Femtosecond Filamentation for Active Typhoon Control

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This paper reviews the emerging field of active typhoon control as a localized application of geoengineering concepts and proposes one new concept. Ground-based techniques and space-borne concepts employing space solar power technology are discussed. This paper also introduces a novel laser-based approach to mitigate the impact of typhoons: laser-induced condensation. The intense laser pulses may be generated from space using solar power technology for a global reach and instant accessibility to remote areas where typhoons and hurricanes generally develop.

Key Words: Typhoon control, climate change, weather control, solar power satellites, hurricane modification

Nomenclature

SST	:	Sea Surface Temperatures
CCN	:	Cloud Condensation Nuclei
SSP	:	Space Solar Power
RH	:	Relative Humidity

1. Introduction

In recent years typhoon control has emerged as a new research topic due to the observed increase in frequency of extreme heat waves and heavy precipitation events. Global warming has been identified as contributing to this increase. The projected warming for the 21st century using global climate models tends to confirm this trend [1)].

Various models have been developed to calculate the increase in frequency of tropical cyclones on a warmer globe. These simulations relate the energy and damage potential of cyclones to SSTs [2)], which are predicted to increase by an average 2°C by the end of the 21st century [3)]. Recent model calculations show that the frequency of categories 4 and 5 storms, which have minimum sustained wind speeds of 209 km/h, is likely to double by the end of the 21st century [4)]. Other modeling work predicts for the same period a tenfold increase in frequency of extreme weather events such as Hurricane Katrina, which hit New Orleans, Louisiana in 2005 and cost $81 billion in property damage and where at least 1833 people lost their lives [5)].

To mitigate future catastrophic impacts of extreme weather events on cities and civilians, researchers are considering possible methods to weaken the intensity of typhoons and tropical cyclones or to change their path [2,6,7)]. This paper presents a review of such typhoon mitigation techniques and assesses their possible implementation in space. A novel typhoon control technique based on femtosecond filamentation is presented in the second part of this paper.

2. Typhoon formation

Typhoons are massive cyclonic storm systems powered by the release of latent heat during condensation. Low-latitude seas continuously provide the heat and moisture needed for the storm to develop. As the warm, humid air rises above the sea surface, it cools and condenses to form clouds and precipitation. Condensation releases latent heat to the atmosphere and warms the surrounding air, adding instability to the air mass and causing air to ascend still further in the developing thundercloud. With more moisture and latent heat released this process can intensify to create a tropical disturbance as the thunderclouds gather in a cluster over the seas. At this stage cyclonic circulation can develop from the Coriolis effect due to Earth's rotation, fuelling additional warm, humid air to the storm's core, resulting in enhanced precipitation and latent heat release. This allows a low-pressure core to develop, increasing further the convergence of warm air towards the center of the disturbance, strengthening the depression as it becomes a tropical storm. This positive feedback process can combine with the increased evaporation at the sea surface due to the strong winds until a distinctive eye and spiral pattern develop. At this stage the storm becomes a typhoon in the northwest Pacific basin and a hurricane in the eastern north Pacific and north Atlantic basins with sustained winds of at least 119 km/h. The current understanding of tropical cyclones is reviewed in [8)].

3. Typhoon dissipation

Several mechanisms can inhibit further strengthening of tropical cyclones or even cause their dissipation:

- Cool SSTs

Tropical cyclones are fuelled by warm moist air evaporating from the sea surface, hence a decrease of SST values will result in a weakening of the cyclone.

- Vertical wind shear

Tropical cyclones are vertically stacked structures that strengthen via their symmetrical three-dimensional circulation. Adding a vertical wind pattern aloft such as wind speeds increasing with height will cause a disruption in the cyclone's symmetry and will impede the release of latent heat in the structure.

- Land

As tropical cyclones make landfall they are deprived of their energy source - latent heat from warm ocean waters - and will quickly weaken. To a lesser extent, the surface roughness of the land increases friction, reduces the circulation pattern hence weakens the storm.

