MODIFYING TROPICAL CYCLONES BY EXPLOITING THEIR NEWLY DISCOVERED VULNERABILITY

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Article Highlights:

- Tropical cyclones are the world's most destructive natural phenomena yet there is currently no plan anywhere to get them under control.
- For the first time this paper reveals why all previous attempts at controlling tropical cyclones, hurricanes and typhoons, failed.
- For the first time, this paper discloses the Achilles Heel of tropical cyclones--a weakness that can be used to tame them.
- Using a fundamental precept of physics, the paper proposes a novel way to attack this cyclo-vulnerability so as to safely control them.

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Abstract

In the past fifty years, 370 tropical cyclones (TCs) (including hurricanes and typhoons) made landfall across the world averaging four billion U.S. dollars per storm in damages. Those 1.5 trillion dollars represent more destruction than all the world's natural disasters combined, yet there is no specific plan on the horizon to get them under control. This study set out to understand why the science of meteorology, tasked with understanding the physics of these phenomena, has invested so much attention in predicting them and so little in interdicting them. To do that the history of tropical cyclone modification was reviewed including the major theories it has relied upon, all the failed attempts, and the reasons for those failures. That brought to view the Achilles Heel of a tropical cyclone, a cyclo-vulnerability, which in turn suggested a procedure that is able to modify them by attacking them at their weakest point. This is a procedure based on sound physics principles, measurable scientific data, and real-world observation. For the first time it is possible to get these murderous storms under control.

1. Introduction

Why do we permit tropical cyclones (TCs) to continue running roughshod over so much of the world? TC's affect many geographic areas in both the northern and southern hemispheres. Since 1970, 370 TCs caused $1.5 trillion dollars in damage and were responsible for over 780,000 deaths. (WMO 2025). What's worse is that they are growing ever more numerous and ever more powerful. (EPA 2025)

Whereas in days gone by, mankind relied on entities such as Zeus (Greek) and China's Dragon King for help in controlling the weather, today we look to meteorologists. Meteorology (which includes atmospheric physics, the study of the inner workings and physical processes of weather events) is the science that's meant to control these TCs, yet these days majorly confines itself with forecasting them. Technological advances now allow the National Hurricane Center to issue accurate 5-day-advance hurricane warnings (NOAA 2025b) and its 2024 record was the most accurate on record. (Vagasky) Such predictions allow for better storm preparation at the same time obviating unnecessary evacuations, but are a far cry from getting TCs under control.

Why haven't we done better at mitigating the destructive effects of tropical cyclones? This paper answers that question. To do that we cover the history of TC modification including the major theories it has relied upon, its failures, and the reasons for those failures; and, after unveiling the previously unknown Achilles Heel of TCs, introduce a procedure that is able to get them under control.

2. Weather Modification / TC Modification

2.1 Aerosol Cloud Interaction

Man's recorded history has seen numerous attempts at moderating the weather. In this paper we are interested in only one of these quests: stopping tropical cyclones. A tropical cyclone (TC) is an intense circular storm that originates over warm tropical oceans and is characterized by low atmospheric pressure, high winds, and heavy rain. It is known as a hurricane or typhoon (depending on the region where it occurs) when its winds exceed 119 km per hour. (Encyclopedia Brittanica). Realizing the destructive effects of TCs, many meteorologists have gone full-throttle to curb TC genesis and growth. The weapon of choice has been the Aerosol. Aerosols are any small particles that exist within a volume of air, but in this case refers to fine particles which are intentionally placed in the atmosphere, either by ground operations or from aircraft, for the purpose of changing the function or structure of a rain cloud or tropical cyclone. Rain-making and TC modification became inextricably bound when three scientists in a GE laboratory in 1946 discovered a way to use aerosols to encourage certain types of clouds to release their water in the form of rain or snow. When aerosols are used to seed clouds for the purpose of either making rain or stopping a TC, the process is called aerosol-cloud interactions (ACI) otherwise known as glaciogenesis, by which ice formation is initiated in supercooled clouds resulting in the growth of ice crystals of a size heavy enough to eventually fall to the ground as rain or snow. Space does not permit us to cover either the rainmaking side of ACI or to review the colorful history of attempts to use it for TC Modification from its simple origins in that laboratory in Schenectady New York to the clouds above the Asian battlefields of the Vietnam War, other than to say that it was mostly based on the research of six U.S. military projects (Cirrus, Scud, Cyclops, Baton, StormFury, and Popeye) conducted between 1943-1983. In the end, although there were some positive results regarding ACI's ability to create precipitation, none of the aforementioned projects demonstrated any success at modifying either the genesis, intensity, or direction of a TC. (Willoughby 1985) (StormFury 2025) (Byers 1974) (Cummins 2018) (Office of the Historian 1967) (Frisinge 1983).

2.2 Other attempts at TC modification

Once the U.S. Military stopped funding these projects in the late 1980s, other meteorologists, dissatisfied with ACI's lack of results at modifying TCs, forged ahead in a different direction. They thought they had a game changer.

One of the best-documented facts about TCs is that warm water must exist under them in order for them to come into existence or survive. When that water cools, even if only a few degrees, the TC can no longer maintain its existence. (NOAA 2025e). In 2007, engineer Stephen Salter, with the support of Bill Gates, patented a device he hoped would weaken hurricanes by cooling the water below them. He'd computed that just 2 or 3 degrees of cooling would be enough to decrease a hurricane's power, but his approach was incapable of reducing the water temperature sufficiently. (Mims 2009) (Benzinga 2012) (Microsoft News 2012) (Emanuel-5 2009) Sometime later Gates patented a modified version that had the surface waters cooled via tubes connected to a line of barges--also found unworkable. (US Patent 2009/0173386A1) A scheme, put forward by the University of Manchester's John Latham and colleagues (including Salter), visualized a fleet of unmanned ships spraying seawater into the atmosphere in hopes of cooling the ocean waters. (Latham) Two Chinese endeavors followed in 2019. One from Shanghai's Donghua University (China Patent Application No. CN201811520085.0) required the construction of a fleet of artificial islands to interfere with the wind shear at the ocean surface. Another, from the south of China, (China Patent Application No. CN201811366714.9) built upon Latham's design to cool the ocean water by using unmanned aircraft to seed a cyclone's predicted path. Although cooling the waters below a TC would have been effective, it was not workable. Too much water would have had to be cooled and whatever method was used for the cooling would have had to simultaneously contend with the huge waves, winds, and lightning bolts of an ongoing hurricane

2.3 Aerosol-Radiation Interaction (ARI)

In 2023, in response to worsening TC disaster risk, a detailed analysis of potential TC-interventions was published as "The Feasibility and Governance of Cyclone Interventions." (Miller 2023). The paper reviewed numerous recent studies (including Tran1 2025 and Tran2 2025) into a different kind of TC intervention called aerosol-radiation interaction (ARI). ARI is a hybrid approach. It uses a different kind of aerosol (one capable of scattering and absorbing sunlight in order to reduce the amount of solar radiation reaching the earth's surface) but it is still working towards modifying convection to, in turn, modify the temperature of the ocean beneath the TC. (Bellouin 2022) (Kuniyal 2019) The Miller study determined that although success at cooling the ocean under a TC was unlikely under realistic conditions of atmosphere and ocean, the deliberate use of aerosols was still the most effective potential strategy for interdicting TCs. (Miller 2023)

3. The Tropical Cyclone: where does its energy come from?

3.1 The red herring in the waters below a TC

A red herring is not just a fish. It can also be defined as a clue or piece of information that is misleading or at least distracting to the matter at hand, and there are plenty of such fishes in the warm waters beneath tropical cyclones.

