Course Name: An Introduction to Climate Dynamics, Variability and Monitoring

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ATMOSPHERIC STRUCTURE AND COMPOSITION

Good morning class and welcome to our continuing lectures on climate dynamics variability and monitoring. In the previous class we had discussed the variation of temperature with altitude. We saw that the temperature profile with altitude had a zigzag kind of a structure and it initially decreased with altitude, then it reversed itself and began to increase with altitude and then again a reversal followed by another reversal. And each of these zones where the temperature is increasing or decreasing with altitude can be separated into individual atmospheric layers, which were described as the troposphere, which is the lowest and the densest of the atmospheric layers, followed by the stratosphere, followed by the mesosphere, then finally followed by the thermosphere. We also saw that while this structure is generic mean temperature profile of atmosphere with altitude, there is considerable variability of this temperature profile gradient with the seasons, with the latitudes as can be seen in the next few figures. We saw that as we change latitudes from equator towards the poles for the lower part of the atmosphere, we saw that the troposphere decreased in thickness and the temperature gradient also fell so that the troposphere and the tropopause regions were significantly different in length and thickness as we move from equator towards the poles.

Similarly, we saw that there were significant changes in the temperature profiles with the seasons. Especially in the high latitudes near the poles, there was a marked temperature inversion where the temperature actually increased with altitude for the first 1 km of the troposphere because of the extreme coldness of the land surface due to the absence of solar radiation. All of these effects could be seen in a combined format when we measure the temperature contours with latitude for the winter, northern hemisphere winter and the northern hemisphere summer seasons and we saw that the location of the tropopause changed considerably from the equator towards the poles and with whether the hemisphere is undergoing a winter season or a summer season. These temperature gradients have significant effect in the climatic conditions that develop in each of the hemispheres and each of the latitude regions as we will see in our following lectures

Now one of the things that we saw is that while in the troposphere there was a decline in temperature with altitude and we also discussed the tropospheric lapse rate which was a decrease of 6.5 kelvins per kilometer of altitude gained which is the mean lapse rate for the planet in the troposphere. However, in the stratosphere the trend reverses itself and we see an increase in temperature with altitude. This stratospheric region is the second layer of the atmosphere, extends from around 18 kilometers as we again discussed stratosphere, the location changes with latitude and with the seasons to around 15 kilometers above the earth's surface. We have a positive lapse rate here.

So temperature is increasing with altitude and the reason why the temperature increases with altitude is because of the absorption of the UV radiation in the stratosphere by the ozone gas molecules that are present in this zone of the atmosphere. So you may have all heard about ozone being a protective layer that is shielding the earth's surface from highly energy intensive and harmful ultraviolet radiation of the sun. This ozone gas is found primarily in the stratospheric zone and is responsible for absorbing the ultraviolet radiation. Because it absorbs ultraviolet radiation the stratospheric air becomes hot because it is absorbing this radiation and as a result the temperature increases with altitude within the stratosphere. This is also the reason why at high latitudes in the winter hemisphere the increase in temperature in the stratosphere is much much lower as can be seen in this zone in northern hemisphere in December, January, February and in this zone in the southern hemisphere in the June, July, August region.

Since there is very little to insignificant solar insulation, solar radiation in the winter hemisphere, Therefore, there isn't much chance for the gases to heat up by absorbing the UV radiation, which is why the stratospheric temperature in the winter hemisphere does not increase markedly. Whereas there is a significant and rapid increase in the stratospheric temperature in the summer hemisphere, which is getting sun's rays for longer periods of the day. Beyond the stratosphere, between the 50 to 90 km region, temperature again starts to fall with altitude because there is no ozone layer in this zone and the normal decline of temperature with altitude happens here. This mesosphere has a minimal effect on the world's climate and hence we will not discuss this here. The final zone is the thermosphere, which is between 90 to 120 kilometers.

It's an extremely rarefied region of the atmosphere with extremely low density of atmospheric gases. Here extremely energetic solar rays like x-rays get absorbed and these solar radiation at this high energy intense regions heat the air molecules here and they ionize the air molecules. So the oxygen and the nitrogen molecules break apart into oxygen and nitrogen radicals for instance. Water molecules break apart into H and OH radicals by absorbing this highly intense X-rays and other energetic radiation frequencies from the sun. And it is because the thermosphere is absorbing this highly energetic section of the solar radiation that it increases in temperature with altitude just like in the stratosphere.

However, it has minimal effect on the world's climate and we will not discuss this segment of the atmosphere in this course. So this kind of completes our preliminary discussion on the temperatures and how the temperature changes with altitude. Next, we will look into atmospheric composition, which is an extremely important parameter, particularly in the context of anthropogenic global warming, because as we know, our emission of CO2 and methane is actively changing the atmospheric gas composition, which is causing the global warming effect we are seeing today. Now what is interesting is CO2 and methane as a fraction of the atmosphere is quite small. Most of air is composed of molecular nitrogen which is around 78% and molecular oxygen which is around 21% of the atmospheric gases.

