THE POTENTIAL OF GEOENGINEERING: EXPLORING THE EFFECT OF PARTICULATES ON CLOUD FORMATION

Scientific research question: To what extent does the addition of particles affect the rate of cloud formation?

ABSTRACT:

This study constructed a cloud chamber to carry out experiments utilising smoke particulates and regression analysis to compare differences between cloud seeding and control experiments. Cloud formation occurs as water vapour condenses to liquid droplets, which releases heat into the chamber. The loss of heat to the surrounding environment outside the cloud chamber was experimentally characterised for both the control and trial experiments. From this, the rate of cloud formation was calculated at 9.96×10^{-6}g $g^{-1}K^{-1}$ which is equivalent to ~0.00001 grams of water per gram of air condensing each second on the smoke nuclei to form a cloud. Thus, this study warrants further research regarding the most effective particulates for cloud seeding and their potential practical applications.

RESULTS

Regression analysis was used to quantify the linear observations in this study. Variations of the Clapeyron equation were also used to characterise the behaviour of the cloud to demonstrate differences between the control and trial experiment (Sun et al., 2022)

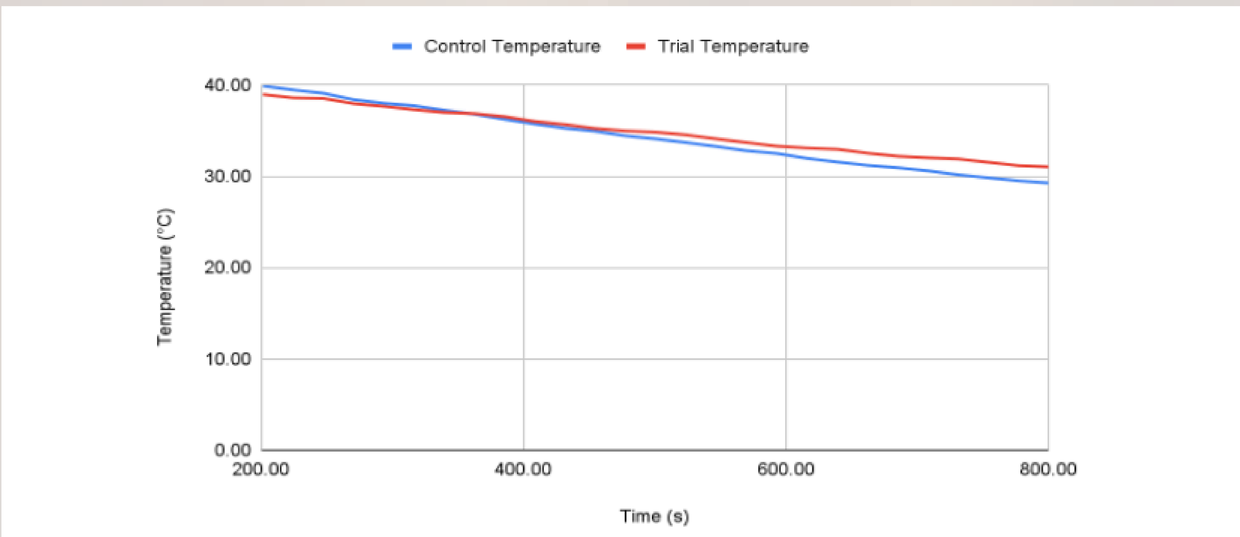


Figure 1: Data set area of interest after cloud has formed and the set-up is cooling down.

