Trends and challenges in weather modification

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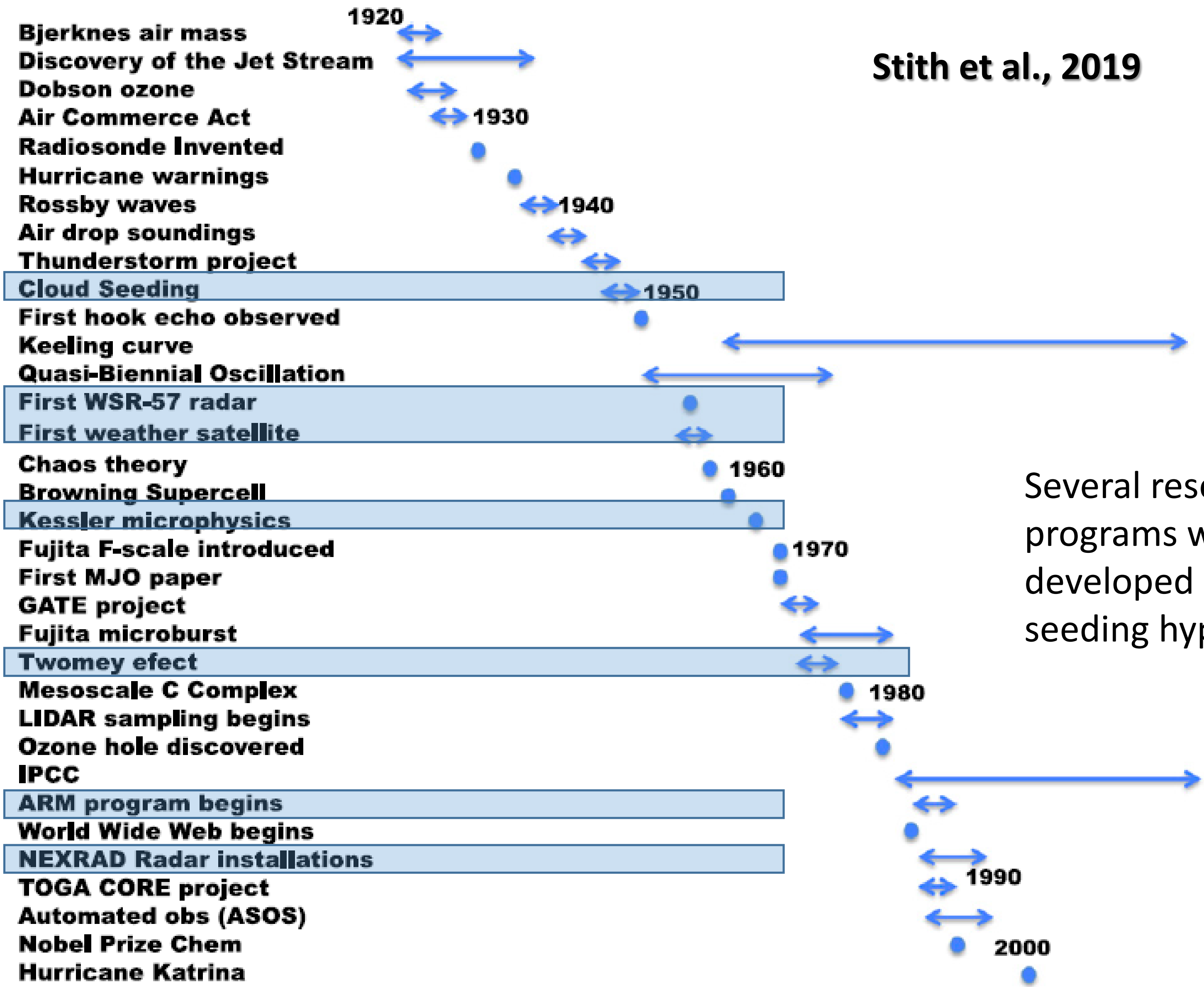

