WEATHER MODIFICATION BY

AIRCRAFT CLOUD SEEDING

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PHYSICAL BASIS FOR ARTIFICIAL REGULATION OF PRECIPITATION BY CLOUD SEEDING

1. Convective instability of atmosphere:

$$\frac{\partial \theta_w}{\partial Z} < 0$$

[negative value of vertical gradient of potential temperature by wet thermometer]

2. Instability of phase state of supercooled liquid water in clouds

$$\frac{\varepsilon_s}{\varepsilon_l} = 1 + \frac{t}{80} \Bigg|\; 0^\circ C \div -40^\circ C$$

3. Low values of efficiency of precipitation formation processes in most of cloud systems:
   - convective systems - 15 to 60 %
   - stratiform systems - 35 to 80 %

Precipitation Enhancement

An aircraft cloud seeding by ice-forming or hygroscopic agents is a basis of the technology. The seeding is produced from aircrafts of a types IL-18, AN-12, AN-26, AN-30, YaK-40, equipped by the complex of onboard instrumentation for measurement of aeronautical parameters and characteristics of atmosphere and clouds necessary for decision making, fulfillment of seeding and assessment of its result, and also by the seeding means which include devices for dropping pyrotechnic generators of an aerosol of silver iodide (AgI), liquid nitrogen generators of fine-dispersed ice particles and generator of hygroscopic particles.

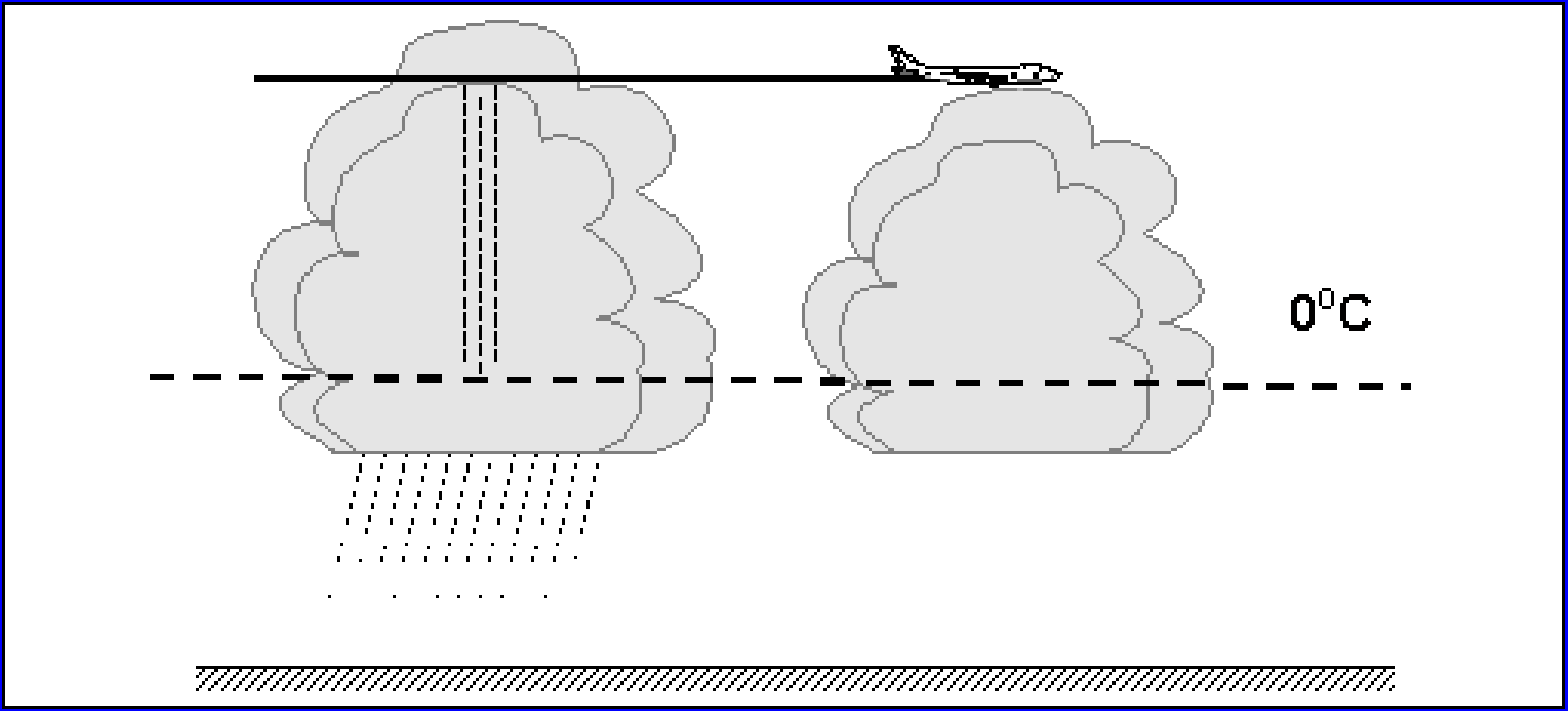
The silver iodide aerosols, entered into a cloud by dropping the pyrotechnical cartridges PV-26 or PV-50 during the flight of an aircraft over the cloud top, is used as the main agent for cold-cloud seeding. Each cartridge PV-26 contains about 40 gram of a pyrotechnic compound with AgI which has an ice-forming efficiency of $5*10^{12}$ nuclei from 1 g of compound (at the temperature of -10^{o} C). The cartridge PV-50 contains 320 gram of similar pyrotechnical compound. Length of a line of an active smoking makes about 2 km for PV-26 and 3.5 km for PV-50.

Precipitation Enhancement

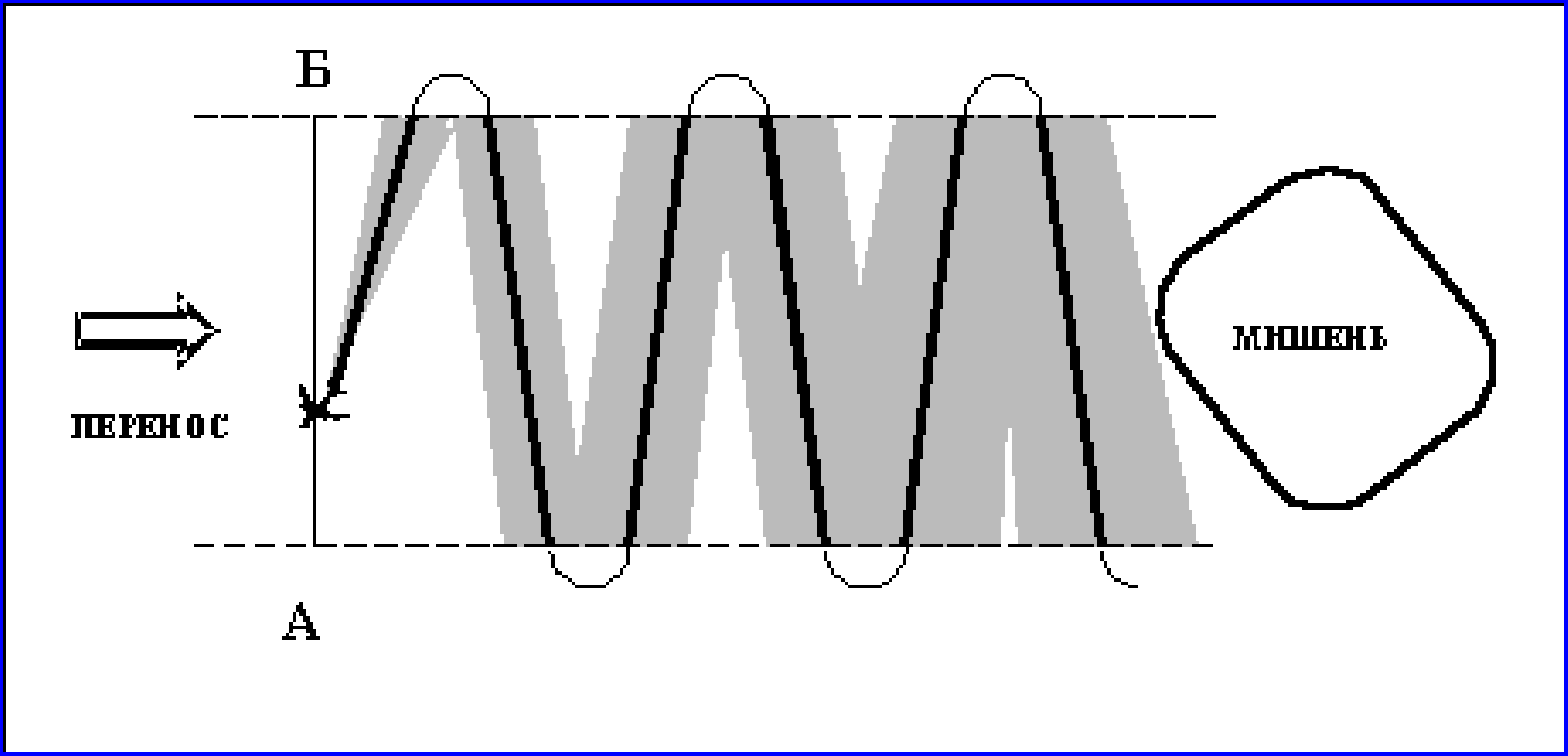
The seeding of the cold clouds which have reached definite stage of development, under condition of maintenance of optimal concentration of ice-forming aerosol particles provide realization of a dynamic seeding hypothesis, i.e. vertical growth of clouds, increase of his lateral dimensions, lifetime and, as a result, increase of amount of precipitations, falling out from cloud.

