Moonshot R&D MILLENNIA* Program

*Multifaceted investigation challenge for new normal initiatives program

“Weather controllability research”

Initiative Report

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”Weather controllability research team”

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I. Concept

1. Proposed MS Goal

1.1 Proposed MS Goal title

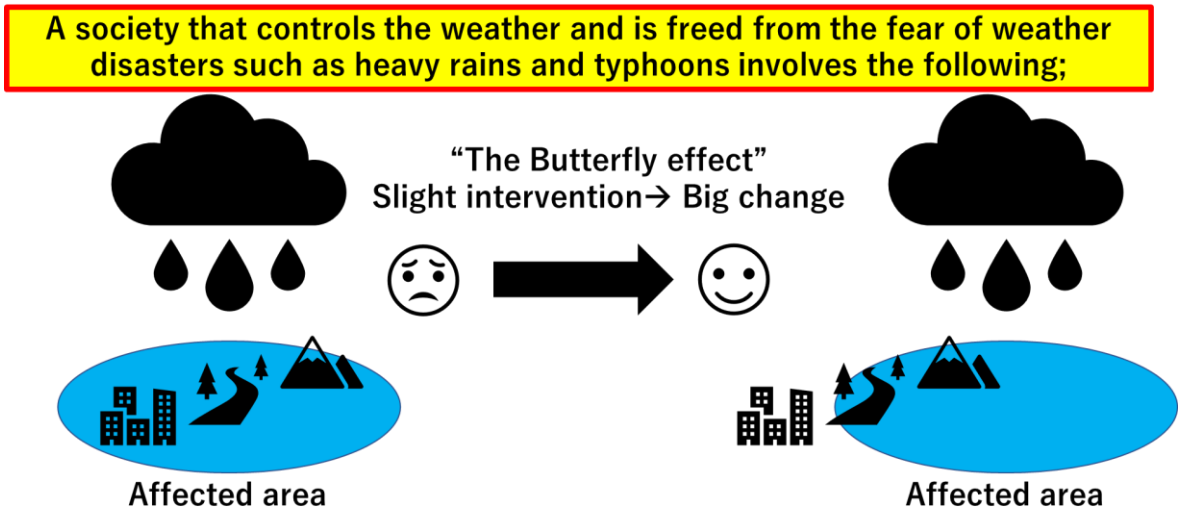
"By 2050, we will have realized a society free of the fear of weather disasters such as heavy rains and typhoons by controlling weather ."

1.2 Vision for 2050 society

Climate change is progressing, and weather disasters such as heavy rains and typhoons are becoming increasingly common. We will no longer be afraid of the unjustifiable misfortune caused by weather disasters if we can alter the location of heavy rains and generate floods or landslides where human activities are not affected. Even if all heavy rains cannot be fully controlled as desired, the weather controls are beneficial to support the optimization of human activities against weather disasters and contribute to considerably reducing the risks of weather disasters. A society freed from the fear of weather disasters is our vision of society in 2050.

Urban activities and natural energy facilities such as wind and solar facilities exchange energy with the atmosphere and change the motion of the air. A future vision of a super-smart society is society 5.0, in which virtual and real worlds are merged by systematically operating these intervention methods as the integrated optimization of a smart city. Losses are reduced and benefits increased with various human activities that are affected by weather such as preventing damage due to typhoons and heavy rains and avoiding rain at outdoor events (a scientific paper doll to which children pray for fine weather). By actively taking the initiative to influence what could previously only be passively responded to based on predictions, this technology may profoundly alter sense of values. The values brought to industry, culture, and society are enormous. In addition, a traditional worldview, in which the weather is nature itself, governed by god, is overturned, so that this technology will affect the comprehensive development of humanity, including religious and ethics..

The influence of weather is significant, and people have wanted to predict it since ancient times, and intervention controls such as praying for rain have been desired. Thus far, studies on artificial rain and thunder instruction have been conducted, and studies and discussions on global-scale geoengineering are also progressing. Here we propose that the "butterfly effect," or the fact that a small change, such as the flap of a butterfly's wings, may grow over time and generate a subsequent major change, is utilized as a lever. The subjects of the control are limited to local or short-term weather phenomena such as heavy rains and typhoons, and intervention controls that pose permanent global-scale effects have not been considered.



