Moonshot R&D MILLENNIA* Program

*Multifaceted investigation challenge for new normal initiatives program

「Research and development on typhoon control and typhoon power generation, and initiative research on practical implementation with the aim of achieving the Moonshot Goal」

Initiative Report

July 2021

Brainstorming Team「**Typhoon Shot**」

Team Leader：
Hironori Fudeyasu
(Professor, Faculty of Education, Yokohama National University)

Sub-Leader：
Shunsuke Kado
(Manager, Deloitte Tohmatsu Consulting LLC)

Team Member：
Kazuhisa Tsuboki
(Professor, Institute for Space-Earth Environmental Research, Nagoya University)
Masaki Satoh
(Professor, Atmosphere and Ocean Research Institute, The University of Tokyo)
Nobuhito Mori
(Professor, Disaster Prevention Research Institute, Kyoto University)
Hideki Hayashi
(Visiting Fellow, New Energy and Industrial Technology Development Organization)
Akio Kawamata
(Senior Staff Officer, Kawasaki Heavy Industries, Ltd.)
Daisuke Kato
(Research Officer, The Tokio Marine Research Institute)
Yutaka Terao
(Professor Emeritus, School of Marine Science and Technology, Tokai University)
Taiga Mitsuyuki
(Associate Professor, Faculty of Engineering, Yokohama National University)

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I. Concept

1. Proposed Moonshot (MS) Goal

1.1 Overall goal

To realize a safe, stable, and sustainable society by converting the "threat" of typhoons into a "blessing" and a resource.

1.2 Vision for a 2050 society

A day in 2050 — a news reporter announces the following: "Today, Typhoon No. △ was generated in the sea south of Japan. The Japanese government predicted that Typhoon No. △ will pass through × city in ○ Prefecture three days from the day of □ at approximately noon. The associated organizations were instructed to reduce the rainfall intensity to a maximum of 50 mm/h and wind speeds to a maximum of 20 m/s. Additionally, typhoon power generation will increase the electricity supply in the region around ○ Prefecture, so this month's electricity bills will be reduced by approximately half…" ○ Prefecture resident says: "I'm so happy that a typhoon is coming! My electricity bills this month will be half the usual price!'.

This is a proposed scene from daily life of the 2050 we envisage (Fig. 1). Typhoons cause enormous levels of damage every year, and humans can do little to prevent this. We aim to transform the typhoon "threat" to a "blessing" that yields water resources and energy by artificially controlling the power of typhoons to generate electricity. This is a vision of the near future proposed by our team. To this end, we seek to achieve "artificial control of typhoons" and "power generation by typhoon power generation vessels utilizing typhoon energy".

Under our 2050 vision, the courses of typhoons are accurately predicted, their forces can be artificially controlled, and their energy can be used to generate power. Typhoons are seen not as "threats" that rob people of their lives and property but as "blessings" that supply energy. This technology will be transferred from Japan to the rest of the world, transforming the lifestyles of many countries suffering from typhoons, cyclones, and hurricanes (e.g., Taiwan, the Philippines, India, and the United States), bringing stability to people all over the world. There is less concern about weather-related natural disasters (specifically typhoons), meaning that production activity in Japan is also stabilized. Weather disaster risks will be reduced, and Japan, having increased its renewable energy supply, has raised its appeal as a base where industry can be conducted in a safe, stable, and environmentally friendly manner.

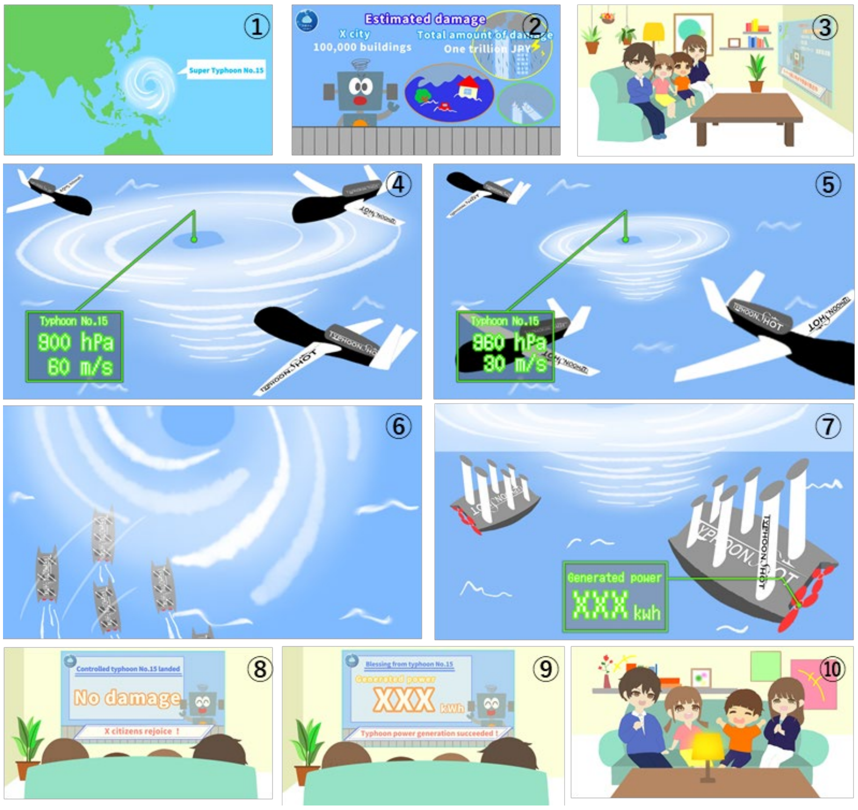

Fig. 1:　Our vision of 2050

2. Targets and milestones

The targets and milestones towards achieving the MS Goal are as follows.

【2050】

- By 2050, technology for typhoon control based on seeding impact substances from aircraft will have been achieved for events expected to cause major damage. Human/economic damage caused by typhoons has been reduced to zero.
- By 2050, electric energy generated and stored by typhoon electricity generators using accurately predicted and controlled typhoons will be transported to Japan.

【2030】

- By 2030, weather prediction and simulation technology will have been developed, and the accuracy of typhoon track and intensity prediction will have been improved. Announcements on appropriate mitigation strategies will be communicated to the public based on a typhoon's intensity and at-risk areas, thereby supporting disaster prevention/reduction action.

This overall MS Goal is to "change typhoons from threats to blessings" (Fig. 2), to shift the negative of losses in human lives and property to zero, and extract energy from typhoons. Reducing typhoon losses to zero does not mean preventing all typhoon influences. Instead, damage can be prevented by lowering the forces of typhoons to within manageable wind speeds and rainfall intensities. While typhoons can cause damage, they can also serve as a water resource. They also play an important role in maintaining the global energy balance and ecosystem in the atmosphere and oceans. Thus, the MS Goal aims to control typhoons only when there is a risk that the capacity of the infrastructure designed to withstand these events could be exceeded.

The ideal form of control is to "minimize the damage caused by typhoons." We will accurately estimate the damage of typhoons predicted to cause disasters and identify controls to minimize damage based on controlled computer-based experiments with the assumption that any damage expected to occur without controlled intervention will not be exceeded in any region. The intensity and course of typhoons will be controlled based on the developed methods. For example, one feasible example is to reduce the intensity of a typhoon by 10% and shift its track by approximately five degrees at most. As the forces acting on buildings are proportional to the square of the wind speed, the impact of storms on buildings can be significantly reduced with even small decreases in wind speed. Thus, if the wind speed of a typhoon with maximum gusts of 60 m/s is reduced by 10%, building damage rates could be reduced to 60–72%. For example, much of the damage caused by Typhoon No. 21 in 2018 was associated with strong winds. Assuming that approximately half of the total damage caused by this event resulted from strong winds, reducing the maximum instantaneous wind speeds during this event (58 m/s in Osaka) by 10 m/s would reduce damage by approximately 130-190 billion yen. Therefore, typhoon disaster mitigation using such methods may greatly reduce economic losses. Furthermore, as typhoon storm regions are limited to approximately 100 km of the right side of the advancing direction of the storm center, even slight changes in a storm track (a few degrees) could greatly reduce damage.

Next, we envisage changing negatives to positives by converting the power of typhoons into usable energy. The principle of power generation is to receive the crosswinds of a typhoon with a sail behind the navigable semicircle (i.e., the semicircle on the left side of the typhoon track where the wind speeds are weakened by the movement of the typhoon itself and, thus, allows for the passage of ships). This would involve navigating sailing vessels at the same speed as the moving typhoon and turning a screw propeller in the ocean to generate power. Assuming a vessel propeller diameter of 28 m, a vessel speed of 9 m/s (i.e., the moving speed of a 32 km/h typhoon), and a twin propeller efficiency of 0.3, the power generation capacity is calculated to be 0.14 GW, which is extremely high compared power generation using ordinary wind and ocean current technologies. This is because the density of seawater is approximately 800 times higher than that of air, and the moving speed of typhoons is approximately three times higher than ocean currents; power generation capacity is proportional to the cube of the flow velocity and directly proportional to the density. Thus, assuming that 20 typhoons per year were tracked for five days, the amount of electricity generated could be 3.3×10^8 kWh per vessel, which compared to a total annual power generation in Japan of approximately 10^{12} kWh. Methods of electrolyzing seawater and transporting the obtained hydrogen, storing energy in batteries at the bottom of the vessels, transporting it to land by ship, and transmitting microwaves to nearby remote islands and offshore bases have all been considered.

The development of a new market (business) of typhoon control and typhoon power generation from the realization of this MS Goal is also important.

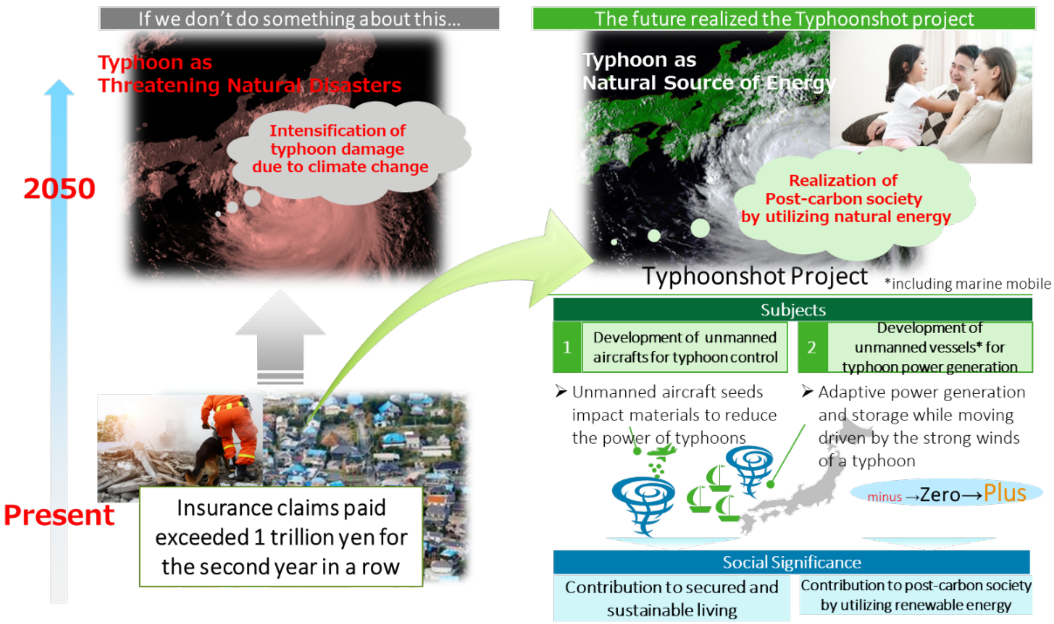

Fig. 2: Targets of the Moonshot Goal

Two important factors indicate that the MS Goal and supporting targets are feasible.