Meteorological literature is full of statements that tell us that "*the energy of a tropical cyclone comes from the heat in the ocean water below the storm" and "* Warm water powers the tropical cyclone and is the most important factor in its development.″ (NOAA 2024b) (NASA 2025a) (climate.gov 2010) (Zhang 2008) (Thankaswamy 2023) (Holton 2004) (Cushman-Roisin 1994). Although both misleading and distractive, the popularity of this idea is understandable as it is supported by the well-documented fact from the National Weather Service (NWS) and others that a necessary condition for a tropical cyclone to develop or sustain itself is that the ocean water temperature beneath a storm must exceed 27º C. Though correct, this NWS datum is an incomplete explanation that does not describe how a hurricane either forms or grows. It provides only part of the picture. An example is Figure 1 from (Miller 2023) which is accompanied by this explanation: "The radial circulation takes warm moist air from the ocean surface, transports it to the center of the cyclone in the lower atmosphere, elevates it up the eyewall and transports it outward in the upper atmosphere." The datum is correct, but it hides the key mechanism creating the underlying energy: *the poles*.

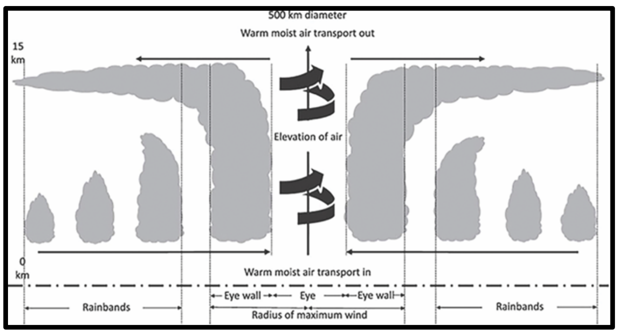

Fig 1. The simplified structure of a tropical cyclone in the Northern hemisphere (Miller 2023). Diagram is correct in every respect, but omits the poles that are the basis of a TC's energy.

3.2 The Role of the Poles

All energy is created through the mechanism of a dichotomy where the energy flows between two poles. In physics, a dichotomy is a pair of opposites which when interplayed cause action. All energy production comes about from this mechanism. Maxwell's equations prove this for both electricity and magnetism. (Glushakow 2022) (ICECE 2021) Common examples are shown in Figure 2. Think of electricity's positive/negative or the plus and minus of magnetism. The principle can be seen clearly in the operation of a battery. The energy flows between the two poles. There is no such thing as a *single-pole-battery*.

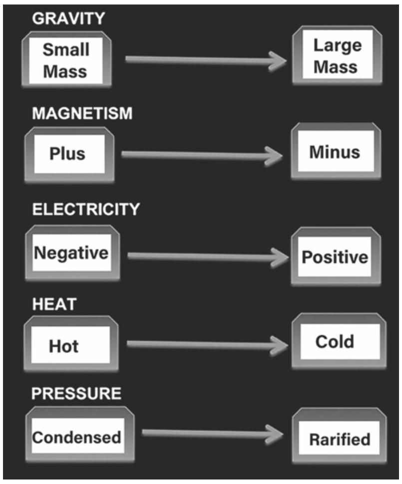

Fig. 2 shows common dichotomies known to produce energy. Diagram from *Energy Miracles: The Global Warming Backup Plan*, Ch. 6.

Meteorologists fully acknowledge this mechanism in the creation of a sea breeze, a local wind that blows from sea to shore, the result of a temperature differential when the sea surface (Pole 1) is colder than the adjacent land (Pole 2). (AMS 2025).

To fully convey a conceptual understanding of tropical cyclones, a scientific definition must include how it comes into being, changes, and then ceases to exist. Kerry Emanuel's "Theory of Hurricanes" released in 1991 is one that does that. His landmark definition that tropical cyclones are essentially "heat engines powered by the temperature disequilibrium between the sea surface (Pole 1) and the troposphere (Pole 2)," (Emanuel-1 1985) (Emanuel-4 1991), remains broadly accepted. He computed it could require as little as 2.5 Celsius degrees of cooling to reverse the equilibrium between the ocean and the tropopause, either making hurricanes more numerous or canceling them out altogether. Ozawa's work on the thermodynamics of cyclones reinforced the concept: "A tropical cyclone is a large-scale convection system driven by a temperature contrast between the hot tropical sea surface (Pole 1) and the cold top of the troposphere (Pole 2)." (Ozawa 2014) Figure 3 shows the simplicity of this concept.

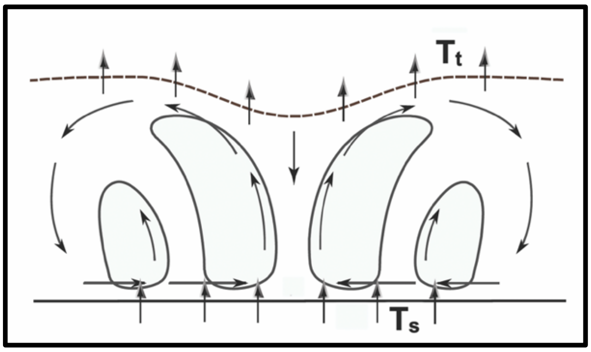

Fig. 3. A schematic cross section of a tropical cyclone. The air is heated at the sea surface with Temperature T_s (Pole 1) and cooled at the top of the troposphere (Pole 2) with Temperature T_t. (Ozawa 2014)

Figure 4 is a more explicit illustration a TC heat engine converting a temperature differential to mechanical energy and producing practical work through physical motion. It operates between the hot reservoir at the ocean surface that provides the heat which is then brought to a lower temperature after flowing into the cold reservoir of the tropopause. As a byproduct, that energy creates the force that amplifies the vorticity of TC winds. In 2008 a workshop sponsored by the U.S. Dept of Homeland Security

(DHS) and NOAA heard a presentation that proposed to use aerosols in the atmosphere above a hurricane that would absorb solar radiation and warm up selective points above a hurricane in order to reduce the differential between the hot and cold reservoirs of the hurricane, thus weakening it. (Launder 2015) (Alamaro 2009) (Hoffman 2005). The idea was never pursued due to lack of funding. (Hoffman, R.N. Personal communication to author, 2025) More recently ANU scientists confirmed the sense of this approach: "Cyclones are energized from the heat imbalance between the upper and lower parts of the atmosphere." (Miller 2023).

