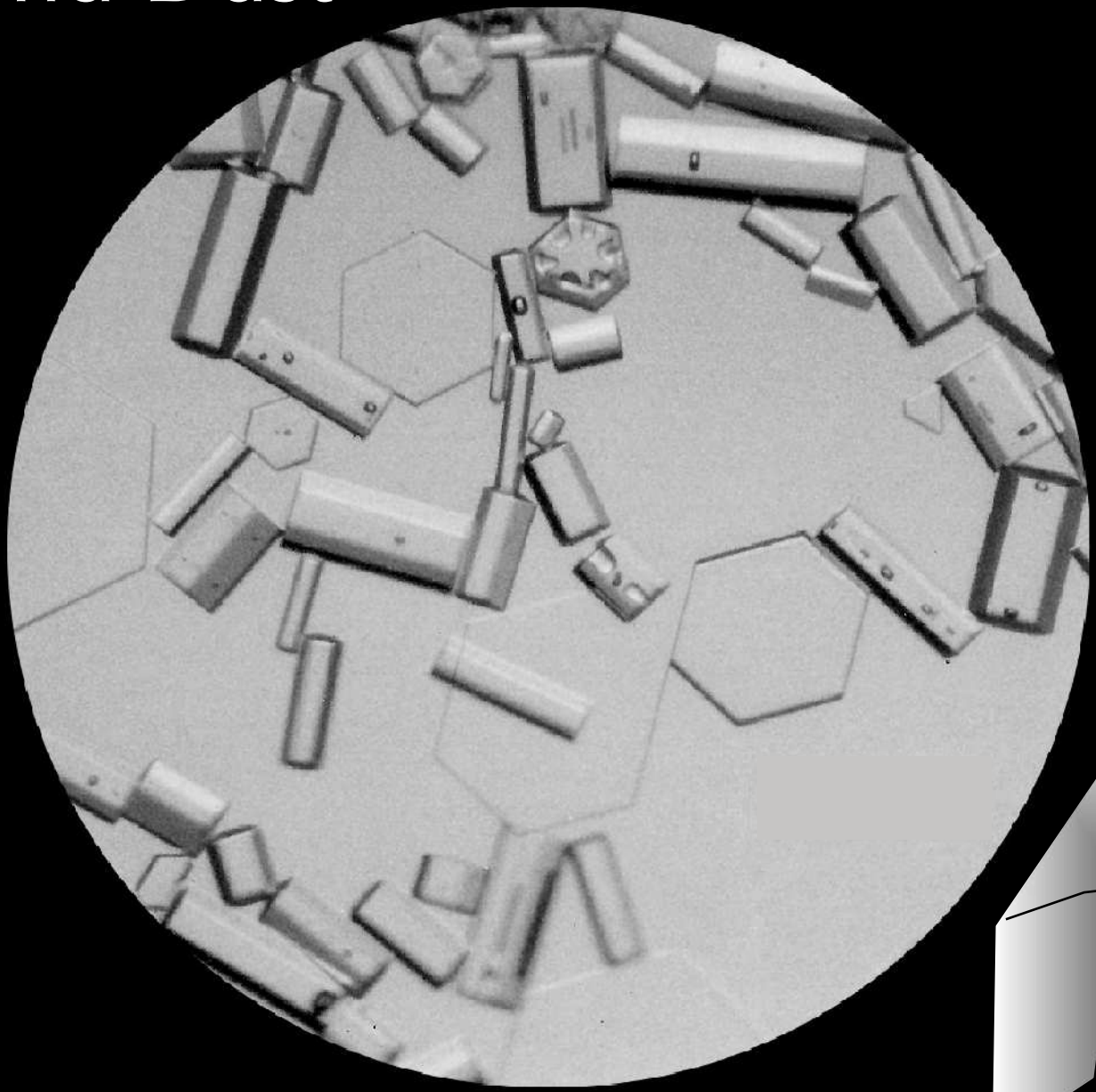
Tiny Crystals—Global Impact

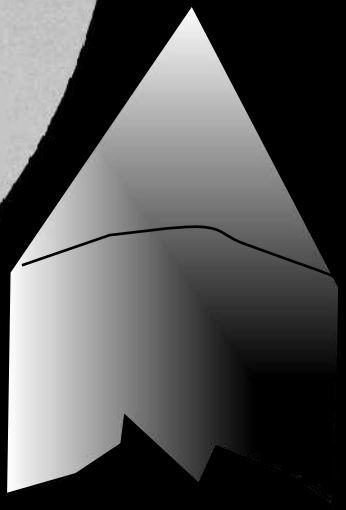
Why Snow Matters to You!

Dr. Matthew Sturm

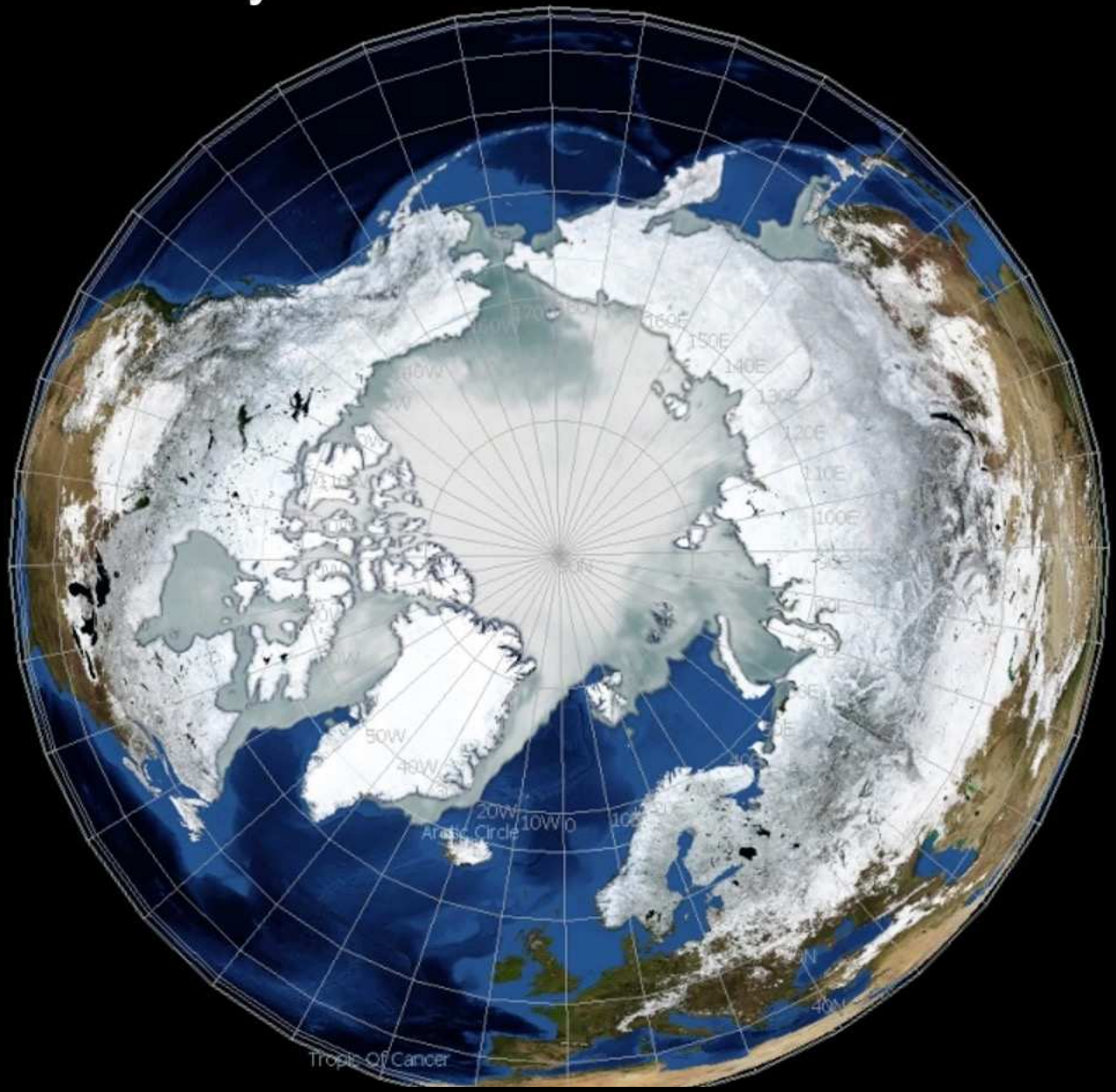
OMSI Science Pub-February 1, 2022

Diamond Dust





January



Max. 48 million square kilometers= 12 billion acres

First, a recent personal connection to Oregon and snow.


Fairbanks: November 2021 in the depths of the pandemic.


Packed up the truck, pop-up camper, and the two dogs & headed to visit family in New Mexico
John Day Fossil Beds


Grand Coulee Dam


BRITISH COLUMBIA
ALBERTA
MONTANA
WASHINGTON
IDAHO
OREGON
WYOMING
NEVADA
UTAH
Pacific Ocean
Canoe
Kinbasket Lake
Columbia
Golden
Revelstoke
Invermere
Okanagan Lake
Nakusp
Kelowna
Duncan
Elk
Nelson
Cranbrook
Kootenay
Kettle
Castlegar
Trail
Okanogan
Methow
Pend Oreille
Flathead
Flathead Lake
Banks Lake
Spokane
Wenatchee
Crab
Yakima
Snake
Cowlitz
Clearwater
Missoula
Clark Fork
Yakima
Longview
Astoria
Lewis
Kennewick
Richland
Lewiston
St. Helens
Vancouver
Pendleton
Portland
The Dalles
Umatilla
Grande Ronde
Salem
Salmon
John Day
Willamette
Deschutes
Corvallis
Henrys Fork
Eugene
Bend
Malheur
Payette
Boise
Idaho Falls
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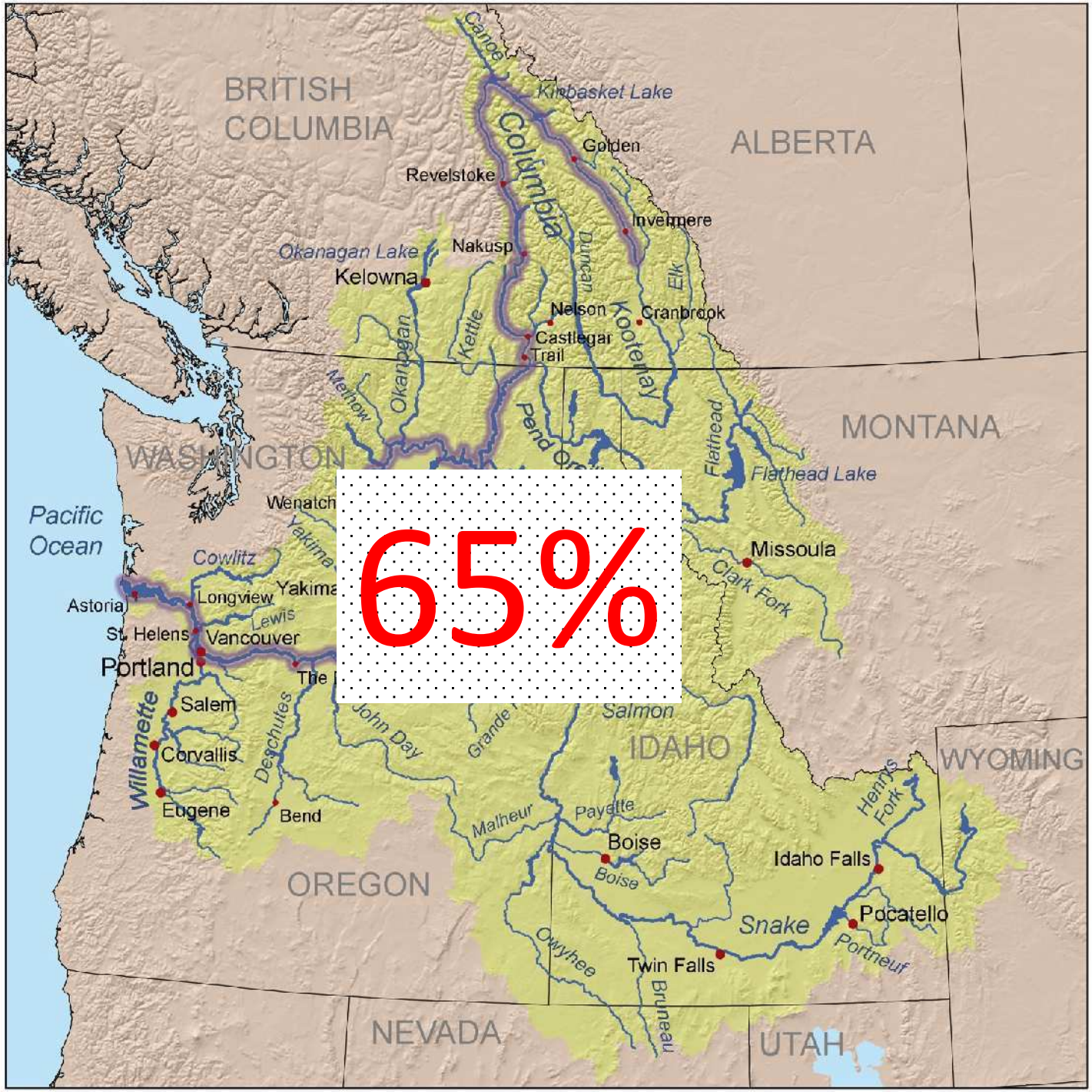
Tracking the Missoula Floods


