Acta Astronautica 107 (2015) 208–217

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Space options for tropical cyclone hazard mitigation

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ARTICLE INFO

Article history:
Received 4 July 2014
Received in revised form
20 October 2014
Accepted 16 November 2014
Available online 25 November 2014

Keywords:
Space systems
Remote sensing
Natural disaster prevention
Space solar power
Tropical cyclones
Hazard mitigation

ABSTRACT

This paper investigates potential space options for mitigating the impact of tropical cyclones on cities and civilians. Ground-based techniques combined with space-based remote sensing instrumentation are presented together with space-borne concepts employing space solar power technology. Two space-borne mitigation options are considered: atmospheric warming based on microwave irradiation and laser-induced cloud seeding based on laser power transfer. Finally technology roadmaps dedicated to the space-borne options are presented, including a detailed discussion on the technological viability and technology readiness level of our proposed systems. Based on these assessments, the space-borne cyclone mitigation options presented in this paper may be established in a quarter of a century.

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 [1,2]. 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 [3,4].

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 [5]. Over the past 10 years, several large tropical cyclones with damage costs higher 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 [6].

While considered traditionally as acts of fate and out of reach of human influence, researchers have started considering possible methods to weaken tropical cyclones to mitigate future catastrophic impacts of tropical cyclones on cities and civilians [7–15]. First attempts to mitigate tropical cyclone hazards occurred in the framework of Project Stormfury, where hurricane seeding experiments were conducted in the United States from 1962 to 1983, injecting silver iodine particles using aircrafts to reduce cyclone wind speeds by targeting the cyclone's internal dynamics [7]. Other concepts were later proposed, such as marine cloud brightening, offshore wind turbines, ocean up-welling, and microwave energy transfer. Numerical simulations of tropical cyclone intensity reduction have been performed and ground-based technical concepts devised [8,9,11–15]. To complement these works,

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http://dx.doi.org/10.1016/j.actaastro.2014.11.022

this paper investigates potential space contributions to currently conceived tropical cyclone hazard mitigation concepts.

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; however their potential for natural disaster prevention might not be fully exploited. In addition to remote sensing applications, space in principle also offers options for a more active role including reducing the threat posed by such developing storm systems. This paper investigates space options to mitigate the impact of tropical cyclones on cities and civilians.

This paper is divided as follows. Section 2 describes the mechanisms of tropical cyclone formation and dissipation. Section 3 presents an overview of ground-based methods and means for threat reduction together with possible space contributions including remote sensing instrumentation. Section 4 presents space-based concepts for tropical cyclone hazard mitigation. Two different mechanisms are considered here: 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 improve the tropical cyclone hazard mitigation efficiency a high-accuracy and high-resolution forecast system would be needed, described as the Earth Meteorological Forecast System in section 4. Section 5 concludes with recommendations for 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 storms to develop. As 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, gathering thunderclouds in a cluster over warm ocean waters. At this stage cyclonic circulation can develop via the Coriolis effect due to Earth's rotation, fueling 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 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 [16].

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 fueled 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 also 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 vapor 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 [17–19].
  Anthropogenic or naturally occurring changes to the tropospheric temperature structure also induce significant wind shear as the latter depends on the horizontal gradient of the temperature field at several vertical levels [19]. 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 could disrupt the cyclone's symmetry, impeding the release of latent heat in the structure and therefore reducing the cyclone intensity. See [20,21] for more information on the impact of vertical wind shear on cyclone intensity change.
- *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 heat 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 for tropical cyclone hazard mitigation

Several ground-based techniques have been proposed to mitigate the damage of tropical cyclones. In this section,