The nitrogen generators of crystallization nuclei provide forming of huge number of the fine-dispersed ice particles from the air water vapor at the expense of action of extremely low temperature during the emitting into the atmosphere of a jet of steam-gaseous mixture of air and liquid nitrogen. In this case the crystallization nuclei are being formed at the level of aircraft flight and on this reason the nitrogen generators are used, mainly, for seeding the relatively thin cloud layers.

The conceptual model for the warm cloud seeding by relatively large hydroscopic particles is based on acceleration the coalescence process by initiating the collision-coalescence process earlier in the life of the cloud. It is postulated that by reducing the time required for the precipitation process to evolve with respect to the time available, rain efficiency will increase such that clouds that would not naturally rain will rain, and clouds that would naturally rain will rain more.



Simplified sketch of aircraft trajectory for seeding of convective clouds



Simplified sketch of aircraft trajectory for seeding of stratiform clouds

1 Forecast of cloud development

2 Radar survey of atmosphere.
Detection of meteorological objects

3 Aircraft take-off to fixed region for cloud research
and choosing of objects for seeding

4 Recognition of clouds suited for seeding
on the base of radar and aircraft observations

5 Operational selection of cloud for seeding on the base of complex
of suitability criteria, evaluation of cloud coordinates and drift velocity

6 Taking decision on cloud seeding

7 Execution of cloud seeding

8 Operational control of seeding efficiency

Aircraft Ground radar Rain-gage network

Sequence of operations in the aircraft work on cloud seeding

Russian-Syrian Project
1991 - 2000

Operational precipitation enhancement project in Syria

The area of the Project -- whole territory of Syria (about 185000 km^2).

The work under the Project was done in four stages:

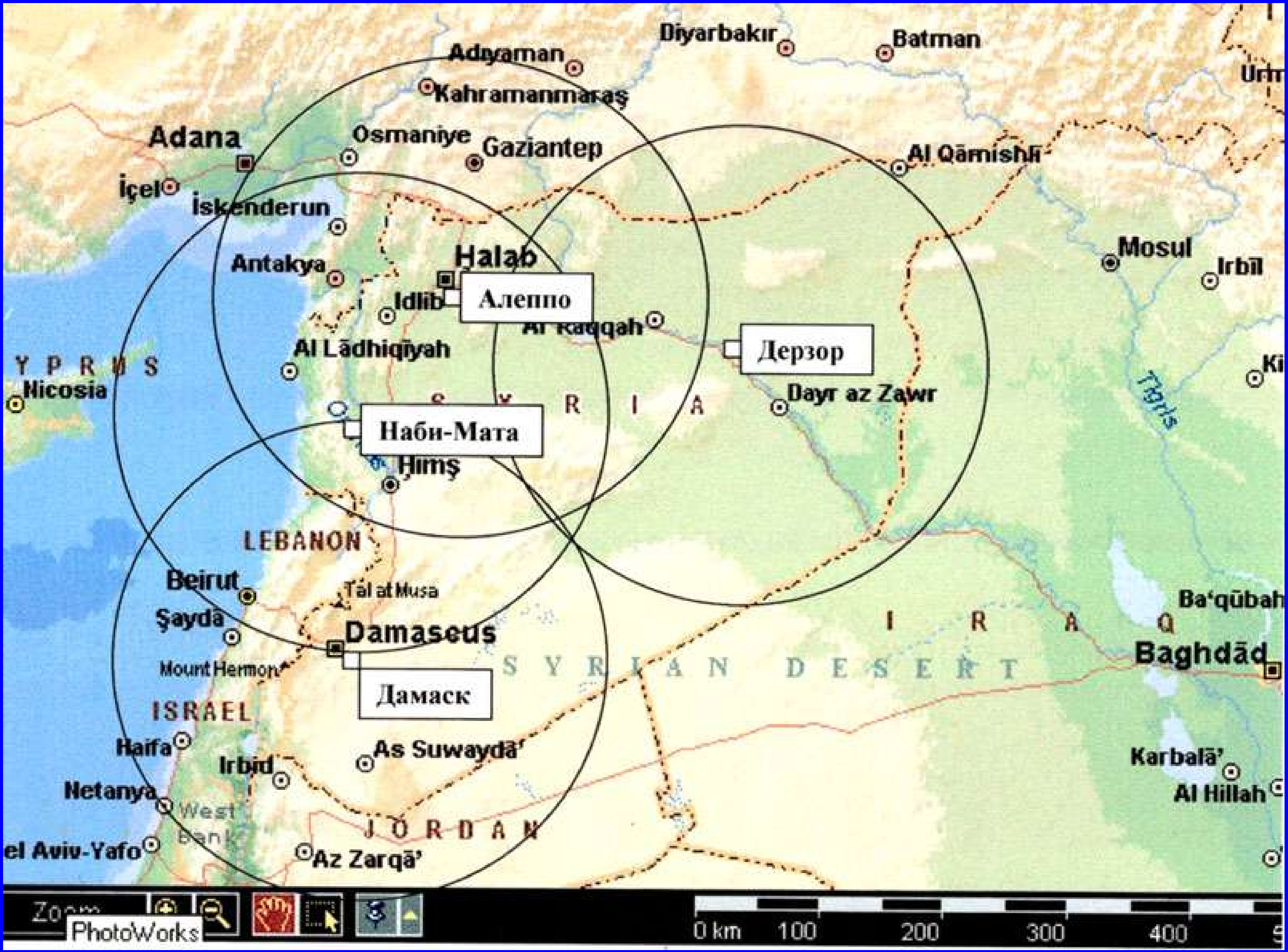
1. Demonstration: April-May 1991
2. One-year project: Winter 1991-1992
3. Five-year project: 1992-1997
4. Metodical supervision: 1997-2000.

