The Mesospheric Energy Budget and Meteor Affects on Chemical Composition

PHYSICS 9710R

Nick Buccongello

Kasia Wisniewski

nbuccong@uwo.ca

kwisnie2@uwo.ca

Department of Physics and Astronomy

Western University

1151 Richmond St, London, ON N6A 3K7

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1.1 The Mesosphere

The mesosphere is a layer within the atmosphere ranging from 50 to 85 kilometers above the Earth's surface, between the stratosphere and thermosphere [6]. The mesosphere's temperature profile decreases as altitude increases, as shown in figure 1, similar to the troposphere but over a larger altitude range.

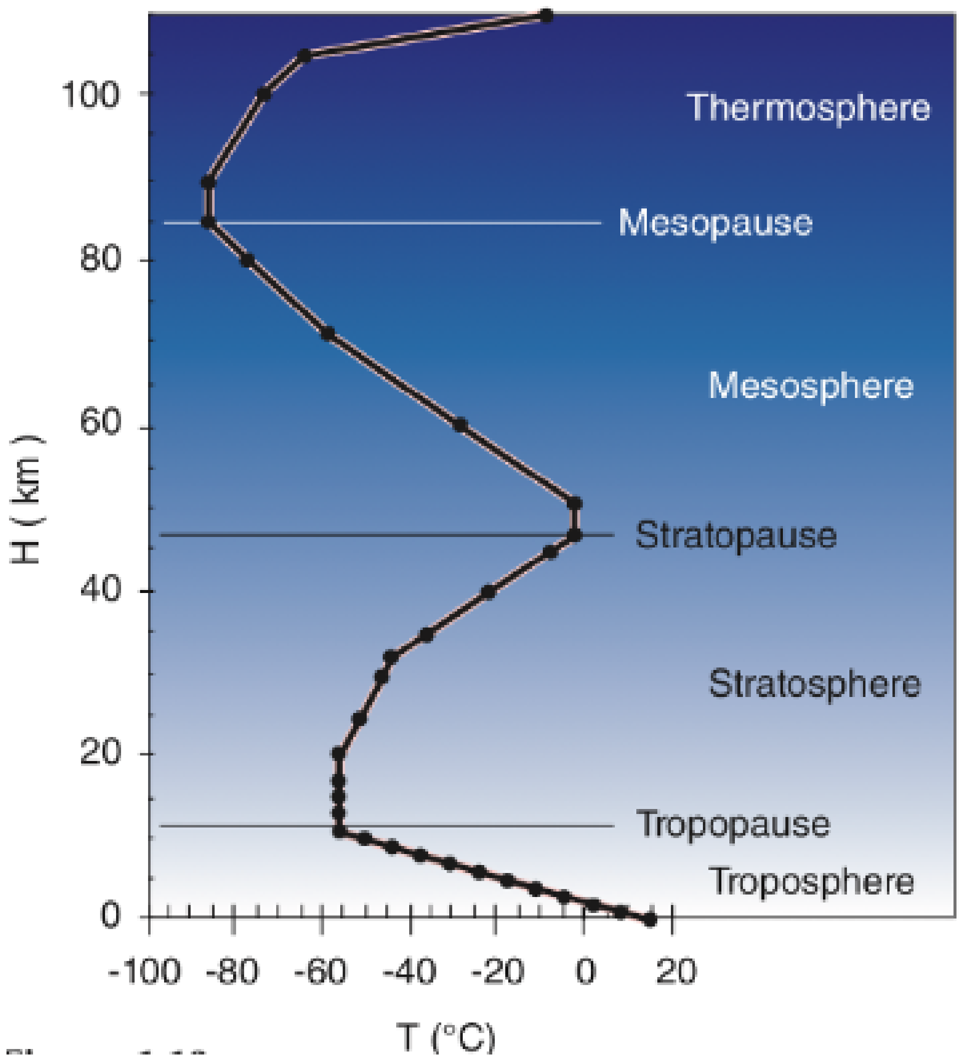

Figure 1: Different layers of the atmosphere for height vs. temperature

The atmosphere reaches its coldest temperature at the point called the Mesopause. An important point, which will be revisited later in this report; is that meteors ablate in this layer of the atmosphere. This is due to the higher density of gases within this layer interacting with meteors and the significant friction causing the meteors to break up and display large tails often visible to any viewers [5].

1.2 The Mesospheric Energy Budget

The mesospheric energy budget for the Earth can be thought of as how balance is achieved between thermodynamic processes, chemical changes, and how the structure evolves over time [20]. As stated in the abstract of [20], the energy budget in this upper portion of the atmosphere differs from that of the lower portions of the atmosphere because the heating and cooling processes are different than the local frame. Figure 2 is taken from [20] is a depiction of the different processes occurring within the mesosphere and how they balance.

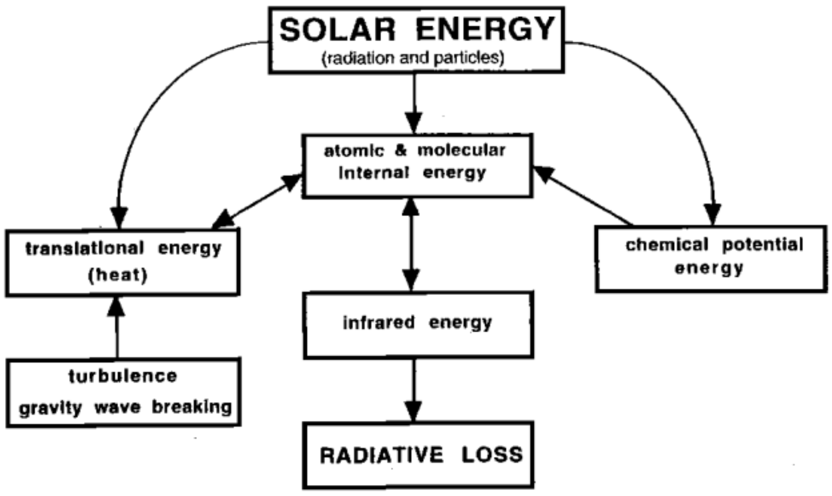

Figure 2: Energy Conservation in the Mesosphere

These processes will be discussed in later sections. This balance or energy budget follows essentially the laws of energy conservation. The main processes at higher altitudes in the mesosphere differ from those at lower altitudes. This is due to collisional processes not being the main energy exchange between radiatively active molecules and the surroundings [20].

