Journal of the Meteorological Society of Japan

## EARLY ONLINE RELEASE



The DOI for this manuscript is
DOI:10.2151/jmsj.2025-015
J-STAGE Advance published date: January 17, 2025

# Historical review of research activities toward typhoons/hurricanes modification in Japan and the United States

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Will be submitted to the ***JMSJ***

11 March, 2024

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## Abstract

This study summarizes the discussions on typhoons or hurricanes modification in Japan and the United States (US) from the 1940s to the present, based on a survey of past literature and interviews with relevant personnel. Research on hurricane modification began approximately 80 years ago with Project Cirrus (1947 – 1952) and Project Stormfury (1962–1983) run by the US government. This project was initiated following a US proposal to Japan in 1965, which aimed to conduct field experiments using cloud seeding techniques for typhoons over the western North Pacific. The proposal sparked in-depth discussions in both academia and the National Diet of Japan. In 1971, the typhoon committee conditionally approved the field experiment in the western North Pacific, but ultimately, the typhoon field experiment was not conducted. This paper identifies the factors that led to the decision not to proceed with the typhoon field experiment despite significant progress, as well as the reasons underlying the decline of typhoon modification and general weather modification research in Japan from that period onward.

## 1. Introduction

In 2022, "Research on Typhoon Control for a Safe and Prosperous Society" was launched as a core research project under Moonshot Goal 8 of the Japan Science and Technology Agency. In this project, methods and technologies for so-called typhoon control or modification (hereinafter typhoon modification), which involves the reduction of typhoon intensity through human intervention, will be developed and examined for their social implementation.

Figure 1 summarizes the history of typhoon modification research in Japan and the United States (US). Research focused on typhoon modification has been conducted since the latter half of the 20th century, beginning in the 1940s and continuing to the present. In the US, this research was part of the "Project Stormfury (1962−1983)," which aimed to modify hurricanes as stated in the objectives of the project; in Japan, the aim was "artificial control" or "artificial modulation" of typhoons. In 1965, when the US proposed conducting field experiments for cloud seeding for typhoons over the western North Pacific, Japan (led by the National Research Center for Earth Science and Disaster Prevention) extensively discussed the idea in academic circles and in the National Diet. At the session of the Economic Commission for Asia and the Far East (ECAFE) and World Meteorological Organization (WMO) Typhoon Committee in 1971, Japan formally expressed its support for the project with the condition of obtaining consent from the

Fig. 1

affected countries. However, bilateral negotiations between the US and the affected countries did not reach a satisfactory conclusion; thus, the US proposal for the typhoon field experiments was withdrawn. Project Stormfury triggered an increase in weather modification research in Japan, including typhoon modification, but interest in this field rapidly declined after 1971.

Through a survey of past literature and interviews with those involved, this paper first summarizes how exchanges related to typhoon modification research occurred in the US and Japan beginning in the 1940s, as well as how the US decided to propose field experiments for seeding typhoons over the western North Pacific. Then, it discusses why the US proposal for typhoon modification field experiments—which had shown significant progress for some time—was ultimately withdrawn; it also discusses factors that led to the decline of typhoon and weather modification research in Japan.

## 2. Hurricane modification research in the United States

### 2.1 Beginnings of hurricane modification research

The concept of hurricane modification arose as a byproduct of wartime research that began in the 1940s. Schaefer and Langmuir, at the request of the Army Air Corps in 1944, began research that aimed to prevent icing on aircraft (Havens, 1952; Corbridge and

79 Moses, 1968). In July 1946, while working in a cloud chamber, Schaefer and Langmuir
80 accidentally discovered that ice crystals formed instantaneously when dry ice was placed
81 in a cloud of supercooled water droplets (Havens, 1952; Murakami, 2015). This
82 observation formed the basis of the cloud seeding concept.

83 On 13 November 1946, the first outdoor experiment of dry ice seeding into
84 supercooled clouds was conducted (Langmuir et al., 1948; Takahashi, 1969; Havens,
85 1952). Schaefer and General Electric test pilot Talbot used a small aircraft to seed 13 kg
86 dry ice in a supercooled cloud extending approximately 30 n mi (48 km) over Greylock
87 Mountain, Massachusetts. A few minutes after seeding, the supercooled cloud became a
88 snow cloud (Isono, 1960).

89 Vonnegut joined the supercooling study in the fall of 1945 (Havens, 1952) and tested
90 three substances with crystal structures resembling ice: lead iodide, antimony, and silver
91 iodide. Through experiments in which the substances were dropped into a cloud chamber,
92 silver iodide was identified as a very effective seeding substance.

93 In 1947, the Project Cirrus—a cloud physics collaboration between the US Army
94 Signal Corps and the Office of Naval Research in consultation with General Electric—
95 was initiated with the goal of obtaining a more complete understanding of physical
96 processes in the atmosphere, particularly cloud formation, growth, and extinction

97 (Langmuir, 1948; Corbridge and Moses, 1968).

98 On 13 October 1947, the first field experiment of seeding was conducted on a
99 hurricane, code named "King" by the Naval Hurricane Office (Langmuir, 1948; Havens,
100 1952; Tsuchiya, 1970). Approximately 86 kg of dry ice were seeded near the center of the
101 hurricane from an altitude of 8000 m. The minimum central pressure of the hurricane was
102 973.9 hPa and the maximum instantaneous wind speed was ~43 $ms^{-1}$. Immediately after
103 seeding, Hurricane King seemed to partially weaken, but it developed again the next day.
104 The hurricane made landfall in Georgia and South Carolina, causing $2 million in damage.
105 The public claimed that the damage in Georgia had been caused by a seeding experiment,
106 and a lawsuit was filed. However, meteorologists pointed out that hurricanes in 1906 and
107 a week ago followed nearly the same path (Suburbs and Disaster Prevention Editorial
108 Committee, 1966), indicating that the path of Hurricane King had begun to change before
109 seeding was performed. Because of the lawsuit, Project Cirrus discontinued seeding
110 experiments. The Project did carry out further non-hurricane seeding after Hurricane King.

111 Despite the concerns about hurricane seeding raised by Project Cirrus, hurricane
112 modification studies were not terminated because six hurricanes—Carol, Edna, and Hazel
113 in 1954 and Connie, Diane, and Ione in 1955—caused extensive damage in the US
114 (Willoughby et al., 1985). After the 1955 hurricane season, the US Weather Bureau

115 launched the National Hurricane Research Project (NHRP). The purpose of the program
116 was to study the structure and dynamics of hurricanes and to research ways to regulate
117 them and to improve forecasting. During its first three years, NHRP, conducted hurricane
118 observations using Air Force aircraft; these investigations revealed a large amount of
119 super-cooled liquid water within hurricanes (Simpson et al., 1962). Within 6 years of
120 establishment, the NHRP had its own aircraft (Willoughby et al., 1985).

121 In 1961, for the second time in the world, the field experiment of seeding against
122 hurricane was conducted on Hurricane Esther, a typical mature and severe hurricane with
123 a minimum central pressure of 927 hPa and maximum wind speeds of over 65 $ms^{-1}$. The
124 purpose of the experiment was to seed the hurricane eye wall cloud to produce negative
125 absolute vorticity and circulation instability (Simpson et al., 1962; Gentry, 1970a).