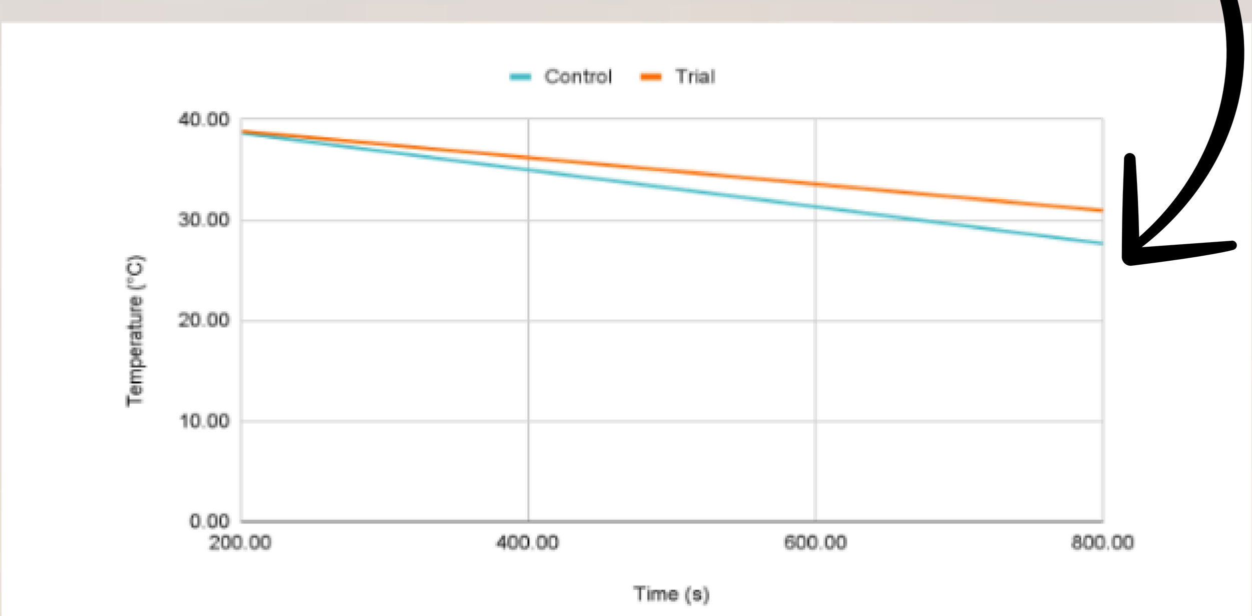


Figure 2: Model dataset from regression analysis of Control and Trial experiments covering region of interest from 200 to 800 seconds.