A
Drumheller Channels National Natural Landmark


BRITISH COLUMBIA
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Pocatello
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Bruneau
65%

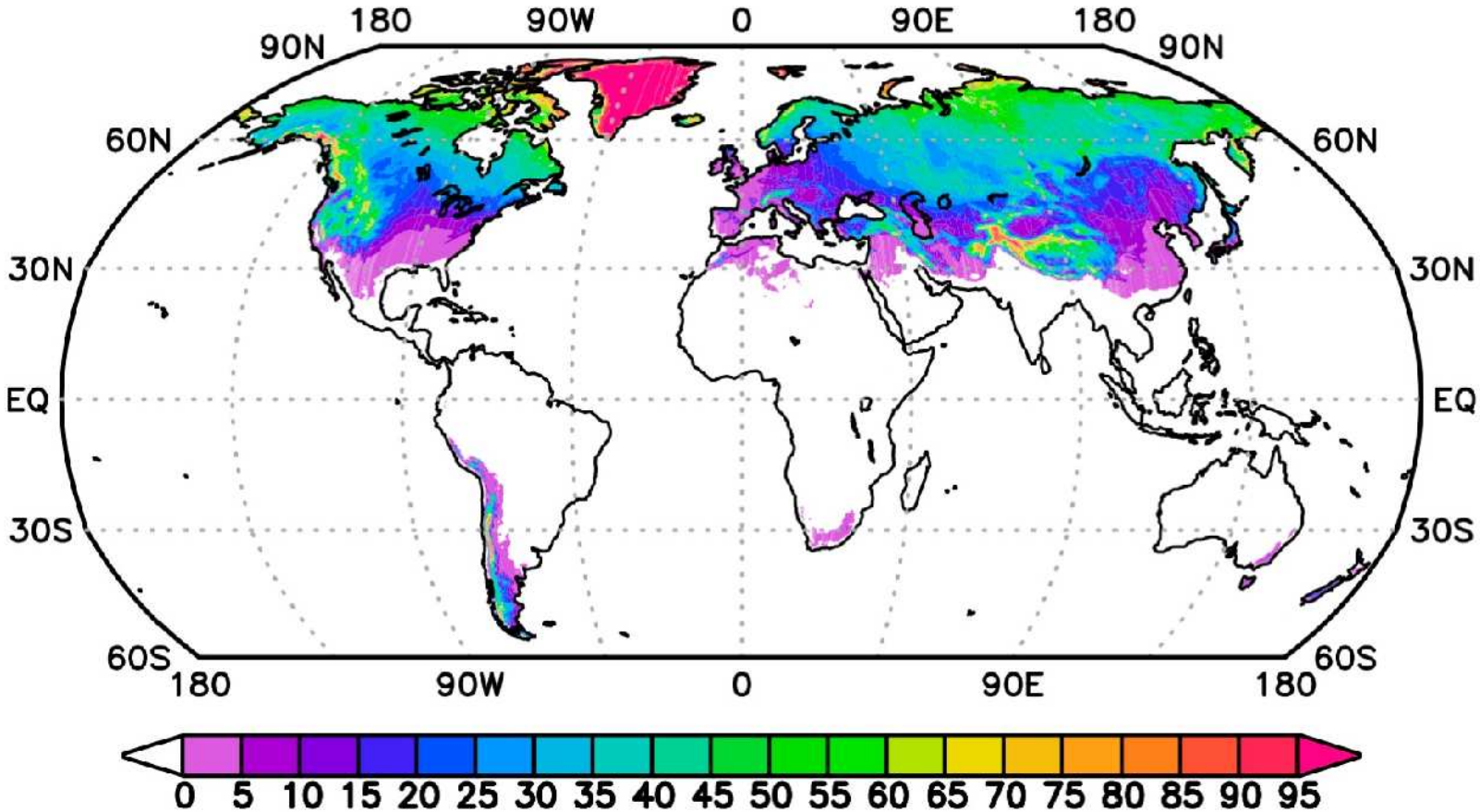


FIG. 3. Percentage of annual water-equivalent precipitation that falls as snow. Antarctica is mostly Ice and therefore not shown. These data were generated by creating annual averages of 39 years of monthly ERA5-Land water-equivalent snowfall and total precipitation data (see section 2b), calculating the ratio of the two variables, and multiplying by 100.

How much runoff originates as snow in the western United States, and how will that change in the future?

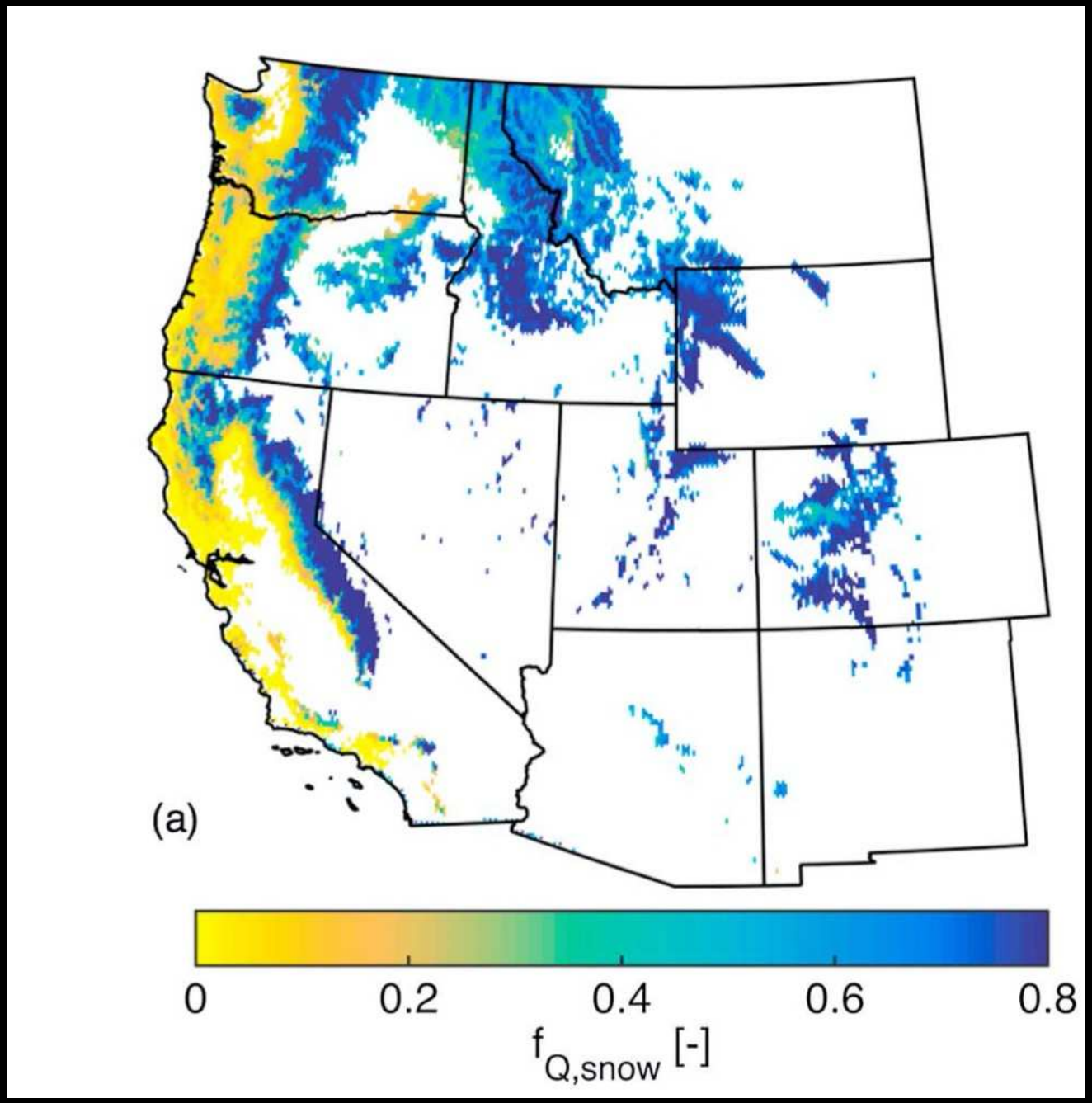
Dongyue Li[1,2], Melissa L. Wrzesien[1], Michael Durand[1], Jennifer Adam[3], and Dennis P. Lettenmaier[2]

[1]School of Earth Sciences and Byrd Polar and Climate Research Center, Ohio State University, Columbus, Ohio, USA, [2]Department of Geography, University of California, Los Angeles, California, USA, [3]Department of Civil and Environmental Engineering, Washington State University, Pullman, Washington, USA

