Project STORMFURY and Hurricane Modification

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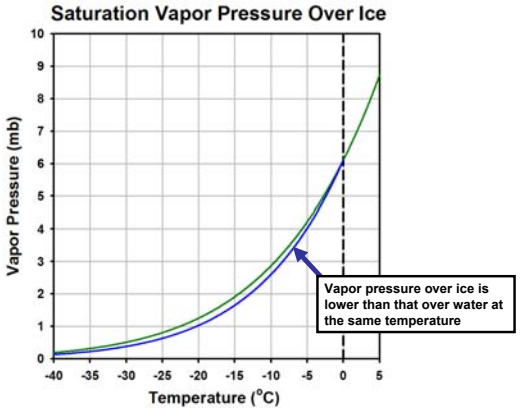
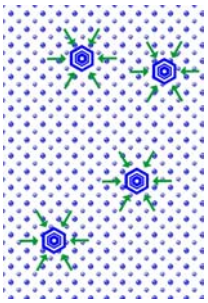


Supercooled Water

- Both freezing and condensation generally require nuclei to start the process
- Natural clouds have plenty of condensation nuclei (100,000/liter) but few freezing nuclei (10-100/liter)
- Consequently clouds colder than 0°C often contain liquid H_20 that has not yet frozen.
- May be as cold as -20°C
- When some ice does form,
  - the ice crystals grow
  - at the expense of supercooled water droplets
  - Bergeron-Findeisen process
- Artificial freezing nuclei can promote growth of snow that melts to form rain

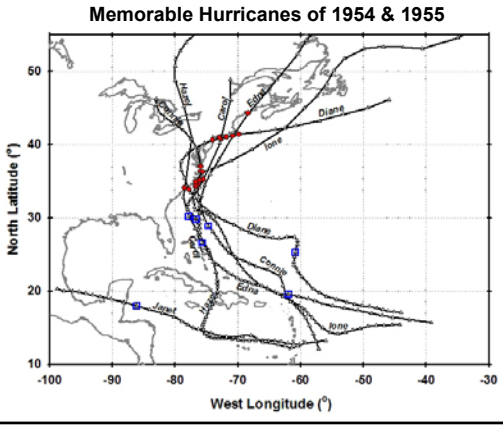


Cloud Seeding

- Vincent Shaefer discovered that CO_2 crystals can start clouds freezing, 1946
- Bernard Vonnegut discovered that Silver Iodide works, too
- Kurt Vonnegut and Ice-9
- Irving Langmuir goes nuts

PROJECT CIRRUS

- Army, Navy, General Electric Co.
- GE quits because of legal worries
- Extensive seeding with AgI smokes to increase rainfall
- Exaggerated claims of success
- Seeded a hurricane off Georgia/Florida coast
  - 13 October 1947
  - 80 kg of solid CO_2
  - Some change in clouds on radar but no other documented changes
  - Reversed track to landfall in Georgia and South Carolina
- But Robert Simpson worked to start a National Hurricane Research Project, modeled on the Thunderstorm Project



Navy P2-V Lost in Hurricane Janet

Results of the 1954 & 1955 Seasons

- Hurricanes Carol, Edna, Hazel, Connie, Diane & Ione
  - 400 dead
  - $2B damage (adjusted to 2005)
- Congress starts National Hurricane Research Project

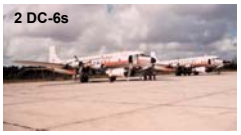
National Hurricane Research Project

- Study hurricane formation
- Study hurricane structure and dynamics
- Seek means for hurricane modification
- Seek means for improvement of forecasts

NHRP, 1959

Started in West Palm Beach Using Military Aircraft

Soon Had Its Own Airplanes and Crews

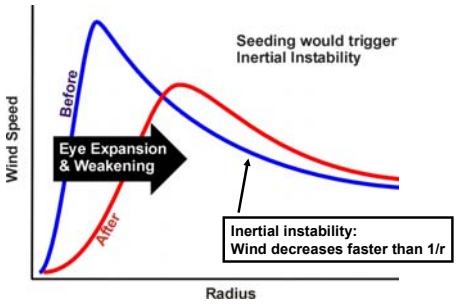


Modification Strategy

- Well thought-out, mainstream science
- Trigger symmetric instability, or
- Construct an outer eyewall, through cloud seeding with AgI
- Required abundant supercooled water
- Expanded eye should have weaker winds through partial conservation of angular momentum