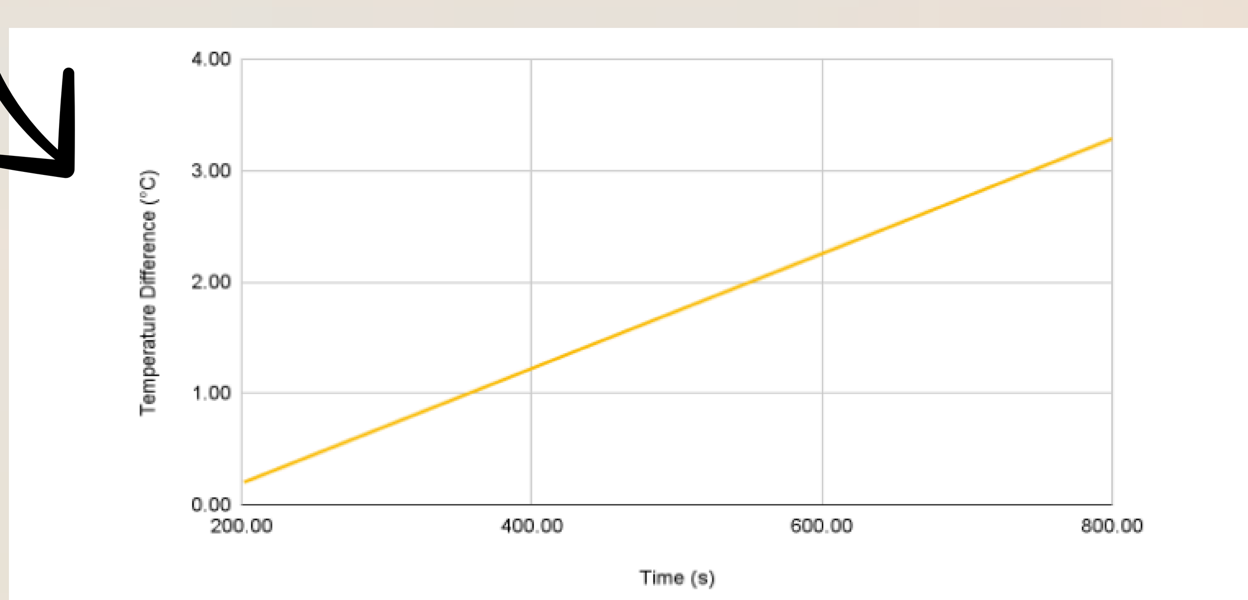


Figure 3: The difference between the Model dataset of Control and Trial experiments covering region of interest from 200 to 800 seconds.

- Three temperature probes were inserted into the side wall of the sealed chamber that were connected to the Data Harvest Vision data logger where it was set to record a 15 minute experiment.
- An aluminium tray containing hot water and ice packs were added to the chamber after 60 seconds.
- For the trial experiment, smoke particles in the form of four lit matches that were just extinguished were added to the container 180 seconds into the experiment to provide particulates to promote cloud formation, and the temperature within the chamber was monitored for the remaining 12 minutes of the experiment.
- From 180 seconds the air parcel within the chamber has mixed sufficiently and the matches are added.
- Figure 1 shows the temperature change after 180 seconds as the heat is lost to the environment

- The data from the first figure underwent regression data analysis to get the intercept and gradient of the lines. The R squared value and p value for both the control and trial experiments are within the range where it is acceptable to assume the models fit the data.
- A high degree of fit was found for both experiments as indicated by both R squared values being 0.99. Further, the P value of each regression model is <<0.05 which provides strong evidence that each experiment is well described by the linear regression model fitted to each data set.

- The difference model was established by finding the difference in temperature predicted by the control and trial models.
- The graphs of the area of interest (200 to 800 seconds) show a small difference in gradient between the two experiments, which was shown through the regression analysis of these data sets, where there was a difference of 0.004 °C s^{-1} between the two gradients. The models created based on the regression analysis further show this effect, with the difference of the two models reaching a maximum of 3.29 °C at 800.64 seconds. The rate of change of temperature over time (dT/dt) was found through linear regression of the difference between the models (Figure 3), and a simplified version of Sun et al. (2022) climate model was used to find the rate at which dqw/dt changes as a cloud droplets forms inside the air parcel. The result from this equation is 9.96×10^{-6}g $g^{-1}K^{-1}$which acts as a measure of how fast droplets are forming. This is equivalent to a rate of ~0.00001 grams per gram of air per second which demonstrates the effectiveness of smoke particulates to seed clouds.

HYPOTHESIS

H_0: The addition of particulates does not affect the rate of water droplet condensation in a cloud.

H_A: The addition of particulates does affect the rate of water droplet condensation in a cloud.

LITERATURE REVIEW

In the last few years, there has been a rising interest in the feasibility to seed clouds with particulates such as salt as a way to combat climate change. Clouds form as a result of decreasing pressure at high altitudes in the atmosphere, leading to an expansion of the space between the gas molecules found in parcels of air. With this expansion as pressure decreases, gas molecules in air will transfer thermal energy into kinetic energy, the resulting decrease in temperature of the parcel of air causes the saturation vapour pressure to also decrease. Once saturation is reached, water vapour will start to condense onto any airborne particulates present in the parcel, leading to the formations of clouds (Yale University, 2023). Clouds have the potential to beneficially decrease the temperature of the earth by reflecting energy in the form of sunlight back out into space.