Precipitation amount in km^3 over the whole territory of Syria for 4-month period (December-March)

Blue Triangles – for one season

Red Squares - mean value for two adjacent seasons

Straight line – rectilinear trend (decrease by 5.5 km^3 or 14% for 32
)


Алеппо
Дерзор
Наби-Мата
Дамаск
Diyarbakır
Batman
Adıyaman
Kahramanmaraş
Adana
Osmaniye
Gaziantep
Al Qāmishlī
İçel
İskenderun
Halab
Antakya
Idlib
Mosul
Irbīl
Al Raqqah
Al Lādhiqīyah
Nicosia
SYRIA
Dayr az Zawr
Tigris
Ḩimş
LEBANON
Beirut
Tal at Musa
Şaydā
Damascus
Mount Hermon
SYRIAN DESERT
IRAQ
Baghdād
Ba'qūbah
ISRAEL
Haifa
Irbid
As Suwaydā'
Karbalā'
Al Hillah
Netanya
West Bank
JORDAN
Tel Aviv-Yafo
Az Zarqā'
Zoom
PhotoWorks
0 km
100
200
300
400

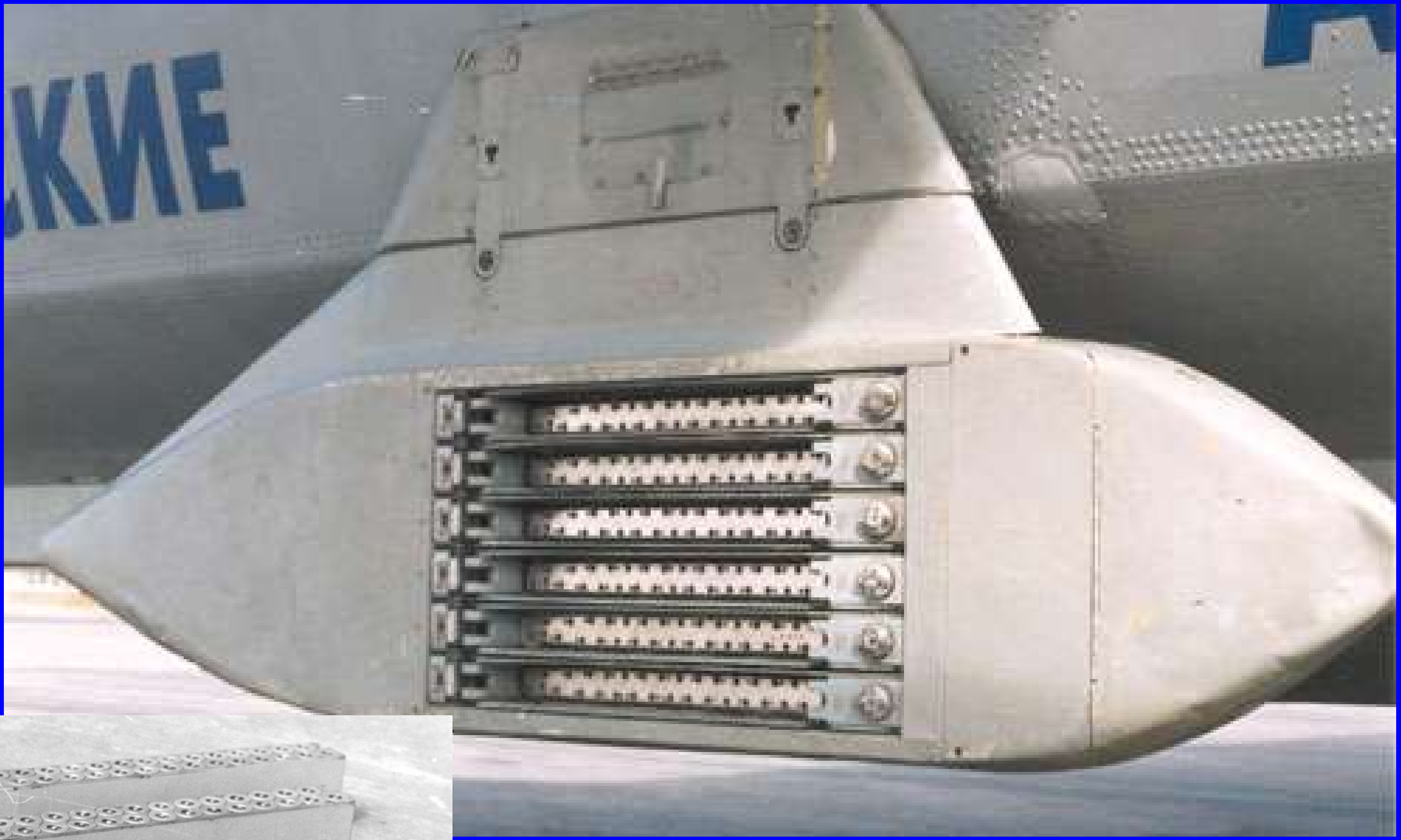
Aircraft-meteolaboratory IL-18 “Cyclon”

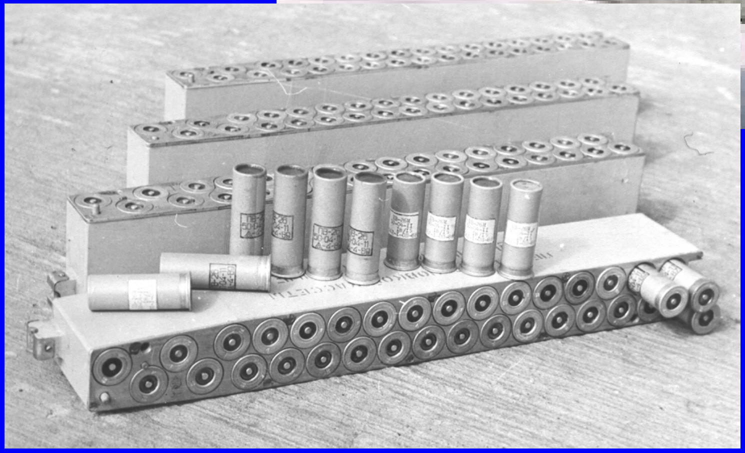
Seeding aircraft AN-12

Aircraft-meteolaboratory AN-26

Aircraft-meteolaboratory YAK-40

Pyrotechnical flares PV-50

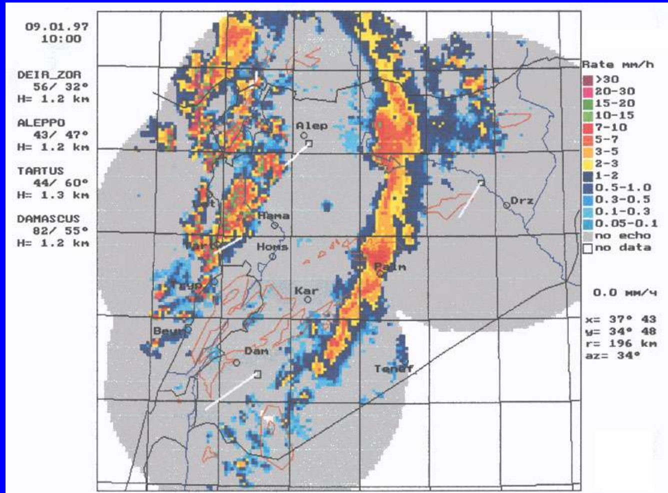
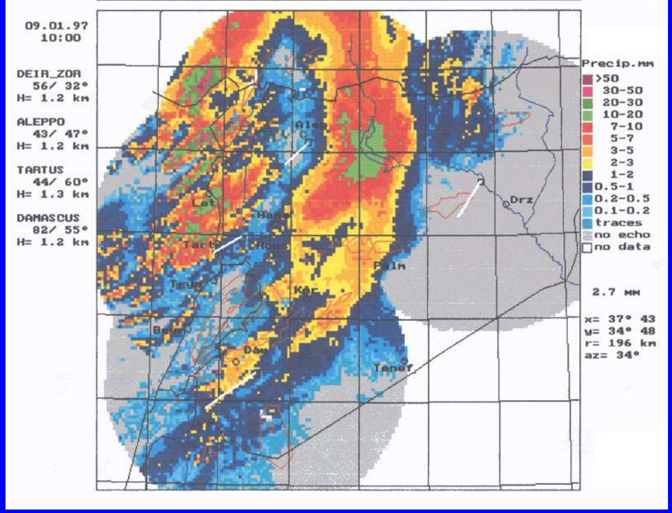




System for releasing pyrotechnical cartridges PV-26 installed on AN-26 aircraft.

