Mitigating tropical cyclone hazards from space

Isabelle Dicaire[a], Ryoko Nakamura[b], Arikawa Yoshihisa[b], Okada Kazuyuki[b], Itahashi Takamasa[b], Leopold Summerer[a*]

[a]*Advanced Concepts Team, European Space Agency (ESA), Noordwijk, The Netherlands*
[b]*Japan Aerospace Exploration Agency (JAXA), Tsukuba, Japan*

*Correspondence to: leopold.summerer@esa.int

This paper reviews the emerging field of tropical cyclone control as one specific application of active weather control. Ground-based techniques together with possible space contributions are presented. Space-borne concepts employing space solar power (SSP) technology are also discussed. Two space-borne cyclone control options are considered here: atmospheric warming based on microwave irradiation and laser-induced cloud seeding based on laser power transfer. We then present dedicated technology roadmaps for the mitigation of cyclone hazards based on the two space platforms.

Key Words: Tropical Cyclones; Hazard Mitigation; Space Systems; Hurricane Control; Space Solar Power

Received . . .

1. Introduction

Tropical cyclones are powerful storm systems that are fueled by the thermal energy stored in warm ocean waters. Strong sustained winds pushing on the ocean surface can give rise to storm surge and hence significant floods, potentially leading to fatalities and property damage. The 2005 and 2012 tropical cyclone seasons were particularly devastating in the North Atlantic Basin following an ongoing era of high hurricane activity (Emanuel 2005; Webster *et al.* 2005). Hurricanes Katrina and Sandy, which hit the Louisiana and New Jersey coasts of the United States, are reported to have caused more than 1800 and 120 fatalities respectively, together with overall losses exceeding $US 135 billion and $US 50 billion, respectively (Enz *et al.* 2006; Strachan and Camp 2013).

In Japan, the most financially devastating tropical cyclone was Tropical cyclone Bess, which was responsible for more than $US 5.9 billion in damage in 1982 (Kitamoto 2005). Over the past ten years, several large tropical cyclones costing more than $US 1 billion occurred in Japan, causing flooding in large areas of standing water. According to the Ministry of Land, Infrastructure, Transport and Tourism Japan (MLIT), the average cost due to flooding from 1999 to 2008 was $US 6 million per year and the number of casualties per year exceeded 640 (MLIT 2008).

The observed increase in frequency of extreme heat waves and heavy precipitation events is expected to further increase the amount of damage associated with tropical cyclones. While considered traditionally as acts of fate and out of the reach of influence of humans, researchers have started considering possible methods to weaken tropical cyclones or change their path to mitigate future catastrophic impacts of tropical cyclones on cities and civilians (Willoughby *et al.* 1985; Hoffman 2002; Henderson *et al.* 2005; Alamaro *et al.* 2006a; Cotton *et al.* 2007; Rosenfeld *et al.* 2007; Klima *et al.* 2011; Latham *et al.* 2012; Jacobson *et al.* 2014). This paper reviews tropical cyclone mitigation concepts from the point of view of contributions from space systems.

Satellites already offer the most convenient method to monitor tropical cyclone development in real-time. A wealth of high-resolution data of tropical cyclone development has been gathered by Earth observation satellites and their full potential especially for impact mitigation is not yet fully exploited. In addition to remote sensing applications, space in principle also offers option for a more active role including influencing or even to some degree controlling such developing storm systems. This paper investigates the space contributions to currently conceivable tropical cyclone hazard mitigation concepts.

Chapter 2 describes the mechanisms of tropical cyclone formation and dissipation. Chapter 3 presents an overview of ground-based methods and means for threat reduction together with possible space contributions. Chapter 4 presents space-based options for influencing tropical cyclone formation. Two different cyclone control mechanisms are considered: atmospheric heating based on microwave irradiation and laser-induced cloud seeding based on laser power transfer. Technology roadmaps for cyclone mitigation based on two space platform types will be introduced. To control tropical cyclone effectively a high accuracy forecast system would be needed, described as the Earth Meteorological Forecast System. Chapter 5 concludes with an outlook on further research steps.

2. Mechanisms of tropical cyclone formation and dissipation

2.1. *Tropical cyclone formation*

Tropical cyclones 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 via the Coriolis effect due to Earth's rotation, fuelling additional warm, humid air to the storm's core, increasing precipitation rates and latent heat release. This can allow 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 tropical cyclone 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 Wang and Wu (2004).

2.2. *Tropical cyclone dissipation*

Tropical cyclone formation and dissipation are governed by the following physical mechanisms:

- Energy exchange at air-sea interface
  Tropical cyclones are fuelled by warm moist air evaporating from the sea surface, hence natural or anthropogenic decreases of sea surface temperature values will very likely cause dissipation within a cyclone. In addition when tropical cyclones make landfall they are deprived of their energy source (i.e. 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.
- Large-scale interactions with the troposphere
  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 (Emanuel 1986; Shen *et al.* 2000; Tang and Neelin 2004).
  Anthropogenic changes to tropospheric temperatures or naturally-occuring warmer troposphere also induces significant wind shear as the latter is approximately related to the gradient of the temperature field (Tang and Neelin 2004). Tropical cyclones are vertically stacked structures that strengthen via their symmetrical three-dimensional circulation; adding a wind pattern aloft such as wind speeds increasing with height would disrupt the cyclone's symmetry, impeding the release of latent heat in the structure and therefore reducing the cyclone intensity.
- Internal dynamics (cloud microphysics and eyewall replacement cycles)
  Tropical cyclones gain energy from the large amounts of latent heat released during condensation and precipitation. One could expect that the redistribution of precipitation patterns induced by changing the cloud microphysical properties could redistribute latent heating leading to changes in the cyclone's internal dynamics and circulation patterns. Specifically targeting the convection outside the inner eyewall might rob the latter of its moisture and energy, leading to the formation of an outer eyewall with reduced surface wind speeds.

