. In other words, the whole region exceeds the threshold of 60 µg/m^{-3}. Over the IGP, the polluted area decreases from around 80% to around 20% in the monsoon months. At the end of July, there is even a day with a polluted area of 0%, which never happens over the NCP. The thresholds of 75 µg/m^{-3} and 60 µg/m^{-3} do show the exact same trend over both regions, where the higher thresholds show a lower polluted area.

Spatial distribution of average PM2.5 and number of polluted days

Now that the temporal characteristics of air pollution have become clear, it is useful to study the spatial distribution of pollution and aerosol concentration. Studying the spatial distribution provides a better explanation of which grids or places are more polluted compared to others. The distribution of aerosol concentration helps to understand the variation of pollution, as a threshold simplifies the quantification of pollution. Therefore, a panel plot displaying the annual average PM2.5 in μg/m^{-3} and the number of polluted days in 2019 over both regions have been created (Figure 2). The left-hand plots display the annual average PM2.5 concentration over each grid, in addition to the average annual flux of the PM2.5 concentration which is given on the top-right side of each plot. The flux provides a deeper insight into the average pollution over the entire region and which region on average has higher pollution. The right-hand plots display the number of polluted days over each grid, according to the threshold of 75 μg/m^{-3} in addition to the average number of polluted days for the entire region. The average number of polluted days again helps compare the two regions and provides insight into which region exceeds the threshold more often. For all of the plots, white stands for the least polluted, and dark red for the most polluted.

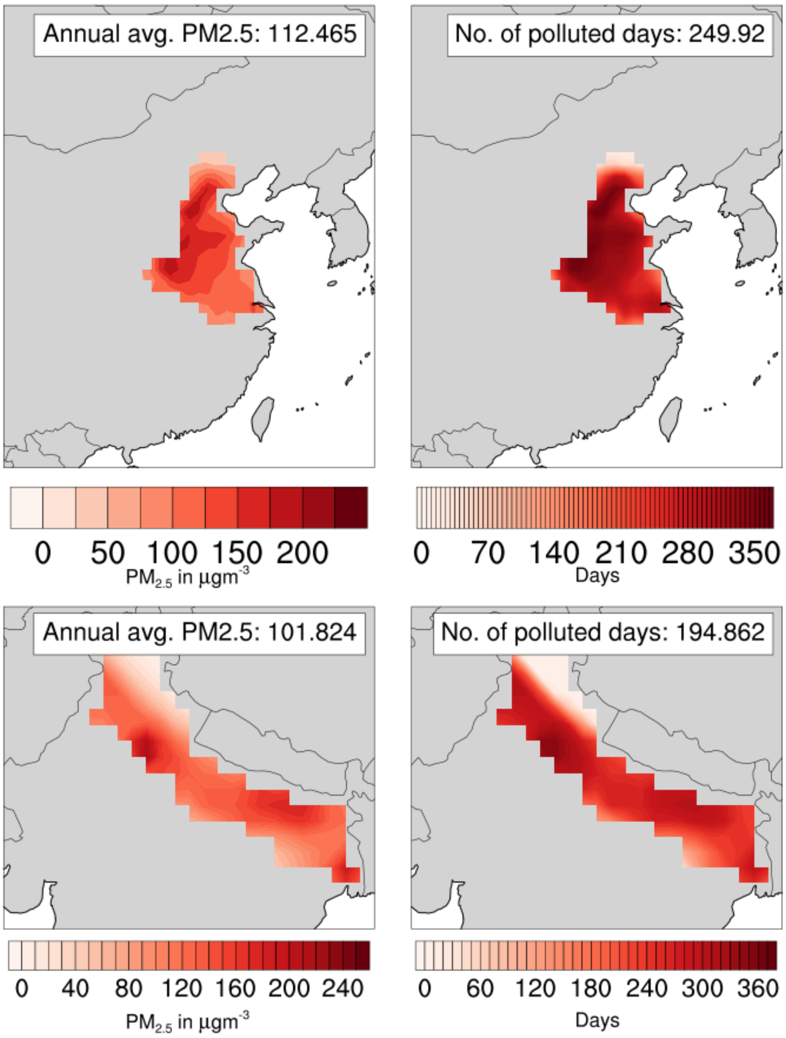

Figure 2: Average PM2.5 and Number of Polluted Days in2019 over the NCP and IGP

Figure 2 provides multiple results on the spatial distribution of PM2.5 over the IGP and NCP. First of all the boxes provide the average annual flux of the PM2.5 concentration and the average number of polluted days for the entire region. For the NCP these equal 112.465 µg/m^{-3} and 249.92 days. For the IGP these are equal to 101.824 µg/m^{-3} and 194.862 days. This means that although the average pollution levels are relatively similar, the polluted days over the NCP are significantly higher. When comparing this result to the previous line graph, it can be explained through a difference in temporal variation. Over the IGP, the polluted area in monsoon months is significantly lower, whereas over the NCP the polluted area stays much more equal throughout the year. IGP can have a similar pollution level through days where some places reach extreme levels of pollution, however, the threshold does not take this into account. This means that if over the NCP pollution levels are consistently a bit over 75 µg/m^{-3}, and the polluted days are significantly higher. Over the NCP, average annual average PM2.5 is the most concentrated, from north to south, over the cities Beijing to Shijiazhuang and Zhengzhou to Xiangyang, with the highest average concentration up to 205 µg/m^{-3}. The further away from these cities, the lower the concentration becomes. The number of polluted days is also highest in these cities with the same fading trend, which is around 300 polluted days or more. However, the number of polluted days appears to stay much higher compared to drifting away from the cities compared for the PM2.5 concentration. Over the IGP, the average annual average PM2.5 is the most concentrated, from east to west, over New Delhi, Patna and Calcutta, with the highest average concentration up to 221 µg/m^{-3}. Just as over the NCP, the further away from these cities, the lower the concentration becomes. The number of polluted days is also again highest in these cities with the same fading trend, which is around 300 polluted days and the number of polluted days appears to stay much higher. Next to this, there also appears to be an additional hotspot of polluted days in the Punjab region.

Investigating the duration of air pollution episodes

Although there is an increased understanding of the spatial distribution of air pollution, an understanding of air pollution episodes is still missing. So far only daily averages have been used to characterize polluted days, however air pollution episodes can last both significantly longer and shorter. To gain insight into the spatial distribution of air pollution episodes in 2019 over the NCP and IGP, a panel plot displaying the number of episodes, the max duration, and the average duration of air pollution episodes over each grid has been made (Figure 3). Here an air pollution episode is characterized when a three hourly data point exceeds the threshold of 75 µg/m^{-3} until it goes below the threshold. This means there can be multiple air pollution episodes within a single day or can last multiple days over the year 2019. The left-hand plots display the number of episodes over each grid. The middle plots display the max duration of an air pollution episode in hours over the regions. Here, the shortest air pollution can be 3 hours, due to the fact that we are making use of 3-hourly data. The right-hand plots display the average duration of an air pollution episode in hours over the regions. For all of the plots, blue stands for the least or shortest episodes, and dark red for the most or longest episodes. However, it should be noted that the three different plots have different color scales, which can be seen at the bottom of the plots.

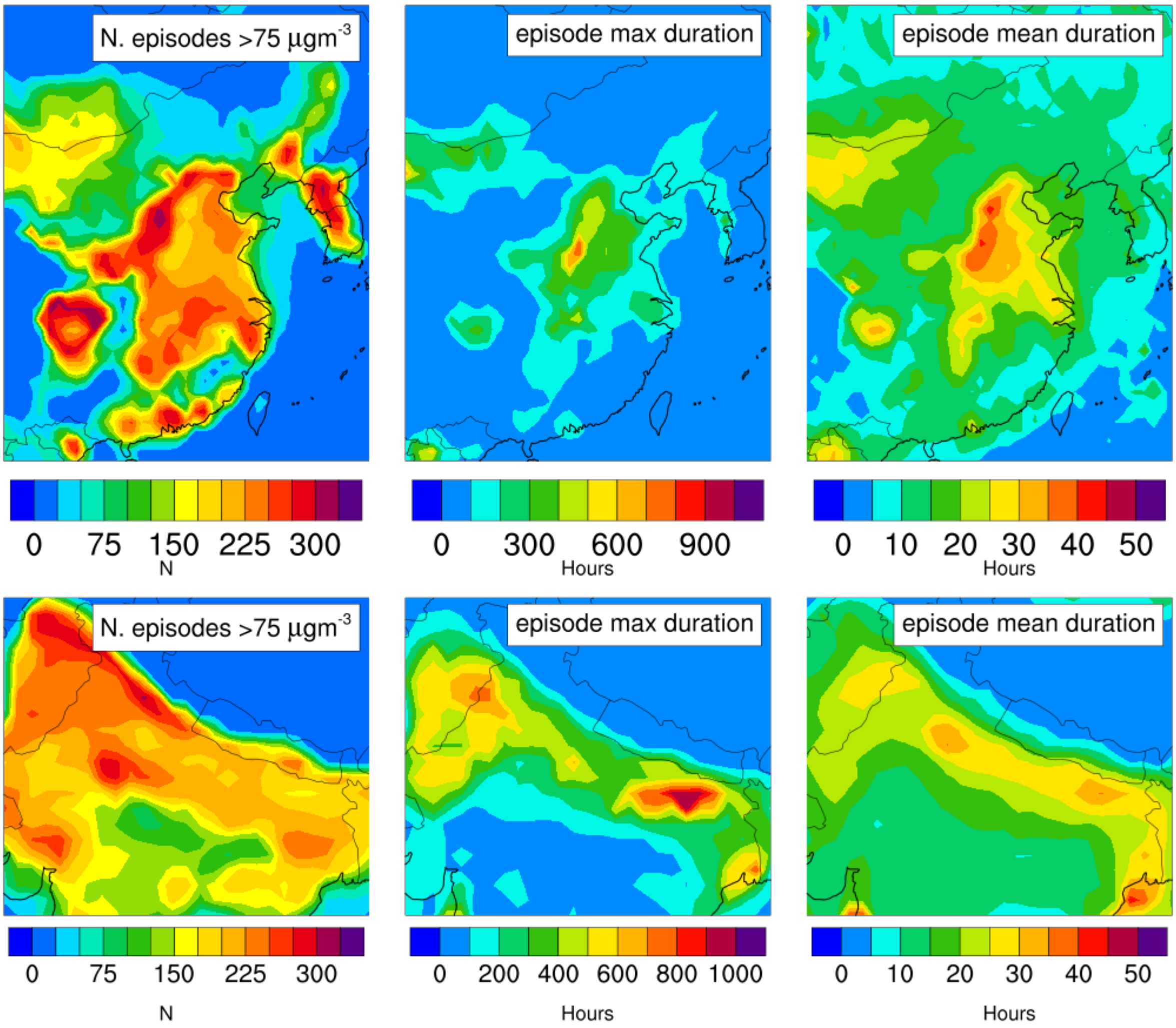

Figure 3: Number, Max Duration, and Average Duration of Air Pollution Episodes in 2019 over the NCP and IGP

Figure 3 provides results on air pollution episodes in 2019 over the NCP and IGP. When focussing specifically on these regions and not their surroundings, a similar trend compared to the PM2.5 concentrations can be observed. When it comes to the number of air pollution episodes, there is also a similar trend to the number of polluted days over both the NCP and IGP. Most air pollution episodes over the NCP are in the cities Beijing to Shijiazhuang and Zhengzhou to Xiangyang. The concentration decreases from around 300 episodes to a maximum of 322, when moving away from these cities, however, on the east side of Shijiazhuang the concentration decreases more compared to the rest of the region. Most air pollution episodes over the IGP are in the cities of New Delhi, Patna, Calcutta, and the Punjab region. The concentration again decreases from around 300 episodes, and a maximum of 314, when moving away from these cities, however, it stays high when south of the regions and decreases close to 0 on the north side of the areas. When it comes to the max duration of air pollution episodes, the high maxima are very concentrated over urban areas and go up to between

900 to 1000 hours over singular regions and quickly decrease to around 400 hours. The longest duration over the NCP and IGP are over Shijiazhuang and Patna respectively, where in Patna it reaches 966 which is significantly higher than in Shijiazhuang where it reaches 789 hours. The average duration of air pollution episodes over both of the regions is most concentrated over more areas and cities. For the NCP, the average duration is highest at 43 hours in Beijing to Shijiazhuang and Zhengzhou to Xiangyang and decreases to between 20 to 30 hours over the rest of the NCP region. For the IGP, the average duration is highest at 43 hours in New Delhi, Patna, Calcutta, and the Punjab region, and decreases to between 20 to 30 hours over the rest of the IGP region. If the results of Figure 3 are compared with Figure 2, there are two additional results. First of all, the mean duration of air pollution episodes appears to be coherent with average pollution. This means that the higher the average pollution levels are, the higher the mean duration of air pollution episodes will be. However, when comparing the number of air pollution episodes to the mean duration of air pollution episodes, there appears to be an anticorrelation. Meaning the more air pollution episodes there are, the lower the mean duration and the other way around. This has to do with the fact that when there are only a few air pollution episodes in polluted areas, they tend to last significantly longer.

Investigating changes in annual emissions of IGP and NCP

Annual Anthropogenic Emissions

Next to understanding spatial and temporal characteristics of PM2.5 and air pollution episodes, it is important to gain insight into spatial characteristics of anthropogenic emissions over the NCP and IGP. Understanding the characteristics of emissions can provide insights into the translation of emissions into aerosols. However, for this, there first needs to be a general understanding of where emissions are concentrated. Figure 4 visualizes these spatial characteristics by displaying the summed-up anthropogenic emissions in KT per year over each grid in 2019. The summed-up emissions include all anthropogenic emissions from different sectors mentioned in the methodology. The box on the top-right side of each of the plots gives the full grid flux in KT per average 10km x 10km grid in the year 2019. Figure four consists of two graphs, one for each of the regions. Both graphs display the total emissions in KT per year over each grid over the year 2019. The right-sided block in each graph shows the full grid flux in KT over the year 2019.

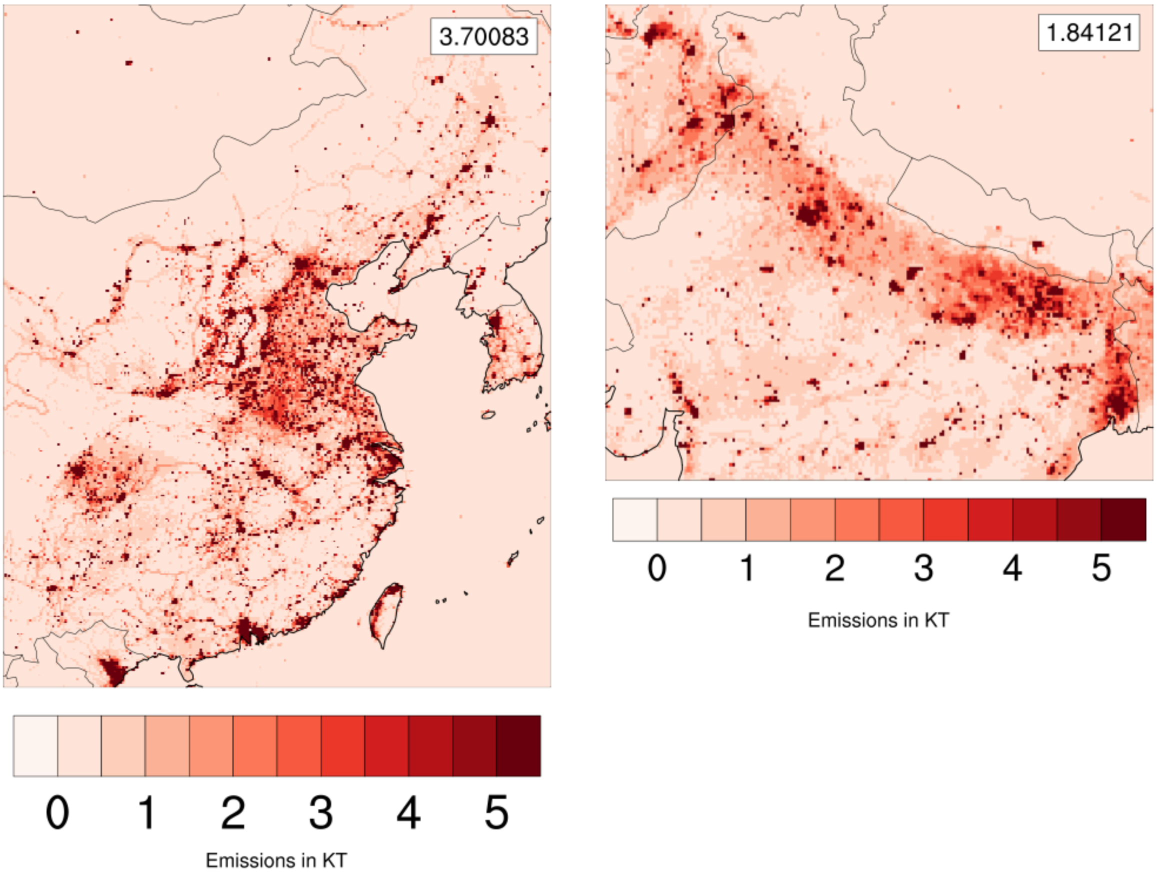

Figure 4: Summed Emissions in 2019 over the NCP and IGP

Over the year 2019, there is a clear distinction between urban areas with significant emissions compared to more rural regions over both the NCP and IGP. However, this also has to do with the enhanced quality of the data, as grids are 10 x 10 kilometers of the emissions data instead of 80 x 80 kilometers for the aerosol data. Figure 4 visualizes the spatial characteristics by displaying the summed-up anthropogenic emissions in KT per year over each grid in 2019. For the NCP, it can be observed that the largest emission hotspots are Beijing to Shijiazhuang and Zhengzhou to Xiangyang in addition to Shanghai on the east coast of China. However, it should be noted that there are many other uniformly distributed small hotspots up to the coast visible over the NCP region and that the full grid flux of 3.7 KT per grid per year is also significantly higher compared to the rest of East China. For the IGP, the full grid flux is 1.8 KT per grid per year. However, there are also much fewer but larger hotspots compared to the NCP. In this case, the main hotspots are over New Delhi, Patna, and Calcutta. If Figure 4 is compared to Figure 2, it becomes clear that even though emissions over the NCP are exactly double compared to the IGP, the aerosol concentration is almost the same as IGP has 90% of the aerosol concentration of the NCP. This means much more emissions are translated into aerosols over the IGP, which has to do with complex relationships between different meteorological and geographical factors. If there would be just as much emissions over the IGP as there were over the NCP, the IGP region might double in aerosol concentration with an average flux of 203 µg/m^{-3}.