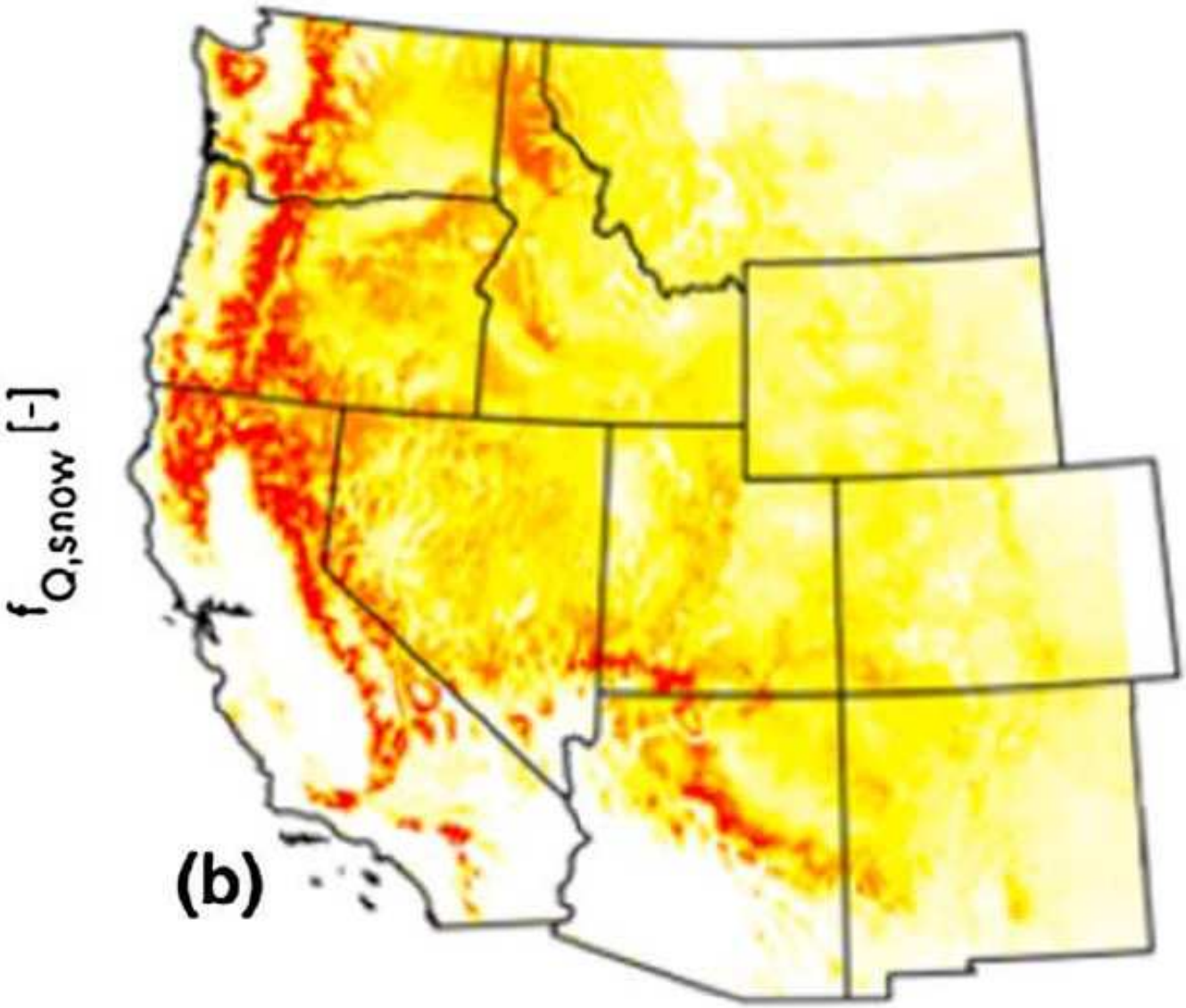
Abstract In the western United States, the seasonal phase of snow storage bridges between winter-dominant precipitation and summer-dominant water demand. The critical role of snow in water supply has been frequently quantified using the ratio of snowmelt-derived runoff to total runoff. However, current estimates of the fraction of annual runoff generated by snowmelt are not based on systematic analyses. Here based on hydrological model simulations and a new snowmelt tracking algorithm, we show that 53% of the total runoff in the western United States originates as snowmelt, despite only 37% of the precipitation falling as snow. In mountainous areas, snowmelt is responsible for 70% of the total runoff. By 2100, the contribution of snowmelt to runoff will decrease by one third for the western U.S. in the Intergovernmental Panel on Climate Change Representative Concentration Pathway 8.5 scenario. Snowmelt-derived runoff currently makes up two thirds of the inflow to the region's major reservoirs. We argue that substantial impacts on water supply are likely in a warmer climate.

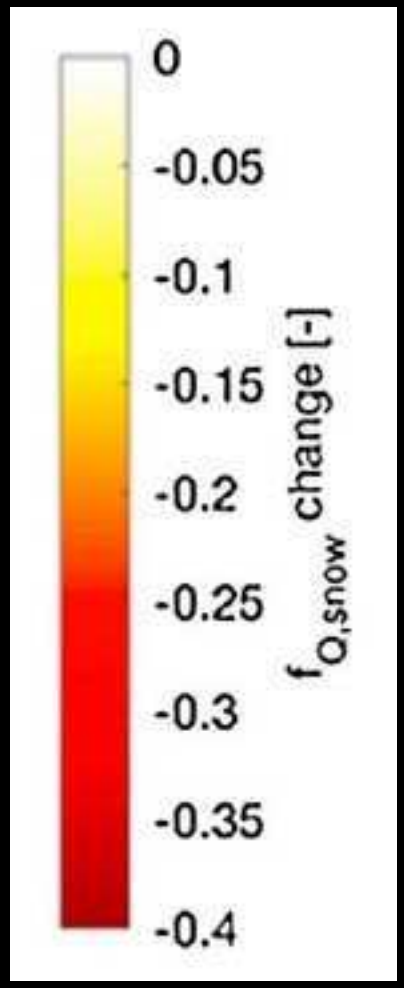
$f_{Q,\ snow}$

Fraction of precipitation that falls as snow

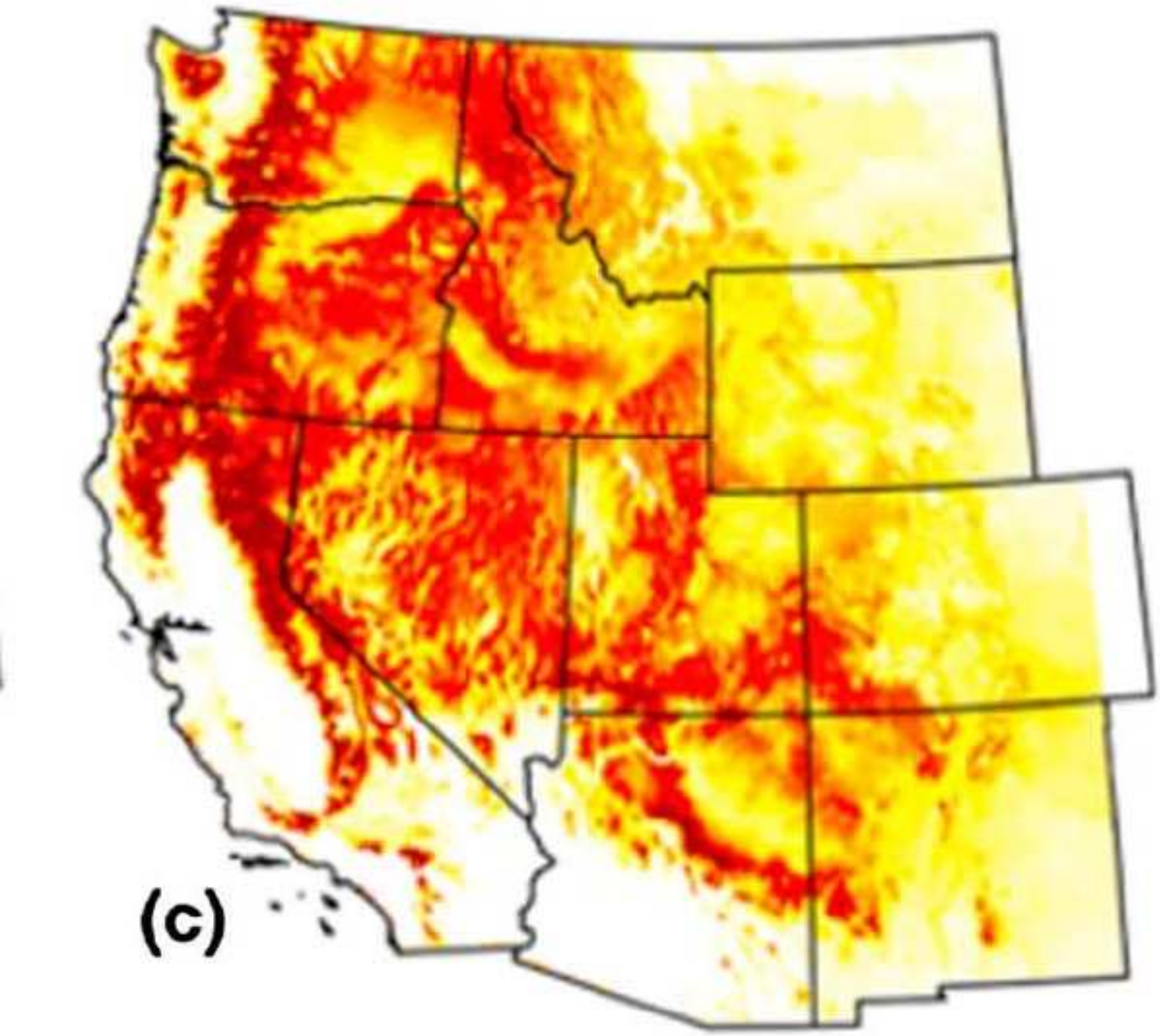


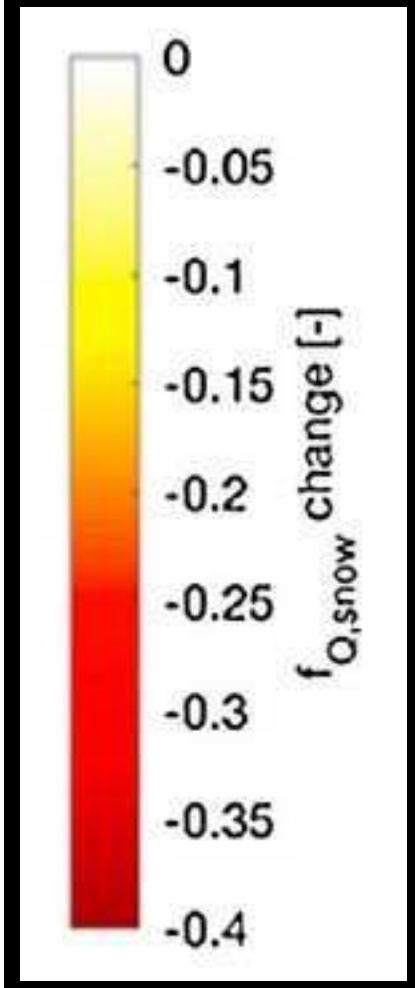
RCP4.5





RCP8.5





Upper Columbia

ANNUAL BASIN STATISTICS:

VOLUME OF RUNOFF FROM SNOW AND RAIN:

18.37M acre-feet

PERCENT OF RUNOFF FROM SNOW:

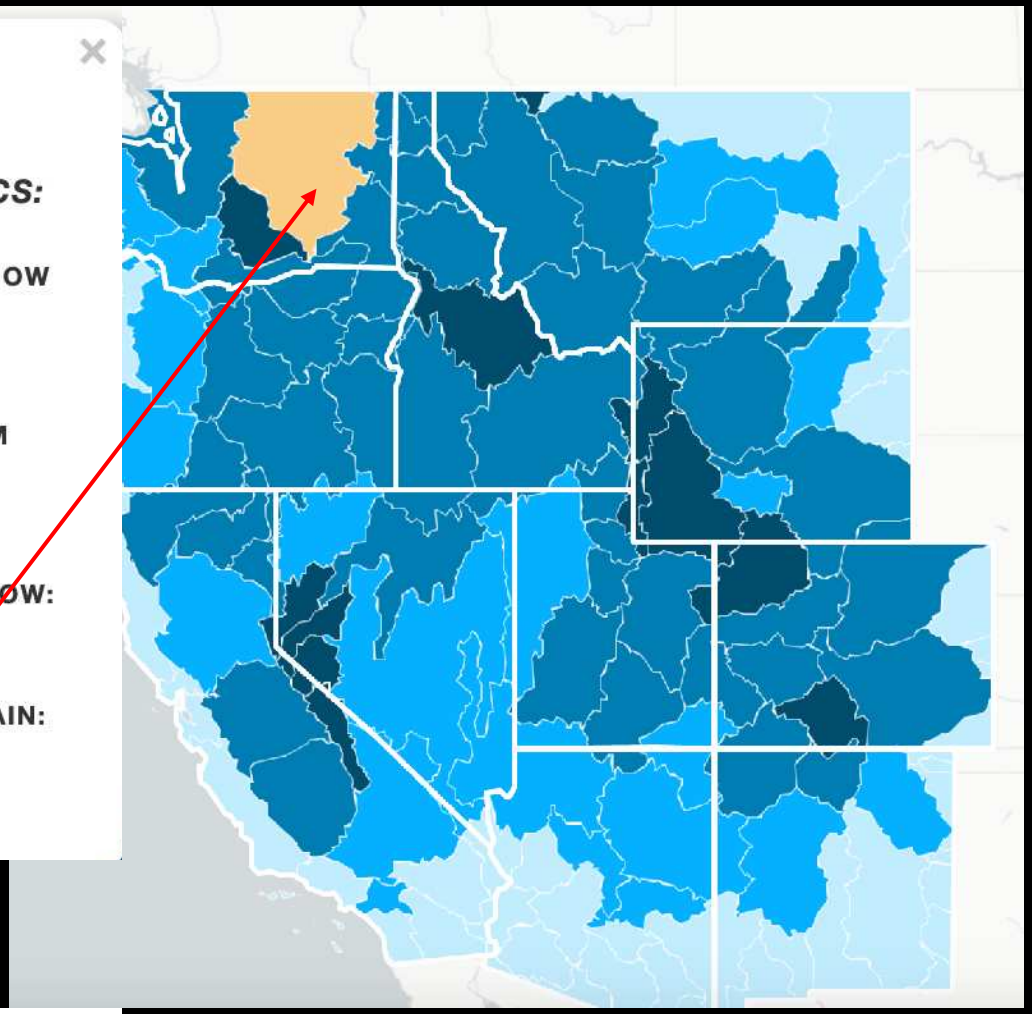
72.4%

VOLUME OF RUNOFF FROM SNOW:

