ICE OBSERVATIONS IN THE ATMOSPHERE 1949 – 2004

Six stories and a status report

June 7, 2004
Ice Inititation Workshop

The stories:

1. The foundation
2. Nucleation prularity
3. The graupel process
4. The multiplication success
5. The cloud seeding question
6. Other facets

GV.

Deutscher Wetterdienst in der US-Zone
Zentralamt Bad Kissingen
Leiter: Prof. Dr. Ludwig Weickmann

Berichte
des
Deutschen Wetterdienstes in der US-Zone

Nr. 6

Die Eisphase in der Atmosphäre

Von Dr. Helmut Wieckmann, Hohenpeißenberg

Bad Kissingen, 1949

Weickmann, 1949

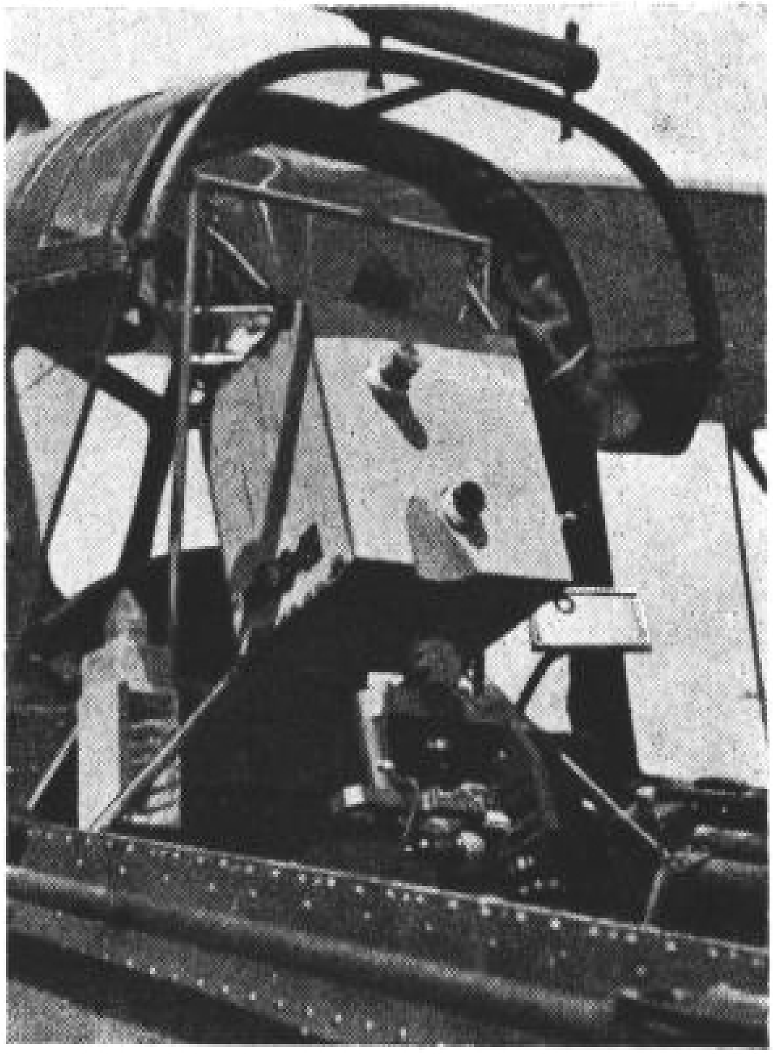
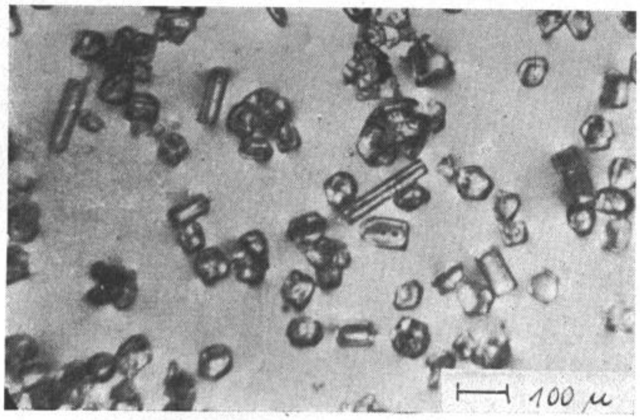


Abb. 16 Mikroskop im Beobachterstand der Nahaufklärermaschine Hs 126

Weickmann, 1949



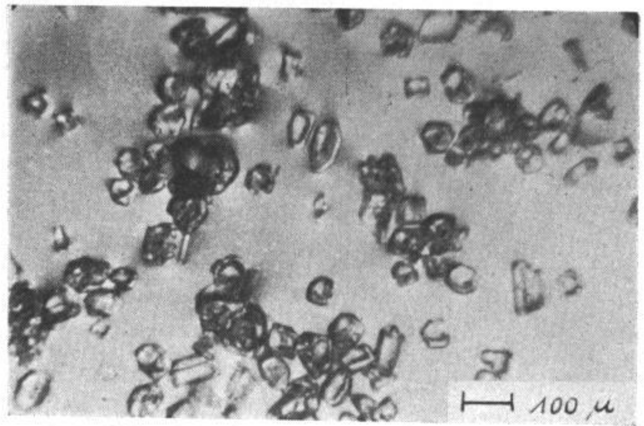


Abb. 45a, b Cirrostratus-Oberteil, 8900 m −47° C

Ci top, 8900m –47°C

Abb. 46 Cirrostratus-Basis, 6000 m −26° C

Ci base, 6000m –26°C

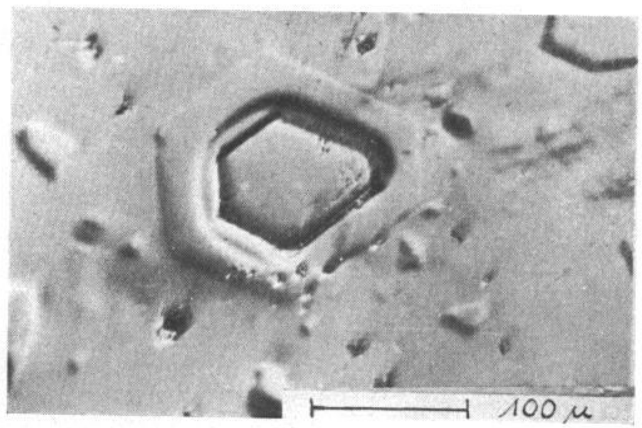
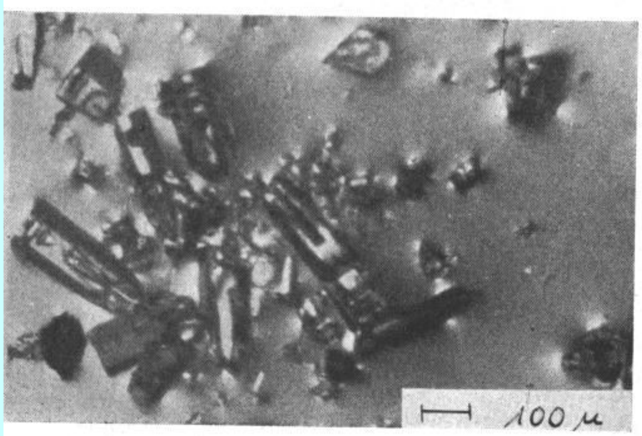


Abb. 47 Basisflächen-Abdruck aus Cs, 6000 m −30° C

Cs, 6000m –30°C



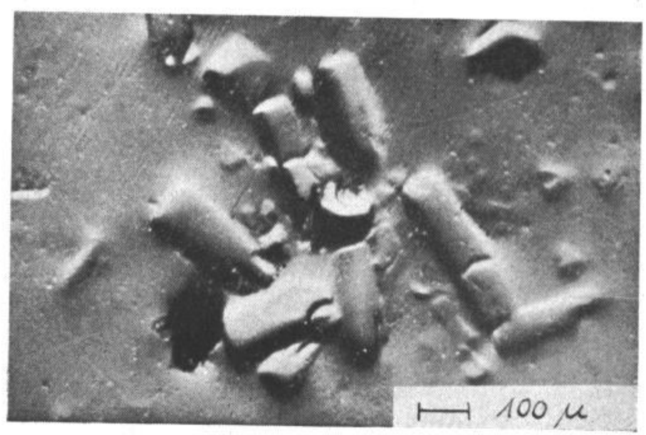


Abb. 48a, b Cirrostratus 6000 m − 30° C

a) Bild der Kristalle

b) Bild der Abdrucke

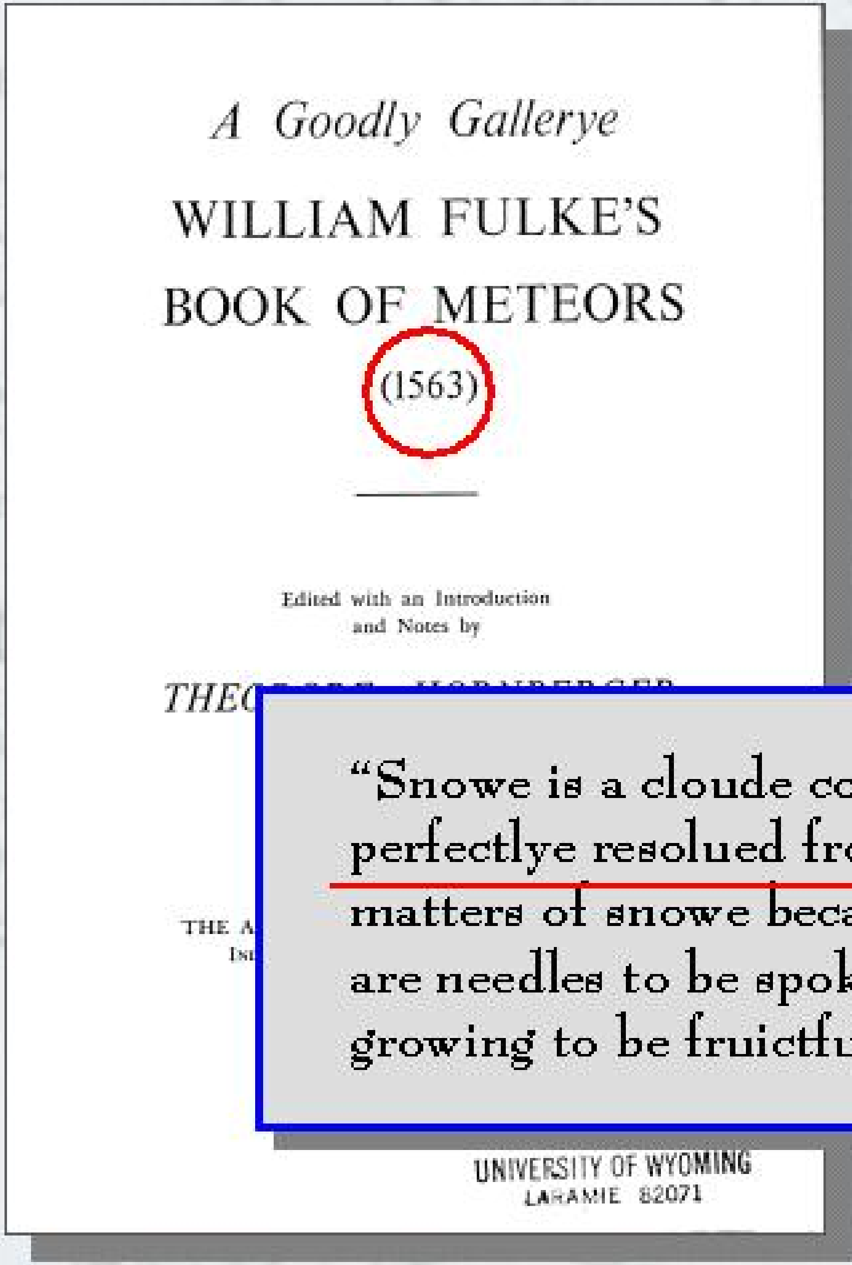
Cs, 6000m –30°C

Weickmann, 1949

1. THE FOUNDATION.

- The large variety of cloud forms, and their varying propensity to produce precipitation proved elusive to meaningful scientific analyses until the beginnings of the 20th century.

- Advances in the physical chemistry of colloids proved to be a useful basis for thinking about clouds in the atmosphere, and to address the perplexing question of precipitation formation.