Stith et al., 2019

Several research programs were developed to test the seeding hypothesis

Timelines in history

- **1940:** Dry ice into supercooled liquid cloud cause glaciation (Schaefer 1946)
    - Silver iodide (AgI), glaciated supercooled clouds (Vonnegut 1947)
- National Academy of Sciences reports, WMO reports, etc.
- Special Commission on Weather Modification (1966)
- Statistical analyses using target and control approaches were flawed (Rangno 1979)
- **1970:** Airborne optical array probes and use of radars (polarization) advancing
- **1980 -90s:** (After the report by Kerr 1982), no funding for cloud seeding research
- Orographic cloud systems in Wyoming and Idaho, Rainfall enhancement research from convective storms from South Africa and Thailand (Silverman 2001a,2003)
- **2003** NAC Report: Potential application of new technology for evaluating cloud seeding
- Physical evaluations for cloud structure with aircraft and radar and to model these clouds
- **2015:** Significant advances (radars of different types, radiometers, airborne probes) in observing technologies and modeling capabilities (Geerts et al. 2015)
- **2016:** 56 countries had active weather modification operations (Bruintjes 2016, WMO).
- **2018:** WMO Peer review report 2018: Physical chain of events demonstrated, need for further research on ice and mixed phase clouds. More research studies…
- **2019:** Several programs exist: Winter time cloud seeding to increase snowpack reservoirs, Hail-suppression operations in North Dakota, Rain enhancement from convective storms in Texas, Orographic clouds for the Snowy Mountains of Australia (Manton and Warren 2011), CAIPEEX (Since 2009),

"There has been little parallel research directed at understanding the ability of humans to intentionally modify the weather. Yet the fundamental physical principles underlying both inadvertent and advertent weather modification are, in many respects, the same." (National Academies)

Combination of the best cloud models with advanced observing systems in carefully designed field tests and experiments

Cloud/Precipitation Microphysics

Document the **background concentration, sizes, and chemical composition of aerosols that participate in cloud processes**.

How nucleation processes relate to characteristics of aerosol particles; ice nucleation; Evolution of the droplet spectra in clouds; Relative importance of drizzle in precipitation processes

Cloud-to-cloud and mesoscale interactions
Updraft and downdraft structures
Cloud evolution and lifetimes

Cloud Dynamics

Cloud and sub-cloud dynamical interactions
Microphysical, thermodynamical, and dynamical interactions within clouds.

Cloud Modeling

Cloud-resolving models to weather modification, including short-term predictive models; Predictive models for severe weather events; Cloud models capability to track dispersion of seeding material both within and outside of seeded areas