13.29M acre-feet

VOLUME OF RUNOFF FROM RAIN:

5.08M acre-feet

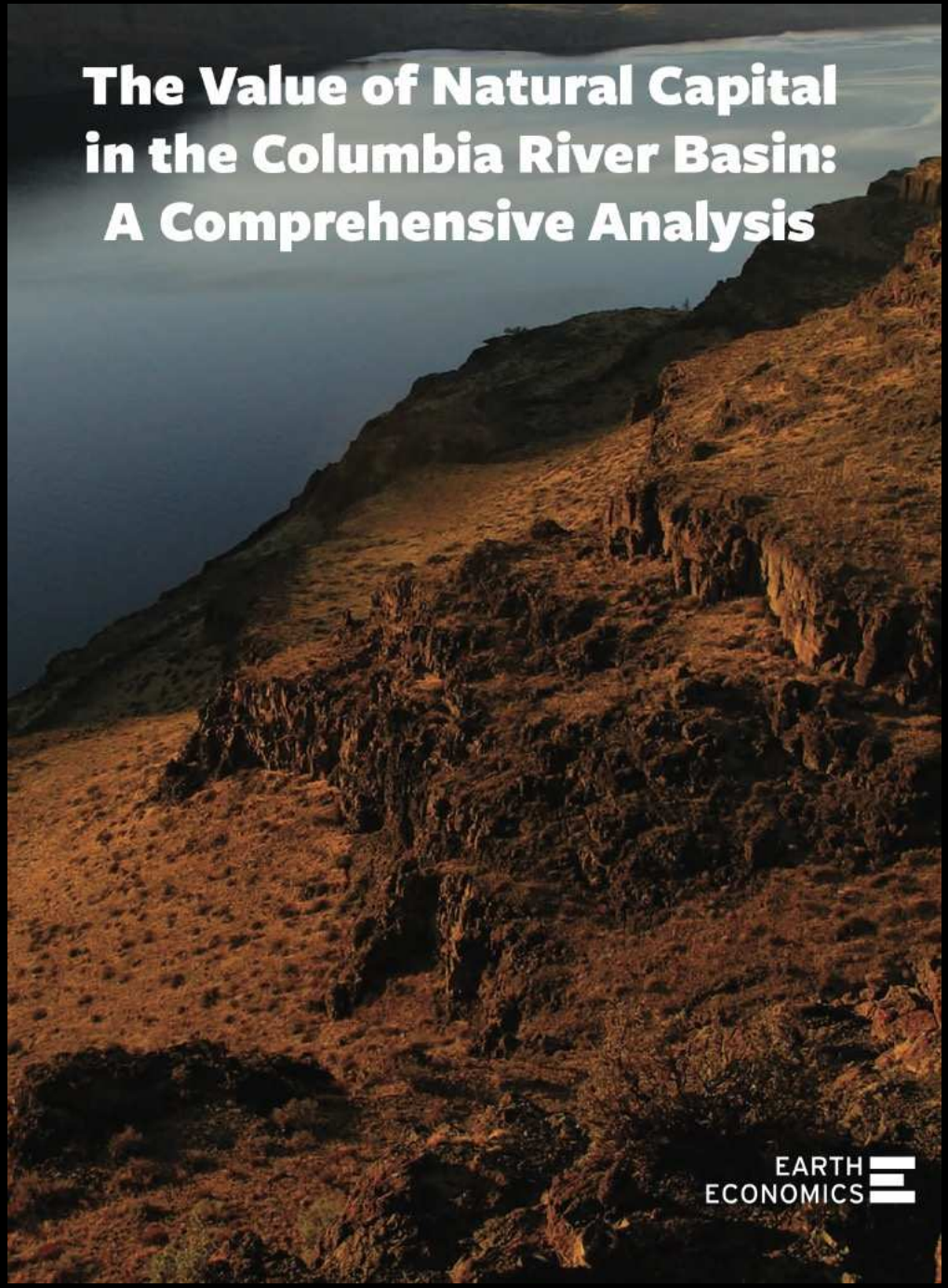


Annual Percentage of Runoff From Snow

25% 50% 75% <100%

states on/off

https://porkloin.github.io/basinSnow/



PACIFIC RIVERS

Save Our wild Salmon

WATERWATCH

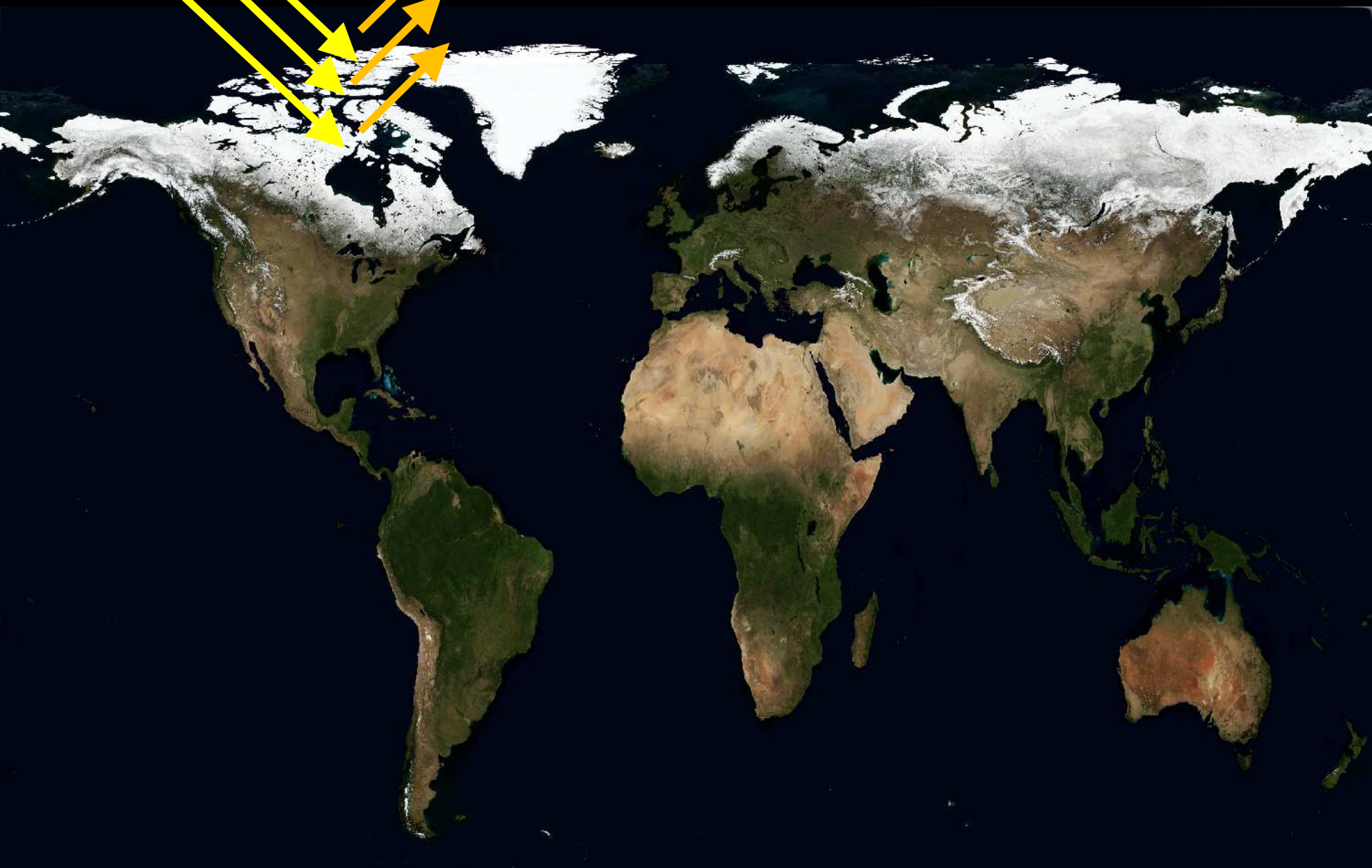
SHOW ME THE MONEY. . . .

HYDROPOWER VALUES	CURRENT CONDITIONS
Driest Water Years	$3,066,514,176
Medium Water Years	$3,388,935,087
Wettest Water Years	$3,664,655,116
WEIGHTED AVERAGE	**$3,373,356,570**

COLUMBIA RIVER BASIN	
Recreational Days	80,598,106
Economic Value	$4,683,458,594

	CROPLAND ACRES		USDA CROPLAND VALUE PER ACRE			
STATE	Irrigated	Non-Irrigated	Irrigated	Non-Irrigated	Difference	Economic Value of Water Supply
Oregon	689,823	2,051,594	$4,650	$2,020	$2,630	$1,814,234,490
Utah	1,390	3,678	$5,350	$1,170	$4,180	$5,810,200
Washington	1,334,598	4,708,974	$8,250	$1,330	$6,920	$9,235,418,160
COLUMBIA RIVER BASIN	**4,913,964**	**9,239,710**				**$21,179,173,370**

Cooling services: $475 billion (Euskirchen et al., 2013)



Outdoor Recreation:

In 2013 there were 144,601 snowmobiles sold worldwide; 48,536 were sold in the U.S. and 44,022 were sold in Canada. At $6000/machine that would be about $0.9 billion in U.S. and $291 million in Canada

The Economic Impact of Snowmobiling

United States—	$26 billion annually
Canada—	$ 8 billion annually
Europe & Russia—	$ 5 billion annually

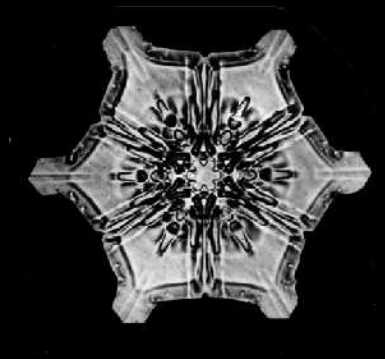
http://www.snowmobile.org/pr_snowfacts.asp

The global ski industry (ski lifts, restaurants and accommodations, ski schools, retail operations, equipment manufacturers) is est. to be worth:

USA:	$9 billion annually (2003)
Canada:	$680 million
Western Europe:	$3 billion
Japan	$1.4 billion
Australia	$94 million
TOTAL:	more than $14 billion

330 million skier visits worldwide

National Ski Areas Association (NSAA) (2004) http://www.nsaa.org. Accessed 1 September 2004
Lazard A (2002) Ski winter: world flat. Ski Area Manage September: 24–27
KPMG Consulting (2000) Victoria alpine resorts – economic significance study 2000. State of Victoria, Australia. http://www.arcc.vic.gov.au/documents/Alpine%20Economic%202000%20Full %20report%20(1356b).pdf. Accessed 26 January 2006



So why care about snow?