3. Ground-based options to influence tropical cyclone formation

Several ground-based techniques have been proposed to weaken tropical cyclones or change their paths. They are summarized in Table 1.

3.1. *Concepts description*

3.1.1. *Hurricane cloud seeding*

First attempts to mitigate tropical cyclones were made by the U.S. government from 1962 to 1983 in the framework of Project Stormfury (Willoughby *et al.* 1985). The hurricane modification technique was based on seeding hurricanes with silver iodine particles to enhance precipitation outside the eye wall. This would increase convection inside that area, leading to a reformation of the eyewall at a larger radius, 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 eyewall. 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 (Cotton *et al.* 2007; Rosenfeld *et al.* 2007). 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} (Cotton *et al.* 2007; Rosenfeld *et al.* 2007).

3.1.2. *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 (Wood 2012). 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

Table 1. Ground-based tropical cyclone control concepts

Concept	Physical process	Space affinity
Hurricane cloud seeding	Internal dynamics	Low
Marine cloud brightening	Energy exchange at air-sea interface	Medium
Offshore wind turbines	Energy exchange at air-sea interface	Low
Compressible free jets	Energy exchange at air-sea interface	Low
Ocean upwelling	Energy exchange at air-sea interface	Low

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 (Wood 2012; Partanen *et al.* 2012).

Marine cloud brightening (MCB) has been suggested as a possible hurricane weakening technique to decrease local SSTs (Latham *et al.* 2012). 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 (Latham *et al.* 2012). 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 (Salter *et al.* 2008).

3.1.3. *Offshore wind turbines*

Recently offshore wind turbines have been proposed as a simple mechanism to extract kinetic energy from cyclone winds with the aim of reducing wind speed and storm surge (Jacobson *et al.* 2014). Numerical simulations of the impact of offshore wind turbines on cyclone surface wind speeds have been performed using a coupled climate-weather forecast model that accounts for the kinetic energy extracted by the turbine rotors. Results showed that large turbine arrays with 300GW electricity capacity may decrease surface wind speeds by 25-41 ms^{-1} and storm surge by 6-79% (Jacobson *et al.* 2014). The turbines could decrease the outer rotational winds by extracting kinetic energy, reducing the wave heights at these locations and decreasing surface friction. As the latter weakens the convergence of surface winds at the eyewall, the convection in the eyewall decreases and the central pressure increases, leading to a weaker cyclone. Simulations were conducted for hurricane Sandy, Katrina, and Isaac and the turbines were assumed to be installed offshore in front of major cities and along key coastal areas.

A simple cost-benefit analysis of this concept revealed that the net cost of offshore turbine arrays might be less than that of today's fossil fuel electricity generation in these areas, taking into account operation costs, electricity generation and costs related to health, climate, and hurricane damage avoidance.

3.1.4. *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 considered 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 (Sforza and Mons 1978). They might be used to weaken hurricanes by inducing large unstable updrafts of humid air from the ocean surface (Alamaro *et al.* 2006b). 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 (Alamaro *et al.* 2006b).

3.1.5. *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 (Isaacs *et al.* 1976). 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 (Kithil 2006). 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 (White *et al.* 2010).

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 (Klima *et al.* 2011). Assuming a deployment time of 12 to 24 hours and knowing in advance the path of the storm, Klima et al. calcualte that 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 (Klima *et al.* 2011).

3.2. *Potential contributions from space*

Space systems can provide insights into the efficacy of tropical cyclone control concepts by providing a synoptic and frequent monitoring of remote areas where tropical cyclones develop. The Dvorak technique is a well-established empirical tool based on cloud feature recognition to estimate tropical cyclone intensity using satellite-derived data (Dvorak 1975; Velden *et al.* 2006). To complement this technique, recent works aiming at integrating newer remote sensing products have yielded promising results as a potential tropical cyclone intensity estimation tool. Such sensors include cloud profiling radars (e.g. CloudSat mission) and imaging spectroradiometers such as the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua platform, both satellites being part of NASA's convoy of A-Train satellites and sharing same orbital characteristics. Combined together, they provide accurate estimates of cloud top pressure and temperature of tropical cyclone eyewalls to estimate tropical cyclone intensity (Sieron *et al.* 2013).

Orbiting radiometers can also be used to estimate surface wind speeds by measuring changes in brightness temperature. Designed to measure soil moisture and ocean salinity (SMOS), ESA's Earth Explorer SMOS mission can provide reliable estimates of cyclone surface wind speeds under stormy, rainy conditions. The MIRAS (Microwave Imaging Radiometer using Aperture Synthesis) instrument onboard the SMOS satellite operates at 1.4 GHz in the L-band and measures brightness temperature, i.e. microwave radiation, which can be affected by oceanic whitecaps - those long white patches of foam that arises in stormy conditions

(Ross and Cardone 1974; Monahan and O'Muircheartaigh 1986; Reul *et al.* 2012; Uhlhorn *et al.* 2007). With its ∼1200-km swath width, 3-day subcycle and average spatial resolution of ∼50km, SMOS offers opportunities to complement the Dvorak technique and standard aircraft dropsonde data (Reul *et al.* 2012).