Understanding pollution forming efficiency: monthly ratio of ambient PM2.5 concentration to emissions

Figure 4 provided the insight that the translation of emissions to aerosols is significantly larger over the IGP as compared to over the NCP. However, this relationship is averaged over time, meaning it might vary throughout the year 2019. Calculating the ratio between anthropogenic emissions and aerosol concentration can provide a better insight into this accumulation potential, as it shows the differences in translation of emissions into aerosols throughout the year. To better understand the relationship between anthropogenic emissions and aerosol concentration, we created a graph displaying the ratio between these two variables (Figure 5). The X-axis depicts the months, however, the three-hourly data has been transformed into monthly averages meaning each plot consists of 12 data points. The blue line depicts the ratio over the IGP, and the red line depicts the ratio over the NCP. The Y-axis displays the ratio in µg/m^{-3}/T. This means the higher the ratio, the stronger the relationship between anthropogenic emissions and aerosol concentration in 2019 over the NCP and IGP.

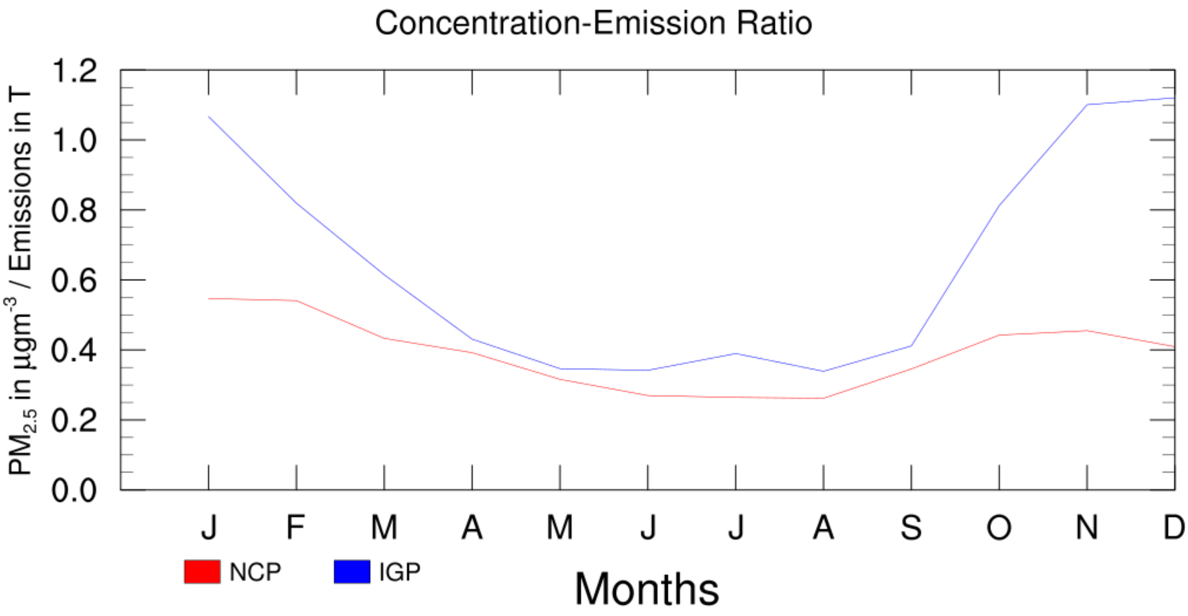

Figure 5: Line Graph Ratio (Aerosol/Emission Concentration) in 2019 over the NCP and IGP

Figure 5 provides results on the relationship between anthropogenic emissions and aerosol concentration. Both accumulation potentials appear to be very different for the NCP and IGP. The ratio over the NCP remains relatively stable at around 0.3 µg/m^{-3}/T and 0.6 µg/m^{-3}/T. Over the IGP, there is much more fluctuation throughout the year, with around 0.3 µg/m^{-3}/T and 1.1 µg/m^{-3}/T. Both regions do have in common that the relationship between anthropogenic emissions and aerosol concentration is the lowest in the months of April up until September. In conclusion, Figure 5 provides the result that the accumulation potential over the IGP is always stronger compared to over the NCP, and that this potential fluctuates significantly stronger throughout the monsoon period. This means the meteorological factors play a significantly larger role in the variation of the accumulation potential throughout the year compared to the NCP.

Pollution forming efficiency

Now that Figure 5 has provided insights on the accumulation potential over the NCP and IGP, it becomes possible to connect this to the different forms of anthropogenic emissions. Comparing the ratio to the different emissions gives us the opportunity to compare if there is a relation between a specific source of emissions and how this source translates into aerosols. Figure 6 visualizes the relationship between anthropogenic emissions and aerosol concentration by displaying both concentrations over the NCP and IGP. The full grid flux of anthropogenic emissions in KT is visualized by the stacked plot, which makes use of the left Y-axis. The stacked plot differentiates between the different emission sources, which in this case are Sulfur Dioxide, Non-Methane VOCs, Nitrogen Oxide, Ammonia, Organic Carbon, and Black Carbon. The legend between the two graphs describes the emission sources with their corresponding color. The line plot displays the full grid flux of aerosol concentration in µg/m^{-3}.

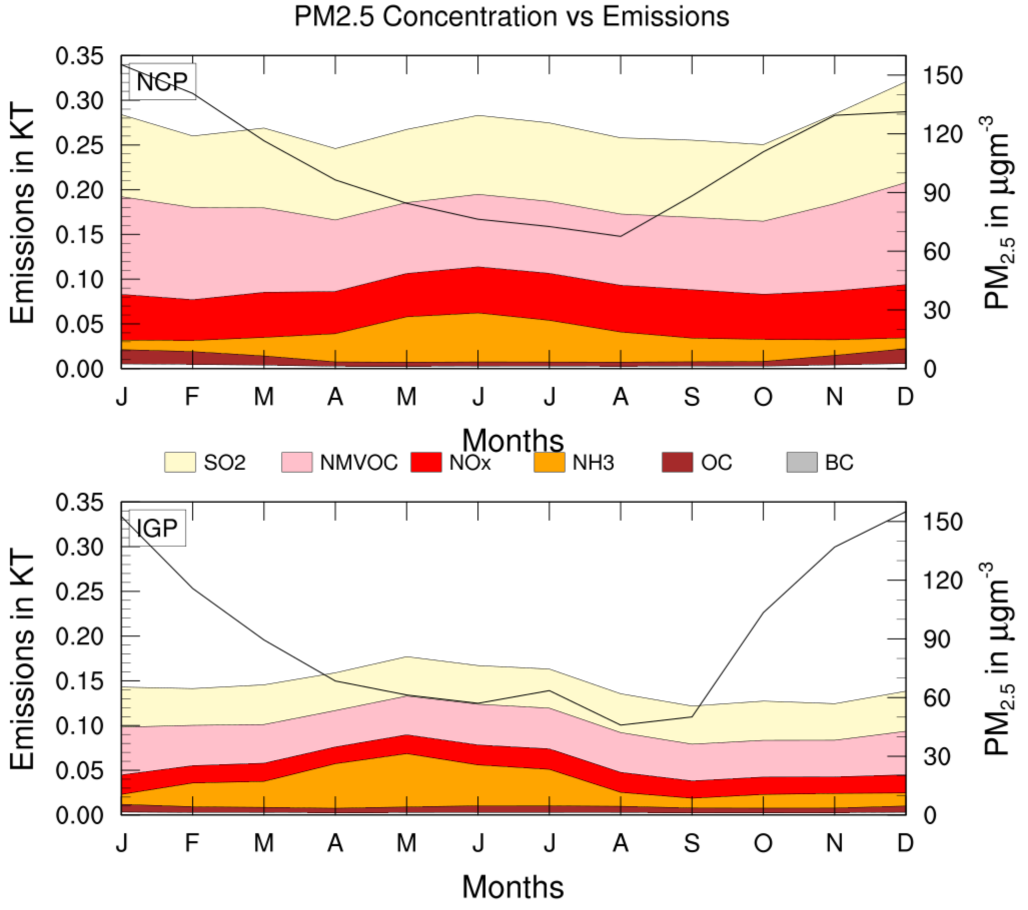

Figure 6: Line Graph Emission and Aerosol Concentration in 2019 over the NCP and IGP

First of all, the aerosol concentration over both the NCP and IGP appears to be lowest in the months of April up until September and highest in the remaining months. The highest aerosol concentration in both regions appears to be around 150 µg/m^{-3}, but the lowest aerosol concentration differs, with around 40 µg/m^{-3} for the IGP and around 60 µg/m^{-3} for the NCP. When it comes to the emissions, Figure 6 shows us that Sulfur Dioxide and Non-Methane VOCs are the biggest emission sources, where these two sources peak in the winter months over the NCP and stay the same over the IGP. Black and Organic Carbon are the smallest emission sources in both regions. There appears to be a peak in NH3 emissions for both regions during the shift from spring to summer, which can be related to the agricultural sector, where spring crops are harvested and summer crops are planted. Both regions also show to have had more emissions during the summer months, May until August, whilst aerosol concentrations are highest in the winter months. However, the NCP clearly emits moreover every month compared to the IGP. These emissions appear to be approximately double. This result is relevant as it repeats the result that the accumulation potential for PM2.5 is much higher over the IGP as compared to the NCP. SO2 and NMVOCs also show to barely translate into particle-phase by chemical transformation, which is significant as these are the largest sources of emissions.

Pollution forming efficiency: separating gaseous and particulate emissions

Figure 6 showed us how different sources of emissions translate into particle pollution, however, considering SO2 and NMVOCs barely translated into this pollution it is useful to take a closer look at the primary particle emissions from BC and OC and the gas Emissions separately. Just like Figure 6, Figures 7 and 8 visualize the relationship between anthropogenic emissions and aerosol concentration by displaying both concentrations over the NCP and IGP. Creating similar graphs for the specific emission sources can provide a deeper insight into the conversion rate to aerosols. The full grid flux of anthropogenic emissions in KT is visualized by the stacked plots, which make use of the left Y-axis. The stacked plots differentiate between the different emission sources, which in this case are Organic Carbon, and Black Carbon for Figure 7. In Figure 8, these are Sulfur Dioxide, Non-Methane VOCs, Nitrogen Oxide, and Ammonia. The legend between the two graphs describes the emission sources with their corresponding color. The line plot displays the full grid flux of aerosol concentration in µg/m^{-3}.

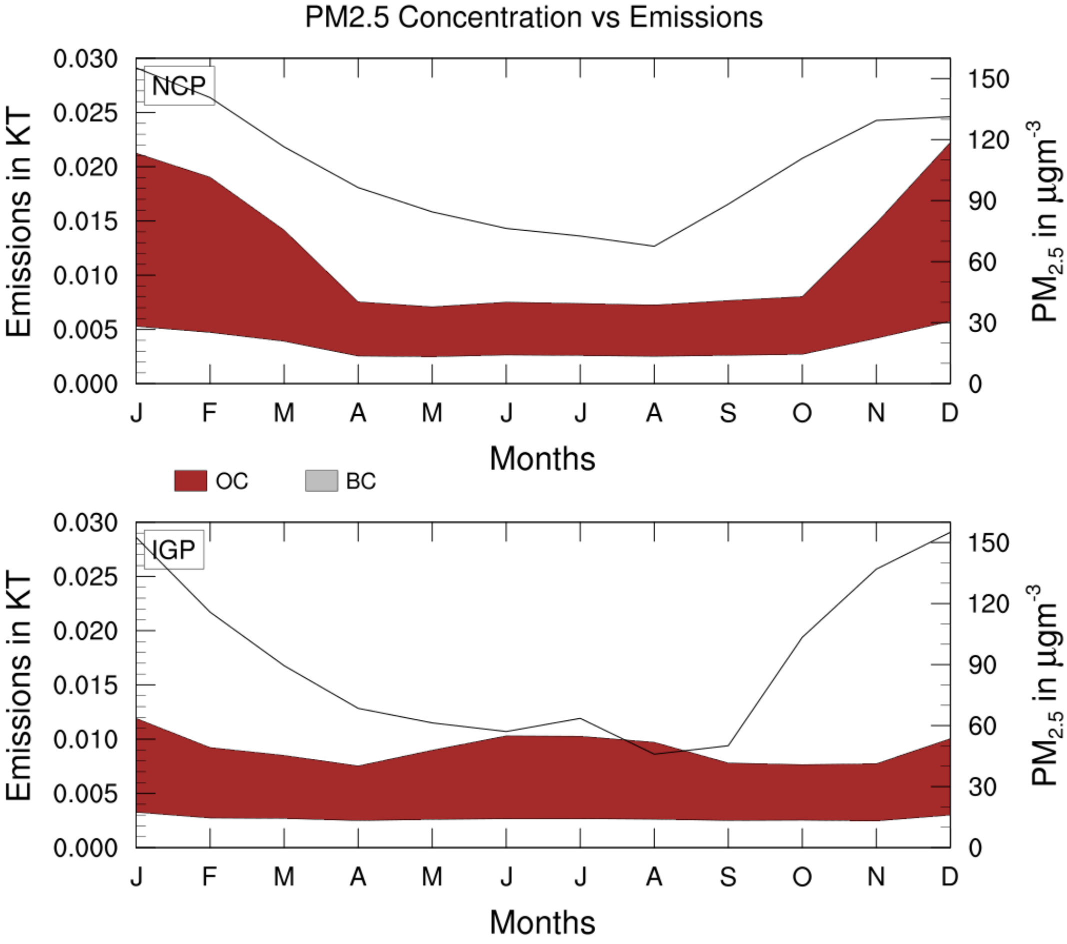

Figure 7: Line Graph Carbon Emissions and Aerosol Concentration in 2019 over the NCP and IGP

Figure 7 provides a close-up of the results for carbon emissions specifically. Over the NCP, there appears to be a consistently strong relationship between carbon emissions and aerosol concentration, however, this relationship is not to be seen over the IGP region where it rather appears to be anticorrelated. The never truly consistent relationship between emissions and aerosol concentration over the IGP asks for a systematic study of the post-monsoon and winter season to reveal if the accumulation rate has also been this strong in earlier years and to understand if the recent climate affected atmospheric stagnation.

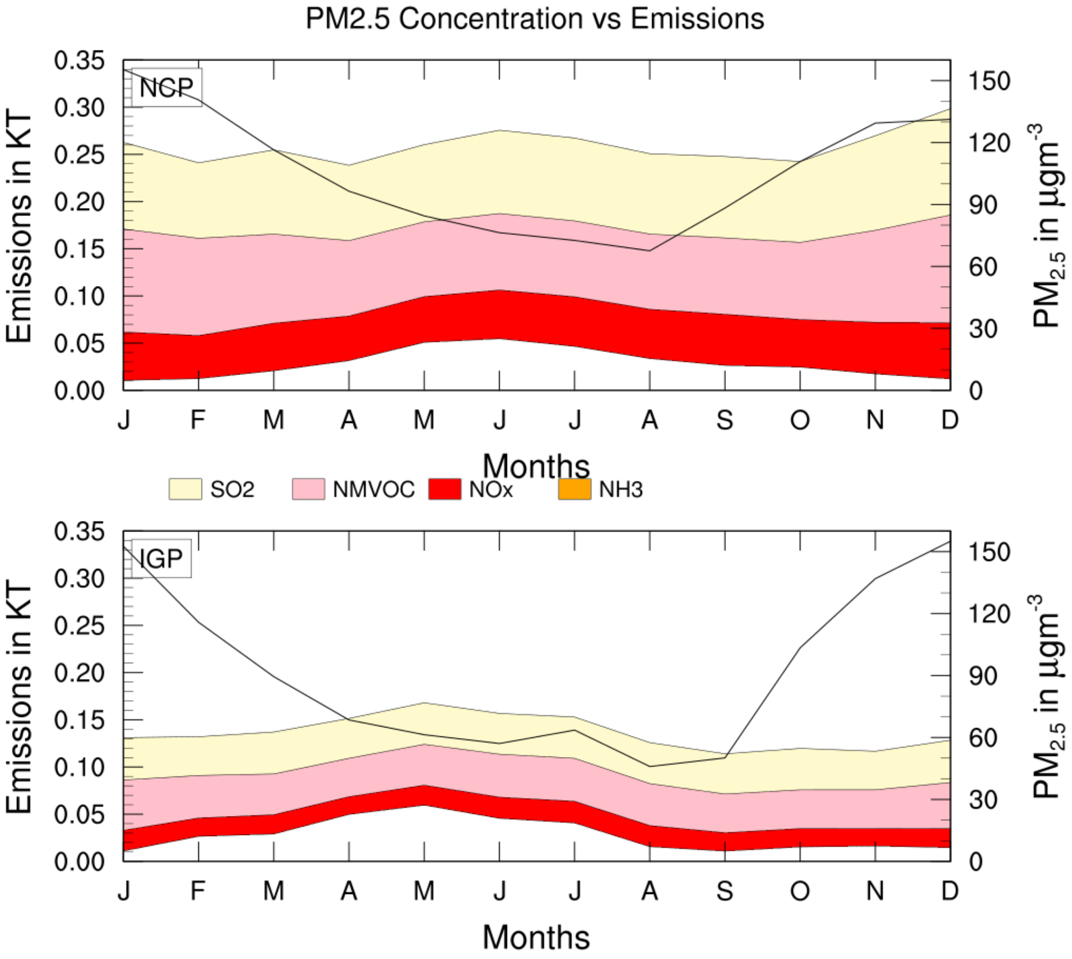

Figure 8: Line Graph Gas Emissions and Aerosol Concentration in 2019 over the NCP and IGP

Finally, Figure 8 provides a close-up of the results for gas emissions. There seems to be no clear relationship between both regions. However, this result can be explained through the different local chemistries, such as temperature, wind, and precipitation rates influencing the regions. meteorology The appendix offers all Figures in their full size and the respective codes to create them in the Appendix.

Discussion

This research tried to further clear out the role of meteorology in exacerbating or avoiding air pollution episodes over the IGP and the NCP regions according to the research question: “How do the frequency and intensity of air pollution episodes in IGP and NCP depend on the distribution and strength of emissions?” To answer this question, the magnitude, duration, and spatial characteristics of air pollution episodes in both the globally significant regions were quantified for one entire year, 2019, and put into perspective by relating them to the regional anthropogenic emissions.

The relationship between air pollution episodes and the distribution and strength of emissions differs significantly between the two regions. The accumulation potential apprears to be significantly stronger over the IGP, as there are only half the emissions, but the same air quality as over the NCP. Areas with the highest numbers of air pollution episodes are found over the NCP, pointing to a greater cleansing capacity of air pollution in the region. These results translate into the fact that it is more difficult for emissions to escape into the atmosphere over the IGP through a combination of local meteorology and geography. This means that if emissions over the IGP would be the same as over the NCP, the region would become double as polluted as it is now. When it comes to PM2.5 concentration in comparison to the anthropogenic emissions, the only conclusion that could be drawn is that the ratio is lowest for both in the monsoon months, especially considering this is a time when both regions have a peek in their emissions whilst PM2.5 concentrations are the lowest.