A Goodly Gallerye

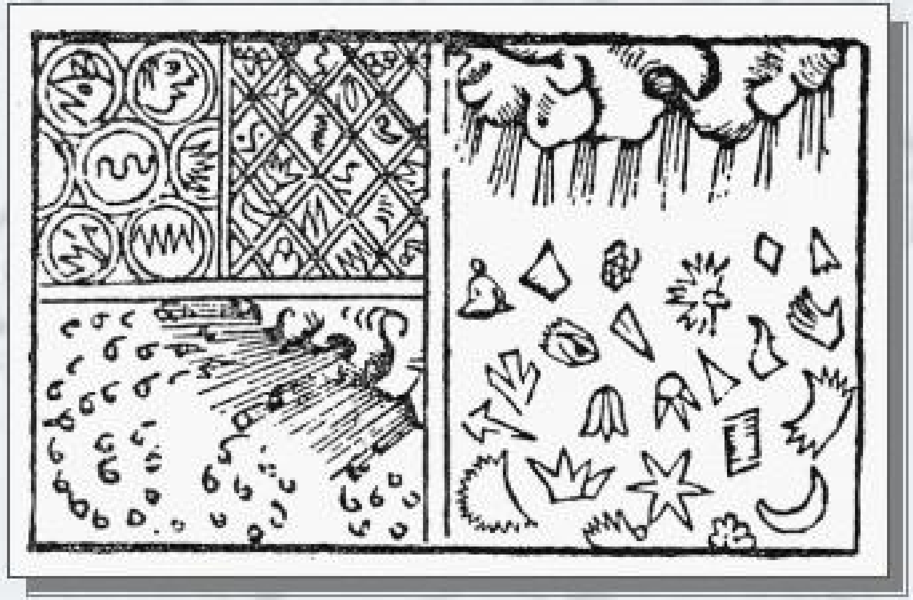
WILLIAM FULKE'S

BOOK OF METEORS

(1563)

Edited with an Introduction
and Notes by

UNIVERSITY OF WYOMING
LARAMIE 82071



Olaus Magnus, 1555

"Snowe is a cloude congeled by greate colde, before it be perfectlye resolued from vapors into water. ….. Other matters of snowe because they are commen with raine, are needles to be spoken of. …. Snowe causeth thinges growing to be fruictfull, …"

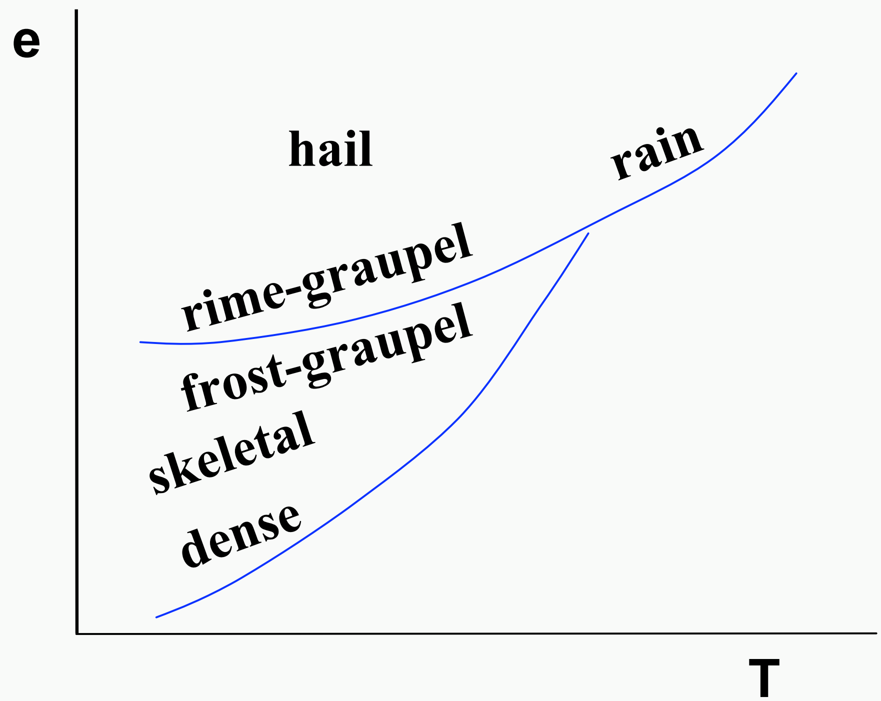
Alfred Wegener, 1911

Based on observations made during arctic expeditions, he argued that ice formation needed *sublimation nuclei* just as droplet formation needs condensation nuclei.

Thought that "isomorphism" is the essential criterion, and that quartz particles fill that role.

Recongmized that colloidal instability results from vapor pressure difference between ice and water at temperatures <0°C.

A. Wegener, 1911:
“Thermodynamik der Atmosphäre”
330 pages



Discusses the importance of the difference between saturation with respect to water or ice, the impact this has on ice forms. Cites evidence for ice contrail in clear air (diagnosed by 22º halo), ice fogs at temp. <-40ºC.

Recognizes that the existence of water droplets at temperatures below 0C play a role in the formation of rime-graupel and hail.

Coniders pileus (if cold enough) to seed cumulus that rises into it.

Frostübersättigung und Cirren.

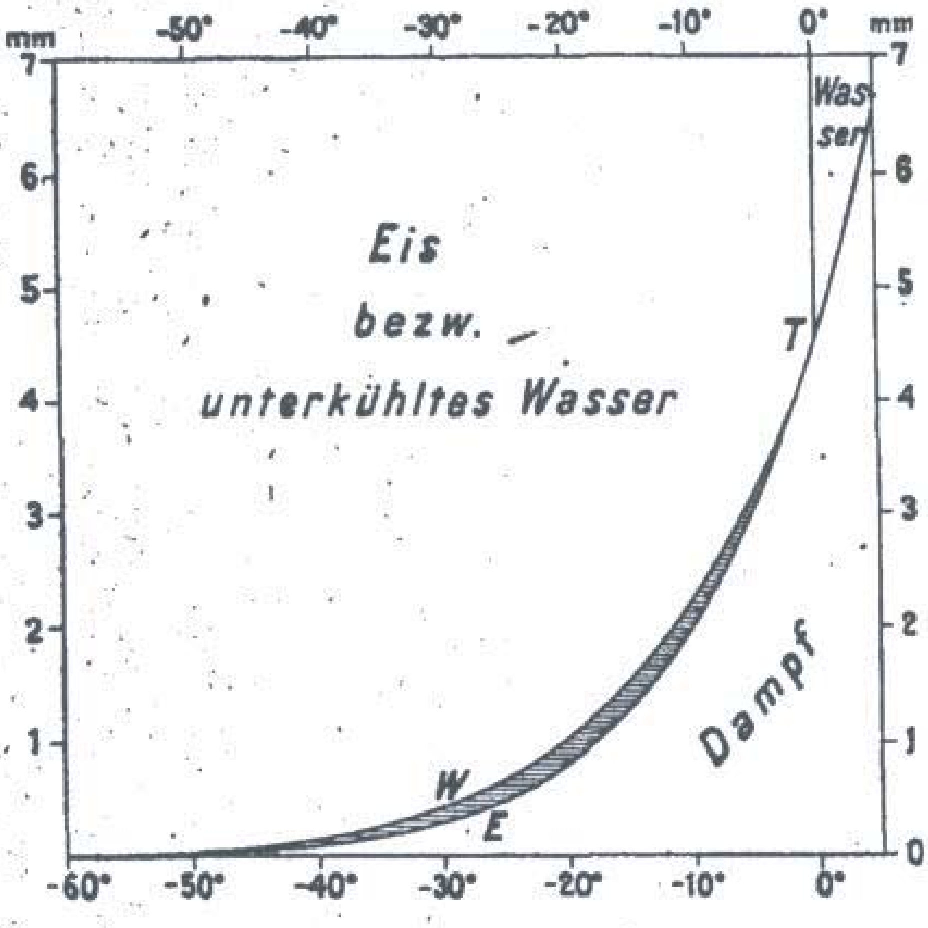
Von ALFRED WEGENER. — (Mit einer Figur.)

Frostübersättigung. Unter den Zuständen des Wasserdampfes in der Atmosphäre gibt es einen interessanten Bereich, in welchem die Luft in bezug auf Eis übersättigt, in bezug auf unterkühltes Wasser aber noch ungesättigt ist. Wir wollen diesen Zustand, um einen kurzen Namen zu haben, als „Frostübersättigung" bezeichnen. Im Roozeboomschen Zustandsdiagramm (s. Figur), in welchem der Dampfdruck nach oben und die Temperatur nach rechts abgetragen wird, liegt der Bereich der Frostübersättigung in dem schraffierten Raum zwischen der Gleichgewichtskurve der beiden Phasen Dampf und unterkühltes Wasser TW und der davon abweichenden Gleichgewichtskurve der Phasen Dampf und Eis TE. Diese beiden Kurven vereinigen sich einerseits im Tripelpunkt T des Wassers (Koordinaten $e = 4{,}57$ … unkt der Temperat… ecksilber und liegt… also stets erheblich… in bezug auf unter…

Nu… uf unter-kühltes V… Jmstande,

1) …

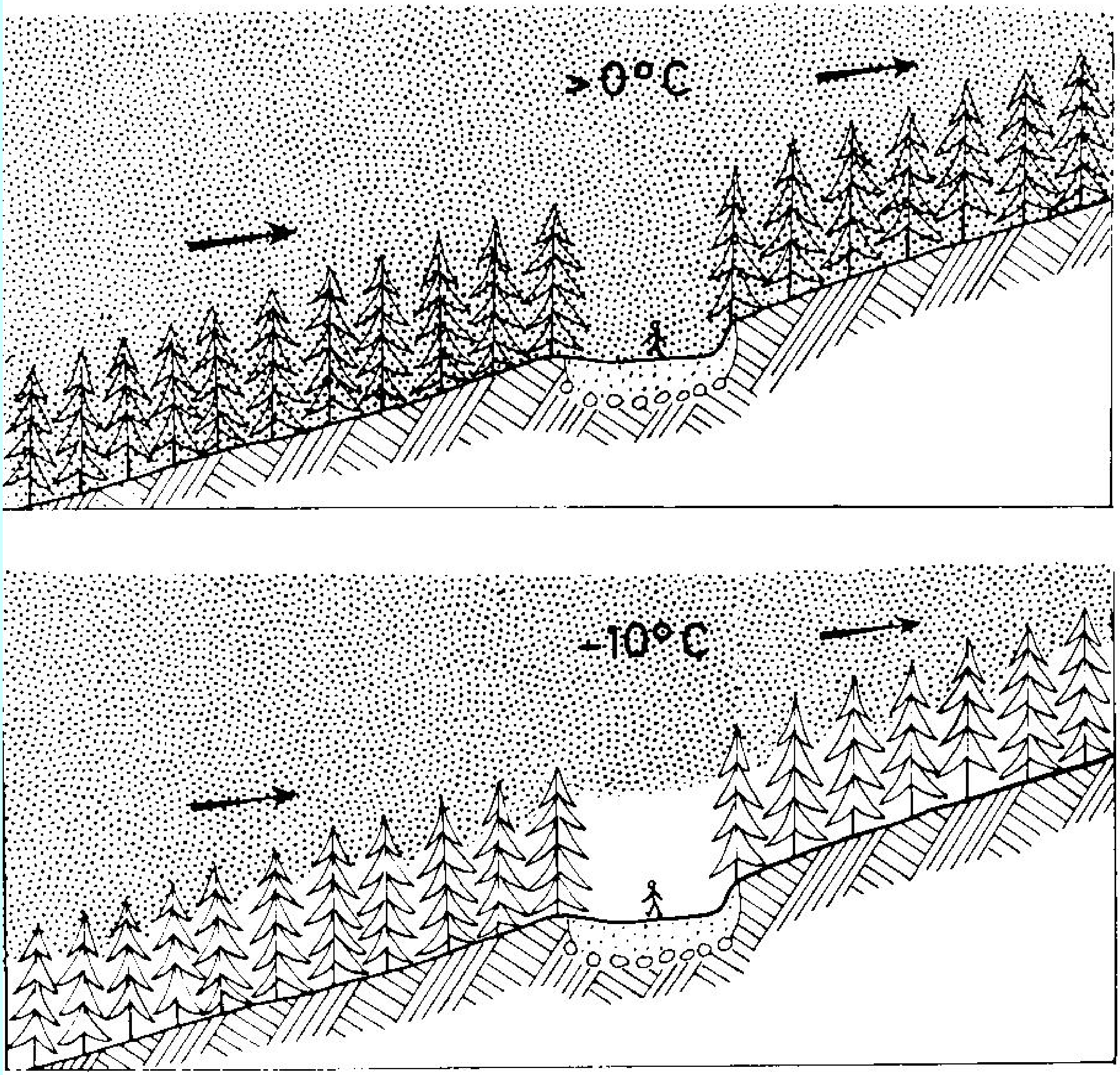
…bleibt, wenn die Kerne fehlen, während die Kondensation …ssenkondensation darstellt, welche das Auftreten wesent- …gestattet. Die konventionell getroffene Auswahl ist daher …amt …ben …ten …ren …von …hen, …ben …iger …lich …hen: …mit …be- …und …von …eckt, …nur …iger …keit. …vor- …idete



…e ein, denn es findet ja nun wegen der Frostübersättigung …an ihm statt.

…ch der Temperatur bei folgenden relativen Feuchtigkeiten:

Wegener, 1920



Distribution du stratus observé en février 1922 dans la forêt de sapins de Voksenkolle d'Oslo, 470 m d'alt., à des températures > 0 °C et environ 10 °C respectivement. La partie ombrée représente la couche de stratus.

Bergeron, 1935

Proc. 5th Assembly U.G.G.I., Lisbon
2, 156-175 (1935)

ON THE PHYSICS OF CLOUD AND PRECIPITATION

by Dr. T. BERGERON, Oslo.

(Recieved June 1933.)

Introduction. The evolution of the theories on the physica and meteorological condition of the formation of cloud and their precipitation offers such a typical example of the "zig-zag progress" of science that an introductory retrospect seems worth while.

no means perform.