1.2.1 Solar Heating by Ozone and Molecular Oxygen

Solar Heating of the mesosphere occurs by the absorption of ultraviolet rays by Ozone and Molecular Oxygen causing photolysis of these atmospheric molecules, as well as infrared absorption. We will consider solar heating from molecular oxygen in the infrared and ozone in the Hartley Band (762 nm and 255 nm respectively).

The first rate we will consider is solar heating by O and O_3. First we consider the first law of thermodynamics, shown in equation 1

$$\epsilon \frac{dQ}{dt} = \rho C_P \frac{dT}{dt} \tag{1}$$

where:

- ϵ is heat efficiency
- ρ is density which is dependant on altitude
- C_P is heat capacity at constant pressure

Then we consider the heating rate from photolysis by the following equation:

$$\frac{dQ}{dt} = JN(h\nu - D) \tag{2}$$

where:

- J is photolysis rate

- N is the absorber density
- hν is the energy of the absorbed photon
- D is the energy required to dissociate the molecule.

Lastly, we need to consider the airglow of $O_2(^1\Delta)$. The airglow is nighttime background luminosity of the sky [1] due to emission of excited states by various processes and thus needs to be accounted for in the heating rate [1]. To visualize it, it's the slight glow the atmosphere has at night.

$$O_2(^1\Delta) = \frac{JO_3}{A + kO_2} \tag{3}$$

where:

- $O_2(^1\Delta)$ is the airglow emission
- J is photolysis rate
- O_3 is the density of ozone
- A is the Einstein coefficient for spontaneous emission by $O_2(^1\Delta)$
- k is the rate of physical quenching
- O_2 is the atomic oxygen density

We can combine the three equations to form a solar heating rate in Kelvins/day:

$$\frac{dT}{dt} = \frac{\epsilon}{\rho C_P}(h\nu - D)(1 + \frac{kO_2}{A})V_\Delta \tag{4}$$

where V_Δ is the volume emission of $O_2(^1\Delta)$ airglow.

The previous 4 equations were taken from [20]. Please refer to the python code file in the GitHub repository for the values of the constants used and their respective units.

1.2.2 Heating due to Exothermic Reactions

When the ozone and molecular oxygen in the atmosphere absorb solar radiation, not all of the energy is realized as heat. Varying proportions of this energy transforms into chemical potential and internal potential energy as seen below in figure 3 from [20]. This chemical energy is created upon photolysis of the ozone and oxygen [20] and can contribute a significant amount of heat into the mesosphere.

	Heat	Chemical Potential	Internal
Ozone			
Hartley band	13%	24%	63%
Huggins band	76%	24%	0%
Chappuis band	76%	24%	0%
Oxygen			
Sch.-Runge contin.	1%	72%	27%
Sch.-Runge band	24%	76%	0%
Lyman α	30%	50%	20%

Figure 3: Energy absorbed by Ozone and Molecular Oxygen

This chemical energy manifests itself as heat in the atmosphere through exothermic chemical reactions which can take place at a subsequent time and place from the initial photon deposition [20]. There are 7 main reactions that account for the majority of this heating which can be seen below [21].

The following reactions and their exothermic energies occur within the mesosphere:

$\mathrm{H} + \mathrm{O_3} \longrightarrow \mathrm{OH} + \mathrm{O_2}$ -76.90 kcal/mol

$\mathrm{H} + \mathrm{O_2} + \mathrm{M} \longrightarrow \mathrm{HO_2} + \mathrm{M}$ -49.10 kcal/mol

$\mathrm{O} + \mathrm{HO_2} \longrightarrow \mathrm{OH} + \mathrm{O_2}$ -53.27 kcal/mol

$\mathrm{O} + \mathrm{OH} \longrightarrow \mathrm{H} + \mathrm{O_2}$ -16.77 kcal/mol

$\mathrm{O} + \mathrm{O} + \mathrm{M} \longrightarrow \mathrm{O_2} + \mathrm{M}$ -119.40 kcal/mol

$\mathrm{O} + \mathrm{O_2} + \mathrm{M} \longrightarrow \mathrm{O_3} + \mathrm{M}$ -25.47 kcal/mol

$\mathrm{O} + \mathrm{O_3} \longrightarrow \mathrm{O_2} + \mathrm{O_2}$ -93.65 kcal/mol

These reactions have been studied in detail, and their roles in the mesospheric energy budget have been determined fairly accurately [21]. It has been found that reaction 1 between atomic hydrogen and ozone is the most significant of these reaction between 80 and 95 km altitude [20]. In order to understand why this is, it is important to note that there is a clear difference in heating rates for each reaction during the day vs the night [20]. During the day, reactions 1, 2 and 5 are responsible for the majority of chemical heating above 60 km [20]. Additionally, during the night, the overall amount of chemical heating above 80 km is much larger than during the day and is almost entirely caused by reaction 1 [20]. This is due to the fact that ozone abundance greatly increases at night, quickly fueling reactions with atomic hydrogen [20]. Also, during the night, atomic hydrogen and oxygen levels fall, limiting the amount of the other reactions [20]. The instantaneous heating rates caused by each of these chemical reactions is defined by [22] and can be seen below:

$$\frac{dT}{dt} = \frac{2}{7} k \frac{1}{k_b} \frac{1}{[M]} [A][B](\Delta H_f) \tag{5}$$

where:

- k is the rate of reaction coefficient
- k_b is the Boltzmann constant
- $[M]$ is the number density
- $[A]$ is the concentration of reactant A
- $[B]$ is the concentration of reactant B
- ΔH_f is the enthalpy of the reaction

This equation applies to each of the biomolecular reactions, 1, 3, 4, and 7, allowing for calculation of heating rate in Kelvins per day at various altitudes [22]. The three remaining reactions, 2, 5 and 6, are recombination reactions. The heating rate equation for these is very similar, except the number density term is replaced by a recombination rate coefficient [22].