Although the cleansing capacity is significantly better in the summer months over the IGP as compared to the NCP, the IGP could never follow the same industrialization trend, where it would rely more on energy generation, industry, and road transportation. This could lead to the area becoming twice as polluted as it already is, and WHO air quality guidelines are already exceeded almost every single day. India is one of the few countries on track to meeting it’s Paris Agreement targets, which include reducing greenhouse gas emissions (The Economic Times, 2021). However, reducing emissions to a certain extent will not lead to the same results of increased air quality everywhere. This means that a reduction in greenhouse gas emissions does not necessarily lead to better air quality, as many pollutants, including PM2.5, are co emitted from the same sources.

Limitations

Through the limited scope of this research, there are multiple limitations that should be taken into account. First of all, the masks that have been used to isolate the IGP and NCP region within the global data did not fit perfectly. Especially over the IGP, this becomes clear in Figure 2 of the results where there is a clear edge where the Himalayas start. Air quality is significantly better in this region compared to urban areas, positively influencing the results over the IGP. This means average air quality and polluted areas might actually be worse than they appear in the results. Secondly, the ‘CAMS global anthropogenic emissions’ included the sources and sectors of anthropogenic emissions which have been used to create the results. However, ‘CAMS global reanalysis of aerosol concentrations’ did not contain the composition of aerosols. Therefore, it was not possible to directly compare which emission sources have the strongest conversion rate. There was only a possibility to make speculations using scientific grounding and Images 6, 7, and 8 but these did not show a clear relationship. Thirdly, this research made use of reanalysis and satellite data. For the research to become more reliable, this data has to be verified against ground observations. The final limitation of the dataset is the temporal scope of this research. Only data from the year 2019 has been used, however, this year might be unrepresentative of the climatological conditions and should be compared to other years to increase reliability.

Recommendations

The research results and limitations lead to recommendations for future research. It is relevant to increase research on the influence of local chemistry on gas to particle pollution, especially between the months of September to March. In other words, the post-monsoon and winter months. The research points out a gap in missing literature on what processes play a role in the accumulation potential and why it is more pronounced in this period. Air pollution relevant to meteorology (temperature, relative humidity, wind speed & direction, planetary boundary layer height) over the two regions should be investigated for these months. Especially comparative studies over the NCP and IGP would be useful as these provide insights on why the accumulation potential is much higher in one region as compared to the other.

Conclusion

This research quantified and contrasted the magnitude, duration, and spatial characteristics of air pollution episodes over the NCP and IGP for one entire year, 2019, and put them into perspective by relating them to the regional anthropogenic emissions, thereby elucidating the role of meteorology in exacerbating or avoiding air pollution episodes in both regions. It was found that the IGP could never follow the same industrialization trend as over the NCP, as the accumulation potential over the region is too high. Although India is one of the few countries on track to meeting it’s Paris Agreement targets, reducing emissions to a certain extent will not lead to the same results of increased air quality everywhere. Therefore, more comparative research on the influence of local chemistry on gas to particle pollution, especially in the post-monsoon and winter months is recommended, to increase effective policy making on emission reducion. Let’s hope the policies will purify the air we breathe, and thus I lay my brick hoping someone else will continue building.

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WHO. (2019, July 30). Air pollution. World Health Organization. Retrieved May 31, 2022, from https://www.who.int/health-topics/air-pollution#tab=tab_1WHO. (2021a, September 22). Ambient (outdoor) air pollution. World Health Organization. Retrieved May 31, 2022, from https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

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Yang, Z., Dong, J., Qin, Y., Ni, W., Zhao, G., Chen, W., Chen, B., Kou, W., Wang, J., & Xiao, X. (2018). Integrated Analyses of PALSAR and Landsat Imagery Reveal More Agroforests in a Typical Agricultural Production Region, North China Plain. Remote Sensing, 10(9), 1323. https://doi.org/10.3390/rs10091323

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Appendix

Appendix 1: Comparative Studies NCP IGP

Comparative Studies on Climate Effects

Sherman, P., Gao, M., Song, S., Archibald, A. T., Abraham, N. L., Lamarque, J. F., ... & McElroy, M. B. (2020). **Sensitivity of modeled Indian Monsoon to Chinese and Indian aerosol emissions**. Atmospheric Chemistry and Physics Discussions, 2020, 1-30.

Gao, M., Ji, D., Liang, F., & Liu, Y. (2018). **Attribution of aerosol direct radiative forcing in China and India to emitting sectors.** Atmospheric Environment, 190, 35–42. https://doi.org/10.1016/j.atmosenv.2018.07.011

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Lin, L., Xu, Y., Wang, Z., Diao, C., Dong, W., & Xie, S. P. (2018). **Changes in Extreme Rainfall Over India and China Attributed to Regional Aerosol-Cloud Interaction During the Late 20th Century Rapid Industrialization.** Geophysical Research Letters, 45(15), 7857–7865. https://doi.org/10.1029/2018gl078308

Rai, M., Kang, S., Yang, J., Rupakheti, M., Rupakheti, D., Tripathee, L., Hu, Y., and Chen, X.: **Insight into seasonal aerosol concentrations, meteorological influence, and transport over the Pan-Third Pole region using multi-sensors satellite and model simulation**, Atmos. Chem. Phys. Discuss. [preprint], https://doi.org/10.5194/acp-2022-199, in review, 2022.

Ramachandran, S., & Rupakheti, M. (2022b). **Trends in the types and absorption characteristics of ambient aerosols over the Indo-Gangetic Plain and North China Plain in last two decades.** Science of The Total Environment, 831, 154867. https://doi.org/10.1016/j.scitotenv.2022.154867

Ramachandran, S., & Rupakheti, M. (2022a). **Trends in physical, optical and chemical columnar aerosol characteristics and radiative effects over South and East Asia: Satellite and ground-based observations**. Gondwana Research, 105, 366–387. https://doi.org/10.1016/j.gr.2021.09.016

Zhang, H., Wang, Z., Guo, P., & Wang, Z. (2009). **A modeling study of the effects of direct radiative forcing due to carbonaceous aerosol on the climate in East Asia.** Advances in Atmospheric Sciences, 26(1), 57–66. https://doi.org/10.1007/s00376-009-0057-5

Sherman, P., Gao, M., Song, S., Archibald, A. T., Abraham, N. L., Lamarque, J. F., Shindell, D., Faluvegi, G., & McElroy, M. B. (2021). **Sensitivity of modeled Indian monsoon to Chinese and Indian aerosol emissions**. Atmospheric Chemistry and Physics, 21(5), 3593–3605. https://doi.org/10.5194/acp-21-3593-2021

Streets, D. G., Shindell, D. T., Lu, Z., & Faluvegi, G. (2013). **Radiative forcing due to major aerosol emitting sectors in China and India.** Geophysical Research Letters, 40(16), 4409–4414. https://doi.org/10.1002/grl.50805

Ma, F., & Guan, Z. (2018). **Seasonal Variations of Aerosol Optical Depth over East China and India in Relationship to the Asian Monsoon Circulation**. Journal of Meteorological Research, 32(4), 648–660. https://doi.org/10.1007/s13351-018-7171-1

Menon, S., Hansen, J., Nazarenko, L., & Luo, Y. (2002). **Climate Effects of Black Carbon Aerosols in China and India**. Science, 297(5590), 2250–2253. https://doi.org/10.1126/science.1075159

Yang, X., Jiang, L., Zhao, W., Xiong, Q., Zhao, W., & Yan, X. (2018). **Comparison of Ground-Based PM2.5 and PM10 Concentrations in China, India, and the U.S.** International Journal of Environmental Research and Public Health, 15(7), 1382. https://doi.org/10.3390/ijerph15071382

<u>Comparative Studies on Health Effects</u>

Gao, M., Beig, G., Song, S., Zhang, H., Hu, J., Ying, Q., Liang, F., Liu, Y., Wang, H., Lu, X., Zhu, T., Carmichael, G. R., Nielsen, C. P., & McElroy, M. B. (2018). **The impact of power generation emissions on ambient PM2.5 pollution and human health in China and India.** Environment International, 121, 250–259. https://doi.org/10.1016/j.envint.2018.09.015

Hu, M., Chen, Z., Cui, H., Wang, T., Zhang, C., & Yun, K. (2021). **Air pollution and critical air pollutant assessment during and after COVID-19 lockdowns: Evidence from pandemic hotspots in China, the Republic of Korea, Japan, and India**. Atmospheric Pollution Research, 12(2), 316–329. https://doi.org/10.1016/j.apr.2020.11.013

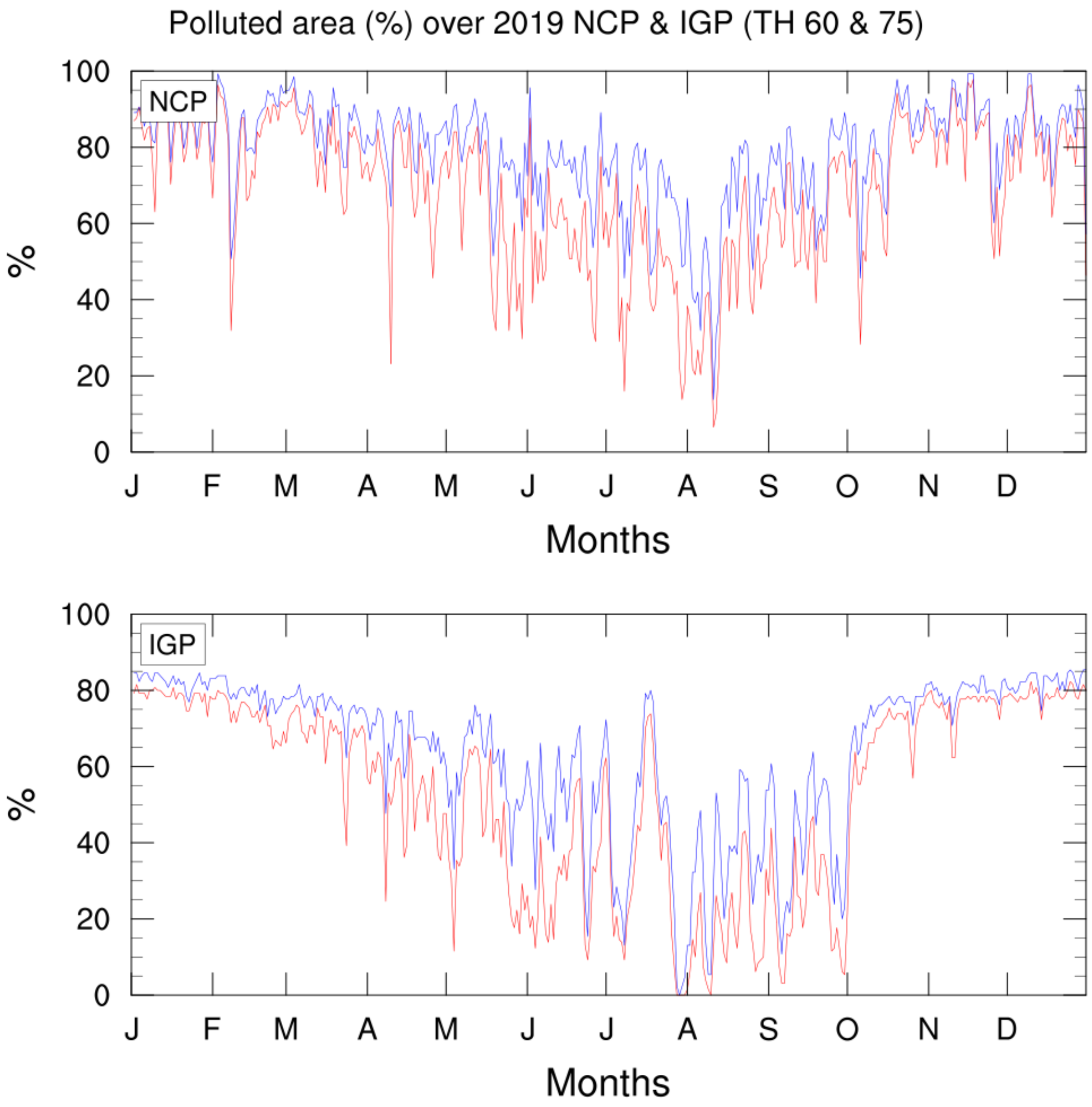
Khan, R., Kumar, K. R., & Zhao, T. (2021). **Assessment of variations of air pollutant concentrations during the COVID-19 lockdown and impact on urban air quality in South Asia.** Urban Climate, 38, 100908. https://doi.org/10.1016/j.uclim.2021.100908

Laakso, L., Koponen, I. K., Mönkkönen, P., Kulmala, M., Kerminen, V. M., Wehner, B., Wiedensohler, A., Wu, Z., & Hu, M. (2006). **Aerosol particles in the developing world; a comparison between New Delhi in India and Beijing in China**. Water, Air, and Soil Pollution, 173(1–4), 5–20. https://doi.org/10.1007/s11270-005-9018-5

Elzein, A., Stewart, G. J., Swift, S. J., Nelson, B. S., Crilley, L. R., Alam, M. S., Reyes-Villegas, E., Gadi, R., Harrison, R. M., Hamilton, J. F., & Lewis, A. C. (2020). **A comparison of PM2.5-bound polycyclic aromatic hydrocarbons in summer Beijing (China) and Delhi (India)**. Atmospheric Chemistry and Physics, 20(22), 14303–14319. https://doi.org/10.5194/acp-20-14303-2020

Li, J., Wang, G., Aggarwal, S. G., Huang, Y., Ren, Y., Zhou, B., Singh, K., Gupta, P. K., Cao, J., & Zhang, R. (2014). **Comparison of abundances, compositions and sources of elements, inorganic ions and organic compounds in atmospheric aerosols from Xi'an and New Delhi, two megacities in China and India.** Science of The Total Environment, 476–477, 485–495. https://doi.org/10.1016/j.scitotenv.2014.01.011

Appendix 2: Daily Time Series Polluted Area (%) Graph over 2019



Code Daily Time Series Polluted Area (%) Graph over 2019

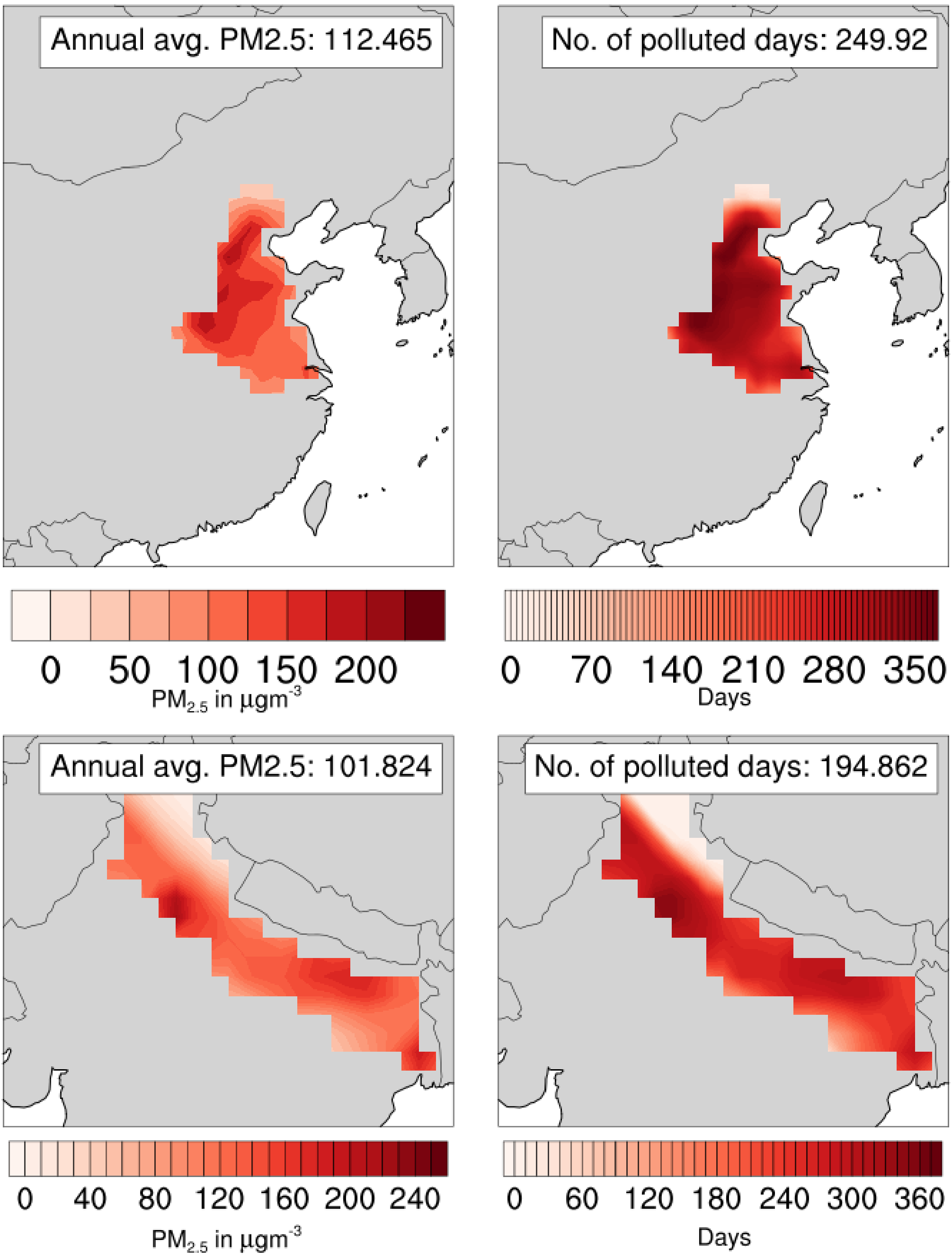
```
begin

;FILES
a =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMSconc_3hourly_NCP2019.nc","r"
)
b = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/NCPmask.nc","r")
NCP = b->NCPmask3d(0,:,:)
c =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMSconc_3hourly_IGP2019.nc","r")
d = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/IGPmask.nc","r")
IGP = d->IGPmask3d(0,:,:)

;PM2P5
pm25NCP = short2flt(a->pm2p5)
```

```
pm25NCP = pm25NCP * 10^9
pm25NCP@long_name="   "
pm25NCP@units = "   "
pm25NCP = pm25NCP(:,::-1,:)

pm25IGP = short2flt(c->pm2p5)
pm25IGP = pm25IGP * 10^9
pm25IGP@long_name="   "
pm25IGP@units = "   "
pm25IGP = pm25IGP(:,::-1,:)

;MASK
do i=0,2919
pm25NCP(i,:,:) = where(NCP.eq.1, pm25NCP(i,:,:), pm25NCP@_FillValue)
end do

do i=0,2919
pm25IGP(i,:,:) = where(IGP.eq.1, pm25IGP(i,:,:), pm25IGP@_FillValue)
end do

;DAILYPM25
dailypm25NCP = new((/365,41,41/),typeof(pm25NCP))
sp = 0
do i=0,364
ep = sp + 7
dailypm25NCP(i,:,:) = dim_avg_n(pm25NCP(sp:ep,:,:),0)
sp = ep + 1
end do


dailypm25IGP = new((/365,21,27/),typeof(pm25IGP))
sp = 0
do i=0,364
ep = sp + 7
dailypm25IGP(i,:,:) = dim_avg_n(pm25IGP(sp:ep,:,:),0)
sp = ep + 1
end do

; Calculating grids over NCP with poor air quality
polareaNCP75 = new(365, float)
counter = new(365, float)
do day = 0,364
aq = dailypm25NCP(day,:,:)
aq = where(dailypm25NCP(day,:,:).gt.75,1,0)
nm =  where(dailypm25NCP(day,:,:).ne.pm25NCP@_FillValue,1,0)
       polareaNCP75(day) = (sum(aq)/sum(nm))*100.0
       counter(day) = day + 1
end do
```

```
polareaNCP60 = new(365, float)
counter = new(365, float)
do day = 0,364
aq = dailypm25NCP(day,:,:)
aq = where(dailypm25NCP(day,:,:).gt.60,1,0)
;print(sum(aq))
nm =  where(dailypm25NCP(day,:,:).ne.pm25NCP@_FillValue,1,0)
       polareaNCP60(day) = (sum(aq)/sum(nm))*100
       counter(day) = day + 1
end do
delete(aq)
delete(nm)

; Calculating grids over IGP with poor air quality
polareaIGP75 = new(365, float)
counter = new(365, float)
do day = 0,364
aq = dailypm25IGP(day,:,:)
aq = where(dailypm25IGP(day,:,:).gt.75,1,0)
nm =  where(dailypm25IGP(day,:,:).ne.pm25IGP@_FillValue,1,0)
       polareaIGP75(day) = (sum(aq)/sum(nm))*100
       counter(day) = day + 1
end do
polareaIGP60 = new(365, float)
counter = new(365, float)
do day = 0,364
aq = dailypm25IGP(day,:,:)
aq = where(dailypm25IGP(day,:,:).gt.60,1,0)
nm =  where(dailypm25IGP(day,:,:).ne.pm25IGP@_FillValue,1,0)
       polareaIGP60(day) = (sum(aq)/sum(nm))*100
       counter(day) = day + 1
end do

 wks   = gsn_open_wks ("png","IGPNCP_threspol_ts")              ; send graphics to png file

res                 = True                    ; plot mods desired
res@vpWidthF = 1
res@xyDashPatterns = (/0,0/)
res@xyLineColors = (/"red", "blue"/)
res@vpHeightF = 0.4
res@tmXBMode       = "Explicit"
res@tmXBLabels      = (/"J","F","M","A","M","J","J","A","S","O","N","D"/)
 res@tmXBValues = (/0,31,59,90,120,151,181,212,243,273,304,334/)
res@tmXBLabelsOn = True
 res@trXMinF = 0
res@trXMaxF = 364
res@trYMinF = 0
res@trYMaxF = 100
res@gsnDraw = False
```

```
res@gsnFrame = False
res@tiXAxisString = "Months"
res@tiYAxisString = "%"


res@tmXBMajorOutwardLengthF = 0.0
res@tmYLMajorOutwardLengthF = 0.0
res@tmXBMinorOutwardLengthF = 0.0
res@tmYLMinorOutwardLengthF = 0.0

 plot1 = gsn_csm_xy (wks, counter, (/polareaNCP75,polareaNCP60/), res) ; create plot

 plot2  = gsn_csm_xy (wks, counter,(/polareaIGP75,polareaIGP60/), res) ; create plot


;PANEL PLOTS
  pnlres                        = True
  pnlres@gsnPanelYWhiteSpacePercent = 5
  pnlres@amJust   = "TopLeft"
  pnlres@gsnMaximize = True
  pnlres@gsnFrame         = False
  pnlres@gsnPanelFigureStrings= (/"NCP","IGP"/)
pnlres@gsnPanelMainString = "Polluted area (%) over 2019 NCP & IGP (TH 60 & 75)"
gsn_panel(wks,(/plot1,plot2/),(/2,1/),pnlres)
 frame(wks)

end
```