Equipment for measurement of cloud parameters

Meteorological radar MRL-5


09.01.97
10:00
DEIR_ZOR
56/ 32°
H= 1.2 km
ALEPPO
43/ 47°
H= 1.2 km
TARTUS
44/ 60°
H= 1.3 km
DAMASCUS
82/ 55°
H= 1.2 km
Rate mm/h
>30
20-30
15-20
10-15
7-10
5-7
3-5
2-3
1-2
0.5-1.0
0.3-0.5
0.1-0.3
0.05-0.1
no echo
no data
0.0 mm/ч
x= 37° 43
y= 34° 48
r= 196 km
az= 34°
Alep
Hama
Homs
Kar
Palm
Dam
Tenef
Drz
Lat
Tryp
Beyr

09.01.97
10:00
DEIR_ZOR
56/ 32°
H= 1.2 km
ALEPPO
43/ 47°
H= 1.2 km
TARTUS
44/ 60°
H= 1.3 km
DAMASCUS
82/ 55°
H= 1.2 km
Precip.mm
>50
30-50
20-30
10-20
7-10
5-7
3-5
2-3
1-2
0.5-1
0.2-0.5
0.1-0.2
traces
no echo
no data
2.7 mm
x= 37° 43
y= 34° 48
r= 196 km
az= 34°
Alep
Hama
Homs
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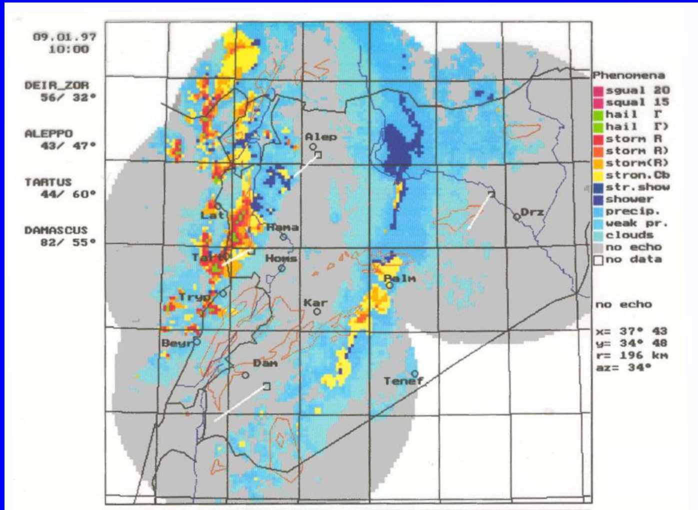
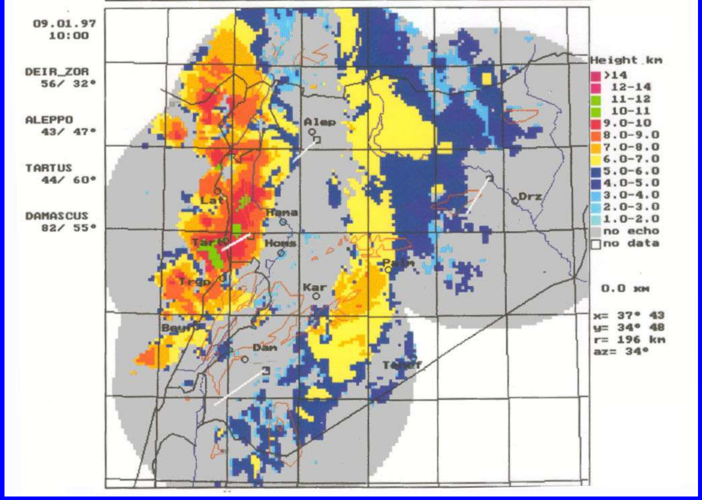
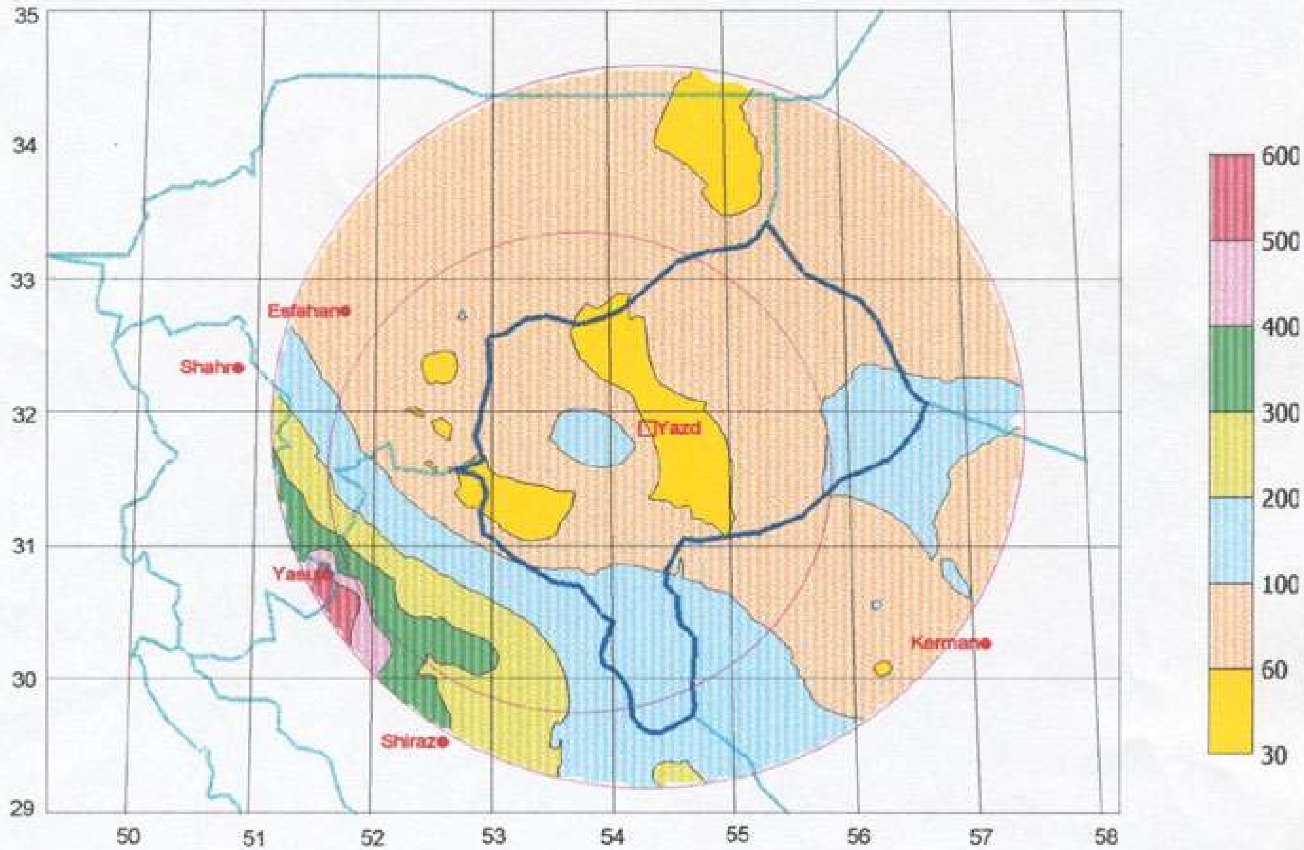
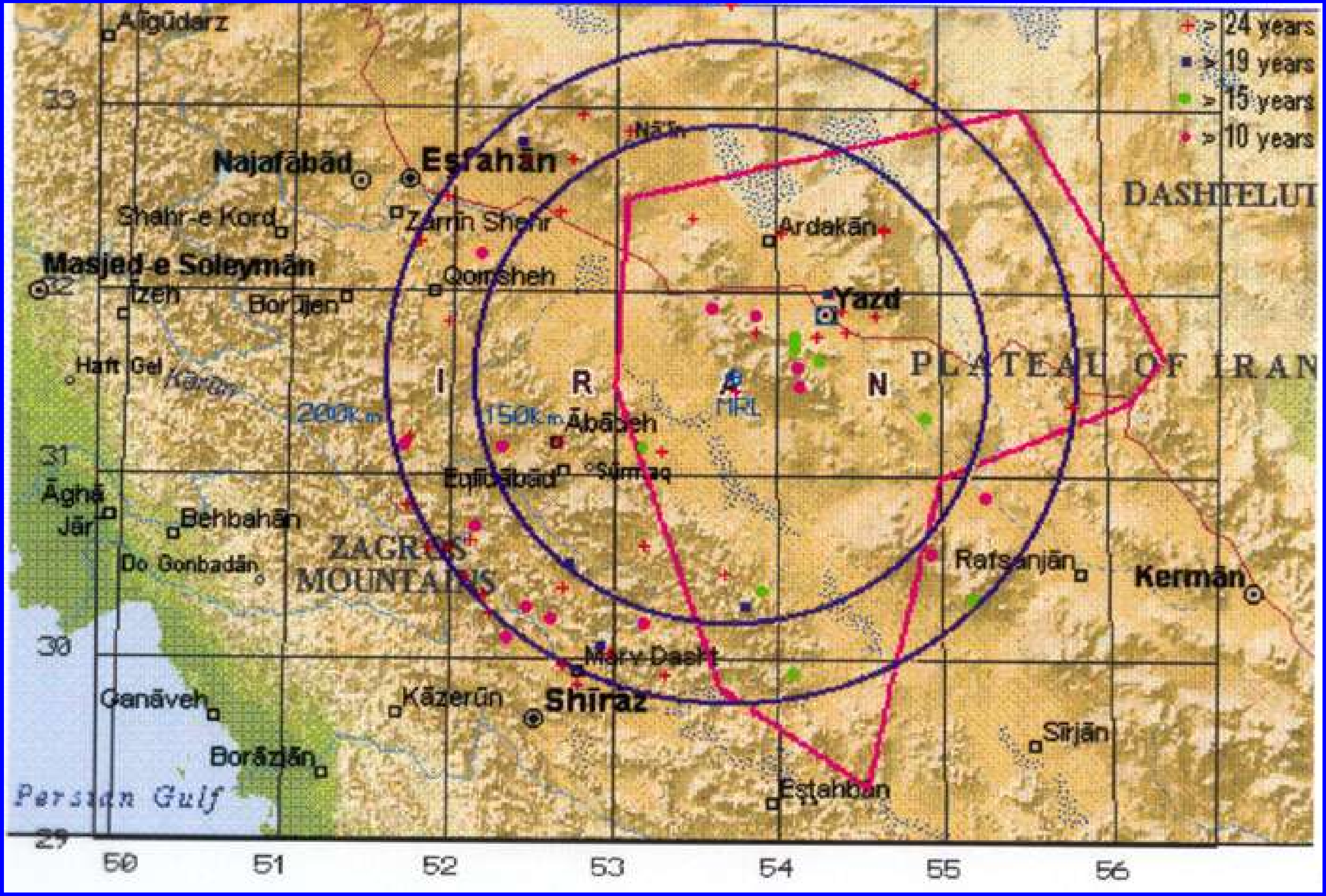