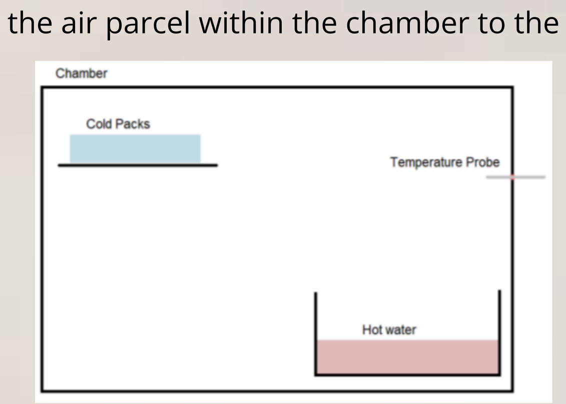
A 2023 study by Diamond modelled the changes in energy reaching the ocean by way of Infrared Aerosol-Cloud Interaction (IRFACI) due to the changes in ship track density after fuel regulation changes in 2020. It was shown that there was a 1 watt per square metre increase in energy reaching the ocean (Diamond, 2023). Ironically, the reduction in particulate emissions, as a result of these tightened regulations, indirectly led to the formation of less clouds and resulted in more energy entering the ocean.

Cloud microphysics

Clouds are made of air that contains water in the form of vapour which, when above saturation and in contact with condensation nuclei, condense into liquids or solids. This air is described as a parcel for experiments and models, meaning it has a definite size and retains its shape and general characteristics as it moves through the atmosphere. The assumptions for these pockets of air are that the amount of moisture is constant, there is no outside source of heat added to the parcel, the temperature of an unsaturated parcel will cool at a fixed rate of 9.8°C per 1000 metres until the relative humidity becomes 100% at which point the saturated cloud will cool slower (National Oceanic and Atmospheric Administration, 2023).

METHODOLOGY

A simplified set-up of a cloud chamber (Figure 3b) was constructed with hot water at the bottom and ice packs at the top of the 25L plastic storage container. Holes were drilled inside the 150x200x200mm tank on the sides of the tank to provide access ports, fit the temperature probes and to create a shelf made from wire rods for the ice packs to be suspended at the top of the chamber. Water was heated with a kettle to boiling point and 600 mL was poured into an aluminium tray to be positioned in the base of the tank to saturate the air parcel within the tank. When preparing to record the temperature changes in the cloud chamber during the experiment, three temperature probes were inserted into the side wall of the sealed chamber that were connected to the Data Harvest Vision data logger where it was set to record a 15 minute experiment. The aluminium tray containing hot water and the ice packs were added to the chamber after 60 seconds of recording temperature data to ensure that the temperature probes were correctly reporting data. From 180 seconds the air parcel within the chamber has mixed sufficiently due to the temperature differential from the hot water and ice packs so that the temperature within the chamber peaks at ~ 40°C. The control experiment condition was recorded from this point for the remaining 12 minutes of the experiment to find the rate that heat is lost from the air parcel within the chamber to the surrounding environment.



Experimental setup used in this investigation.

Formation of a cloud within the chamber during the trial experiment.

DISCUSSION

Geoengineering, both incidentally and intentionally, can have major effects on the environment and should be studied to understand human impacts and potential ways of managing climate change in the future. This study successfully demonstrated that smoke particles affect the rate of water droplet condensation, as a gradient difference was observed and the mixing ratio of the cloud was found to be 9.96×10^{-6} g $g^{-1}K^{-1}$, therefore, the null hypothesis can be rejected. The difference between the two data sets was experimentally confirmed utilising a physical model of cloud parcels and regression analysis which showed both lines had an R squared value of 0.99. The strong agreement with the regression models in all cases highlights the high degree of internal reliability and value present in this investigation

CONCLUSION

This study demonstrated the effectiveness of cloud seeding with smoke particulates, resulting in a 0.004 °C s^{-1}difference in gradient from the control experiment. Regression analysis was used to find this difference and create models of both the control and trial experiments. Through the use of the Clapeyron equation (Stevens & Bony, 2013) and its derivatives (Sun et al., 2022), the increased heat in the system is characterised as the result of ~0.00001 grams of water condensing each second on the smoke nuclei to form a cloud. The null hypothesis has been rejected as the P value for the models created were <<0.05, meaning the difference in gradient is statistically significant. This study highlights a highly effective methodology for demonstrating and exploring cloud microphysics concepts in a high school setting.