And on up the river is Grand Coulee Dam
The mightiest thing ever built by a man
To run the great factories and water the land
So roll on, Columbia, roll on.

Woody Guthrie, 1941

But why is there snow? Cosmic serendipity.

Not too hot……not too cold.

Planet	Diameter (km)	Distance from Sun (x10 6 km)	Surface temperature (°C)	Density (g/cm 3)	Main atmospheric constituents
Sun	1,392,000	-	5,800		-
Mercury	4,880	58	260	5.4 (rocky)	-
Venus	12,100	108	480	5.3 (rocky)	CO2
Earth	12,750	150	15	5.5 (rocky)	N2, O2
Mars	6,800	228	-60	3.9 (rocky)	CO2
Jupiter	143,000	778	-150	1.3 (icy)	H2, He
Saturn	121,000	1,427	-170	0.7 (icy)	H2, He
Uranus	52,800	2,869	-200	1.3 (icy)	H2, CH4
Neptune	49,500	4,498	-210	1.7 (icy)	H2, CH4
Pluto	2,300	5,900	-220	2.0	CH4

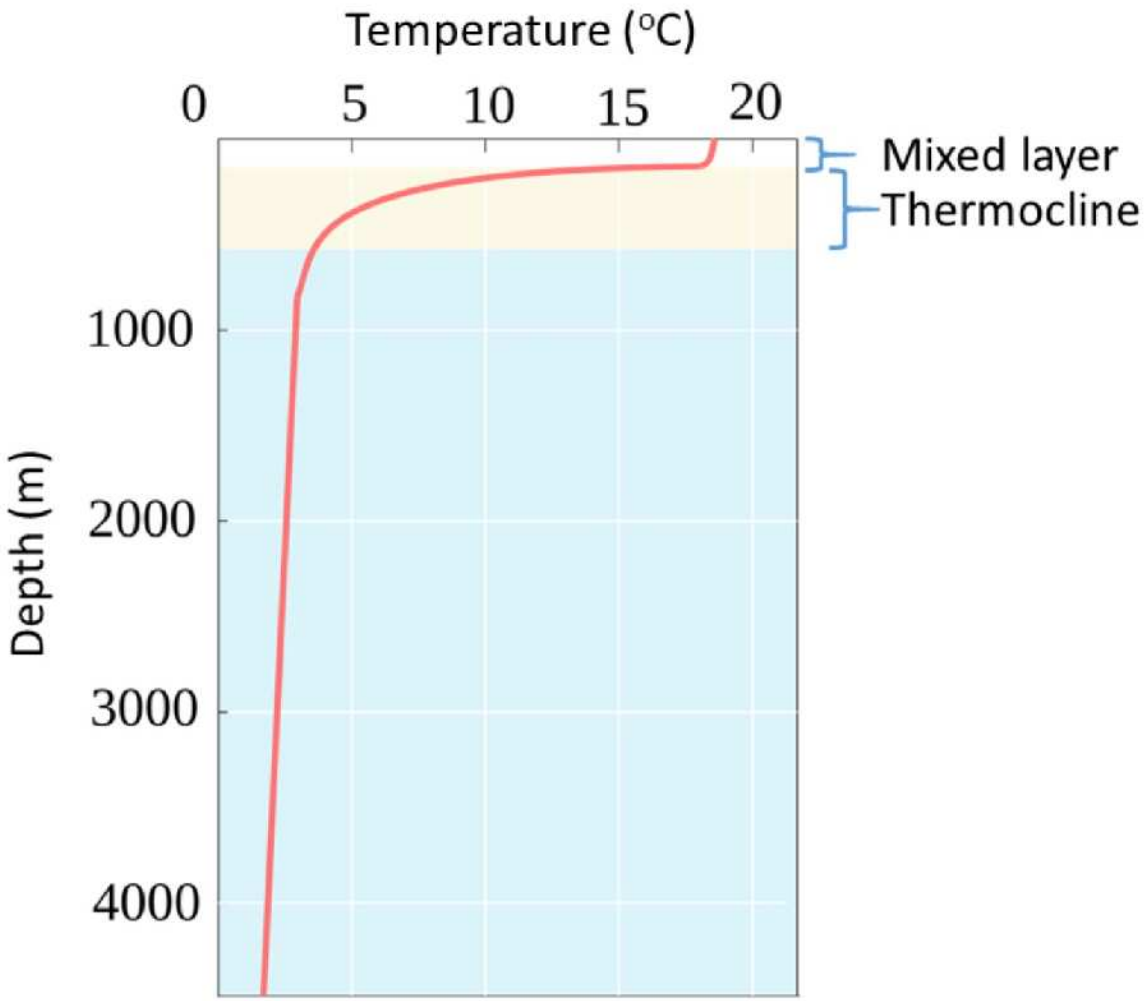
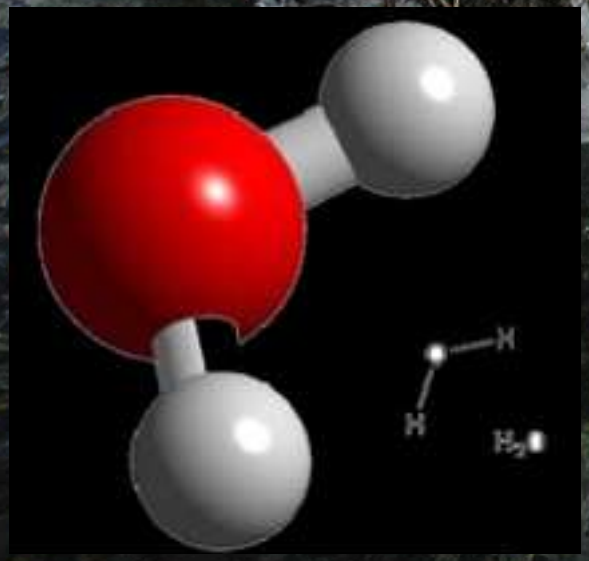
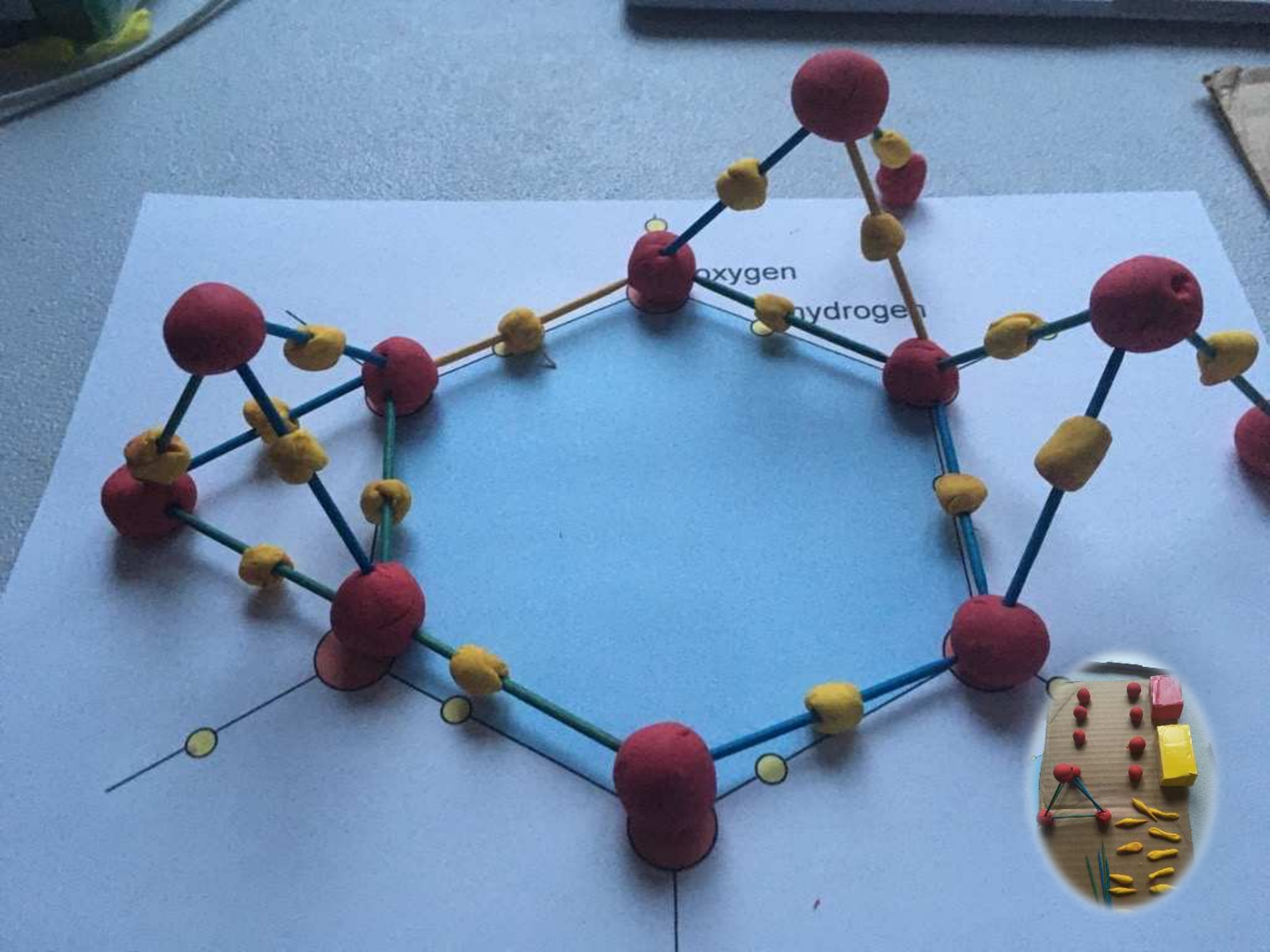


Figure 6.2.2 *Typical open ocean temperature profile for a mid-latitude region, showing the mixed layer, steep thermocline, and relatively stable temperature at depth (Public domain via Wikimedia Commons).*

On Earth, the three phases of water exist and often co-exist.




oxygen
ydrogen

Material	Latent Heat of Melting *(kJ/kg)*
Gold	67
Iron, gray cast	96
Lead	22
Silver	88
Water, Ice	334
Zinc	118

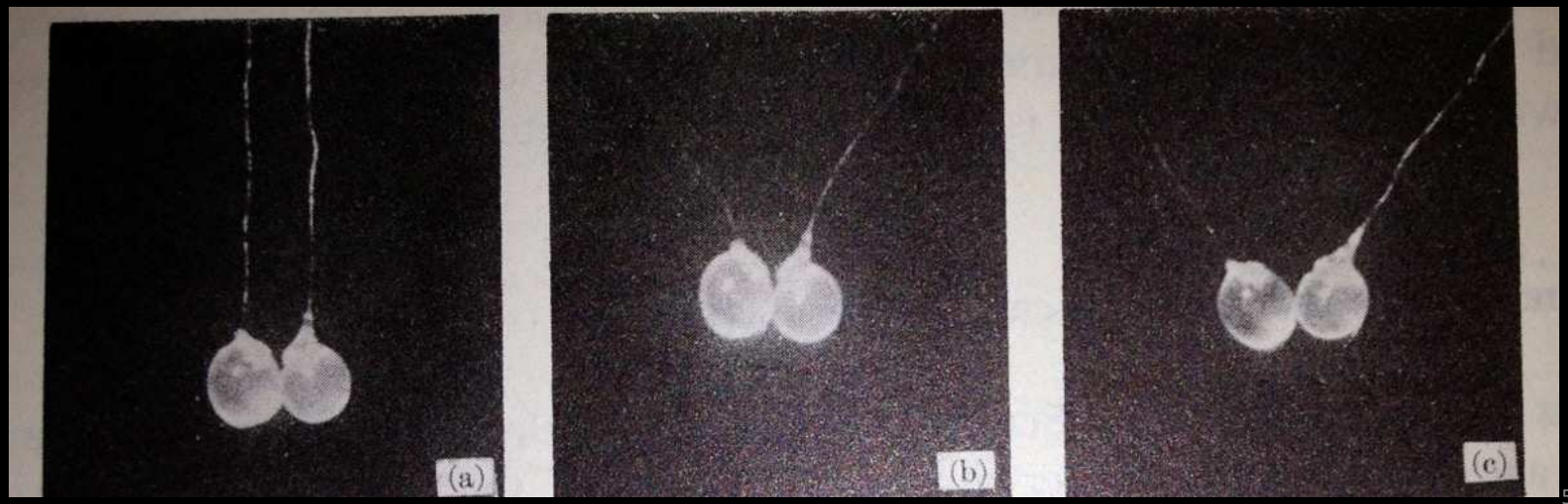
Material	Specific Heat *(kJ/kg K)*
Gold	0.13
Iron, gray cast	0.45
Lead	0.13
Silver	0.23
Water, Ice	2.0
Zinc	0.39