II. We have thus tried to show that none of the hitherto recognized factors of cloud coagulation represent the *universal* release of *real* precipitation (real rain and snow). Either the factor is only active at special times of the day (3), or under abnormal electric conditions (1b), or can only coagulate droplets of fog dimensions or smaller, without causing few great drops (1a), (2), (4), or is ineffective on the whole as a *release* of coagulation (5).

6. Then there remains only one factor : neighbouring elements of *different phase* (i. e. some cloud elements liquid, some solid) at temperatures below the freezing point — an effect that seems to have been too little heeded hitherto, but which I hope to show is the chief one, physically and meteorologically.

We will first treat the more *physical* side of the question. A supercooled mixture of crystals and droplets must be colloidal-thermodynamically unstable, due to the difference of maximal vapour tension over ice and water at frost-temperatures. This difference Δe amounts to 0.24 mb at — 10°C, and is thus much greater than the corresponding differences due ~~to the~~ factors (1) or (2) above ever can get when $d > 5\ \mu$. As to the factor (3), a $\Delta e = 0{,}24$ mb corresponds to a Δt of almost 1,0°C at — 10°C,

Vali - June 7, 2004

"..... the difference in phase between neighbouring elements ... can in two cases occur without any considerable relative motions:

> **a) Berson, Wegener, Douglas and others have observed fogs consisting of droplets down to temperatures of −20° or even −30°C. ... In the air there will, however, probably be a small amount of such particles, which can gradually get into action as sublimation nuclei, as the temperature falls. ... Thus, to every temperature < 0°C will correspond a certain probability of crystallization resp. a certain frequency of crystals within supercooled water cloud ...**
>
> **b) ... layers above the isotherm of −10° or −20°C mostly contain ice crystals ..... ascending water cloud mass, protruding into this region, may then become infected by some crystals by trubulence ..."**

" In our mixed or supercooled cloud the three phases ice, vapour and liquid water are in contact with each other through the vapour. ... the process of transporting tha total water quantity of the droplets by molecular diffusion to the crystals would be achieved in 10 – 20 minutes."

the stable layer clouds in the former picture.

Conclusions. — This cloud genetics and classification is only a first attempt. The International Cloud Year, I hope, will give us the necessary data to verify, modify or abandon it. But in any case it might perhaps serve as a base of discussion and help to tell us what we have to look for in the abundant material which has been collected now.

The historical display of the theories of cloud and rain have also shown us that theories, once completely done away with, may rise to great honour again, as for instance the „ barometric fog " — revived by SWOBODA and me 1924, and now even exaggerated by GIÃO 1931 — and that an entirely one-sided theory is less helpful to our extremely complex science.

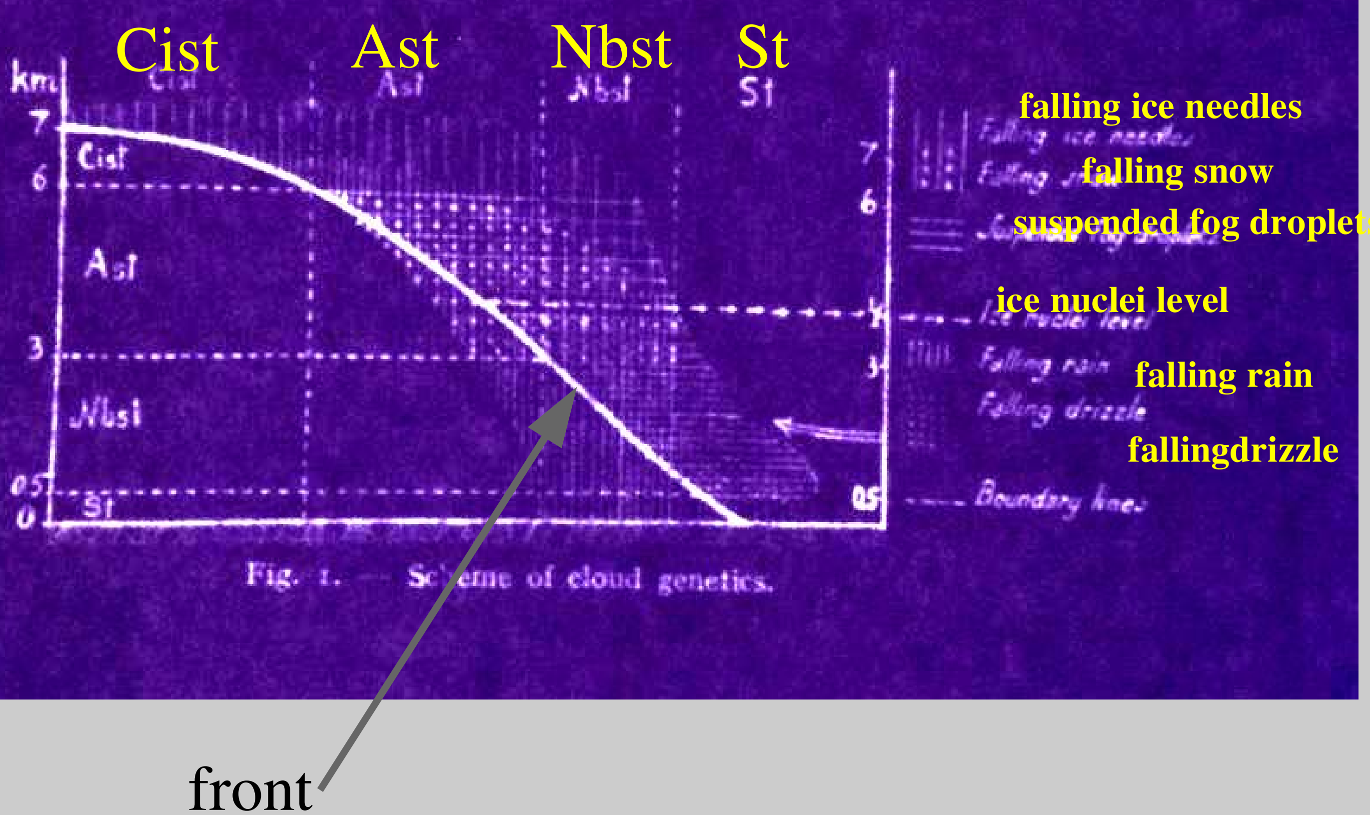


Fig. 1. — Scheme of cloud genetics.

Bergeron, 1935 (paraphrased):

In addition to other processes that can induce precipitation in colloidally stable clouds, a physically and meteorologically important process arises from the special situation at temperatures below 0°C created by the simultaneous presence of supercooled liquid and ice.

As a consequence of this realization, it became imperative to look carefully at how ice particles originate, how many get started at various temperatures, how other factors (cloud type, etc.) might have importance.

- 1100 -

Forschungs- und Erfahrungsberichte
des Reichswetterdienstes

Im Auftrage des
Reichsministers der Luftfahrt und Oberbefehlshabers der Luftwaffe
herausgegeben vom

Reichsamt für Wetterdienst

Reihe B, Nr. 1

Unterkühlte Wasserwolken und Eiswolken

Von Wilhelm Peppler

Berlin 1940 * Gedruckt in der Reichsdruckerei

kühlung für alle Aufstiege dargestellt; die Kurve

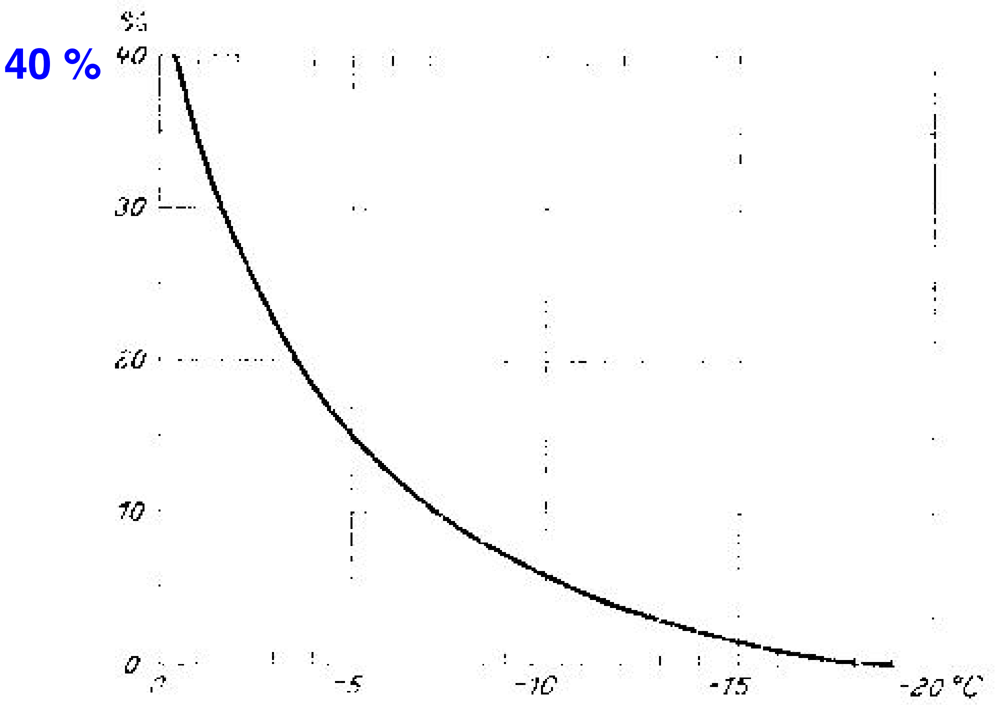


Fig. 9

Häufigkeit der Unterkühlungstemperaturen

m, darüber re bis zur alhöhe. Un- äßigkeiten hichtungen in diesem tmittel hervor.

Fig. 12 ist Vorkommen swolken zu- n mit dem nterkühlten wolken im tmittel in gigkeit von öhe darge- Während die keit des Vor- ns der Eis-

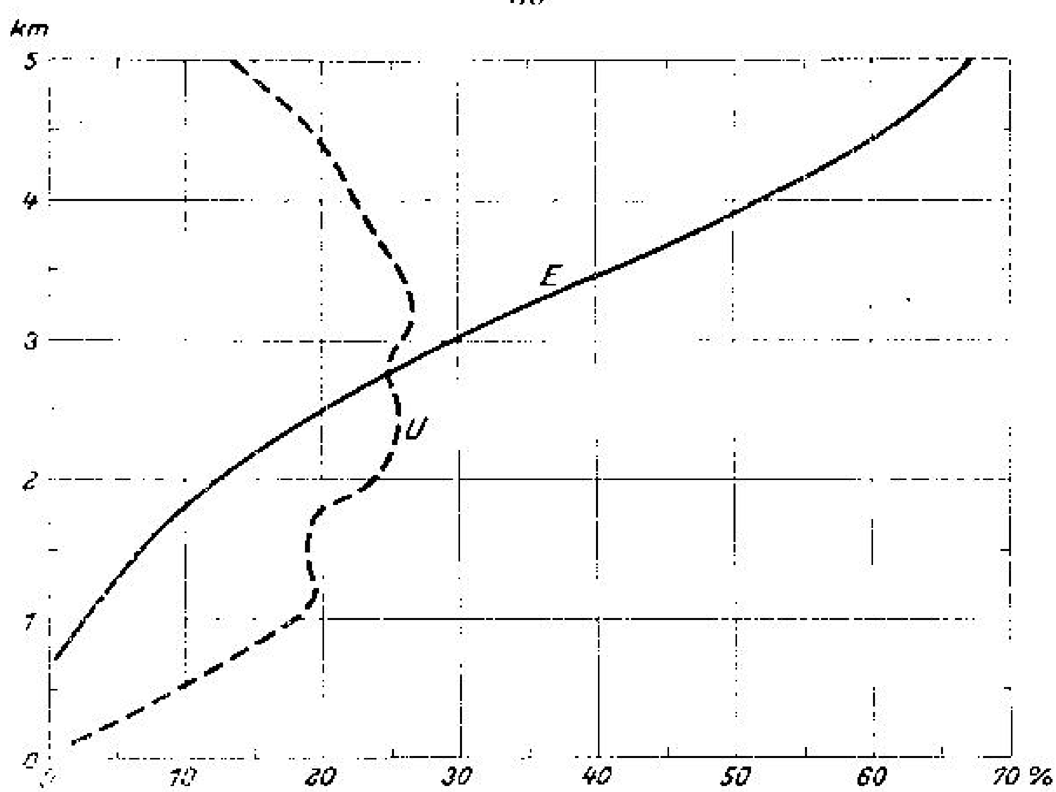


Fig. 12

Vorkommen der Unterkühlungen und der Eiswolken

wolken von 1 km Höhe a 5 km stetig stark zunimr auf fast 7 zeigt die K der Häufigke Vorkommens unterkühlten serwolken wesentlich a ren Verlauf, lich starke nahme vom E bis etwa 1 dann lang Zunahme bis Maximum bis 3 km, darüber ke Abnahme zur Maximal

Peppler, 1940

Prüfnr. 637

Forschungs- und Erfahrungsberichte
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Im Auftrage des
Reichsministers der Luftfahrt und Oberbefehlshabers der Luftwaffe
herausgegeben vom