Appendix 3: Panel plot Average PM2.5 and Number of Polluted Days



Code Panel plot Average PM2.5 and Number of Polluted Days

```
begin

;FILES
DIR = "/mnt/c/Users/Maya/Downloads/Capstone-data/"
a = addfile(DIR+"CAMSconc_3hourly_NCP2019.nc","r")
b = addfile(DIR+"CAMSconc_3hourly_IGP2019.nc","r")
c =  addfile(DIR+"NCPmask.nc","r")
d = addfile(DIR+"IGPmask.nc","r")

NCP = c->NCPmask3d(0,:,:)
IGP = d->IGPmask3d(0,:,:)
```

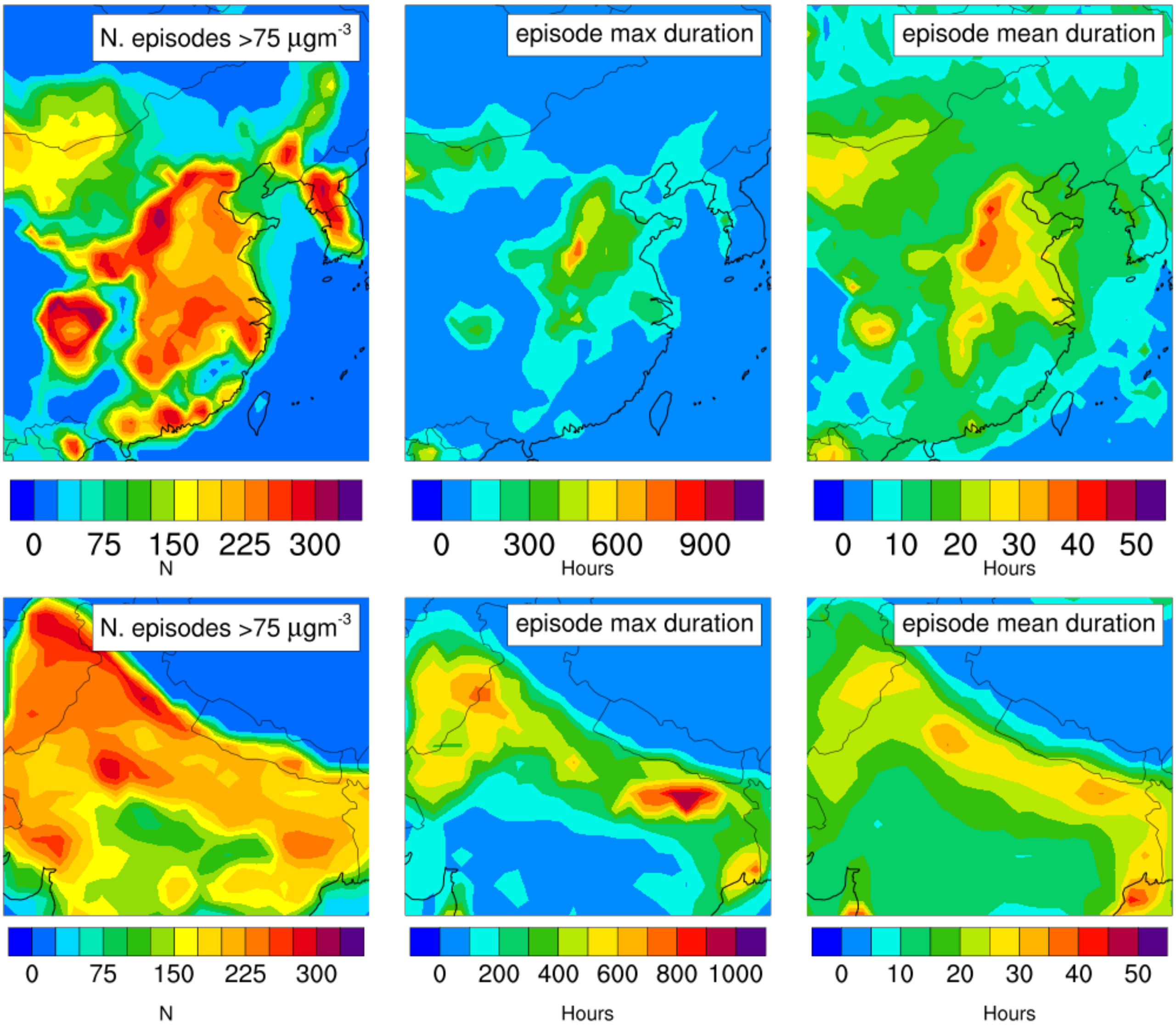
```
;PM2P5
pm25NCP = short2flt(a->pm2p5)
pm25NCP = pm25NCP * 10^9
pm25NCP@long_name="   "
pm25NCP@units = "   "
pm25NCP = pm25NCP(:,::-1,:)


pm25IGP = short2flt(b->pm2p5)
pm25IGP = pm25IGP * 10^9
pm25IGP@long_name="   "
pm25IGP@units = "   "
pm25IGP = pm25IGP(:,::-1,:)

;;;;;;;;MASK;;;;;;;;;
do i=0,2919
pm25NCP(i,:,:) = where(NCP.eq.1, pm25NCP(i,:,:), pm25NCP@_FillValue)
end do

NCPmsum = sum(NCP) ;to keep a count of total grids in NCP

do i=0,2919
pm25IGP(i,:,:) = where(IGP.eq.1, pm25IGP(i,:,:), pm25IGP@_FillValue)
end do

IGPmsum = sum(IGP) ;to keep a count of total grids in IGP

;;;;;;; PREPARING TIME-AVERAGED DATA;;;;;;;;;
pm25NCPavg = dim_avg_n_Wrap(pm25NCP,0)
pm25IGPavg = dim_avg_n_Wrap(pm25IGP,0)

NCPavgsum = sum(pm25NCPavg) ;reducing it to a single number over NCP
IGPavgsum = sum(pm25IGPavg) ;reducing it to a single number over IGP

NCPavgflux = NCPavgsum / NCPmsum
IGPavgflux = IGPavgsum / IGPmsum
print("NCPavgflux" + " " + NCPavgflux)
print("IGPavgflux" + " " + IGPavgflux)

;;;;;;;;;;;;;;;;; DAILYPM25 NCP;;;;;;;;;;;;;;;;;;;;
dailypm25NCP = new((/365,41,41/),typeof(pm25NCP))
sp = 0
do i=0,364
ep = sp + 7
dailypm25NCP(i,:,:) = dim_avg_n(pm25NCP(sp:ep,:,:),0)
sp = ep + 1
end do
```

```
;;;;;;;;;;;;;; N DAYS EXEEDING 75mg/m3 MAP NCP;;;;;;;;;;;;;;;;;;;;;;;;;
accmapNCP = dailypm25NCP(0,:,:)             ; initializing 2D accmap variable
copy_VarCoords(pm25NCP(0,:,:), accmapNCP)   ;inheriting variable metadata
accmapNCP = where(accmapNCP.gt.75,1,0)
do day = 0, 364
 aq = dailypm25NCP(day,:,:)
 aq = where(aq.gt.75,1,0)
 accmapNCP = accmapNCP + aq
end do

;;;;;;;;;;;;;;;;DAILYPM25 IGP;;;;;;;;;;;;;;;;;;;;;
dailypm25IGP = new((/365,21,27/),typeof(pm25IGP))
sp = 0
do i=0,364
ep = sp + 7
dailypm25IGP(i,:,:) = dim_avg_n(pm25IGP(sp:ep,:,:),0)
sp = ep + 1
end do
delete(aq)

;;;;;;;;;;;;;;;; N DAYS EXEEDING 75mg/m3 MAP IGP;;;;;;;;;;;;;;;;;;;;;;;
accmapIGP = dailypm25IGP(0,:,:)
copy_VarCoords(pm25IGP(0,:,:), accmapIGP)
accmapIGP = where(accmapIGP.gt.75,1,0)
do day = 0, 364
 aq = dailypm25IGP(day,:,:)
 aq = where(aq.gt.75,1,0)
 accmapIGP = accmapIGP + aq
end do

NCPpoldaysum = sum(accmapNCP) ;reducing it to a single number over NCP
IGPpoldaysum = sum(accmapIGP) ;reducing it to a single number over IGP

NCPpoldayflux = NCPpoldaysum / NCPmsum
IGPpoldayflux = IGPpoldaysum / IGPmsum
print("NCPpoldayflux" + " " + NCPpoldayflux)
print("IGPpoldayflux" + " " + IGPpoldayflux)
printMinMax(pm25NCPavg,True)
printMinMax(pm25IGPavg,True)


 wks   = gsn_open_wks ("png","IGPNCP_avgconc_poldays")              ; send graphics to png
 res                    = True
  res@gsnDraw            = True           ; don't draw
  res@gsnFrame           = True           ; don't advance frame
  res@gsnMaximize         = True    ; Maximize plot in frame
  res@cnFillOn           = True           ; turn on color
  res@cnFillPalette       = (/"MPL_Reds"/)   ; set color map
  res@cnLinesOn          = False          ; no contour lines
```

```
  res@gsnRightString      = ""          ; assign right string
  res@gsnAddCyclic        = False
  res@mpFillOn            = True          ; no map fill

  res@mpGeophysicalLineThicknessF = 2.0
  res@mpDataBaseVersion   = "MediumRes"
  res@mpOutlineBoundarySets       = "Allboundaries"

;Selecting NCP region from the map
  res@mpProjection          = "Mercator"
  res@mpLambertParallel1F    = 30.
  res@mpLambertParallel2F    = 40.
  res@mpLambertMeridianF     = 115.

  res@mpLimitMode           = "Corners"          ; choose region of map
  res@mpLeftCornerLatF       = 20.
  res@mpLeftCornerLonF       = 100.
  res@mpRightCornerLatF      = 50.
  res@mpRightCornerLonF      = 130.
  res@pmLabelBarOrthogonalPosF = -0.025
  res@lbLabelFontHeightF = 0.03
  res@gsnDraw             = False       ; don't draw yet
  res@gsnFrame            = False       ; don't advance frame yet
  res@cnLevelSelectionMode = "ManualLevels"

  res@cnMinLevelValF = 0.
  res@cnMaxLevelValF = 225.
  res@cnLevelSpacingF = 25.

 plot1 = gsn_csm_contour_map(wks, pm25NCPavg, res) ; create plo

 res@cnMinLevelValF = 0.
 res@cnMaxLevelValF = 365.
 res@cnLevelSpacingF = 5.

 plot2 = gsn_csm_contour_map(wks, accmapNCP, res) ; create plot

;Selecting IGP region from the map
  res@mpProjection          = "Mercator"
  res@mpLambertParallel1F    = 25.
  res@mpLambertParallel2F    = 30.
  res@mpLambertMeridianF     = 80.

  res@mpLimitMode           = "Corners"          ; choose region of map
  res@mpLeftCornerLatF       = 20.
  res@mpLeftCornerLonF       = 70.
  res@mpRightCornerLatF      = 35.
  res@mpRightCornerLonF      = 89.5
```

```
 res@cnMinLevelValF = 0.
 res@cnMaxLevelValF = 250.
 res@cnLevelSpacingF = 10.

 plot3 = gsn_csm_contour_map(wks, pm25IGPavg, res) ; create plot

 res@cnMinLevelValF = 0.
 res@cnMaxLevelValF = 365.
 res@cnLevelSpacingF = 10.
plot4 = gsn_csm_contour_map(wks, accmapIGP, res) ; create plot


;---Retrieve the height used for the first plot and apply to subsequent plots
  getvalues plot1
    "vpWidthF" : vph
  end getvalues

setvalues (/plot2,plot3,plot4/)
  "vpWidthF" : vph
end setvalues


;PANEL PLOTS
  pnlres                          = True
  pnlres@gsnPanelXWhiteSpacePercent = 5
  pnlres@amJust   = "TopRight"
  pnlres@gsnMaximize = True
  pnlres@gsnFrame        = False
  pnlres@gsnPanelFigureStrings= (/"Annual avg. PM2.5: 112.465","No. of polluted days:
249.92","Annual avg. PM2.5: 101.824","No. of polluted days: 194.862"/)

 gsn_panel(wks,(/plot1,plot2,plot3,plot4/),(/2,2/),pnlres)

; Draw a text string at the bottom
  txres             = True
  txres@txFontHeightF = 0.012
  gsn_text_ndc(wks,"PM~B~2.5~N~ in ~F33~m~F21~gm~S~-3~N~",0.33,0.15,txres)
  gsn_text_ndc(wks,"PM~B~2.5~N~ in ~F33~m~F21~gm~S~-3~N~",0.33,0.52,txres)
  gsn_text_ndc(wks,"Days",0.67,0.15,txres)
  gsn_text_ndc(wks,"Days",0.67,0.52,txres)

frame(wks)

end
```

Appendix 4: Panel Plot Number, Max Duration, and Average Duration of Air Pollution Episodes



Code Panel Plot Number, Max Duration, and Average Duration of Air Pollution Episodes

```
begin

;FILES

DIR = "/mnt/c/Users/Maya/Downloads/Capstone-data/"
a = addfile(DIR+"CAMSconc_3hourly_NCP2019.nc","r")
b = addfile(DIR+"CAMSconc_3hourly_IGP2019.nc","r")

;PM2P5
pm25NCP = short2flt(a->pm2p5)
pm25NCP = pm25NCP * 10^9
pm25NCP@long_name="   "
pm25NCP@units = "   "
pm25NCP = pm25NCP(:,::-1,:)
```

```
pm25IGP = short2flt(b->pm2p5)
pm25IGP = pm25IGP * 10^9
pm25IGP@long_name="   "
pm25IGP@units = "   "
pm25IGP = pm25IGP(:,::-1,:)


;;;;;;; NUMBER  & DURATION MAXMEAN OF EPISODES NCP;;;;;;;;
nepisodeNCP = pm25NCP(0,:,:)
maxdurNCP = pm25NCP(0,:,:)
avgdurNCP = pm25NCP(0,:,:)
do lat = 0,40
do lon = 0,40

pm25tsNCP = pm25NCP(:,lat,lon)
pm25tsNCP = where(pm25tsNCP.gt.75,1,0)
avgdur = 0.0
maxdur = 0
dursum = 0
episode = 0
count = 0
do i = 0,dimsizes(pm25tsNCP)-1
if(pm25tsNCP(i).eq.1)then
        count = count + 1
end if

if(pm25tsNCP(i).eq.0)then
        dur = count * 3
        dursum  = dursum + dur
          if (dur.gt.maxdur)then
                maxdur = dur
          end if
        ;print(episode + " " + dur)
     if(dur.ne.0)then
        ;print(i+" "+ dur+ " ")
        episode = episode + 1
     end if
        count = 0
end if
end do
if (episode.ne.0)then
        avgdur = tofloat(dursum) /tofloat(episode)
end if

nepisodeNCP(lat,lon) = episode
maxdurNCP(lat,lon) = maxdur
avgdurNCP(lat,lon) = avgdur
end do
end do
```