- Warm tropospheric temperatures

Tropical cyclones feed on latent heat released during condensation. Moist warm air parcels rising in the cyclone will adiabatically expand and cool at the moist adiabatic lapse rate according to several °C per km. An air parcel will continue rising provided its adiabatic lapse rate is higher than the environment lapse rate. In other words the water vapour contained inside the cooling air parcel condenses, releasing latent heat and allowing that air parcel to stay warmer relative to the environment so that it continues its ascension in the unstable atmosphere. Theoretically, a rising air parcel would tend to be impeded by warm tropospheric temperatures, as it would be colder and denser than its surroundings, preventing further intensification of the storm. Measurements of the difference between tropospheric temperatures and SSTs are of primary importance in tropical cyclone intensification theory [9-11]. It must be noted here that atmospheric warming can induce significant wind shear as the latter is approximately related to the gradient of the temperature field [11].

4. Typhoon control concepts

To weaken typhoons or change their paths several techniques have been proposed. They are summarized in Table 1.

Table 1. Typhoon control techniques

Technique	Mechanism	Space affinity
Hurricane seeding	Disrupt the 3D structure	Low
Marine cloud brightening	Decrease SSTs	Medium
Compressible free jets	Decrease SSTs	Low
Ocean upwelling	Decrease SSTs	Low
Microwave beaming	Increase tropospheric temperatures	High

4.1. Hurricane seeding

The first attempt of mitigating tropical cyclones was made by the U.S. government from 1962 to 1983 in the framework of project Stormfury [12]. The hurricane modification technique involved seeding hurricanes with silver iodine particles to increase precipitation outside the eye wall. This would increase convection inside that area, leading to a reformation of the eye wall at larger radii, thus decreasing wind speeds through partial conservation of angular momentum. The silver iodine particles would serve as nuclei for the formation of ice from supercooled water vapour and would precipitate as snow outside the eye wall. However observations performed later showed that contrary to earlier beliefs tropical cyclones already contain large amounts of ice and very little super-cooled water vapour. Positive results obtained in the 1960s were later explained by the inability to discriminate between the results of human intervention and the natural behaviour of hurricanes. These hurricane seeding experiments ceased in 1983.

Project Stormfury aimed at increasing convection outside the eye wall through the release of the latent heat of freezing from supercooled water vapour. To increase the amount of supercooled water available for freezing, other authors have suggested loading a tropical cyclone with large amounts of sub-micron aerosol particles known as CCN to partially suppress the very effective raindrop formation [13,14]. More water droplets would reach the 0°C isotherm level and beyond, increasing the release of the latent heat of freezing in the outer parts of the storm. As in the Stormfury experiment, this would lead to a reformation of the eye wall at a larger radius, eventually leading to its dissipation. Typical CCN densities of 1000 cm^{-3} were considered in the simulations compared to the natural background of 100 cm^{-3} [13,14].

Potential contributions from space

The availability of reliable measurement data constitutes a critical challenge for verifying the effectiveness of such techniques. Several quantities and their evolution need to be measured during the experiments:

- Minimum pressure inside the cyclone eye
- Maximum wind speeds
- Cloud water content
- CCN concentration
- Precipitation
- Eye radius

Space systems can provide insights into the effectiveness of tropical cyclone control concepts by providing a global perspective and constant monitoring of remote areas where tropical cyclones usually develop. Space-borne lidars can measure wind profiles and can acquire atmospheric profiles of cloud water content, ice water content, and aerosol extinction coefficient. For instance the ESA-JAXA ADM-Aeolus mission with its Doppler lidar will measure global wind profiles with 2m/s velocity accuracy and 1km vertical resolution, which would be sufficient to characterize cyclone wind speeds. However the horizontal resolution of the ADM-Aeolus mission (~100 km) [15] is much lower than that required here as the mission aimed at identifying global wind patterns, a goal opposite to characterizing regional weather events such as cyclones. Due to this passive monitoring role the affinity of this typhoon control concept with space systems is estimated to low.

4.2. Marine cloud brightening

Marine stratocumulus clouds are low-level clouds that form along the western coasts of continents and cover approximately one quarter of the ocean surface [16]. Their albedo typically ranges from 0.3 to 0.7, meaning that these clouds can reflect large amounts of incident solar radiation back to space, leading to cooler surface temperatures. To further increase the albedo of these clouds, seawater droplets with a mean diameter of 0.3 to 0.8 μm may be injected into these clouds, a concept known as marine cloud brightening. In this particular cloud seeding technique these submicron aerosols act as condensation nuclei for small cloud droplets to form on, enhancing the cloud reflectivity by increasing the total effective surface area. The cloud lifetime is also possibly enhanced due to a reduction in precipitation rates [16,17).