Typhoons are sensitive

Typhoons are extremely large and fierce phenomena, but they change drastically in response to slight changes in seawater temperature and atmospheric conditions. The intensity and course of typhoons are known to change due to changes in the eyewall of typhoons, as well as spiral rainbands and cirrus clouds in the upper outflow layer. Furthermore, the MS Goal is not the first time humans have explored opportunities to control typhoons. In the 1960s, when humanity aimed for the Moon, the United States implemented the hurricane control experimental 'Project Stormfury' (Willoughby et al., 1985)[41][15]. This was an attempt to diminish the intensity of hurricanes using silver iodide seeding. Available records indicate that this approach was successful, although efforts were eventually suspended as a direct causal link could not be proved. Today, we have the advantages of computer simulations, which were not available even 50 years ago. Thus, scientifically evaluating effective typhoon control methods is increasingly feasible based on numerical models and typhoon simulators on the basis of aircraft- and satellite-based observation data.

Ships can be designed to withstand typhoons

The image of an anchored tanker becoming unmoored and colliding with the connecting bridge at Kansai International Airport due to the landing of Typhoon No. 21 in the Kansai region in 2018 both shocked many people and made them realize the powerlessness of humans in the face of typhoons. Can a ship head straight into a typhoon with sufficient energy and remain intact? Theoretically, this is possible.

Sailing ship at typhoon speeds in the navigable semicircle of a typhoon and rotating a screw propeller in the ocean to generate electricity has been theoretically considered and verified by the model test in pools. There have also already been international certification applications for marine-based turbines to obtain wind power in typhoons. In the case of ships or vessels, autonomous ship operation is required to ensure the safety, and the technologies for remote control is already at the demonstration stage. Indeed, autonomous ship maneuvering and operation is at the initial stages of research, indicating sufficient potential feasibility.

3. Background

3.1 Why now?

Social demand

Intensifying meteorological disasters

Strong typhoons have continued to make landfalls over Honshu in recent years, and associated severe damage from storms and floods have continuously occurred. Figure 3 shows the number of deaths and missing individuals due to major typhoons as well as changes in pressure drops and storm surge from 1945 to 2018. Many strong typhoons (pressure drops) that landed on Honshu were observed before 1965 and after 1990, and typhoons accompanied by storm surge anomalies of over 2 m have tended to change similarly. There was also a significant amount of damage, including several hundred deaths and missing people before 1960, but this has greatly reduced since. Notably, the passage of strong typhoons through Osaka and Tokyo in 2018 and 2019 resulting in damage unlike anything previously recorded.

Typhoon No. 21 in 2018 (Jebi) reached 915 hPa on August 30 and inflicted extensive damage centered in the Kinki region. Typhoon No. 15 in 2019 (Faxai) passed over the Miura Peninsula before 3 am on the 9th and reached maximum wind speeds of 35.8 m/s in Chiba city, causing significant damage in Chiba Prefecture. Typhoon No. 19 (Hagibis), which occurred after Faxai in October, developed into a large-scale and violent typhoon that landed with great force (central pressure = 960 hPa) on the Izu Peninsula. Maximum instantaneous wind speeds of 43.8 m/s were recorded in Yokohama city, and the 24-hour precipitation amount in Hakone city was 945.2 mm. The non-life insurance payments from these three typhoon events in 2018 and 2019 exceeded one trillion yen each year.

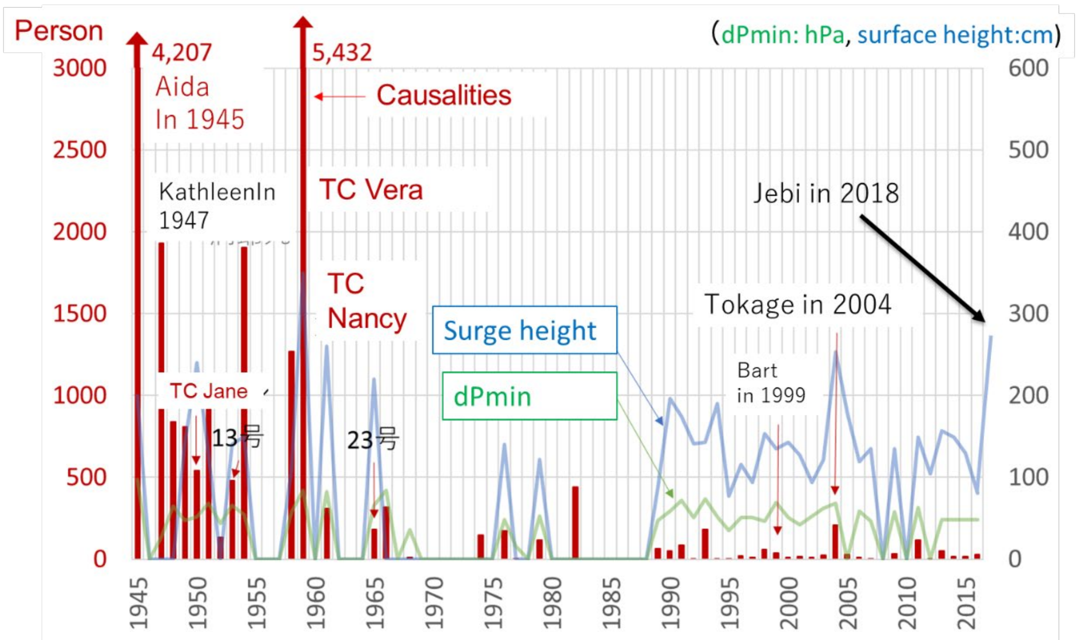

Fig. 3: Deaths and missing people from major typhoons as well as changes in pressure drops and storm surge anomalies over time (modified materials created from Professor Isobe, Kochi University, based on examples recorded by the Japan Meteorological Agency[19]).

The Japan Society of Civil Engineers Resilience Technical Review Committee (2018)[20] estimated that direct and indirect economic damage and flood damage in the event of a maximum-level storm surge in Tokyo would be 110 and 62 trillion yen, respectively. As well as significant damage to infrastructure and other physical assets, an estimated 8,000 and 2,100 lives would be lost due to storm surge damage and flood damage, and 1.4 and 1.26 million people would be affected overall, respectively.

Increased greenhouse gas emissions and global warming are not only increasing global atmospheric temperatures and sea levels but will also affect natural disasters. Warmer future climate conditions are predicted to change the sea-surface temperature and stability of the atmosphere, which are important features for typhoon development, and many studies have predicted an increase in the intensity of typhoons (Knutson et al. 2015[9]; Yoshida et al. 2017[18]; Yamada et al. 2017[17]). Indeed, an increase in the intensity of meteorological hazards in the mid-latitudes, including typhoons and extremely strong winds from super-typhoons making landfall on the Japanese mainland, has been predicted (Tsuboki et al. 2015[12]).

Among the effects of global warming, the most critical influence on storm and flood damage to Japan is the intensification of typhoon forces and significant increases in damage caused by strong winds, slope failures, river floods, and coastal floods. It is predicted that global warming will further increase previous damage estimates that will have catastrophic implications for Japan. The forces applied to structures due to water level increases from storm surges and wind are proportional to the square of wind speed. Therefore, an increase in typhoon intensity of just 10 hPa will have major effects on the scale of the resulting disaster. Dealing with these risks requires the further strengthening of disaster prevention infrastructure alongside long-term responses and substantial costs.

The MS Goal focuses on research that can directly lead to reducing potential damage by adjusting the level of risk and the intensity of hazards associated with typhoons. Specifically, the MS research is expected to reduce the costs of disaster prevention/reduction projects, which are currently heavily focused on disaster recovery. As such, this work is expected to be a highly beneficial research investment.

Expectations for new 'green energy'

Japan declared the "2050 Carbon Neutral" strategy with the aim of promoting green growth to become carbon neutral by 2050 in line with global greenhouse gas reduction targets. Green growth strategies require the more active introduction and efficient operation of renewable energy technologies with an emphasis on supporting offshore wind power and storage batteries. At the same time, satisfying electricity demand using only existing renewable energy sources is unrealistic, and it is assumed that this will require the development of additional renewable energy sources. Therefore, research and development of alternative renewable energy acquisition methods are needed alongside the efficient operation of existing renewable energy technologies. Unlike conventional offshore wind power generation, typhoon power generation can expand the available methods of renewable energy generation, which has great potential for supporting Japan's long-term green growth strategy.

Scientific and technical demand aspects

Supercomputer development

The hurricane control experimental 'Project Stormfury' implemented in the United States in the 1960s provides records of success in mitigating hurricanes, but it was not proven whether this was due to the intervention or occurred naturally (Willoughby et al. 1985[15]). Therefore, subsequent control demonstration experiments were suspended. The term "artificial control against typhoons" was also mentioned in the Basic Act on Disaster Countermeasures enacted in Japan in 1961, but this did not reach a technical level where the government could provide sufficient support.

Recent developments in computer technologies have allowed the use of detailed numerical prediction models to create an environment in which typhoon simulations can be implemented over a wide range of regions. Therefore, it is now possible to distinguish between artificial control effects and natural phenomena by implementing highly accurate observational monitoring data and aircraft observations while considering a range of initial values/boundary conditions using numerical simulations.

Multiple strong typhoons have recently hit Japan and have caused significant damage. There is a strong demand, therefore, for refining numerical prediction models and acquiring highly accurate initial values/boundary conditions to tackle these issues using Japanese technologies in support of the artificial control of typhoons as stipulated by the Basic Act on Disaster Countermeasures.