126 The project was conducted over a total of 2 days, 16 and 17 September 1961, with
127 silver iodide seeding in the wall cloud on the 16th and outside of the wall cloud on the
128 17th; the seeding on the 17th did not reduce the maximum wind speed, but the seeding
129 on the 16th was found to reduce the maximum wind speed by ~10 % over a 2-hour period
130 (Simpson et al., 1962; Sheets, 1981). This decrease in wind speed corresponded to
131 outward diffusion of kinetic energy (Fig. 2). Several additional experiments were
132 proposed to see if results from the 16th were caused by seeding or by natural variations

Fig. 2

133 in the structure and intensity of the hurricane. It was also requested that silver iodide be
134 continuously applied during the additional experiments. After 2 days of experimentation,
135 there was an obvious change in intensity due to seeding, and the experiment was
136 considered a success.
137
138 **2.2 Project Stormfury**
139 On 30 July 1962, following the successful seeding experiment on Hurricane Esther,
140 the US Navy and the Department of Commerce initiated the Project Stormfury, a joint
141 effort led by Simpson and Gentry, who had coordinated the Hurricane Esther experiment
142 (the US Department of Commerce/Environmental Science Services Administration 1967).
143 There were three main reasons for public support of Project Stormfury at that time (Gentry,
144 1969; 1970a). First, advances in hurricane research had improved the understanding of
145 hurricanes and their developmental mechanisms, making modification methods seem
146 realistic; there was a belief that aircraft observations, combined with seeding, would
147 enhance understanding of hurricane mechanisms. Second, the amount of hurricane-
148 related damage in the US was rapidly increasing. Including the six hurricanes of 1954 and
149 1955, the average annual damage from 1960 to 1969 jumped to $432 million, a 650%
150 increase in less than 50 years. Finally, the perceived benefits of seeding were thought to

151 greatly outweigh the costs of developing and implementing the technology. A 10%
152 reduction in damage from a single hurricane comparable to Hurricane Betsy in 1965,
153 which caused $1.4 billion in damage, could yield benefits exceeding 1000% of the
154 project's cost after 10 years of ongoing hurricane research.

155 However, there were few actual opportunities for field experiments during Project
156 Stormfury. Only three experiments were conducted, involving Hurricane Beulah (1963),
157 Hurricane Debbie (1969), and Hurricane Ginger (1971). Figure 3 shows the tracks and
158 seeded locations of these three hurricanes, along with Hurricane Esther (1961).

Fig. 3

159 In the field experiment for Hurricane Beulah, a total of approximately 455kg of silver
160 iodide were seeded on 23 and 24 August 1963 (Simpson and Malkus, 1964; Dunn et al.,
161 1963; Sheets, 1981). The minimum central pressure and maximum wind speed of
162 Hurricane Beulah were 958 hPa and 54 $ms^{-1}$, before seeding (Dunn, 1963). The minimum
163 central pressure and maximum wind speed did not change significantly after the first
164 seeding, but after the second seeding, the minimum central pressure decreased by 15 hPa
165 and the maximum wind speed by over 30 kt (15.4 $ms^{-1}$). These differences were attributed
166 to the fact that the first silver iodide seeding procedure was performed in a nearly
167 cloudless area (Simpson and Malkus, 1964).

168 In the field experiment for Hurricane Debbie, seeding was conducted five times using

169 approximately 371 kg of silver iodide over 2 days, on 18 and 20 August 1969 (Gentry
170 1970b; the US Department of Commerce, and NOAA 1977). The minimum central
171 pressure of Hurricane Debbie was 950 hPa, and the maximum wind speed was 57 $ms^{-1}$
172 before seeding (Chafee et al., 1970; Simpson et al., 1970). Figure 4 shows the wind speed
173 distribution before and after seedings. After seeding, the wind strength varied, but on
174 average, the wind speed decreased from just after the second seeding to 5 or 6 hours after
175 the fifth seeding (Gentry, 1970b). The wind speed was recorded at 43 $ms^{-1}$ on 20 August
176 1969 (Chafee et al., 1970).

Fig. 4

177 On 26 September 1971, a seeding experiment was conducted on Hurricane Ginger
178 (Dorst 2007; Wilford 1971). Fourteen aircraft, manned by 250 people, were used for this
179 experiment. Ginger, being a small hurricane with light winds and no strong convection
180 over the entire area, had seeding conducted in the outer rain bands rather than near the
181 eyewall cloud. Post-seeding, radar signals and winds showed no objective changes due to
182 seeding. Hurricane Ginger made landfall in North Carolina on 30 September 1971
183 (Omoto, 1971a).

184

185 **2.3 Criteria for the Experiments and proposal to conduct field experiment for**
186 **typhoons over the western North Pacific**

During Project Stormfury, a seeding experiment in Hurricane Betsy in September 1965 was considered; however, it was abandoned because Hurricane Betsy was particularly close to land (Willoughby, 1985). Hurricane Betsy eventually made landfall in south Florida and Louisiana; it caused over 80 fatalities and $1.4 billion in damage, earning the nickname "Billion Dollar Betsy" (NOAA, 2015; Kiner, 2015). On 31 August 1965, Hurricane Betsy was forecast to be within Project Stormfury's experimental area, and a seeding experiment was scheduled for 1 September 1965. In the morning, aircraft departed from Roosevelt Roads Naval Air Station. However, the National Hurricane Center reported that Hurricane Betsy had changed course overnight, with a southward track that would avoid the experimental area. Consequently, the seeding experiment was cancelled, and the mission was altered to a rehearsal. The aircraft flew as originally planned, but no silver iodide was released. Because neither Project Stormfury nor the Weather Bureau had informed the public or the press of the seeding cancellation, many people believed it had been carried out and a link to its unusual path seemed plausible. Although it was later clarified that the seeding had not occurred, doubts lingered regarding its potential impact (NOAA, 2015).

In 1967, LaSeur from Florida State University and 4 other members of the Stormfury Advisory Board recommended setting criteria for field experiments (Science, 1967).

205 Previously, hurricanes were considered for seeding only if they were located in a specific
206 geographic area between Bermuda and Puerto Rico. An attempt was then made to select
207 storms for experimentation based on hurricane tracks and location predictions. In
208 accordance with this recommendation, Project Stormfury members established the
209 following criteria: a tropical cyclone in the southwestern North Atlantic Ocean, Gulf of
210 Mexico, or Caribbean Sea is considered eligible for seeding as long as there is only a
211 small probability (10 percent or less) of the hurricane center coming within 50 n mi of a
212 populated land area within 24 hours after seeding (Chafee et al., 1969). The dotted line in
213 Figure 5 represents the 50 n mi distance from inhabited areas.

Fig. 5

214 Seeding was not implemented on or near land for two main reasons. First, seeding at
215 sea would allow the hurricane to revert to its natural state before reaching land. Second,
216 hurricanes undergo substantial structural changes when passing over land, complicating
217 the scientific evaluation of seeding effects (Chafee et al., 1969; 1970).

218 Beginning in 1970, the scope of Project Stormfury was expanded, and the criteria were
219 relaxed to include hurricanes with less than a 10% chance of coming within 50 n mi of a
220 populated area within 18 hours of the last seeding. The experimental period was extended
221 from the original 1 August, start date and 15 October end date to a new period from late
222 July and the end of October. With these new criteria, it was estimated that an average of

two feasible hurricanes could be tested annually.

The US (Project Stormfury members) estimated that using Okinawa and Guam as test sites (Fig. 6) and conducting filed experiments against typhoons over the western North Pacific could allow for an average of about 6.0 experiments per year, even under the initial safety criteria (Black, 1971). This frequency would be about three times higher than that in the Atlantic Ocean. Consequently, it was decided to explore conducting field experiments over the western North Pacific and to approach concerned countries, including Japan.