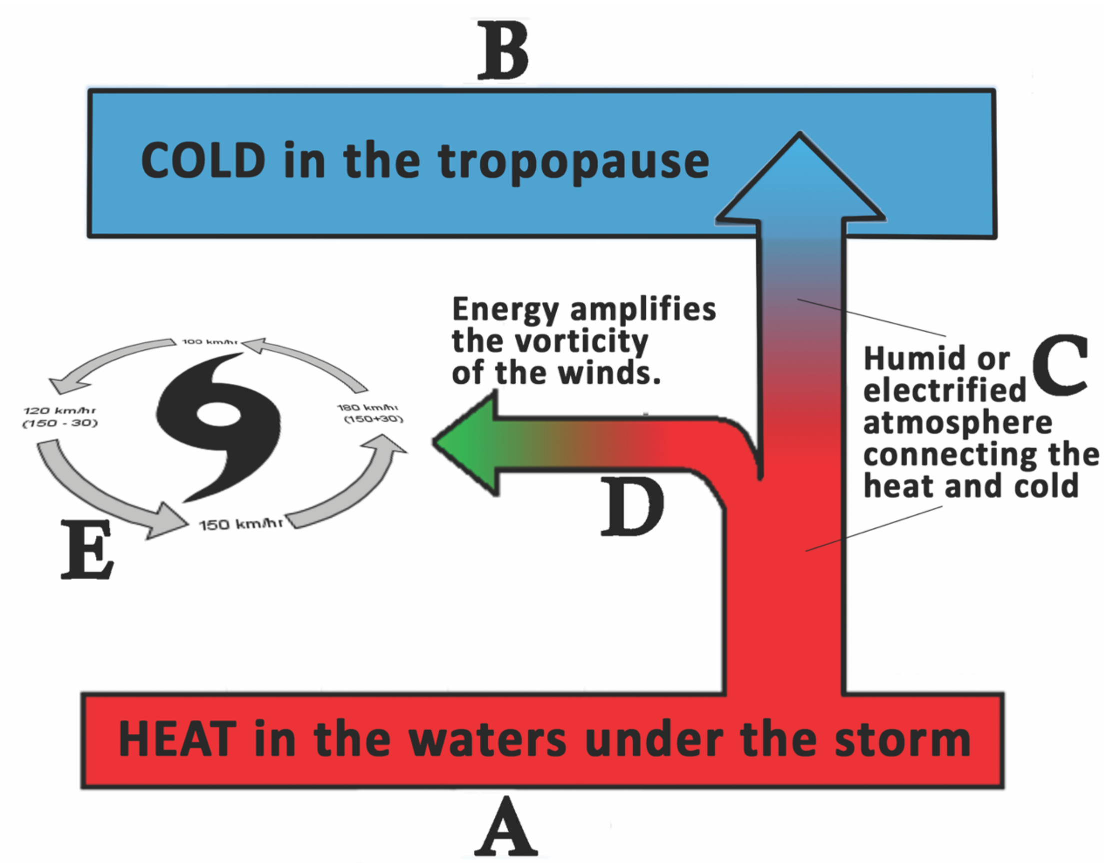

Fig. 4. Tropical Cyclone Heat Engine Structure. Energy created between **(A)** the heat in the waters under the storm--Pole 1-- and **(B)** the cold of the tropopause--Pole 2-- creates **(D)** the work that **(E)** amplifies the TC winds. Note: **(C)** is the connection between the heat and the cold that must be interrupted to de-intensify a TC.

Although this principle is generally understood to have applicability to tropical cyclones, the point being made here is that it has far more importance than has heretofore been ascribed. With regard to energy, there is never just one pole involved. If a TC is "fueled by heat energy from the ocean," (NOAA 2024b) it is only because of the interplay between that ocean heat and the relatively much colder condition above the storm system.

To emphasize this basic mechanism, we suggest the following definition: *(*See Figure 5.)

A tropical cyclone is a violent tropical storm identified by amplified wind vorticity caused by the interaction of warm ocean waters with the cold temperature of the tropopause when these two poles are connected by sometimes-electrified but always moist conductive particles.

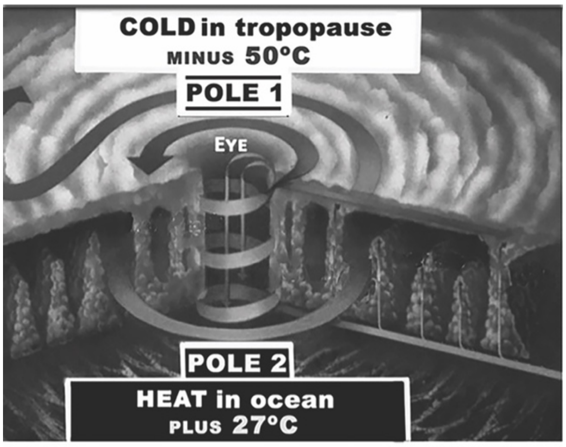

Fig. 5. The Two Poles are the components that energize a tropical cyclone, i.e. generate its energy. Hurricane structure from NOAA.

TC modification experiments based on ACI all proceeded from the assumption that modifying tropical cyclones depended on making a change in the convective conditions of clouds outside the TC's eye. (National Academy of Sciences 1959) The working hypothesis was that the area around the TC's eye was unstable with the clouds full of supercooled water and seeding them would trigger that instability and cause a change in convection and an outward migration of the eyewall. (Simpson 1962) They would have done far better had they realized that convection was merely a secondary process and it was the heat differential between the two poles which they needed to address.

4. The Achilles Heel of a Tropical Cyclone

2024 highlighted a TC vulnerability that gives us a direct method of controlling them. The Atlantic hurricane season got off to its slowest start in 10 years due to a large stationery **heat dome** over Central America and Mexico. (NASA 2025b) A **heat dome** is a weather phenomenon of extreme heat caused when the lower atmosphere traps hot air at or below an altitude of approximately 9-10 km. (NOAA 2021) Although tough on folks in Mexico and the southern and western U.S, the 2024 heat dome had another effect: it prevented the generation and growth of major tropical cyclones for almost three months during the peak hurricane season between June's Hurricane Beryl and the end of September's Hurricane Helene. (National Hurricane Center 2024) This event highlighted 2 key facts about TCs which are illustrated in Figure 9:

1) In all known cases of a TC, conditions (a) and (b) below have both been present:

(a) The tropopause temp to which TC is connected is -50ºC or colder

(b) The ocean water temp to which TC is connected is +27ºC or warmer

That is a differential of 77 absolute degrees C.

2) Contrariwise, by either cooling the water below the TC or heating the atmosphere above it, that condition is nullified and no new TC will form. (In the event one already has, it will quickly cease to exist.)

Example: Water below a TC cools from +27ºC down to +20ºC. The differential drops 7 degrees from 77 degrees to 70 degrees. No TC is possible.

Example: Atmosphere above the TC warms up from -50ºC to -45ºC. The differential drops 5 degrees from 77 degrees to 72 degrees. No TC is possible.

Example: Atmosphere above the TC becomes colder than -50ºC or water beneath the TC becomes warmer than 27 ºC. In either case the minimum (77-degree) differential is maintained and the TC may even strengthen.

4.1 Attack a TC at its weakest point

Hurricanes are scored into five categories based on their sustained wind speed per the Safir-Simpson Hurricane Scale. The higher the wind speed, the higher the category. Salter and Gates estimated that reducing the temperature differential between the ocean water and the tropopause by just 1 degree C could reduce the force of a hurricane by one level on the hurricane scale: e.g. from Category 4 to Category 3. (Microsoft News). (Launder 2015) computed that from a thermodynamic perspective, a cooling of only 2.5°C of the waters under a TC's eyewall would prevent any increase in energy transfer and even a 1°C cooling under the storm center would have an important influence on the storm’s intensity. (Emanuel-5) suggested that cutting the differential by 4.5 degrees C would totally kill a hurricane. (At the same time, he was skeptical that trying to handle the ocean-water side was workable.) Our conundrum has been how do we use this vital information without joining the caravan of failed attempts at cooling the waters beneath a rampaging TC.

4.2 The other pole

The answer is we look to the other pole--the cold in the tropopause--where the temperature is normally a relatively steady -50ºC within 10 degrees of the equator. (Albert 1958) (NOAA-2024-c) (MeteoSwiss 2024). If we cannot nullify a TC's heat differential by cooling the waters underneath it, why not warm the atmosphere just above it instead? We've seen how heat created by a Heat Dome above potential cyclones interferes with the temperature differential required for a TC to form. Attacked at this vulnerable point, a tropical cyclone is no longer an unstoppable force of nature. The 2024 heat dome shows that TCs can be weakened or destroyed by heating the area ABOVE the storm. As shown in Figure 6, this is the Achilles Heel of a TC.

Note: Temperature measurements made with different instruments at different altitudes and latitudes and under different conditions produce a range of results. These are all valid candidates for an "actual" temperature of the tropopause or that of the TC eyewalls connected to it. A variation here of 15-20% makes no difference whatsoever to the thesis of this paper. For purposes of illustration, we have used -50ºC as an average stable tropopause point with which to compare the +27 deg C (far easier to measure) temperature of the ocean water.