2. Targets

These two concepts are targets for 2050.

- Greatly reduce the occurrence and damage of weather disasters using weather controls that change the location and intensity of weather events such as heavy rains and typhoons by 2050.
- Obtain a wide range of benefits through weather controls such as shifting the timing of rain at the time of a rocket launch and harvesting the fruit by 2050.

The feasibility of these achievement scenarios is discussed below.

Numerical weather forecasts using computers began in the 1950s and have seen the advancement of mathematical models and computational algorithms during the first 30 years. Studies and methods of predictability have continued in the next 30 years since the 1980s. As a result, the accuracy of numerical weather forecasts has been steadily improved. Data assimilation, which incorporates actual measurement data into the mathematical model, has been highly developed to improve the forecast; however, the method of data assimilation is the same as that of the control. Thus far, although weather forecast research has focused on predictability, it is now ready for new developments from a control perspective.

When the aforementioned trend of the trend in studies on numerical weather forecast is extrapolated, it is a highly feasible scenario that a theory of controllability will progress during an approximately next 30 year period from the 2020s. Considering that data assimilation emerged around the 1980s and that the predictability study was established in the form of ensemble forecasts in the mid-90s, establishing controllability research in 2030 becomes a reasonable target. At the same time, the feasibility of to what extent the weather can be changed with a feasible intervention operation is on the horizon. The actual demonstration of the proof of concept will become a milestone around 2040, which makes this technology practical in 2050.

Regarding feasibility on the social side, a real-time decision making method based on economic rationality has to be developed. In addition, a method to settle a dispute when an unanticipated side-effect occurs should be investigated. A mechanism of signing a treaty may be necessary in the case of an international dispute. Concerning economic rationality, techniques for calculating disaster damage, including ripple effects have been developed in recent years. Concerning dispute settlement, it is similar to court cases regarding environmental pollution in the past; therefore, it is effective to examine the adverse effects of new technologies that humanity has experienced so far. Since it is a technological development that can have a significant influence on religion and ethics, it is expected that there will be twists and turns before it is accepted by people and social implementation is

realized. However, by pursuing the social-side feasibility listed above successively and communicating with residents, the technology may be socially accepted by 2050.

3. Background

3.1 Why now?

Anthropogenic global warming is steadily progressing, and it is becoming impossible to halt it. Meteorological disasters have increased in recent years due probably to climate change. Recently many unprecedented meteorological disasters have occurred such as: the heavy rain of July 2020; the typhoon of 2019; the heavy rain in western Japan and the typhoon in 2018; the heavy rain in northern Kyushu in July 2017; the heavy rain in Kanto and Tohoku in September 2015; and the heavy rain in Hiroshima in August 2014. In addition, due to the coronavirus pandemic, the overcrowded environment in shelters poses a risk of infection.

It is undoubtedly important to suppress emissions of greenhouse gases such as carbon dioxide, to utilize natural energy, and to promote recycling.At the same time, it is necessary to enhance the ability to respond to the changing climate. Technology to control the weather is a promising new force for humanity.

Humanity has thus far greatly improved predictability with regard to numerical weather forecasting using a computer. For example, the trajectory of a typhoon can now be predicted over several days with far higher accuracy than that of 30 years ago. This advanced weather forecasting technology includes sensor technology, supercomputing technology, information and communication technology, artificial satellite technology, and simulation technology and can be said to be the result of humanity's collective wisdom.

Forecasting is the foundation for control. The weather exhibits a chaotic nature. This feature is known as the "butterfly effect" that states that a slight variation produces a huge difference afterward, as demonstrated by the metaphor of the wings of a butterfly flapping producing a storm a few days later. Due to this chaotic nature, forecasting is difficult, and predictability is limited. In other words, it may be possible to generate a small disturbance that induces a large difference afterwards. With a better understanding of predictability, we can unfold the novel controllability.