The next most abundant gas is argon which is an inert noble gas and constitutes 1% of the atmosphere. So if you see the volume fraction here is the list of the composition of the atmosphere by the gases and volume fraction is close to the mole fraction or if you take 100 moles of air how many moles of each of the gases are there. So in nitrogen 78 mole percentage or volume percent of nitrogen is present in the air. Oxygen is around 20.95%. Argon is 0.934%. And these three forms the majority of the gas that is present in atmosphere. Water vapor is the next most abundant gas but water vapor we cannot give a specific composition because it's highly variable. There is a significant amount of water vapor in the tropics whereas in the colder upper latitudes like the North Pole and the South Pole the concentration of water vapor decreases significantly.

So, you will have a large variability of the water vapor concentration depending on the location and depending on the seasons. We will discuss water vapor composition as a separate aspect when we discuss humidity of air and how humidity varies with temperature, latitude, etc. After this we get into carbon dioxide which is the most significant greenhouse gas in our atmosphere. The amount of carbon dioxide is around 391 parts per million in volume percentage. This is value is valid in 2011.

We will see that this has gone up over 400 parts per million by 2020. Now, what is parts per million? Basically, this is $391 * 10^{-6}$. So, just as 0.934 percentage means $0.934 * 10^{-3}$.

Similarly, parts per million means $391 * 10^{-6}$. Okay. So, percentage is parts per 100. parts per million is one part in one million parts. So that's how this unit works.

So if you look at carbon dioxide, its concentration is much, much lower than nitrogen, oxygen, argon, etc. So if you see the total mass of atmosphere as we discussed earlier is around $5.1 * 10^{21}$. Of this dry air that is air without water vapor is around $5.12 * 10^{21}$. Out of this, nitrogen is $3.87 * 10^{21}$ grams. Oxygen is $1.18 * 10^{21}$ grams.

Argan is $6.59 * 10^{19}$ grams. Then you get water vapor, which is $1.7 * 10^{19}$ grams. So this is like thousand times, at least thousand times lower than even argan, for example, 100 times lower than argan. And carbon dioxide is even one order of magnitude lower even compared to water vapor or argon.

It's around 2.76 * 10^{18} grams. So on a mass basis, these are the values. It's around 5.3 * 10^{-7} as a fraction of that atmosphere's total mass. Alright. After carbon dioxide, we have a series of inert gases, neon, krypton and helium, which are around 18 parts per million, 1 part per million and 5.24 parts per million. Okay. Then you have methane, which is around 1.8 parts per million. So 1.8 * 10^{-6} in terms of mole fractions. In terms of total mass, it's 4.9 * 10^{15}. methane is the next most important greenhouse gas contributing to global warming after carbon dioxide okay then after methane we have another inert gas like xenon then we have ozone which is approximately in on mass basis it's 3.3 * 10^{15} so close to what methane is On a mass basis, its concentration is somewhat variable.

As we remember, it depends on the geographic location. And recently, due to the presence of chlorofluorocarbons in the atmosphere, the amount of ozone in the stratosphere has decreased significantly. You may have heard of the ozone hole issue. Especially in the southern hemisphere and the northern hemisphere, it develops a region of extremely low ozone concentration.

So this one is also variable. Then you have nitrous oxide, which is the third most significant greenhouse gas after CO2 and methane. Its value is even lower. It's 324 parts per billion. So instead of 10 * 10^{-6}, you have 10 * 10^{-9}. So these are some of the most important gases in terms of their contribution to the atmospheric dynamics.

So the main thing I want to show you in this compositional analysis is that while nitrogen and oxygen and to some extent argon are the three main gases, these gases do not contribute to the present change in climate. What is contributing to the present change in climate is CO2, methane and nitrous oxide primarily. And their concentrations are at extremely low values. From 400 parts per million to maybe 2 parts per million.

3 parts per million. Because these are present at low values but have an outsized impact on the heat budget of the atmosphere, significant emissions of these gases can perturb the atmospheric dynamics a lot. And it is why our emissions of CO2, methane and nitrous oxide is causing so much difference in climate dynamics. We will discuss at a later stage how this happens, how does a small amount of gas can contribute so much to the heat budget of the atmosphere. The fourth most important gas is water vapor. Now water vapor is extremely important in determining the precipitation, how much precipitation one is getting.