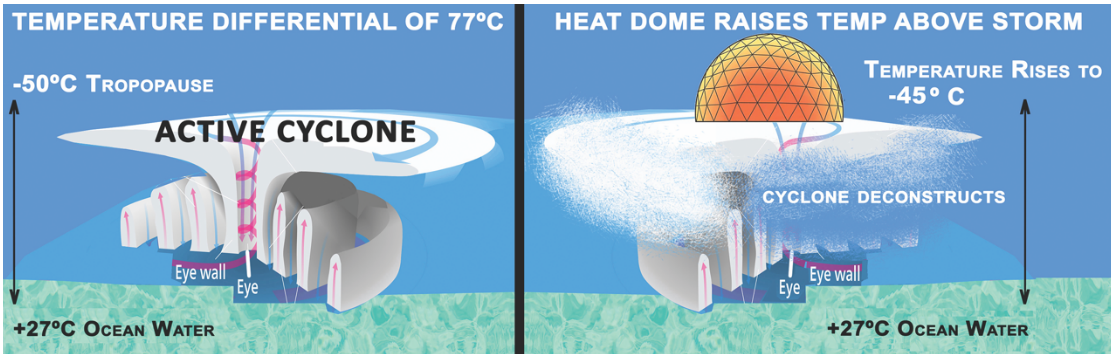

Figure 6. The Achilles Heel of a cyclone. **Left frame** shows that in every case known, for a TC to form or persist, a differential of at least 77 degrees C has existed between the tropopause cold and the heat in the ocean waters below the storm. **Right frame** shows when this is violated, such as when a heat dome raises the temperature in the atmosphere above a TC, a TC can no longer survive. Hurricane structure from NOAA.

5. The Solution to TC Modification: An Artificial Heat Dome

To prevent a TC from forming (or to reduce its power if already formed) we investigated whether a heat dome could be reproduced artificially on a smaller scale, limited to the area above a forming tropical cyclone. A mixture of solar radiation and common sand provides one avenue. By seeding the atmosphere above the cyclone's eye with inexpensive silica sand which absorbs energy directly from the sun and turns that energy into heat, we can increase the temperature in the area above the storm enough to disrupt the connection between the heat in the warm waters below and the cold in the atmosphere above the storm. Cloud seeding is a thriving industry, but its common usage has been to use chemicals that *cool* clouds and cause precipitation. The opposite is required to control a tropical cyclone: something that WARMS.

There has been opposition to cloud seeding over safety concerns at dumping poisonous chemicals over populated areas. Such objections do not apply to our cyclone control operation because cyclones form over water, not populated areas, and, more importantly, we are seeding the clouds with harmless silica sand, whose only property is to directly absorb energy from the sun and temporarily warm up a few square kilometers of atmosphere over a nascent cyclone. Silica (SiO_2) is composed of elemental silicon and oxygen, the two most abundant elements found in Earth's crust. (Callister 2014) The insertion of sand/dust into the atmosphere has been a common occurrence on planet Earth for many thousands of years. A single sandstorm in northern Africa lasting only five days puts more than **20 million metric tons** of sand/dust particles into the atmosphere. (Bou Karam 2010) That is many orders of magnitude more sand than would ever be needed for cyclone control and once the job is complete with a cyclone under control, the sand particles drop harmlessly into the sea.

5.1. Solar Radiation

Although the sun emits radiation over the entire electromagnetic spectrum, Figure 7 shows that almost all of the most dangerous gamma, x-rays, and ultra-violet rays are filtered out by the atmosphere before reaching earth. Gases in Earth’s atmosphere absorb some wavelengths of electromagnetic radiation, but appear transparent to others. The main types of energy that make it all the way to the earth’s surface are visible light, Ultra Violet (UV) and near Infrared Radiation (IR). The two major constituents of the atmosphere, molecular oxygen and nitrogen, are very nearly transparent to that range of wavelengths (Trenberth 2009) (Emanuel 2 1988) (Emanuel 3 1998) filtering out only 3% of those solar wavelengths by either absorption or reflection (Bellouin 2022) and making them the operational parts of the electromagnetic spectrum insofar as heating our planet is concerned. (Chamberlin)

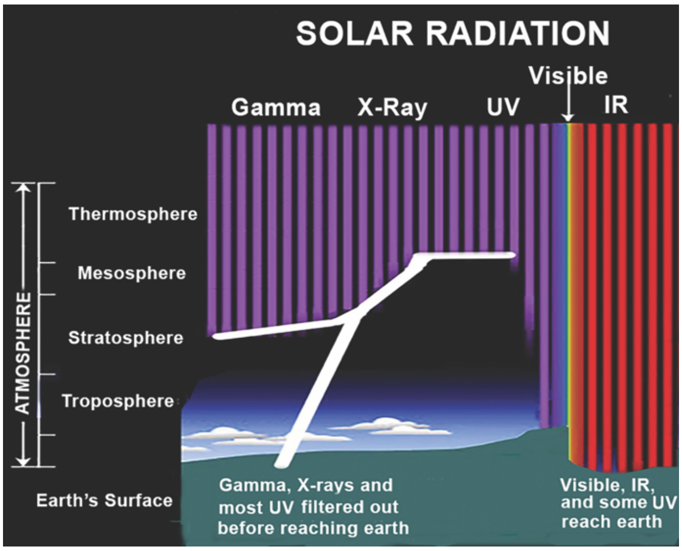

Figure 7. The atmosphere is almost transparent to most radiation in the visible, near-IR and UV range, which sails straight through to the Earth's surface, causing heat. (Extracted from NASA)

When solid material at the earth's surface absorbs this solar energy, it is usually released as heat. Of interest to the subject of cyclone control is that this can also occur in the upper atmosphere. Larger, more solid particles in the upper troposphere and tropopause can and do trap this solar radiation. For example, the fuselage of an airplane flying through the tropopause will become significantly hotter on the side facing the sun than the side facing away from it. One study of the heat produced by this radiation at lower altitudes called it "fierce" and pointed out the main reason most airplane fuselages are painted white is to reduce the heat on the outside surfaces by reflecting solar radiation. (Zhang, Y. 2024) (Kämpf 2015) At altitudes of 8 km external solar radiation can raise the outside temperature of an aircraft from minus 51ºC to minus 1ºC. (ASHRAE 2024). Solar radiation heating is also a major concern for low earth orbit satellites. Studies cite solar radiation-caused temperatures of the outside shells of these vehicles as high as 37^{0}C (Elshaer 2023).

We focus on this fact because in order to weaken a tropical cyclone by disrupting the differential between the heat in the ocean and the cold in the tropopause, we require material that can be placed above the TC that is substantial enough to interact with the sun's energy.

5.2. Sand Qualities

Sand might be thought of as ready-made for this purpose. For one thing, you can find it almost everywhere. Common sand is provenly able to produce heat from the sun up to temperatures of 58ºC and higher. The reason sand makes such a great heat producer is that its most common constituent is silica (silicon dioxide), usually in the form of quartz. Even the most common dry sand, with its high density (1631 kg/m^3), low specific heat (670 J/kg K), and 0.9 emissivity, make it well-suited for absorbing solar radiation and turning it into heat. Its low specific heat means that the sand needs very little energy from the sun to warm up, and its high density allows storage of a large amount of that energy. Its high emissivity indicates an outstanding capability to radiate heat. For use in cyclone control, darker sands are preferable because they are able to absorb more of the sun's rays. Black (carbon) sand is the most highly absorbent component in the atmosphere (Chow 2000) and can be found in dozens of volcanic beaches around the world, where sand can get so hot it will burn your feet. But black sand need not be volcanic--it can also be formed from other minerals.