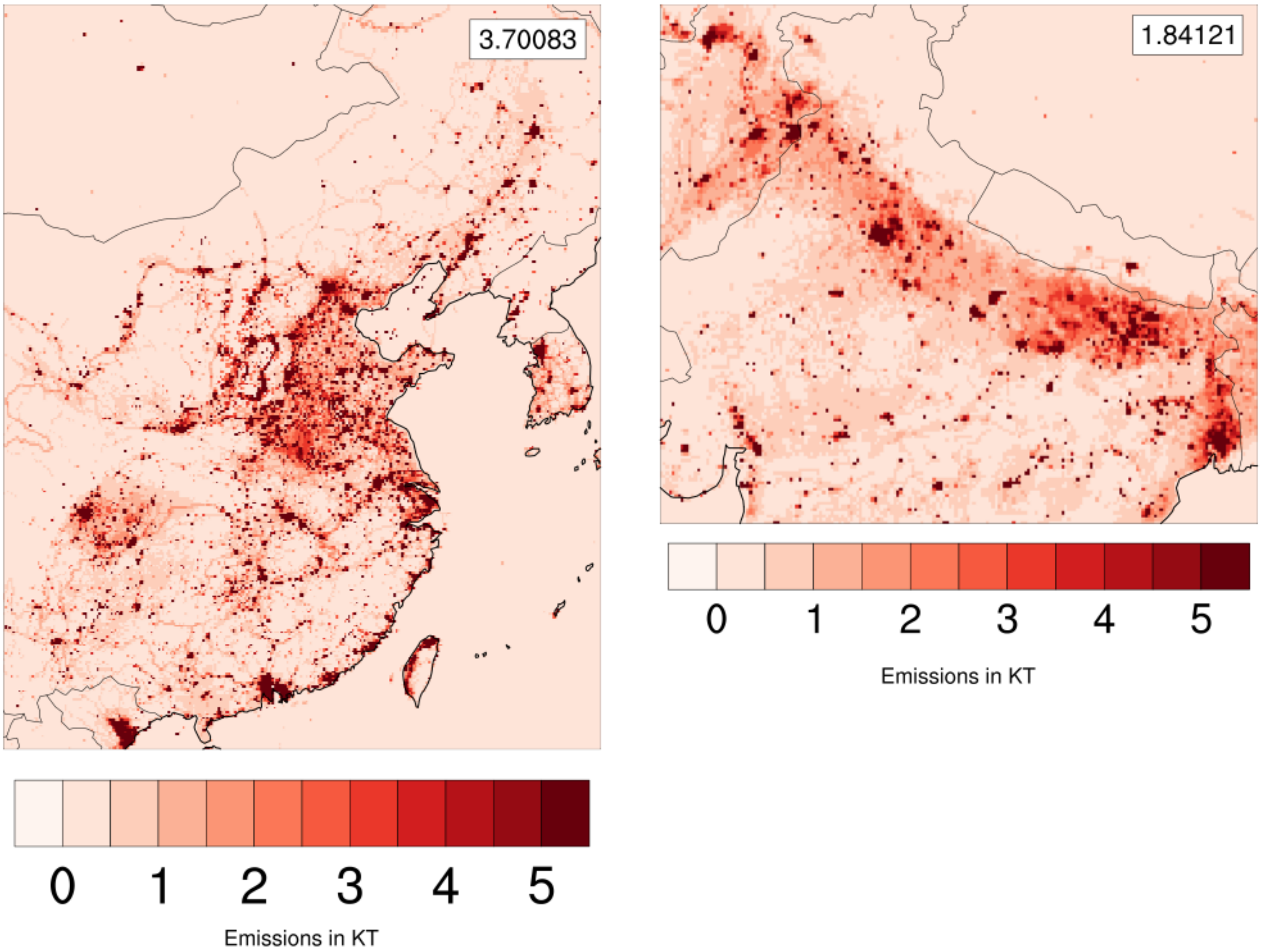
```
printVarSummary(pm25NCP)
printMinMax(nepisodeNCP, True)
printMinMax(maxdurNCP, True)
printMinMax(avgdurNCP, True)

;;;;;;; NUMBER  & DURATION MAXMEAN OF EPISODES IGP;;;;;;;;
nepisodeIGP = pm25IGP(0,:,:)
maxdurIGP = pm25IGP(0,:,:)
avgdurIGP = pm25IGP(0,:,:)
do lat = 0,20
do lon = 0,26

pm25tsIGP = pm25IGP(:,lat,lon)
pm25tsIGP = where(pm25tsIGP.gt.75,1,0)
avgdur = 0.0
maxdur = 0
dursum = 0
episode = 0
count = 0
do i = 0,dimsizes(pm25tsIGP)-1
if(pm25tsIGP(i).eq.1)then
      count = count + 1
end if

if(pm25tsIGP(i).eq.0)then
      dur = count * 3
      dursum  = dursum + dur
        if (dur.gt.maxdur)then
             maxdur = dur
        end if
      ;print(episode + " " + dur)
    if(dur.ne.0)then
      ;print(i+" "+ dur+ " ")
      episode = episode + 1
    end if
      count = 0
end if
end do
if (episode.ne.0)then
      avgdur = tofloat(dursum) /tofloat(episode)
end if

nepisodeIGP(lat,lon) = episode
maxdurIGP(lat,lon) = maxdur
avgdurIGP(lat,lon) = avgdur
end do
end do
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```

```
 wks   = gsn_open_wks ("png","IGPNCP_avgconc_poldays")               ; send graphics to png

  res                  = True
  res@gsnDraw            = True          ; don't draw
  res@gsnFrame           = True          ; don't advance frame
  res@gsnMaximize        = True    ; Maximize plot in frame
  res@cnFillOn           = True           ; turn on color
  res@cnFillPalette       = (/"BlAqGrYeOrReVi200"/)   ; set color map
  res@cnLinesOn          = False          ; no contour lines
  res@gsnRightString      = ""        ; assign right string
  res@gsnAddCyclic        = False
  res@mpFillOn           = True          ; no map fill
  res@mpGeophysicalLineThicknessF = 2.0
  res@mpDataBaseVersion   = "MediumRes"
  res@mpOutlineBoundarySets      = "Allboundaries"

;Selecting NCP region from the map
  res@mpProjection          = "Mercator"
  res@mpLambertParallel1F    = 30.
  res@mpLambertParallel2F    = 40.
  res@mpLambertMeridianF     = 115.

  res@mpLimitMode           = "Corners"         ; choose region of map
  res@mpLeftCornerLatF       = 20.
  res@mpLeftCornerLonF       = 100.
  res@mpRightCornerLatF      = 50.
  res@mpRightCornerLonF      = 130.
 res@pmLabelBarOrthogonalPosF = -0.025
  res@lbLabelFontHeightF = 0.03
  res@gsnDraw            = False       ; don't draw yet
  res@gsnFrame           = False       ; don't advance frame yet

res@cnLevelSelectionMode = "ExplicitLevels" ; set explicit contour levels
res@cnLevels = (/0,25,50,75,100,125,150,175,200,225,250,275,300,325/)

 plot1 = gsn_csm_contour_map(wks,nepisodeNCP, res) ; create plo

 delete(res@cnLevels)
 res@cnLevelSelectionMode = "ExplicitLevels" ; set explicit contour levels
 res@cnLevels = (/0,100,200,300,400,500,600,700,800,900,1000/)

 plot2 = gsn_csm_contour_map(wks, maxdurNCP, res) ; create plot

 delete(res@cnLevels)
 res@cnLevelSelectionMode = "ExplicitLevels" ; set explicit contour levels
 res@cnLevels = (/0,5,10,15,20,25,30,35,40,45,50/)

 plot3 = gsn_csm_contour_map(wks, avgdurNCP, res) ; create plot
```

```
;Selecting IGP region from the map
  res@mpProjection          = "Mercator"
  res@mpLambertParallel1F    = 25.
  res@mpLambertParallel2F    = 30.
  res@mpLambertMeridianF     = 80.

  res@mpLimitMode           = "Corners"         ; choose region of map
  res@mpLeftCornerLatF       = 20.
  res@mpLeftCornerLonF       = 70.
  res@mpRightCornerLatF      = 35.
  res@mpRightCornerLonF      = 89.5

 delete(res@cnLevels)
 res@cnLevelSelectionMode = "ExplicitLevels" ; set explicit contour levels
 res@cnLevels = (/0,25,50,75,100,125,150,175,200,225,250,275,300,325/)

 plot4 = gsn_csm_contour_map(wks, nepisodeIGP, res) ; create plot

 delete(res@cnLevels)
 res@cnLevelSelectionMode = "ExplicitLevels" ; set explicit contour levels
 res@cnLevels = (/0,100,200,300,400,500,600,700,800,900,1000/)

res@cnLevelSelectionMode = "ExplicitLevels" ; set explicit contour levels

 plot5 = gsn_csm_contour_map(wks, maxdurIGP, res) ; create plot

 delete(res@cnLevels)
 res@cnLevelSelectionMode = "ExplicitLevels" ; set explicit contour levels
 res@cnLevels = (/0,5,10,15,20,25,30,35,40,45,50/)

 plot6 = gsn_csm_contour_map(wks, avgdurIGP, res) ; create plot

;---Retrieve the height used for the first plot and apply to subsequent plots
  getvalues plot1
    "vpWidthF" : vph
  end getvalues

setvalues (/plot2,plot3,plot4,plot5,plot6/)
  "vpWidthF" : vph
end setvalues

;PANEL PLOTS
  pnlres                          = True
  pnlres@gsnPanelXWhiteSpacePercent = 5
  pnlres@amJust   = "TopRight"
  pnlres@gsnMaximize = True
  pnlres@gsnFrame        = False
```

```
  pnlres@gsnPanelFigureStrings= (/"N. episodes >75 ~F33~m~F21~gm~S~-3~N~","episode
max duration","episode mean duration", "N. episodes >75
~F33~m~F21~gm~S~-3~N~","episode max duration","episode mean duration"/)
 gsn_panel(wks,(/plot1,plot2,plot3,plot4,plot5,plot6/),(/2,3/),pnlres)

; Draw a text string at the bottom
  txres              = True
  txres@txFontHeightF = 0.012
  gsn_text_ndc(wks,"N",0.15,0.15,txres)
  gsn_text_ndc(wks,"N",0.15,0.52,txres)
  gsn_text_ndc(wks,"Hours",0.50,0.15,txres)
  gsn_text_ndc(wks,"Hours",0.50,0.52,txres)
  gsn_text_ndc(wks,"Hours",0.85,0.15,txres)
  gsn_text_ndc(wks,"Hours",0.85,0.52,txres)

  frame(wks)
end
```

Appendix 5: Panel Plot Annual Anthropogenic Emissions



Code Panel Plot Annual Anthropogenic Emissions

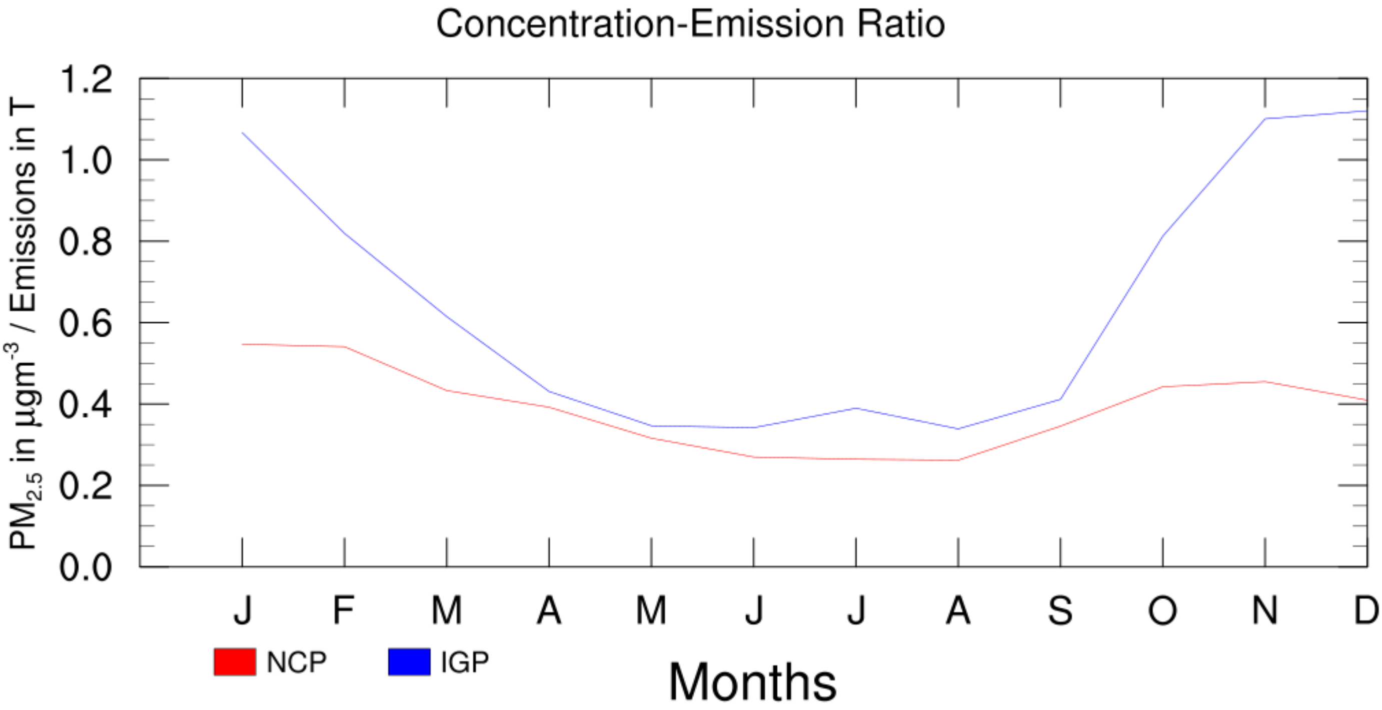
```
begin

a =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMSconc_3hourly_NCP2019.nc","r"
)
b = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/NCPmask.nc","r")
NCP = b->NCPmask3d(0,:,:)
c =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMSconc_3hourly_IGP2019.nc","r")
d = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/IGPmask.nc","r")
IGP = d->IGPmask3d(0,:,:)
e = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/NCPmask10.nc","r")
f = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/IGPmask10.nc","r")
IGPem = f->IGPemismask3d(0,:,:)
NCPem = e->NCPemismask3d(0,:,:)

g =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_ammonia_2
019.nc","r")
```

```
h =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_black-carbo
n_2019.nc","r")
l =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_nitrogen-oxi
des_2019.nc","r")
j =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_non-methan
e-vocs_2019.nc","r")
k =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_organic-car
bon_2019.nc","r")
l =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_sulphur-dio
xide_2019.nc","r")

ANTammonia = g->sum
ANTblackcarbon = h->sum
ANTnitrogenoxides = l->sum
ANTnonmethanevocs = j->sum
ANTorganiccarbon = k->sum
ANTsulphurdioxide = l->sum
lat = g->lat
lon = g->lon

emissionssum = ANTammonia ; just to inherit shape and metadata
emissionssum = ANTammonia + ANTblackcarbon + ANTnitrogenoxides +
ANTnonmethanevocs + ANTorganiccarbon + ANTsulphurdioxide;emissionssum =
aerosolsum



totalemis = dim_avg_n_Wrap(emissionssum,0)
totalemis = totalemis(::-1,:)
totalemis@standard_name=""

;converting emissions into full grid flux in KiloTonnes per year
totalemis = totalemis*(60*60*24*365)*(10000.0*10000.0)/1000000.0

;;;;;;MASK;;;;;;;;;;
totalemisNCP = where(NCPem.eq.1, totalemis, totalemis@_FillValue)
NCPemissum = sum(totalemisNCP) ;reducing it to a single number over NCP
NCPmsum = sum(NCPem) ;to keep a count of total grids in NCP
print("NCP region emits "+NCPemissum+" pollutants (Kt per year) from "+NCPmsum+"
grids")


totalemisIGP = where(IGPem.eq.1, totalemis, totalemis@_FillValue)
IGPemissum = sum(totalemisIGP) ;reducing it to a single number over IGP
```

```
IGPmsum = sum(IGPem) ;to keep a count of total grids in IGP
print("IGP region emits "+IGPemissum+" pollutants (Kt per year) from "+IGPmsum+" grids")
IGPflux= IGPemissum/IGPmsum
NCPflux=NCPemissum/NCPmsum

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
opt =True
opt@PrintStat=True
print(stat_dispersion(totalemis, opt ))

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;PLOTTING BEGINS;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
 wks   = gsn_open_wks ("png","IGPNCP_summed_emissions")            ; send graphics to
png

  res                   = True
  res@gsnDraw           = True           ; don't draw
  res@gsnFrame          = True           ; don't advance frame
  res@gsnMaximize       = True    ; Maximize plot in frame
  res@cnFillOn          = True           ; turn on color
  res@cnFillPalette     = (/"MPL_Reds"/)   ; set color map

  res@cnLevelSelectionMode = "ManualLevels" ; set explicit contour levels
;  res@cnLevels = (/-5,-4,-3,-2,-1,0,1,2,3,4,5/) ; set levels for normalized benefits -10% to
10%
  res@cnMinLevelValF = 0.
  res@cnMaxLevelValF = 5.
  res@cnLevelSpacingF = 0.5


  res@cnLinesOn         = False          ; no contour lines
  res@gsnRightString     = ""        ; assign right string
  res@gsnAddCyclic       = False
  res@mpFillOn          = True          ; no map fill

  res@cnFillMode = "RasterFill"
  res@mpGeophysicalLineThicknessF = 2.0
  res@mpDataBaseVersion   = "MediumRes"
  res@mpOutlineBoundarySets       = "National"

;Selecting NCP region from the map
  res@mpProjection          = "Mercator"
  res@mpLambertParallel1F    = 30.
  res@mpLambertParallel2F    = 40.
  res@mpLambertMeridianF     = 115.

  res@mpLimitMode           = "Corners"         ; choose region of map
  res@mpLeftCornerLatF       = 20.
  res@mpLeftCornerLonF       = 100.
  res@mpRightCornerLatF      = 50.
```