Fig. 6

At the first ECAFE WMO Experts Meeting in Manila, Philippines, in December 1965, the US made this proposal to concerned countries, including Japan. The Japanese representatives were Michio Yanai (Japan Meteorological Agency, JMA) and Akira Mizuno (Embassy of Japan in Thailand). Japan was the only country to oppose the US proposal (Mizuno, 1971). Reasons for this opposition included a lack of full theoretical understanding of the experiment; issues of compensation and liability for unexpected damage; concerns about altering typhoon paths and precipitation patterns, which are important for Japan's water resources; and a belief that conventional engineering methods were sufficient to address flood damage. Although other participating countries, including Taiwan, Hong Kong, South Korea, Laos, the Philippines, Vietnam, and Thailand favored

241 the proposal, Japan's opposition resulted in the decision not to conduct field experiments
242 against typhoons in the western North Pacific.
243
244 **3. Typhoon and weather modification research in Japan**
245 **3.1 Beginnings of typhoon and weather modification research in Japan**
246 Typhoon modification research in Japan began after Typhoon Vera (1959), also
247 known as the Isewan Typhoon. This typhoon made landfall west of Cape Ushio in
248 Wakayama Prefecture on September 26, 1959, causing storm surge and levee breaches in
249 low-lying coastal areas that resulted in 4697 fatalities nationwide. In response, an
250 extraordinary typhoon science committee meeting was held, where the concept of
251 typhoon modification in Japan was mentioned for the first time in November 1959
252 (Nakasone, 1960); records indicate that the first mention of typhoon modification
253 occurred at this meeting.
254 The report of the ad hoc typhoon science committee emphasized that "establishing a
255 scientific basis is the first priority for the time being, and furthermore, research on
256 typhoon modification, such as reducing the destructive power of typhoons at sea or
257 altering their direction, should be considered. Promoting research on artificial rainfall and
258 other basic research for typhoon modification is also important.". Article 8, paragraph (2),

item (ix) of the Basic Act on Disaster Management, promulgated in November 1961, stipulates that "The State and local governments must particularly endeavor to carry out the following matters: matters on international cooperation with respect to human control of typhoons…."

Although the Japanese government opposed field experiments against typhoons at the 1965 conference, this opposition led to the initiation of full-scale weather modification research in Japan, spearheaded by the National Research Institute for Earth Science and Disaster Prevention (NIED). At that time, research concerning artificial interference with the weather was termed weather modification research, encompassing areas such as typhoon modification, artificial rainfall, artificial snowfall, hail suppression, and fog dissipation.

In 1965, the NIED initiated a 2-year project titled “Research on Weather Modification" (Ozawa et al., 1978), and the First Conference on Weather Modification Research was held in 1967. This conference served as a platform for Japanese researchers in the field to gather, report research findings, and exchange ideas. Participants included researchers from the NIED, the Atmosphere and Ocean Research Institute of the University of Tokyo, Tohoku University, Nagoya University, the JMA, the Meteorological Research Institute, the National Agricultural Technology Research Center,

277 and the Japan Weather Association. The second Meteorological Modification Research
278 Roundtable Meeting was convened the following year.

279 Beginning in 1968, a 5-year special research project titled “Research on the
280 Prevention of Hailstorms by Artificial Modification of Cumulonimbus Clouds” was
281 begun (Ozawa et al., 1978). Although it was regarded as “a cloud catching story” by the
282 Ministry of Finance, the project received a substantial budget exceeding ¥2.7 million
283 (Iwabuchi, 1988). The primary artificial modification method for cumulonimbus clouds
284 considered was seeding. The conventional methods—ground fuming and aircraft
285 spraying—were hindered by efficiency issues and a lack of suitable aircraft for
286 experiments. Thus, new methods were explored, such as using rockets to spray silver
287 iodide. Considering Japan’s small size, large population, and residential density, the
288 development of an annihilation rocket—which would disappear mid-air after launch
289 without falling to the ground—was deemed necessary. Nissan Motor Co., Ltd. developed
290 such a rocket, nearly completing it, and field seeding experiments were conducted at the
291 Ground Self-Defense Force Hinode-dai Training Area, the Gunma Prefectural Asama
292 Farm, and the Ground Self-Defense Force Somagahara Training Area beginning in 1969
293 (Ozawa et al., 1978). The rocket was small—weighing ~2.9 kg and measuring ~78 cm in
294 length—and cost ¥430,000 per unit at that time. However, if production of about ~50,000

rockets per year could be sustained for several years, the cost was realistically estimated to be less than ¥50,000 per unit (Iwabuchi, 1988).

### 3.2 Consideration of safety criteria for the field experiment of typhoons in the western North Pacific

In 1969, Norihiko Fukuta, a Japanese researcher at the University of Denver, visited Japan to investigate the state of weather modification research and discuss future directions with Kazuhiko Terada, Yasuo Omoto, and others at the National Research Institute for Earth Science and Disaster Prevention (NIED). Upon return to the US, Fukuta proposed organizing a Japan−US scientific cooperation seminar concerning the artificial modification of hurricanes and typhoons. In response, the Center for Science and Technology for Disaster Prevention formed an expert committee to consider this proposal. However, the committee concluded that a seminar on typhoon modification was not feasible, based on the current status of Japanese research and its previous history. The US researchers expressed substantial interest in this seminar and suggested focusing on themes of “artificial modification of cumulus clouds” or “weather regulation”; the seminar was viewed as a step toward future hurricane and typhoon modification efforts. Ultimately, the chosen seminar theme was "Cumulonimbus Modification of Tropical

313 Nature," and the first Japan–US scientific cooperation seminar was held in 1970.

314 Japanese attendees included Terada and Omoto from the Disaster Prevention Center,
315 Kitaoka, Fujiwara, and Ono from the Meteorological Research Institute, Magono from
316 Hokkaido University, and Takeda from Kyushu University. The US attendees were Gentry,
317 Fujita, Fukuta, Ooyama, Hawkins, and Mallinger.

318 The seminar also discussed field experiments involving typhoons over the western
319 North Pacific, with varying opinions throughout. By the end of the seminar, the Japanese
320 attendees expressed their preference for conducting the experiments under conditions that
321 would not affect Far Eastern countries; they agreed to consult with the affected countries
322 to determine appropriate safety criteria upon their return to Japan. At that time, Japan
323 favored experiments in the western North Pacific for three main reasons: the absence of
324 meteorological observation aircraft: Japanese researchers expected the US Project Stormfury
325 members would provide aircrafts to conduct field experiments, reported minimal lasting effects
326 from the US experiment on Hurricane Debbie in 1969, and significant advancements in
327 tropical cyclone theory (Omoto, 1971b).

328 After the seminar, participants sought to establish Japanese hurricane safety criteria
329 similar to criteria utilized in the US. Discussions with various ministry officials were held,
330 and recorded in the minutes of Diet members' meetings (Special Committee on Disasters,

1967; Special Sub-committee for the Promotion of Science and Technology, 1970; Special Committee on Agriculture, Forestry and Fisheries, 1971). Terada's statements included a desire to conduct joint typhoon and hurricane research involving the US and Japan. Despite extensive discussions, Japan's safety criteria were not established within 1 year.

Additionally, the minutes of the Special Committee on Agriculture, Forestry, and Fisheries (1971) include a discussion on typhoon modification using nuclear power. A committee member inquired about the problematic nature of this approach with respect to peaceful use of nuclear energy. Terada responded that the idea had been considered shortly after the war due to similarities in energy between typhoons and atomic bombs. However, he acknowledged that then-current methods of reducing typhoon force were entirely different and represented a significant advancement over the use of nuclear power. Omoto (1971b) noted that although promises were made at the Japan–US talks in Miami to establish the desired safety criteria and inform Project Stormfury Director Gentry, no conclusion had been reached by October, despite repeated discussions.

## 4. Decline of Project Stormfury

### 4.1 Cancellation of the field experiment on typhoons in the western North Pacific

**and its background**

At the 4th session of the ECAFE and WMO Typhoon Committee in Tokyo, 4–11 October 1971, members discussed conducting a typhoon modification experiment in the western North Pacific in 1972. In principle, all members welcomed the proposed transfer of Project Stormfury to the western North Pacific in 1972, provided that agreements were made concerning appropriate criteria and restrictive conditions for seeding experiments (ECAFE and WMO, 1971; Mizuno, 1971). In particular, the South Korean and Philippine representatives affirmed their full support for the US proposal (Japan ECAFE Association, 1971). Although the Typhoon Committee's minutes indicated agreement in principle, the JMA's representatives expressed reservations. They supported experiments with certain restrictions to increase typhoon knowledge but emphasized the need for clarity about potential adverse effects before they could confirm agreement (JMA, 1975).