Some processing can improve sand efficiency, such as mixing it with other substances such as carbon, darkening it, or making other changes that reduce reflection and maximize heat absorption/retention qualities. The National Renewable Energy Laboratory has tested and recommended an inexpensive silica sand as a means of directly storing thermal energy from the sun. (NREL 2020)

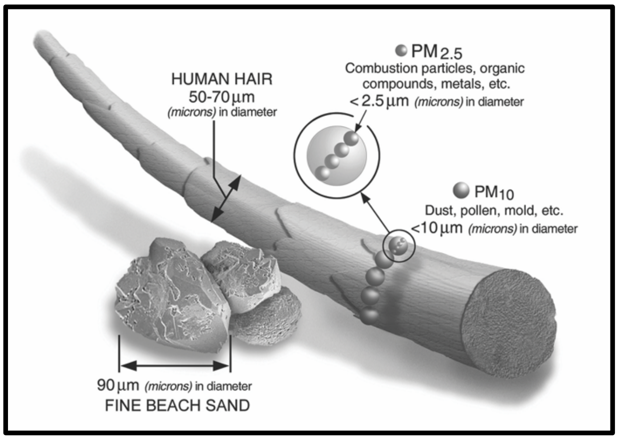

Figure 8. Fine beach sand is 40-50 times larger than harmful $PM_{2.5}$ particulate matter. (image from EPA)

Figure 8 shows that fine beach sand has a diameter of ≅90 microns, far larger than the PM 2.5 (i.e. particulate matter with a diameter of 2.5 microns) that can enter the bloodstream and lead to health issues. (Pan 2021) suggests that an optimal density for cloud seeding over the ocean is 1.5 $\mu g/m^3$ of fine aerosols which is far below the PM 2.5 threshold of 15 $\mu g/m^3$ which the World Health Organization specifies as the level at which health risks become a concern. (WHO 2021)

Studies have shown that sand between 70-100 microns, released below the level of the tropopause can remain aloft between 5 days and 3 weeks (Martel 1970) (Gray 1968) (Frank 1973), sufficient time to handle a single cyclone without posing any threat to human health or the climate. (NOAA 2016) (Schepanski 2018) (NASA 2010). Common sand is able to directly absorb solar radiation, and then convert it to heat as per Stefan Boltzmann's Law.

5.3 Narrowing the Target

It's clear that climate events such as heat domes covering all of the southwestern United States and most of Mexico would take care of our hurricane problems. Seeding 3000 sq km of atmosphere with a layer of sand would also do the trick, but the billion tons of sand it would require makes that impractical. And is needless.

Intense tropical cyclones often produce a cloud-free center with calm winds, called the eye. Surrounding that eye is an **eyewall,** a narrow ≈16 km-thick (≈10-mile) cylindrical barrier which is the most active and energetic part of the eye and the location of its greatest turbulence. The eyewall is also the coldest part of the eye, directly connected to the -50^{0}C temperature of the tropopause. (Meteorological Institute of München 2024) As shown in Figure 9, the temperature of the TC's eyewall is virtually the same as that of the tropopause. (Knapp 2018 NOAA) Further, it is documented that tropospheric heat sources reduce the velocity of the winds at the inner section of the eyewall and modify the storm. (Rozoff 2008)

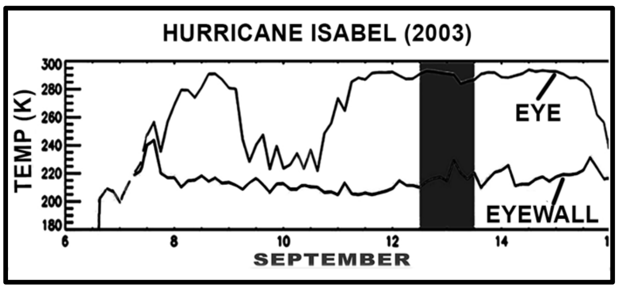

Fig. 9. Eyewall measured temperature (bottom plot) shows a relatively constant temperature of 218º K (≈ minus 55º C), very close to the minus 50º C measured temperature of the tropopause. (Knapp 2018 NOAA)

Eyewalls of fully developed cyclones vary in cross-sectional area from more than 1200 sq km to as small as 5.7 sq km. (Wilma-National Hurricane Center 2025) The area of greatest turbulence and wind is at the surface of the innermost eyewall extending from its surface at the eye to the first “moat” separating the inner section of the eyewall from its outer sections. (Rozoff 2008).

Evidence from visual and radar observations shows that the cirrostratus outflow of the hurricane tends to be fed primarily from a small convective chimney situated near the eye, usually in the right front quadrant in the northern hemisphere, and that most of the mass transported by the lower inflow circulation escapes upward to the outflow layer through a chimney no larger than 16 km x 32 km. This suggests that our seeding target could be confined to an area of 500 sq. km, less than 1% of the surface area ordinarily affected by damaging winds. (Simpson 1962). NASA data shows that in the Northern Hemisphere, where the right front quadrant of the eyewall is usually the most destructive and violent area of the storm, that quadrant, once developed could encompass, a (mean) area of 430 km^2 or more, but potentially, if caught early enough) only 25 km^2 (NASA-2025-b) (See Figure 10.)

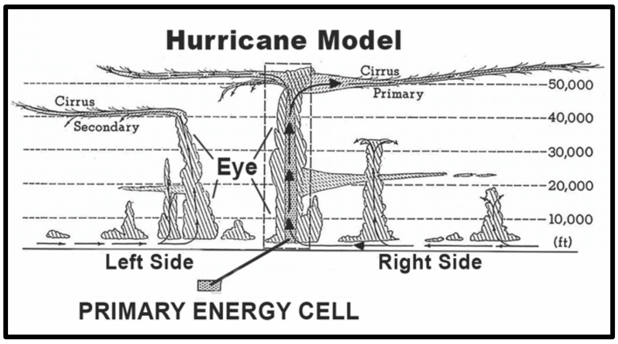

Fig. 10. Target. The primary energy cell (convective chimney) is located in the area enclosed by the broken line. This is the innermost eyewall. This right front quadrant (in the northern hemisphere) is the most energetic and destructive as well as the coldest section of North American storms. Diagram from Simpson.

A NOAA study of every TC from 1982 to 2015 disclosed that only slightly more than half of them developed actual eyes, but those TCs with eyes had average winds three times greater than those without them. (Knapp 2018) What's more, smaller eyes generally mean greater wind turbulence. (Shen). Therefore, our primary targets are **TCs with eyes**. And more specifically (in the northern hemisphere) **the front right quadrant of the eyewall of TCs with eyes.** Using these guidelines halves the number of TCs needing attention, at the same time focuses on the potentially most dangerous storms and reduces the amount of sand needed for those TC's that we choose to interdict.

Thanks to NOAA, we know that for all storms with eyes, the eye will appear within the first 6.6 days of tracking the storm. More significantly, in over 90% of cases, the time from when the storm reaches 34kt (thirty-four nautical miles per hour is the point at which a hurricane is named) to the first spotting of an eye, is less than 4.25 days; and 50% of storms will develop their first eye within 45 hours of being named. (Knapp 2018) This means that in 90% of cases there is a 2-4-day window in which to deal with a newly-birthed cyclone.

5.4 Sand Quantities

Here we shall attempt to estimate the amount of sand required to produce a 10-degree K temperature change somewhere within the column of air covering the right front quadrant of a nascent TC's eyewall. (Gray 1968) (Gray 1974) (Gray 1976) estimated that 94% of the heat absorbed by aerosols is conducted to the air with most of the remaining 6% reabsorbed by the remaining aerosols. As a baseline we've taken three Category 4 and 5 hurricanes with small to medium sized eyes and averaged the areas involved. 2005 Hurricane Wilma (a super typhoon) with winds of 290 km/h at landfall had an eye with a diameter of 3.2 km. (Wilma) 2021 Hurricane Ida (Category 4) had an eye 27 km in diameter. 2024 Milton (one of the most intense hurricanes on record in the Atlantic basin) had an eye diameter of only 5 km. Averaging them gives an eye area of 129 sq km. Assuming an inner eyewall thickness half of the eye's radius, we can compute the average cross-sectional area of the eyewall to be less than 200 sq. km and the area of the right front quadrant to be about 50 sq. km. To cover more bases and provide sufficient latitude, we've allowed for enough sand to cover almost 5 times that area: 225 sq. km.