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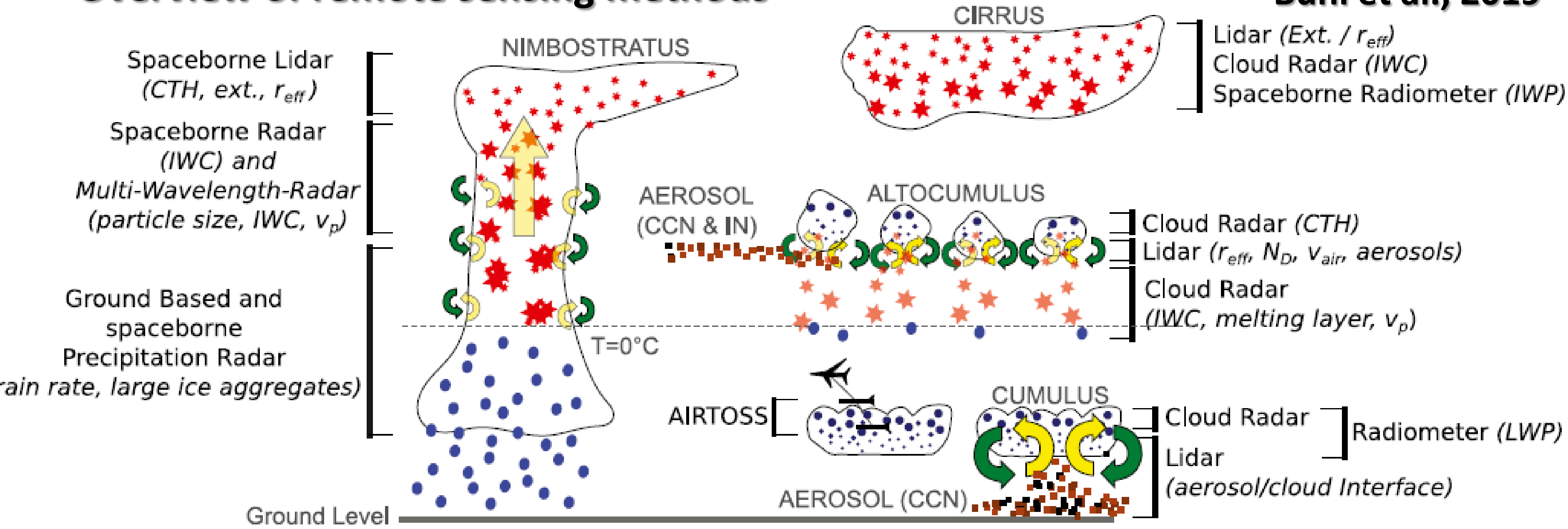
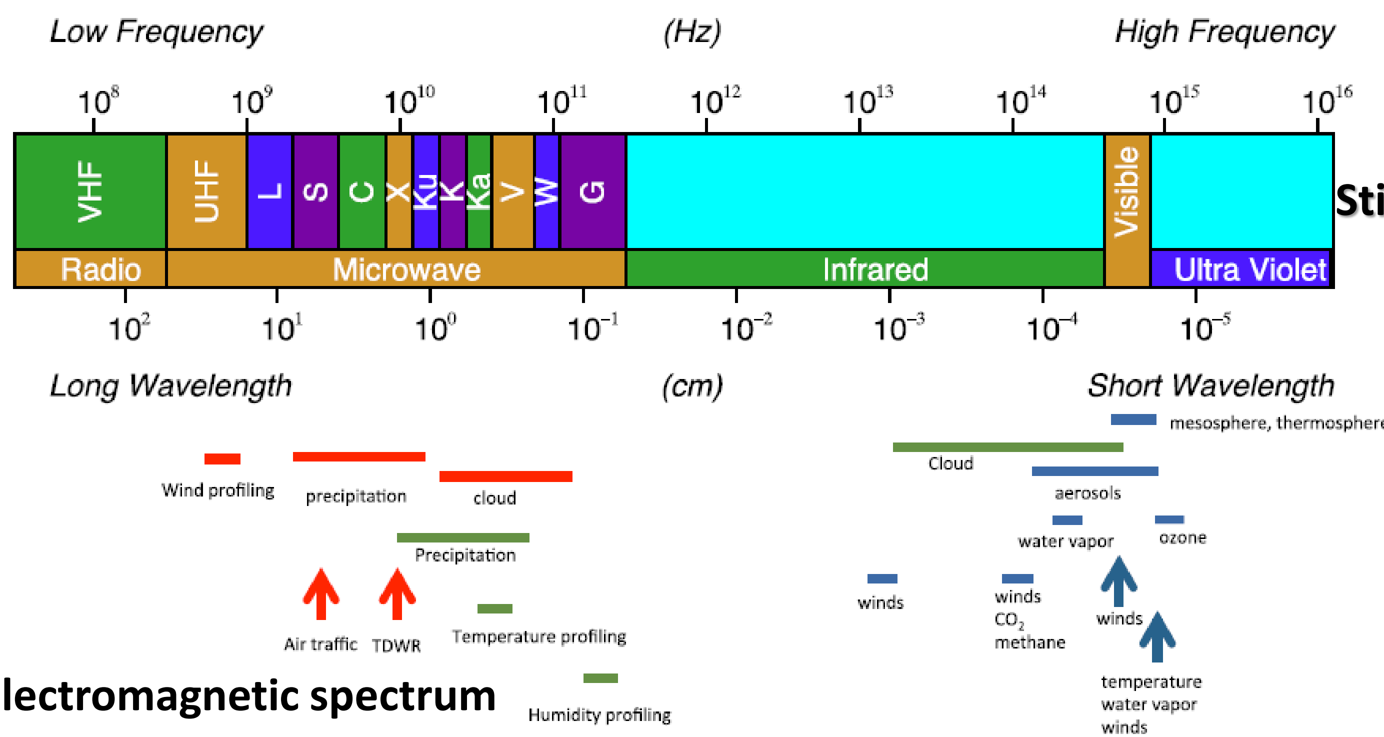
Advances in the recent years

- **Remote and in situ observational tools**
  - Polarimetric radars
  - Doppler lidar and airborne radars
  - Cell-tracking software (TITAN)
  - MW radiometer
  - Airborne instrumentation
  - cloud condensation nuclei and ice-nucleating particle observations
- **Cloud and precipitation physics modeling involving seeding effects**
- **Advanced targeting and evaluation tools (Models for plume tracking, seeding effects, etc.)**