Observational technology development

Except for meteorological satellites, there are almost no current means of observing typhoons developing offshore in the Western North Pacific. With the exception of observations of typhoons made by Taiwan, aircraft observations have not been conducted since the termination of the US military observation in 1987, and so large errors have been included in estimates of typhoon intensity based on satellite observations, and predictions improved little. To solve these problems, a group led by Nagoya University in 2017 and 2018 succeeded in high-altitude penetration observations in the eye of a super-typhoon using a commercial Japanese aircraft, and conducted in situ dropsonde observations of central pressure and maximum surface wind speed (Yamada et al. 2021[16]). Improvements in typhoon prediction were achieved by enabling the observation of the full layer from a high altitude in the warm-core inside the eye, which controls typhoon intensity, to the sea surface, and incorporating aircraft observation data into numerical weather prediction models by data assimilation (Ito et al. 2018[6]). Furthermore, the warm-core structure of the observed super-typhoon was reproduced using a numerical model that resolves clouds, and its characteristic formation mechanism was clarified (Tsujino et al. 2021[13]). The development of meteorological satellites also showed the possibility of learning about the movement in the typhoon eye by obtaining high-accuracy knowledge on the movement of clouds (Tsukada and Horinouchi, 2020[14]). Aircraft observational data were also used to verify the satellite observations. Aircraft observations of unique typhoons have also become possible in Japan, and these serve as a foundation for the proposal of the MS Goal. These recent developments have rapidly increased the feasibility of achieving this goal.

Unmanned maneuvering technology

The development of unmanned maneuvering technology has rapidly advanced, mainly in the automobile sector, owing to the evolution of the Internet of Things (IoT) and artificial intelligence (AI) technologies as well as improvements in the communication environment. The development of unmanned operation is also expanding in the aircraft and shipping sectors. The Nippon Foundation initiated a joint technology development program for demonstration experiments of unmanned vessels in 2019, and announced their aims for the practical development of unmanned vessels by 2025[23].

Having a vessel crew on board typhoon power generation vessels rushing into typhoons and operating under strong winds is unrealistic in terms of safety. Therefore, unmanned maneuvering and operation are an essential requirements, and existing research and development indicates that practical applications are within reach.

3.2 Social significance

"Contribution to a safe, lively, and sustainable society" by typhoon control

In recent years, the typhoons hitting Japan have intensified and cause significant amounts of damage. At the same time, the government is taking measures by ensuring that Japanese infrastructure is resistant to disasters through national resilience strategies. On the other hand, Japan is blessed with abundant and seasonally diverse nature that has fostered a rich culture. A world in which we are surrounded by artificial concrete structures, far removed from nature, poses a threat to this important aspect of Japanese culture. Furthermore, whether continuing to build stronger infrastructure in the face of environmental hazards is questionable, as tax revenue is expected to decrease in the future with a shrinking population.

Accepting such limits to national resilience plans, the social need for minimizing the intensity of natural disasters is clear. Our goal for normalizing typhoon control is to remove the threat of catastrophic disasters and enable coexistence with nature. It is our belief that this would create a sustainable society in which people living in Japan would be able to live safe and vibrant lives.

"Contribution to a carbon-free society" by creating renewable energy through typhoon power generation

As mentioned above, Japan has announced the promotion of green growth strategies along with becoming carbon neutral by 2050 in support of global greenhouse gas reduction targets. Green growth strategies aim for the active introduction and efficient operation of renewable energy technologies, but it must be recognized that research and development on new renewable energy acquisition methods is needed in addition to the efficient operation of existing renewable energy sources. Offshore wind power generation, for which there are high future expectations, is also thought to reach the upper limit of cost-benefit as a power-generation resource. Furthermore, the quantity of the wind energy resource is limited by the availability of suitable offshore locations and the need to maintain transmission lines.

Typhoons could be added to the list of potential renewable energy resources if energy can be efficiently obtained from them. Japan has an advantage for achieving typhoon power generation because it is regularly hit by typhoons with massive amounts of energy, and the country has a vast exclusive economic zone. It is entirely possible for Japan, which has been called 'energy-poor', to become a renewable energy superpower in a carbon-free society by turning the threat of typhoons into a blessing.

"Contribution to the technological superpower of Japan" through typhoon innovations

The scientific and technological capabilities of Japan have significantly declined compared to the rest of the world, both in terms of the quantity and quality of publications and various competitiveness indices. Japan boasted the second-largest share of publications in the world in the early 2000s but has since fallen to fifth place in 2017 behind the United States, China, the United Kingdom, and Germany. Furthermore, of the top 1% of "high-impact publications" commonly cited by other researchers, Japan fell from fifth to twelfth between 2002 and 2017.

Parallel to these changes in scientific and technological capabilities, the industrial competitiveness of Japan has been declining. For example, in the semiconductor industry, which has been called the "rice" of industry, Japan swept the world in the mid-1980s and exceeded 50% of the global share; yet the current share is just 6%. In the case of shipbuilding, Japan controlled a majority of the global share for a long period after World War II, but this has since decreased to 22% of the global share (of construction volume) in 2020.

Investing in research and development as well as human resources, which other nations like China and the United States have been steadily implementing for over 20 years, is essential for reviving the scientific and technological capabilities and industrial competitiveness of Japan. However, improving existing industrial technology is difficult. The development of Moonshot-type technologies that support a future society that is entirely different from todays, that creates new markets, and that enables the development of new technologies and products is, therefore, necessary. Japan should once again aim to become a world leader in technology with a focus on these new potential technologies and industries.

Achieving the goal of controlling and utilizing typhoons (for power generation) is a significant opportunity in this context, and can support the revival of Japan as a technological superpower. As well as having significant benefits for Japan, it is also our belief that a focus on developing these new technologies can bring the same blessings to other countries affected by typhoon damage.

"Contribution to the development of globally competitive human resources" with seamless industry-academia research

Young researchers and entrepreneurs will be trained in the process of achieving the MS Goal. This is essential as achieving this goal requires solving a wide range of scientific/technological and social issues, and developing human resources that will be responsible for the long-term research and development (until 2050) to solve these challenges. Therefore, the research initiatives supporting the goal should be seen as an opportunity to strategically develop human resources for research. This not only includes expertise in meteorology, computer science, marine engineering, and aerospace engineering, but also new emerging research fields such as geoengineering, with a specific focus on typhoon control. In addition, social science research that targets innovation should also be included. As a consequence, a broad scope of research by fostered researchers is expected to be developed and activated.

Promoting the commercialization of research outputs for wider implementation and the establishment of start-ups that utilize by-products created during research and development would further attract investment, enabling a stable and sustainable research and development sector and accelerating advances towards the overall MS Goal. As with the development of young researchers, supporting entrepreneurs during this commercialization process would further help achieve the goal.

Overall, by providing training and support for researchers and entrepreneurs as part of the Moonshot project, a younger generation of globally competitive individuals could be created. As well as supporting progression towards achieving the MS Goal, this has the potential to restore the industrial competitiveness of Japan.

3.3 Action outline

Achieving this proposed goal requires the participation of researchers not only in meteorology but also in disaster prevention/reduction, computer science, marine engineering, and aerospace engineering. Participation in industry is also essential. For example, the participation of heavy industry and electrical industry will be needed for the development and manufacture of the aircraft required for typhoon control as well as the typhoon power generation ships and power generation, storage, and transmission systems required for typhoon power generation. The participation of insurance companies that have past disaster data and consulting companies that conduct trial calculations will also be needed to determine when control interventions should be made.

Typhoons are a phenomenon in East Asia, and so typhoon control and power generation will need to be conducted based on a consensus with neighboring countries. International laws need to be developed, and guidelines need to be formulated by international organizations.

It is assumed that it will be appropriate for a government to determine whether to implement actions such as controlling a typhoon likely to affect an extensive area and many people. Decisions to implement an intervention would need to be made quickly following the development of a typhoon, which will require smooth cooperation beyond the existing framework of administrative organizations.

Above all, it is essential that new typhoon control and typhoon power generation technologies are fully understood by all stakeholders, including the general public, to foster demand and ensure wider support.

4. Benefits for industry and society

Changes brought to society

Achieving typhoon control would not only free society from the mental pain of loss of human life but can also provide a greater sense of social and industrial security by reducing economic damage and uncertainty. Reduced human and financial costs of disaster prevention at the national and municipal levels would also release resources for investment elsewhere. The realization of such a stable society would increase the appeal of Japan for international investments and the influx of high-quality human resources. Furthermore, the quantity of new and renewable energy resources that would be realized through typhoon power generation can promote the transition to renewable energy and support a carbon-free society. The international standing of Japan is also expected to increase by presenting effective and novel solutions in supporting a carbon-free society, which is a common worldwide aspiration.

Changes brought to industrial structure

Typhoon control and typhoon power generation technologies will require input from many different fields, and it is expected that various businesses markets would be generated not only during the achievement of the MS Goal but also in the subsequent years and decades. While progressing towards the achievement of typhoon control, the development, manufacturing, and operation of satellites, unmanned aerial vehicles (UAVs), and high-performance super computers will be required, with associated development in related fields. The control implementation stage will require aircraft, impact substance seeding equipment, and impact substance procurement, which will require the development of associated industries. Infrastructural industries have been at the center of disaster prevention and mitigation to date. Still, there have been high barriers to technology exports overseas due to regional characteristics and the large scale of the projects. On the other hand, industries closely related to the MS Goal are manufacturing industries such as aircraft manufacturing and ship manufacturing so that export would be much easier. In other words, it is possible to expand the market of industries related to disaster prevention and mitigation on a global scale.

Business prerequisites would change considerably in a world in which the MS Goal is realized, where the damage caused by typhoons was no longer a concern. For example, if strong typhoon winds are no longer an issue, more skyscrapers could be built in Japan; and if storm surges are no longer a concern, cities could be built on the waterfront or on the water with substantial lower risk. In these ways, the degree of freedom that businesses could have increases, having a beneficial effect on urban development. It is also expected that new industries will be created by applying safe flight technologies over and inside typhoons, utilizing typhoons as tourism opportunities, such as sightseeing and rushing into the eye of a typhoon, and further utilizing the data acquired from typhoon control and power generation systems.

The realization of a society where no human or asset damage occurs from typhoons would also change the premise of supply chain management and business continuity planning (BCP). Typhoon impacts would no longer need to be considered on production bases and distribution networks, and so an efficient supply chain could be constructed and resources currently allocated to typhoon countermeasures could be allocated elsewhere. The stabilization of the business macroenvironment, i.e., the natural environment, would also improve the appeal of Japan as a business base, having a positive effect on Japan's economic development including foreign investment, the number of companies expanding into Japan, and the working population.

Typhoon control market

The damage caused by meteorological disasters worldwide is increasing every year due to the effects of global warming, corresponding to an average 5% increase between 2000 and 2020[21]. Assuming that this trend will continue in the future, the damage costs of typhoons (including cyclones and hurricanes) is expected to reach 7.8 trillion yen in Japan and 30.5 trillion yen worldwide. The typhoon control that we propose aims to reduce this damage to zero. Assuming that for the MS project, the Benefit (B) / Cost (C) = 2, the 2050 domestic and global market size of typhoon control is estimated at 3.9 and 15.2 trillion yen, respectively.