Reichsamt für Wetterdienst (Luftwaffe)

Reihe B, Nr. 8

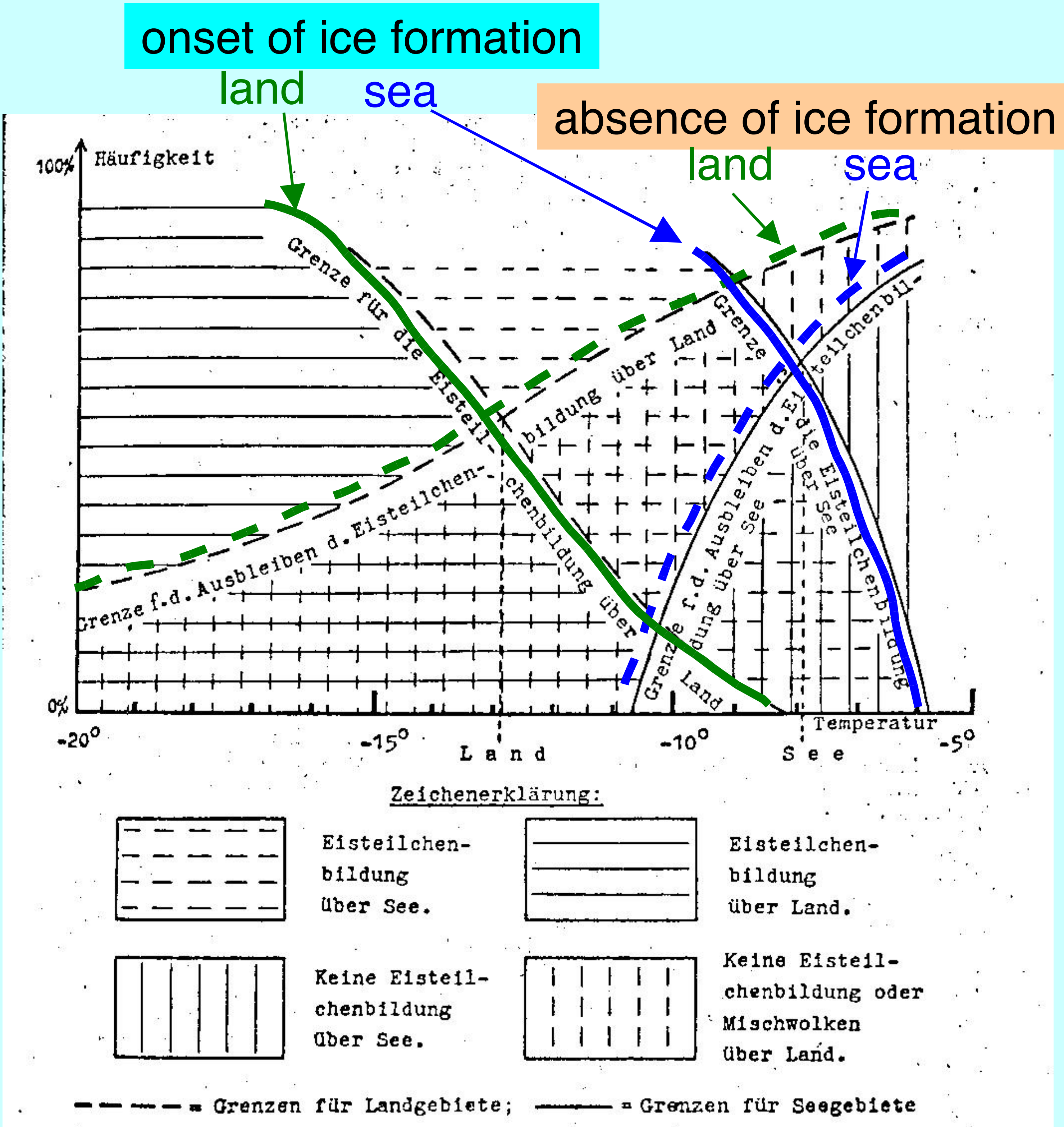
Geheim!

Ergebnisse von Wolken- und Niederschlagsbeobachtungen bei Wettererkundungsflügen über See

Von W. Findeisen, Prag

Berlin 1942 * Gedruckt in der Reichsdruckerei

Findeisen, 1942



Quellwolkenstatistik nach Beobachtungen über Seegebieten;
zum Vergleich Werte aus der Wolkenstatistik nach W. Peppler für Landgebiete.

Findeisen, 1942

late 1930s

Findeisen (building on Wegener and Bergeron, and using observations of Peppler and of his own):

> ***Examined frequencies of supercooled clouds from soundings and the occurrence of ice from optical phenomena and found that ice clouds are frequent only at temperatures below −10°C or even −20°C.***
>
> ***Recognized that riming further accelerates the growth of ice crystals. Dependence on droplet size is speculated. Discussed the link to aircraft icing (translated by National Advisory Committee for Aeronautics).***
>
> ***Foresaw possibility of deliberately influencing precipitation due to sparcity of sublimation nuclei.***

The Wegener–Bergeron–Findeisen theory is now complete and is rapidly accepted. All of cloud physics revolves around two kinds of nuclei – *condensation nuclei* and *sublimation nuclei,* and the competition between them under various conditions (e.g. Findeisen, 1938). "Colloid–meteorology" to become a partner to "meteorology" and "aerology".

2. NUCLEATION PRULARITY.

up to late 1940s:

- Concept of germ formation - nucleation - is well known for variety of systems (Volmer, Krastanow, others).

- Freezing of water is studied in the laboratory (Dorsey, Rau)

- Weickmann (1942) reported little and very slow ice formation at T = -40°C and S_w< 1 on particles placed on a chilled mirror. Ice always formed at S_w>1, in amounts depending on materaial tested.

- Cwilong, Fournier d'Albe found the same as Weickmann, and noted critical temperatures of -33° for ice always forming, and -41°C at which ice formation became abundant.

- Findeisen and Schulz (1944, Prague) used a 2-m^3 chamber with slow adiabatic expansion. Found very few sublimation nuclei. Water clouds formed after S_w>1 even at T<-30°C with just a few crystals observed.

1940s

aufm Kampe, Wall, Fournier-d'Albe:

Ice crystals in contrails and in fogs form only when water saturation is reached or exceeded; 'freezing nuclei' are needed.

The hope (expectation) arose that nucleus measurements can quantify ice occurrence and can be used to predict ice initiation in clouds.

The possibility of cloud seeding seemed to have an ample and open window.

late 1940s

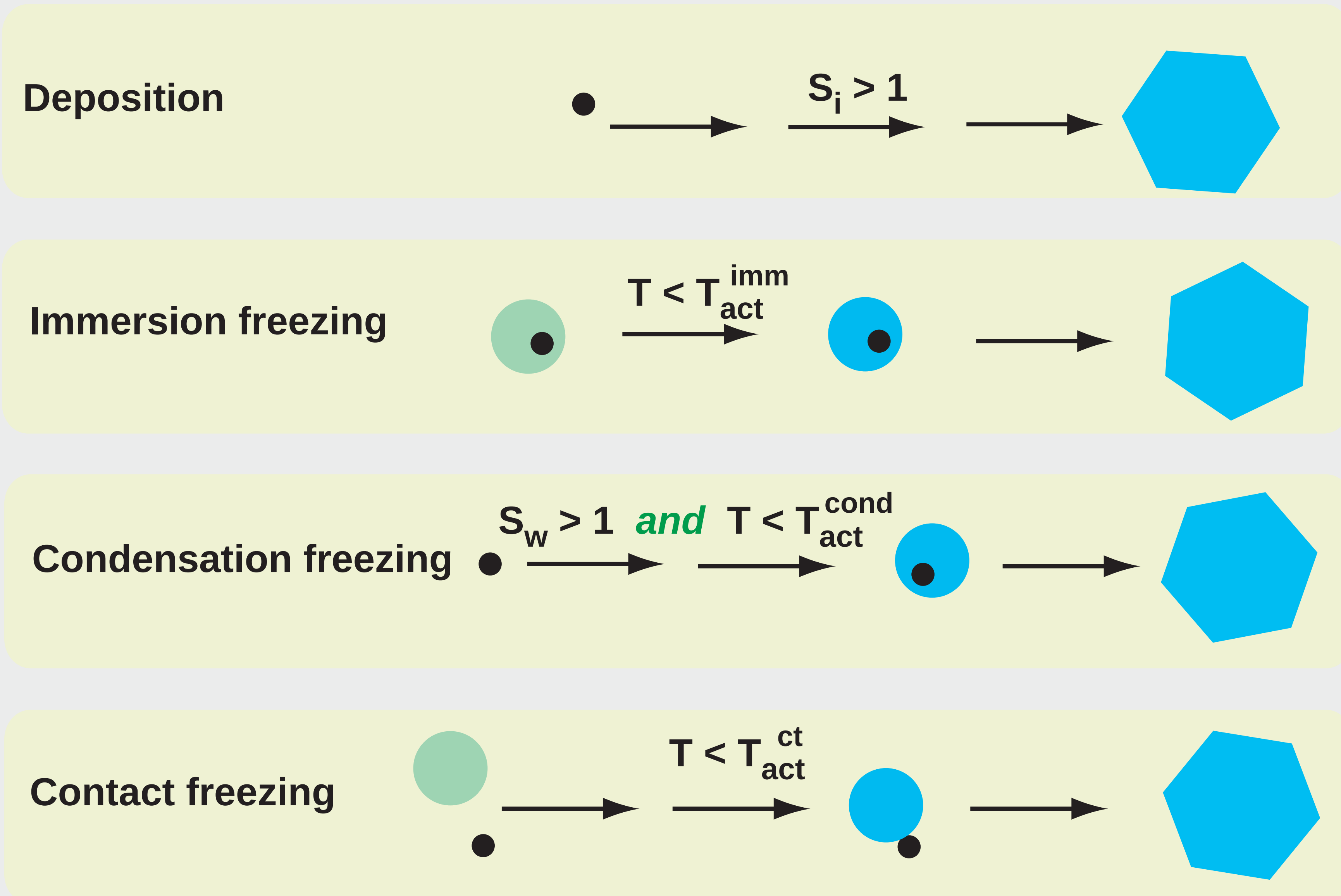
Langmuir, Schaefer, Vonnegut (Project Cirrus)
Bowen :
Cloud seeding tests show that supercooled clouds can be "glaciated" with the addition of AgI nuclei.

Confirmation of Bergeron's thesis. Start of many weather modification projects.

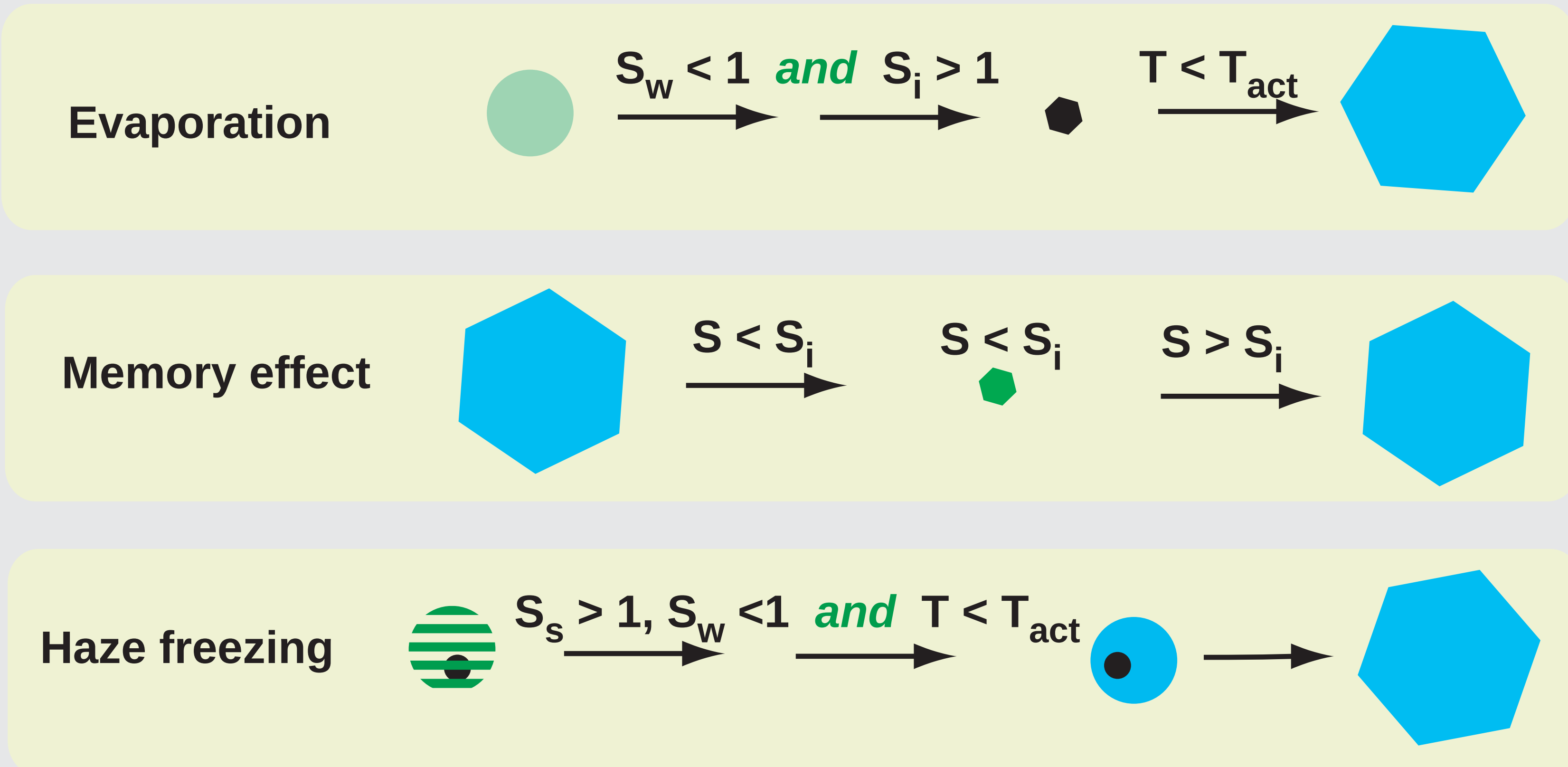
Cwilong, Dorsey, Weickmann:
Laboratory measurements of ice nuclei support or even explain the trend observed in clouds toward more ice at lower temperatures. Metals and metal halides are effective freezing nuclei.