Since the weather affects human activities in various ways, people have wanted to predict it since ancient times, and intervention controls such as praying for rain have also been expected. As such, it can be said that humanity has commonly imagined controlling the weather. Modern science in terms of advanced measurements such as satellite, information-communication technologies, and supercomputing has gathered the wisdom of humanity to improve weather prediction. Technology has made things possible that were once difficult to predict. We can imagine the future world in which things that were once thought difficult can be controlled. Pursuing weather control will give humanity a shared goal which can be achieved by gathering a wide range of wisdom.

3.2 Social significance

Meteorological disasters are regarded as misfortunes sent from the sky. Weather control would enable us to avoid unnecessary misfortune and contribute to equality in society and industry. In addition, a large variety of human activities are affected by the weather, and the impact of weather control on industry and society would be enormous. Furthermore, controlling the weather, which often causes disasters, so as to avoid unnecessary misfortune and contribute to an equal society and industry is in agreement with the United Nations (UN) sustainable development goals (SDGs), hence sharing humanity's common sense of values.

3.3 Action outline

It is assumed that favorable and unfavorable cases would coexist due to weather control. For example, moving the location of heavy rain would be favorable in the area where heavy rain is originally supposed to fall. On the other hand, heavy rain may fall in an area where it was not originally supposed to fall. Therefore, it is necessary to prepare a treaty or legal framework to reach agreement in such a case and to have a method to settle any disputes. Because there are common viewpoints with the issues that humanity has experienced so far concerning dam construction and public disruption, it is necessary to examine an appropriate countermeasure before realizing weather control technology based on prior experiences.

4. Benefits for industry and society

So far, humans have passively predicted and responded to the weather, recognizing that it is provided from above. The idea of weather control may change this current belief and would fundamentally revolutionize every social system regarding weather. This idea leads to the realization that something can be altered in the expected direction with even a small intervention, even if we cannot completely control weather as desired. This way of thinking and concept that things can be controlled brings changes to society and improves weather control technology in its entirety, including the optimization of human activities. This is new enlightenment.

II. Analysis

1. Essential scientific/social components

Regarding the technological challenges, a new research trend is necessary to change the current approaches of studies on weather prediction that has been so far progressed with predictabilityby introducing the new view point of controllability.

In addition, even if it is technically feasible, actual implementation requires the formation of an agreement among various stakeholders. There may be a case where one control is favorable to someone, while it is detrimental to others. If the control is favorable to everyone, or there is no chance at all that it causes a detriment to anyone, agreeing becomes easy. However, it is more likely that we face disagreement.

Moreover, it is also necessary to settle disputes in the event of undesired consequences. At the initial stage of technology development, one cannot expect that things will go as planned; therefore, special attention is required when a demonstration is performed, including the experimental design.