Active options to measure cyclone wind speeds include making use of their distorting effect on reflected signals from Global Positioning Systems (GPS) or active synthetic aperture radar (SAR) data via an increase in small-scale ocean roughness. Wind speeds retrieved via SAR imagery has been shown to agree well with dropsonde data and with an accuracy comparable to microwave radiometer data (error ∼ 4m/s in C-band), with the benefit of higher spatial resolution (Uhlhorn *et al.* 2007; Horstmann *et al.* 2013). Moreover wind speeds in excess of 40 m/s could be retrieved via GPS signals (in L-band) with 5-8 m/s accuracy (Katzberg *et al.* 2006, 2013). Planned for launch within the next few years is the CYGNSS (Cyclone Global Navigation Satellite System) mission from NASA consisting of eight microsatellites designed to measure cyclone surface wind speeds by detecting direct and reflected GPS signals. The complete constellation will provide gap-free coverage of Earth's surface with a 4-hour revisit time over the tropics (Ruf *et al.* 2013).

In addition to monitoring surface wind speeds and tropical cyclone intensity, space instruments could provide additional information specifically for each concept. For instance cloud profiling radars could help to assess the impact of cloud seeding. The main issue with the experimental verification of precipitation-enhancement experiments lies in the high level of noise present in naturally-precipitating clouds. In particular difficulties arise in tracking the seeding particles over the target area, and to relate changes in liquid water content and ice particle size distribution to anthropogenic seeding activity (Miao and Geerts 2013). Cloud-profiling radars, space-borne backscatter lidars and imaging radiometers can be used in synergy to accurately retrieve the vertical distribution of cloud microphysical properties such as liquid water content, ice water content and ice particle size (Miao and Geerts 2013; Delanoë and Hogan 2010). Due to the passive monitoring role the affinity of this control technique with space systems is estimated to be low. As for the marine cloud brightening concept, the wind-powered sea-going vessels used for injecting submicron seawater droplets could be remotely controlled from space to allow the unmanned fleet to follow suitable cloud fields. The space affinity of this control concept is evaluated to be medium. Finally for the offshore wind turbines, the compressible free jets and ocean upwelling techniques, the space contribution would mostly be restricted to the passive monitoring role described above; the space affinity here is low.

4. Space-based options to influence tropical cyclone formation

This section proposes space-based techniques based on space platforms to weaken tropical cyclones. They are summarized in Table 2.

4.1. *Cyclone modification via space-based microwave energy transfer*

One of the causes for cloud formation is the cooling of the humid air, as described in section 2.1. This concept therefore proposes a heat irradiation system to control the cloud formation and tropical cyclone development. Energy will be deposited via microwaves to slightly warm humid air from a space-based platform. Such as system has been proposed as an additional application to space-based solar power stations in a dual use mode (Nakamura *et al.* 2012).

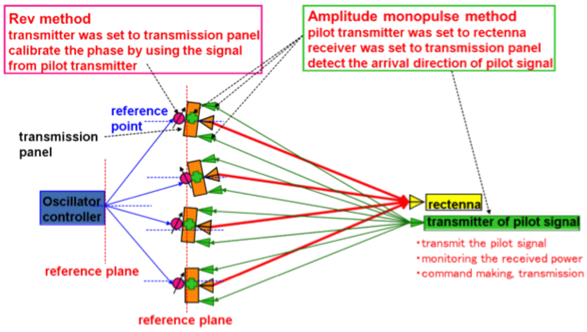

Figure 1. Schematic view of the beam-pointing technology.

The accurate transmission of thermal energy via microwaves to tropical cyclones requires highly accurate pointing and forecast accuracy regarding the storm's position and path. Details and development items for each system are shown below.

4.1.1. *Heat Irradiation System*

The functions of this system consist of (i) generating power with solar energy, (ii) converting electric power to a radio frequency applied to tropical cyclone control, and (iii) heat irradiation to the tropical cyclone from space. Such technologies are studied in the frame of space solar power station concepts and would thus strongly benefit from developments in this field. There are three general key technologies that would need to be developed: transmission, beam pointing, and frequency switching. The viability of these technologies is described in the next subsection. To heat atmosphere effectively, a frequency of 183 GHz is chosen, which is in the absorption band of water vapor, the main component of a tropical cyclone.

In addition, high-accuracy pointing technology is needed to irradiate energy to the tropical cyclone. We assume that (i) the Rev method and (ii) the Amplitude monopulse method, which have been studied as part of the Japanese work on space solar power concepts, are applicable. A schematic view of these methods is shown in Fig. 1. In the Rev method, we set the transmitter on the transmission panel (on the left of Fig. 1) and calibrate the phase by using the signal from a pilot transmitter (on the right of Fig. 1). In the amplitude monopulse method, a pilot transmitter and receiver are set on the rectenna and the transmission panel, respectively, and we detect the arrival direction from the pilot signal.

With these energy transmission and beam-pointing systems, we estimate the irradiation time needed for tropical cyclone control. Hoffmann (2004) reported the simulation result that the temperature of mere tenths of a degree increase causes the route modification or the reduction of the tropical cyclone (Hoffman 2004). Under the following assumptions: (i) 1 space platform with a transmission power of 1.5 GW, (ii) the target is only water vapor, and the absorption rate of the power is 100%, (iii) the density of the water vapor is 5 g/m^3 (Takayama 2004), and (iv) the irradiation area is 100 km x 100 km, the irradiation for 1.6 days over a 100 km^2 area can heat a tropical cyclone by 0.1 °C. Heat irradiation for only a 100 km^2 area could be effective for tropical cyclone control with the assumption that the irradiation is done during the early development of the tropical cyclone. Under these assumptions such a system appears to be able to actively influence tropical cyclone and eventually control some of its parameters. Heat irradiation from space has the advantage of instantaneousness and global operability as compared to a ground-based tropical cyclone control system. More detailed system-level studies and more considerations on the size and dynamics of the irradiation area are needed to mature the concept.