Nakaya, Kumai, Weickmann:
Ice crystal form also varies sytematically with temperature.

Principal ice nucleation modes



Some additional modes



? ? ?

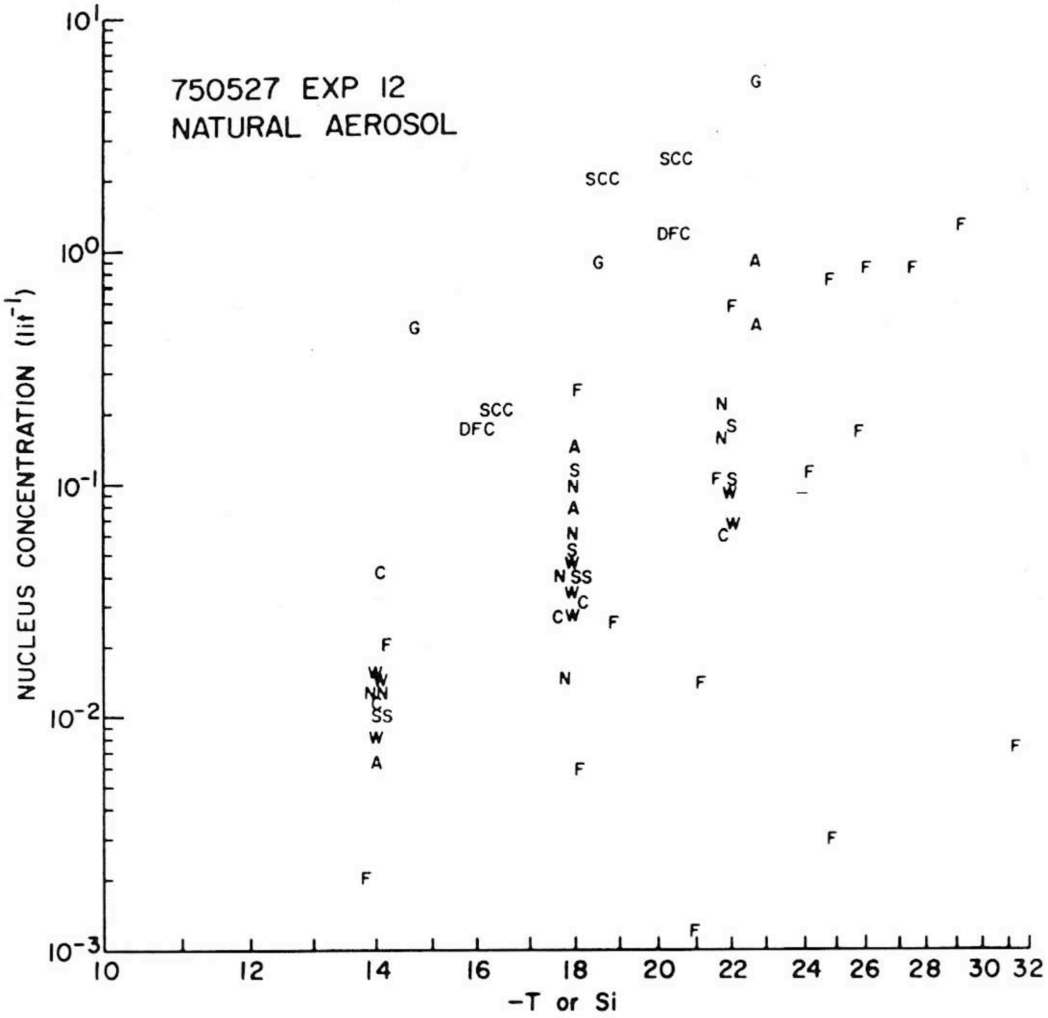
Boulder, January 11, 2002

• Only most basic of cloud processes can be simulated in labratory chambers and samples are not fully representative.

• Prularity of nucleation modes (pathways) presents a complex instrumentation challenge.

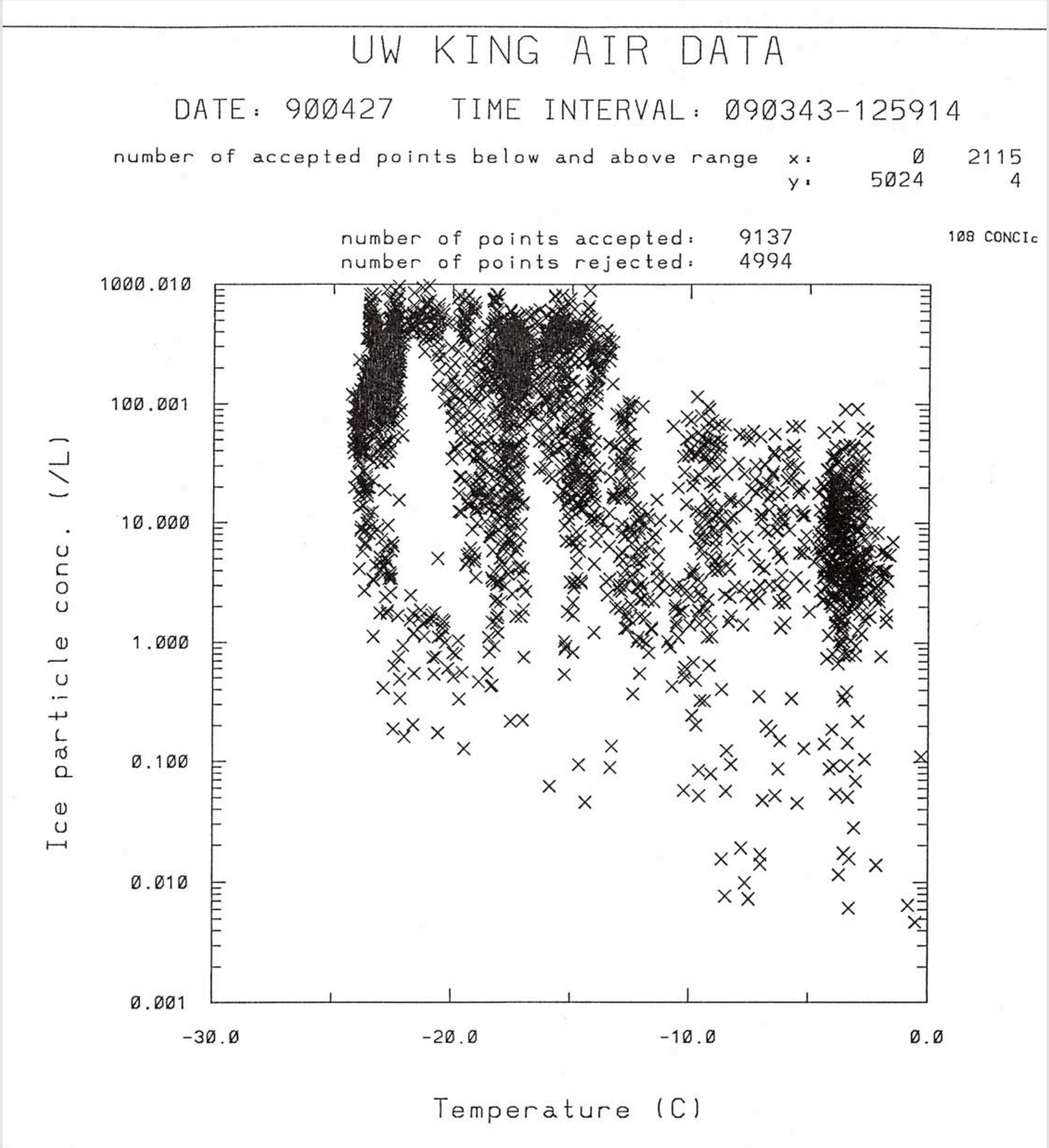
• Reverse path: the examination of crystal residues, or the interpretation of crystal form (“droplet centers”), can offer some important distinctions, but never fully overcome the inherent ambiguity of the evidence.

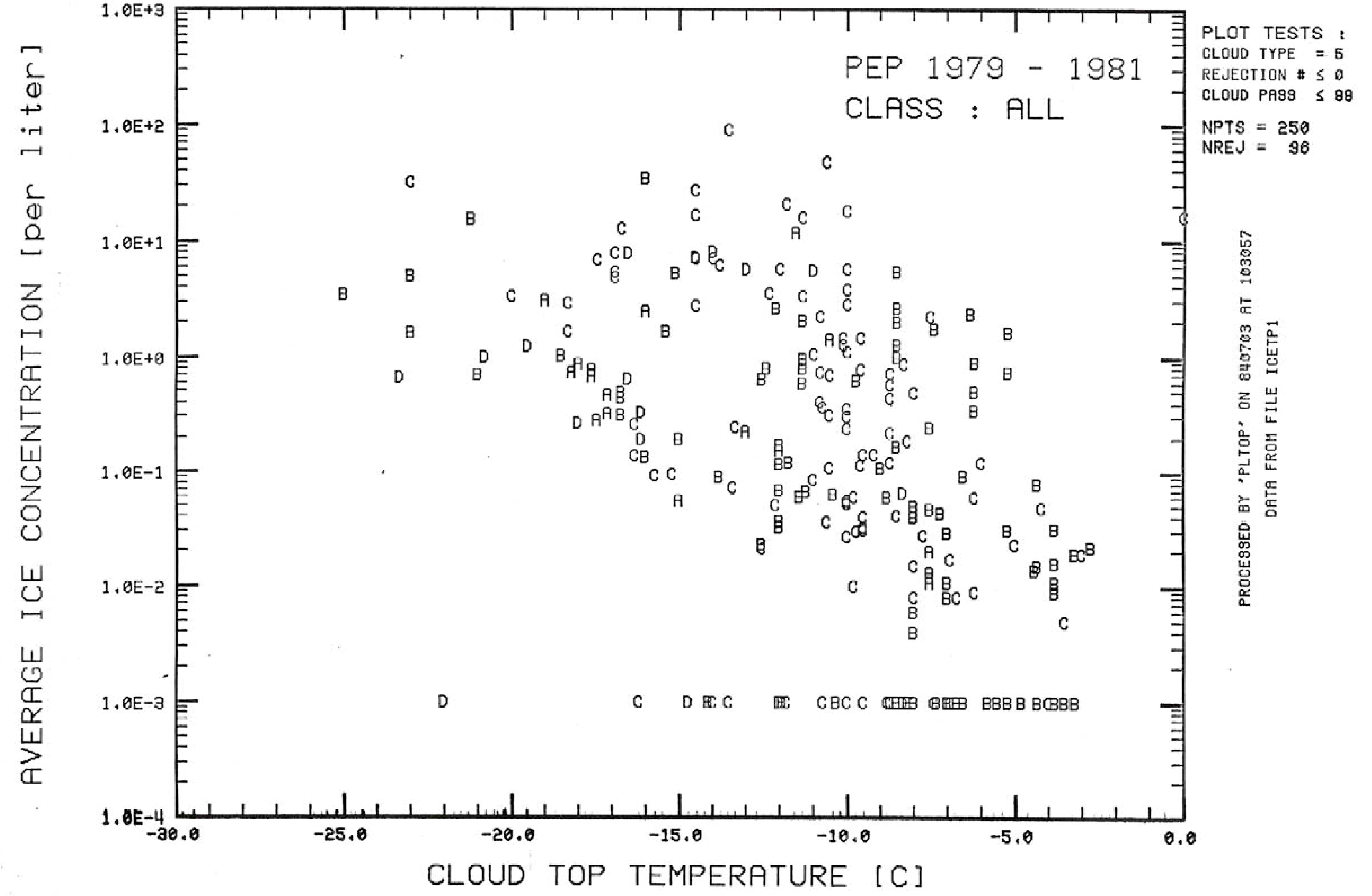
• Shocks, cavitation, collisions, electric fields and discharges, ...



igure 1. Nucleus concentrations measured by various instruments for natural aerosols in Experiment 12 (750527, 1400-1800). Data points are designated with symbols which are coded according to the instrument from which the measurement originated: A = Arizona low pressure chamber, F = Frankfurt low pressure chamber, C = NCAR continuous flow chamber, G = Gotz centrifuge with "puff" humidification, N = NOAA static diffusion chamber, S = SUNYA static diffusion chamber; W = Wyoming static diffusion chamber, DFC = Wyoming drop freezing counter, SCC = settling cloud chamber. The values on the abscissa are S_i supersaturation with respect to ice, except for the DFC and SCC for which the values are -T (°C).