1.2.3 Infrared Radiative Cooling by Carbon Dioxide

Cooling in the mesosphere occurs by a few different processes, which are dependant on altitude. In the lower regions of the layer, cooling occurs by ozone, water vapour and CO_2, but as the altitude reaches between 75 and 110 km, cooling from CO_2 becomes the only mechanism at the 15 μm band [20].

Theoretically, modeling CO_2 cooling in the mesosphere is not an easy task. The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on board the Thermosphere Ionosphere Mesosphere Energetics Dynamics (TIMED) satellite from NASA provides a wide range of data measurements to better understand the mesosphere and lower thermosphere [10]. This instrument has been collecting data for just about 2 decades.

These cooling rates are measured constantly with the SABER instrument, in which a profile of the rate in Kelvins per day is computed. About 500'000 profiles are combined in order to create a yearly cooling rate that varies with altitude [22]. Taken from [22], this figure is an example of a heating and cooling rate for the year 2004.

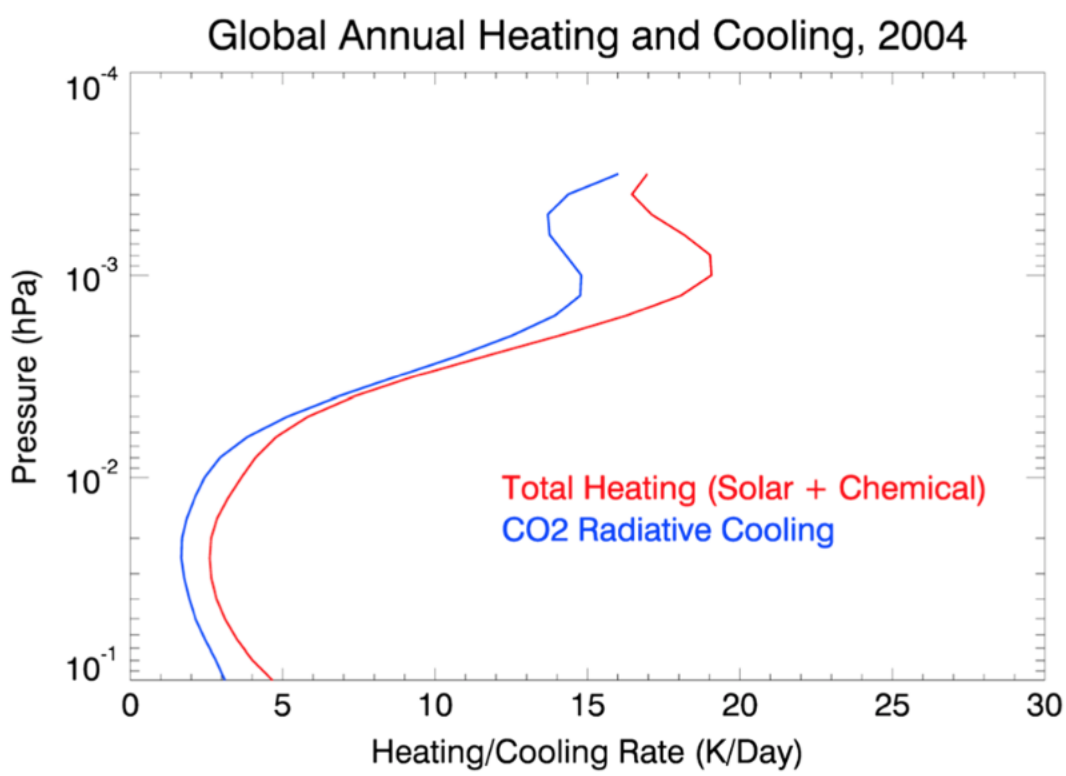

Figure 4: Total Heating and Cooling for the Mesosphere for 2004

Due to the difficulty of modelling these cooling rates, and the limited scope of this report, we will use existing cooling curves measured by SABER like the one seen in 4. We will use this in addition to our own computed curves for solar heating and chemical heating to get a model for total temperature change per day.

2 Results and Discussion

The first step to computing a total heating rate was to consider the heating due to solar absorption by Ozone and molecular Oxygen. These were calculated using equation 4. Standard constants, for example the speed of light, heat capacities, Planck's constant etc. were easily found online as they are common values. However, finding exact values for other parameters was not as easy. The physical quenching rate (k) from equation 3 was determined from [22]. Searching through other related literature did not reveal any insight on how the quenching parameter differs for Ozone. This one value was used for both calculations, despite it being defined for O2 only. Einstein's Coefficient for Spontaneous Emission was taken from [23].

There were multiple parameters that depended on the altitude change. We used the range of 50 km to 110 km because most reference plots also used that range. The airglow O_2 density, $O_2(^1\Delta)$ is one of those parameters. Dr. Martin Mlynczak provided a text file with these values from SABER Data. Dr. Mlynczak also provided the paper [10] in which this plot for volume emission was included.