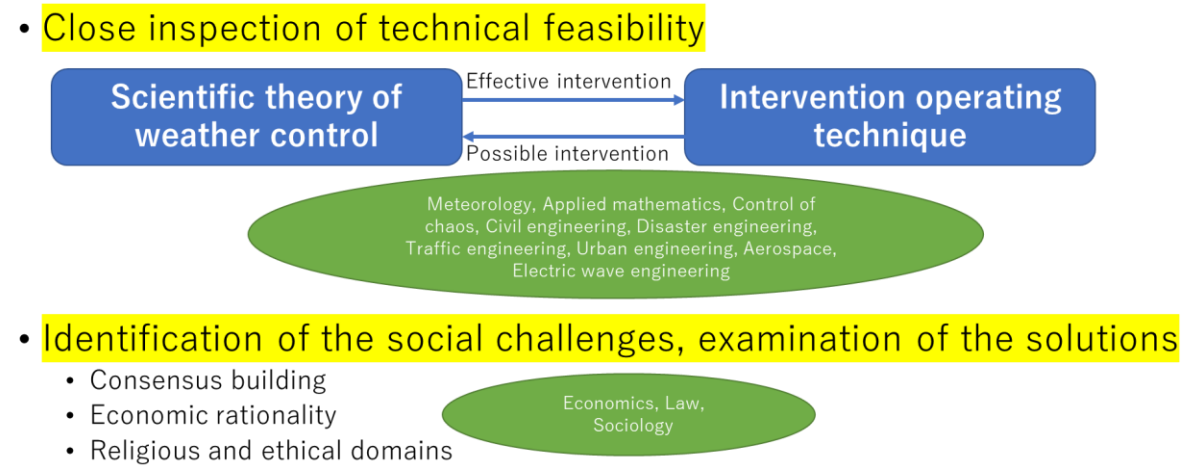
2. Science and technology map

A theoretical research field regarding controllability, which is the pair of predictability in the field of meteorology, is being developed. In addition, the appropriate technology to invervene the real atmosphere is being examined. The intervention that brings enough change to the weather can be clarified in the theoretical research of controllability. In addition to the theoretical consideration, it is necessary to develop an effective and feasible intervention operation method which can be realistically installed in society. Various academic fields such as meteorology, applied mathematics, control of chaos, civil engineering, disaster engineering, traffic engineering, urban engineering, aerospace, and electric wave engineering must come together to execute this research in an integrated manner.

In addition, even if a technology is technically feasible, an examination from the social sciences' perspective is also necessary to make it accepted by society. Methods to build consensus and to quantify economic rationality are necessary for real-time decision-making and intervention operation execution. Furthermore, some issues should be solved

carefully offline including a legal system on religious and ethical domains, consensus building, and dispute settlement. Various academic fields such as economics, law, and sociology must come together to address these issues .

It is necessary to bring together the wisdom of humanity in the following fields by integrating STEM (Science, Technology, Engineering, and Math) and non-STEM fields to realize weather control:



3. Japan's position in the global trends

Investigating weather control from the predictability viewpoint based on the theory of the chaotic dynamical system is completely new and original. So far, studies on data assimilation and predictability have been conducted to improve the prediction. The fact that a small change leads to a big change implies the possibility of control. However, to my knowledge, there have been no studies on data assimilation and predictability from the viewpoint of weather control, which leads to the novelty and originality of our study proposition. Although there is an approach called control of chaos in the mathematics of a dynamical system, there was no viewpoint to apply this approach in a high-dimensional dynamical system like the weather in which the solvability of its inverse problem was intrinsically difficult.

In addition, a scientific methodology to control weather has not been established. Though there are previous studies on artificial rain, the effects have not been definitive.

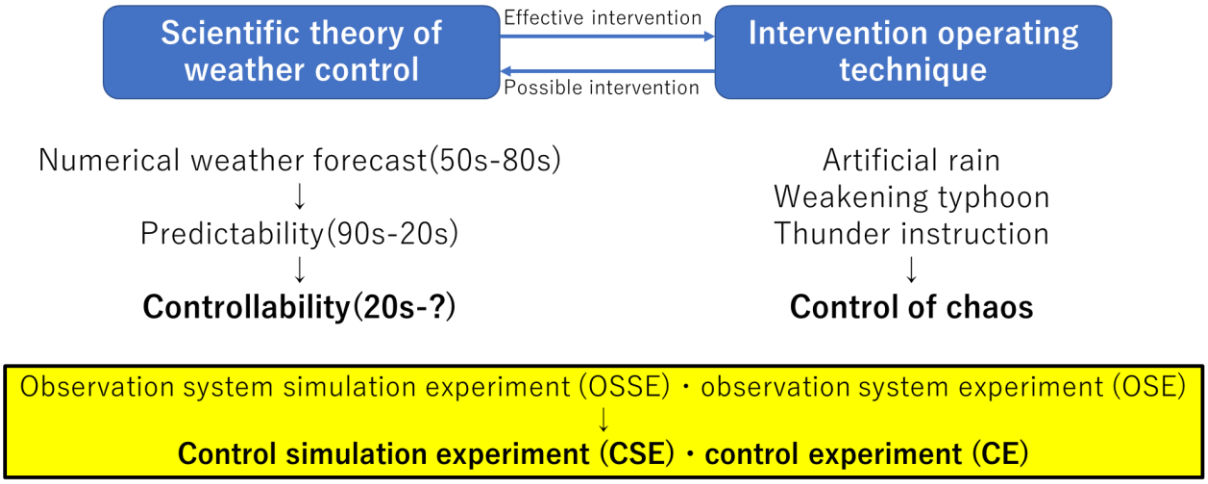
Japan has a large-scale weather simulation technology and a numerical weather forecast technology that has been fostered for the last 20 years by the world's top-level supercomputers such as the earth simulator (2002) (Tomita et al., 2005), the supercomputer "K" (2012) (Miyamoto et al., 2013), and the supercomputer "Fugaku" (2021). A large-scale simulation is required to regulate real weather, and the use of "Fugaku" for a large-scale ensemble simulation (Miyoshi et al., 2014, 2015; Kondo & Miyoshi, 2016, 2019; Necker et al., 2020a, 2020b; Yashiro et al., 2020) offers a distinctive advantage.