REFERENCES

- Camuffo, D. (2014, January 1). Chapter 2A - Theoretical Grounds for Humidity (D. Camuffo, Ed.). ScienceDirect; Elsevier. https://www.sciencedirect.com/science/article/abs/pii/B9780444632968000020
- Diamond, M. (2023). Detection of large-scale cloud microphysical changes within a major shipping corridor after implementation of the International Maritime Organization 2020 fuel sulfur regulations. Atmospheric Chemistry and Physics, 23(14), 8259–8269. https://doi.org/10.5194/acp-23-8259-2023
- Engineers Edge. (2014, May 1). Water - Density Viscosity Specific Weight | Engineers Edge | www.engineersedge.com. Engineersedge.com. https://www.engineersedge.com/physics/water__density_viscosity_specific_weight_13146.htm
- Goti, R., Thakore, B., & Srivastava, R. (2007). Measurement of Cloud Properties Using a Self- Designed Cloud Chamber. https://arxiv.org/ftp/arxiv/papers/2008/2008.00417.pdf
- Griffin, R. J. (2013). The Sources and Impacts of Tropospheric Particulate Matter | Learn Science at Scitable. Www.nature.com. https://www.nature.com/scitable/knowledge/library/the-sources-and-impacts-of-tropospheric-particulate-102760478/
- NASA Science Editorial Team. (2018, September 24). NASA study untangles smoke, pollution effects on clouds. Science.nasa.gov. https://science.nasa.gov/earth/earth-atmosphere/nasa-study-untangles-smoke-pollution-effects-on-clouds/
- National Oceanic and Atmospheric Administration. (2023). Parcel Theory. Noaa.gov. https://www.noaa.gov/jetstream/upperair/parcel-theory#:~:text=The%20temperature%20of%20any%20parcel
- Stevens, B., & Bony, S. (2013, June). Water in the Atmosphere. Physics Today. https://www.wcrp-climate.org/images/documents/grand_challenges/GC4_clouds_StevensBony_PT_2013.pdf
- Sun, J., Zhang, J., Deng, W., Hu, W., & Wang, Y. (2022, September 1). Cloud Droplet Nucleation Simulation and Parameterization. AMS Journals. https://journals.ametsoc.org/configurable/content/journals$002fatsc$002f79$002f9$002fJAS-D-22-0010.1.xml?t:ac=journals%24002fatsc%24002f79%24002f9%24002fJAS-D-22-0010.1.xml&tab_body=fulltext-display
- Travis, D. J., Carleton, A. M., & Lauritsen, R. G. (2002). Contrails reduce daily temperature range. Nature, 418(6898), 601–601. https://doi.org/10.1038/418601a
- Wallace, J. M., & Hobbs, P. V. (2006, January 1). 3 - Atmospheric Thermodynamics (J. M. Wallace & P. V. Hobbs, Eds.). ScienceDirect; Academic Press. https://www.sciencedirect.com/science/article/abs/pii/B9780127329512500089
- Yale University . (2024). GG 140 - Lecture 11 - Clouds and Precipitation (Cloud Chamber Experiment) | Open Yale Courses. Yale.edu. https://oyc.yale.edu/geology-and-geophysics/gg-140/lecture-11
- Zhu, H. X., Li, X. D., & Yang, R. J. (2016). A novel catalyst of warm-cloud seeding to enhance precipitation. IOP Conference Series: Materials Science and Engineering, 137(1), 012002. https://doi.org/10.1088/1757-899x/137/1/012002