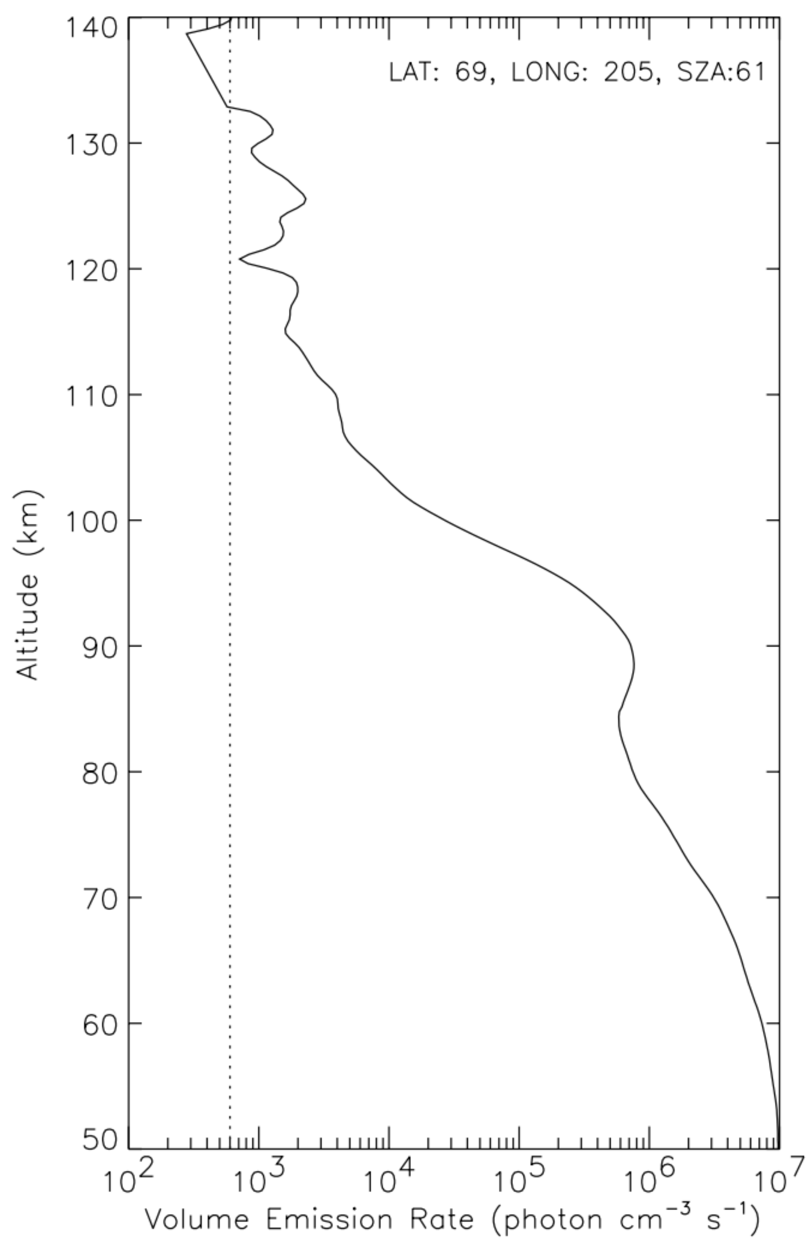

Figure 5: Volume Emission Rate for O_2

Unfortunately, we couldn't gain access to SABER data, so volume emission rates had to be extrapolated from this curve, however, the general order of magnitude at each altitude should suffice for our purposes.

The last bit of information needed was the gas density for both O_2 and O_3. Again, Dr. Martin Mlynczak provided data sets with the pressure and temperature changes with increasing altitude. We used this rearranged version of the Ideal Gas Law:

$$\rho = \frac{PM}{RT} \tag{6}$$

where:

- P is the pressure of the atmosphere

- M is the molar mass of the gas
- R is the ideal gas constant
- T is the temperature

The densities of the O_2 and O_3 gasses could be calculated, and thus the combined total solar heating rate is given by the following plot.

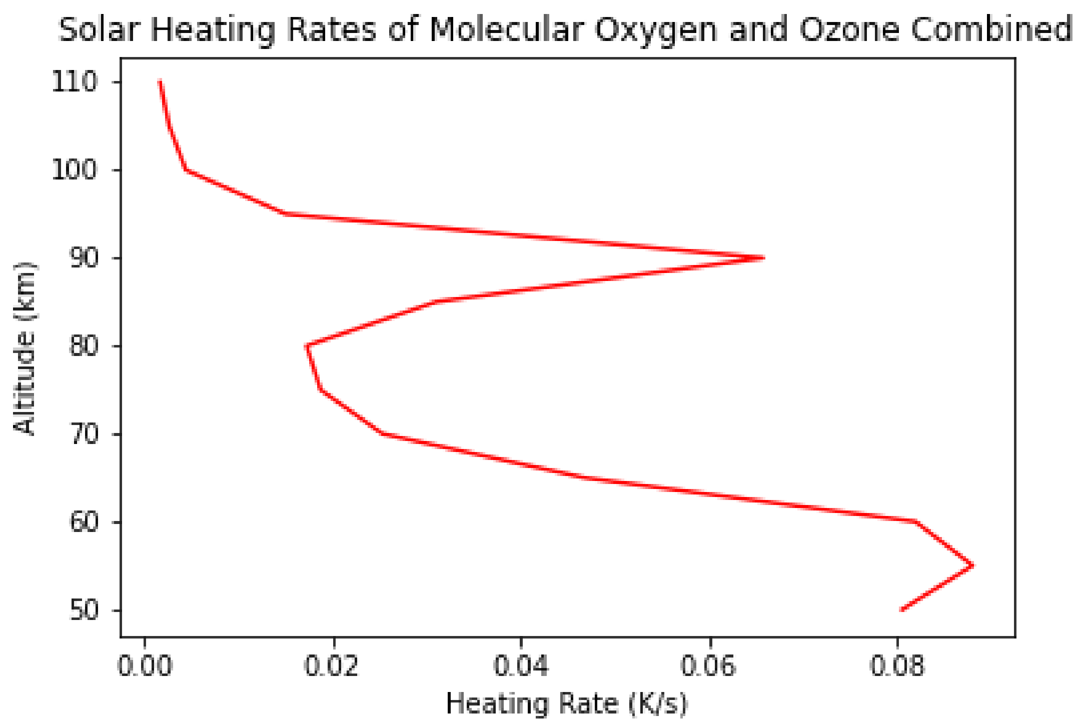

Figure 6: Total Solar Heating Rate

Next, we calculated the chemical heating rates. As mentioned in section 1.2.2, there are 7 main chemical reactions that provide significant sources of heat to the mesosphere. The most significant of those being reaction 1 between atomic hydrogen and ozone. While the other 6 reactions when combined do have significant effects on temperature [20], due to the time required to model each reaction individually and the scope of this report, all reactions will be ignored except reaction 1. Equation 5 was used to calculate the instantaneous heating rate. Rate of reaction coefficient k has been studied and is known to be 0.6 for this reaction [22]. The Boltzmann constant and enthalpy of the reaction are known values found online [20]. The concentrations of reactants A and B (atomic hydrogen and ozone) have been measured by the SABER instrument at various altitudes and were also reported by [22]. Values were recorded at 5 km intervals between 50 and 110 km. It is important to note that ozone concentration is negligible at altitudes below 80 km so the heating curve for this reaction begins there instead of 50 km. Number density $[M]$ was also calculated at 5 km increment altitudes between 50 and 110 km. In order to calculate these values, a weighted average was used to find molar mass of the atmosphere (assuming homogeneity) to be 14.3 g/mol. Dividing the known atmospheric densities at each altitude by this molar mass, and multiplying by Avogadro's number resulted in the number density in units of $1/cm^3$. Calculations resulted in the instantaneous heating rate which can be seen below in the figure.