Table 2. Space-based tropical cyclone control concepts

Concept	Physical process	Space affinity
Microwave energy transfer	Large-scale interactions with troposphere	High
Laser-induced condensation	Internal dynamics	High

Table 3. Key technologies and R&D steps

Key technology	TRL	Steps to raise TRL
Earth Meteorological Forecast System		
Earth Observation Satellite	9	N/A
Earth Observation Ground System	9	N/A
Numerical weather model	2	I
Supercomputer	2	I
Total System Assimilation	1	I,II
Heat Irradiation System (Thermal Transmission System)		
Energy transmission	2	I-III
Beam pointing	3	II-III
Frequency switching	2	I-III

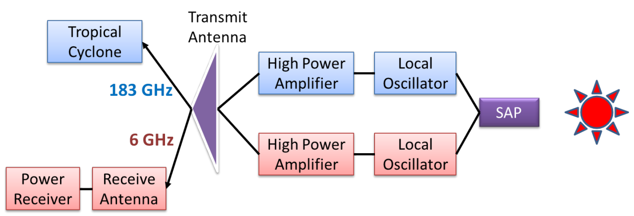

Figure 2. Operation image of the heat irradiation system.

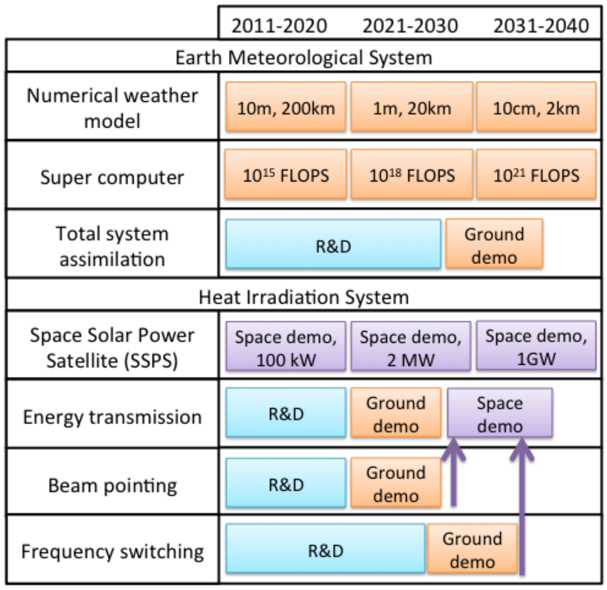

Figure 3. Technology roadmap

An interesting aspect of the concept is its potential to act as a dual use system, generating electricity at remore locations during most of its operational time when not used as a heat irradiation system. The JAXA SSPS development team assumes that a frequency of 6 GHz is used to transmit power to the Earth. Such a system requires as a critical technology an efficient frequency switching technology between 183 GHz and 6 GHz. Figure 2 shows the operation image of the heat irradiation system. We assume that the transmitting antenna will be shared between the 183 GHz and 6 GHz microwave transmission.Local oscillator and high power amplitude will be prepared individually.

4.2. *Technological Viability*

The viability of our proposed system from the standpoints of technology is examined. To evaluate the technological viability, we identified the key technologies of our proposed system and their Technology Readiness Level (TRL). Then we set a R&D plan to raise the TRL of each key technology on the basis of its present TRL (see Table 3).

We assume that the technology which has been developed by SSPS R&D team will be used as much as possible. Specific technology for the tropical cyclone control system are high frequency (183GHz) transmission and frequency switching. The 183-GHz transmission system might be based on the 94-GHz transmission system developed by EarthCare (Aida *et al.* 2013). Technical difficulties are low although there are some technical issue such as low noise countermeasure. As for the frequency swiching system, the most difficult issue foreseen is the antenna development. Finally further research activities to improve high gain antenna and high mirror accuracy (on the order of 1/50f, where f is frequency) are required for high frequency transmission. Figure 3 shows the technology roadmap, in which our proposed system can be established in a quarter of a century.

4.3. *Cyclone modification via space-based laser energy transfer*

Here we suggest a novel tropical cyclone control concept based on femtosecond laser filamentation and space-based laser energy transfer. In this technique, femtosecond terawatt-scale laser pulses 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 (Couairon and Mysyrowicz 2007). Ground-based femtosecond filamentation has been demonstrated recently by propagating terawatt laser pulses in the atmosphere over more than 20 km distance using a mobile laser and detection system embedded in a standard freight container (Rodriguez *et al.* 2004).

4.3.1. *Laser-induced condensation*

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 (Rosenfeld *et al.* 2007, 2012). Recently, laser-induced condensation has been demonstrated using intense femtosecond laser pulses in a controlled laboratory environement as well as outdoor conditions (Ju *et al.* 2012; Henin *et al.* 2011). Strong droplet formation was observed over a wide range of diameters (25nm-10μm), temperatures (2-36°C), and RH (70-100%). In particular the density of 25-nm diameter particles increased to 10^5 cm^{-3} close ($\sim$2cm) to the laser filaments using 120-fs laser pulses with a 220-mJ pulse energy. 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 which are in turn very efficient at absorbing moisture (Henin *et al.* 2011).