Typhoon power generation market

Power consumption in Japan by 2050 is estimated to be 1.3–1.5 trillion kWh. Furthermore, the Ministry of Economy, Trade, and Industry proposed a study based on the following power source composition in 2050[25]:

・Renewable energy： 50–60%
・Thermal / nuclear power： 30–40%
・Hydrogen / ammonia energy： 10%

Efforts to increase the fraction of renewable energy are global, and it is expected that research and development will proceed toward this in Japan; however, based on the current trajectory, at the most, the proportion of renewable energy is estimated to be 25% by 2030. Achieving the renewable energy goals would, therefore, require a further increase of 25–35%. Typhoon power generation could undoubtedly contribute to achieving this. Adopting a medium/long-term renewable energy (wind power) cost target of 8–9 yen/kWh, the typhoon power generation market estimate covering the expected increase in the renewable energy fraction by 2050 is estimated at 4.7 trillion yen; under a 100% renewable energy (typhoon power generation 65%) scenario, the market estimate is 8.8 trillion yen.

II. Analysis

1. Essential scientific/social components

The proposed MS Goal is to achieve the vision of "changing typhoons from a threat to humanity to a blessing" by 2050. The two items of typhoon control and typhoon power generation have been set as technological development targets, but high-accuracy predictions of typhoons are an essential and common requirement for achieving these targets from a scientific and social perspective. High-accuracy predictions must distinguish between artificial control effects and natural phenomena, so that informed decisions can be made. The comparison of the effects of typhoon control and power with its potential costs (i.e., business feasibility evaluations) is also an important issue when evaluating the sustainability of this technology.

In the following sections, we summarize the scientific and technological issues that need to be considered when developing high-accuracy predictions of typhoons, typhoon control, and typhoon power generation, for evaluating business feasibility, and for addressing potential social challenges while working towards the overall MS Goal.

Scientific and technological issues in high-accuracy typhoon prediction

The current state of typhoon prediction is such that high-accuracy predictions are expected to be realized through high-resolution and large-scale numerical models using supercomputers; however, no direct measurement data has yet been obtained, including the central pressures and wind speeds of typhoons. Furthermore, the change/vulnerabilities and mechanisms of the initial perturbations of typhoons are insufficiently understood. Therefore, there remains a need to develop high-accuracy numerical prediction models based on the continuous development of supercomputers, accurate monitoring, and the elucidation of detailed typhoon mechanisms based on direct observations from aircraft and remote sensing observations from satellites and ground-based radars. Specifically, accurate typhoon monitoring (via the acquisition of true values and boundary conditions), the construction of high-resolution typhoon prediction models, and the utilization of supercomputers assist in the refinement of accurate prediction simulations and enable the evaluation of typhoon control, typhoon power generation, and business feasibility.

Scientific and technological issues in typhoon control

As mentioned above, a bottleneck exists in current predictions whereby artificial typhoon control effects and natural changes cannot be easily distinguished. Efforts are needed to resolve this issue, including the development of high-accuracy prediction models, the construction of a typhoon control theoretical framework, and establishment of the typhoon control systems themselves. The manner in which a typhoon changes when a certain intervention is made (e.g., different types and amounts of materials seeded in a certain location within the typhoon) represents the typhoon control theory, which should be predicted by high-accuracy typhoon simulations, and on which basis artificial control system can be development and implemented in practice. This approach is underpinned by the need to verify the differences between artificial control effects and natural changes.

Efforts toward the construction of a typhoon control theory must include the selection of appropriate impact substances as well as the setting and optimization of seeding methods. Impact substances are transported to the ocean where typhoons develop and are seeded in large quantities over the ocean. This means they not only need to have a minimal environmental impact but must also show high mass vs. effectiveness. The extent to which these impact substances need to be seeded in a typhoon could be analyzed using typhoon control experiments under various conditions using computer simulations. This would inform typhoon control theory by identifying those conditions under which different control effects are observed. Technologically and economically optimizing this process by considering feasible seeding conditions by aircraft (i.e., flight methods that aircraft can perform) and the conditions assumed for artificial control becomes a major issue. In addition to high-accuracy typhoon simulations, there is a need to understand the likely behaviors of typhoons following artificial control interventions. Efforts to establish a typhoon control system must include aircraft planning for implementing the control operations, which must be based on the typhoon control theory. Aircraft operations and design (e.g., load capacity) also need to be realized with as little cost and as few aircraft as possible.

Scientific and technological issues in typhoon power generation

Currently, offshore power generation research is mainly focused on fixed foundation or floating wind turbines . Importantly, wind speeds in Japan are highly variable because typhoons pass frequently, and the failure rate of wind turbines is high relative to other countries. This had meant that the introduction of this technology had lagged behind in Japan. There are, nevertheless, examples of wind turbine development for stable power generation not only in normal environments but also under typhoon conditions, although currently no effort has been made to generate power from typhoons using moving bodies, such as using ships or vessels to track typhoons.

The three scientific and technological issues that need to be addressed to realize typhoon power generation are (1) the high-accuracy prediction of typhoons, (2) the planning of typhoon power generation vessels, and (3) the establishment of a typhoon power generation/storage/transmission system. The high-accuracy prediction of typhoons is essential because typhoons tracks (including their rate of advance and dissipation) need to be predicted with high accuracy. In the case of typhoon power generation vessels, it is necessary to generate the power more than the power demands needed for vessels to head into typhoons and return to port. Although various options can be considered, moving vessels with hard-wing sails or Flettner rotors that track typhoons using their associated strong winds while also generating power by rotating a submersible turbine installed at the bottom of the vessel is desirable. The generated power electricity will need to be stored via direct power transmission, hydrogen conversion and transportation, or storage batteries onboard the vessels. There are various options for electricity storage, and further investigations are required on the types of designs that will be needed.

For the establishment of a typhoon power generation/storage/transmission system, the construction of an overall system for implementing operations is needed. Specific requirements include a remote/unmanned typhoon power generation vessel operation method and storage systems that are optimized for typhoon power generation vessels. Additionally, ships or vessels are complex systems for which individual technologies need to be effectively integrated and installed. Optimizing technologies is, therefore, required to ensure that rapidly evolving individual technological are adopted and successfully integrated into operational systems. Furthermore, full-scale tests will be required, and our aim is to construct a power generation vessel system suitable for commercialization by 2050.

Scientific and technological issues for business feasibility evaluation

The cost: benefit ratio of typhoon control and typhoon power generation is an important element in the business feasibility of the MS project. Typhoon control can be considered a form of disaster prevention/reduction and, therefore, as with embankment and seawall construction, there is a need to identify what the costs are, the extent to which beneficial effects can be achieved, and demonstrate the rationality of the financial investment requirement. The construction of a system that quantitatively demonstrates the effects of typhoon control by reviewing the human and economic costs brought by typhoons in detail is needed to achieve this. Similarly, for typhoon power generation to be considered feasible, its advantageous must be demonstrated relative to other power generation methods in terms of both cost and environmental impact. Importantly, both the potential costs and benefits must also be scientifically verified for a sustainable social system to form.

Social issues for achieving the overall MS Goal

Fostering social acceptance is a potential social issue. A questionnaire survey conducted on 10,000 Japanese citizens nationwide indicated that approximately 62% of the respondents would like typhoon control to be realized. With regard to typhoon power generation, approximately 60% responded that this was appealing. Based on these results, the majority of Japanese citizens have positive expectations for typhoon control and typhoon power generation. That said, approximately 37% of the respondents raised concern about negative impacts on the environment, and some ethical resistance was identified with respect to the notion of artificially controlling nature. Furthermore, approximately 31% of the respondents raised concerns about possible damage to equipment caused by strong winds during typhoon power generation. Fostering public understanding through activities that carefully communicate typhoon control and power generation efforts as well as their effects on nature and society, while also taking concerns seriously, is essential to foster social acceptance.

Discussions involving various stakeholders will also be needed, assuming that typhoon control and power generation will be delivered as a commercial enterprise. This includes who will determine its implementation, who will bear responsibility should undesired outcomes occur, how the public and private sectors will act from decision-making to implementation, the formulation of certification for the aircraft and ships used, and the formulation of international guidelines for the control and utilization of typhoons.

2. Science and technology map

Figure 4 shows an overview of the scientific and technological issues outlined in the previous sections. Here, we explain the research and development requirements for each item, and identify the breakthrough items that will lead to the realization of the MS Goal.

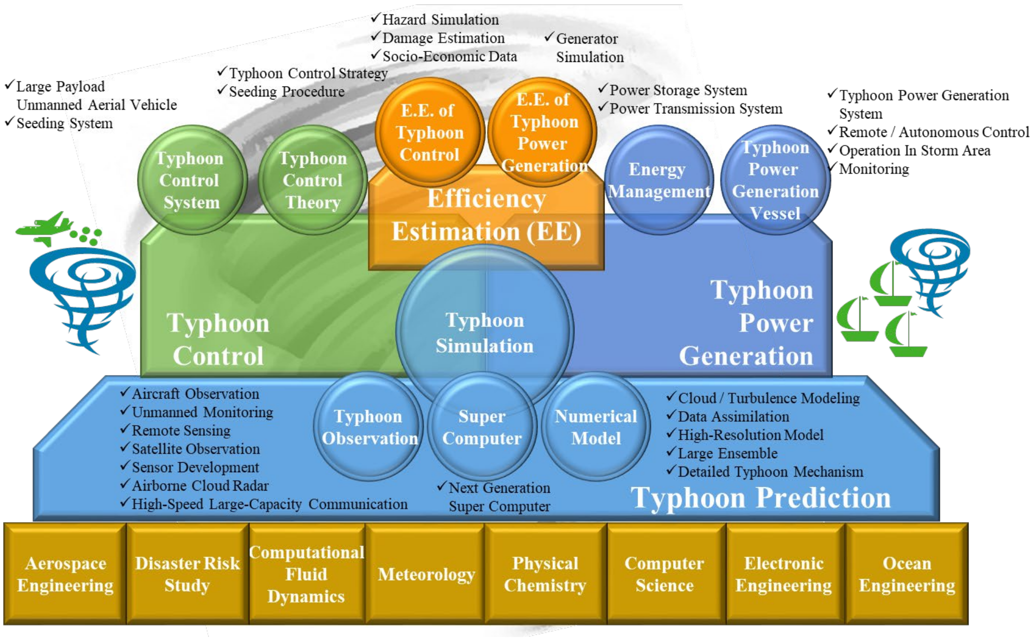

Fig. 4: Overview of the research and development required to achieve the MS Goal

High-accuracy prediction of typhoons

Progress in each of the following items is needed to improve the prediction accuracy of typhoons. Predictions such as the course and intensity of typhoons can be obtained by conducting numerical model simulations on supercomputers by utilizing field observation data. Improvements to numerical models (e.g., by increasing resolution and clouds/turbulence modeling) are also needed to realistically reproduce typhoons, and this requires progress in the scientific understanding of typhoons and time-evolution of environmental atmosphere.

High-resolution observations

Observational data for typhoons over the ocean are currently insufficient, and improving typhoon prediction accuracy requires a greater spatial and temporal resolution of high-accuracy data. To deliver this, direct observations by aircraft are required. It is estimated that approximately 400 million yen is needed annually to observe all typhoons approaching Japan using aircraft, and this will be needed during the first half of the project by 2050. During the second half of the project, the development of observational technologies using unmanned aircraft and ships will be necessary. These data must be transmitted in real-time to typhoon research and forecasting institutes on the ground. Large-scale capacity communication will also be required.