```
  res@mpRightCornerLonF      = 130.
  res@pmLabelBarOrthogonalPosF = -0.025
  res@lbLabelFontHeightF = 0.03
  res@gsnDraw             = False       ; don't draw yet
  res@gsnFrame             = False       ; don't advance frame yet

 plot1 = gsn_csm_contour_map(wks,totalemis, res) ; create plot

;Selecting IGP region from the map
  res@mpProjection           = "Mercator"
  res@mpLambertParallel1F    = 25.
  res@mpLambertParallel2F    = 30.
  res@mpLambertMeridianF     = 80.

  res@mpLimitMode            = "Corners"          ; choose region of map
  res@mpLeftCornerLatF       = 20.
  res@mpLeftCornerLonF       = 70.
  res@mpRightCornerLatF      = 35.
  res@mpRightCornerLonF      = 89.5

 plot2 = gsn_csm_contour_map(wks, totalemis, res) ; create plot
;---Retrieve the height used for the first plot and apply to subsequent plots
  getvalues plot1
    "vpWidthF" : vpw
  end getvalues

setvalues (/plot2/)
  "vpWidthF" : vpw
end setvalues

;PANEL PLOTS
  pnlres                          = True
  pnlres@gsnPanelXWhiteSpacePercent = 5
  pnlres@amJust   = "TopRight"
  pnlres@gsnMaximize = True
  pnlres@gsnFrame         = False
  pnlres@gsnPanelFigureStrings= (/NCPflux , IGPflux/)
 gsn_panel(wks,(/plot1,plot2/),(/1,2/),pnlres)

 ;text string at the bottom
  txres               = True
  txres@txFontHeightF = 0.012
  gsn_text_ndc(wks,"Emissions in KT",0.25,0.15,txres)
  gsn_text_ndc(wks,"Emissions in KT",0.75,0.35,txres)

frame(wks)
end
```

Appendix 6: Line Graph Ratio (Aerosol Concentration/Emissions) in 2019



Code Line Graph Ratio (Aerosol Concentration/Emissions) in 2019

```
begin

;;;;;;;;;;;FILES;;;;;;;;;;;;;;
a =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMSconc_3hourly_NCP2019.nc","r"
)
b = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/NCPmask.nc","r")
NCP = b->NCPmask3d(0,:,:)
c =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMSconc_3hourly_IGP2019.nc","r")
d = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/IGPmask.nc","r")
IGP = d->IGPmask3d(0,:,:)
e = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/NCPmask10.nc","r")
f = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/IGPmask10.nc","r")
IGPem = f->IGPemismask3d(0,:,:)
NCPem = e->NCPemismask3d(0,:,:)

g =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_ammonia_2
019.nc","r")
h =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_black-carbo
n_2019.nc","r")
l =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_nitrogen-oxi
des_2019.nc","r")
```

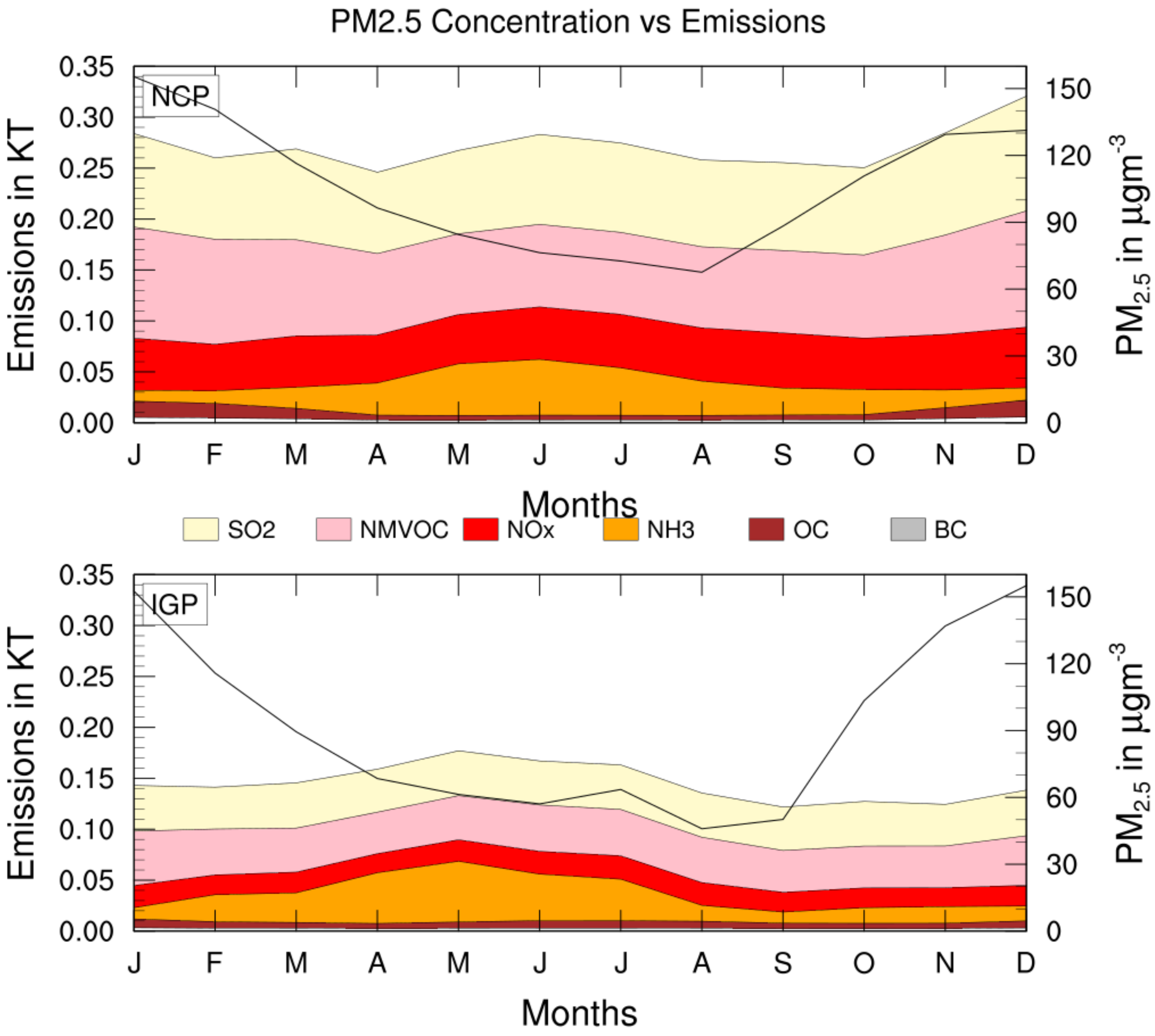
```
j =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_non-methan
e-vocs_2019.nc","r")
k =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_organic-car
bon_2019.nc","r")
l =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_sulphur-dio
xide_2019.nc","r")

;;;;;;;;;VARIABLES EMISSIONS;;;;;;;;;;;;;;;;;;
ANTammonia = g->sum
ANTblackcarbon = h->sum
ANTnitrogenoxides = l->sum
ANTnonmethanevocs = j->sum
ANTorganiccarbon = k->sum
ANTsulphurdioxide = l->sum

totalemis =
ANTammonia+ANTblackcarbon+ANTnitrogenoxides+ANTnonmethanevocs+ANTorganiccarb
on+ANTsulphurdioxide
; Total monthly emissions in KT
totalemis = totalemis*60*60*24*365*(10000.0*10000.0)/(12.0*1000.0)
totalemis = totalemis(:,::-1,:)

;;;;;;;;;;;;;;PM2P5;;;;;;;;;;;;;;;;
pm25NCP = short2flt(a->pm2p5)
pm25NCP = pm25NCP * 10^9
pm25NCP@long_name="   "
pm25NCP@units = "   "
pm25NCP = pm25NCP(:,::-1,:)

pm25IGP = short2flt(c->pm2p5)
pm25IGP = pm25IGP * 10^9
pm25IGP@long_name="   "
pm25IGP@units = "   "
pm25IGP = pm25IGP(:,::-1,:)

printVarSummary(NCP)
printVarSummary(pm25NCP(0,:,:))
;;;;;;;;;;;;;;MASK PM2.5;;;;;;;;;;;;
do i=0,2919
pm25NCP(i,:,:) = where(NCP.eq.1, pm25NCP(i,:,:), pm25NCP@_FillValue)
end do

do i=0,2919
pm25IGP(i,:,:) = where(IGP.eq.1, pm25IGP(i,:,:), pm25IGP@_FillValue)
end do
```

```
;;;;;;;;;;;;;;MASK EMISSIONSSUM;;;;;;;;;;;;
totalemisNCP = totalemis
totalemisIGP = totalemis

do i = 0,11
totalemisNCP(i,:,:) = where(NCPem.eq.1, totalemisNCP(i,:,:), totalemisNCP@_FillValue)
end do

do i = 0,11
totalemisIGP(i,:,:) = where(IGPem.eq.1, totalemisIGP(i,:,:), totalemisIGP@_FillValue)
end do

;spatial averaging
totalemisNCPsum1 = dim_avg_n(totalemisNCP,2)
totalemisNCPsum = dim_avg_n(totalemisNCPsum1,1)

totalemisIGPsum1 = dim_avg_n(totalemisIGP,2)
totalemisIGPsum = dim_avg_n(totalemisIGPsum1,1)


;;########################################################################
############
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;MONTHLY PM25 CONCENTRATIONS;;;;;;;;;;;;;;;;;
len1 = 248 ;JMMJAODlen
len2 = 240 ;AJSNlen
len3 = 224 ;Flen


monthlypm25NCP = new((/12,41,41/),typeof(pm25NCP))
sp = 0
do i=0,11
len = len1

if((i.eq.3).or.(i.eq.5).or.(i.eq.8).or.(i.eq.10)) then
  len = len2
end if

if(i.eq.1) then
 len = len3
end if

ep = sp + len -1
monthlypm25NCP(i,:,:) = dim_avg_n(pm25NCP(sp:ep,:,:),0)
sp = ep + 1
end do

monthlypm25NCPsum1 = dim_avg_n(monthlypm25NCP,2)
monthlypm25NCPsum = dim_avg_n(monthlypm25NCPsum1,1)
```

```
monthlypm25IGP = new((/12,21,27/),typeof(pm25IGP))
sp = 0
do i=0,11
len = len1

if((i.eq.3).or.(i.eq.5).or.(i.eq.8).or.(i.eq.10)) then
  len = len2
end if

if(i.eq.1) then
 len = len3
end if

ep = sp + len -1
monthlypm25IGP(i,:,:) = dim_avg_n(pm25IGP(sp:ep,:,:),0)
sp = ep + 1
end do


monthlypm25IGPsum1 = dim_avg_n(monthlypm25IGP,2)
monthlypm25IGPsum = dim_avg_n(monthlypm25IGPsum1,1)


;############## RATIO IGP NCP ####################
print("############# IGP ####################")
print("Emissions="+totalemisIGPsum+ "   Conc.= "+monthlypm25IGPsum+"    Conc/Emis
ratio="+monthlypm25IGPsum/totalemisIGPsum)
print("############# NCP ####################")
print("Emissions="+totalemisNCPsum+ "   Conc.= "+monthlypm25NCPsum +"   Conc/Emis
ratio="+monthlypm25NCPsum/totalemisNCPsum)

ratioNCP = monthlypm25NCPsum/totalemisNCPsum
ratioIGP = monthlypm25IGPsum/totalemisIGPsum

;############################################################################
######################
;;;;;;;;;;;MAKING THE PLOTS;;;;;;;;;;;;;;
wks   = gsn_open_wks ("png","ratio_conc_vs_emissions")              ; send graphics to png
file

montharray = fspan(1,12,12)
 res                = True                    ; plot mods desired
res@vpWidthF = 1
res@xyDashPatterns = (/0,0/)
res@xyLineColors = (/"red", "blue"/)
res@vpHeightF = 0.4
res@tmXBMode       = "Explicit"
res@tmXBLabels      = (/"J","F","M","A","M","J","J","A","S","O","N","D"/)
 res@tmXBValues = montharray
```

```
res@tmXBLabelsOn = True
 res@trXMinF = 0
 res@trYMinF = 0
res@trYMaxF = 1.2
res@tiXAxisString = "Months"
res@tiYAxisFontHeightF = 0.02
res@tiYAxisString = "PM~B~2.5~N~ in ~F33~m~F21~gm~S~-3~N~ / Emissions in T"
res@gsnDraw = False
res@gsnFrame = False

res@tmXBMajorOutwardLengthF = 0.0;
res@tmYLMajorOutwardLengthF = 0.0
res@tmXBMinorOutwardLengthF = 0.0
res@tmYLMinorOutwardLengthF = 0.0

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;Draw some individual labelbars.
;-------------------------------------------------------------------
 colors1 = (/"red", "blue"/)
 labels1  = (/"NCP", "IGP"/)
  lbres                    = True          ; labelbar only resources
  lbres@vpWidthF           = 0.10          ; labelbar width
  lbres@vpHeightF          = 0.20          ; labelbar height
  lbres@lbBoxMajorExtentF  = 0.1           ; puts space between color boxes
  lbres@lbMonoFillPattern  = True          ; Solid fill pattern
  lbres@lbLabelFontHeightF = 0.015         ; font height. default is small
  lbres@lbPerimOn          = False

 xpos = 0.15
  do i=0,1
     lbres@lbFillColors     = colors1(i)
     lbres@lbLabelFontColor = "black"
     gsn_labelbar_ndc(wks,1,labels1(i),xpos,0.37,lbres)
     xpos = xpos+0.12
 end do

plot = gsn_csm_xy (wks,  montharray,(/ratioNCP, ratioIGP/), res) ; create plot


;PANEL PLOTS
  pnlres                          = True
  pnlres@gsnPanelYWhiteSpacePercent = 5
  pnlres@amJust   = "TopLeft"
  pnlres@gsnMaximize = True
  pnlres@gsnFrame         = False
pnlres@gsnPanelMainString = "Concentration-Emission Ratio"
gsn_panel(wks,plot,(/1,1/),pnlres)

 frame(wks)
end
```

Appendix 7: Line Graph Emission and Aerosol Concentration in 2019



Code Line Graph Emission and Aerosol Concentration in 2019

```
begin

;;;;;;;;;;;FILES;;;;;;;;;;;;;;
a =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMSconc_3hourly_NCP2019.nc","r"
)
b = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/NCPmask.nc","r")
NCP = b->NCPmask3d(0,:,:)
c =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMSconc_3hourly_IGP2019.nc","r")
d = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/IGPmask.nc","r")
IGP = d->IGPmask3d(0,:,:)
e = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/NCPmask10.nc","r")
```

```
f = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/IGPmask10.nc","r")
IGPem = f->IGPemismask3d(0,:,:)
NCPem = e->NCPemismask3d(0,:,:)

g = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_ammonia_2019.nc","r")
h = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_black-carbon_2019.nc","r")
I = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_nitrogen-oxides_2019.nc","r")
j = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_non-methane-vocs_2019.nc","r")
k = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_organic-carbon_2019.nc","r")
l = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_sulphur-dioxide_2019.nc","r")

;;;;;;;;;VARIABLES EMISSIONS;;;;;;;;;;;;;;;;;;
ANTammonia = g->sum
ANTblackcarbon = h->sum
ANTnitrogenoxides = I->sum
ANTnonmethanevocs = j->sum
ANTorganiccarbon = k->sum
ANTsulphurdioxide = l->sum

te1 = ANTblackcarbon
te2 = te1+ANTorganiccarbon
te3 = te2+ANTammonia
te4 = te3+ANTnitrogenoxides
te5 = te4+ANTnonmethanevocs
te6 = te5+ANTsulphurdioxide


; Total monthly emissions in KT
te1 = te1*60*60*24*365*(10000.0*10000.0)/(12.0*1000000.0)
te1 = te1(:,::-1,:)
te2 = te2*60*60*24*365*(10000.0*10000.0)/(12*1000000.0)
te2 = te2(:,::-1,:)
te3 = te3*60*60*24*365*(10000.0*10000.0)/(12*1000000.0)
te3 = te3(:,::-1,:)
te4 = te4*60*60*24*365*(10000.0*10000.0)/(12*1000000.0)
te4 = te4(:,::-1,:)
te5 = te5*60*60*24*365*(10000.0*10000.0)/(12*1000000.0)
```

```
te5 = te5(:,::-1,:)
te6 = te6*60*60*24*365*(10000.0*10000.0)/(12*1000000.0)
te6 = te6(:,::-1,:)

;;;;;;;;;;;;;PM2P5;;;;;;;;;;;;;;;
pm25NCP = short2flt(a->pm2p5)
pm25NCP = pm25NCP * 10^9
pm25NCP@long_name="   "
pm25NCP@units = "   "
pm25NCP = pm25NCP(:,::-1,:)

pm25IGP = short2flt(c->pm2p5)
pm25IGP = pm25IGP * 10^9
pm25IGP@long_name="   "
pm25IGP@units = "   "
pm25IGP = pm25IGP(:,::-1,:)


printVarSummary(NCP)
printVarSummary(pm25NCP(0,:,:))
;;;;;;;;;;;;;MASK PM2.5;;;;;;;;;;;
do i=0,2919
pm25NCP(i,:,:) = where(NCP.eq.1, pm25NCP(i,:,:), pm25NCP@_FillValue)
end do

do i=0,2919
pm25IGP(i,:,:) = where(IGP.eq.1, pm25IGP(i,:,:), pm25IGP@_FillValue)
end do

;;;;;;;;;;;;;MASK EMISSIONSSUM;;;;;;;;;;;
totalemisNCP = te6
totalemisIGP = te6
totalemis1NCP = te1
totalemis1IGP = te1
totalemis2NCP = te2
totalemis2IGP = te2
totalemis3NCP = te3
totalemis3IGP = te3
totalemis4NCP = te4
totalemis4IGP = te4
totalemis5NCP = te5
totalemis5IGP = te5


do i = 0,11
totalemisNCP(i,:,:) = where(NCPem.eq.1, totalemisNCP(i,:,:), totalemisNCP@_FillValue)
end do

do i = 0,11
```

```
totalemisIGP(i,:,:) = where(IGPem.eq.1, totalemisIGP(i,:,:), totalemisIGP@_FillValue)
end do

;spatial averaging
totalemisNCPsum1 = dim_avg_n(totalemisNCP,2)
totalemisNCPsum = dim_avg_n(totalemisNCPsum1,1)

totalemisIGPsum1 = dim_avg_n(totalemisIGP,2)
totalemisIGPsum = dim_avg_n(totalemisIGPsum1,1)

do i = 0,11
totalemis1NCP(i,:,:) = where(NCPem.eq.1, totalemis1NCP(i,:,:), totalemis1NCP@_FillValue)
end do

do i = 0,11
totalemis1IGP(i,:,:) = where(IGPem.eq.1, totalemis1IGP(i,:,:), totalemis1IGP@_FillValue)
end do