During the meeting, Japan's representatives acknowledged the scientific value of the US plan but expressed concerns about effects on public opinion in Japan. They suggested establishing safety criteria in consultation with other countries and conducting tests only on agreed-upon typhoons (Omoto, 1971a). Japan's concerns included insufficient observational data from previous Project Stormfury experiments, administrative issues that could arise if problems occurred, legal aspects under international law, and

differences between hurricanes and typhoons (Mizuno, 1971).

The committee noted that the US would take the initiative in approaching the affected countries (Japan, Taiwan, and the Philippines) to seek bilateral agreement on criteria and restrictive conditions (ECAFE and WMO, 1971). All experimental data would be made publicly available to the Typhoon Committee and other affected countries (Mizuno, 1971; Inada, 1971).

However, a serious issue arose: the US needed to decide on conducting the experiment by 1 January 1972, to secure the US military support due to budget constraints. This urgency led to hurried bilateral negotiations (Mizuno, 1971). No records of these negotiations have been found, but a 14 July 1972 Asahi Shimbun article revealed Japan's opposition to the experiment in 1972. It reported that the project, scheduled to begin in August, had been postponed for at least 1 year due to Japanese reluctance (Asahi Shimbun, 1972).

Preliminary evaluations by Japan's Ministry of Construction and the JMA suggested more risks than benefits. The Ministry's concerns included potential deviations in typhoon paths if modified, limited effectiveness in reducing typhoon force, water crisis risks if typhoons disappeared, and possible the US motives for experimenting on typhoons instead of their own hurricanes (Fujiwara, 1974).

385 At the 28th ECAFE General Assembly in Bangkok, March 1972, the US announced
386 no field experiments would be conducted in 1972 because of multiple difficulties
387 (Matsumoto, 1972). At the 5th session of ECAFE and WMO Typhoon Committee in
388 November 1972, the US representatives reported that aircraft operations could not
389 continue without military support; considering the planned Global Atmospheric Research
390 Program in 1974, experiments were unlikely in 1973 and 1974 (ECAFE and WMO, 1972).
391 After the 1972 hurricane season, Project Stormfury funding was substantially reduced
392 due to Vietnam War-related economic conditions (Dorst, 2007; Fujiwara, 1974).
393 In early August 1974, the US again proposed field experiments in the western North
394 Pacific. Japanese representatives received the proposal through the US Embassy in Japan.
395 In the 1974 proposal, Okinawa was excluded from the list of candidate test sites. This was
396 because Japan had insisted that no experiments be conducted on typhoons with the
397 potential for landfall in Japan, noting that such tests might alter the paths of typhoons or
398 increase their rainfall, the "side effects" (Yomiuri shimbun, 1974).
399 At the 7th session of the ECAFE and WMO Typhoon Committee in Manila in
400 October 1974, the US again proposed field experiments in the western North Pacific
401 (Nakamura, 1975). The US representatives stated that they would conduct bilateral
402 negotiations with each country individually and report back to the General Assembly for

403 a decision regarding whether or not to conduct experiments (ECAFE and WMO, 1974).
404 The representative from the Philippines responded in a positive manner, mentioning that
405 his country had begun its own 5-year typhoon modification research program as a national
406 project in January 1974. The Japanese representative was cautious, noting that the
407 experiment might change the tracks of typhoons and increase rainfall (Nakamura, 1975).
408 Suda, Director of the Meteorological Research Institute of the JMA at the time, said, "The
409 experiment itself is really fascinating, and I would like to try it from the standpoint of
410 progress in typhoon research. However, we cannot assure that there will be no side effects,
411 and if public opinion says to do it, we will do it (Nakamura, 1975; 1978). An informal
412 discussion of typhoon modification was held on the evening of the first day of the fall
413 meeting of the Meteorological Society of Japan (MSJ) (29 October 1974); the transfer of
414 experiments to the western North Pacific was discussed among members of the Society.
415 The following opinions of the MSJ members at the meeting below (Abe et al., 1975),
416 "Gentry and some researchers say that wind speeds have weakened, but I doubt it because
417 the way if they wanted to do the experiment is unknown. Why don't they conduct direct
418 verification such as taking pictures of clouds or collecting ice crystals? This does not
419 seem like a scientific attitude. The JMA officials say that the experiment will not have
420 much effect, but if there is a big effect (e.g., a typhoon making landfall), it would be a big

problem. Some the US scholars are concerned about the possible changes in the air supply caused by the modification. We need the principles of independence, democracy, and openness. Japan's independence is necessary, and Since interdisciplinary studies are shared by all humankind, we should not have the attitude that it does not affect our country, so it does not matter which way we go." The majority of the participants agreed that "the results of experiments conducted in the Atlantic Ocean, which are used as a basis for forecasting phenomena resulting from experiments currently planned in the western North Pacific, such as changes in wind speeds, rainfall intensity, and paths of typhoons in the region, are not necessarily clear, and that large-scale experiments should not be conducted in the western North Pacific" (Isono, 1975). Abe and his colleagues also commented, "The authorities of the JMA should reflect greatly on their previous attitude. A meeting like this one should have been held a few years ago. Even now, I think the authorities should write an article in the "Weather" section to solicit the opinions of a wider range of academics." The western North Pacific experiment was to be conducted at sea within a radius of 1000 km (540 n mi) centered on Guam, and the conditions were set to "allow only typhoons that do not approach within 500 km (270 n mi) of land within 24 hours of their last seeding". This condition was stricter than the Atlantic experimental condition of "only hurricanes with a 10% or less chance of coming within 50 n mi of

439 human habitation within 18 hours of last seeding (1970)" (Nakamura, 1975; 1978). The
440 Philippines, South Korea, Hong Kong, and Thailand had positive views of the US
441 proposal, but Japan and China were cautious; at the Economic and Social Commission
442 for Asia and the Pacific (ESCAP) meeting in New Delhi in March 1975, China stated that
443 it could not "agree to the US proposal" (Nakamura, 1978). The report of the Typhoon
444 Committee meeting in Bangkok in November 1975 concluded that the field experiments
445 on typhoons over the western North Pacific would not be conducted because bilateral
446 negotiations and other discussions had not reached a satisfactory conclusion (ESCAP and
447 WMO, 1975). There is no record of any discussion of field experiments in the western
448 North Pacific by the Typhoon Committee after 1976.

449 Taiwan, one of the three countries engaged in bilateral negotiations with the US,
450 experienced an important change. On October 25, 1971, at the United Nations (UN)
451 General Assembly, the People's Republic of China (PRC) joined the UN and was
452 recognized as the sole legitimate government of China, replacing the Republic of China
453 (Taiwan) in the UN system and other related international organizations. Consequently,
454 Taiwan lost its seat in the UN General Assembly, its membership in the ECAFE, and its
455 membership in the Typhoon Committee. Details of the bilateral negotiations between
456 Taiwan and the US are unclear, but Taiwan's loss of membership in the Typhoon

Committee likely impacted the outcome.

During the implementation of Project Stormfury, discussions primarily between the US and the Union of Soviet Socialist Republics (USSR) focused on preventing the military use of weather modification technology, especially in the context of the Vietnam War (1954-1975). In Operation Popeye, the US attempted to disrupt North Vietnamese troop movements and suppress missile fire using artificial rainfall in Vietnam, Laos, Thailand, and Cambodia. However, some individuals strongly opposed using artificial rainfall in warfare (Wilford, 1972). After these events during the Vietnam War, discussions began in October 1971 to establish a treaty on banning the hostile use of environment-modifying technologies.