Assuming we are heating a layer of air between 150hPa and 200hPa over an area of 15km x 15km, the corresponding mass of air would be:

$$250\text{kg/m}^2 \times 10 \text{ deg K} \times 15 \text{ km} \times 15 \text{ km} \quad (1)$$

$$= 562{,}500 \text{ kg } 5.62 \times 10\text{E}4$$

The heat capacity of air at constant temperature is about 1 x 10E3 j/kg/K so the energy required is:

$$1\times 10\text{E}3 \text{ j/kg/K} \times 5.62 \times 10\text{E}4 \text{ kg} \times 10\text{K} \quad (2)$$

$$= 5.6 \times 10\text{E}9 \text{ total joules needed}$$

Assuming the deployed sand will absorb 670J/kg/K, the amount of sand required would be

$$5.6 \times 10\text{E}9 \div 6.7 \times 10\text{E}3 \text{ joules/kg} \quad (3)$$

$$= 8.4 \times 10\text{E}5 \text{ kg} = 840 \text{ metric tons}$$

A Boeing 747 can carry 140 metric tons, so one complete seeding of the target area would require:

$$840 \text{ metric tons} \div 140 \text{ metric tons} \quad (4)$$

= 6 trips by a single Boeing 747

= 3 trips by a pair of Boeing 747s

=2 trips by a trio of Boeing 747s

Sand is cost effective. In these quantities fine sand can be purchased commercially for under $50/ton, but in many countries which sustain regular TC damage there are literally billions of tons of sand on government lands that might be put to use at a cost little more than required to dig it up and transport it to a Cyclone Control Project site. A recent study of the cost of high altitude seeding such as would be required here estimates the cost of handling a single TC to be below ten million U.S. dollars. (Miller 2023). Gray (1976) made similar estimations. But those computations did not take into account the unique benefits and availability of sand, which reduce those estimates by 70% or more.

6. The path forward: Cyclone Control Project

We propose the establishment of a multi-national Cyclone Control Project, consisting of a fleet of specially-equipped cloud-seeding aircraft, based on airfields within range of the most common TC spawning grounds. Adequate stocks of sand will be accumulated prior to hurricane season, at which point the planes will be serviced at night, while, by day, the crews will be on alert for instant deployment when meteorology radar or satellite data detects an eye in a nascent cyclone. During cyclone season, a control center collects and evaluates available meteorological data and coordinates the actions of the fleet. Besides the flight crews, ground personnel, and control office staff, an aerosol unit will see to the availability, storage, and swift reloading of aerosols between runs.

The aim is, to identify cyclone eyes as early in their development as possible and to jump on them without delay as soon as confirmed. Once identified, the hurricane-control process begins with aircraft seeding sand particles over the target area along the track of the storm. The sand is usually distributed above the eyewall's right front quadrant, above the weather, avoiding complications from the dynamic stresses of the storm. The sand is pre-warmed to give it a head start, but once launched, it begins absorbing solar radiation. By the process of convection, the hot sand heats up the atmosphere above the cyclone and perturbs its link to the cold in the tropopause.

The average direct sun exposure in the tropics is 12-14 hours per day in the summer months. The sand seeded into the atmosphere continues to release its absorbed heat for a short while after the sun has set, but sand's low thermal conductivity means it will run out of heat sometime in the darker hours, to be restarted first thing the following sunrise. For 16-18 hours-a-day the sun's energy is being pushed back out into the surrounding atmosphere interfering with the differential between the two poles and so de-energizing the hurricane. Seeding continues until the storm is under control.

It is not the purpose of this unit to eradicate every hurricane; but if it can stamp out just 2 or 3 of the deadliest ones each year it will have achieved a 300:1 ROI for the government or insurance company that backs it.

7. Conclusions

Previous TC modification theories were unprovable, because of the difficulty simulating a TC in a lab and because many of the theories and mathematical simulations being advanced were not grounded on sufficient observation or facts. There is an analysis of this trend in (Glushakow 2022). The Cyclone Control Project proposal in this paper departs from this trend in five respects:

i. It is based on a fundamental principle of physics that meteorologists all know yet have not fully applied, i.e. that all energy derives from a dichotomy, and in particular, a TC's energy is essentially a function of the difference between the heat in the ocean and the cold in the tropopause.

ii. It is based on the most incontrovertible facts about TCs that have been both observed and measured, namely that the water temperature below them must be no colder than 27º C, and that the temperature in the tropopause above them to which they are connected must be no warmer than -50º C.

iii. It is based on ample evidence that when either of the two conditions just specified are nullified, TCs lose their force or disappear.

iv. It is further based on the fact (proven by almost 100 years of failed attempts) that it is a losing proposition to try and cool the waters below a tempestuous hurricane.

v. Lastly, it is based on the fact that aerosols have the ability to replicate the actions of a heat dome by absorbing or scattering solar radiation and thereby heating up the atmosphere above a TC.

The Cyclone Control Project is a localized operation having no effect on the earth's climate or on rainfall or on the direction of a hurricane. Its single effect: as the cold in a limited area above a TC is warmed, the TC's energy is gradually siphoned out until it shuts down.

For the first time, using the above principles that identify and attack the Achilles Heel of a tropical cyclone, we have a procedure that can bring hurricanes and typhoons under control. We emphasize the use of sand here because it fits the chemical bill, is cheap and ubiquitous, but any method or material capable of using the sun's radiation to produce heat in the upper troposphere above a TC will mitigate the planet's problem with them. Tropical cyclones can be controlled and herein is a way to do it.

References

Alamaro, M., My Journey to Engineer the Weather, Infinite Connection News 2009 https://web.archive.org/web/20090820024920/https://alum.mit.edu/news/WhatMatters/Archive/200906

Albert, E.G., A Case Study of the Tropopause, Scientific Report No. 6, New York University College of Engineering Research Division, AF 19(604)-1958

AMS American Meteorological Society, AMS Glossary: sea breeze. Accessed Jan. 15, 2025.

ASHRAE Handbook Chapter 13, AIRCRAFT Design Conditions, Figure 1 Ambient Profiles. Accessed Dec. 15, 2024. https://handbook.ashrae.org/Handbooks/S16/SI/s16_ch13/s16_ch13_si.aspx

Bellouin, N., Yu, H.B., Chapter 11 Aerosol-radiation Interactions, pp 445-487 in Aerosols and Climate, Elsevier, 2022. https://ntrs.nasa.gov/api/citations/20230002445/downloads/Bellouin_Yu_chapter_5_ari_science-final.pdf...

Benzinga, Could Bill Gates Have Stopped Hurricane Ian?, Sept 30, 2022, https://www.benzinga.com/general/topics/22/09/29080703/could-bill-gates-have-stopped-hurricane-ian-the-machine-he-patented-to-control-storms

Bou Karam, D., et al, Dust Emission and Transport associated with a Saharan depression: February 2007 case, Journal of Geophysical Research, Vol. 115, 2010. https://doi.org/10.1029/2009JD012390

Byers, H.R., History of Weather Modification, Weather and Climate Modification, W.N. Hess Ed., Wiley and Sons, New York, N.Y. pp 3-44, 1974

Callister, J.W.D., Rethwisch, D.G., Materials Science and Engineering, an Introduction 9E, John Wiley Sons, Inc., p. 266, 2014

Chamberlin, W.S., Shaw, N., Rich, M., Chapter 9.3 How the Sun Warms the Earth in Our World Ocean: Understanding the Most Important Ecosystem on Earth, Blue Planet Publishing, Fullerton College, 2023.

Chow, J.C. et al "Light Absorption by Black Sand Dust", article in Applied Optics, Vol 39, Iss. 24, September 2000, https://doi.org/10.1364/AO.39.004232

Climate.gov, Landsea, C. Science & Operation's Officer at NOAA's National Hurricane Center, Miami, Florida, Does a Warmer World Make Hurricanes Stronger?, 2010, https://www.climate.gov/news-features/videos/does-warmer-world-make-hurricanes-stronger., accessed January 15, 2025.

Cummins, E., With Operation Popeye, the U.S. Government made Weather an Instrument of War, Popular Mechanics, March 20, 2018, accessed June 6, 2025, https://www.popsci.com/operation-popeye-government-weather-vietnam-war/

Cushman-Roisin, B., 1994: Introduction to Geophysical Fluid Dynamics, Prentice Hall, 320pp.