Bob and Joanne Simpson

Initial STORMFURY Hypothesis

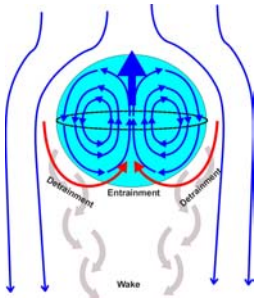


Latent Heats of Condensation, Freezing and Deposition

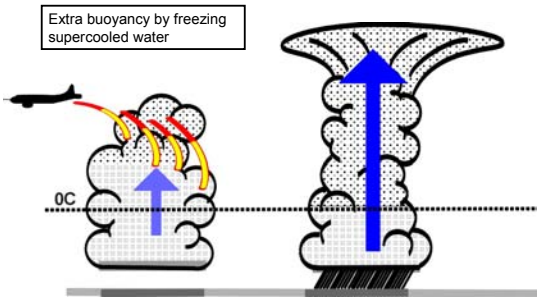
- Condensation L_c/c_p = 2.5 ^oC per gm/kg
- Freezing L_f/c_p = 0.334 ^oC per gm/kg
- Deposition L_d/c_p = 2.834 ^oC per gm/kg
- Condensate loading: It takes 3 gm/kg of liquid or ice to offset the buoyancy of 1^{o}C temperature excess.
- That 1^{o}C of temperature excess can generate a >20 m/s updraft that reaches the tropopause.

Entraining Bubble Models

- Cloud composed of discrete bubbles
- Entrainment balances detrainment so mass stays constant
- Entrainment dilutes
  - Buoyancy
  - Moisture
  - Upward momentum
- Large bubbles entrain less per unit volume: ***Hot Towers***
- Detrained water moistens environment for next bubble
- Hydrometeors fall out of the bottom of each bubble
- Models based on these physics used to assess seeding efficacy

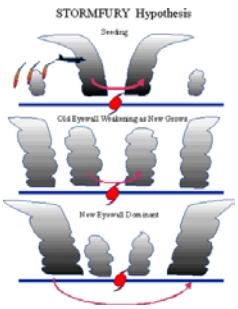


Dynamic Seeding

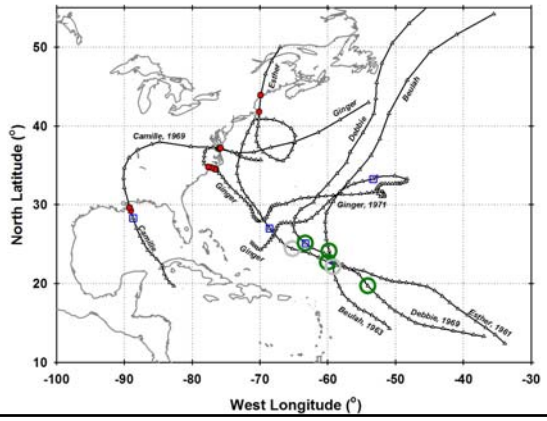


Revised STORMFURY Hypothesis

- Targeted intense hurricanes with small eyes
- Seed the first rainband outside the eye
- Build a new eyewall around the old
- New eyewall strangles the old



STORMFURY Hurricanes



Apparent Successes

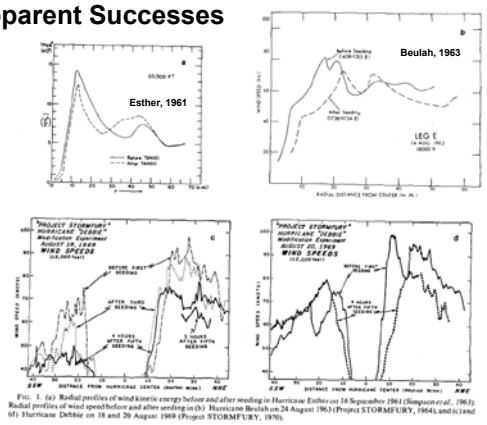


FIG. 1. (a) Radial profiles of wind kinetic energy before and after seeding in Hurricane Esther on 16 September 1961 (Simpson *et al.*, 1963). Radial profiles of wind speed before and after seeding in (b) Hurricane Beulah on 24 August 1963 (Project STORMFURY, 1964), and (c) and (d) Hurricane Debbie on 18 and 20 August 1969 (Project STORMFURY, 1970).

Summary of STORMFURY Experiments

Year	Hurricane	Result
1961	Esther	2 Attempts: I, Apparently slowed intensification; II, Missed eyewall (Hypothesis I)
1963	Beulah	2 Attempts: I, Apparently missed. Did not fit experimental design. II; Eye reformed, winds weaker by 20%
1969	Debbie	2 Attempts, both apparently successful. Winds apparently by weakened by 31% and 15%
1971	Ginger	2 Attempts, did not fit experimental design, no effect

Feasibility Criteria

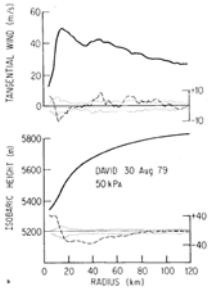
- ***Political***: Willingness to spend money and accept risks
- ***Operational***: Aircraft, intruments, scientists and aircrew available
- ***Microphysical***: Clouds with supercooled water
- ***Dynamic***: Hurricanes vulnerable to modification strategy
- **Statistical**: Had to be able to distinguish the results of seeding from natural behavior