09.01.97
10:00
DEIR_ZOR
56/ 32°
ALEPPO
43/ 47°
TARTUS
44/ 60°
DAMASCUS
82/ 55°
Phenomena
squal 20
squal 15
hail Г
hail Г)
storm R
storm R)
storm(R)
stron.Cb
str.show
shower
precip.
weak pr.
clouds
no echo
no data
no echo
x= 37° 43
y= 34° 48
r= 196 km
az= 34°
Alep
Hama
Homs
Kar
Palm
Dam
Tenef
Drz
Lat
Tart
Tryp
Beyr

09.01.97
10:00
DEIR_ZOR
56/ 32°
ALEPPO
43/ 47°
TARTUS
44/ 60°
DAMASCUS
82/ 55°
Height km
>14
12-14
11-12
10-11
9.0-10
8.0-9.0
7.0-8.0
6.0-7.0
5.0-6.0
4.0-5.0
3.0-4.0
2.0-3.0
1.0-2.0
no echo
no data
0.0 km
x= 37° 43
y= 34° 48
r= 196 km
az= 34°
Alep
Hama
Homs
Kar
Palm
Dam
Tenef
Drz
Lat
Tart
Tryp
Beyr

Efficiency of cloud seeding in Russian-Syrian project

Season	Actual precipitation km^3	Estimated precipitation km^3	Effect km^3	Effect %
1991-1992	33,857	29,073	4,784	16,5
1992-1993	28,814	24,731	4,083	16,5
1993-1994	30,246	27,077	3,169	11,7
1994-1995	14,058	13,152	0,906	6,9
1995-1996	36,607	34,023	2,584	7,6
1996-1997	37,769	35,150	2,619	7,5
1997-1998	33,682	32,132	1,550	4,8
1998-1999	24,014	21,900	2,114	9,7
1999-2000	25,002	21,773	3,229	14,8

Map of seasonal distribution of precipitation amounts over the project area.
Iran, January - April, 1973 - 1998.