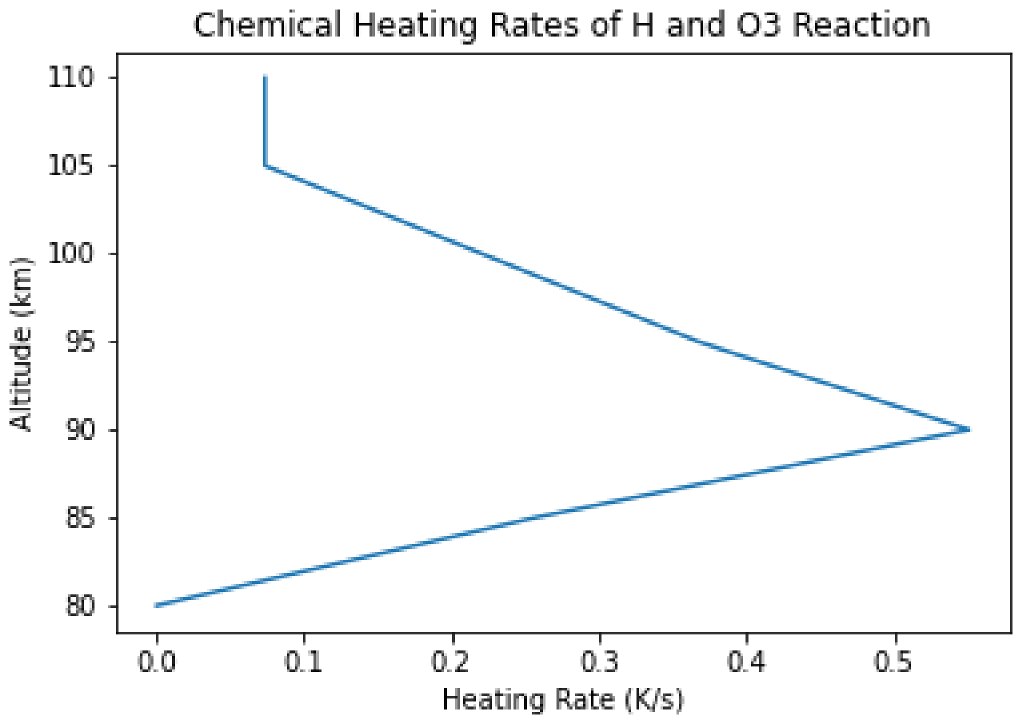

Figure 7: Total Chemical Heating for 80 - 110 km

Finally, we considered the cooling rates from radiative cooling from CO_2. As stated in the theory section for radiative cooling, there wasn't a theoretical model we could set up sample calculations with, as confirmed with our discussion with Dr. Mlynczak. The rates were extracted from SABER measurement plots. We decided then to recreate a model from the known plot 4 found in [22]. This was done by extrapolating points. The figure below is the reconstruction of the plot.

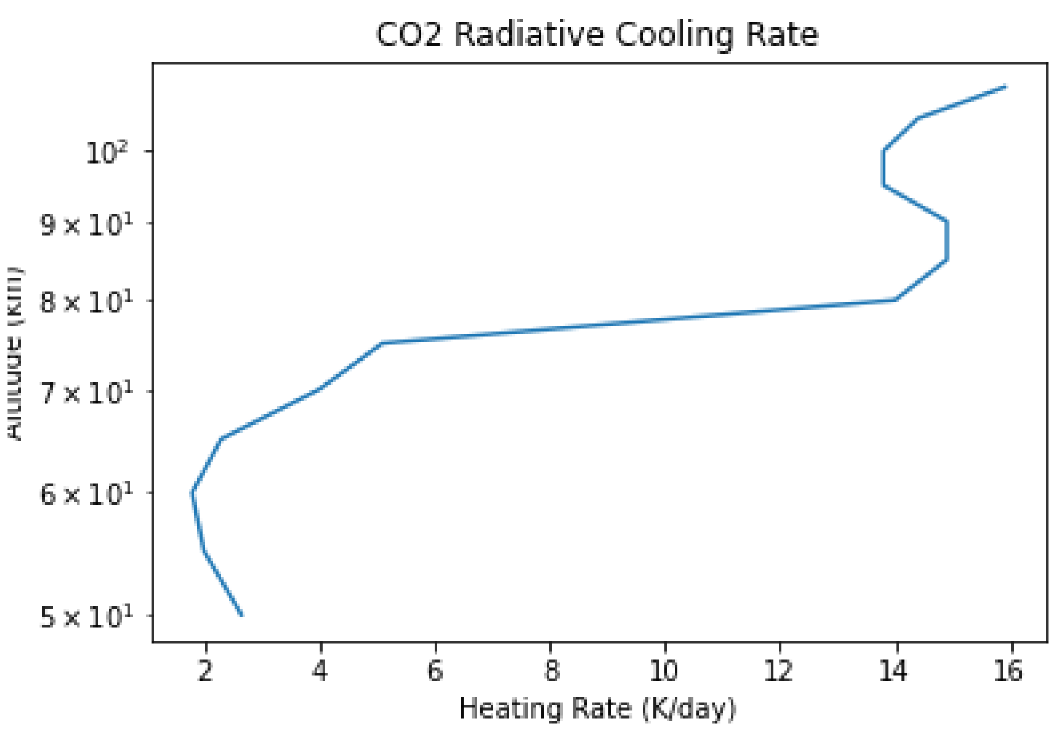

Figure 8: Reconstruction of Radiative Cooling

With these three rates computed and constructed, a total temperature change was determined, and is represented by the green line in the figure below.