;spatial averaging
totalemis1NCPsum1 = dim_avg_n(totalemis1NCP,2)
totalemis1NCPsum = dim_avg_n(totalemis1NCPsum1,1)

totalemis1IGPsum1 = dim_avg_n(totalemis1IGP,2)
totalemis1IGPsum = dim_avg_n(totalemis1IGPsum1,1)


do i = 0,11
totalemis2NCP(i,:,:) = where(NCPem.eq.1, totalemis2NCP(i,:,:), totalemis2NCP@_FillValue)
end do

do i = 0,11
totalemis2IGP(i,:,:) = where(IGPem.eq.1, totalemis2IGP(i,:,:), totalemis2IGP@_FillValue)
end do

;spatial averaging
totalemis2NCPsum1 = dim_avg_n(totalemis2NCP,2)
totalemis2NCPsum = dim_avg_n(totalemis2NCPsum1,1)

totalemis2IGPsum1 = dim_avg_n(totalemis2IGP,2)
totalemis2IGPsum = dim_avg_n(totalemis2IGPsum1,1)


do i = 0,11
totalemis3NCP(i,:,:) = where(NCPem.eq.1, totalemis3NCP(i,:,:), totalemis3NCP@_FillValue)
end do

do i = 0,11
totalemis3IGP(i,:,:) = where(IGPem.eq.1, totalemis3IGP(i,:,:), totalemis3IGP@_FillValue)
end do
```

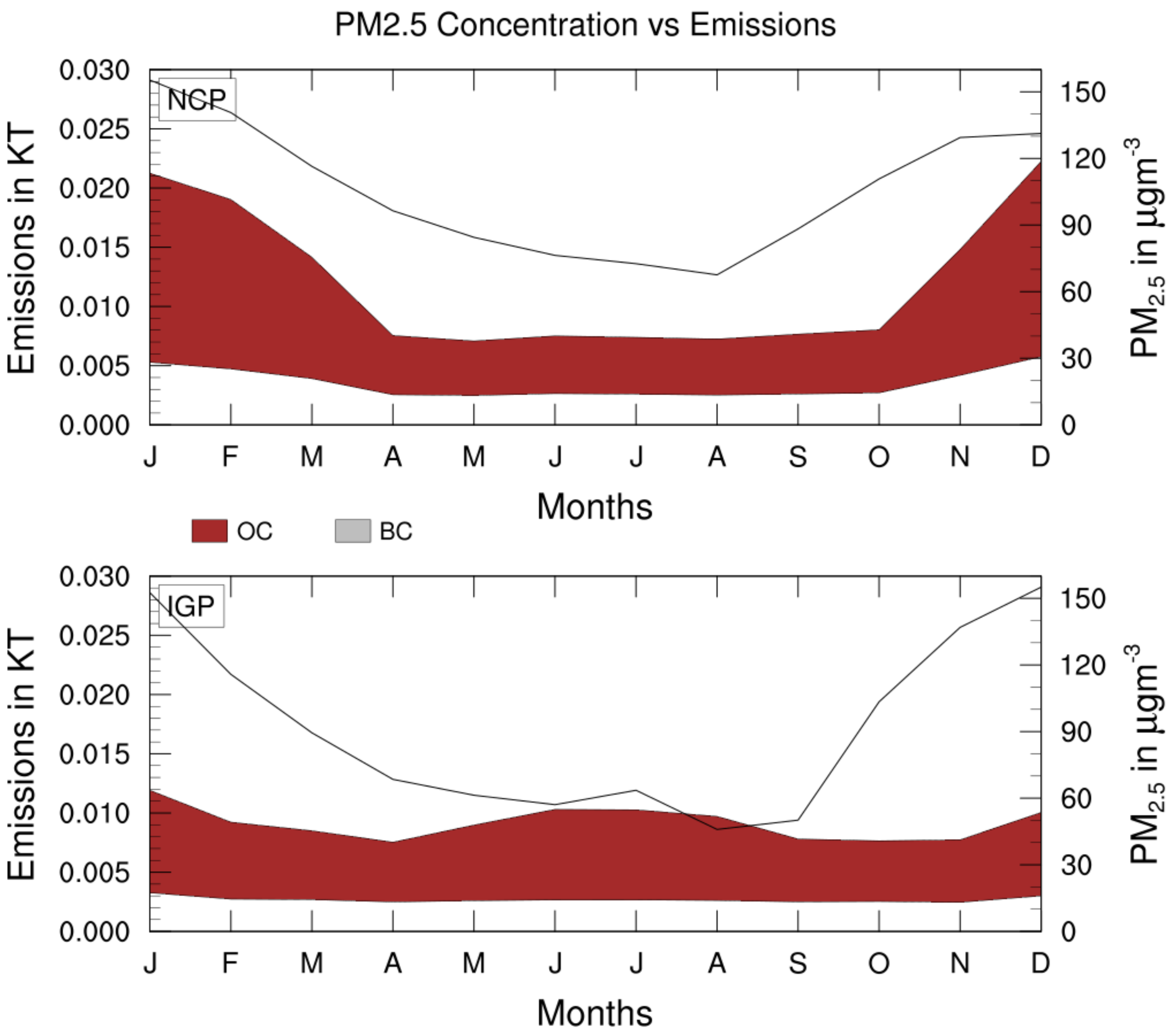
```
;spatial averaging
totalemis3NCPsum1 = dim_avg_n(totalemis3NCP,2)
totalemis3NCPsum = dim_avg_n(totalemis3NCPsum1,1)

totalemis3IGPsum1 = dim_avg_n(totalemis3IGP,2)
totalemis3IGPsum = dim_avg_n(totalemis3IGPsum1,1)


do i = 0,11
totalemis4NCP(i,:,:) = where(NCPem.eq.1, totalemis4NCP(i,:,:), totalemis4NCP@_FillValue)
end do

do i = 0,11
totalemis4IGP(i,:,:) = where(IGPem.eq.1, totalemis4IGP(i,:,:), totalemis4IGP@_FillValue)
end do

;spatial averaging
totalemis4NCPsum1 = dim_avg_n(totalemis4NCP,2)
totalemis4NCPsum = dim_avg_n(totalemis4NCPsum1,1)

totalemis4IGPsum1 = dim_avg_n(totalemis4IGP,2)
totalemis4IGPsum = dim_avg_n(totalemis4IGPsum1,1)

do i = 0,11
totalemis5NCP(i,:,:) = where(NCPem.eq.1, totalemis5NCP(i,:,:), totalemis5NCP@_FillValue)
end do

do i = 0,11
totalemis5IGP(i,:,:) = where(IGPem.eq.1, totalemis5IGP(i,:,:), totalemis5IGP@_FillValue)
end do

;spatial averaging
totalemis5NCPsum1 = dim_avg_n(totalemis5NCP,2)
totalemis5NCPsum = dim_avg_n(totalemis5NCPsum1,1)

totalemis5IGPsum1 = dim_avg_n(totalemis5IGP,2)
totalemis5IGPsum = dim_avg_n(totalemis5IGPsum1,1)

;;########################################################################
############
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;MONTHLY PM25 CONCENTRATIONS;;;;;;;;;;;;;;;;;
len1 = 248 ;JMMJAODlen
len2 = 240 ;AJSNlen
len3 = 224 ;Flen


monthlypm25NCP = new((/12,41,41/),typeof(pm25NCP))
sp = 0
```

```
do i=0,11
len = len1

if((i.eq.3).or.(i.eq.5).or.(i.eq.8).or.(i.eq.10)) then
  len = len2
end if

if(i.eq.1) then
 len = len3
end if

ep = sp + len -1
monthlypm25NCP(i,:,:) = dim_avg_n(pm25NCP(sp:ep,:,:),0)
sp = ep + 1
end do


monthlypm25NCPsum1= dim_avg_n(monthlypm25NCP,2)
monthlypm25NCPsum = dim_avg_n(monthlypm25NCPsum1,1)

monthlypm25IGP = new((/12,21,27/),typeof(pm25IGP))
sp = 0
do i=0,11
len = len1

if((i.eq.3).or.(i.eq.5).or.(i.eq.8).or.(i.eq.10)) then
  len = len2
end if

if(i.eq.1) then
 len = len3
end if

ep = sp + len -1
monthlypm25IGP(i,:,:) = dim_avg_n(pm25IGP(sp:ep,:,:),0)
sp = ep + 1
end do


monthlypm25IGPsum1 = dim_avg_n(monthlypm25IGP,2)
monthlypm25IGPsum = dim_avg_n(monthlypm25IGPsum1,1)


;############## PRINTING BEFORE PLOTTING #####################
print("############# IGP ###################")
print("Emissions="+totalemisIGPsum+ "   Conc.= "+monthlypm25IGPsum+"    Conc/Emis
ratio="+monthlypm25IGPsum/totalemisIGPsum)
print("############# NCP ###################")
```

```
print("Emissions="+totalemisNCPsum+ "   Conc.= "+monthlypm25NCPsum +"   Conc/Emis
ratio="+monthlypm25NCPsum/totalemisNCPsum)

;##########################################################################
#####################
;;;;;;;;;;;MAKING THE PLOTS;;;;;;;;;;;;;
wks   = gsn_open_wks ("png", "conc_vs_emissions")              ; send graphics to png file

montharray = fspan(1,12,12)
 res                 = True                    ; plot mods desired
res@vpWidthF = 1
res@xyDashPatterns = (/0,0,0,0,0,0/)
colors1 = (/"lemonchiffon1", "pink", "red", "orange", "brown", "grey"/)
res@gsnXYFillColors = colors1
res@vpHeightF = 0.4
res@tmXBMode       = "Explicit"
res@tmXBLabels      = (/"J","F","M","A","M","J","J","A","S","O","N","D"/)
 res@tmXBValues = montharray
res@tmXBLabelsOn = True
 res@trXMinF = 1
 res@trYMinF = 0
res@trYMaxF = 0.35


res@tiXAxisString = "Months"
res@tiYAxisString = "Emissions in KT"
res@gsnDraw = False
res@gsnFrame = False

res@tmXBMajorOutwardLengthF = 0.0
res@tmYLMajorOutwardLengthF = 0.0
res@tmXBMinorOutwardLengthF = 0.0
res@tmYLMinorOutwardLengthF = 0.0

res2=True
res2@trYMinF=0
res2@xyLineThicknesses = (/2.0/)
res2@tiYAxisString = "PM~B~2.5~N~ in ~F33~m~F21~gm~S~-3~N~"
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;Draw some individual labelbars.
;-----------------------------------------------------------------
  labels1  = (/"SO2", "NMVOC" ,"NOx", "NH3", "OC", "BC"/)
  lbres                    = True          ; labelbar only resources
  lbres@vpWidthF           = 0.10          ; labelbar width
  lbres@vpHeightF          = 0.20          ; labelbar height
  lbres@lbBoxMajorExtentF  = 0.1           ; puts space between color boxes
  lbres@lbMonoFillPattern  = True          ; Solid fill pattern
  lbres@lbLabelFontHeightF = 0.015         ; font height. default is small
  ;lbres@lbLabelJust       = "center"  ; left justify labels
  lbres@lbPerimOn          = False
```

```
 xpos = 0.15
  do i=0,5
     lbres@lbFillColors      = colors1(i)
     lbres@lbLabelFontColor = "black"
     gsn_labelbar_ndc(wks,1,labels1(i),xpos,0.58,lbres)
     xpos = xpos+0.12
  end do

 plot1 = gsn_csm_xy2 (wks, montharray,(/totalemisNCPsum, totalemis5NCPsum,
totalemis4NCPsum, totalemis3NCPsum, totalemis2NCPsum,
totalemis1NCPsum/),monthlypm25NCPsum, res,res2) ; create plot

 plot2 = gsn_csm_xy2 (wks, montharray,(/totalemisIGPsum,totalemis5IGPsum,
totalemis4IGPsum, totalemis3IGPsum, totalemis2IGPsum,
totalemis1IGPsum/),monthlypm25IGPsum, res,res2) ; create plot


;PANEL PLOTS
  pnlres                           = True
  pnlres@gsnPanelYWhiteSpacePercent = 5
  pnlres@amJust   = "TopLeft"
  pnlres@gsnMaximize = True
  pnlres@gsnFrame         = False
  pnlres@gsnPanelFigureStrings= (/"NCP","IGP"/)
pnlres@gsnPanelMainString = "PM2.5 Concentration vs Emissions"
gsn_panel(wks,(/plot1,plot2/),(/2,1/),pnlres)
 frame(wks)

end
```

Appendix 8: Line Graph Carbon Emissions and Aerosol Concentration in 2019



Code Line Graph Carbon Emissions and Aerosol Concentration in 2019

```
begin

;;;;;;;;;;;FILES;;;;;;;;;;;;;;
a =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMSconc_3hourly_NCP2019.nc","r"
)
b = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/NCPmask.nc","r")
NCP = b->NCPmask3d(0,:,:)
c =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMSconc_3hourly_IGP2019.nc","r")
d = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/IGPmask.nc","r")
IGP = d->IGPmask3d(0,:,:)
```

```
e = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/NCPmask10.nc","r")
f = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/IGPmask10.nc","r")
IGPem = f->IGPemismask3d(0,:,:)
NCPem = e->NCPemismask3d(0,:,:)

g = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_ammonia_2019.nc","r")
h = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_black-carbon_2019.nc","r")
I = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_nitrogen-oxides_2019.nc","r")
j = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_non-methane-vocs_2019.nc","r")
k = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_organic-carbon_2019.nc","r")
l = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_sulphur-dioxide_2019.nc","r")

;;;;;;;;;VARIABLES EMISSIONS;;;;;;;;;;;;;;;;;;
ANTammonia = g->sum
ANTblackcarbon = h->sum
ANTnitrogenoxides = I->sum
ANTnonmethanevocs = j->sum
ANTorganiccarbon = k->sum
ANTsulphurdioxide = l->sum

te1 = ANTblackcarbon
te2 = te1+ANTorganiccarbon

; Total monthly emissions in KT
te1 = te1*60*60*24*365*(10000.0*10000.0)/(12.0*1000000.0)
te1 = te1(:,::-1,:)
te2 = te2*60*60*24*365*(10000.0*10000.0)/(12*1000000.0)
te2 = te2(:,::-1,:)


;;;;;;;;;;;;;PM2P5;;;;;;;;;;;;;;
pm25NCP = short2flt(a->pm2p5)
pm25NCP = pm25NCP * 10^9
pm25NCP@long_name="   "
pm25NCP@units = "   "
pm25NCP = pm25NCP(:,::-1,:)
```

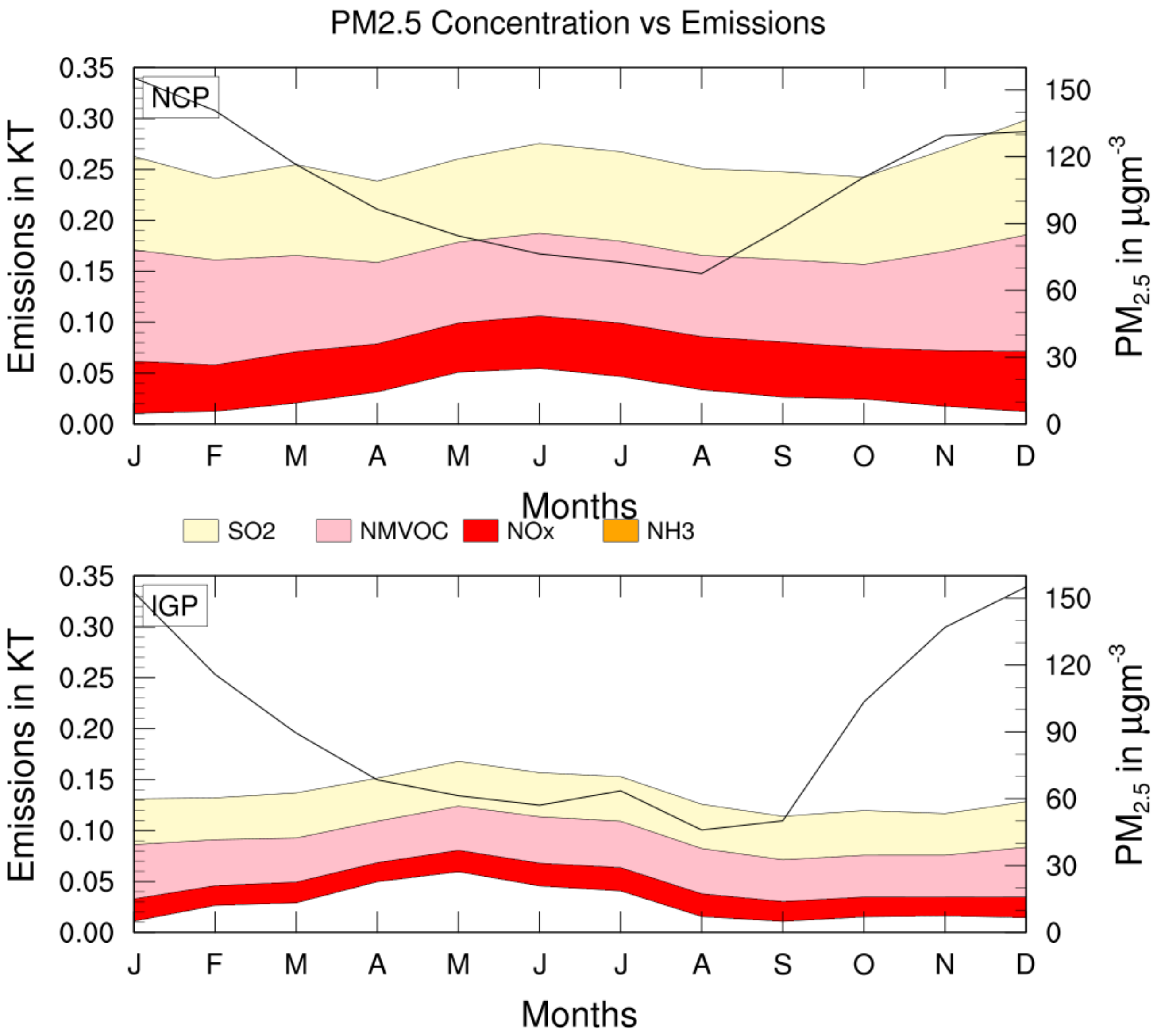
```
pm25IGP = short2flt(c->pm2p5)
pm25IGP = pm25IGP * 10^9
pm25IGP@long_name="   "
pm25IGP@units = "   "
pm25IGP = pm25IGP(:,::-1,:)

printVarSummary(NCP)
printVarSummary(pm25NCP(0,:,:))
;;;;;;;;;;;;;MASK PM2.5;;;;;;;;;;;
do i=0,2919
pm25NCP(i,:,:) = where(NCP.eq.1, pm25NCP(i,:,:), pm25NCP@_FillValue)
end do

do i=0,2919
pm25IGP(i,:,:) = where(IGP.eq.1, pm25IGP(i,:,:), pm25IGP@_FillValue)
end do