To improve the representation of the internal structure of typhoons, a more accurate determination of their spatiotemporal distribution based on high-resolution and high-frequency (km, approximately five minutes) is needed. A data assimilation database of the internal structure of typhoons must be constructed by utilizing meteorological satellite, aircraft, and ship observations, and ground observations in an integrated manner. This must then be assimilated with the appropriate numerical models. Current knowledge is sufficient for such efforts, and so this line of research should be rapidly advanced. There is large uncertainty in the expression of cloud/precipitation processes in numerical models, which means that understanding of typhoon cloud physics must be verified, improved, and refined based on remote sensing data constraints.

Comprehensive satellite observations, such as from the geostationary meteorological satellite Himawari, are currently used to monitor typhoons. These satellites have a lifespan of approximately 5–10 years, and will need to be continued in the future. The Himawari satellite plays a particularly important role in typhoon monitoring, and so continuing observations in the future is key. Furthermore, the construction and maintenance of an international geostationary meteorological satellite observation network is needed. The Japan Meteorological Agency is currently conducting studies on geostationary meteorological satellites that will act as the successor to Himawari 9, with the goal of a 2028 launch. A potential risk is that the next generation of geostationary meteorological satellites will require new sensors that are internationally in demand, including infrared sounders and lightning-detection devices.

High-resolution and high-frequency radar-based terrestrial remote sensing observations are needed of the typhoons approaching Japan. There is a need to deploy a nationwide phased array of weather radar and dual-polarization weather radar stations. Observations on remote islands in the South Sea (e.g., Ogasawara), where observations are currently sparse, will also be required. Such ground-based remote sensing observation data can be directly used for detailed monitoring of the internal structure of typhoons. This will also be essential to verify and improve understanding of cloud precipitation and to construct a central typhoon database through data assimilation. Recent radar technologies include polarization radar and phase array weather radar, which enable observation at extremely large scales. Therefore, developing large-scale capacity communication is essential for transmitting these data to typhoon research and prediction institutes in real time.

High-accuracy monitoring of typhoon intensity is conducted by implementing dropsonde observations of each development process of a typhoon from a stratospheric UAV capable of flying for approximately one month. A dropsonde device is mounted on a stratospheric UAV, the center of the typhoon is constantly tracked, and long-term and high-resolution dropsonde observations are obtained. Softbank HAPS mobile succeeded in UAV-based stratospheric flight experiments in 2020, and the potential for one-month flights is soon expected to be possible.

Simultaneously, manned aircraft will need to be used to fly around typhoons, and dropsonde observations will need to be conducted at an altitude of approximately 45,000 feet (approximately 14 km) to acquire environmental field data. Penetration observations in the eye of typhoons have been successfully conducted by manned aircraft at high altitudes. Dropsonde observations have also been conducted in the eyes of typhoons to obtain intensity and internal structure data. Given these techniques have already been demonstrated, the next phase is to implement this for many typhoons.

Observing how typhoon clouds change due to the seeding of impact substances is essential for verifying the impact of such substances. This requires a Ka-band cloud radar mounted on an aircraft. While airborne phased array radar in the X and C bands has been successfully developed in the United States, the technology needed to airborne Ka-band phased array radar requires further development.

Continuous improvement and development of high-resolution and high-accuracy numerical models to simulate typhoons

Predicting changes in typhoon intensity, especially rapid intensification, requires numerical models with a sub-km-scale mesh as well as the refinement of physical processes such as cloud physics and turbulent processes. With regard to resolution and the number of ensembles, higher resolutions and more ensembles will contribute to improved prediction accuracy. The numerical reproducibility of the internal structure of typhoons (i.e., eye-walls and outer rainbands) is essential for predicting typhoon intensity, but this remains insufficient. The formation and strengthening of the eye-wall, multiple eye-walls, and eye-wall replacement are associated with changes in typhoon intensity. There are many challenges for improving current numerical models (both dynamic and physical); improving numerical model performance is needed alongside improving the resolution and number of ensembles to improve the accuracy of future typhoon predictions. This requires verification based on actual observation data. Advances in the understanding of typhoon internal dynamics are needed to improve the prediction of changes in typhoon intensity. Furthermore, advances in the understanding of the interactions between typhoons and the environmental field, and improvements in the accuracy of environmental field measurements itself, are needed to improve typhoon track predictions. Investigating dynamic numerical schemes and improving physical schemes, such as clouds and turbulence/radiation, and improving understanding of ocean/land-atmosphere interactions is required to improve numerical models.

High-performance supercomputers

With regard to the future development of supercomputers, it is difficult to expect progress of the technology as an extrapolation of the present progress. Advances have been made in the next generation of supercomputers after the supercomputer "Fugaku," but it is expected that there will be limits to performance based on conventional architecture. Numerical models will also be required to adapt in accordance with a new generation of computers considering limiting factors such as memory throughput and power. Developments such as reconstructing numerical model programs with domain specific language (DNS) will also be needed to correspond to various architectures, and there is a need to train researchers with an adequate computational science background for model development.

Typhoon control

The following sections outline the research and development needs for achieving the MS Goal of controlling typhoons to reduce the level of threat to zero.

Construction of typhoon control theory

Identifying effective typhoon control methods

With respect to methods of typhoon control, the proposed approach involves the seeding of impact substances, as was adopted as part of Project Stormfury in the 1960s. Tropical cyclones such as typhoons and hurricanes form and develop by clouds formation, and their intensity is controlled by the structure and characteristics of the clouds that constitute them. Therefore, the intensity of typhoons changes when their cloud structure changes. It is also known that the distribution of clouds alters the dynamic field of typhoons, thereby changing their course (Fiorino and Elsberry, 1989[3]). Khain et al. (2010)[7] showed that during Hurricane Katrina, which caused catastrophic damage in the United States in 2005, the amount of cloud condensation nuclei (aerosols that form cloud particles) changed the structure around the typhoon, and differences in central pressure occurred of up to 40 hPa. Many studies have shown that changing the aerosols that affect the formation of clouds can, therefore, alter the intensity of tropical cyclones (e.g., Carrió and Cotton, 2011[1]; Rosenfeld et al. 2007[10]; Rosenfeld et al. 2012 [11]). Previous studies have also shown that in addition to aerosols, the distribution of the cloud itself controls the intensity of typhoons (e.g., Fovell et al. 2016[4]). Methods such as blocking heat from the ocean and heating the upper part of the typhoon cloud with microwaves from space could be considered, although this would have a significant negative impact on the marine environment and require substantial space facilities, respectively. Therefore, controlling typhoon intensity by manipulating cloud formation is the most feasible option. Recently, typhoon prediction models have become extremely sophisticated, and the potential of using these in typhoon control experiments was demonstrated in the above-mentioned research. There is high potential for these approaches to be further refined and optimized.

The simulations investigated during this study using computer simulation were as follows. The simulation target was set as Typhoon No. 15 in 2019, and a condition was given where a large quantity of ice crystals was seeded in the eye of the typhoon within 30–50 km square area. As a result of this, the central pressure of the typhoon increased by 3–5 hPa, and the maximum windspeed decreased by 1–3 m/s compared to the simulations without any control intervention. The evaporation of the ice seeded in the eye of the typhoon in the dry area, and the associated evaporative cooling effect, partially cooled the warm air in the center of the typhoon, thereby reducing the pressure and the maximum windspeed.

The adopted area for this artificial control simulation was rather wide, and the quantity of ice crystals seeded was in the order of 10^{12}–10^{13} kg, which would prove difficult to implement in practice. Mass-effectiveness and feasible typhoon control methods must, therefore, be considered in future simulations.

Establishment of an impact substance seeding procedure for typhoon control

When conducting typhoon control by using aircraft, impact substances (e.g., hygroscopic aerosols) are seeded while manned and unmanned aircraft are in flight, so the density of the seeded hygroscopic aerosols is high in the area immediately in the vicinity of the seeding and varies with distance from the seeding point (Fig. 5). This process is, therefore, complex and involves various parameters that vary over time. Effectively modeling the effects of seeding impact substances will, therefore, be key to the implementation of this typhoon control method.

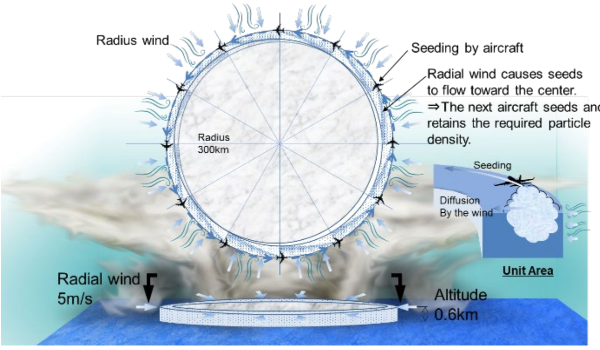

Fig. 5: Image of impact substance seeding

Furthermore, clarifying the sensitive areas of typhoons (where seeding should be focused) will help to reduce the amount of impact substances required and ensure that the maximum effect is achieved from the least resources and over the shortest seeding duration. Based on one hurricane structure/energy balance model (Malkus and Riehl 1960[7], Riehl and Malkus 1961[5]), 50–60% of the total kinetic energy of a hurricane is derived from the release of latent heat in the updraft in the wall cloud, which covers just 2–5% of the total hurricane area. The wall clouds in the eye of a typhoon may, therefore, serve as efficient seeding points. As well as clarifying these technical aspects, investigations are required to optimize the cost effectiveness of this approach.

Establishment of a typhoon control system

Developing aircraft suited to seeding impact substances and the seeding systems that can be installed on them are critical aspects of a successful typhoon control system. Regarding suitable aircraft, Fig. 6 shows the results of estimating the number of aircraft required for seeding conducted by small aircraft with the payload of 1.5 t compared to large aircraft with the payload of 36 t. It is assumed that the aircraft are operated at variable speeds until each aircraft reached the upper limit of the cruising range or the payload. The particle density of the impact substances and the seeding duration are used as the simulation parameters to estimate how large an aircraft would need to be to achieve economically viable typhoon control. Assuming a particle density of 1 kg/km^3 and a seeding duration of 2.5 days based on the literature (Rosenfeld et al. 2007[10]; Rosenfeld et al. 2012[11]), approximately 10 large aircraft or several hundred small aircraft are necessary. Since the number of necessary aircraft of large aircraft is within economically viable range, while that of small aircraft is out of the range, even if aircraft procurement cost is high, aircraft with a greater payload offer advantages in terms of both economic feasibility and technical feasibility. Even if an optimal aircraft size was selected for the typhoon control method, developing aircraft with as large a payload as possible will be an important focus in terms of economic feasibility to reduce the number of aircraft required. Furthermore, the seeding systems to be installed in the aircraft should realize the effective seeding planed through simulation, and they are installed to the aircraft with limited payload. Therefore, it will be necessary to develop the seeding systems which satisfy various conditions such as weight, airworthiness, and so on.