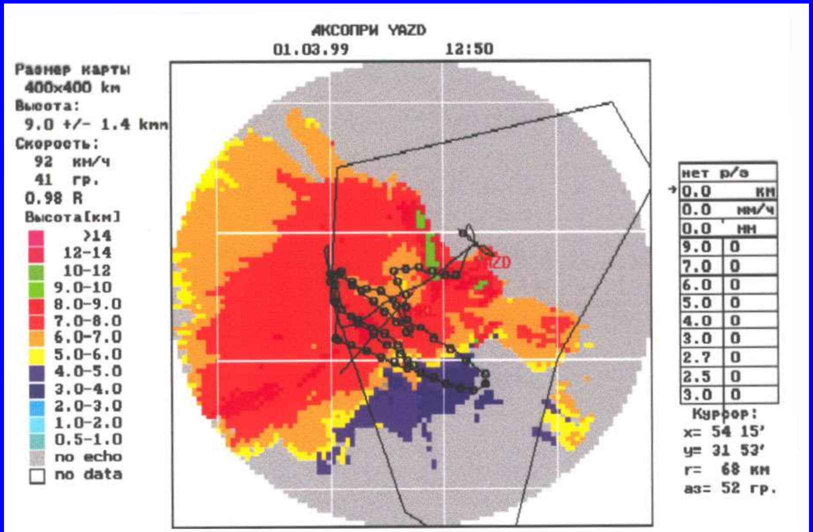


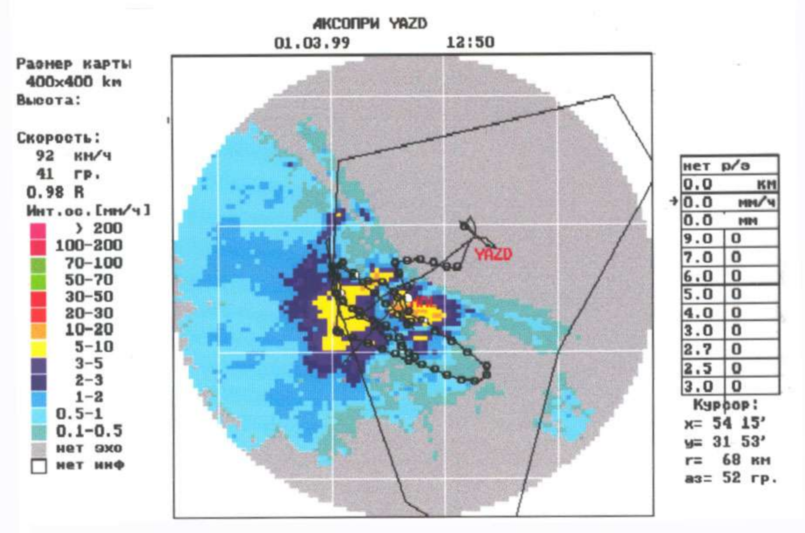
> 24 years
> 19 years
> 15 years
> 10 years
Alīgūdarz
Najafābād
Esfahān
Nā'īn
Shahr-e Kord
Zarrīn Shahr
Ardakān
Masjed-e Soleymān
Qomsheh
Īzeh
Borūjen
Yazd
Haft Gel
Kārūn
I
R
A
N
MRL
PLATEAU OF IRAN
DASHTELUT
200km
150km
Ābādeh
Eqlīdābād
Sūrmaq
Āghā Jārī
Behbahān
ZAGROS MOUNTAINS
Do Gonbadān
Rafsanjān
Kermān
Marv Dasht
Ganāveh
Kāzerūn
Shīrāz
Sīrjān
Borāzjān
Estahbān
Persian Gulf
33
31
30
29
50
51
52
53
54
55
56

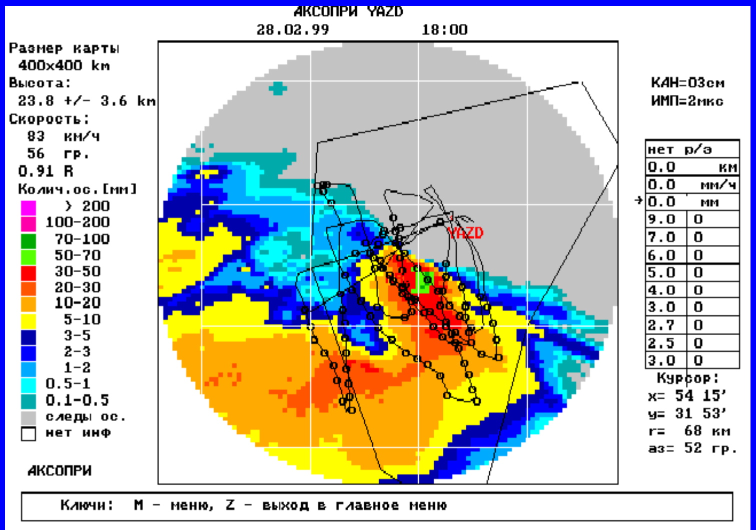
Aircraft-meteolaboratory AN-30 is equipped by measuring-computational complex and technical means for cloud seeding by silver iodide and liquid nitrogen

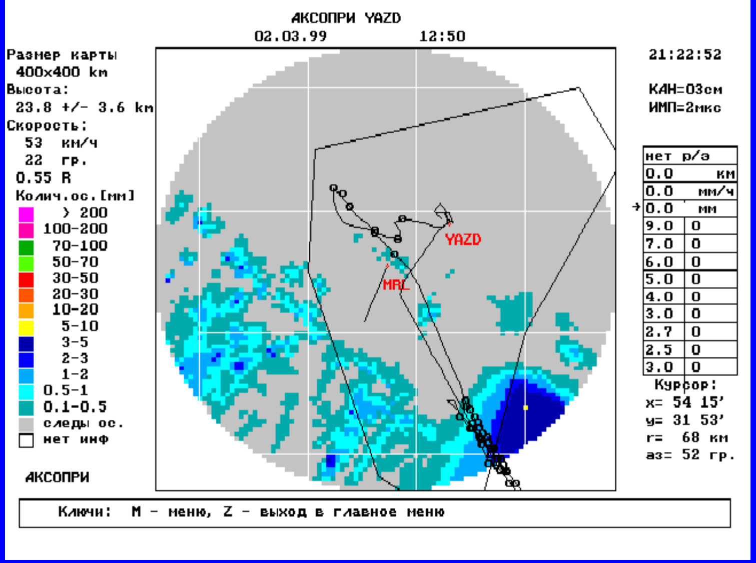
Aircraft liquid nitrogen generator of ice particles

Automated weather radar complex AKSOPRI-E


АКСОПРИ YAZD
01.03.99 12:50
Размер карты
400x400 km
Высота:
9.0 +/- 1.4 km
Скорость:
92 км/ч
41 гр.
0.98 R
Высота[км]
>14
12-14
10-12
9.0-10
8.0-9.0
7.0-8.0
6.0-7.0
5.0-6.0
4.0-5.0
3.0-4.0
2.0-3.0
1.0-2.0
0.5-1.0
no echo
no data
YAZD
нет р/э
0.0 км
0.0 мм/ч
0.0 мм
Курсор:
x= 54 15'
y= 31 53'
r= 68 км
аз= 52 гр.


АКСОПРИ YAZD
01.03.99 12:50
Размер карты
400x400 km
Высота:
Скорость:
92 км/ч
41 гр.
0.98 R
Инт.ос.[мм/ч]
> 200
100-200
70-100
50-70
30-50
20-30
10-20
5-10
3-5
2-3
1-2
0.5-1
0.1-0.5
нет эхо
нет инф
YAZD
нет р/э
0.0 км
0.0 мм/ч
0.0 мм
Курсор:
x= 54 15'
y= 31 53'
r= 68 км
аз= 52 гр.


АКСОПРИ YAZD
28.02.99 18:00
Размер карты
400x400 km
Высота:
23.8 +/- 3.6 km
Скорость:
83 км/ч
56 гр.
0.91 R
Колич.ос.[мм]
> 200
100-200
70-100
50-70
30-50
20-30
10-20
5-10
3-5
2-3
1-2
0.5-1
0.1-0.5
следы ос.
нет инф
АКСОПРИ
YAZD
КАН=03см
ИМП=2мкс
нет р/э
0.0 км
0.0 мм/ч
0.0 мм
Курсор:
x= 54 15'
y= 31 53'
r= 68 км
аз= 52 гр.
Ключи: М - меню, Z - выход в главное меню


АКСОПРИ YAZD
02.03.99 12:50
21:22:52
Размер карты
400x400 km
Высота:
23.8 +/- 3.6 km
Скорость:
53 км/ч
22 гр.
0.55 R
Колич.ос.[мм]
> 200
100-200
70-100
50-70
30-50
20-30
10-20
5-10
3-5
2-3
1-2
0.5-1
0.1-0.5
следы ос.
нет инф
АКСОПРИ
YAZD
КАН=03см
ИМП=2мкс
нет р/э
0.0 км
0.0 мм/ч
0.0 мм
Курсор:
x= 54 15'
y= 31 53'
r= 68 км
аз= 52 гр.
Ключи: М - меню, Z - выход в главное меню

Evaluation of efficiency of cloud seeding for precipitation enhancement on the Project territory in Iran in 1999 - 2001

Season	Actual precip., Km cub.	Evaluated precip., Km cub.	Effect, Km cub.	Effect, %
1999	8.34	6.48	1.86	28.7
2000	2.46	1.75	0.71	40.3
2001	9.08	7.43	1.65	22.2

Improving weather conditions and flush flood control

Throughout the half-century history of the artificial modification of hydrometeorological processes, which is an important direction in experimental meteorology, the focus of attention has been on designing techniques and technical aids to dissipate clouds and fogs, as well as to prevent or reduce precipitation.