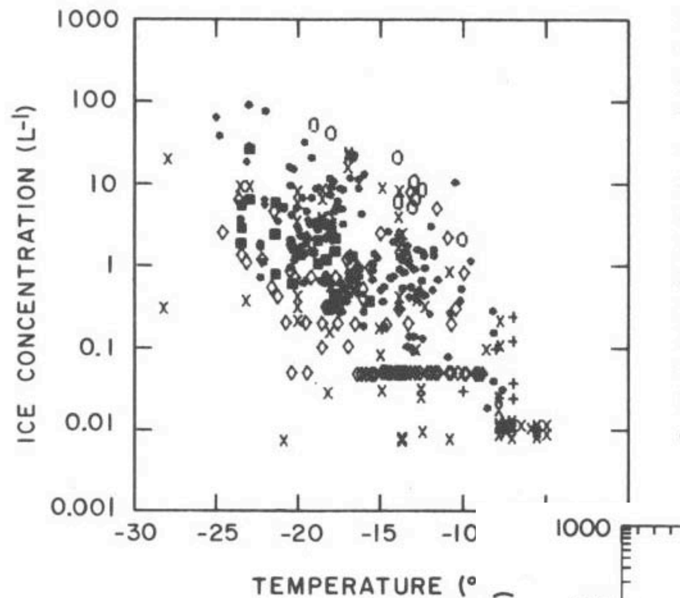
Nucleation Workshop, 1975

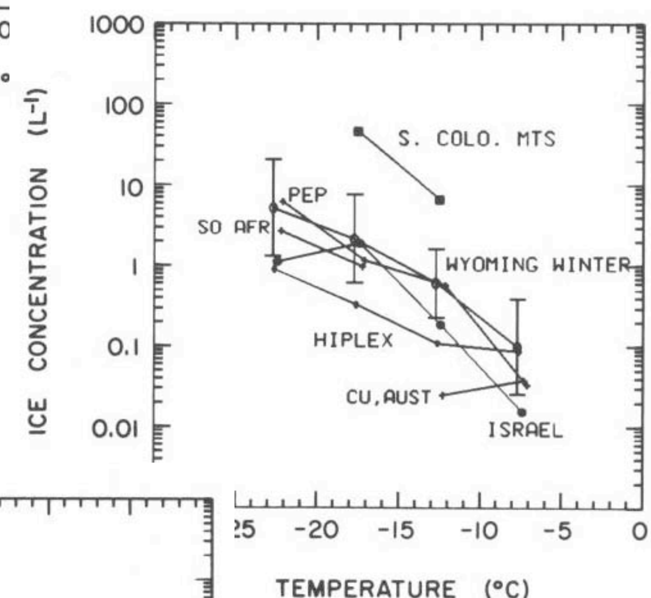

UW KING AIR DATA
DATE: 900427 TIME INTERVAL: 090343-125914
number of accepted points below and above range x: 0 2115
y: 5024 4
number of points accepted: 9137
number of points rejected: 4994
108 CONCIc
1000.010
100.001
10.000
1.000
0.100
0.010
0.001
Ice particle conc. (/L)
-30.0
-20.0
-10.0
0.0
Temperature (C)

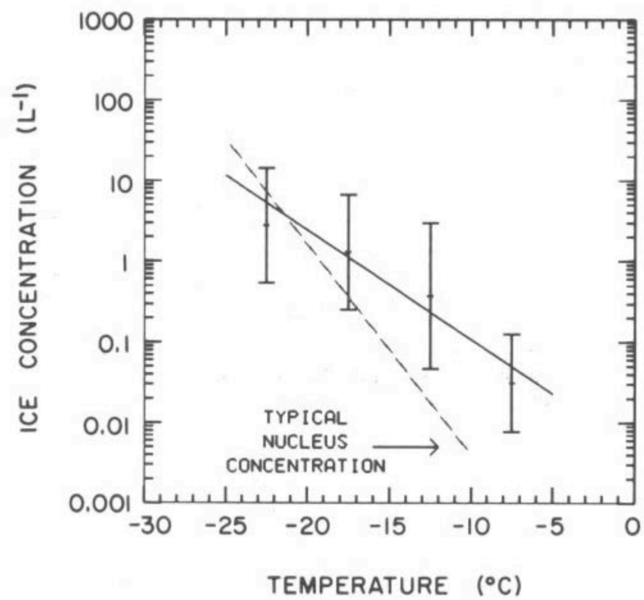

AVERAGE ICE CONCENTRATION [per liter]
1.0E+3
1.0E+2
1.0E+1
1.0E+0
1.0E-1
1.0E-2
1.0E-3
1.0E-4
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
CLOUD TOP TEMPERATURE [C]
PEP 1979 - 1981
CLASS : ALL
PLOT TESTS :
CLOUD TYPE = 5
REJECTION # ≤ 0
CLOUD PASS ≤ 99
NPTS = 250
NREJ = 96
PROCESSED BY 'PLTOP' ON 840703 AT 103357
DATA FROM FILE ICETP1

Cooper,1986

for cases where ice concentration can be attributed to nucleation







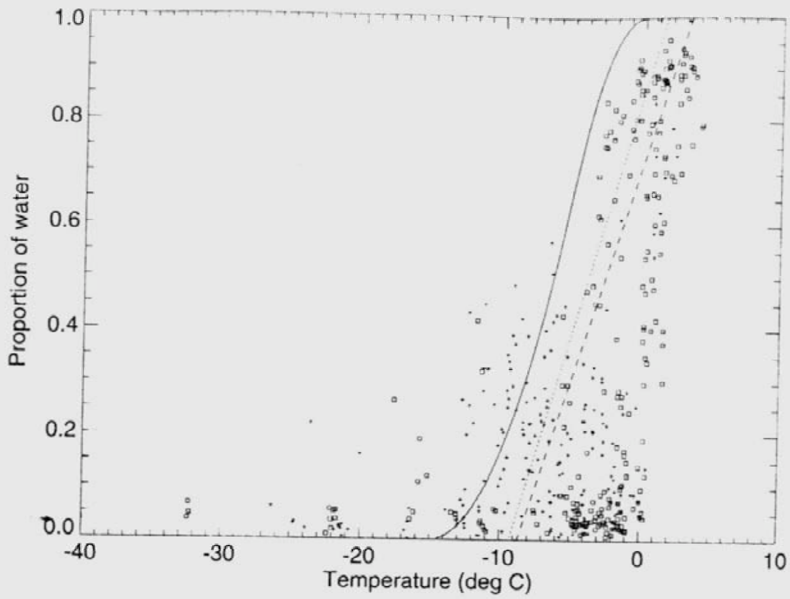


FIG. 5. Plot of the phase ratio (the proportion of water to ice) in cloud against temperature from 11 frontal flights. Each point represents the average over a 2-min horizontal leg in cloud. Crosses indicate clouds in continental airmasses and squares indicate clouds in maritime airmasses. The dotted line is the best fit to the data for continental clouds and the dashed line for maritime clouds. The solid line is the current parameterization in the U.K. Meteorological Organization Atmospheric GCM (courtesy S. Moss and D. Johnson).

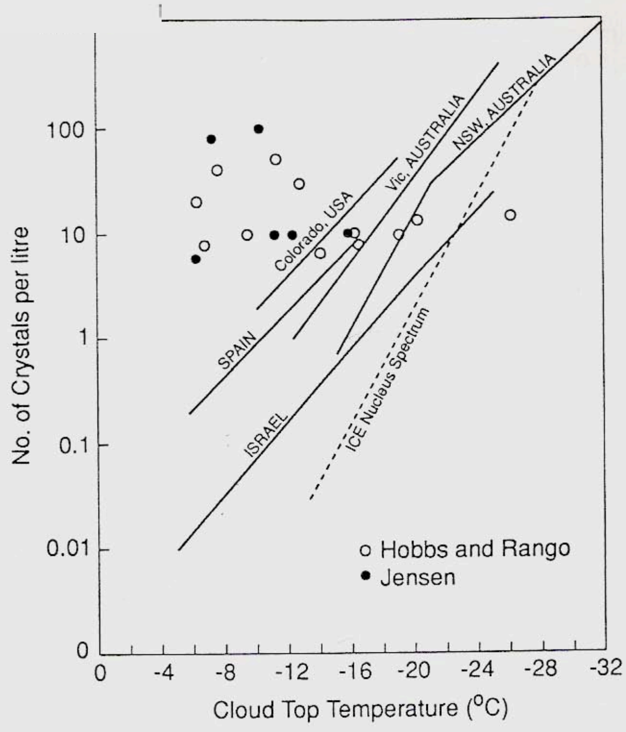


FIG. 6. Observations of ice crystal concentrations (no. L^{-1}) as a function of cloud top temperature. The ice nucleus spectrum is from Fletcher (1962), the Australian data from Mossop (1968) and King (1982), the Spanish data from Vali et al. (1988), and the Colorado data from Cooper and Saunders (1980) are shown as linear fits to the data. Observations from Hobbs and Rangno (1985) over the Pacific Northwest of the United States are shown as open dots, and observations from the Australian Winter Storms Experiment (J. Jensen 1994, personal communication) are shown as closed dots.

Ryan, 1996

3. THE GRAUPEL STORY.

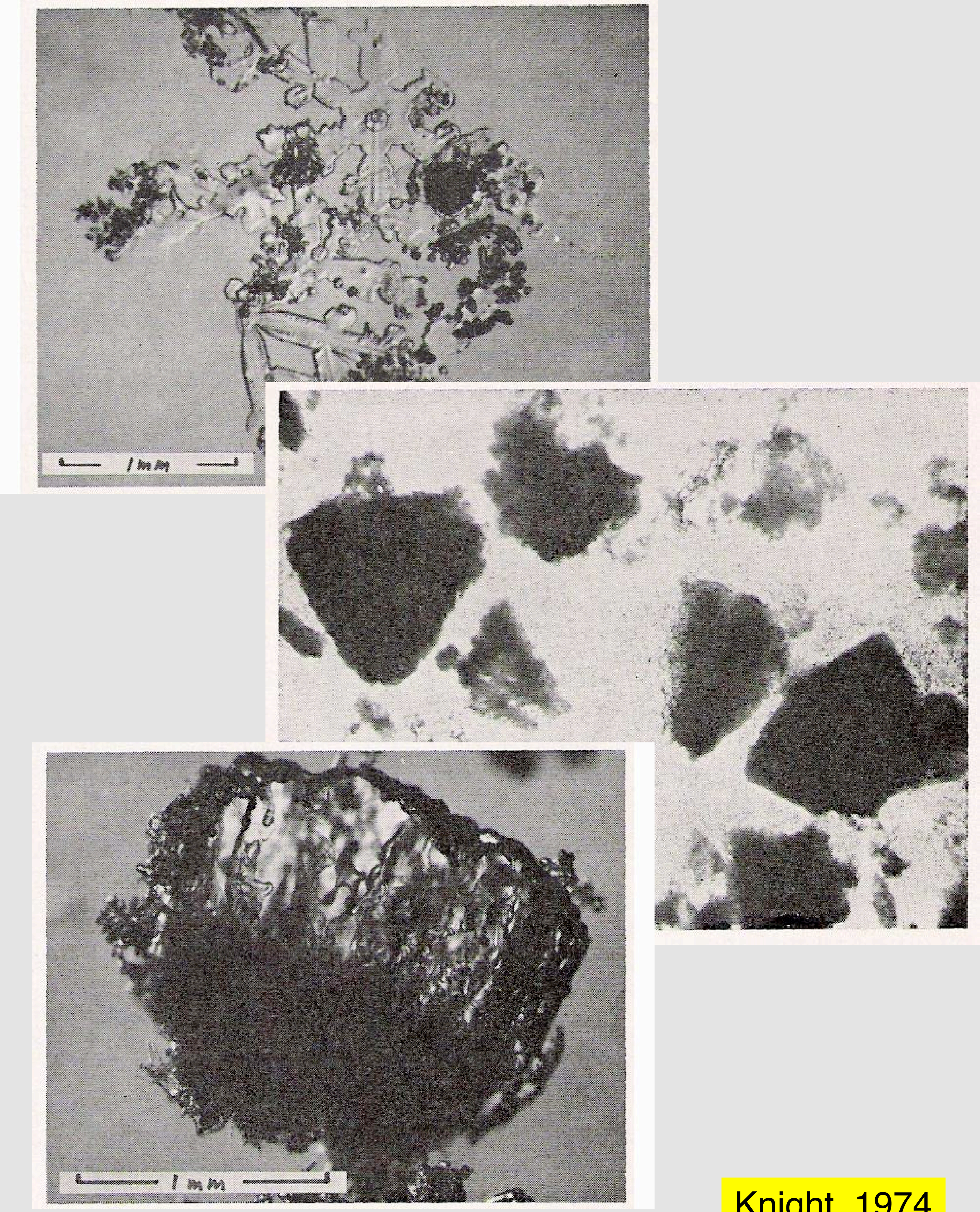
- The importance of riming has been recognized from Wegener and Findeisen on, but primarily in connection with snow.