In 1972, the US renounced the use of weather modification technology for hostile purposes. In 1973, the US Senate passed a bill prohibiting any environmental or geophysical modification activity as a weapon of war. In August 1975, the US and the Soviet Union tabled a draft treaty of a convention to the Geneva Conference on Disarmament. This treaty was adopted by the UN General Assembly at its 31st session on 10 December 1976, as the Convention on the Prohibition of the Hostile Use of Environmental Modification Technology and was later approved by the Japanese Diet on 4 June 1982.

475

476 **4.2 Termination of Project Stormfury**

477 In the 1980s, two scientific discoveries (1) the absence of supercooled water droplets
478 and (2) the observed reformation of the eyewall in non-seeding hurricanes led to the
479 rejection of the Stormfury hypothesis and the Stormfury members discontinued additional
480 field experiments.

481 The proposed Stormfury hypothesis involved artificial stimulation of convection
482 outside the eyewall through seeding with silver iodide to release the heat the supercooled
483 water. The invigorated convection, it was argued, would compete with the original
484 eyewall, lead to reformation of the eyewall at larger radius, and thus, through partial
485 conservation of angular momentum, produce a decrease in the strongest winds (Gentry,
486 1970a; Gentry, 1970b; Simpson, 1962). For seeding to be successful, the clouds must
487 contain supercooled water, but observations made in the 1980s suggested that most
488 hurricanes didn't have enough supercooled water for the Stormfury hypothesis to work
489 (Black and Hallett, 1986; Hallett and Mossop, 1974).

490 In seeding experiments on hurricane Eshter, Beulah, and Debbie, the eyewall was
491 observed to have moved outward, as hypothesized. However, since the 1980s, non-
492 seeding hurricanes have also been observed to naturally form outward eyewalls

493 (Willoughby, 1990; Willoughby et al., 1982). This phenomenon suggested that it was
494 impossible to isolate the effects of seeding from natural changes in field experiments and
495 prevented additional field experiments.

496 A special committee of the US National Academy of Sciences concluded that a more
497 complete understanding of the physical processes of hurricanes was needed before
498 additional corrective experiments could be conducted, and Project Stormfury was
499 terminated in 1983.

500

501 **5. Decline of typhoon and weather modification research in Japan**

502 According to Ozawa et al. (1978), the typhoon and weather modification research
503 committee had not convened for various reasons since its third meeting on 12 June 1970.
504 Additionally, Ozawa et al. (1978) noted that the committee's composition underwent
505 extensive changes in the 2 to 3 years after 1971; therefore, the resulting infrastructure for
506 weather modification research was considerably less advanced compared with the period
507 of discussion concerning field experiments in the western North Pacific. Figure 7 shows
508 that 120 references regarding typhoon modification research were published in Japan
509 from 1947 to 2023. The literature was collected from various sources, including the
510 National Diet Library Online, National Diet Library Search, National Diet Library Digital

Fig. 7

511 Collection, National Diet Conference Proceedings Search System, MAISAKU, *Asahi*
512 *Shimbun* Cross Research, Yomidas History Museum, and National Archives of Japan
513 Digital Archive. The number of references peaked at 21 in 1971, then decreased to 11 in
514 1972 and 3 in 1973. Considering that academic articles often closely reflect changes in
515 research priorities, it is evident that typhoon modification research declined concurrently
516 with weather modification research. However, there is no literature or reference material
517 that explicitly describes the reasons for these changes. Consequently, a literature review
518 and interview survey were conducted based on the hypothesis that an adverse event
519 impacting weather modification research in Japan occurred around 1971. Several reasons
520 for the decline in meteorological modification research were identified.

521 First, according to Omoto (1971a), the media coverage of typhoon modification
522 experiments around 1970 in Japan was problematic. After the 4th session of the Typhoon
523 Committee in October 1971, reports inaccurately indicated that artificial typhoon
524 modification experiments were definitively scheduled for the following year (Yomiuri
525 shimbun, 1971). Newspapers and television often oversimplified the experiment's nature,
526 describing it as "typhoon destroy," "silver iodide sprinkling," or "attack" (Asahi Shimbun,
527 1971a; Asahi shimbun, 1971b; Yomiuri shimbun, 1971). Additionally, Science Fiction
528 Magazine (SF Magazine) suggested that compared to the US's proactive approach,

529 Japan's lack of action in typhoon modification was frustrating. The magazine speculated
530 that Japan's negative attitude toward typhoon modification research would not be
531 conducting field experiments for another 10 years, compared to 4 field experiments in the
532 Atlantic and observations in south Pacific conducted in the US (Kato, 1971). Although
533 this perspective could be interpreted as support for seeding experiments in the western
534 North Pacific, the negative representation may have contributed to public opposition.

535 Second, an accident was caused by an artificial landslide experiment in Kawasaki on
536 11 November 1971. In that experiment, an attempt to artificially recreate a landslide by
537 dumping large amounts of water on a slope led to an unexpected massive slope failure
538 (Kuronuma, 1972; Oishi, 1971). This resulted in the deaths of 15 researchers and media
539 personnel present at the site. The incident received widespread domestic and international
540 media coverage (New York Times, 1971). Since the accident, research and experiments
541 that involve artificial intervention in nature were feared (Asahi shimbun, 1971c). The
542 accident also had a serious impact on public perception and support for weather
543 modification research.

544 Third, Terada resigned as director of the NIED, based on his assumption of
545 responsibility for the Kawasaki accident. Terada was a key figure in typhoon modification
546 research; he actively promoted relevant studies and organized the Japan–US Science and

Technology Seminar. His leadership in the "Research on Weather Modification (1965–1967)" project had considerably enhanced the investigation, extending the project's initial duration by 1 year (Ozawa et al., 1978). However, after his resignation, Sugawara, who opposed typhoon modification, became the director. Sugawara's stance was clarified on 14 July 1972, Asahi Shimbun article, where he indicated disagreement with the typhoon modification approach previously considered under Terada's direction.

Fourth, media portrayal of the accident in Kawasaki had a negative impact. The accident was reported on television news as an investigation of artificial rainfall-induced cliff collapse, which led the public to believe that artificial rainfall was dangerous. However, the actual experiment solely involved spraying water via pumps; no artificial rainfall techniques were used. Nevertheless, the public likely associated the term "artificial rainfall"—and, by extension, weather modification research—with the accident (NHK, 2021; Yamada and Inokuchi, 2022).

Fifth, transition of Project Stormfury to the western North Pacific was cancelled. Japan's participation in the 1972 western North Pacific experiment would have provided detailed typhoon observation data using the US aircraft. The number of references to typhoon modification research in Japan decreased from 1971 to 1972 substantially (Fig. 7), indicating a rapid decline in typhoon modification research in Japan at the same time

565 the experiment cancelled.

566 Sixth, the termination of the Special Research Project "Research on Hailstorm
567 Prevention by Artificial Modification of Cumulonimbus Clouds" in 1972, along with the
568 discontinuation of all related research and field experiments, primarily arose from
569 changes in meteorological research trends during that period. Meteorological research
570 was transitioning from aircraft-based observations to satellite-based observations, which
571 represented a significant shift. This considerable shift was driven by the launch of the
572 world's first meteorological satellite, US TIROS-1 (Television Infrared Observation
573 Satellite Program), in April 1960; Japan’s first geostationary meteorological satellite,
574 Himawari, was launched in 1977, and the initiation of the World Weather Watch project
575 was initiated by the WMO in 1963, promoting a global meteorological satellite
576 observation network (JMA, 1975). This sixth reason highlights a broad transformation in
577 meteorological research trends, which contributed to the overall decline in meteorological
578 modification research.