Elshaer, A.M. et al, Thermal Control of a Small Satellite in Low Earth Orbit, Egyptian Journal of Remote Sensing and Space Sciences, Nov 26, 2023. https://doi.org/10.1016/j.ejrs.2023.11.007

Emanuel-1, Emanuel, K.A., An Air-Sea Interaction Theory for Tropical Cyclones, Part 1: Steady State Maintenance, Journal of the Atmospheric Sciences, Vol. 43, No. 6, Oct. 29, 1985. https://doi.org/10.1175/1520-0469(1986)043%3C0585:AASITF%3E2.0.CO;2

Emanuel-2 Emanuel, K.A., The Maximum Intensity of Hurricanes, Journal of the Atmospheric Sciences, Vol. 45, No. 7, April 1, 1988, https://doi.org/10.1175/1520-0469(1988)045%3C1143:TMIOH%3E2.0.CO;2

Emanuel-3 Emanuel, K.A., Massachusetts Institute of Technology Program in Atmospheres, Ocean and Climate, Lecture 2, Physics of the Tropical Atmosphere, I, April 13, 1998, Accessed June 6, 2025, https://wind.mit.edu/~emanuel/geosys/node3.html#SECTION00030000000000000000

Emanuel-4, Emanuel, K.A., The Theory of Hurricanes, Annual Review Fluid Mechanics, Vol. 23, pp. 179-96, 1991. Accessed June 6, 2025, https://texmex.mit.edu/pub/emanuel/PAPERS/Ann_rev_1991.pdf

Emanuel-5, Emanuel, K., Professor Emeritus of Atmospheric Science, Massachusetts Institute of Technology, quoted in an interview by ABC News, Hurricane Calming Technology? Bill Gates Has a Plan, July 17, 2009, accessed June 6, 2025, https://abcnews.go.com/Technology/story?id=8100460&page=1

EPA, Climate Change Indicators: Tropical Cyclone Activity, Data source: NOAA, 2023, Vecchi and Knutson, 2011, Web Update 2024, accessed Jan. 15, 2025. https://19january2017snapshot.epa.gov/climate-indicators/climate-change-indicators-tropical-cyclone-activity_.html (Note: this is not the current EPA website)

Frank, W.M., Characteristics of Carbon Black Dust as a Large-Scale Tropospheric Heat Source, Dept of Atmospheric Science, Colorado State University, Paper #195, National Science Foundation GA-32589X1, Jan. 1973

Glushakow, H.B. Energy Miracles: the Global Warming Backup Plan, Jenny Stanford Publishing, 2022, 299 pages, Published in Chinese by Hunan Science and Technology Press, Changsha, 2025

Gray, W. M., Global view of tropical disturbances and storms, Mon. Weather Rev., 96, 669– 700, 1968. https://doi.org/10.1175/1520-0493(1968)096%3C0669:GVOTOO%3E2.0.CO;2

Gray, W. M., Frank, W.M., Corrin, M.L., Stokes, C.A., Weather Modification by Carbon Dust Absorption of Solar Energy, Journal of Applied Meteorology and Climatology, Vol. 15, Issue 4. April 1, 1976. https://doi.org/10.1175/1520-0450(1976)015%3C0355:WMBCDA%3E2.0.CO;2

Hoffman, R.N. Controlling Hurricanes, Scientific American, Vol. 291 No. 4 October 2004. doi:10.1038/scientificamerican102004-6o7Ip3Jj7K7x1eLwGgji7d

Holton, J. R. (primary), 2004: An Introduction to Dynamic Meteorology, 4th Edition, Academic Press, 535pp.

ICECE 2021, International Conference on Energy Conservation and Efficiency sponsored by IEEE, presentation by Glushakow, H.B., In Search of an Energy Miracle.

Kämpf, P, What is the typical temperature of an airliner's hull during flight? Aviation Stack Exchange, 2015, Accessed 15 March 2025, https://aviation.stackexchange.com/questions/23747/what-is-the-typical-temperature-of-an-airliners-hull-during-flight

Knapp, K.R., Velden, C.S., Wimmers, A.J., (NOAA) A Global Climatology of Tropical Cyclone Eyes, Monthly Weather Review of the American Meteorological Society, May 4, 2018. https://doi.org/10.1175/MWR-D-17-0343.1

Kuniyal, J.C., Guleria, R.P., The current state of aerosol-radiation interactions: a mini review, Journal of Aerosol Science, Vol. 130, pp 45-54, 2019, https://doi.org/10.1016/j.jaerosci.2018.12.010

Latham, J., Parkes, B., Gadian, A., Salter, S., Weakening of Hurricanes via Marine Cloud Brightening (MCB), Atmospheric Science Letters, 13(4), 231-237 https://rmets.onlinelibrary.wiley.com/doi/epdf/10.1002/asl.402

Launder, B., Hurricanes: an Engineering View of their Structure and Strategies for their Extinction, in Turbulence, Heat & Mass Transfer 8, (ed. K. Hanjalić et al.), Begell House, New York, (2015).

Martell, E. A., (1970): "Transport Patterns and Residence Times for Atmospheric Trace Constituents vs. Altitude", Advances in Chemistry Series, 93, American Chemical Co. Washington, pp. 421-428, https://doi.org/10.1021/BA-1970-0093.CH009

Mateus, P., Mendes, V.B., Pires, C.A.L, Global Empirical Models for Tropopause Height Determination, Remote Sens. 2022, 14(17), 4303; https://doi.org/10.3390/rs14174303.

MeteoSwiss (Swiss Federal Office of Meteorology and Climatology—Troposphere and Tropopause, accessed June 7, 2025. https://www.meteoswiss.admin.ch/weather/weather-and-climate-from-a-to-z/troposphere-and-tropopause.html#:~:text=The%20tropopause%20has%20an%20average%20temperature%20of%20around,degrees%20Celsius%20depending%20on%20the%20region%20and%20season.

Miller, J., Tang, A, Tran, L.T., Prinsley, R., and Howden, M., The Feasibility and Governance of Cyclone Interventions, Journal of Climate Risk Management 41 (2023) 100535. https://doi.org/10.1016/j.crm.2023.100535

Mims, C., Hurricane Forcing: Can Tropical Cyclones by Stopped?, Scientific American, Oct. 23, 2009. Accessed 15 May 2025, https://www.scientificamerican.com/article/can-tropical-cyclones-be-stopped/

Microsoft News, earlier called MS_PowerUser, Bill Gates backing Hurricane Suppression system using car tyres, long tubes that could save billions, published

Nov. 4, 2012. https://mspoweruser.com/bill-gates-backing-hurricane-suppression-system-using-car-tyres-long-tubes-that-could-save-billions/

NASA 2010 National Aeronautics and Space Administration, Goddard Institute for Space Studies, Research article: Aerosols: From Ash in the Wind to Smoke from the Stack. April 16, 2010. accessed March 15, 2025, https://www.giss.nasa.gov/research/features/archive/201004_aerosols/

NASA 2025a National Aeronautics and Space Administration, Halverson, J., NASA Hurricane Scientist). Hurricanes/Exploring Energy, Retrieved Jan. 15, 2025. http://svs.gsfc.nasa.gov/vis/a010000/a010600/a010664/G2010-128_ESW2010_Hurricanes_appletv.m4v

NASA 2025b (National Aeronautics and Space Administration) NASA Earth Observatory maps based on data from the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor on the NASA-NOAA Suomi NPP satellite. https://earthobservatory.nasa.gov/images/152843/derecho-darkens-houston&quot

National Academy of Sciences, Skyline Conference On the Design and Conduct of Experiments in Weather Modification, Publication 742, Washington DC 1959. https://climateviewer.com/downloads/report-of-the-skyline-conference-on-the-design-and-conduct-of-experiments-in-weather-modification.pdf

National Hurricane Center, 2024 Atlantic Hurricane Season, https://www.nhc.noaa.gov/data/tracks/tracks-at-2024.png and https://www.nhc.noaa.gov/data/tcr/index.php?season=2024