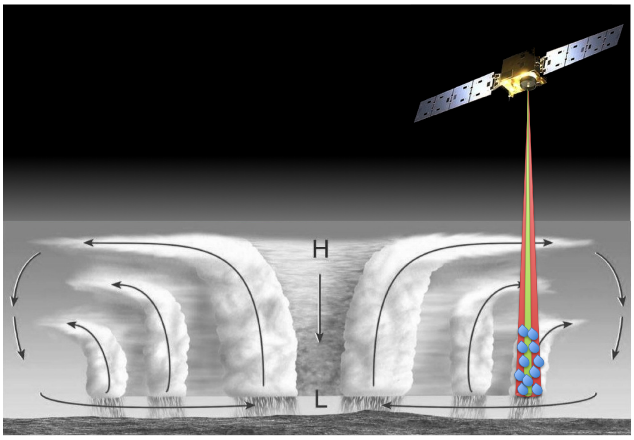

Figure 4. Artistic representation of the concept of laser-induced condensation for tropical cyclone control (not to scale). The red and green laser beams represent the femtosecond pump beam and nanosecond probe beam, respectively.

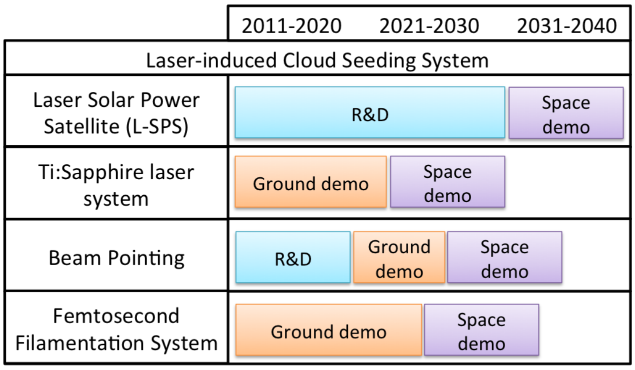

Figure 5. Technology roadmap for the laser-induced cloud seeding system

Based on these results, laser-induced condensation is suggested here as a possible cyclone control technique. The basic principle is to apply intense femtosecond laser pulses to outer cloud bands of a cyclone (see Fig. 4). 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 (see updrafts in (Ju *et al.* 2012)) induced by the filaments 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 (Rosenfeld *et al.* 2007). These thunderclouds would compete with the original eye-wall, creating a wider eye, resulting in a decrease in wind speeds through conservation of angular momentum.

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 highly nonlinear generation of CCN as a function of the laser intensity, potentially offering attractive opportunities for large-scale atmospheric implementation. 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 multiphoton dissociation and ionization of oxygen, respectively (Petrarca *et al.* 2011). Contrary to aerosol injection, laser-induced condensation may be switched off, allowing 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 injections might have.

4.3.2. *Space-based laser-induced cloud seeding system*

This active tropical cyclone control technique may be based on the following laser SSP scheme for global perspective and instant accessibility to remote areas. A laser-based SSP station with an assumed transmission power of 1.5 GW provides the demanding power source required for the laser-induced cloud seeding system. The SSP station could be based on the modular electric laser concept as described in (Mankins 2011), comprising a series of numerous individual elements beaming their optical energy towards ground-based photovoltaic (PV) arrays. However instead of beaming their energy towards ground stations, the various optical beams would target specific areas within a cyclone, following cloud coverage data obtained using satellite microwave imagery.

To generate the laser filaments from such distances, 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. Precise pointing of the femtosecond beam would allow the generation of artificial CCN over several kilometers along these narrow light filaments. To induce significant weakening, CCN density levels in the range 1000-2000 cm^{-3} would be required at the cyclone periphery (e.g. a 50-km band located at a 300-km distance from the storm center). Similarly other schemes could be used to alter the tropical cyclone track to prevent the latter from devastating a particular zone on the continent.

To measure the laser-induced condensation in seeded cyclones, a backscatter space Lidar is proposed here in a pump-probe configuration, where the femtosecond laser pulses act as the pump beam and nanosecond laser pulses colinear with the filaments probe the artificial CCN generated by the filaments (size distribution, concentration) (Kasparian and Wolf 2012). To evaluate the effectiveness of this cyclone control technique a Doppler module could be integrated in the Lidar detection system to retrieve cyclone wind speeds. Other options include making use of the distortion effect of small-scale ocean roughness on reflected GPS signals and synthetic aperture radar (SAR) data as presented in section 3.2.

4.3.3. *Technological Viability*

The laser-induced cloud-seeding system is based on a space platform, which could in principle be similar to space-based solar power platforms transmitting energy via laser beams. Compared to other transmission systems, these have relatively small-size components due to the latter scaling with optical wavelengths. A modular, self-assembling space infrastructure would keep the *Cost to First Power* relatively low. Key technologies to be developed would be the following: high-accuracy beam pointing technology to target specific areas within a cyclone, high-efficiency solar power generation via multi-bandgap PV cells, and an effective thermal management system to dissipate the significant waste heat generated by the laser systems. Figure 5 shows a potential schematic technology roadmap for a laser-induced cloud seeding system, which could be established in a quarter of a century.

As a first implementation of the laser-induced cloud seeding system in orbit, a single femtosecond laser system based on the analogy to the tested terrestrial system referred to in (Wille *et al.* 2002) would require the high but technically already achievable

Table 4. Key technologies for the laser-induced cloud seeding system

Key technology	TRL
Laser Solar Power Satellite (L-SPS)	3
Ti:Sapphire laser system	6
Beam Pointing	5
Femtosecond Filamentation System	6

power level of 30 kW in orbit. One important technological issue regarding the high-power laser system is that it should operate under extended temperature range and harsh radiation environment. Research is currently under way to develop space-qualified ultrashort-pulse terawatt lasers (Lotshaw 2011).