579

580 **6. Conclusion**

581 This review explored the history of typhoon and hurricane modification research in
582 Japan and the experiments by the US influenced similar research in Japan, but substantial

583 interest in typhoon modification in Japan arose after Typhoon Vera (1959). Despite initial
584 hesitancy, Japan began to explore weather modification, establishing a foundation for
585 future typhoon research.

586 The turning point for Japanese typhoon modification research was the 1965 ECAFE
587 and WMO Typhoon Expert Meeting, which contained a US proposal for regional field
588 experiments that stimulated debate in Japan. By 1971, Japanese researchers were more
589 amenable to participation in experiments in the western North Pacific, although
590 discussions about safety criteria remained unresolved.

591 In the early 1970s, there were conflicting views within Japan about participation in
592 field experiments proposed the US. By 1975, due to the lack of agreement, the US
593 abandoned plans for experiments in the western North Pacific. Concurrently, Japan's
594 weather modification research, active during the Project Stormfury era, sharply declined
595 due to negative media coverage and shifts in meteorological research focus.

596 Decades of advances in meteorology and numerical simulations now suggest the
597 scientific feasibility of typhoon modification. Moreover, it is quite likely that society
598 would need to mitigate extreme weather events as an option for disaster prevention
599 methods. The various data show that global warming and other environmental
600 challenges will intensify rainfall and winds in the near future (IPCC, 2023).

Based on these circumstances, in 2022, a research project on weather modification, the Moonshot Goal 8, was launched by the Cabinet Office, Government of Japan. The ambitious goal of the project is to implement typhoon mitigation technologies by 2050. Prior to implementation, several field experiments should be conducted to verify feasibility. The target year for typhoon field experiments is 2040. By this time, we need to address the scientific challenges left unsolved since Project Stormfury.

Designing the experiments and developing effective modification methods, require a comprehensive understanding of typhoon dynamics, particularly in the areas of generation mechanisms, intensity change, and structural transformation. Furthermore, to accurately evaluate the effects of intervention relative to natural typhoon behavior in field experiments, it is necessary to develop numerical models capable of accurately reproducing turbulence and cloud formation. Establishing an integrated observation system that combines multiple approaches, such as conventional meteorological satellite observations and direct aircraft observations, is also critical to precisely monitor changes in typhoon intensity.

Moreover, building on the international discussions during Project Stormfury, it is necessary to approach the realization of field experiments from a social perspective, including the establishment of safety criteria. Overall, this review is expected to

contribute to the advancement of typhoon modification research.

***Acknowledgments.***

The authors would like to thank Drs. T. Furukawa, T. Hashida, M. Murakami, and M. Yamanaka for valuable talks on the history of weather modification research.. The National Research Institute for Earth Science and Disaster Prevention (NIED) provided information for this research. This work was supported by JST Moonshot R&D Program (JPMJMS2282-11 and JPMJMS2282-03).

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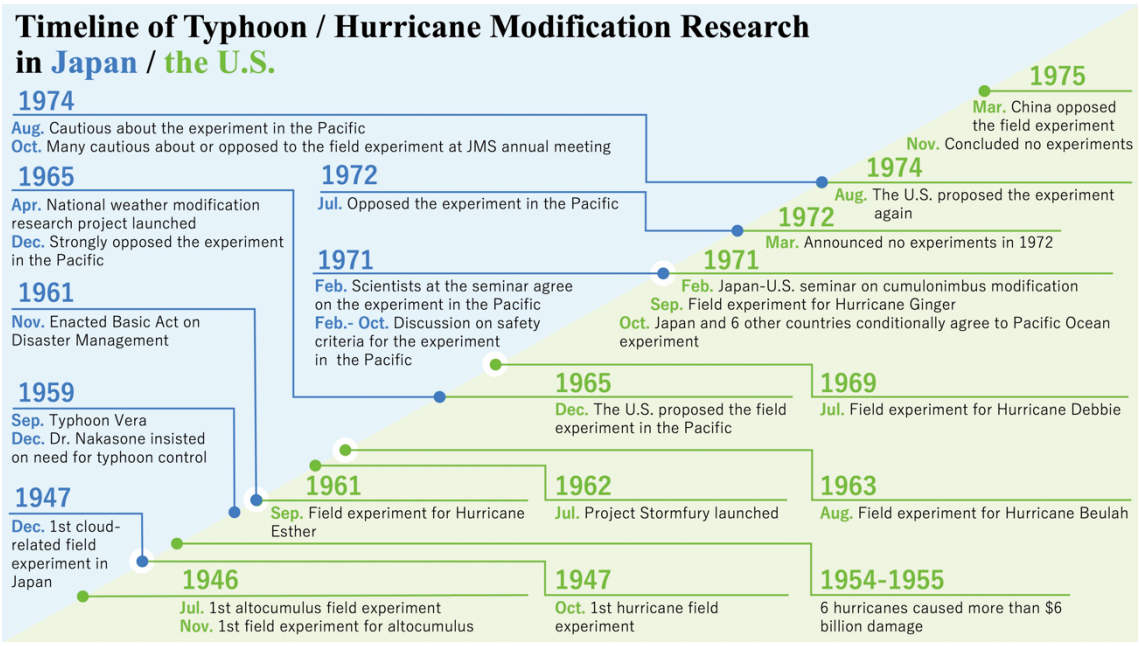



Figure 1 Trends related to typhoon and hurricane modification research in Japan (blue) and the United States (green) in the second half of the 20th century.

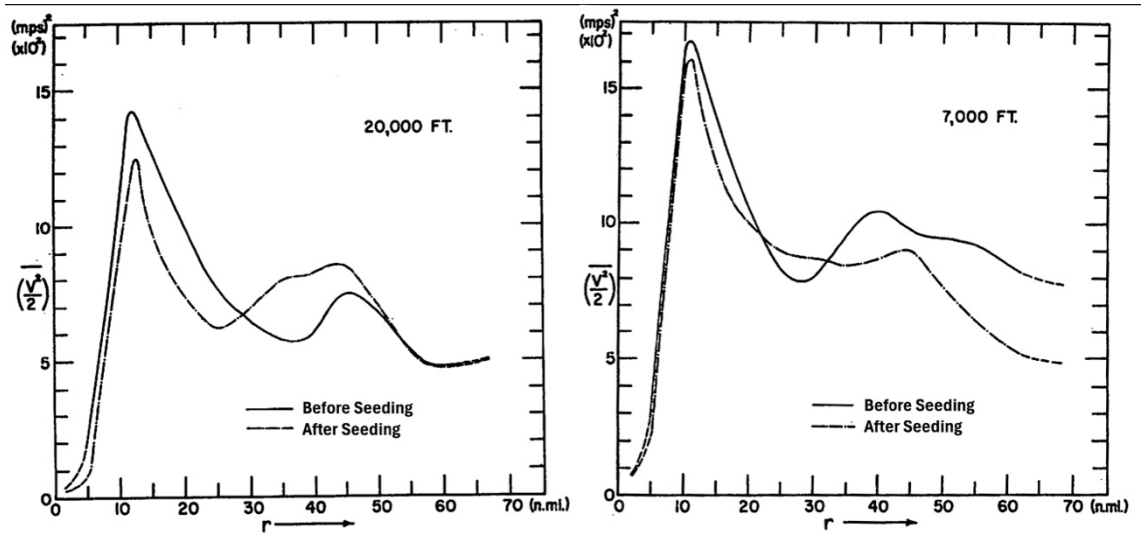



Figure 2 Distribution of mean values of kinetic energy before and after seeding and distance from the hurricane center in the experiment on Hurricane Esther on 16 September. Right: altitude 20,000 ft (~6100 m); left: altitude 7000 ft (~2130 m) (Simpson et al., 1962).