NOAA 2016 (National Oceanic and Atmospheric Administration), The Dirt on Atmospheric Dust, July 22, 1016. Retrieved May 9, 2025. https://www.nesdis.noaa.gov/news/the-dirt-atmospheric-dust

NOAA 2021 (National Oceanic and Atmospheric Administration, National Ocean Website) What is a Heat Dome? Accessed Feb. 1, 2025, NOAA 2024b (National Oceanic and Atmospheric Administration-National Ocean Service), Fuel for the Storm, last updated Aug. 8, 2024. https://oceantoday.noaa.gov/every-full-moon/episode11-hurricane/welcome.html

NOAA 2024c (National Oceanic and Atmospheric Administration), "Layers of the Atmosphere." 20 Aug. 2024. https://www.noaa.gov/jetstream/atmosphere/layers-of-atmosphere

NOAA 2025b (National Oceanic and Atmospheric Administration), Improving Severe Weather Forecasts, Accessed May 9, 2025 https://www.nesdis.noaa.gov/news/improving-severe-weather-forecasts-leo-and-geo-satellite-observations

NOAA 2025e (National Oceanic and Atmospheric Administration), Ocean Exploration, How Does the Ocean Affect Hurricanes, accessed May 15, 2025. https://oceanexplorer.noaa.gov/facts/hurricanes.html

NOAA 2025f (National Oceanic and Atmospheric Administration), Tropical Cyclone Introduction), accessed March 15, 2025, https://www.noaa.gov/jetstream/tropical/tropical-cyclone-introduction

NREL, National Renewable Energy Lab, 26th SolarPACES Conference 2020, Thermal Stability of Silica for Application in Thermal Energy Storage, Davenport, P., et al., Oct. 2, 2020. https://doi.org/10.1063/5.0085641

Office of the Historian, 1967, Foreign Relations of the United States, 1964–1968, Volume XXVIII, Laos, No. 274. Memorandum From the Deputy Under Secretary of State for Political Affairs (Kohler) to Secretary of State Rusk, Subject: Weather Modification in North Vietnam and Laos (Project Popeye), Accessed May 15, 2025, https://history.state.gov/historicaldocuments/frus1964-68v28/d274

Ozawa, H., Shimokawa, S., Thermodynamics of a tropical cyclone: generation and dissipation of mechanical energy in a self-driven convection system, Tellus Dynamic Meteorology and Oceanography, International Meteorology Institute in Stockholm, Oct. 19, 2014. https://doi.org/10.3402/tellusa.v67.24216

Pan, Z., Rosenfeld, D., Zhu, Y., Mao, F., Gong, W., Zang, L., Lu, X., 2021. Observational quantification of aerosol invigoration for deep convective cloud lifecycle properties based on geostationary satellite. J. Geophys. Res. Atmos. Vol 126, Issue 9, May 16, 2021. https://doi.org/10.1029/2020JD034275

Rozoff, C.M., Schubert, W.H., Kossin, J.P., Some dynamical aspects of tropical cyclone concentric eyewalls, Journal of the Royal Meteorological Society, 14 May 2008. https://doi.org/10.1002/qj.237

Schepanski, K., Transport of Mineral Dust and its Impact on Climate, Geosciences Review, 2018, Vol 8, 151. https://doi.org/10.3390/geosciences8050151

Secretary of Commerce Report Nov. 1979, National Weather Modification Policies and Programs, A report by Secretary of Commerce to the President and Congress, U.S. Department of Commerce, https://library.oarcloud.noaa.gov/noaa_documents.lib/Digitization_Scans/FY23_Scans/National_Weather_Modification_Policies_and_Programs_Submitted_by_the_Secretary_of_Commerce_in_Compliance_with_Public_Law_94-490.pdf

Shen, W.X., Does the size of a hurricane eye effect its intensity, Geophysical Research Letters, Vol. 33, Issue 18, Sept. 2006. https://doi.org/10.1029/2006GL027313

Smith, R., Hurricane Force, Physics World, 2006, Accessed June 6, 2025, https://www.meteo.physik.uni-muenchen.de/~roger/Publications/PWJUNE06smith.pdf

Simpson, R.H., Ahrens, M.R., Decker, R.D., A Cloud Seeding Experiment Hurricane Esther 1961, U.S. Weather Service, Dept. of Commerce, (Publisher), 1962 https://library.oarcloud.noaa.gov/noaa_documents.lib/NOAA_historic_documents/WB/National_Hurricane_Research_Project_Report/NHRP_60_1962.pdf

StormFury (http://en.wikipedia.org/wiki/Project_Stormfury) (accessed April 15, 2025).

Thankaswamy, A, Xian, T, Wang, L.P., Typhoons and their ocean response over South China Sea using COAWST model, Earth Science, 19 June 2023. http://dx.doi.org/10.3389/feart.2023.1102957

Tran 2025a - Tran, T.L., Fan, J.W., Rosenfeld, D., Zhang, Y.W., Cleugh, H., Hogg, A.M., Prinsley, R., Investigation of the Sensitivity of Tropical Cyclogenesis to Aerosol Intervention, Journal of Geophysical Research: Atmospheres, Vol. 130, Issue 8, April 14, 2025 https://doi.org/10.1029/2024JD041600

Tran 2025b - Tran, T.L., Prinsley, R., Rosenfeld, D., Cleugh, H., Fan, J.W., Can We Mitigate Tropical Cyclone Formation Using Aerosols? A Review of Cyclogenesis and Aerosol Effects as a Theoretical Basis, Journal of Atmospheric Research, Vol. 314 (2025) 107779. https://doi.org/10.1016/j.atmosres.2024.107779

Trenberth, K.E., Fasullo, J.T., Kiehl, J., Earth's Global Energy Budget, Bulletin of American Meteorological Society, March 2009. https://doi.org/10.1175/2008BAMS2634.1

Vagasky, C., Hurricane Forecasts Are Better Than Ever But NOAA Cuts Could Change That, Insurance Journal, May 6, 2025, https://www.insurancejournal.com/news/southeast/2025/05/06/822669.htm

WHO, 2021, World Health Organization Global Air Quality Guidelines. Particulate Matter (PM 2.5 and PM 10), Ozone, Nitrogen Dioxide, Sulphur Dioxide, and Carbon Monoxide. https://www.who.int/news-room/questions-and-answers/item/who-global-air-quality-guidelines

Willoughby, H.E., Jorgensen, D.P., Black, R.A., Rosenthal, S.L., Project STORMFURY: A Scientific Chronicle 1962-1983, Bulletin of American Meteorological Society, Vol.66, No. 5, May 1985. https://doi.org/10.1175/1520-0477(1985)066%3C0505:PSASC%3E2.0.CO;2

Wilma-National Hurricane Center reports that Hurricane Wilma in 2005 had an eye that was just 2 nautical miles wide when it was a Category 5 hurricane in the northwest Caribbean. That eye was replaced by another eye around a day later that was 40 nautical miles wide, and it remained between 40 and 60 nautical miles wide for the rest of Wilma's existence. Accessed 28 April 2025. https://hurricanescience.org/history/storms/2000s/wilma/

WMO-World Meteorological Association, "Tropical Cyclone" accessed Jan. 15, 2025. https://wmo.int/topics/tropical-cyclone#:~:text=Over%20the%20past%2050%20years%2C%201%2C945%20disasters%20have,deaths%20and%20US%24%2078%20million%20in%20damages%20daily.

Zhang, J.A., Black, P.G., French, J.R., Drennan W.N., First direct measurements of enthalpy flux in the hurricane boundary layer: The CBLAST results, Geophysical Research Letters Atmospheric Science, 30 July 2008. https://doi.org/10.1029/2008GL034374

Zhang, Y., Guo, Z., Liu, L. et al. Microclimate Studies by Coupling Effects of Solar Radiation and Heat Transfer in the Aircraft Cabin. Braz J Phys 54, 47 (2024). https://doi.org/10.1007/s13538-024-01423-z