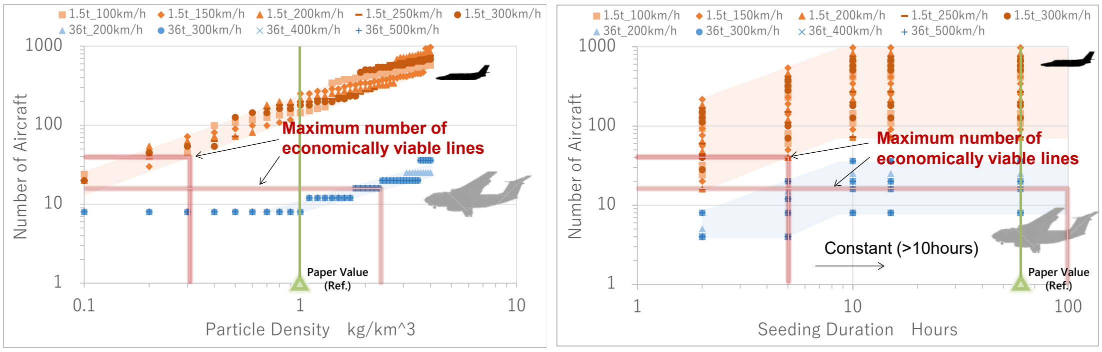

Fig. 6: Number of aircraft needed for economically viable seeding of impact substances for typhoon control

Typhoon power generation

The following sections identify the scientific and technological needs to achieve the MS target for the "utilization of typhoons as a resource" with respect to energy generation.

Typhoon power generation ships

There are various options that can be considered for generating energy power from typhoons using moving vessels; however, considering power generation efficiency, one of the most desirable approach is to use moving vessels to track typhoons with hard-wing sails or a Flettner rotor with rotating submersible turbines underneath to generate power (Fig. 7).

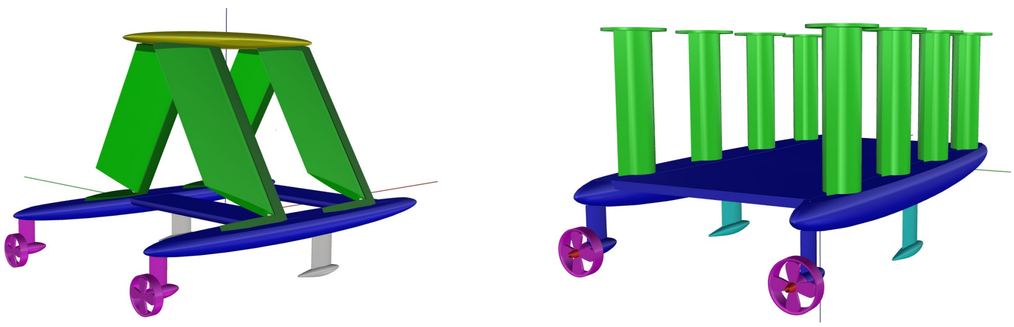

Fig. 7: Concept image of typhoon power generation ship

The technology for propelling ships using the force of the wind with hard-wing sails and Flettner rotors is currently focused on yachts but has also been applied to larger ships or vessels. Using the Flettner rotor as a propulsion device is currently only adopted as an auxiliary form of propeller propulsion; however, in terms of sailing performance, medium-sized yachts propelled by sails were developed for the America's Cup that can travel at three times the wind speed. A power generation vessel tracking a typhoon would easily be propelled without impairing lateral stability if maneuvered from the crosswinds. Carefully design of such a vessel will be required so as to maximize stability and minimize the risk of capsizing when subject to strong typhoon winds.

Maneuvering and operating vessels under typhoons conditions are unrealistic from a safety perspective. The unmanned or remote navigation of vessels is essential. Simultaneously, constructing a mechanism for constantly evaluating the structural safety of power generation vessels based on appropriate monitoring and digital twin technologies alongside a suitable system of maintenance will be essential.

Power storage/transmission system development

Several candidates exist for the storage and transmission of energy onboard vessels. The first approach is to store electrical energy in batteries and transport them to sailing vessels. Many technological developments have been promoted for such storage technologies, including lithium-ion batteries, all-solid-state batteries, silicon anode batteries, air batteries, next-generation supercapacitors, and redox flow batteries. However, for typhoon power generation, these batteries would need to be loaded onto sailing vessels in large quantities, meaning that their manufacturing costs and weight must be fully considered. Another option for energy transport is to obtain hydrogen by electrolyzing pumped seawater, which also allows for the recovery of rare metals contained in seawater. Methods of compressing or liquefying hydrogen as well as absorbing them in liquids (such as toluene) have been developed for hydrogen transport and are already being put into practical use. However, smaller and lighter systems will need to be developed that are suitable for application on sailing vessels. Whether by battery or hydrogen storage, the generated energy could be transported to the mainland directly (on the ship) or to nearby remote islands or offshore bases using microwaves.

Effect calculation

Typhoon control effect calculation

The benefits of typhoon control are estimated based on damage avoidance and mitigation. Estimating damage mitigation requires the development of simulation technologies to predict all human and economic damages associated with typhoons, including the impacts of strong winds, landslides, local runoff, river flooding, and storm surges.

The current state of predictions of wind and flood damage is limited to hazard predictions linked to wind speed, rainfall, river water levels, and bulk/diagnostic damage predictions. Quantitative evidence that typhoon control would not increase damage to individuals and society overall is needed to ensure public understanding and support. Estimates of direct economic damage require ultra-high-resolution (i.e., at the scale of individual households) land-level prediction models of storm and wind damage. Estimates of indirect damages require developing economic damage prediction models that account for the loss of industrial and other critical infrastructure at the district level. Estimates of human damage also require detailed evacuation models capable of considering large-scale evacuations. Furthermore, the development of models that predict human and economic damages requires demonstration experiments and model optimization, but there is currently an overwhelming lack of observation data for large-scale disasters. The construction of damage prediction models also requires three-dimensional (3D) city and building datasets, asset value data, and near-real-time vital data for the entire country, which do not currently exist.

Typhoon power generation effect calculation

The benefits of typhoon power generation are estimated by the difference in the amount of power generated by typhoons and the costs needed for power generation, including its transport to land. With regard to the amount of power generation, the extent to which typhoon power generation vessels can generate power must be estimated through demonstration experiments as well as at the model scale. With regard to cost, not only do the CAPEX costs needed for developing/building a typhoon power generation vessel need to be considered but also the OPEX costs of moving this from the port to the typhoon, its operating in the typhoon, and subsequently moving it from the typhoon to the port. Currently, there are no implemented examples of a power generation system based on moving vessels on the ocean, and so the manner in which costs are calculated will greatly depend on how such a system will be implemented in practice. Finally, successful power generation using full-scale demonstration experiments will need to be achieved.

3. Japan's position in overseas trends

Typhoon control

As well as Japan and the United States, countries where typhoons, hurricanes, and cyclones cause disasters include other countries in East Asia; India, Bangladesh, and other coastal countries around the Indian Ocean; and island countries in the Southern Hemisphere, Australia, and New Zealand. In the United States, the Federal Emergency Management Agency (FEMA) issues instructions for evacuation, although evacuation decisions are left to the individual. Long-term disaster prevention and mitigation measures are under the jurisdiction of the US Army Corps, similar to the Ministry of Land, Infrastructure, Transport and Tourism in Japan, and there has not been any research investment in active disaster control.

The current status of typhoon and hurricane control research, and the feasibility of future research, was surveyed for countries conducting observations and simulation studies of tropical cyclones, including typhoons. The target countries included Taiwan, South Korea, the United States, the United Kingdom, France, China, Canada, and Bangladesh. Common to all these countries is that there have not been any typhoon or hurricane control experiments since Project Stormfury in the US, and there are no plans to do so in the near future. Furthermore, while potential problematic points were raised during our enquiries, most respondents welcomed efforts by Japan to engage in typhoon control research. There is potential, therefore, for Japan to be the only country pursuing typhoon control research, placing it at the forefront of this field.

Typhoon power generation

Europe is one of the leader in wind power generation, but typhoon power generation requires mobile vessels on the sea in the form of ships instead of fixed or floating offshore wind turbines. The strength of Japan in implementing typhoon power generation in this regard is that shipowners, shipyards, marine equipment manufacturers, ship classification societies, and electric power companies all currently exist as part of Japan's "maritime cluster." Excluding some small companies, this is not the case in other countries, and, currently, only Japan is capable of developing the engineering solutions required for developing operational typhoon power generation vessels. Furthermore, the practical implementation of typhoon power generation requires advances in technologies for storing and transmitting (transporting) energy. Fortunately, research and development in this field is advancing rapidly in Japan. Finally, it is important to recognize that many of the waters through which typhoons pass are within Japan's exclusive economic zone. By developing typhoon power generation innovations, this current risk to Japan can be seen a potential major economic and social opportunity.

III. Plan for Realization

1. Challenging research and development areas: future priorities for realization

Identifying the challenging areas of research and development helps target aspects that must be prioritized for realizing the MS vision. These challenging areas are characterized by having few current research examples, low technological maturity, and a limited fundamental research base, as classified under the third quadrant in Fig. 8 and discussed in the following sections.

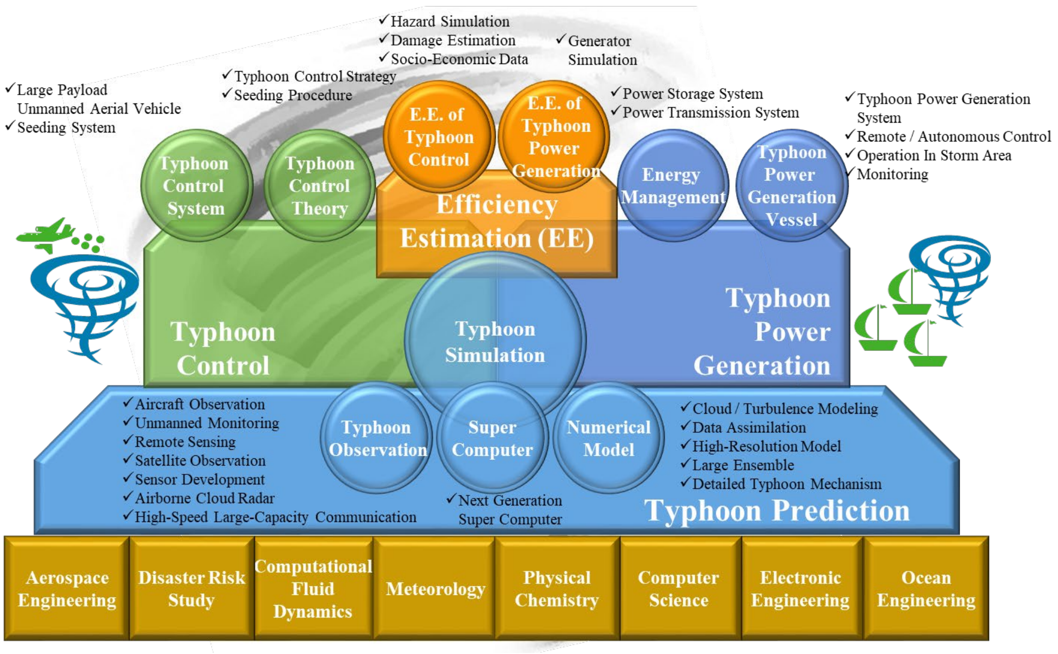

Fig. 8: Positioning of research and development necessary for the reaization of of the Moonshot vision

Typhoon simulation models

A "typhoon simulator" capable of simulating the internal structure of a typhoon in detail and predicting its course and intensity with high accuracy needs to be developed. The typhoon simulator will be developed based on numerical meteorological prediction models currently being developed by operational agencies or research institutes. Typhoons have complex internal structures including km-scale eye-wall clouds and outer rainbands, and their course is regulated by large-scale circulation such as the North Pacific High and the jet stream. Therefore, the typhoon simulator must be a large-scale (or global) and high-resolution numerical model that will ultimately encompasses the entire planet with a mesh of 1 km or less. The typhoon simulator will need to implement thousand members of ensemble calculations and obtain probability-based outputs. Observation data that accurately reflect the internal structure of typhoons will be needed, which will be used as the initial values to construct the simulator and for model verification. Typhoon simulations will be used to determine the effects of typhoon control interventions and the potential for typhoon power generation as well as damage prediction. The typhoon simulator is a fundamental development goal for all the research themes in this study.