Finally applied research on femtosecond filamentation is already well under way, with a ground-based prototype already demonstrated in environmental conditions (Henin *et al.* 2011). Recent works have shown a strong relationship between the laser parameters required for the filamentation process and the atmospheric conditions along the propagation path. This results in the need for a better understanding of the impact of atmospheric turbulence and upper-atmospheric cold plasma conditions on the filamentation process to adjust the laser parameters. Any practical implementation of a femtosecond filamentation system in space would require a continuous research commitment to obtain a detailed understanding of underlying physics principles in order to reduce the risk and uncertainty associated with such a system. This equally applies to other applications of femtosecond filamentation such as hyperspectral remote sensing and free-space optical telecommunications.

4.4. *Earth Meteorological Forecast System (EMFS)*

The Global Earth Observation System of Systems (GEOSS) is a integration system through which data and information acquired by the Earth observation satellites can be accessed from the Internet in Japan. Figures 6 and 7 illustrate the concepts of the Earth Environmental Observation Satellites and the GEOSS, respectively. The GEOSS integrates across nine social sectors: disaster, health, energy, climate, agriculture, ecosystem, biodiversity, water, and meteorological phenomenon. The Earth Meteorological Forecast System (EMFS) is assumed to be applied next or next-of-next generation of the GEOSS. Data aquired by the Global Change Observation Mission (GCOM), which JAXA is promoting, will enable a higher simulation accuracy

Accuracy improvement of the EMFS is needed to improve data accuracy acquired by the GCOM. Therefore, the accuracy of the simulation before the EMFS operation will be able to be improved using data acquired by the GCOM. To control the tropical cyclone, high accuracy forecast system will be needed. The Earth Meteorological Forecast System (EMFS) consists of the Earth Observation System Family, the Ground Observation System Family, and the Meteorological Forecast System.

The meteorological forecast is implemented by the simulation, which is calculated based on the data acquired via the Earth observation satellites and the numerical weather model using a supercomputer. Both (i) accuracy improvement of the numerical weather model, which is less than 10 cm with calculated accuracy at 500 hPa altitude and less than 10 km with calculated accuracy of the cyclone's trace, and (ii) upgrade of the supercomputer, which is more than 10^{21} floating-point operations per second (FLOPS), are needed in order to simulate the meteorological phenomenon with high-speed and accurate processing and real-time processing, including movement of the cyclone. Improved accuracy of the EMFS is needed for regular total system assimilation to correct for the bias error of both observed data and simulated predicted data.

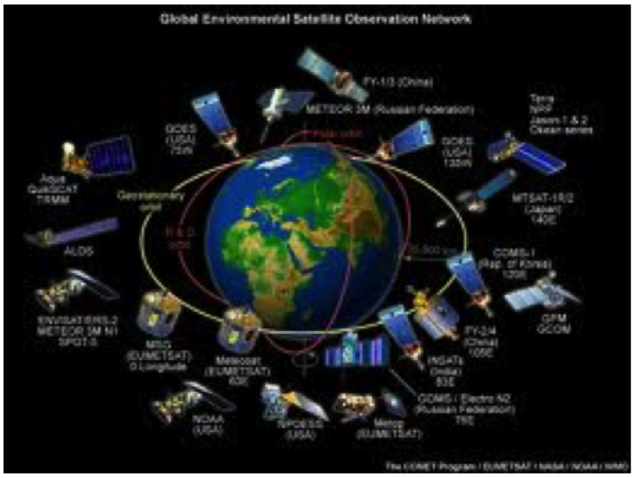

Figure 6. Earth Environmental Observation Satellites

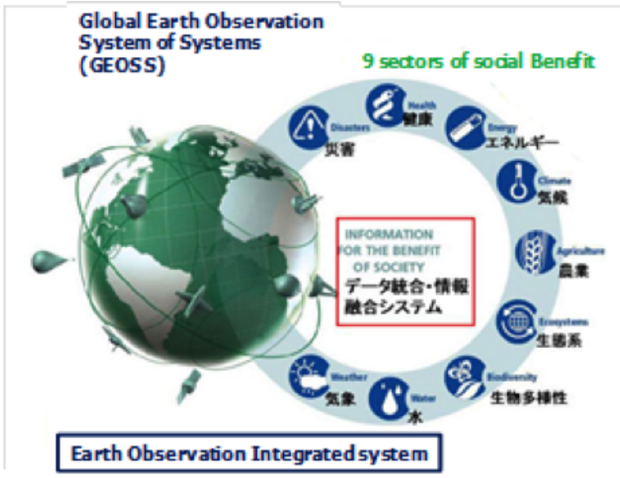

Figure 7. Concept of the Global Earth Observation System of System (GEOSS).

5. Outlook of future research steps

This paper is mainly dealing with a discussion of different concepts proposed for active control of weather phenomena, in particular tropical cyclone control options. Even though the large-scale human and material losses associated with such extreme weather phenomena might justify attempting their mitigation, any active interference would require the evaluation of their impact on the climate system. 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.

6. Conclusions

Various tropical cyclone weakening concepts are presented in this paper and assessed concerning the potential contributions from space assets: hurricane cloud seeding, marine cloud brightening, offshore wind turbines, compressible free jets, ocean upwelling, microwave energy transfer, and laser-induced cloud seeding. These different techniques either target the energy exchange at the air-sea interface, large-scale interactions with the troposphere or the cyclone internal dynamics via modifications of the cloud microphysical properties with the objective of dissipating cyclones or altering their path to mitigate their impact on cities and civilians. It can be anticipated that cyclone weakening field tests might be conducted to evaluate the effectiveness of tropical cyclone 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 cyclone control concepts from the point of view of space applications are microwave energy transfer to induce temperature perturbations at different atmospheric depths and laser-induced condensation to disrupt the 3D structure of cyclones using orbiting laser-emitting stations.