Material	Insulation Value (W/ m K)
Concrete	0.40
Pine	0.12
Fiberglass batts	0.04
Foam board	0.03
Snow (depth hoar)	0.04
Snow (wind slab)	0.40

Material	Albedo *% sunlight reflected*
Asphalt	4
Sand	40
Soil	17
Grass	25
Snow (new)	90
Ocean	6

A few other important snow and ice properties

- ***Super-cools to -40°C***
- ***Practically a universal solvent***
- ***Miscible with salts***
- ***Always has a QLL (quasi-liquidlike layer)***




The QLL in action

Getting it to snow:
harder than you think.

It all happens here.

But this is the problem:

Freezing water requires nucleation

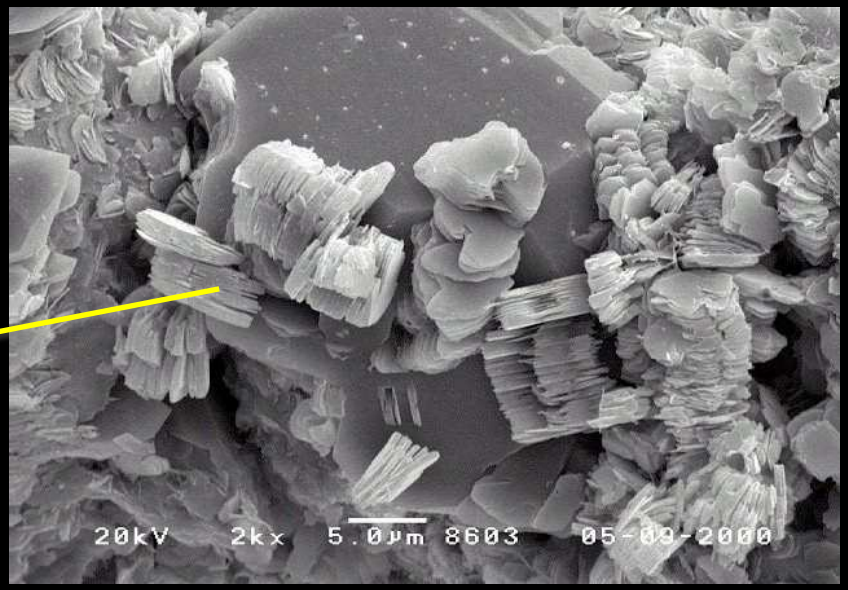
Homogeneous nucleation: only in the coldest of clouds (-40°F)

Heterogeneous nucleation: the major mechanism for the formation of cloud droplets and possibly ice particles.

CCN: Cloud Condensation Nuclei → droplets

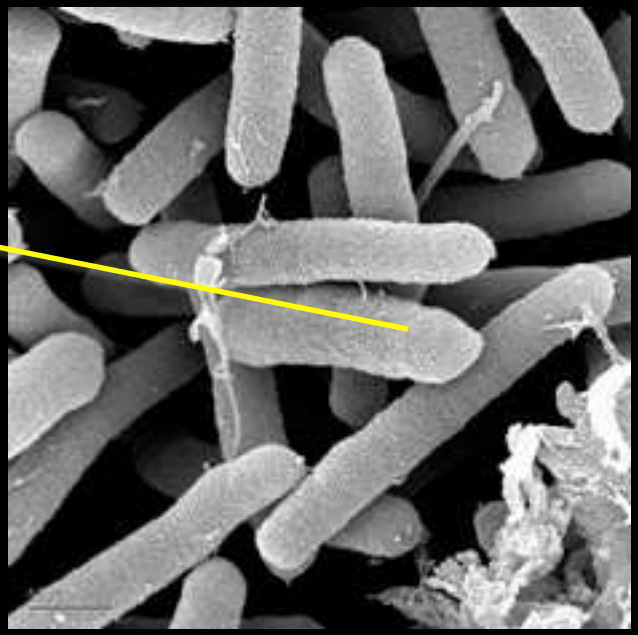
IN: Ice Nuclei → ice particles

CCN Nuclei



- Illite
- Kaolinite
- vermiculite

- Biogenic IN
- Anthropogenic IN
- Decomposing organics
- Bacteria (*Pseudomonas syringae*)
- Viruses

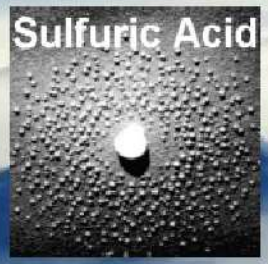


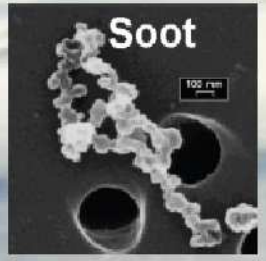
Ideal Properties

- Insoluable
- Larger
- Similar structure to ice
- Strong hydrogen bonds

Source of solute in droplets?

Real atmosphere is not clean - aerosols act as Cloud Condensation Nuclei

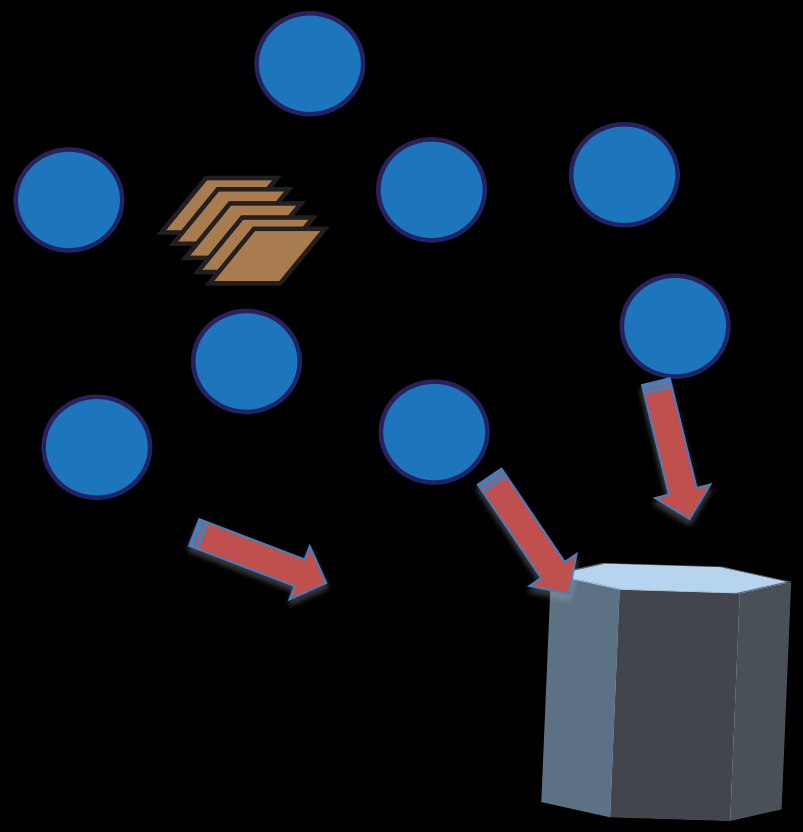




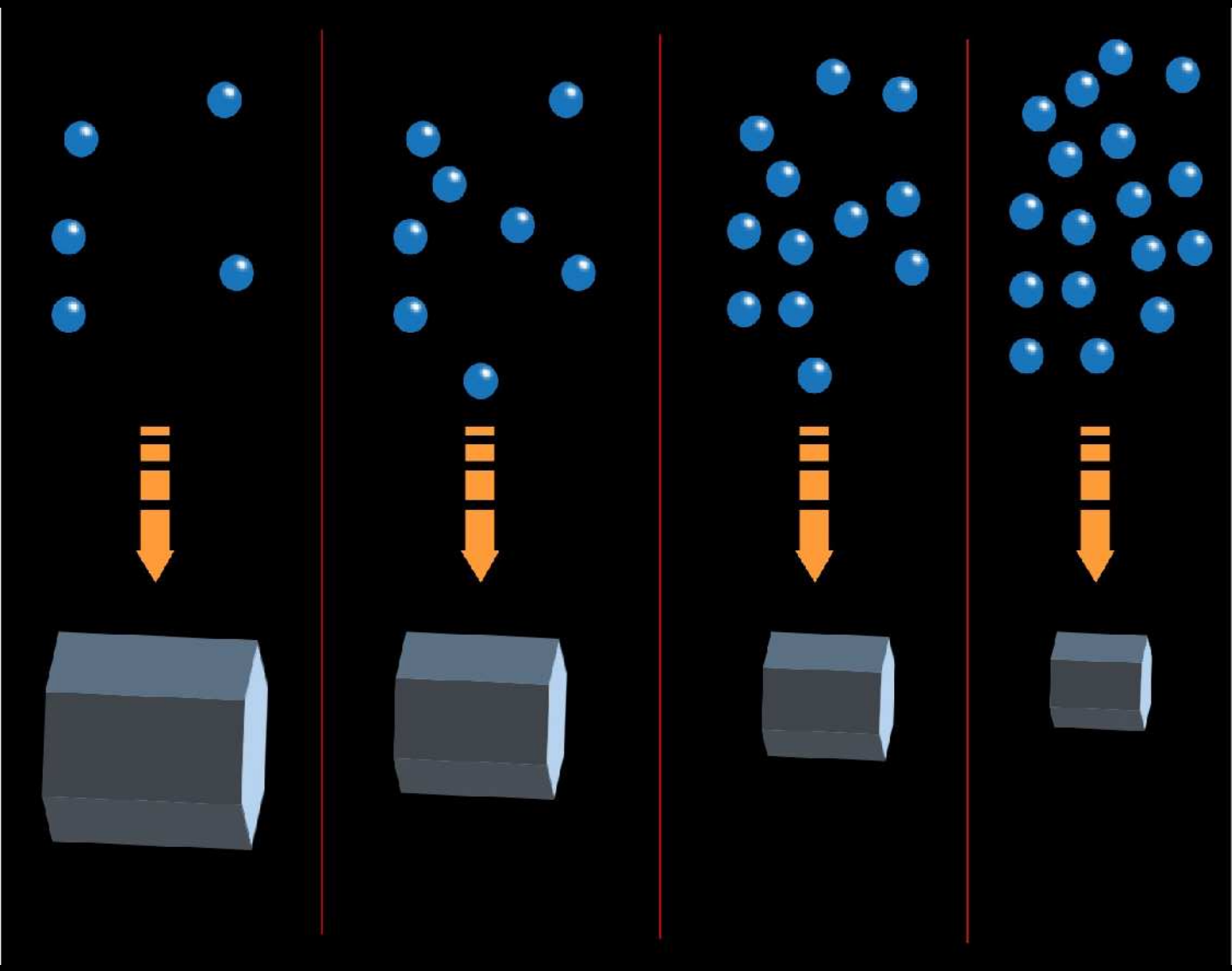
But how do these get up in the sky?