So it has a very important role in the water cycle and in the precipitation cycle of the atmosphere. But also climate change is causing a significant change in the water vapor concentrations in the atmosphere. As we discussed, we will go over this in detail in the next class. next few classes as the temperature of air rises it can hold more water vapour the absolute amount of water vapour in the atmosphere is actually rising with temperature and water vapour itself is also a very significant greenhouse gas so there is a feedback loop that is happening between CO2 and water vapour more CO2 and methane emissions means that temperature of earth is rising temperature of earth's air atmosphere, high heated atmosphere can hold more water vapor and water vapor itself increases the heat trapping ability of the atmosphere. So, the increase in water vapor further contributes to a temperature rise.

So, there is a positive feedback loop between CO2, methane and water vapor that is accelerating the global warming effect. And this is something that we will discuss much later in the later sections of the class. So here is the data on the change in CO2 concentration as has been noted by many of the observatories situated in different parts of the world. So here we have three or four different observatories.

One is in Moanalua in Hawaii. One is present in South Pole. This is a global observatory and this is a satellite based observation. And this is CO2 concentration in parts per million. So in 1960, it was around 320 parts per million. In 2020, this has increased to more than 410, 412 parts per million.

And you see the values of all the observatories are matching with each other. With the difference between them is of the order of just 4 parts per million. So, this is in Hawaii and this is in South Pole. The difference between the Hawaii observed CO2 concentration and South Pole observed CO2 concentration is between 2 to 4 parts per million only.

All right. Another interesting aspect is this cyclical up and down of CO2 concentration. This is happening between the winter season and the summer season. What happens is during the summer season, there is a significant growth spurt of the plants, especially in the northern hemisphere, which has a significant amount of landmass. As a result, because plants absorb a lot of CO2, the CO2 concentration decreases in the atmosphere because a lot of it is being absorbed by growing plants. Then in winter, plants stopped growing, but animals are still there.

So as a result, CO2 concentration moves back up. So this is a natural winter to summer cycle that you can see, which is over and above the trend of CO2 increase, which is caused by human emissions of fossil fuel based combustion systems. This section we will discuss much later in the class, but this is the attributed temperature change relative to 1750 base. We discussed up to 1850. There was some heating between 1750 and 1850 as well. And what we see here with 1750 as 0, the total temperature change is around 1.3 degrees rather than 1.1 or 1.2 degrees from 1850 base. That is number one. Number two is here the researchers have differentiated between the contributions of the various types of gases emitted by human activity. How much each of them is contributing to the heating or the cooling effect. So you can see CO2 which is this violet colored line which is the mean projection and this is the variability among different models.

This CO2 is the main driver of the atmospheric heating that we are seeing, followed by methane, which is this brown line here. And then you have the green line and the blue line. So, halogenated gases, these are the chlorofluorocarbons that are emitted from the air conditioning systems. Not only do they have an impact in decreasing the ozone layer, they also have an impact in increasing the heat budget.

So, they are also very strong greenhouse gases. Similarly, ozone also has an effect, but it is an opposite effect. when the concentration of ozone decreases it also has a heating effect in on the world because it is allowing the uv rays to penetrate to the earth surface so decrease in ozone also causes a global heating effect okay then you have nitrous oxide which is the green line here yes this is the green line here so these Four are the positive drivers of atmospheric heating. Against this, there are two or three other contributors. One major contributor to a negative or atmospheric cooling effect is the presence of aerosols. Aerosols are small particles of dust or soot that are floating in the atmosphere.

Emissions from fossil fuels also contain a lot of soot emissions and this soot kind of decreases the transparency of atmosphere to solar radiation causing a larger amount of sunlight to be reflected back into space. So while the presence of soot and associated smog has a very detrimental effect to human health because of the respiratory diseases and illnesses, it also has a cooling effect. And this cooling effect had in the past partially mitigated the heating effect by all the global warming gases that we have emitted over the last two and a half centuries. However, as we go into more cleaner types of fuel sources, and we try to have clean air pollution standards with filtrations, et cetera, the amount of smog and soot emissions tend to decrease over time with more clean technologies, and hence the soot emissions have, as you can see, kind of plateaued from 2000 or 1990 onwards. And this paradoxically have accelerated the observed heating rates of Earth's atmosphere because CO2 emissions have not changed significantly while soot emissions have plateaued.

So these are some of the intricacies and complexities of the various contributors to global warming and global cooling due to human activity, which we will touch upon again later in the class. But clearly atmospheric composition, especially of this trace species, and trace aerosol particles has an extremely important effect on the heat budget and global warming phenomena that we are observing in the world today. So, I will stop the lecture here. We will in the next class discuss a little bit of quantitative analysis on how we can measure the concentrations of various atmospheric gases and how we can use them to calculate simple ideas. So, thank you for listening and see you again in the next class. Thank you.