Currently, large uncertainties exist in the prediction of the intensity and course of typhoons, and slight differences in the initial conditions and environmental fields can greatly impact typhoon activity. The mechanisms by which these changes occur are, therefore, not yet sufficiently understood. The dynamics of the eye-wall of a typhoon and the mutual interactions between the environmental field and sea surface are thought to be key factors, but further understanding of detailed typhoon mechanisms is needed to reliably derive prediction information and control effects. Trial experiments using a simulator should lead to such improvements in understanding of typhoon processes and formation mechanisms.

Aircraft-based typhoon observations

Currently, with the exception of some limited aircraft observations around typhoons in Taiwan, all typhoon observations are conducted by meteorological satellites. Therefore, the central pressure and maximum wind speed of typhoons are estimated from satellites, and the large errors for very strong typhoons is a bottleneck for determining high-accuracy quantitative predictions. Indeed, detailed information on typhoon pressure, temperature, and water vapor conditions cannot be obtained from satellites. Therefore, a research and development challenge exists to enable direct observation from high altitudes using manned aircraft and long-term monitoring with UAVs. Doing so would improve our understanding of the circumstances and mechanisms of typhoon formation and dynamics as well as the acquisition of data for numerical models, which are key milestones for improving the accuracy of typhoon prediction. Finally, aircraft-mounted cloud radar will need to be developed to observe the spatiotemporal fluctuations of typhoon clouds in three dimensions. This will allow detailed observation of cloud responses to impact substance seeding.

Developing typhoon control methods: simulation and demonstration

Seeding the area outside typhoon eye-wall clouds is considered a conventional method for controlling their force. The seeding method involves seeding dry ice or silver iodide on supercooled water, which is not frozen even in sub-zero temperature, thereby promoting coagulation, ice particle formation, and convective clouds. Promoting convective clouds outside the eye-wall clouds suppresses the inflow of water vapor to the center of the typhoon, thereby controlling its forces. However, the seeding area and amounts of seeded substances involved are problematic in terms of cost-effectiveness. There are also concerns that this would take several days before any significant mitigation effects would be evident. Utilizing recent advanced numerical simulations and devising more effective typhoon control methods is, therefore, a priority for achieving typhoon control.

Unmanned aerial vehicles (UAVs) for typhoon control

Among existing unmanned vehicles, endurance-type UAVs are capable of high-altitude flight, and combat-type UAVs are characterized by high cruising speeds. However, the load capacities of these vehicles are currently insufficient for application in typhoon control, which requires the quick and long-range transport of large quantities of impact substances to be economically efficient. One of key breakthroughs for the practical implementation of typhoon control is, therefore, designing a specialized aircraft for the specific purposes of typhoon control.

Unmanned vessels for typhoon power generation and storage

A typhoon power generation vessels must be designed based on the entirely new and unprecedented concept of generating power electricity from typhoons. With regard to elemental technologies, mechanisms of propulsion using the strong winds of typhoons, the efficient generation and storage power using submersible turbines, unmanned navigation and operation, monitoring technologies for ensuring safety under adverse conditions are all required. Furthermore, it is necessary to design an overall control system to manage not only individual elemental technologies but also the various risks and operational schemes required for economically feasible application.

Impact evaluation for typhoon control and power generation

Depending on the method of power transmission and storage, the benefits of typhoon power generation can be estimated based on the total amount of power generated. In the case of typhoon control, beneficial impacts can be estimated based on the mitigated damage (i.e., avoided costs), for which the development of real-time estimation technology is important. The costs and benefits involved in typhoon control and power generation must be optimized through operations research along with associated model development. Evaluating the benefits of typhoon control requires improved simulation technologies able to predict the damages resulting from strong winds, local runoff, river floods, and storm surges both with and without typhoon control intervention. Estimates of direct economic damage require ultra-high resolution and land-level storm and flood damage cost prediction models to determine damage at the scale of individual properties. Furthermore, estimates of indirect damages will require spatially applied general equilibrium models that resolve industrially associated structures at the district level. Lastly, estimates of risk and loss to human life will require evacuation prediction models, such as agent-based models. These models need to be developed, demonstrated, and optimized, for which 3D city data and near real-time vital data must be generated for the entire country of Japan.

2. Direction of R&D for realization of goals

Figure 9 shows our roadmap summarizing the key MS milestones in 2030, 2040, and 2050, the research and development priorities for achieving these milestones, and their associated ripple effects.

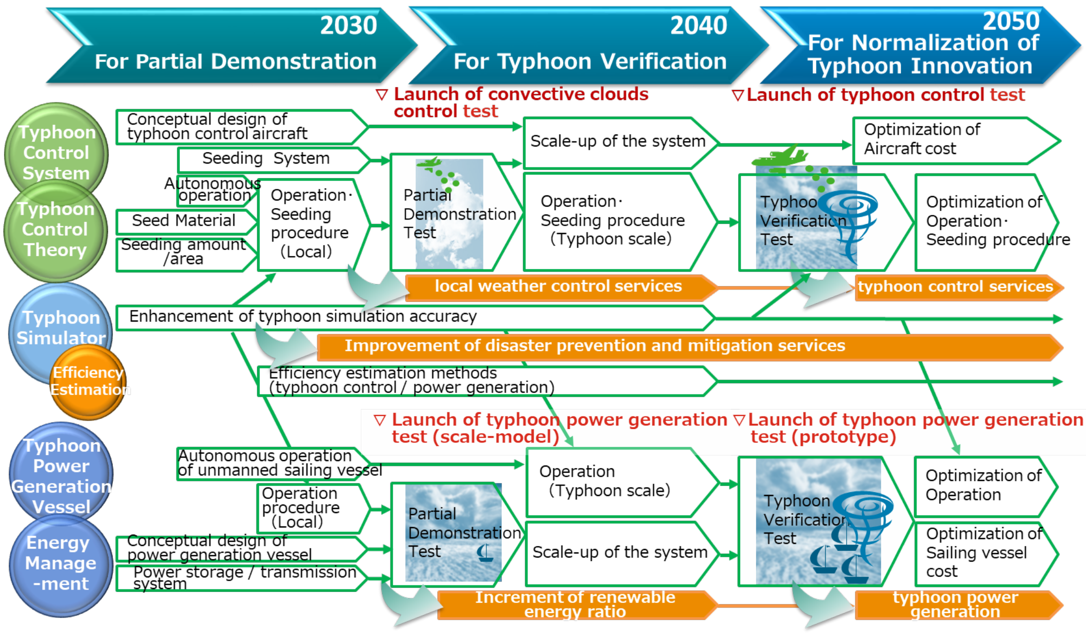

Fig. 9: Roadmap for the realization of the Moonshot vision

[2030] Aiming the launch of partial demonstration test

	TYPHOON CONTROL	TYPHOON POWER GENERATION
① SPECIFIC GOALS (MILESTONES)		
	Launch of demonstration test of convective clouds control using prototype aircraft As a miniature experiment of typhoon control, the seeding test will be carried out to convective	Launch of demonstration test of power generation and storage system using scale model As a miniature experiment of typhoon power generation, the power generation and storage

	TYPHOON CONTROL	TYPHOON POWER GENERATION
	clouds such as cumulonimbus.	test using a small vessel will be carried out.

② SPECIFIC RESEARCH THEMES

Enhancement of typhoon simulation accuracy

The research will be carried out for more accurate typhoon simulation. In particular, the clarification of typhoon mechanism by direct typhoon observation and the refinement of simulation model will realize accurate typhoon simulation.

Construction of typhoon control theory

The study to find out typhoon control methods will be carried out by examining what and how much to seed in which part of typhoon.
Furthermore, the study will be carried out to find out methods to achieve larger effect more simply.

Conceptual design of typhoon control aircraft

The aircraft conceptual design will be carried out aiming large payload to carry enough seed with high economical efficiency. Autonomous operation technology will be also studied for unmanned aircraft.

Development of seeding system

The seeding system will be developed to realize the seeding methods based on typhoon control theory. Installation of the system to aircraft will be also examined.

Aircraft operation and seeding procedure

With a view to the demonstration test of convective clouds control, aircraft operation (number of aircraft, routes, etc.) and seeding procedure will be set up via typhoon simulation which simulates seeding.

Development of method to evaluate typhoon control effect

The method will be developed to evaluate an amount of economical damage reduction due to typhoon control and to calculate the cost to conduct typhoon control.

Conceptual design of power generation vessel

The conceptual design of vessel to generate power stably and efficiently under strong wind will be carried out. Once performance and economical rationality is sighted, the scale model will be developed incorporating these technology.

Autonomous operation of unmanned sailing vessel

The study will be carried out to stably generate thrust utilizing strong wind. Also, autonomous operation technology will be developed for unmanned sailing vessel operation.

Development of power storage system

The highly efficient power storage and transmission system will be developed, considering to apply existing technology. Size and weight reduction is essential for installation of the system to sailing vessel.

Power generation vessel operation

With a view to the demonstration test of power generation and storage system under general strong wind, vessel operation(number of vessels, routes, etc.) will be set up to achieve the expected amount of power generation.

Development of method to evaluate power generation effect

The method will be developed to evaluate an effect of power generation, etc. based on the state of strong sea wind and the route of power generation vessel.

③ SOCIAL EFFECT

Improvement of disaster prevention and mitigation services

As the accuracy of typhoon simulation is improved, it will be possible to take proactive action from a few days before according to the course of the typhoon.