- **In particular, it is practicable to carry out artificial weather modification operations aimed at:**
- **A. Dissipation of stratiform clouds.**
- **B. Destruction of cumulonimbus clouds by a dynamic technique in order to prevent shower rains and thunderstorms.**
- **C. Inducing an early fall out of precipitation from cloud systems on the windward side of a target area through artificial seeding of these cloud systems, which leads to the formation of a ‘shadow‘ of precipitation, i.e. to precipitation reduction over the given site.**
- **D. Intensive seeding of perceptible clouds, aimed at weakening the mechanism of precipitation generation through the ‘overseeding’ of cloud layers, i.e.**

Improving weather conditions

- The feature that the first and the last two have in common is the use of ice-producing agents (“dry ice” and liquefied nitrogen) and aerosols (silver iodide).

- The effect of dry ice pellets and liquefied nitrogen is due to an abrupt decrease of the ambient temperature in the immediate vicinity of their granules and drops, which results in forming a multitude of ice crystals.

- Microscopic particles of silver iodide serve as crystallization nuclei on which ice crystals form and then solid hydrometeors (snowflakes and graupel) grow to fall out as precipitation.

Improving weather conditions

- To crystallize one cubic km of supercooled cloud, it is usually enough to seed it by several hundred grams of dry ice or several grams of silver iodide. After seeding a cloud or fog by ice particles in favorable conditions an intensive cloud crystallization process begins, and in 5-10 minutes ice crystals are observed to fall out of the cloud.
- In this case, one passage of a seeding airplane results in producing a dissipation zone with an average 3-5 km width.
- The full clearing of the target site from cloud drops and precipitation particles occurs in 35-50 minutes after seeding.

Improving weather conditions

- The methods to destroy developing convective clouds differing in intensity, from cumulus congestus to cumulonimbus, using a dynamic technique, i.e. artificially generated downdrafts, were theoretically justified by scientists from the Russian Institute of Applied Geophysics and thoroughly tested under laboratory and field conditions by specialists from the CAO.

- It has been found out that downdrafts in the upper cloud part can be produced by an artificial air jet directed downward, through seeding powders or dispersing water mass in it.

- Also, downdrafts in a cumulonimbus congestus can be generated by enhancing precipitation falling into them from aloft.

Improving weather conditions

- The dynamic destruction of cumulonimbi through seeding their tops by powdery material has proved sufficiently effective.
- Thus, the seeding of single-cell isolated air-mass clouds and frontal clouds accounts for a 90% and 60-65% score, respectively.
- The seeding of 30 kg or more of coarse-dispersion powders (per cloud top) resulted in the destruction of single-cell isolated clouds within 10-20 minutes and frontal ones within 30-35 minutes.

Improving weather conditions

- The other two methods out of the four mentioned at the beginning of this section use weather modification techniques similar to that employed in the first method aimed at the dissipation of clouds and fogs.
- The zone of reduced precipitation is commonly referred to as “precipitation shadow”.
- In both cases it is possible to estimate the distance of advance seeding relative to the protected territory so as to prevent undesirable clouds and precipitation from reaching it.

Improving weather conditions

- The fourth approach to the problem is advisable to employ when frontal clouds are oncoming. On the windward side of this territory, supercooled cloud layers are continuously seeded by increased doses of ice-producing agents until precipitation in this area ceases or is noticeably reduced.

- Overseeding, i.e., producing ice crystals inside clouds in concentrations many times those of naturally generated ice, brings about a situation an abrupt increase of the number of simultaneously growing precipitation particles is accompanied by a marked slowdown in their growth and a reduction of their falling speed. This, in turn, leads to noticeable temporary reduction of precipitation.

Improving weather conditions

- In some synoptic situations, overseeding may prove to be the most appropriate procedure. This is due to its capability to reduce precipitation significantly and to its faster action facilitating the production of an artificial crystallization zone (with reduced or no precipitation) over a protected territory, which is especially important in conditions of a complex and variable wind field.
- In cloud overseeding operations, the distance of seeding paths from the borders of a protected territory is chosen so as to be approximately the same as the distance of a half-hour or one-hour wind transport of clouds.

Improving weather conditions

- The methods described can be applied with the help of instrumented aircrafts. Instrumentation includes systems to release pyrotechnic flares, devices to seed granulated dry ice, generators of ice particles, using liquefied nitrogen, and systems to introduce 25-30-kg powdery material packages which open automatically after their release.

- All the procedures and technical aids described above were employed successfully in the activities associated with eliminating the consequences of Chernobyl disaster and improving weather condition in Moscow (November 7, 1986; May 8-9, 1995; September 5-7, 1997; July 13 and 19, 1998; May 9, 2000; September 2-3, 2000; September 1-2, 2001; June 12 and 15, 2002; August 31 and September 1, 2002), Tashkent (1994-2002), and Astana (June 9-10, 1998).

Russian research aircraft ILYUSHIN-18

The main specification of ILYUSHIN-18 aircraft:

- **-flight level range: ……………………………. from <u>50 to 10,000 m;</u>**
- **-working speed range: ……………………….. from <u>350 to 650 km/h</u>;**
- **-maximum duration of the flight: …………… <u>8 hours</u>;**
- **-fuel consumption: ……………………………. <u>2.5 tons per hour</u>;**
- **-maximum start mass: ……………………………. <u>64,000 kg</u>;**

Aboard instruments

1. Gust probe system
   - -Inertial Navigation System;
   - -Global Positioning System GPS;
   - -Pitot Tube, static and dynamic pressure sensors;
   - -High response temperature sensor (designed in CAO);
   - -Spherical pressure probe (designed in CAO) and differential pressure sensor;
   - -Gyrovertical;
   - -Vertical accelerometer mounted on the gyroplatform;
   - -Board recording computer DEC.

2. Particle Measuring System PMS
   - -Sensor FSSP-100;
   - -Sensor OAP2D2;
   - -Sensor PCASP-100x;
   - -Data acquisition system.

3. Clouds measuring system
   - -Water content gauge (designed in CAO);
   - -Spectrometer of large cloud particles (designed in CAO);
   - -Gauge of cloud limpidity (designed in CAO).

4. Air humidity measuring system
   - -Aircraft Condensation Hygrometer (designed in CAO);
   - -Ultraviolet Hygrometer (designed in CAO).

5. Radiometric instruments
   - -Net radiometer CNR-1;
   - -Microwave 3-mm radiometer (designed in CAO);
   - -Microwave 8-mm radiometer (designed in CAO);
   - -Aboard recording computer.