;;;;;;;;;;;;;MASK EMISSIONSSUM;;;;;;;;;;;
totalemis1NCP = te1
totalemis1IGP = te1
totalemis2NCP = te2
totalemis2IGP = te2

do i = 0,11
totalemis1NCP(i,:,:) = where(NCPem.eq.1, totalemis1NCP(i,:,:), totalemis1NCP@_FillValue)
end do

do i = 0,11
totalemis1IGP(i,:,:) = where(IGPem.eq.1, totalemis1IGP(i,:,:), totalemis1IGP@_FillValue)
end do

;spatial averaging
totalemis1NCPsum1 = dim_avg_n(totalemis1NCP,2)
totalemis1NCPsum = dim_avg_n(totalemis1NCPsum1,1)

totalemis1IGPsum1 = dim_avg_n(totalemis1IGP,2)
totalemis1IGPsum = dim_avg_n(totalemis1IGPsum1,1)


do i = 0,11
totalemis2NCP(i,:,:) = where(NCPem.eq.1, totalemis2NCP(i,:,:), totalemis2NCP@_FillValue)
end do

do i = 0,11
totalemis2IGP(i,:,:) = where(IGPem.eq.1, totalemis2IGP(i,:,:), totalemis2IGP@_FillValue)
end do

;spatial averaging
totalemis2NCPsum1 = dim_avg_n(totalemis2NCP,2)
```

```
totalemis2NCPsum = dim_avg_n(totalemis2NCPsum1,1)

totalemis2IGPsum1 = dim_avg_n(totalemis2IGP,2)
totalemis2IGPsum = dim_avg_n(totalemis2IGPsum1,1)

;;##############################################################################################
##############
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;MONTHLY PM25 CONCENTRATIONS;;;;;;;;;;;;;;;;;
len1 = 248 ;JMMJAODlen
len2 = 240 ;AJSNlen
len3 = 224 ;Flen


monthlypm25NCP = new((/12,41,41/),typeof(pm25NCP))
sp = 0
do i=0,11
len = len1

if((i.eq.3).or.(i.eq.5).or.(i.eq.8).or.(i.eq.10)) then
  len = len2
end if

if(i.eq.1) then
 len = len3
end if

ep = sp + len -1
monthlypm25NCP(i,:,:) = dim_avg_n(pm25NCP(sp:ep,:,:),0)
sp = ep + 1
end do


monthlypm25NCPsum1= dim_avg_n(monthlypm25NCP,2)
monthlypm25NCPsum = dim_avg_n(monthlypm25NCPsum1,1)

monthlypm25IGP = new((/12,21,27/),typeof(pm25IGP))
sp = 0
do i=0,11
len = len1

if((i.eq.3).or.(i.eq.5).or.(i.eq.8).or.(i.eq.10)) then
  len = len2
end if

if(i.eq.1) then
 len = len3
end if

ep = sp + len -1
```

```
monthlypm25IGP(i,:,:) = dim_avg_n(pm25IGP(sp:ep,:,:),0)
sp = ep + 1
end do


monthlypm25IGPsum1 = dim_avg_n(monthlypm25IGP,2)
monthlypm25IGPsum = dim_avg_n(monthlypm25IGPsum1,1)

;############## PRINTING BEFORE PLOTTING #####################
print("############# IGP ####################")
print("Emissions="+totalemis2IGPsum+ "   Conc.= "+monthlypm25IGPsum+"    Conc/Emis
ratio="+monthlypm25IGPsum/totalemis2IGPsum)
print("############# NCP ####################")
print("Emissions="+totalemis2NCPsum+ "   Conc.= "+monthlypm25NCPsum +"   Conc/Emis
ratio="+monthlypm25NCPsum/totalemis2NCPsum)

;###########################################################################
#####################
;;;;;;;;;;;MAKING THE PLOTS;;;;;;;;;;;;;
wks   = gsn_open_wks ("png", "conc_vs_emissions_carbon")              ; send graphics to png
file

montharray = fspan(1,12,12)
 res                 = True                   ; plot mods desired
res@vpWidthF = 1
res@xyDashPatterns = (/0,0,0/)
colors1 = (/"brown", "grey"/)
res@gsnXYFillColors = colors1
res@vpHeightF = 0.4
res@tmXBMode       = "Explicit"
res@tmXBLabels      = (/"J","F","M","A","M","J","J","A","S","O","N","D"/)
 res@tmXBValues = montharray
res@tmXBLabelsOn = True
 res@trXMinF = 1
res@trYMinF = 0
res@trYMaxF = 0.03
res@tiXAxisString = "Months"
res@tiYAxisString = "Emissions in KT"


res@gsnDraw = False
res@gsnFrame = False


res@tmXBMajorOutwardLengthF = 0.0
res@tmYLMajorOutwardLengthF = 0.0
res@tmXBMinorOutwardLengthF = 0.0
res@tmYLMinorOutwardLengthF = 0.0
```

```
res2=True
res2@trYMinF=0
res2@xyLineThicknesses = (/2.0/)
res2@tiYAxisString = "PM~B~2.5~N~ in ~F33~m~F21~gm~S~-3~N~"
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;Draw some individual labelbars.
;----------------------------------------------------------------------
  labels1  = (/"OC", "BC"/)
  lbres                    = True          ; labelbar only resources
  lbres@vpWidthF           = 0.10          ; labelbar width
  lbres@vpHeightF          = 0.20          ; labelbar height
  lbres@lbBoxMajorExtentF  = 0.1          ; puts space between color boxes
  lbres@lbMonoFillPattern  = True          ; Solid fill pattern
  lbres@lbLabelFontHeightF = 0.015         ; font height. default is small
  ;lbres@lbLabelJust        = "center"  ; left justify labels
  lbres@lbPerimOn          = False

 xpos = 0.15
  do i=0,1
    lbres@lbFillColors     = colors1(i)
    lbres@lbLabelFontColor = "black"
    gsn_labelbar_ndc(wks,1,labels1(i),xpos,0.58,lbres)
    xpos = xpos+0.12
  end do

 plot1 = gsn_csm_xy2 (wks, montharray,(/totalemis2NCPsum,
totalemis1NCPsum/),monthlypm25NCPsum, res,res2) ; create plot

 plot2 = gsn_csm_xy2 (wks, montharray,(/totalemis2IGPsum,
totalemis1IGPsum/),monthlypm25IGPsum, res,res2) ; create plot


;PANEL PLOTS
  pnlres                          = True
  pnlres@gsnPanelYWhiteSpacePercent = 5
  pnlres@amJust   = "TopLeft"
  pnlres@gsnMaximize = True
  pnlres@gsnFrame        = False
  pnlres@gsnPanelFigureStrings= (/"NCP","IGP"/)
pnlres@gsnPanelMainString = "PM2.5 Concentration vs Emissions"
gsn_panel(wks,(/plot1,plot2/),(/2,1/),pnlres)

 frame(wks)
end
```

Appendix 9: Line Graph Gas Emissions and Aerosol Concentration in 2019



Code Line Graph Gas Emissions and Aerosol Concentration in 2019

```
begin

;;;;;;;;;;;FILES;;;;;;;;;;;;;;
a =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMSconc_3hourly_NCP2019.nc","r"
)
b = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/NCPmask.nc","r")
NCP = b->NCPmask3d(0,:,:)
c =
addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMSconc_3hourly_IGP2019.nc","r")
d = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/IGPmask.nc","r")
IGP = d->IGPmask3d(0,:,:)
```

```
e = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/NCPmask10.nc","r")
f = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/IGPmask10.nc","r")
IGPem = f->IGPemismask3d(0,:,:)
NCPem = e->NCPemismask3d(0,:,:)

g = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_ammonia_2019.nc","r")
h = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_black-carbon_2019.nc","r")
I = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_nitrogen-oxides_2019.nc","r")
j = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_non-methane-vocs_2019.nc","r")
k = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_organic-carbon_2019.nc","r")
l = addfile("/mnt/c/Users/Maya/Downloads/Capstone-data/CAMS-GLOB-ANT_v4.2_sulphur-dioxide_2019.nc","r")

;;;;;;;;;;VARIABLES EMISSIONS;;;;;;;;;;;;;;;;;;;;
ANTammonia = g->sum
ANTblackcarbon = h->sum
ANTnitrogenoxides = I->sum
ANTnonmethanevocs = j->sum
ANTorganiccarbon = k->sum
ANTsulphurdioxide = l->sum

te3 = ANTammonia
te4 = te3+ANTnitrogenoxides
te5 = te4+ANTnonmethanevocs
te6 = te5+ANTsulphurdioxide


; Total monthly emissions in KT
te3 = te3*60*60*24*365*(10000.0*10000.0)/(12*1000000.0)
te3 = te3(:,::-1,:)
te4 = te4*60*60*24*365*(10000.0*10000.0)/(12*1000000.0)
te4 = te4(:,::-1,:)
te5 = te5*60*60*24*365*(10000.0*10000.0)/(12*1000000.0)
te5 = te5(:,::-1,:)
te6 = te6*60*60*24*365*(10000.0*10000.0)/(12*1000000.0)
te6 = te6(:,::-1,:)
```

```
;;;;;;;;;;;;;PM2P5;;;;;;;;;;;;;;;
pm25NCP = short2flt(a->pm2p5)
pm25NCP = pm25NCP * 10^9
pm25NCP@long_name="   "
pm25NCP@units = "   "
pm25NCP = pm25NCP(:,::-1,:)

pm25IGP = short2flt(c->pm2p5)
pm25IGP = pm25IGP * 10^9
pm25IGP@long_name="   "
pm25IGP@units = "   "
pm25IGP = pm25IGP(:,::-1,:)


printVarSummary(NCP)
printVarSummary(pm25NCP(0,:,:))
;;;;;;;;;;;;;MASK PM2.5;;;;;;;;;;;
do i=0,2919
pm25NCP(i,:,:) = where(NCP.eq.1, pm25NCP(i,:,:), pm25NCP@_FillValue)
end do

do i=0,2919
pm25IGP(i,:,:) = where(IGP.eq.1, pm25IGP(i,:,:), pm25IGP@_FillValue)
end do

;;;;;;;;;;;;;MASK EMISSIONSSUM;;;;;;;;;;;
totalemisNCP = te6
totalemisIGP = te6
totalemis3NCP = te3
totalemis3IGP = te3
totalemis4NCP = te4
totalemis4IGP = te4
totalemis5NCP = te5
totalemis5IGP = te5

do i = 0,11
totalemisNCP(i,:,:) = where(NCPem.eq.1, totalemisNCP(i,:,:), totalemisNCP@_FillValue)
end do

do i = 0,11
totalemisIGP(i,:,:) = where(IGPem.eq.1, totalemisIGP(i,:,:), totalemisIGP@_FillValue)
end do

;spatial averaging
totalemisNCPsum1 = dim_avg_n(totalemisNCP,2)
totalemisNCPsum = dim_avg_n(totalemisNCPsum1,1)

totalemisIGPsum1 = dim_avg_n(totalemisIGP,2)
totalemisIGPsum = dim_avg_n(totalemisIGPsum1,1)
```

```
do i = 0,11
totalemis3NCP(i,:,:) = where(NCPem.eq.1, totalemis3NCP(i,:,:), totalemis3NCP@_FillValue)
end do

do i = 0,11
totalemis3IGP(i,:,:) = where(IGPem.eq.1, totalemis3IGP(i,:,:), totalemis3IGP@_FillValue)
end do
;spatial averaging
totalemis3NCPsum1 = dim_avg_n(totalemis3NCP,2)
totalemis3NCPsum = dim_avg_n(totalemis3NCPsum1,1)

totalemis3IGPsum1 = dim_avg_n(totalemis3IGP,2)
totalemis3IGPsum = dim_avg_n(totalemis3IGPsum1,1)


do i = 0,11
totalemis4NCP(i,:,:) = where(NCPem.eq.1, totalemis4NCP(i,:,:), totalemis4NCP@_FillValue)
end do

do i = 0,11
totalemis4IGP(i,:,:) = where(IGPem.eq.1, totalemis4IGP(i,:,:), totalemis4IGP@_FillValue)
end do

;spatial averaging
totalemis4NCPsum1 = dim_avg_n(totalemis4NCP,2)
totalemis4NCPsum = dim_avg_n(totalemis4NCPsum1,1)

totalemis4IGPsum1 = dim_avg_n(totalemis4IGP,2)
totalemis4IGPsum = dim_avg_n(totalemis4IGPsum1,1)

do i = 0,11
totalemis5NCP(i,:,:) = where(NCPem.eq.1, totalemis5NCP(i,:,:), totalemis5NCP@_FillValue)
end do

do i = 0,11
totalemis5IGP(i,:,:) = where(IGPem.eq.1, totalemis5IGP(i,:,:), totalemis5IGP@_FillValue)
end do

;spatial averaging
totalemis5NCPsum1 = dim_avg_n(totalemis5NCP,2)
totalemis5NCPsum = dim_avg_n(totalemis5NCPsum1,1)

totalemis5IGPsum1 = dim_avg_n(totalemis5IGP,2)
totalemis5IGPsum = dim_avg_n(totalemis5IGPsum1,1)

;;#######################################################################
############
```

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;MONTHLY PM25 CONCENTRATIONS;;;;;;;;;;;;;;;;;
len1 = 248 ;JMMJAODlen
len2 = 240 ;AJSNlen
len3 = 224 ;Flen


monthlypm25NCP = new((/12,41,41/),typeof(pm25NCP))
sp = 0
do i=0,11
len = len1

if((i.eq.3).or.(i.eq.5).or.(i.eq.8).or.(i.eq.10)) then
  len = len2
end if

if(i.eq.1) then
 len = len3
end if

ep = sp + len -1
monthlypm25NCP(i,:,:) = dim_avg_n(pm25NCP(sp:ep,:,:),0)
sp = ep + 1
end do


monthlypm25NCPsum1= dim_avg_n(monthlypm25NCP,2)
monthlypm25NCPsum = dim_avg_n(monthlypm25NCPsum1,1)

monthlypm25IGP = new((/12,21,27/),typeof(pm25IGP))
sp = 0
do i=0,11
len = len1

if((i.eq.3).or.(i.eq.5).or.(i.eq.8).or.(i.eq.10)) then
  len = len2
end if

if(i.eq.1) then
 len = len3
end if

ep = sp + len -1
monthlypm25IGP(i,:,:) = dim_avg_n(pm25IGP(sp:ep,:,:),0)
sp = ep + 1
end do


monthlypm25IGPsum1 = dim_avg_n(monthlypm25IGP,2)
monthlypm25IGPsum = dim_avg_n(monthlypm25IGPsum1,1)
```

```
;############## PRINTING BEFORE PLOTTING #######################
print("############# IGP #####################")
print("Emissions="+totalemisIGPsum+ "   Conc.= "+monthlypm25IGPsum+"    Conc/Emis
ratio="+monthlypm25IGPsum/totalemisIGPsum)
print("############# NCP #####################")
print("Emissions="+totalemisNCPsum+ "   Conc.= "+monthlypm25NCPsum +"   Conc/Emis
ratio="+monthlypm25NCPsum/totalemisNCPsum)

;#################################################################################
#######################
;;;;;;;;;;;;MAKING THE PLOTS;;;;;;;;;;;;;;;
wks   = gsn_open_wks ("png", "conc_vs_emissions_gas")              ; send graphics to png
file

montharray = fspan(1,12,12)
 res                  = True                    ; plot mods desired
res@vpWidthF = 1
res@xyDashPatterns = (/0,0,0,0/)
colors1 = (/"lemonchiffon1", "pink", "red", "orange"/)
res@gsnXYFillColors = colors1
res@vpHeightF = 0.4
res@tmXBMode       = "Explicit"
res@tmXBLabels      = (/"J","F","M","A","M","J","J","A","S","O","N","D"/)
 res@tmXBValues = montharray
res@tmXBLabelsOn = True
 res@trXMinF = 1
 res@trYMinF = 0
res@trYMaxF = 0.35
res@tiXAxisString = "Months"
res@tiYAxisString = "Emissions in KT"

res@gsnDraw = False
res@gsnFrame = False


res@tmXBMajorOutwardLengthF = 0.0
res@tmYLMajorOutwardLengthF = 0.0
res@tmXBMinorOutwardLengthF = 0.0
res@tmYLMinorOutwardLengthF = 0.0

res2=True
res2@trYMinF=0
res2@xyLineThicknesses = (/2.0/)
res2@tiYAxisString = "PM~B~2.5~N~ in ~F33~m~F21~gm~S~-3~N~"
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;Draw some individual labelbars.
;-------------------------------------------------------------------------------
  labels1  = (/"SO2", "NMVOC" ,"NOx", "NH3"/)
  lbres                    = True          ; labelbar only resources
```

```
 lbres@vpWidthF          = 0.10          ; labelbar width
 lbres@vpHeightF         = 0.20          ; labelbar height
 lbres@lbBoxMajorExtentF  = 0.1           ; puts space between color boxes
 lbres@lbMonoFillPattern  = True          ; Solid fill pattern
 lbres@lbLabelFontHeightF = 0.015          ; font height. default is small
 ;lbres@lbLabelJust        = "center"  ; left justify labels
 lbres@lbPerimOn          = False

xpos = 0.15
 do i=0,3
   lbres@lbFillColors     = colors1(i)
   lbres@lbLabelFontColor = "black"
   gsn_labelbar_ndc(wks,1,labels1(i),xpos,0.58,lbres)
   xpos = xpos+0.12
 end do

plot1 = gsn_csm_xy2 (wks, montharray,(/totalemisNCPsum, totalemis5NCPsum,
totalemis4NCPsum, totalemis3NCPsum/),monthlypm25NCPsum, res,res2) ; create plot

plot2 = gsn_csm_xy2 (wks, montharray,(/totalemisIGPsum,totalemis5IGPsum,
totalemis4IGPsum, totalemis3IGPsum/),monthlypm25IGPsum, res,res2) ; create plot


;PANEL PLOTS
 pnlres                         = True
 pnlres@gsnPanelYWhiteSpacePercent = 5
 pnlres@amJust   = "TopLeft"
 pnlres@gsnMaximize = True
 pnlres@gsnFrame         = False
 pnlres@gsnPanelFigureStrings= (/"NCP","IGP"/)
pnlres@gsnPanelMainString = "PM2.5 Concentration vs Emissions"
gsn_panel(wks,(/plot1,plot2/),(/2,1/),pnlres)

frame(wks)
end
```