- Focus on hail damage reduction led to studies of riming in more detail.

NE Colorado summer *Cu con*.

- No evidence for coalescence process.
- Particles collected in clouds (sailplane) are graupel. Often observed at the ground as well.
- Evidence for prior vapor growth is infrequent but has been found.
- No large frozen drops centers in hail.
- First echo heights are above 0°C level, or are at melting band. Rough quantitative agreement between measured echo intensity and reflectivity calculated for observed graupel sizes and concentrations.

Knight et al., 1974



Knight, 1974

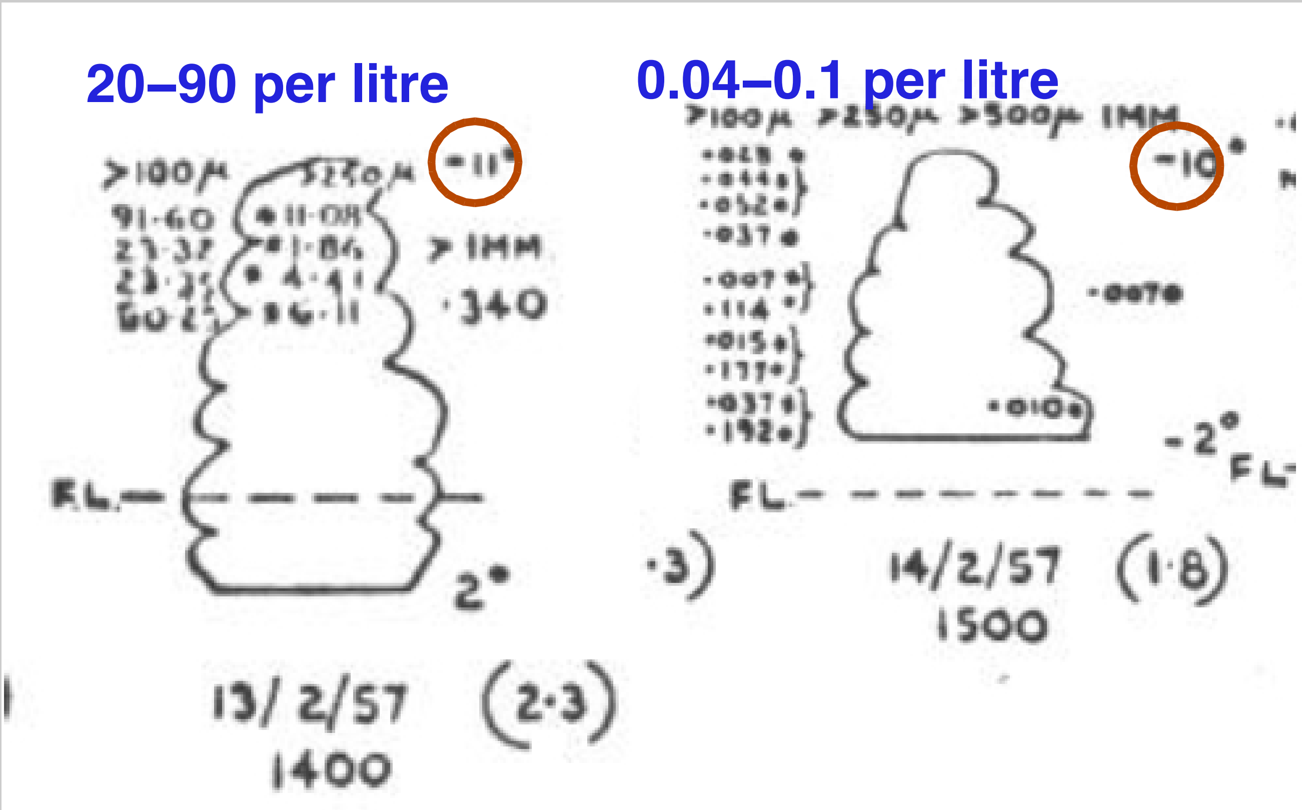
Observations consistent with the Knight et al. conclusions were obtained by Krauss et al. in S. Africa, and perhaps others.

The main question remaining is the origin of the ice crystals, or frozen cloud droplets, that start the graupel growth.

4. THE MULTIPLICATION SUCCESS.

Prologue:

By the mid–fifties, the importance of ice particles to precipitation formation is well accepted and the search is on to discover how many ice particles get inititated, and how, in different cloud types in relation to other parameters like liquid water content, droplet concentration, etc.



small, isolated Cu, southern England

foil impactor

"It has been suggested that the explanation lies in some process of self–multiplication (e.g. splintering) by which a large number of ice crystals could build up from very few parent crystals."

Murgatroyd and Garrod, 1960

TABLE 1. Summary of data obtained—Project Whitetop, Mo., 1961.

Date	Cloud description			Number pellets	Freezing temperatures	
	Type	Top height	Top temp.		warmest	median
20 June	two Cu	21, & 25,000	−15 & −22C	22	−23 C	−25 C
1 July	Cu	19,000	−10	26	−20	−23
2 July	As	15,500	−7	63	−19	−24
7 July	Cu	19,000	−9	13	−24	−26
14 July	Cu	unknown	unknown	8	−23	−24
1 Aug	Cu	19,500	−9	110	−16	−24
9 Aug	Cu	20,000	−11	53	−16	−26
22 Aug	As-Ac	unknown (collection temp. −8)	unknown	5	−23	−25
30 Aug	Cu shelf	22,000	−15	1	−21	−21

Ice pelletts captured via a tube leading into the aircraft,when melted and refrozen are found to freeze at temperatures 6–10°C colder than the cloud top temperature. This casts doubt on freezing nucleation as the cause of ice initiation.

Hoffer and Braham, 1962

Koenig (1963) concludes that some chain reaction process, propagated by the formation of satellite ice particles during the solidification of water drops, may be responsible for the observed concentrations of ice particles much in excess of nuclei concentrations.

–6°C cloud top

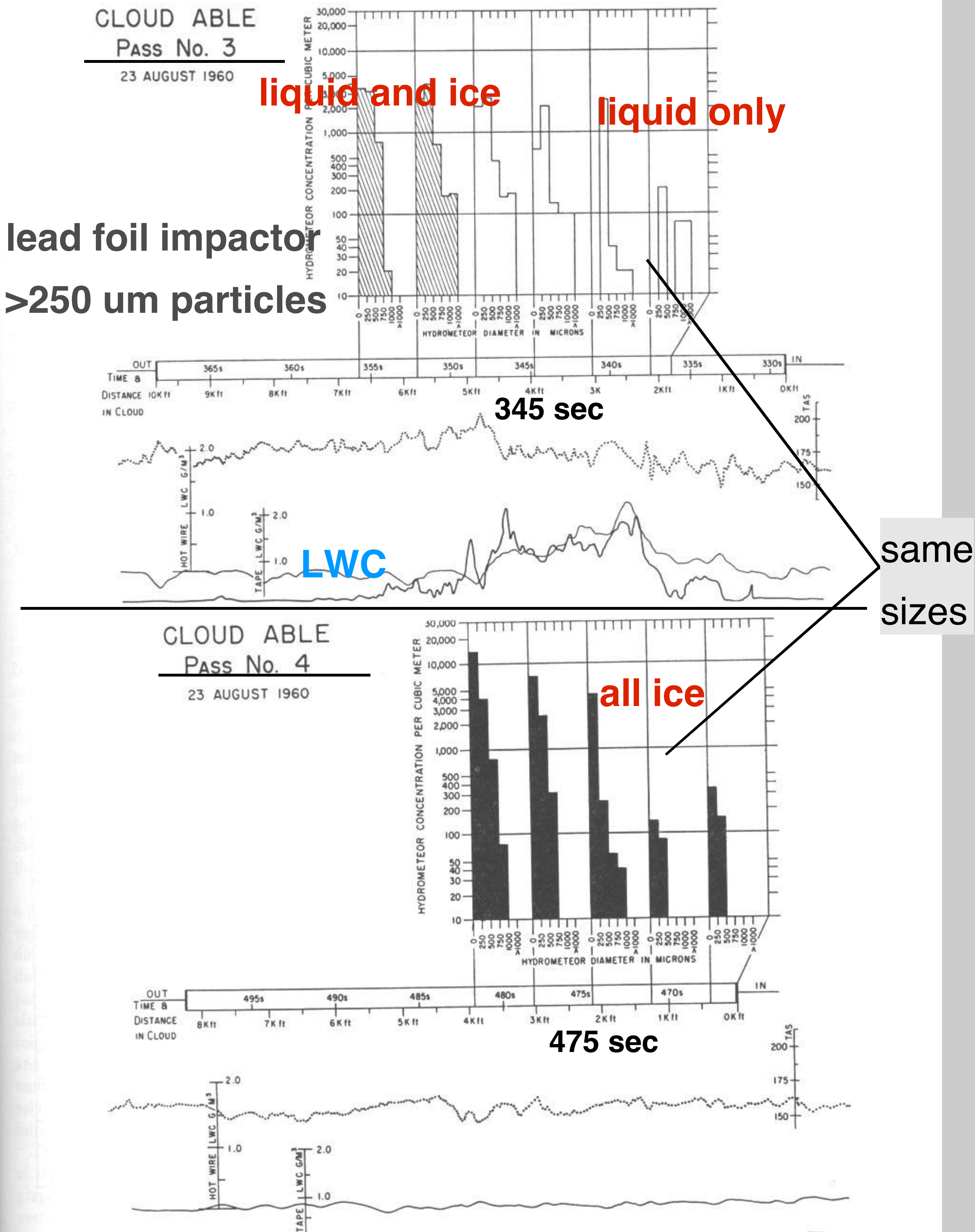


Fig. 7. (*Continued from preceding page.*)

Koenig, 1963

ameter of the original drop; and 2) the shat- by the chloroform) near the replica. A 400 μ f

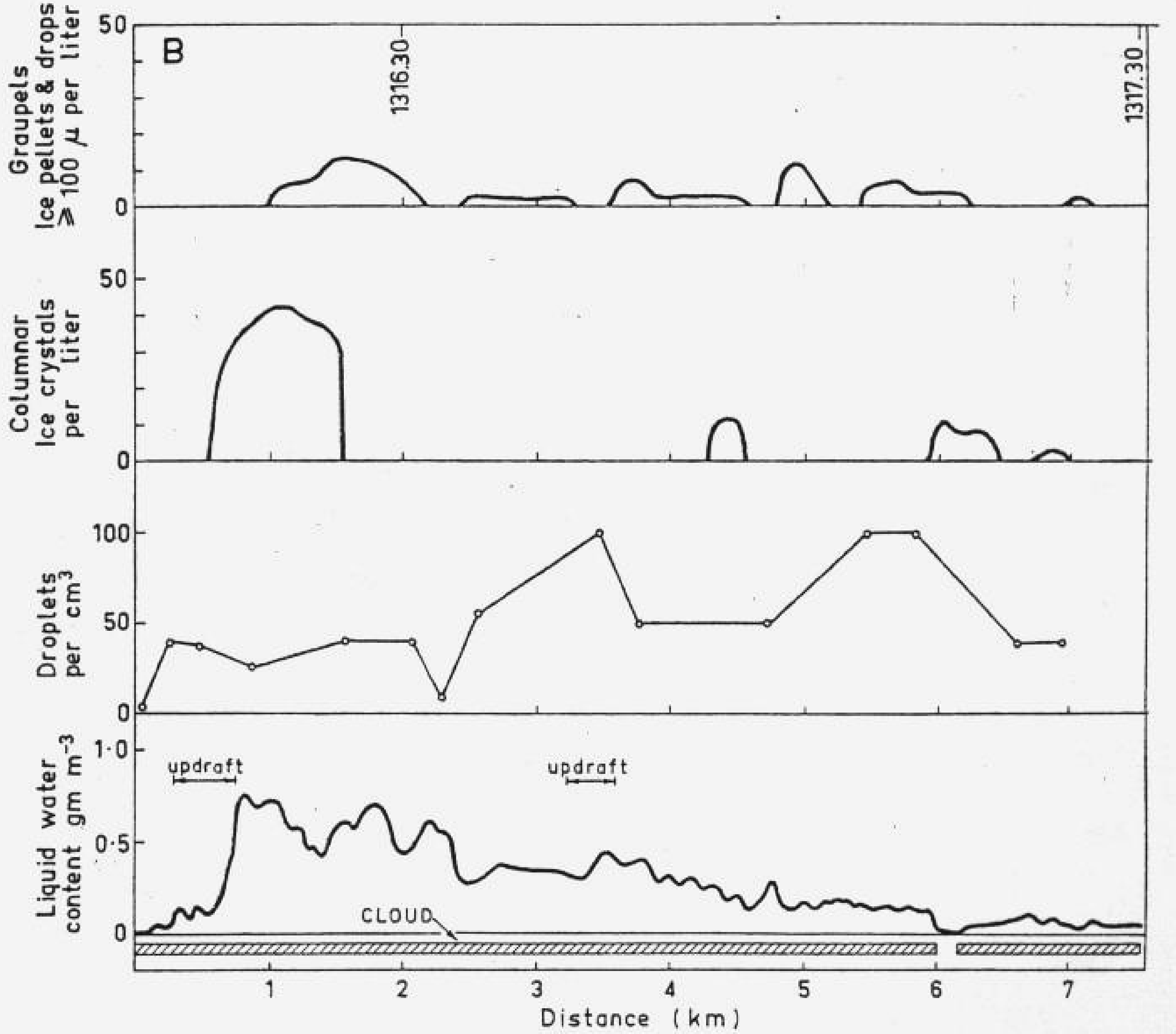


FIG. 4. Measured cloud and particle parameters, Pass B, Constellation aircraft, altitude 2.0 km (6600 ft), 1316.10–1317.30.