Creation of local weather control services

By finding out local weather control methods, weather control services will be provided by convective cloud control for large-scale outdoor events such as Olympic games, national athletic festivals, etc.

[2040] Aiming the launch of verification test

	TYPHOON CONTROL	TYPHOON POWER GENERATION
① SPECIFIC GOALS (MILESTONES)		
	Launch of verification test of typhoon control using prototype aircraft The typhoon control test will be carried out to	**Launch of verification test of power generation using prototype vessels** The power generation test will be carried out to

	actual typhoons in stages.	actual typhoons in stages.
②	SPECIFIC RESEARCH THEMES	
	Enhancement of typhoon simulation accuracy The research will be continued for more accurate typhoon simulation. Particularly, the steady typhoon observation technique, and large scale ensemble method will be applied.	
	Operation and seeding procedure -typhoon scale Considering the result of partial demonstration test, aircraft operation and seeding procedure will be set up via typhoon scale simulation which simulates seeding.	**Operation Settings -typhoon scale** An unmanned sailing vessel operation will be set up to obtain an amount of energy expected by typhoon scale simulation.
	Scaling Up the System for verification The scaled-up system will be prepared for the verification test.	**Scaling Up the System for verification** The scaled-up system will be prepared for the verification test.
③	SOCIAL EFFECT	
	Reduction of typhoon damage and increase in renewable energy ratio After the verification test, typhoon damage will be reduced, the ratio of renewable energy of Japan will be increased.	

[2050] Aiming normalization of typhoon control and typhoon power generation

	TYPHOON CONTROL	TYPHOON POWER GENERATION
①	SPECIFIC GOALS (MILESTONES)	
	Normalization of typhoon control project Typhoon control will be applied to typhoons beyond disaster prevention infrastructure capacity, and there will be almost no typhoon damage.	**Normalization of typhoon power generation** Typhoon power generation will become one of renewable energy sources and contribute to Japan's electricity supply.
②	SPECIFIC RESEARCH THEMES	
	Enhancement of typhoon simulation accuracy To judge the optimum typhoon control method and typhoon power generation scheme, a typhoon simulator will be put into practical use.	
	Optimization of operation The study will be conducted to pursue cost reduction of aircraft, seeding equipment and impact material, and to optimize aircraft operation and seeding procedures.	**Optimization of operation** The study will be conducted to pursue cost reduction of sailing vessels, power generation and storage system, and to optimize vessel operation.
③	SOCIAL EFFECT	
	Further reduction of typhoon damage by typhoon control As typhoon control projects will become normal, typhoons will no longer be a threat, since even if some typhoons come with extreme severity exceeding the capacity of disaster prevention infrastructure. The coexistence of life with nature and life of safety will be realized. **Further increase of renewable energy ratio due to typhoon power generation** Japan's renewable energy ratio will increase as typhoon power generation expands. In the future, Japan may become an energy powerhouse by transporting energy to neighboring countries.	

3. International cooperation

International collaboration in research

As mentioned previously, Project Stormfury undertaken in 1969 in the United States is thought to be the last typhoon control experiment. We interviewed researchers in the United

States, Taiwan, South Korea, China, Canada, the United Kingdom, France, and Bangladesh on subsequent typhoon control research. All of the interviewed researchers from these countries confirmed that no typhoon control experiments have been conducted since Project Stormfury, nor are there any plans to do so in the future. When asked whether typhoon control would generate social benefits and what concerns are raised, almost all respondents indicated that great benefits could be achieved from such work. Concerns were raised about the possibility of unexpected consequences and their associated risks, and the loss of typhoons as a water resource. Finally, when asked whether they would engage in joint research with Japan on typhoon control research, with the exception of China, all of the interviewed researchers responded positively. Based on these responses, there is a significant opportunity and need for Japan, which is positioned in an important typhoon generation and landing region of the western North Pacific Ocean, to lead the way in typhoon control research.

International cooperation in regulation

The international framework associated with meteorological modification is mainly overseen by a team of experts in atmospheric research and environmental planning within the World Meteorological Organization (WMO). The WMO has provided guidelines for implementing meteorological control, although this is primarily intended for artificial rainfall; there are no guidelines for artificial typhoon control and power generation. Furthermore, organizations such as the International Maritime Organization (IMO) and the International Association of Classification Societies (IACS) have discussed a framework for issues such as safety, although typhoon power generation have not been specifically considered.

Typhoons affects multiple countries, and so their control and use must be done in accordance with internationally agreed principles and guidelines. Japan must, therefore, initiate discussions with the relevant authorities and organizations, such as the WMO, the IMO, and the IACS, to formulate universal guidelines for typhoon control and power generation.

4. Interdisciplinary cooperation

Seamless inter-agency cooperation

The ultimate beneficiaries of typhoon control and power generation are the people of the nation, so it is assumed that the government will lead the project at the time of implementation. To establish this project, wider cooperation among various agencies is considered necessary. This includes the Cabinet Office, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), and the Ministry of Agriculture, Forestry and Fisheries (MAFF) in terms of comprehensive disaster management; the Japan Meteorological Agency

(JMA) in terms of typhoon forecasting; the Ministry of Economy, Trade and Industry (METI) in terms of energy, the Ministry of the Environment (MOE) in terms of the environmental impact, the MAFF in terms of the impact on crops and fishery resources, the MLIT in terms of aviation and ship operations, and the Japan Coast Guard in terms of maritime safety.

For such inter-agency collaboration, it is necessary to clarify which agency has primary jurisdiction. According to interviews with central government officials, the agency with primary jurisdiction tends to be determined in light of the primary policy objective, and this will likely determine which government agency will have primary jurisdiction over typhoon control and power generation up to 2050.

Importantly, decision-making within inter-agency and national initiatives, which impact the entire country, is not expected to be carried out by a single agency but by each relevant party alongside high-level guidance from central government. Accordingly, we believe that it will be necessary to involve the government in shaping future project discussions.

Private sector involvement

The cooperation of the private sector is indispensable for the realization of typhoon control and power generation. A wide variety of industries are expected to be involved including shipbuilding, aircraft, heavy industry, heavy electric machinery, communications equipment, observation equipment, general contracting, engineering, chemicals, satellites, automotive, electric power companies, shipping, airlines, and insurance industries. It is important to invite these companies to participate in efforts to achieve the wider project goal.

Academia-driven platform for cooperation

Fundamental academic research will be important in defining requirements for operations, and research and development in the areas of cooperation and fusion between meteorology and aeronautical engineering, and marine and electrical engineering, and others, will be necessary. In addition, to accelerate these researches, universities and other research institutions are expected to cooperate to establish co-creative research centers. New initiatives are also being launched, including the Typhoon Research and Development Center at Yokohama National University, which will conduct comprehensive research on typhoons. Academia plays a significant role in this kind of research and development, which also involves a diverse range of stakeholders from the public and private sectors. Academia can not only promote fundamental research but can also provide a platform where companies in the same or different industries to participate and cooperate more easily.

5. Ethical, Legal, Social Issues (ELSI)

Ethical issues

Exerting control over typhoons, a natural phenomenon in the face of which humanity has always assumed to be helpless, raises some ethical issues. It is, therefore, important to gauge the public's understanding and support by providing robust and clear evidence that typhoon control will not make the situation worse than it is without such intervention.

Legal issues

To realize typhoon control, it is necessary to establish laws governing whether that can or cannot be implemented, the location and scope of responsibility, and decisions related to implementation. Typhoon control is expected to result in both advantages and disadvantages for different people within Japan, and may also impact other countries. Therefore, the development of national and international laws is essential to reconcile the interests of society and to clarify compensation needs under worst-case scenarios. This will necessitate cooperation with legal and economic experts.

Even when operations are executed with the utmost care, there is always an element of risk involved in pioneering projects. Operational risks, such as accidents associated with the navigation of aircraft and ships, can be mitigated using appropriate insurance. On the other hand, for risks that are difficult to insure, such as damage caused to foreign countries due to negligence in typhoon control, it is necessary to consider the establishment of an international risk diversification system, such as a mechanism by which countries with similar interests contribute funds for compensation.

Social issues

Typhoon control and power generation can only be implemented with the understanding and support of the public but, as mentioned above, a survey of 10,000 citizens revealed that there is a segment of the population that has some concerns. These concerns can be broadly categorized into those related to (1) the natural sciences, such as the disruption of the natural equilibrium and unexpected adverse effects on ecosystems; (2) concerns related to the social sciences, such as harm to neighboring countries and the political use of typhoon control; and (3) concerns related to the humanities, mainly in the area of ethics, which argues that humans should not manipulate nature. To realize typhoon control, it is necessary to work closely with people with diverse positions, interests, and ethics, and foster understanding through patient explanation. While the concerns over typhoon power generation are not as significant as those for typhoon control, some question its feasibility. It is necessary to explain the mechanism of typhoon power generation in an easy-to-understand manner and show that it is feasible while ensuring economic viability.

Building consensus with those who have concerns and who question the feasibility of the project goals will be a major challenge, but we believe it is not impossible. Our team organized a symposium on May 15, 2021, that brought approximately 300 people together to discuss the wider project themes. The symposium introduced research results on past typhoon damage and expected changes in typhoons in the future as well as the possibility of typhoon control. In a questionnaire survey taken after the symposium, 85% of the participants answered that they would like to see typhoon control implemented. Compared to survey of 10,000 people, the percentage of those who placed expectations in typhoon control was more than 20 percent higher. This can be attributed to differences in the respondents to the questionnaire and survey. The questionnaire conducted after the symposium targeted informed individuals and experts who already had an interest in typhoon control and power generation. This implies that with a greater understanding of typhoon control and power generation, acceptability is higher, and that targeted educational initiatives could be effective in gaining public support. It will likely take a long time to develop public awareness, perhaps 10 to 20 years, but this is feasible with the 2050 time horizon of the MS project. Thus, whilst most attention has been given to the natural science aspects of typhoon control and power generation, in the future, the aim is to address broader social and ethical issues in cooperation with experts in the social sciences and humanities.

IV. Conclusions

The feasibility, roadmap, and social significance of the typhoon control and power generation proposed by our team have been studied for six months in the Moonshot MILLENNIA Program, with an interdisciplinary cooperative body of industry, academia, and government. During the expert interviews, we received a wide range of opinions from a total of approximately 160 experts from Japan and overseas in various fields including scientists, engineers, and related companies as well as the author of *Tokyo Daikouzui* ("The Great Tokyo Flood"). We also received diverse opinions from a wide range of citizens through a public survey.

Typhoon control and power generation are ideas that at first glance seem very difficult to realize, yet the results of our research have clarified the key scientific and social challenges, and a feasible way forward. The vision for the form of society discussed in this report has been conceived by the members of our team over many years, and we are confident that our vision has become more appropriate through the research conducted under the MILLENNIA Program. We hope to meet people's expectation and lead to the well-being of humankind by 2050, by sharing and realizing our positive vision of a safe, stable and sustainable future where typhoons are seen a blessing rather than an inherent threat to society.

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