Most of citizens in Japan recognized that Japan is the country in which catastrophic disasters happen very frequently.. Based on data summarizing the economic impacts of past disasters, such recognition has been found to be objectively correct. As a developed country with frequent disasters, Japan's initiative to lead an innovative technology development such as weather controlseems to be an obligation to human civilization as a whole. The conduction of weather control studies in Japan cannot be overemphasized.

III. Plan for Realization

1. Area and field of challenging R&D, research subject for the realization of the Goals

The scientific theory of weather control (meteorology, applied mathematics, calculation science, control engineering) and specific intervention-operating techniques (in various engineering fields) should work closely together. Numerical weather forecasting, which began in the 1950s with the advent of the computer, has evolved into the branch of predictability. The development toward control as a pair of prediction is a natural course of things, and will be the predominant research trend for the next 30 years. At the same time, without any actual feasible intervention-operating technique, the control becomes a mere theory applied only to computer simulation. Therefore, the simulation experiment of the control should be performed while keeping the concrete feasible intervention-operating techniques in mind.



2. Direction of R&D for the realization of the following goals:

	~2030	~2040	~2050
Science & Technology	-Theory of the controllability -Verification method for the effectiveness of the intervention operation -Control simulation experiment (CSE) -Get a clear idea of the possibility of an experiment	-Realizing the method of intervention operation -Establishing the verification method for effectiveness -Control experiment -Realizing the proof-of-concept (POC)	Putting into practical use
Social adaptation	-Close inspection of the challenges -Examination of the solutions	-Close inspection of the solutions -Begin implementation	Implementation of the solutions (e.g. signing a treaty)

Each milestone is summarized in Table 1. With computer simulations, a theory on implementing an effective control will be constructed, and techniques to quantitatively estimate the effects when the control is implemented will be developed by 2030. Thus, a mathematical theory to enable the realization of weather control will be constructed,providing the roadmap to realize weather control in the real world.. From the standpoint that predictability and controllability are two sides of a coin, such a construction of the theory on controllability may also greatly contribute to predictability, i.e., the improvement of the accuracy of weather prediction. Achieving the 2030 milestone will result in a positive outcome on society through improvement in the accuracy of conventional weather prediction. In addition, basic studies on the possibility of social implementation will also be conducted until 2030.

The means of intervention in real-world weather will be made concrete through the theory of controllability mentioned above by 2040. Hence, the proof-of-concept will be realized by executing the intervening control experiment in the real world on a small scale. Once this milestone is accomplished, the controllability of weather will be widely known throughout the world. This accomplishment will create an opportunity for promoting discussions involving non-specialists, and the preparation of actual legislation regarding the mechanisms for forming a consensus on specific weather control and disputing settlement.

We will aim for practical use of weather control by 2050. Small-scale control experiments and theoretical research will be repeated to continue strict verification of the safety and stability of the technology. Social implementation will be realized through the accumulation of these trials. At this stage, we will prepare laws and treaties for social implementation, as well as mechanisms of compensation in the unlikely event that something goes wrong. This is the beginning of a "world wherein the weather can be controlled."

3. International cooperation

Since there is a possibility that the weather control technology may be used for military purposes, it is also necessary for the world to cooperate to prevent a certain country from standing out in terms of receiving benefits of the technology. In addition, there may be cases wherein weather control for the benefit of a certain country may become disadvantageous for other countries. For example, because of the control that leads to rainfall in an area where it does not rain, it stops raining in the area that should have originally had the rainfall. In such a case, one weather control generates a benefit for one country and a disadvantage for other countries, which may result in a dispute. There are similar situations in the pollution and construction of dams on international rivers, and it is possible to forestall a dispute or settle the same by signing a treaty.