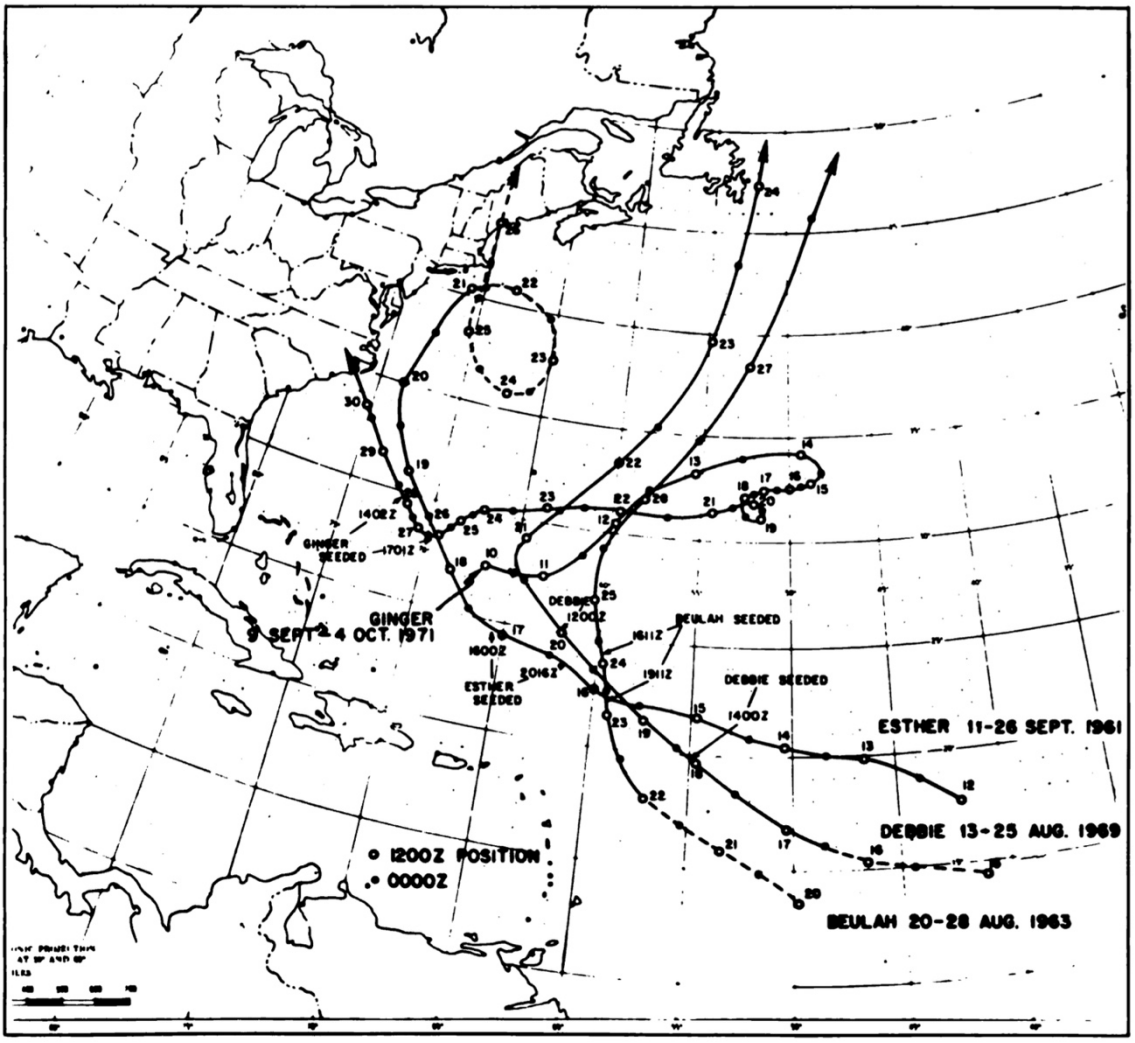



Figure 3 Tracks of Hurricane Esther (1961), Hurricane Beulah (1963), Hurricane Debbie (1969), and Hurricane Ginger (1971) and seeded locations (Sheets, 1981).

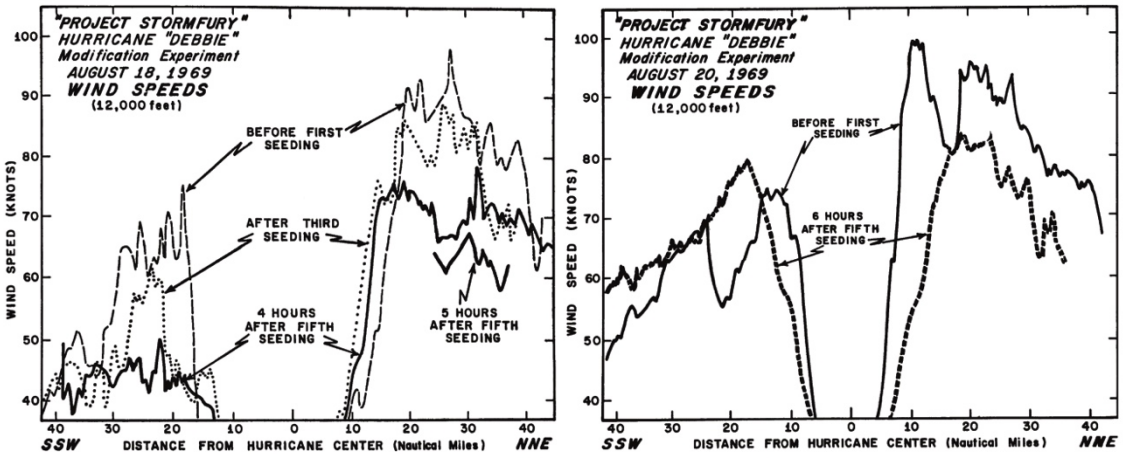
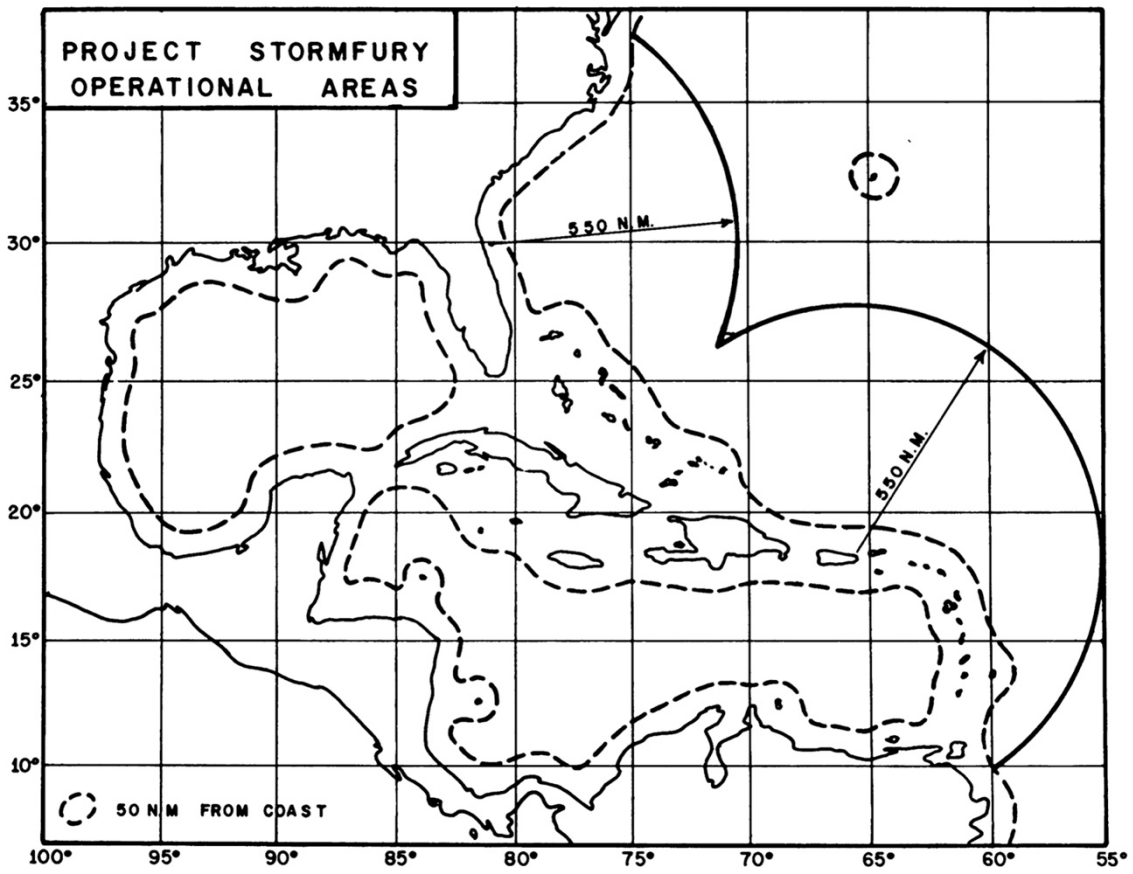