Marine cloud brightening (MCB) has been suggested as a possible hurricane weakening technique to decrease local SSTs [2)]. Simulations of its local negative radiative forcing indicate that MCB might significantly reduce SSTs in regions where hurricanes develop and weaken their intensity by seeding during their genesis and early development [2)]. To inject the seawater droplets into the atmosphere Salter et al. (2008) proposed an engineering implementation based on spray systems mounted on unmanned wind-powered sea-going vessels. [18)].

Potential contributions from space

Potential space contributions to this typhoon control concept include the passive monitoring role described in section 4.1. Space systems could also play a more active role by remotely controlling the vessels. Satellite communications with the spray vessels would allow the unmanned fleet to follow suitable cloud fields. The space affinity of this typhoon control concept is evaluated to medium.

4.3. Compressible free jets

A free jet flow is an unbounded flow of one fluid into another fluid due to the pressure difference at the nozzle of a jet engine. The free jet flow is said to be compressible when the exhaust velocity is comparable to the sound velocity in the ambient fluid. Compressible free jets are typically turbulent and can transport energy and momentum to the surrounding field [19)]. They might also be used to weaken hurricanes by inducing large unstable updrafts of humid air from the ocean surface [20)].

In this concept multiple jet engines mounted on sea-going vessels introduce intense atmospheric perturbations prior to an advancing cyclone and extract enthalpy (heat) from the ocean surface, decreasing local SSTs. The advancing hurricane would then be partly deprived of its source of energy and would thus weaken. Whether this hurricane modification technique would be effective is unknown at this point [20)].

Potential contributions from space

The space contribution would mostly be restricted to passive monitoring of local SST and cyclone wind speeds; the space affinity of this typhoon control concept is evaluated to low.

4.4. Ocean upwelling

Artificial ocean upwelling is a geoengineering technique that aims at bringing cool, nutrient-rich deep-sea water to the ocean surface using an array of floating pipes [21)]. The pipes may be several hundred meters long to allow mixing of surface waters with deep colder waters (typically 11°C at 315m depths). Each pipe is attached to a surface buoy at the top and a one-way valve is installed at the bottom. The ocean waves force the valve to open in a wave trough and close at the next wave crest, generating upward movement of cold water through the pipe [23,24)].

Field experiments of wave-driven upwelling pumps have demonstrated pumping rates of 45 m^3 per hour using 300m-long wave pumps and local SSTs reduction of more than 1°C for a duration of 15 hours [24)].

Artificial ocean upwelling has been suggested as another mean to weaken tropical cyclones by deploying an array of wave-driven upwelling pumps in front of an advancing cyclone [25)]. Assuming a deployment time of 12 to 24 hours and knowing in advance the path of the storm, this technique could lower SSTs by 0.5-1°C, leading to a decrease in cyclone wind speeds of 15% for a two hour period spent in the altered SST area [25)].

Potential contributions from space

As in section 4.3 the space contribution would be mostly restricted to passive monitoring of local SSTs and cyclone wind speeds; the space affinity of this typhoon control concept is therefore evaluated to low.

4.5 Microwave beaming

Microwave beaming using SSP technology has been recently suggested as a new mean to weaken typhoons or to change their path by providing an atmospheric heating source [6,26)]. Energy would be transmitted to upper cyclone regions especially during their early stage at microwave frequencies using wireless power transmission technology. By tuning the transmission frequency around 183 GHz, a strong water vapour absorption line, different levels in the troposphere may be heated because of the dependence of heating rates on altitude and frequency. Accurate beam-pointing technology would be required to irradiate energy to the cyclone [6)].

Potential contributions from space

Such a system is the more effective, the earlier in the formation phase of a typhoon it could be deployed. In comparison to Earth-based emitting stations, space-based stations which harvest solar energy in space before transferring it in form of microwaves have the potential to cover a much larger area and intervene faster.

Numerical simulations of tropical cyclones development using a data assimilation approach have shown that temperature increments of ± 3°C at high altitudes near the storm center combined with large-scale minor temperature adjustments of ± 0.2°C across the whole region could lead to a large decrease in cyclone wind speeds [26)]. The energy contained in the perturbations was estimated at several petajoules, corresponding to a power source of several tens of gigawatts operating over a day [26)]. Conceivably, a fleet of SSP stations may provide the energy required to weaken a tropical cyclone or change its path. The space affinity of this typhoon control concept is evaluated to be high.