Overview of remote sensing methods

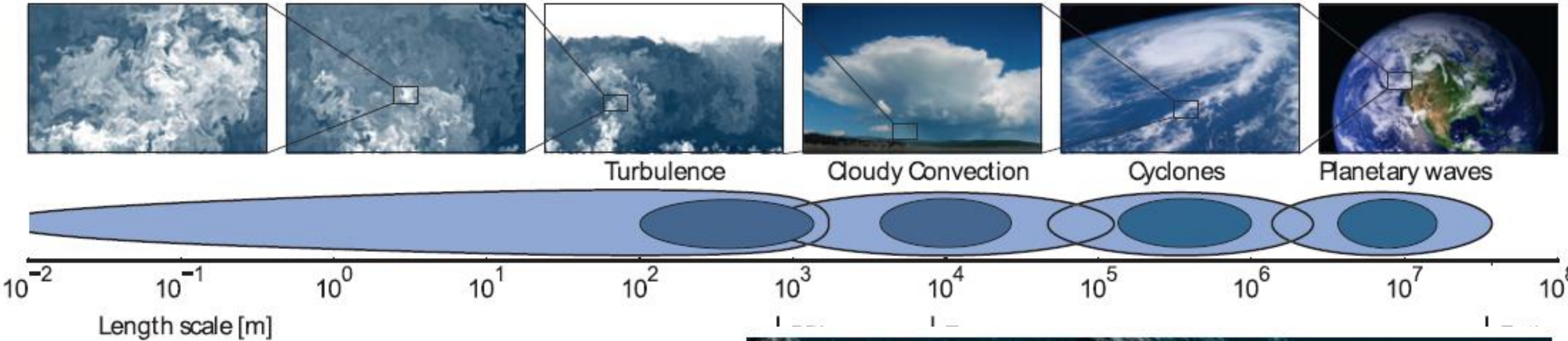
Bühl et al., 2019



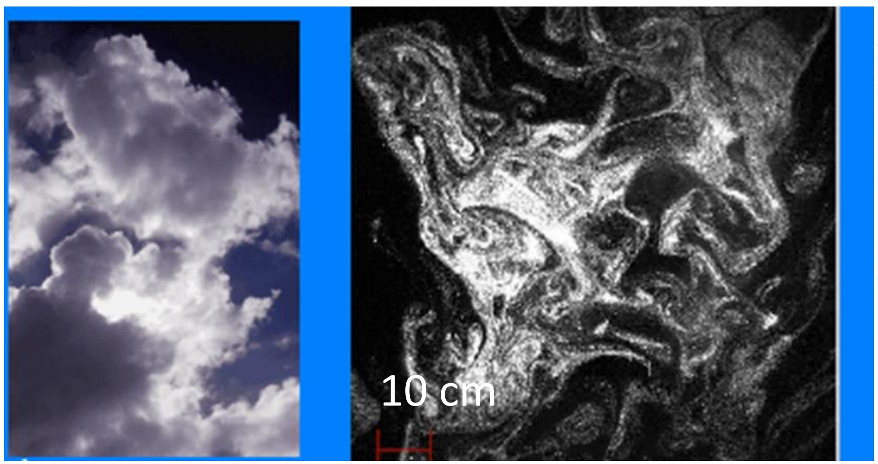


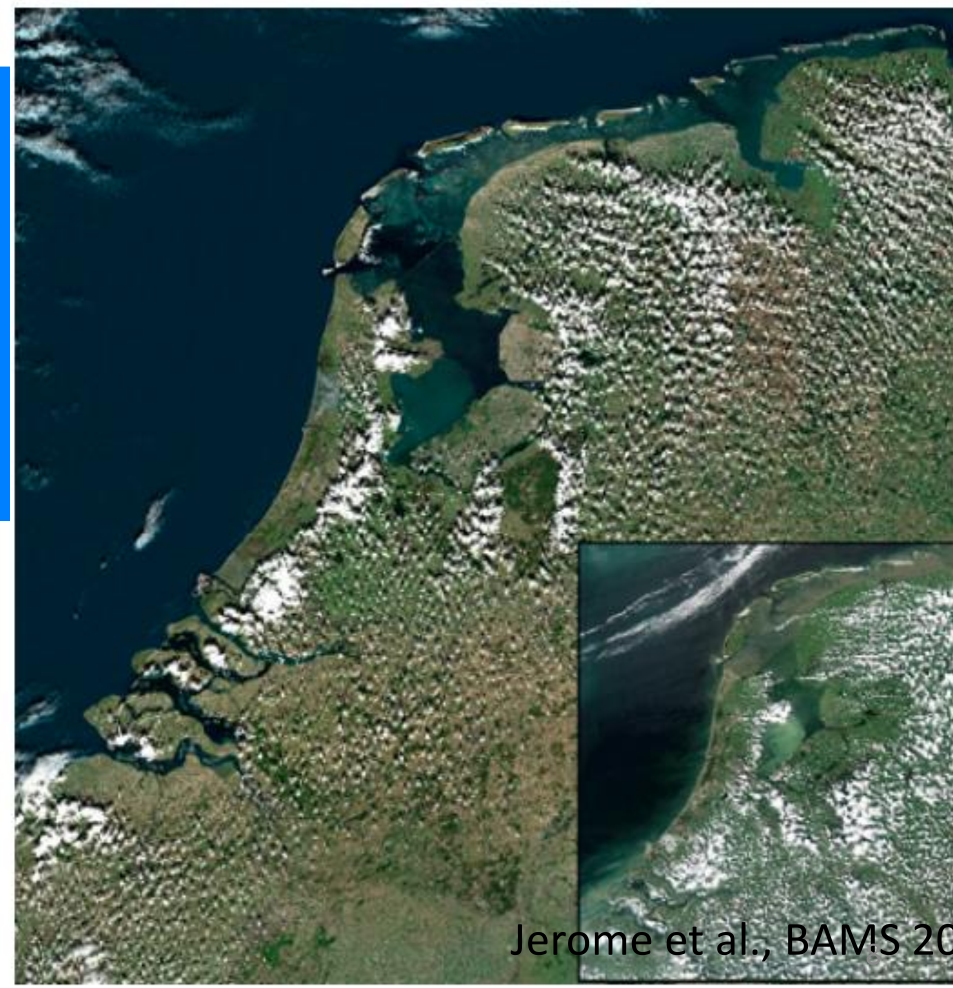
Stith et al., 2019

Use of electromagnetic spectrum



Cumulus Laboratory





Basic understanding of convection:

- transitions in convective cloud populations from stable boundary layer to cloud population
- mesoscale dynamics and dynamical/microphysical interaction on a range of scales, from turbulent elements within individual drafts to MCSs

Tracking seeding material

- Diffusion and transport
- Spread of seeding effects in the cloud volume.
- Adequate measurement capabilities
- Limitations of cell-tracking software
- Radar and other instrumentation to observe seeding effects.

Complicated by

- Interactions between different hydrometeors in clouds
- Modeling and prediction of seeded and unseeded clouds;
- Transfer the storm-scale effect into an area-wide precipitation
- Tracking downwind changes at the single cell, cloud cluster, and floating target scales.

Single cell to multi-cell

- Cloud and cell properties (structure, intensity, evolution, and lifetime) and their interactions between themselves and with large scale systems to be documented
- Impact of local seeding on the large scale systems to be documented

Documentation of cloud microphysical processes is critical

- ❖Clouds cannot be modified operationally unless their **natural precipitation processes are well understood.**
- ❖Clouds cannot be modified operationally **until we can measure a seeding effect with the seeding agent of choice**.

- ➢ **Weather modification should have a sound scientific basis**
- ➢ **There should be a hypothesis for seeding effect on surface precipitation, which has to be scientifically proven through documentation of chains of processes**

What is the background aerosol / CCN/INP concentration in various places, at different times of the year, and during different meteorological conditions?
To what extent would weather modification operations be dependent on these background concentrations?
There has to be a fundamental understanding on how clouds make rainfall in different types of clouds?
We also need to know how cloud seeding affect microphysical processes and dynamics of the cloud

Documenting Extra area effects

- Verification by randomized seeding efforts together with high-resolution cloud modeling to simulate cloud seeding.
- Transport of seeding agents, tracer studies, and confirmatory physical measurements are needed