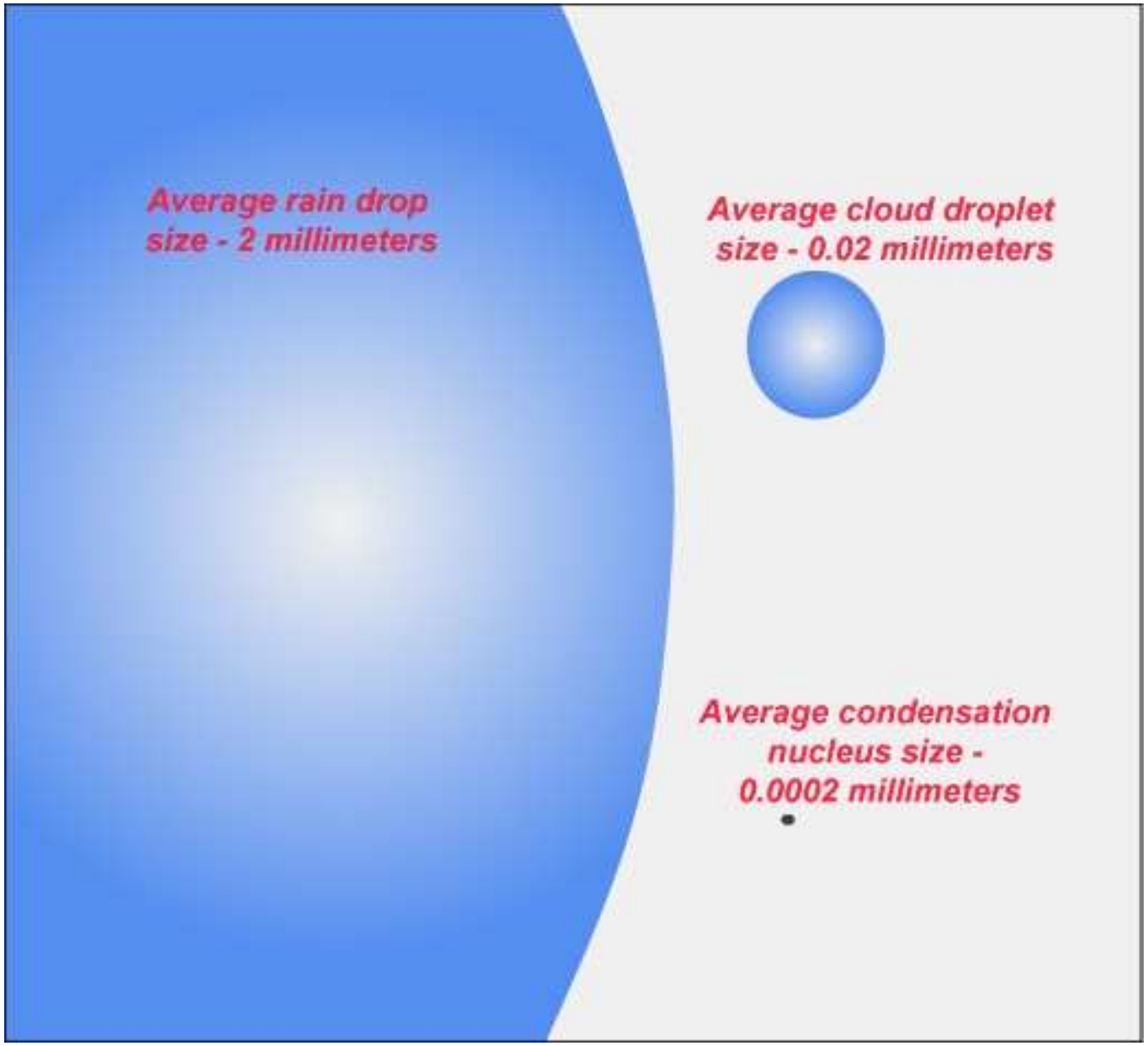
Dust storms—clay particles
Biomass burning—carbon, dust, ash
Volcanic activity—SO_2, tephra
Ocean bubble burst—salts (NaCl, K^+, Mg^{+2}, CO_3^{2-})
Pollen, fungi spores, bacteria, virus

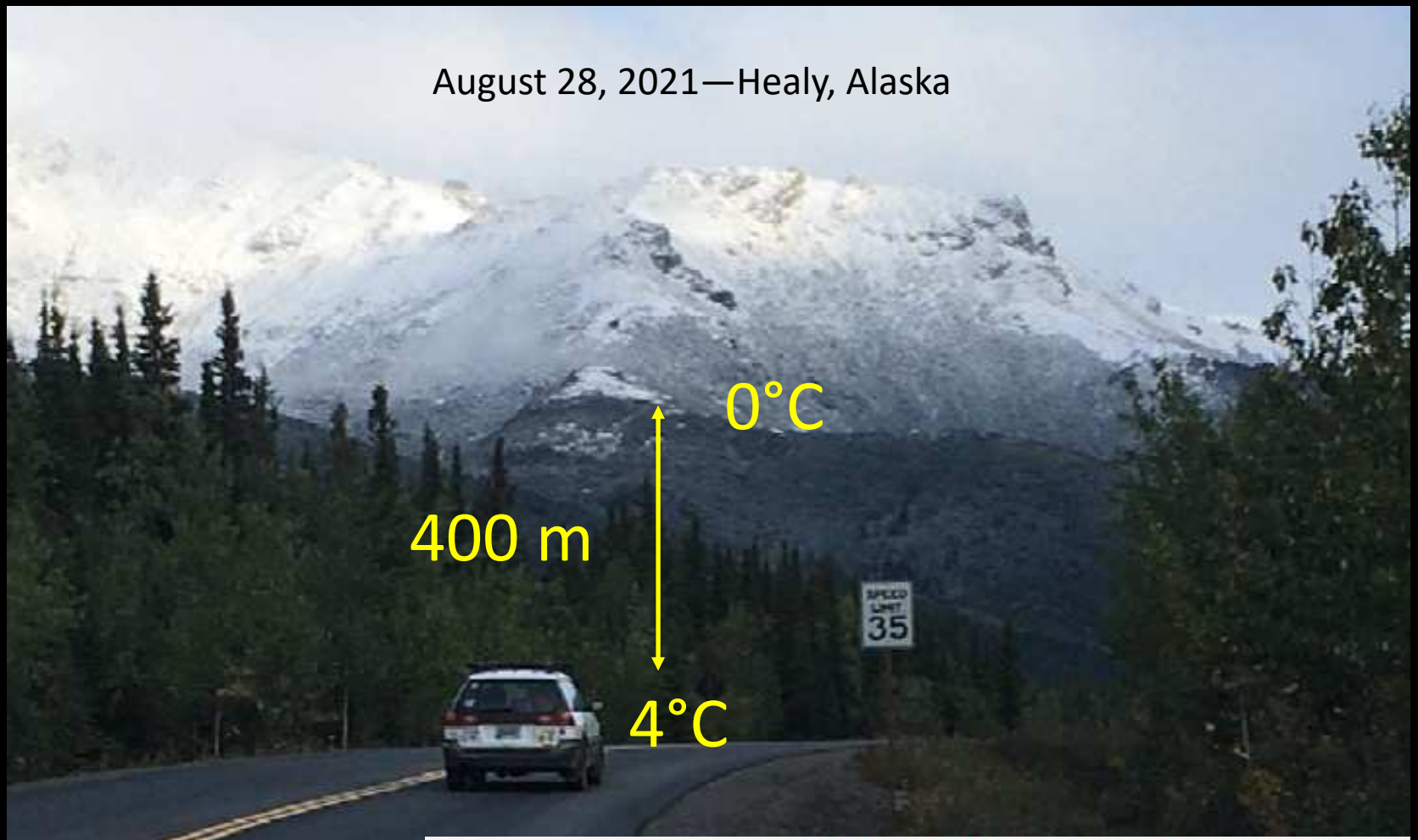
Heterogeneous Nucleation



Wegener–Bergeron–Findeisen process



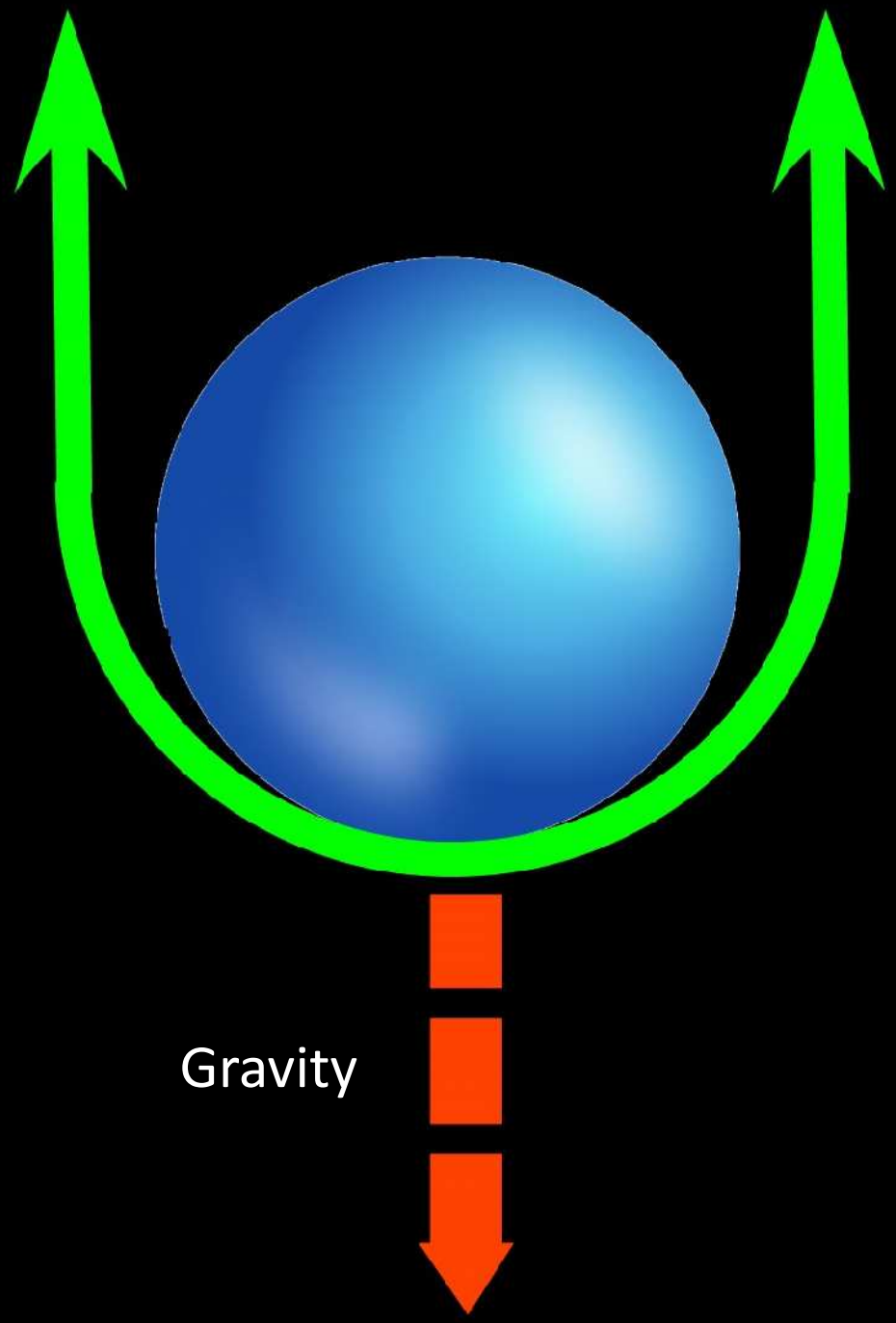

Average rain drop
size - 2 millimeters
Average cloud droplet
size - 0.02 millimeters
Average condensation
nucleus size -
0.0002 millimeters