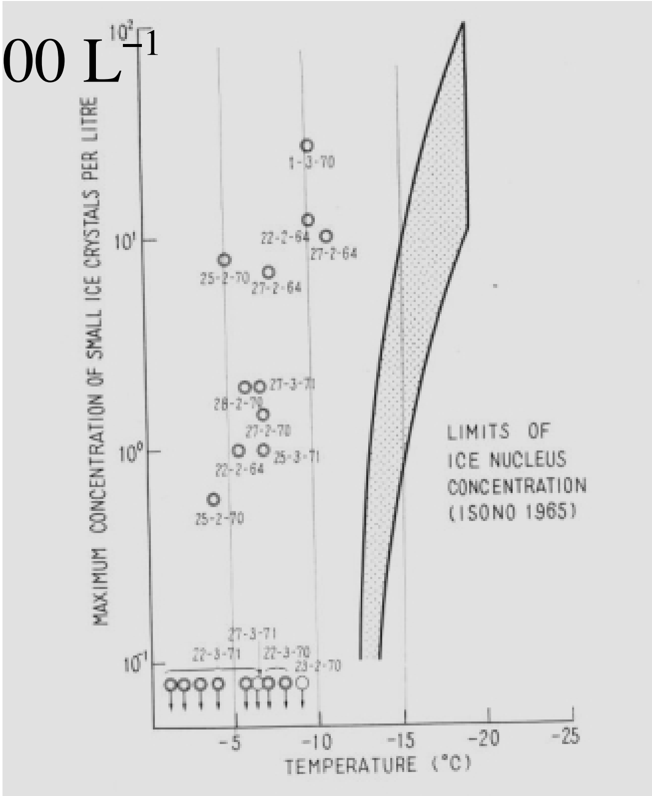
Measured ice nucleus concentrations <u>much</u> lower.

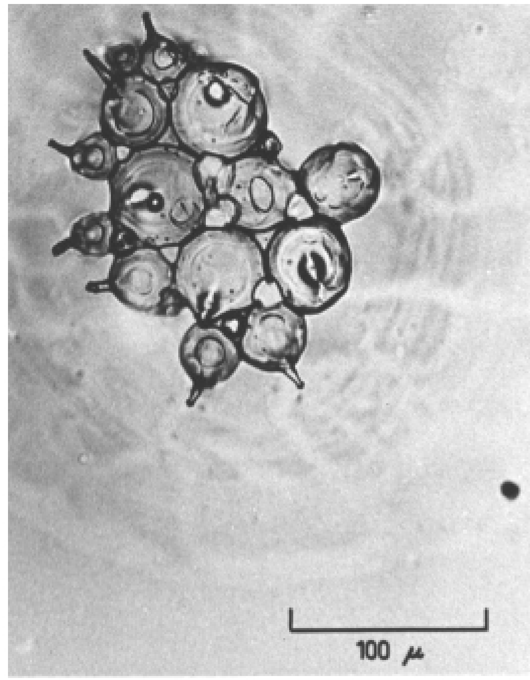
Pre–activation of nuclei

Accumulation of crystals in time.

<u>Multiplication:</u> splinters from drop freezing or electric effect associated with riming (both controversial).

Mossop, Ruskin and Heffernan, 1968





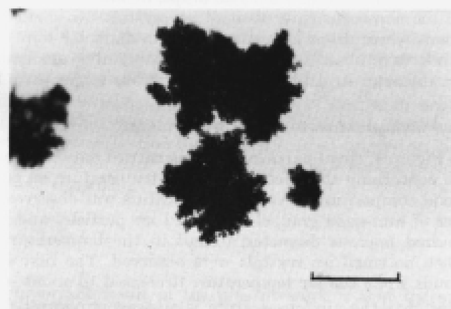
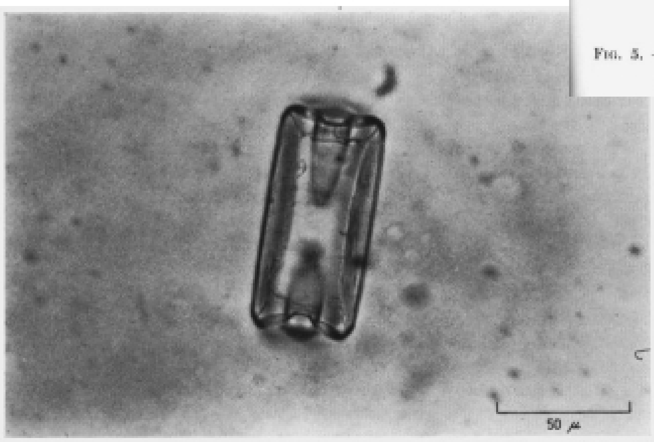


FIG. 5. — Graupel-like rimed ice particles associated with the occurrence of the small ice crystals. Comparison scales are 1 000 μ.



d-2

Fig. 3 Replicas of the small regular ice crystals (d) Observed at −8.5C in Cloud No. 1-b, May 26 1968.
Also clearly shown are the replicas of drops up to 100μ in diameter.

In the temperature range –4 to –10°C, high concentrations of small columns are found in association with graupel.

Ono 1971, 1972

Vali - June 7, 2004

and rimes in its turn, there should be no difficulty in provid-

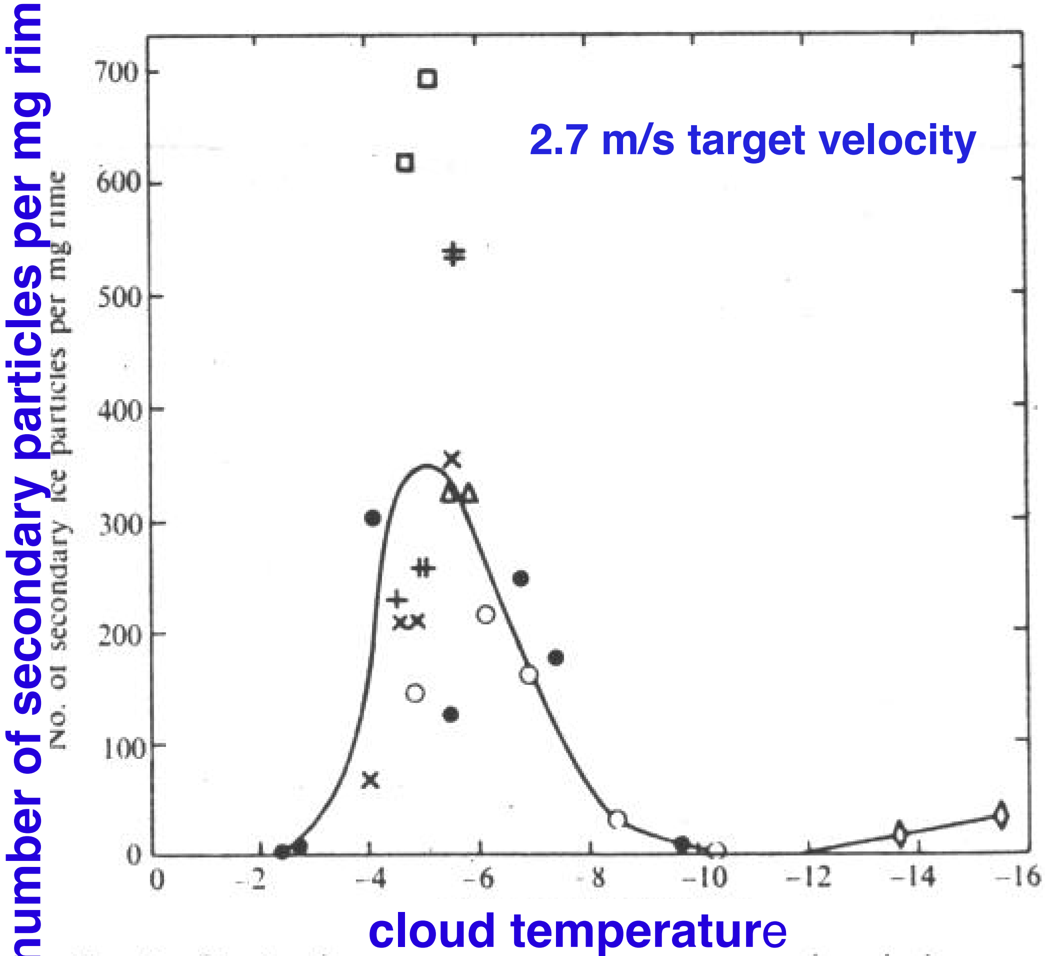
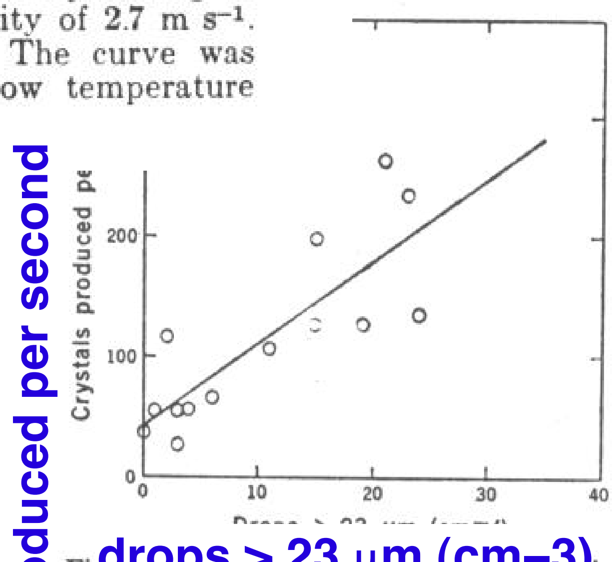


FIG. 2 Production of secondary ice particles by riming as a function of temperature at a target velocity of 2.7 m s^{-1}. Different symbols indicate different days. The curve was drawn by averaging the points over narrow temperature intervals.



Fi… ls produced per second plotted against the concentration of drops larger than 23 μm in diameter in the cloud through which the riming rod was moving. The temperature was —4.7°C and the riming rate was approximately the same in all experiments. The line of best fit by the least-squares method is shown.

–4.7°C; riming rate roughly the same

Hallett &Mossop, 1974

Rime–splintering story wrapped up:

Hallett, Sax, Lamb and Murty (1978) in Florida demonstrate the graupel to needle sequence.

Harris–Hobbs and Cooper (1987) in Montana show quantitative agreement between the rate of generation of secondary particles and predictions based on laboratory findings.

Other secondary ice generation processes:

Hobbs & Farber, 1972 – crystal fragmentation

Vali, 1980 – rime fragmentation

electric effects, shock waves .....

There is ample evidence for unexpectedly high ice concentrations in many situations where the Hallett-Mossop mechanism is not active.

5. CLOUD SEEDING PROSPECTS:

• Creation of numerous ice crystals in supercooled clouds is clearly possible. This confirms the basic Bergeron concept, and is consistent with the paucity of ice nuclei of comparable activity to those of the artificial nuclei.

• Precipitation on the ground is not a sure consequence of the creation of more ice crystals at some point in the cloud. This can be due to insufficient cloud volume getting seeded, the timing of seeding not being optimal, other processes out-competing the ice created by seeding, etc.

• The interplay of cloud seeding with studies of ice initiation in undisturbed clouds is beneficial.

• Industrial, or other well-defined sources, which create cloud glaciation deserve more attention.

6. OTHER ISSUES:

- **Ice frequency** vs. cloud type and other parameters is depicted by a large body of observations, but there are few repeated and generalizable patterns. Even definitions vary a great deal.

  Schemenauer and Isaac
  Nevzorov
  Rangno and Hobbs - OSCIP

- **Phenomenology** of ice particles is also well advanced.

- **Cloud dynamics** frames all ice initiation studies.

- **Aerosol physics and chemistry**, and perhaps air chemistry, provide useful characterizations of cloud input, but forward links to ice formation are teneous at this point.

CHALLANGES AND RESPONSES
(from the observational point of view)

- May be still missing some fundamental process of ice nucleation. Theories are of limited help at this point. ➞ **Aerosol physics and chemistry. Laboratory work.**

- Time lapse between nucleation and an observable result (measurable ice particle) introduces the ambiguities of growth history through imperfectly known condition and cloud motions. ➞ **Cloud physics framework.**

- Conditions at cloud/clear air interface are difficult to define on the scale that may be determinant for ice nucleation. ➞ **Finescale observations.**

- Distinction between primary and secondary generation mechanisms may be hard to draw in some cases. ➞ **Clarification of secondary processes.**