Caveats

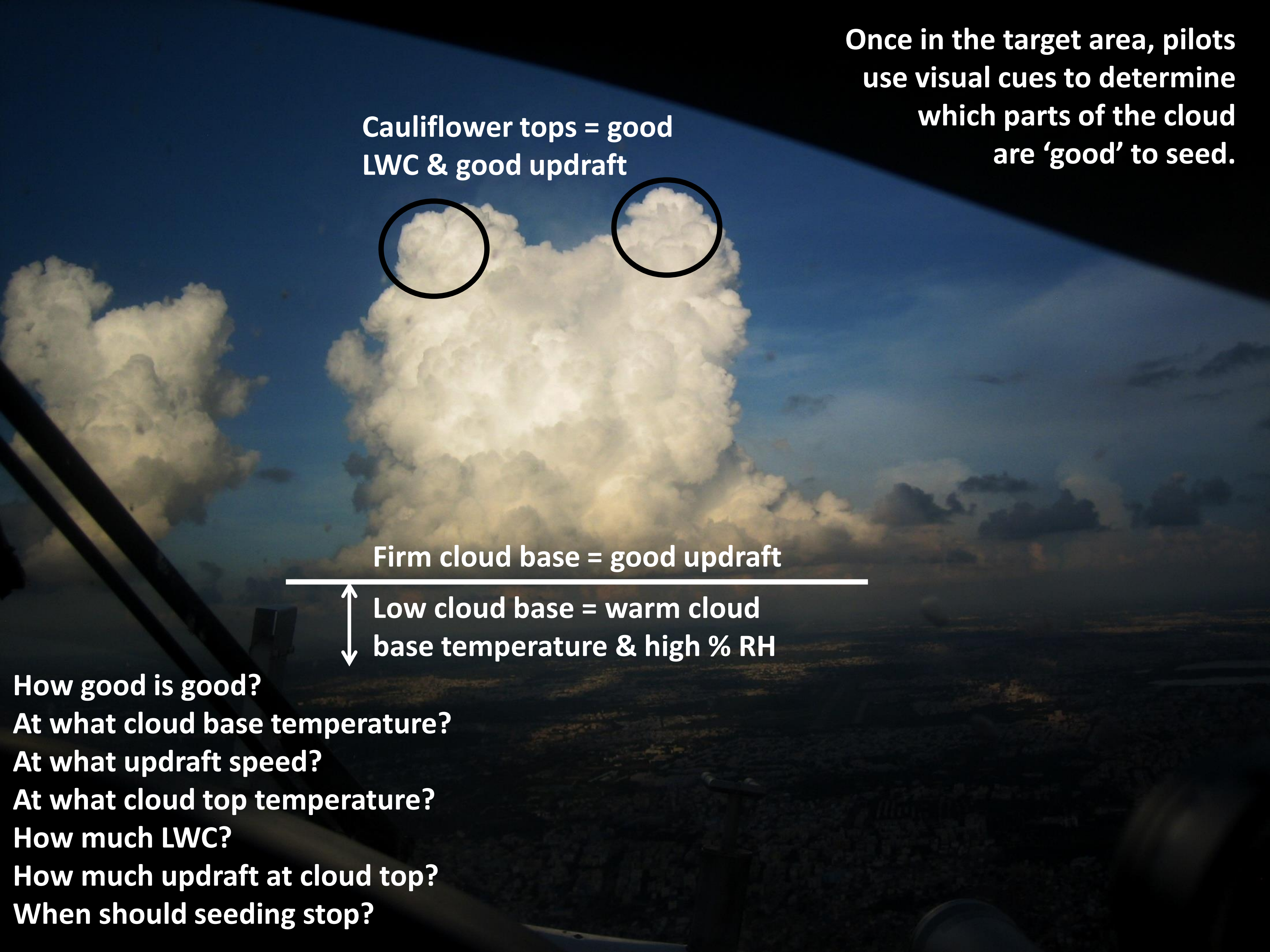
- **The cloud seeding signal may be several orders smaller than the natural variability and to document the seeding effect is thus very challenging**
- **As a result, following the chains of processes after seeding is essential to the precipitation at the surface**
- **Tracking seeded plume**
- **Interaction between seeded and unseeded clouds**
- **Extra area effects may be studied with specially suited model experiments supported by well calibrated radar observations and rain gauges**