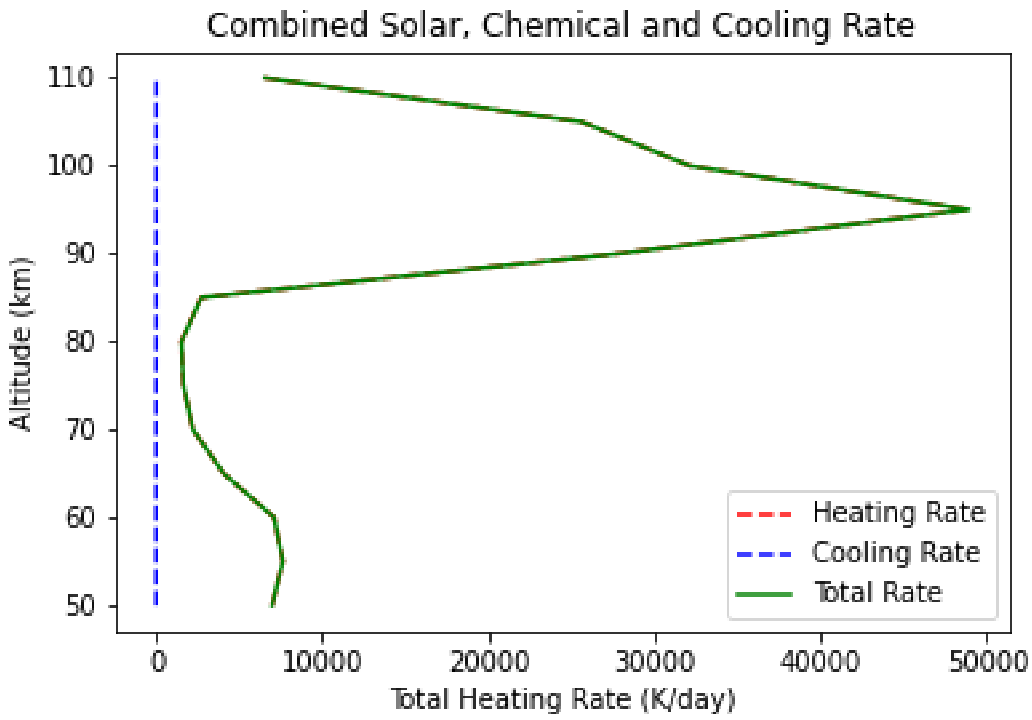

Figure 9: Total Temperature Change Rate

Some things to note are the computed rates are in units of Kelvins per second rather than Kelvins per day. We choose to leave the units this way because all of the calculations done seemed to be the same order of magnitude off from the known values and we wanted to observe the shape of the curves. However, when creating the final combined plot, we had to convert to Kelvins/day in order to compare to the literature so the data is of course is unreasonable. This error could be due to a unit conversion, or a incorrect value fetched for a constant, however all collected data was checked multiple times for errors and unit conversions. This is due to the fact most papers studied did not outline some of these constants used for their calculations, and with a large variety of units that can be used for most of the thermodynamic principles, one wrong value could change a lot. Also note, a lot of assumptions were made due to lack of data and time constraints. In the future, if time permits, cross checking with authors of papers could eliminate this error.

Looking at each of the individual calculated heating rates, the solar heating seems to follow the expected trend for what we know about the mesosphere. As already mentioned, the mesosphere is the coolest part of the atmosphere, so we see in figure 6 that from altitudes of 55 to 80 km, the heating rate is decreasing and as the altitude approached the thermosphere, the rate climbs back up until it decreases again. The chemical heating agrees with what we expect to see as well. For the cooling rate, it is exactly as predicted because it is an existing model.

For reference, the chemical and solar heating rates should be on the order of a few Kelvin/day as shown in the following plot taken from a presentation *Coupled Energetics, Chemistry, and Dynamics in the Terrestrial Mesosphere and Lower Thermosphere* by Dr. Martin Mlynczak for the Ninth Annual CEDAR Meeting [19].

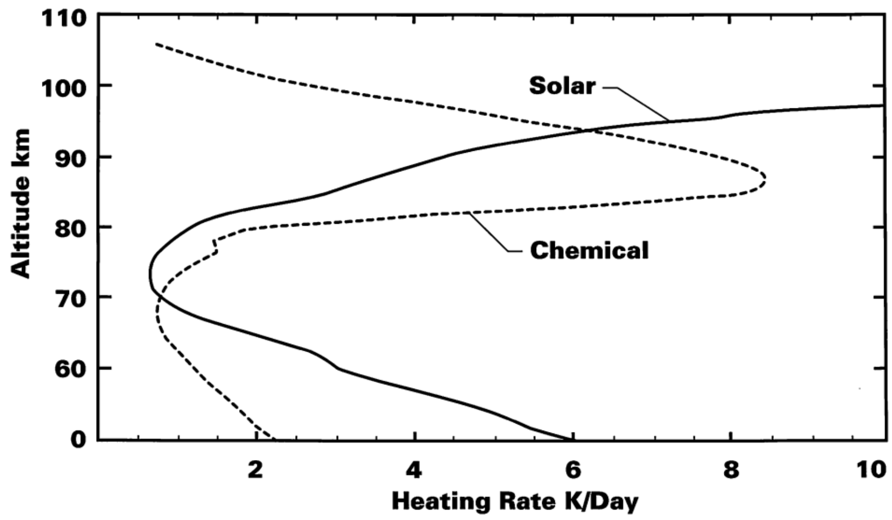

Figure 10: Expected Idea of the Solar and Chemical Heating Rates

Our plots follow the same expected "curve" at approximately the same altitudes of the curves in the figure above, which is another good indication there was an error with either unit conversions or in values not explicitly outlined in the literature that were found online, or even a scaling factor we missed.