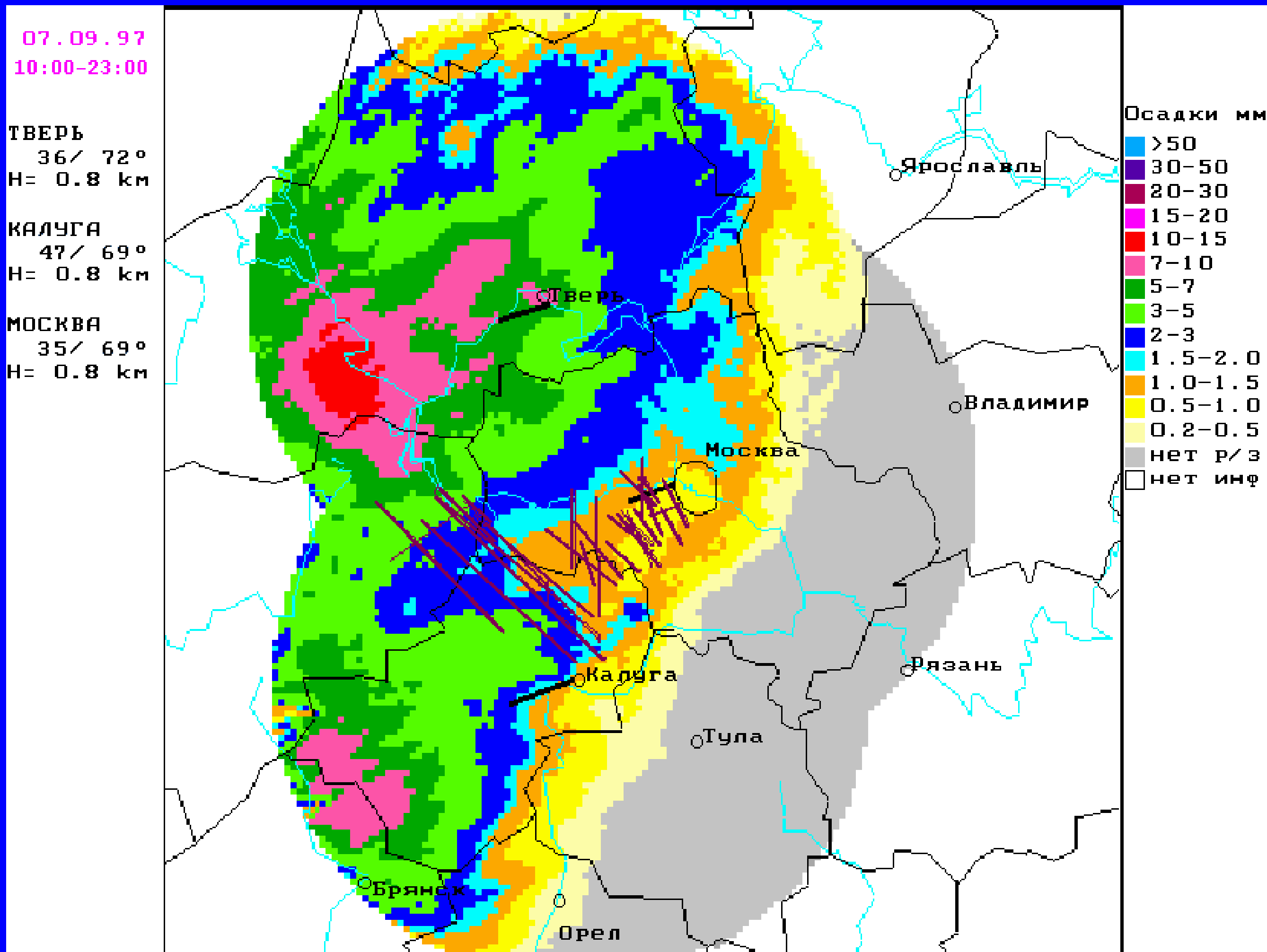
6. Thermodynamic measuring system
   - -Global Positioning System GPS;
   - -Doppler Navigation System;
   - -System of Air Signals;
   - -Temperature sensor;
   - -Aboard recording computer.

Stationary liquid nitrogen system for cold fog dissipation

Mobile liquid nitrogen system for cold fog dissipation

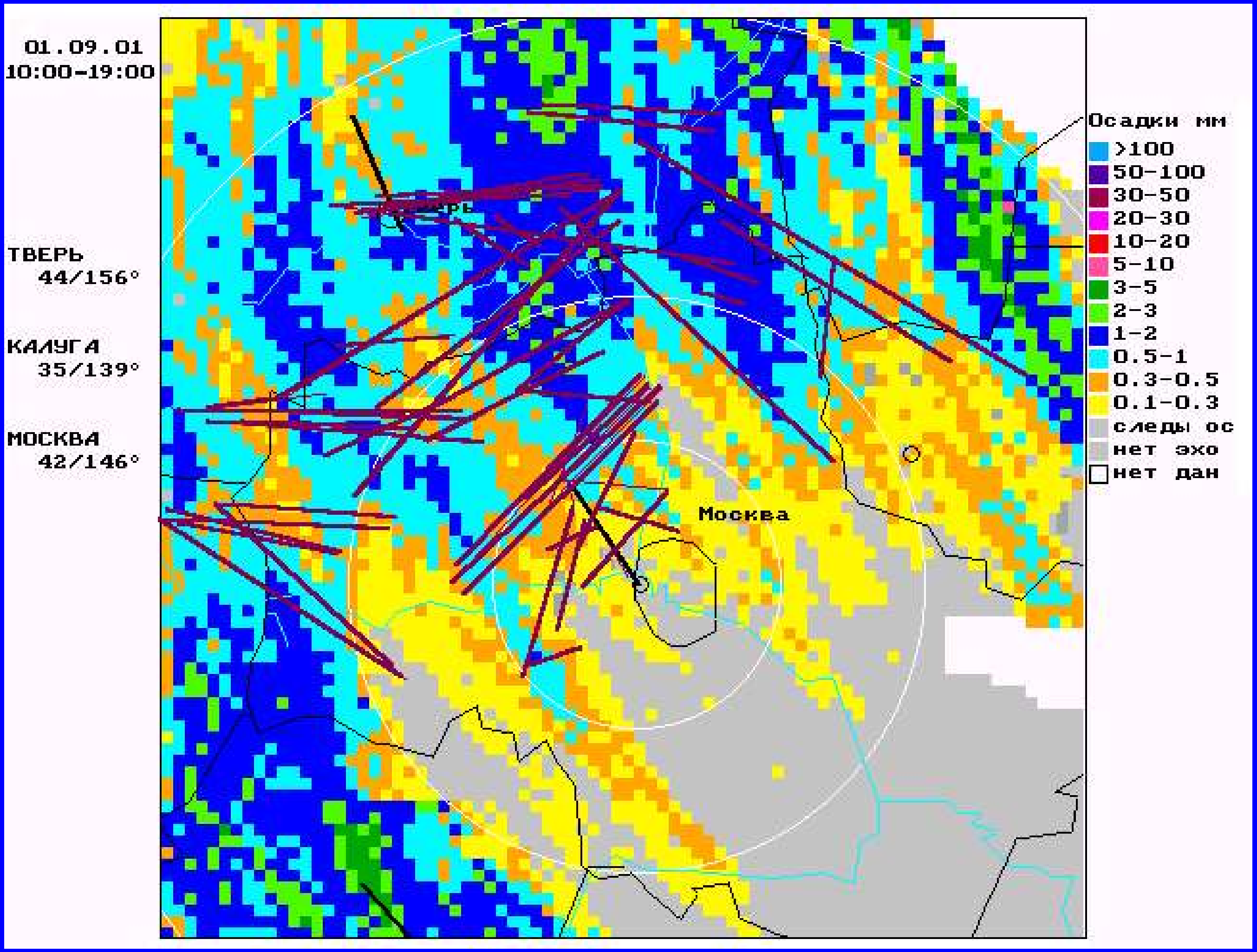

26 12 1999
7:15:09

Improving weather conditions



Results of improving weather conditions during festivities of the 850th anniversary of Moscow (7 September, 1997)

Improving weather conditions



Results of improving weather conditions during festivities to mark Moscow Day (1 September, 2001)

Entry of silver to natural environment (tons/year) from the weather modification activities

Environment	Place/Time of investigations	Background concentration of Ag	Concentration of Ag after weather modification	Maximum concentration limit
Air	URSS (Moldavia) 1984-1987	0.014 mcg / м^{3}	0.015 mcg / м^{3}	10 mcg / м^{3}
Reservoires	URSS (Moldavia) 1983-1987	2.75 mcg / l	2.6 mcg / l	50 mcg / l
Soil	USA SAN JOAN ECOLOGY PROJECT	0.01 mcg / l	0.1-1 mcg / l	10 mcg / l
Precipitation	URSS (North Kavkaz) 1976-1988	0.01 mcg / l	0.1-1 mcg / l	50 mcg / l

Entry of silver to atmosphere (tons/year) from different pollution sources

Natural pollution sources				Anthropogenic pollution sources			
Wind soil erosion	Volcanoes eruption	Cosmic dust	Transfer from ocean	Forest fires	Thermo-electric power stations	Industry, transport	Weather modifi-cation
50	10	0.09	10	80	800	1400	10