“ Identify window of opportunity” : Key aspects

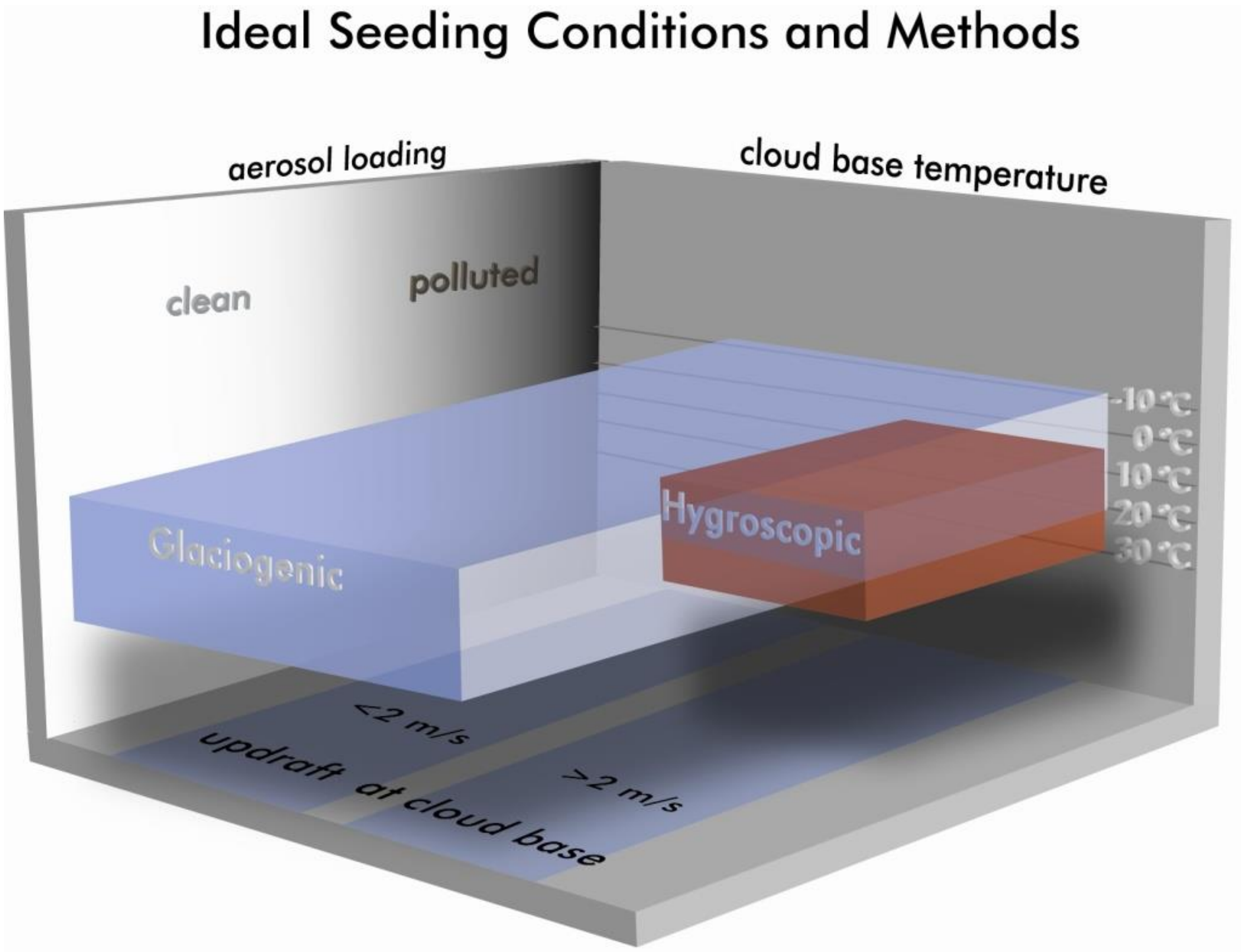
- Scientific understanding on rain or snow production
- Time and place to seed clouds to be determined
- The cloud life cycle should be understood better
- Tracking the seed material to precipitation formation
- Understanding on the boundary layer dynamics

What is needed to improve success?

- (4 x Right): Delivery of the “right” amount of the “right” seeding agent at the “right” time and in the “right” place.
- Proper targeting is critical
- Difficult to design and evaluate.
- Information to Pilot: Incomplete information on the storm developing around the aircraft.
- Minutes and hours old information can lead to less effective targeting.
- Technology of high operational readiness of near real-time for precise targeting and timely seeding actions.
- Knowledge on observational and modelling uncertainties


Once in the target area, pilots use visual cues to determine which parts of the cloud are ‘good’ to seed.
Cauliflower tops = good LWC & good updraft
Firm cloud base = good updraft
Low cloud base = warm cloud base temperature & high % RH
How good is good?
At what cloud base temperature?
At what updraft speed?
At what cloud top temperature?
How much LWC?
How much updraft at cloud top?
When should seeding stop?