4. Interdisciplinary cooperation

Items	Specialized fields
New developments in controllability study Construction of weather control theory Simulation technique for the intervention operation The sequential update of the probabilistic prediction that takes the intervention operation into consideration	Predictability study Weather / climate simulation Data assimilation Applied mathematics (dynamical system theory, quantification of uncertainty)
Intervention operating technique	Weather measurement technique Natural energy engineering
Optimal control of human activities to be affected by weather Coregulation of the weather control and human activities	Hydrometeorology, civil engineering Crowd control, evacuation simulation
Ethics of weather control, social adaptation Examination of situation where the intervention operation produces an unexpected consequence	Technological ethics, religion, philosophical approach to science

As shown in Table 2 above, to achieve our goals, collaboration and cooperation among a wide range of academic fields, not limited to the ones that have direct responses against floods such as meteorology, hydrology, and civil engineering, are indispensable. The

weather cannot be controlled yet, but humanity has already been skillfully controlling many things using mathematical theories. The control over an extremely large system such as the weather is unprecedented. Therefore, while one can learn many things from existing applied mathematics and control engineering, weather control poses a new challenge to them as well. Cooperation with the field of mathematics is essential for achieving this goal.

For weather control, we must consider every possibility as to how to intervene and disrupt the real earth. We must collaborate and cooperate with many academic fields to consider the potential of every intervention operation such as the intervention using an electromagnetic wave, the change in land utilization, and the operation of existing natural energy facilities.

In addition, there are many challenges concerning humanities and social science that must be solved on implementing weather control technology, as discussed so far. How should we use a new and powerful technology efficiently? How can we resolve disputes that may arise as a result of such technology? Or, what kind of approach is necessary so that such new technology is accepted in society? Collaboration and cooperation with many academic fields are indispensable in the discussion of these questions.

5. ELSI (Ethical, Legal, Social Issues)

The experience that the international community has worked on in the construction of dams on international rivers or pollution is useful for the social challenges recognized as we have already discussed above. In the case of an international river flowing across multiple borders, the environmental impact of the development such as the dam construction extends over other countries. The rules governing development of river basins and methods for settling disputes in such cases is beginning to be established with various international treaties such as the Espoo Convention. It is important to promote forming an international agreement for the introduction of weather control technology to society by effectively incorporating such an existing framework.

Weather control technologies could have a significant impact on people's worldviews and moral values. Therefore, even if enough safety can be secured scientifically, it is easy to imagine that there would be a certain resistance toward the implementation of weather control technologies. It is important to make a ceaseless effort to eliminate people's concern about implementing the technology by preparing for various compensation mechanisms (for cases wherein something may go wrong), starting with the preparation of legislation, as mentioned above. It cannot be said that the weather control technology based on the chaos theory is easy to understand intuitively. The mechanism promoting appropriate scientific communication needs to be constructed from an early stage based on the examples of regenerative medicine that exist thus far.

IV. Conclusion

We invited excellent external experts from various fields and held a total of 16 seminars on the potential of weather control. With their collaboration, these seminars widely examined the possibility of the weather control technology from the perspective of not only natural science of weather control technology, such as meteorology and control engineering, but also social science humanities, such as economics, international law, science communication, and ethics. The seminars were open for everyone, and we conducted an open discussion with external experts, our MS team, and participants. Furthermore, we held a workshop once where we discussed the initial results of our study on the theory of the probability of weather control based on computer simulation with the researchers in the related fields. We were able to have an open discussion on how close we are to reaching controllability at the current level of research.

The conclusions drawn in this report are based on the understanding regarding the current level of research obtained through the discussion seminars and workshops and task analysis for the future.

The conclusions of our investigation are the following:

- Investigating weather control is inspiring, because this difficult challenge will greatly contribute to sustainable development by fully solving meteorological disasters and renewing our civilization.
- Investigating weather control is imaginable, because the vision of a society free from the fear of meterological disasters realized by weather control can easily be shared with general public, and this technology has a high potential to innovate our society.
- Investigating weather control is credible, because although our idea of weather controllability based on chaotic theory is completely new and original, it can be realized by fusing the existing scientific fields such as weather predictabiolity, can be scientifically validated, and is worth to be pursued by the long-term research project.

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