References

Aida Y, Tomita E, Nakatsuka H, Seki Y, Okada K, Kadosaki G, Iide Y, Horie H, Sato K, Ohno Y, *et al.* 2013. Earthcare/cpr design results and pfm performance. In: *SPIE Remote Sensing*. International Society for Optics and Photonics, pp. 88 890A–88 890A.

Alamaro M, Michele J, Pudov V. 2006a. A preliminary assessment of inducing anthropogenic tropical cyclones using compressible free jets and the potential for hurricane mitigation. *Journal of Weather Modification* **38**: 82–96.

Alamaro M, Michele J, Pudov V. 2006b. A preliminary assessment of inducing anthropogenic tropical cyclones using compressible free jets and the potential for hurricane mitigation. *Journal of Weather Modification* **38**: 82–96.

Cotton WR, Zhang H, McFarquhar GM, Saleeby SM. 2007. Should we consider polluting hurricanes to reduce their intensity. *Journal of Weather Modification* **39**: 70–73.

Couairon A, Mysyrowicz A. 2007. Femtosecond filamentation in transparent media. *Physics Reports* **441**(2–4): 47–189.

Delanoë J, Hogan RJ. 2010. Combined cloudsat-calipso-modis retrievals of the properties of ice clouds. *Journal of Geophysical Research: Atmospheres (1984–2012)* **115**(D4).

Dvorak VF. 1975. Tropical cyclone intensity analysis and forecasting from satellite imagery. *Monthly Weather Review* **103**(5): 420–430.

Emanuel K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436**(7051): 686–688.

Emanuel KA. 1986. An air-sea interaction theory for tropical cyclones. part i: Steady-state maintenance. *Journal of the Atmospheric Sciences* **43**(6): 585–605.

Enz R, Zanetti A, Hess T. 2006. *Natural catastrophes and man-made disasters 2005: High earthquake casualties, new dimension in windstorm losses*. National Emergency Training Center.

Henderson JM, Hoffman RN, Leidner SM, Nehrkorn T, Grassotti C. 2005. A 4D-Var study on the potential of weather control and exigent weather forecasting. *Quarterly Journal of the Royal Meteorological Society* **131**(612): 3037–3051.

Henin S, Petit Y, Rohwetter P, Stelmaszczyk K, Hao Z, Nakaema W, Vogel A, Pohl T, Schneider F, Kasparian J, Weber K, Wöste L, Wolf JP. 2011. Field measurements suggest the mechanism of laser-assisted water condensation. *Nat Commun* **2**: 456.

Hoffman RN. 2002. Controlling the global weather. *Bulletin of the American Meteorological Society* **83**(2).

Hoffman RN. 2004. Controlling hurricanes. *Scientific American* .

Horstmann J, Wackerman C, Falchetti S, Maresca S. 2013. Tropical cyclone winds retrieved from synthetic aperture radar. *Oceanography* **26**(2): 46–57.

Isaacs JD, Castel D, Wick GL. 1976. Utilization of the energy in ocean waves. *Ocean Engineering* **3**(4): 175–187.

Jacobson MZ, Archer CL, Kempton W. 2014. Taming hurricanes with arrays of offshore wind turbines. *Nature Climate Change* **4**(3): 195–200.

Ju J, Liu J, Wang C, Sun H, Wang W, Ge X, Li C, Chin SL, Li R, Xu Z. 2012. Laser-filamentation-induced condensation and snow formation in a cloud chamber. *Optics Letters* **37**(7): 1214–1216.

Kasparian J, Wolf JP. 2012. Ultrafast laser spectroscopy and control of atmospheric aerosols. *Physical Chemistry Chemical Physics* **14**(26): 9291–9300.

Katzberg SJ, Dunion J, Ganoe GG. 2013. The use of reflected gps signals to retrieve ocean surface wind speeds in tropical cyclones. *Radio Science* **48**(4): 371–387.

Katzberg SJ, Torres O, Ganoe G. 2006. Calibration of reflected gps for tropical storm wind speed retrievals. *Geophysical research letters* **33**(18).

Kitamoto A. 2005. Digital typhoon: Near real-time aggregation, recombination and delivery of typhoon-related information. In: *Fourth International Symposium on Digital Earth*.

Kithil PW. 2006. A device to control sea surface temperature and effects on hurricane intensity. In: *27th Conference on Hurricanes and Tropical Meteorology*.

Klima K, Morgan MG, Grossmann I, Emanuel K. 2011. Does it make sense to modify tropical cyclones? a decision-analytic assessment. *Environmental Science & Technology* **45**(10): 4242–4248.

Latham J, Parkes B, Gadian A, Salter S. 2012. Weakening of hurricanes via marine cloud brightening (MCB). *Atmospheric Science Letters* **13**(4): 231–237.

Lotshaw WT. Spring 2011. Emerging technologies: Ultrashort-pulse lasers for space applications. Technical Report 1, The Aerospace Corporation.

Mankins JC. 2011. Space solar power the first international assessment of space solar power: opportunities, issues and potential pathways forward. *International Academy of Astronautics* .

Miao Q, Geerts B. 2013. Airborne measurements of the impact of ground-based glaciogenic cloud seeding on orographic precipitation. *Advances in Atmospheric Sciences* **30**(4): 1025–1038.