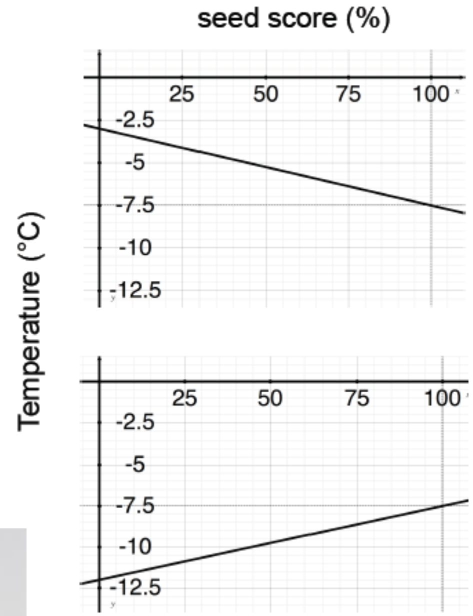
Sensor based identification of seeding opportunity



Identifying the ‘window of opportunity’ for cloud seeding …

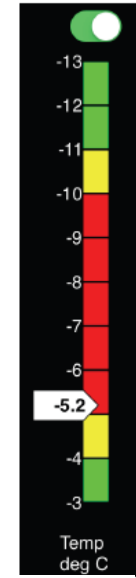
Targeting clouds effectively

- Aircraft targeting same size cloud
- Same thermodynamic conditions
- Reduce human bias in selection

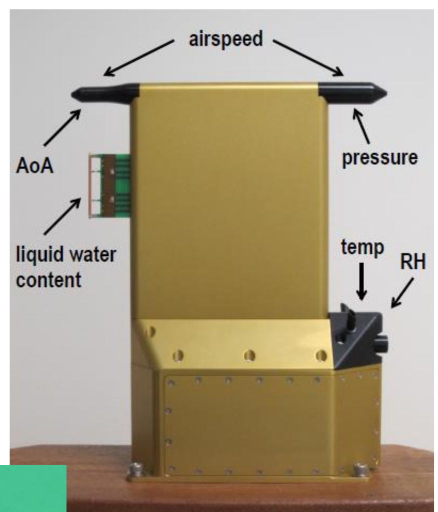


Range -3 to -7.5°C
Temp seed score = (-temp – 3)/0.045

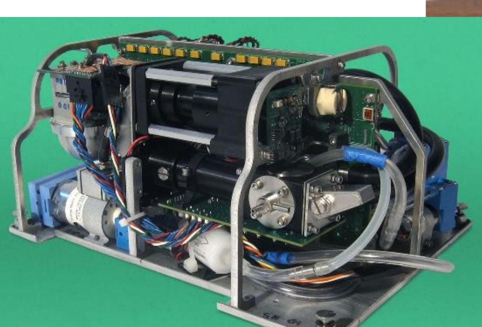
Range -7.5 to -12°C
Temp seed score = (-temp + 12)/0.045



Cloud water inertial probe
- -Cloud liquid water content
- -Temperature
- -Pressure
- -Relative humidity
- -Air speed
- -Vertical velocity



Pilot decision making tool for the targeting the cloud (on ipad)



Aerosol Counting, Composition, Extinction, and Sizing System (ACCESS)

Outstanding research and progress needed in the following:

- Interactions between natural CCN and INP
- Cloud microphysics Cloud Dynamics, their interactions and impact on precipitation efficiency
- Observational capabilities needs to be improved
- Aerosol processes: competition and tail effect between the seed particles and natural aerosol
- Understanding on secondary ice formation: the formation and growth of soil hydrometeors incomplete : need to represent these in models correctly
- Model intercomparison projects : optimize modelling of cloud microphysics
- Using observational datasets from field campaigns
- Huge uncertainty with mixed phase convective systems
- International analysis and model intercomparison projects
- Seeding strategy requires a precise knowledge on the cloud system and its evolution
- Location, timing and method of seeding need to be adapted based on local conditions and lessons learned from field campaigns
- Promote best scientific practices through transparency and peer reviewed publication
- Have a research component in every cloud seeding program
- Upscaling: Exploration of exploratory studies to extended areas
- Toxicological, ecological, sociological and legal issues to be discussed
- Large variation in the randomized seeding results (0-20%) to be understood (estimation of natural precipitation in target area)

Most promising results for the clouds that have a natural tendency to make precipitation