In summary, an attempt was made to model the total heating rate of the mesosphere. It was found that our model does agree the trends seen in the literature, the actual magnitude of the rates do not agree, potentially due to the errors already mentioned. As a final exploration and both being meteor students, we were interested in exploring potential meteor effects on this heating rate.

3 Meteors and the Mesosphere

The vast majority of meteors burn up, or ablate in the mesosphere. This is because the mesosphere is the first region of the atmosphere that meteors run into where the density is not negligible. The first two regions are the thermosphere and exosphere with gas densities maxing out at 10^{-6} kg/m^3. In these two regions there is just simply not enough gas particles to have any noticeable effect on incoming meteors. However once these meteors hit the mesosphere with a max density of 10^{-3} kg/m^3, 3 orders of magnitude higher, the effects of atmospheric gas are not negligible anymore.While this air is still fairly thin compared to Sea level on Earth, there is enough there to cause friction and therefore heat on a meteors that pass through [11]. While not every meteor will completely ablate and burn up in the mesosphere, only about 5-10 percent actually make it all the way to Earth [18], all meteors that pass through the mesosphere and feel the tangible effects of friction. As mentioned earlier, this friction also means heat is generated. This leads us to the question, how much of this heat energy generated by meteors is deposited in the mesosphere, and how does it affect the current model we have for temperature?

When attempting to quantify the amount of heat energy deposited by meteors in the mesosphere, we are attempting to model an extremely complicated scenario. Due to the scope of this project, an attempt was made to simplify this process as much as possible, while still calculating a reasonably accurate prediction for heating rate in the mesosphere. At minimum, we will need to calculate two parameters. First, the average kinetic energy of meteors in our atmosphere every year, and second the efficiency at which that energy is deposited into our atmosphere as heat.

The kinetic energy can be calculated using the standard equation:

$$E = \frac{1}{2}mv^2 \tag{7}$$

where E is the total kinetic energy in Joules, m is the total mass in kg and v is the velocity in m/s. First, an attempt was made to quantify the total mass of meteoric material that enters Earth's atmosphere every year. It is important to note that the vast majority of this material is dust [25], this dust is defined as extremely small particles with masses less than 10^{-4} grams [25]. Luckily, this is useful for our estimation, as it allows us to neglect a parameter known as heat conductivity, which determines how well a material conducts or transfers heat [25]. This is something we would otherwise need to account for as it would directly affect each meteor's ability to transfer energy to heat and would therefore impact our result. Recent analysis shows us that we may neglect this parameter as it's effect is negligible on such small meteors [17]. In terms of total mass, NASA estimates about 48.5 tons of meteoric material falls onto the Earth every day [3]. Multiplying by 365 days per year, that's about 17,700 tons, or 1.6×10^7 kg of material per year. Now that we have a total mass, we will need an average velocity in order to obtain kinetic energy.

Using official data from the IAU Meteor Data centre website, it was found that average meteor velocities from showers range anywhere from 3.3 km/s (October gamma Cetids) to 75 km/s (zeta Cetids). It is worth noting that not all meteors come from meteor showers, the sporadic background does contribute a significant portion of meteor activity. However, for our purposes these values provide a sufficiently accurate estimate. Also, these velocities are determined while the meteors are resting in space, not their final velocities. The meteors will end up accelerating due to Earth's gravity once they get close enough and begin to enter the atmosphere. Therefore we will move the minimum value from 3.3 to 11.2 km/s which is Earth's escape velocity, and is therefore the minimum velocity that a meteor can enter the atmosphere [7]. After summing all velocities and taking an average, it was found that 41 km/s (41,000 m/s) was the average speed. While we know that in reality, the distribution of meteor flux is not equally spread perfectly equally across each shower. However, for simplicity we will assume an equal amount of mass enters the Earth's atmosphere for each shower. We can now plug this velocity (41,000 m/s) and the total mass $1.6 \times 10^7 kg$ into our kinetic energy equation. When we do this, we find a total kinetic energy of about 1.35×10^16 J or 13.5 petajoules. For comparison, the atomic bomb known as "Fat Man" that was dropped on Nagasaki during WWII, causing over 150,000 casualties, only contained 9×10^{13} J of energy [29]. That means that the total kinetic energy of all the meteors entering the Earth's atmosphere in a year is approximately equal to 150 "Fat Man's" detonating.

So how much of this enormous amount of kinetic energy is converted to heat? The answer seems to be most of it. Only about 1 percent of that energy is transformed into visible light which we can see as the meteor fireball [7]. Another small portion of the energy is transformed into sound [12], however the majority of the remaining energy is transformed into heat through both friction and compression of the atmospheric gasses surrounding the meteor [7]. Being conservative, we will assume 90 percent of the kinetic energy is converted to thermal. This means every year, about 1.2×10^{16} J of thermal energy is deposited in the atmosphere. The next question is, does this have any tangible effect on the temperature of the mesosphere?

Using the basic heat capacity equation:

$$Q = mc\Delta T$$

(8)

we can find the change in temperature of the mesosphere. In this equation, Q represents the change in energy in J (which we just calculated), m represents the mass of the object (in our case the mesosphere) in kg, delta T represents the change in temperature in K, and c represents the specific heat capacity of the object in J/kg. Heat capacity varies depending on what the object is made of. The chemical makeup of the mesosphere is the same as the layers below it, being about 78 percent N, 21 percent O and 1 percent other [2]. Nitrogen and Oxygen have specific heat capacities of about 1.05×10^{-3} J/kgK [8] and 9.2×10^{-4} J/kgK [9]. Taking a weighted average, we get a specific heat capacity of 1.01×10^{-3} J/kg K for the mesosphere. In terms of mass, the total atmospheric mass of the Earth is approximately 5.1×10^{18} kg [4], and the mesosphere makes up about 0.01 percent of that [30]. This means the total mass of the mesosphere is approximately 5.1×10^{16} kg.