5. Laser-based approach

Here we suggest a novel typhoon control concept based on femtosecond laser filamentation. In this technique, femtosecond laser pulses with peak optical power values in the terawatt range propagate in the atmosphere in a self-focused beam owing to the dynamic competition between the optical Kerr effect focusing the beam and the induced plasma effect defocusing the beam. This results in the formation of thin (100 μm) plasma filaments with typical lengths of several hundred meters and light intensities clamped at around 10^{13} W/cm^2 [27]. Ground-based femtosecond filamentation has been demonstrated recently by propagating terawatt laser pulses in the atmosphere over more than 20 km distance [28]. The experimental setup consisted of a Ti:sapphire oscillator and chirped-pulse amplification chain integrated in a mobile laboratory, providing 100 fs pulses with a peak power of 3 TW in the near infrared 793 nm region at a repetition rate of 10 Hz. At full power the mobile system requires 30 kW during operation [29].

The laser-based approach to active typhoon control is summarized in Table 2.

Table 2. Laser-based typhoon control techniques

Technique	Mechanism	Space affinity
Laser-induced condensation	Suppress warm rain to disrupt the 3D structure	High

5.1. Laser-induced condensation

As discussed above, the conventional way of locally controlling precipitation is to disperse aerosol particles in the atmosphere using aircraft or ground-based dispersion devices such as canisters fired from rockets. Recently, laser-induced condensation has been demonstrated using intense femtosecond laser pulses in both controlled laboratory conditions and real atmospheric conditions [30-32]. Strong droplet formation was observed over a wide range of diameters (25nm-10μm), temperatures (2-36°C), and RH (70-100%). In particular the Ti:sapphire laser increased the density of 25nm-diameter particles to 10^5 cm^{-3} close (~ 2cm) to the laser filaments using 240-fs laser pulses with a 160-mJ pulse energy [30]. The effect was attributed to the very effective atmospheric photochemistry induced by the multi-photon dissociation and ionization of air molecules, creating highly reactive species that lead to the generation of hygroscopic molecules such as HNO_3 that are very efficient in capturing water molecules [30].

Based on these results, laser-induced condensation is suggested here as a possible typhoon control technique. The basic idea is to apply intense femtosecond laser pulses to outer cloud bands of a cyclone (see Fig. 1). These would generate large amounts of artificial CCN, i.e. water droplet embryos, which would compete for the available water vapour and thus locally reduce precipitation. Intense upward air currents (i.e. updrafts) induced by the filaments [33] would efficiently advect the water droplets to the 0°C isotherm and beyond, so that the water droplets release more latent heat of freezing, thus invigorating convection at the cyclone periphery [34] These thunderclouds would compete with the original eye-wall, creating a wider eye, resulting in a decrease in wind speeds through angular momentum conservation.

Laser-induced condensation might offer an effective way to remotely control tropical cyclones. Laser beams propagate with little perturbation through thunderclouds, generating artificial CCN along their beams. In addition laboratory experiments have demonstrated a nonlinear relationship between the generation of CCN and the laser intensity, potentially offering opportunities for large-scale atmospheric implementation [35]. Although the exact nonlinear contribution could not be determined due to the limited number of experimental data points, the generation of droplet embryos is believed to be scaling between the 5th and 8th power law with respect to incident laser intensity, corresponding to multi-photon dissociation and ionization of oxygen, respectively [35]. Contrary to aerosol injection, laser-induced condensation could be switched on and off and would allow for a precise control of the injection region. Finally laser-induced condensation relies on molecules already present in the atmosphere, thus by avoiding the introduction of additional chemicals in the atmosphere it would also eliminate some of the secondary effects aerosol injections might have.

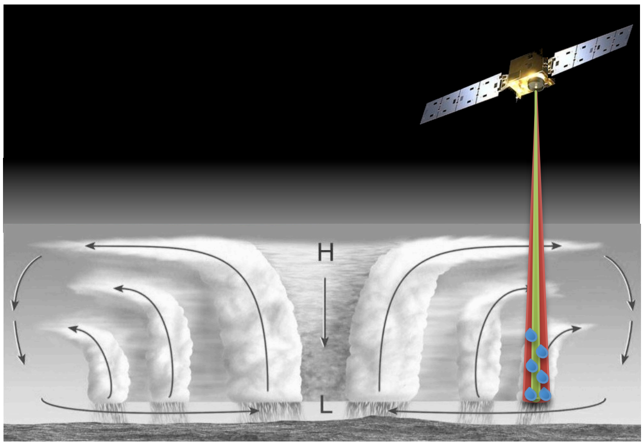

Fig. 1 Concept of laser-induced condensation for active typhoon control. The red and green laser beams represent the femtosecond pump beam and nanosecond probe beam, respectively.