Figure 4 Change in wind speed when Hurricane Debbie was seeded (Chafee et al., 1970).




842

843 Figure 5 Operational area in the Atlantic (Chafee et al., 1969).

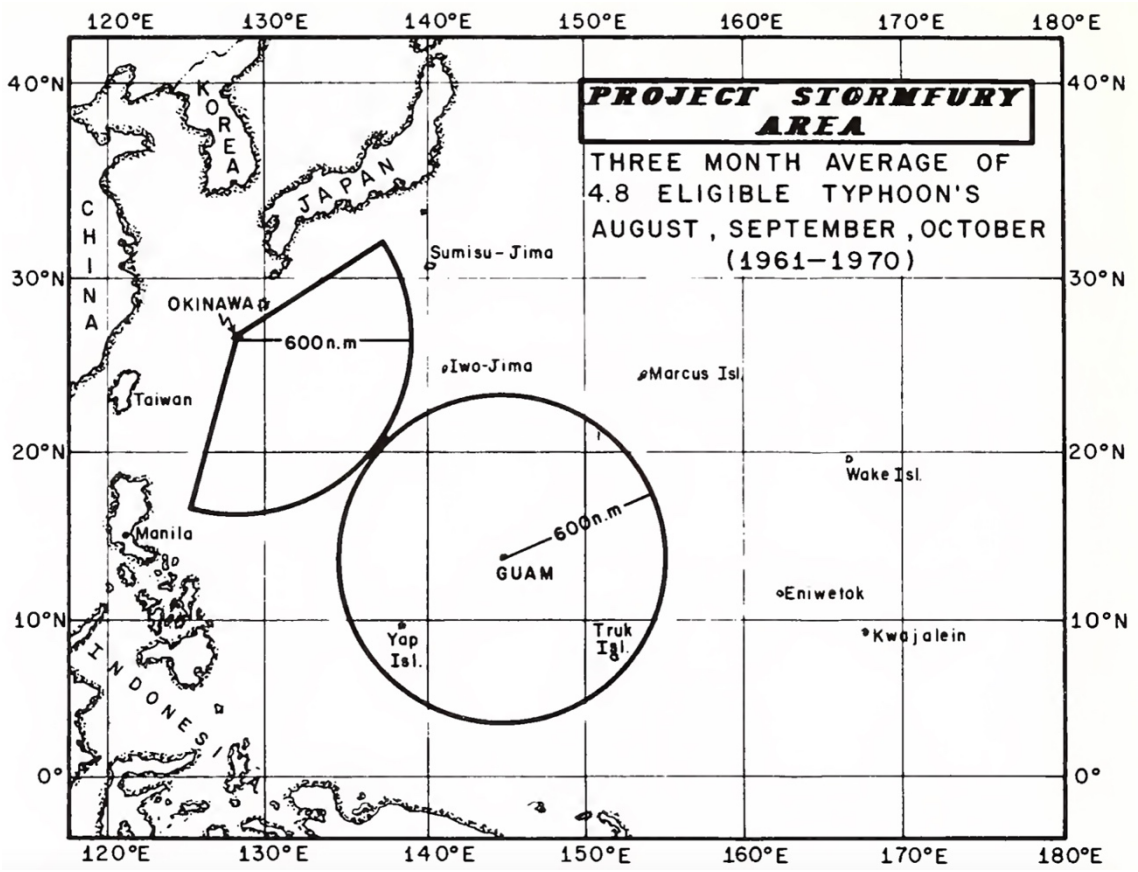



Figure 6 Operational area in the Pacific (Mallinger, 1971).

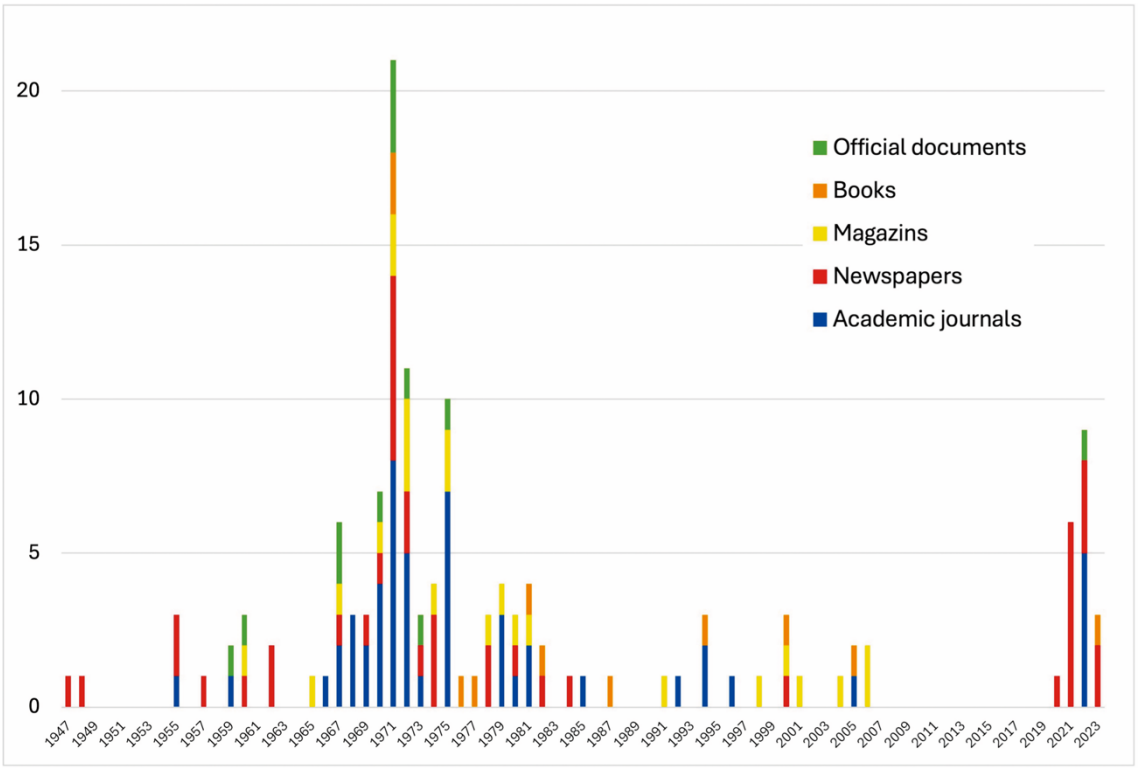



Figure 7 Published literature concerning typhoon modification in Japan (1947–2023), including articles in academic journals (blue), newspapers (red), magazines (yellow), books (orange), and official documents (green).