NOAA WP-3Ds

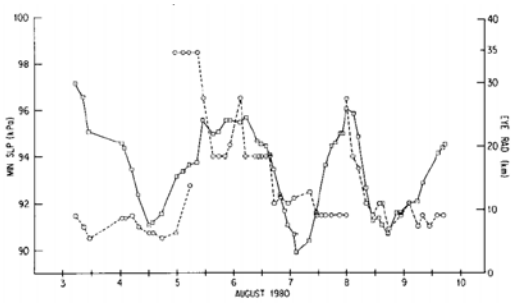
Procured to replicate Debby experiments

Lack of hurricanes in the target area led to extensive observations of unmodified hurricanes

Concentric Eyewalls in Unmodified Hurricanes

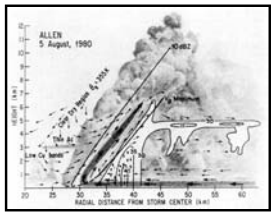


Hurricane Allen



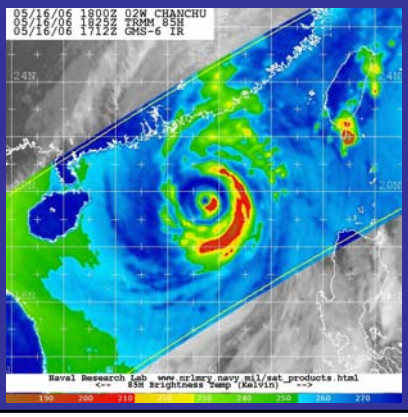
New Understanding of Structure & Dynamics

- Most updrafts weaker than previously thought
- Inclined updrafts unloaded condensate
- Liquid water contents lower
- Observations of widespread radar brightband
- Widespread stratiform rain and mesoscale up- & downdrafts



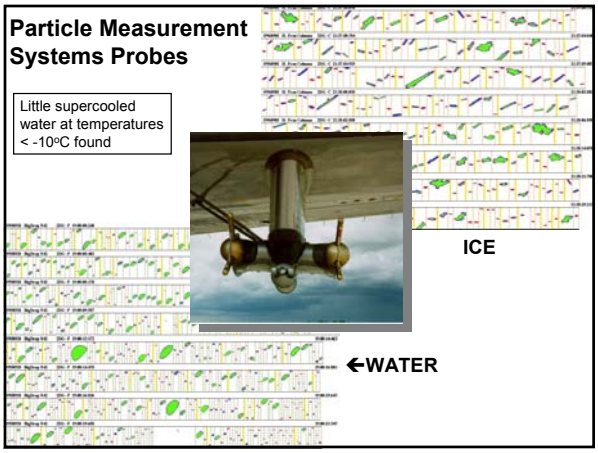
Jorgensen 1984b

Spaceborne Remote Sensing Revealed Many Concentric Eyewalls



Particle Measurement Systems Probes

Little supercooled water at temperatures < -10°C found

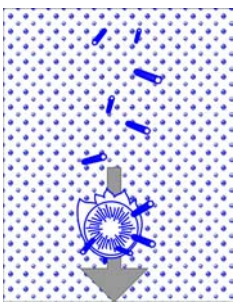


ICE

←WATER

Ice Multiplication

- Radar and Knollenberg probes showed little ice
- Hallett-Mossop Process
  - Graupel undergoing wet accretion of supercooled clouds droplets grow whiskers-like ice crystals
  - $-8 \leq T \leq -3^{o}C$,
  - Droplet diameter > 23 μm
  - Break off
  - Natural cloud seeding
- Happens in maritime clouds only
- Explains lack of supercooled water
- Doesn't look good for cloud seeding in the tropics



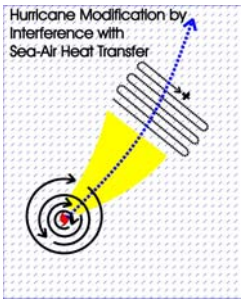
Hallett & Mossop, 1974, *Science*

STORMFURY Abandoned Because

- Limited supercooled water
- Eye expansion happens in unmodified hurricanes
- Political difficulty with finding experimental subjects

Other Strategies

- Slicks to retard heat surface heat transfer
- Artificial ocean cooling
- Nuke-em
- Fans to blow hurricanes away from shore
- Exploit sensitivity to initial conditions
- Get them while they are little
- Most proposals underestimate the scale of the undertaking



Protocol for Future Hurricane Modification Strategies

- Laboratory or small-scale field trial
- Numerical simulation
- Quantitative plan for logistics and operations
- Assessment of benefits in relation to costs

Summary

- NHRP grew from hurricane disasters of 1954 & 1955
- Bob & Joanne Simpson
- "Amelioration" was part of the original mission
- Dynamic seeding to increase cumulus buoyancy
- Two hypotheses
  - Trigger inertial (or symmetric) instability
  - Construct outer eyewall
  - Weakening through eye expansion under partial conservation of angular momentum
- Tried 8 times in 4 hurricanes with apparent 50% success.
- Abandoned because:
  - Not enough supercooled water (Hallett Mossop)
  - Natural eyewall replacements mimic expected experimental results
  - Political problems with finding subjects and resources