<u>Potential contributions from space</u>

Such an active typhoon control technique could be implemented based on the following scheme. The typhoon control system would be based in orbit with a near global scope and instant accessibility to remote areas. Orbiting SSP stations would power the femtosecond laser sources. To generate the laser filaments from such remote location, a significant frequency chirp would be added to the initial laser pulses thus compensating for group velocity dispersion in the atmosphere, which would spread the laser pulses in the time domain and correspondingly decrease its peak power due to conservation of energy. The laser chirp would be set so that the laser filaments are generated in the troposphere (0-12 km) inside the cyclone. The orbital altitude would need to be considered carefully to allow remote filamentation from orbital distances. This trade-off will need to take into account several parameters such as pointing accuracy, beam divergence, re-visit times, total mass and complexity of operations (one geostationary spacecraft versus several lower Earth orbiting ones). It also still needs to be investigated whether femtosecond filamentation inside the troposphere could be initiated from geostationary orbit, as significant beam divergence could occur, potentially preventing reaching the critical power levels required by the filamentation process.

Precise pointing of the femtosecond beam would be required to allow the generation of artificial CCN along these narrow light filaments. Significant hurricane weakening would require generating CCN densities in the range of 1000 cm^{-3} over a 100-km band located at a 300-km distance from the storm center [13,14)]. This may be achieved by sending one or several laser beams along circles at the cyclone periphery, generating nanoparticles, which would grow to stable micrometer-size water droplets. Experimental tests have demonstrated particle stability over at least 20 minutes [29)]. Given these results, the laser beam could circle around the cyclone and irradiate one given area with a period close to the particle lifetime.

As a first order rough estimate based on the analogy to the tested terrestrial system referred to in [29)], a single laser system would require the high but technically already achievable power level of 30 kW in orbit.

To measure the laser-induced condensation in seeded cyclones, a backscatter space lidar is proposed here in a pump-probe configuration, where femtosecond laser pulses act as a pump beam and nanosecond laser pulses collinear with the filaments probe the artificial CCN generated by the filaments (size distribution, concentration) [31)]. To evaluate the effectiveness of this typhoon control technique a Doppler module could be integrated in the lidar detection system to retrieve cyclone wind speeds.

The space affinity of this typhoon control technique is evaluated to be high.

6. Discussion

This paper is mainly dealing with a discussion of different concepts proposed for active control of weather phenomena, in particular typhoon control options. Even though the large-scale human and material losses associated to such extreme weather effects might justify attempting to mitigate these, any such active interference also needs to take into careful account the impact such actions have on other functions of such weather phenomena. For example, tropical cyclones provide a natural mechanism to remove large amounts of heat energy from ocean waters. Large scale, or even systematic mitigation of tropical cyclone intensity could thus have negative unforeseen consequences, which would need to be considered carefully. Any such scheme would therefore need to be conducted under a proper regulatory framework and oversight.

7. Conclusions

Various tropical cyclone weakening concepts are presented in this paper and assessed concerning the potential contributions from space assets: hurricane seeding, marine cloud brightening, compressible free jets, ocean upwelling, and microwave beaming. In addition, based on recent experimental results with femtosecond lasers, a novel laser-based approach is presented using laser-induced condensation on the outer regions of cyclones based on femtosecond filamentation. These different techniques aim at decreasing SSTs, increasing tropospheric temperatures or disrupting the 3D structure by suppressing warm rain to dissipate cyclones or to eventually alter their path to avoid densely populated areas.

It can be anticipated that different cyclone weakening field tests might be conducted to evaluate the effectiveness of typhoon control concepts. One key challenge will be to ensure the ability to distinguish between changes in the storm state due to anthropogenic perturbations and the natural development of the storm. In this respect, space systems could provide valuable remote-sensing data using Earth observation satellites.

Perhaps the most interesting typhoon control concepts from the point of view of space systems are microwave beaming to induce temperature perturbations at different atmospheric depths and laser-induced condensation to disrupt the 3D structure of cyclones using orbiting laser emitting stations.

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