MLIT. 2008. Damage cost caused by flooding in 2008. Press Release.

Monahan EC, O'Muircheartaigh IG. 1986. Whitecaps and the passive remote sensing of the ocean surface. *International Journal of Remote Sensing* **7**(5): 627–642.

Nakamura R, Arikawa Y, Itahashi T. 2012. Active typhoon control with space solar power technology. In: *Proceedings of the 63rd International Astronautical Congress, Naples, Italy*, vol. 12.

Partanen AI, Kokkola H, Romakkaniemi S, Kerminen VM, Lehtinen KE, Bergman T, Arola A, Korhonen H. 2012. Direct and indirect effects of sea spray geoengineering and the role of injected particle size. *Journal of Geophysical Research: Atmospheres* **117**(D2).

Petrarca M, Henin S, Stelmaszczyk K, Bock S, Kraft S, Schramm U, Vaneph C, Vogel A, Kasparian J, Sauerbrey R, Weber K, Wöste L, Wolf JP. 2011. Multijoule scaling of laser-induced condensation in air. *Applied Physics Letters* **99**(14).

Reul N, Tenerelli J, Chapron B, Vandemark D, Quilfen Y, Kerr Y. 2012. Smos satellite l-band radiometer: A new capability for ocean surface remote sensing in hurricanes. *Journal of Geophysical Research: Oceans* **117**(C2).

Rodriguez M, Bourayou R, Méjean G, Kasparian J, Yu J, Salmon E, Scholz A, Stecklum B, Eislöffel J, Laux U, Hatzes AP, Sauerbrey R, Wöste L, Wolf JP. 2004. Kilometer-range nonlinear propagation of femtosecond laser pulses. *Physical Review E* **69**(3): 036 607.

Rosenfeld D, Khain A, Lynn B, Woodley W. 2007. Simulation of hurricane response to suppression of warm rain by sub-micron aerosols. *Atmospheric Chemistry and Physics* **7**(13): 3411–3424.

Rosenfeld D, Woodley WL, Khain A, Cotton WR, Carrió G, Ginis I, Golden JH. 2012. Aerosol effects on microstructure and intensity of tropical cyclones. *Bulletin of the American Meteorological Society* **93**(7): 987–1001.

Ross DB, Cardone V. 1974. Observations of oceanic whitecaps and their relation to remote measurements of surface wind speed. *Journal of Geophysical Research* **79**(3): 444–452.

Ruf C, Unwin M, Dickinson J, Rose R, Rose D, Vincent M, Lyons A. 2013. Cygnss: Enabling the future of hurricane prediction [remote sensing satellites]. *Geoscience and Remote Sensing Magazine, IEEE* **1**(2): 52–67.

Salter S, Sortino G, Latham J. 2008. Sea-going hardware for the cloud albedo method of reversing global warming. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **366**(1882): 3989–4006.

Sforza PM, Mons RF. 1978. Mass, momentum, and energy transport in turbulent free jets. *International Journal of Heat and Mass Transfer* **21**(4): 371–384.

Shen W, Tuleya RE, Ginis I. 2000. A sensitivity study of the thermodynamic environment on GFDL model hurricane intensity: Implications for global warming. *Journal of Climate* **13**(1): 109–121.

Sieron SB, Zhang F, Emanuel KA. 2013. Feasibility of tropical cyclone intensity estimation using satellite-borne radiometer measurements: An observing system simulation experiment. *Geophysical Research Letters* **40**(19): 5332–5336.

Strachan J, Camp J. 2013. Tropical cyclones of 2012. *Weather* **68**(5): 122–125.

Takayama Y. 2004. Research for observation of vertical profile of water vapor with microwave radiometer (original in japanese). Technical Report 06A0970665, Institute of Meteorological research of Japan.

Tang BH, Neelin JD. 2004. ENSO influence on atlantic hurricanes via tropospheric warming. *Geophysical Research Letters* **31**(24): L24 204.

Uhlhorn EW, Black PG, Franklin JL, Goodberlet M, Carswell J, Goldstein AS. 2007. Hurricane surface wind measurements from an operational stepped frequency microwave radiometer. *Monthly Weather Review* **135**(9).

Velden C, Harper B, Wells F, Beven JL, Zehr R, Olander T, Mayfield M, Guard C, Lander M, Edson R, *et al.* 2006. The dvorak tropical cyclone intensity estimation technique: A satellite-based method that has endured for over 30 years. *Bulletin of the American Meteorological Society* **87**(9).

Wang Y, Wu CC. 2004. Current understanding of tropical cyclone structure and intensity changes – a review. *Meteorology and Atmospheric Physics* **87**(4): 257–278.

Webster PJ, Holland GJ, Curry JA, Chang HR. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309**(5742): 1844–1846.

White A, Björkman K, Grabowski E, Letelier R, Poulos S, Watkins B, Karl D. 2010. An open ocean trial of controlled upwelling using wave pump technology. *Journal of Atmospheric & Oceanic Technology* **27**(2).

Wille H, Rodriguez M, Kasparian J, Mondelain D, Yu J, Mysyrowicz A, Sauerbrey R, Wolf JP, Wöste L. 2002. Teramobile: A mobile femtosecond-terawatt laser and detection system. *The European Physical Journal - Applied Physics* **20**(03): 183–190.

Willoughby H, Jorgensen D, Black R, Rosenthal S. 1985. Project stormfury: A scientific chronicle 1962-1983. *Bulletin of the American Meteorological Society* **66**(5): 505–514.

Wood R. 2012. Stratocumulus clouds. *Monthly Weather Review* **140**(8).