We can now plug in our total thermal energy of the meteors, our average specific heat capacity of the mesosphere and our total mass of the mesosphere to calculate for a change in temperature. This results in a change in temperature of approximately 233 K/year or 0.64 K per day of heating caused by meteors. This value seems quite reasonable, as when we compare this to the heating and cooling processes in the literature, it is only 1 order of magnitude less.

In summary, it would appear that meteors have a non-negligible effect on the temperature of the mesosphere. Total meteor mass flux was used along with the average velocity of meteors to determine the total kinetic energy of meteors in our atmosphere every year. The total thermal energy was then found from the kinetic by making a conservative estimate for for how much of the energy was transformed. Approximate heat capacity of the mesosphere was calculated by taking a weighted average of the most common atmospheric components, Nitrogen and Oxygen. Finally, total temperature change of the mesosphere was calculated using 8 and found to be 0.64 K per day of heating. This value was then added to our current model for total mesospheric temperature change per day (seen in the figure above). Due to time limitations of this project, many assumptions and approximations were made in the interest of time. If given future opportunity to improve this meteor model, there is some improvements that could be made. The most logical next step would be to take into account the size distribution of meteors.This would allow for multiple accuracy improvements in calculations. For example, the altitude that meteors break up at depends mostly on how massive they are, as heavier meteors are more likely to make it deeper into the atmosphere. While it was assumed in this report that every meteor could be considered dust, that is simply not the case as a number large meteors hit the Earth each day. Therefore, including a more accurate meteoric size distribution along with known atmospheric density as a function of altitude would allow for determination of the altitudes that various sizes of meteors break up at. This would allow for localizing the thermal energy deposition by altitude, improving the calculated accuracy of the energy deposited in the mesosphere. Furthermore, a realistic size distribution would require inclusion of the heat conductivity parameter that was previously ignored. This would affect the amount of heat energy generated by larger meteors, further improving accuracy.

4 Meteors in Indigenous Culture

The Indigenous peoples of Australia have a vast belief system and rich oral history surrounding meteoric phenomena. More specifically, the Yarrungkanyi and Warlpiri peoples of Northern Australia as well as the Arrernte and Luritja peoples of Central Australia were especially interested in these topics having a number of cultural ties to meteors and meteorites. Central Australia, seen below in green, is loosely defined as the southern half of the Northern Territory. Many aspects of these peoples' culture and belief systems heavily involve meteors, and it is clear that these phenomena have been an important part of their history and spiritual framework.

Figure 11: Area of Australia in which the legends originate

The exact opinions of all the indigenous people across Australia are not entirely consistent when it comes to meteors and the like. Beliefs vary greatly, ranging from evil spirits inhabiting meteors, to creation stories that state meteors as being the very thing that brought life to the planet Earth [15]. For the most part though, they are generally viewed as negative things, often being associated with serpents, evil magic, death and punishment for breaking laws and traditions [16]. For example, some of the inhabitants in Central Australia believed that a meteor was an omen or spirit of someone that had died far away and was returning home [13].

One of the most interesting meteoric beliefs was that of the Arrernte. They believed that meteors and the like, contained an evil magic known as Arungquilta [15]. This is a magic that could be harnessed in certain ceremonies and was meant to inflict harm or death (usually upon someone that broke a taboo, such as infidelity) [15]. Other sources of this evil magic of Arungquilta include toadstools and mushrooms, many of which are known to be poisonous [16].

In order to harness Arungquilta, certain rituals were performed by the Arrernte to cause death through magical means. One such ritual involved a person chanting a spell over a bone or stick, before throwing the object as far as they could in the direction of the intended victim [28], [27]. Afterwards, the person that performed the spell would look to the sky, and if they saw a meteor, it was believed to represent the spirit of the person they had killed [28], [27]. A similar ritual was designed to punish a man for stealing another man's wife. This involved throwing a spear imbued with Arungquilta magic in the direction of the target's house [28], [27]. If the ritualist observed a fireball streaking across the sky, it meant the dark magic had located the target [28], [27]. Next they would wait and listen for a "thunderous boom," likely an air burst caused by that meteor, which signalled the man was dead [28], [27]. These along with other rituals seem to describe single events, where the rare appearance of a comet or meteor air burst event was coincidental to the ritual, and then explained by the ritual itself [15].

In Luritja culture, meteorites they found were valued and believed to be sacred. Meteorites are said to come from celestial deities, known as Walanari, who would throw them like stones down to the Earth as punishment [24]. Some even say these "glowing stones" have killed people in the past. For example, when a meteorite was thrown onto one of their campsites, punishing a man for his secrets [24]. Any meteorites the Lurijta were able to find were later made into tools, used for both punishment and approval of tribe members [24].

Not all beliefs surrounding meteors are negative, for example the Yarrungkanyi and Warlpiri people of the Northern Territory speak of dreaming men travelling through the sky as falling stars [15]. These stars would land in a certain area and bring dreams to all of the people sleeping nearby [15]. Another example, which might be the most incredible of all, is that many of the tribes in Northern Australia have creation stories involving comet debris (AKA meteors) bringing life to the planet Earth [15]. This is remarkably consistent with Western science's current best theory surrounding the beginning of life, which proposes amino acids forming the basis of life were first transported to Earth by a comet [14]. One account from a member of the Arrente states that the first human couple originated from a pair of stones that were thrown down to Earth by a "great old man" [26]. They describe how a meteor named Kulu landed on Earth, split into three pieces and brought life to the planet [26]. Regardless of whether the people had evidence that caused them to believe this, or if it was a pure prediction, it is quite incredible that the forefront of science is talking about the same theory so many years later.

Overall, meteors, meteorites and their associated phenomena are a valued and important part of Australian Indigenous cultures. This is especially true with the Arrernte and Luritja tribes of Central Australia, and the Yarrungkanyi and Warlpiri tribes of Northern Australia. Beliefs vary greatly between people, ranging from evil spirits inhabiting meteorites that can be harnessed to kill enemies, to cometary meteorites bringing life to Earth. Meteoric phenomena are truly embedded deep within these cultures and their belief systems.

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