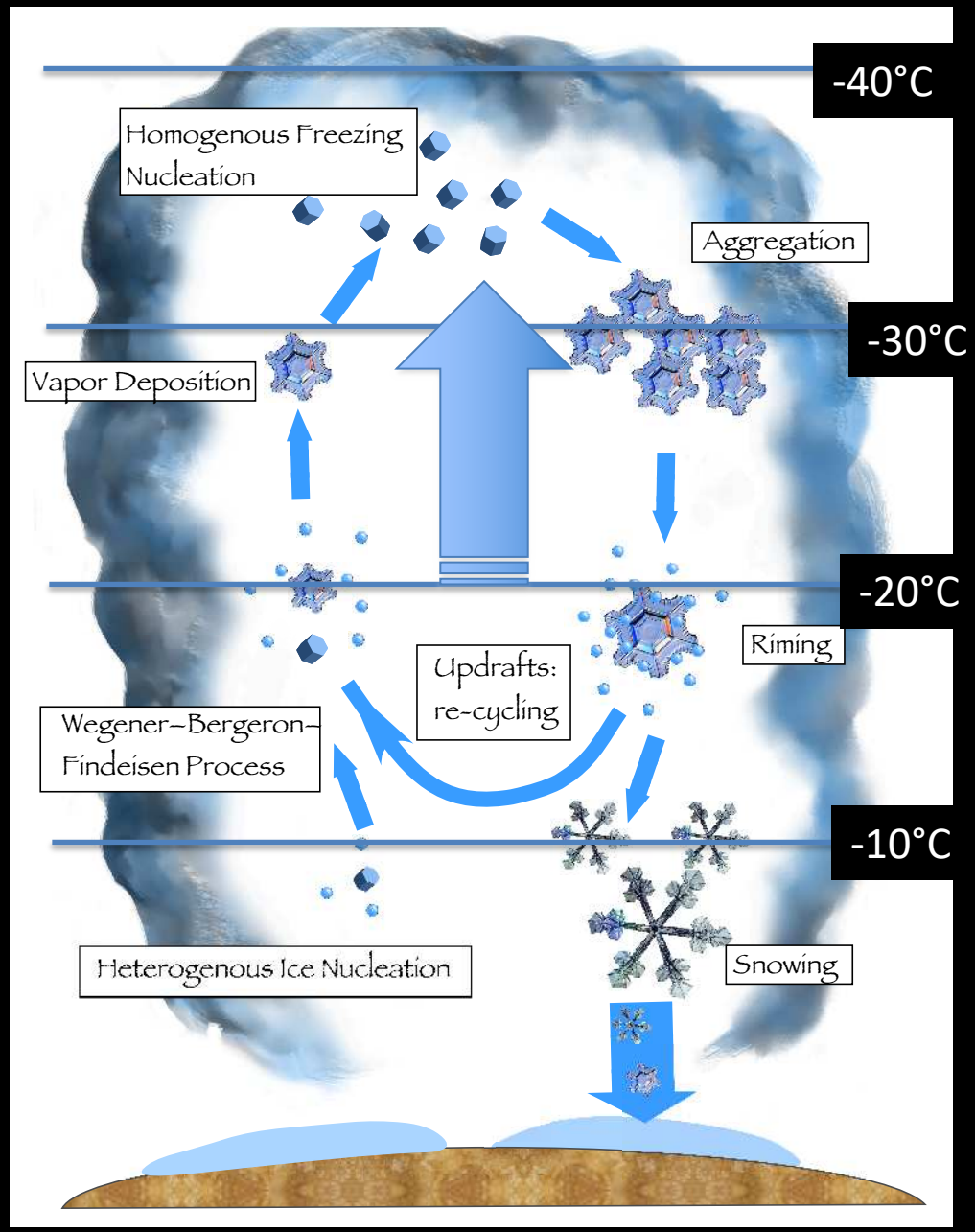


Dry Adiabatic Lapse Rate (Γ_d):

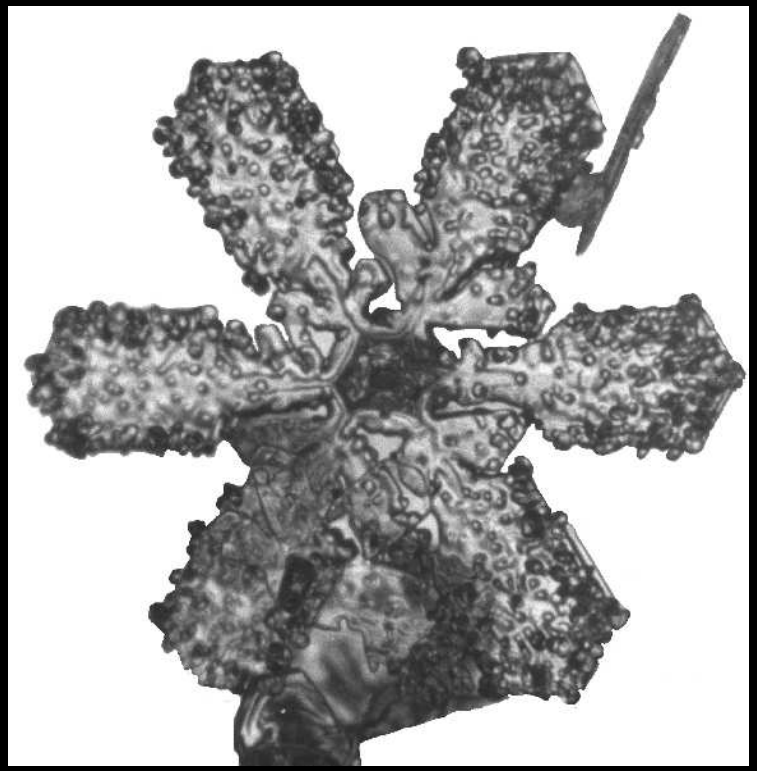
$$\Gamma_d = \frac{dT}{dz} = -\frac{g}{c_p} = -9.8°C/km$$

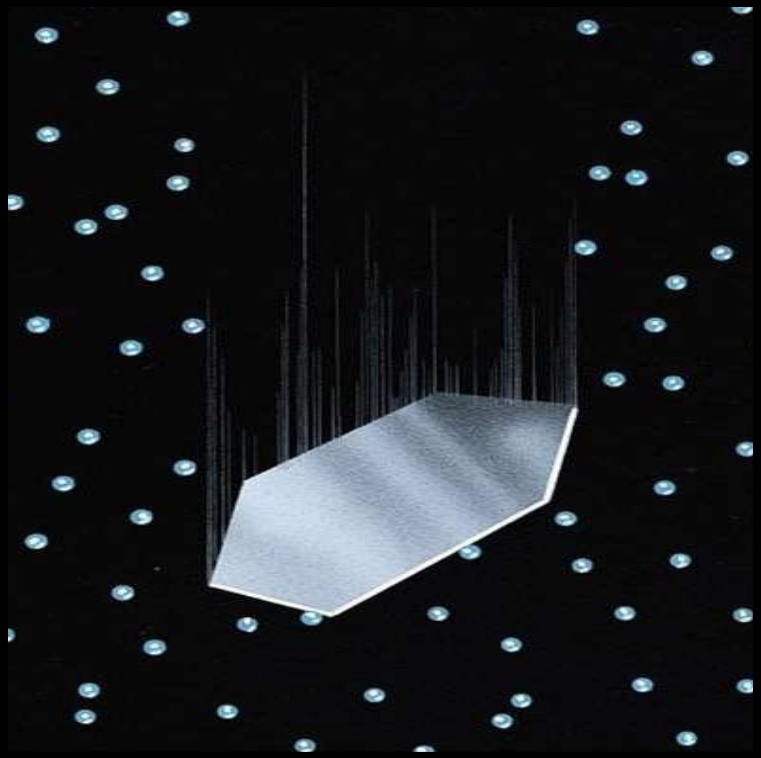
Stoke's settling velocity & Air resistance



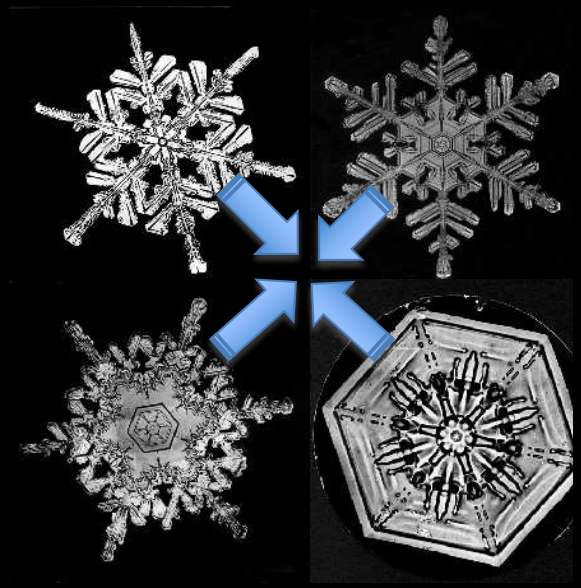

-40°C
Homogenous Freezing Nucleation
Aggregation
-30°C
Vapor Deposition
-20°C
Riming
Updrafts: re-cycling
Wegener–Bergeron–Findeisen Process
-10°C
Heterogenous Ice Nucleation
Snowing

Riming





Aggregation



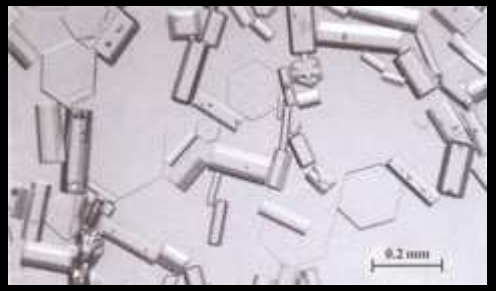
From the crystal factory . . . .

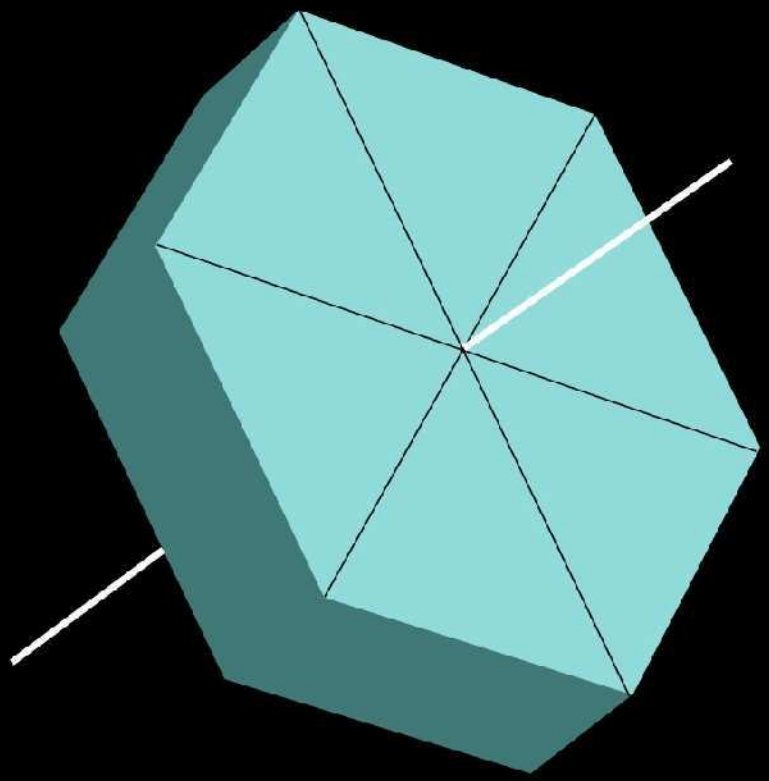


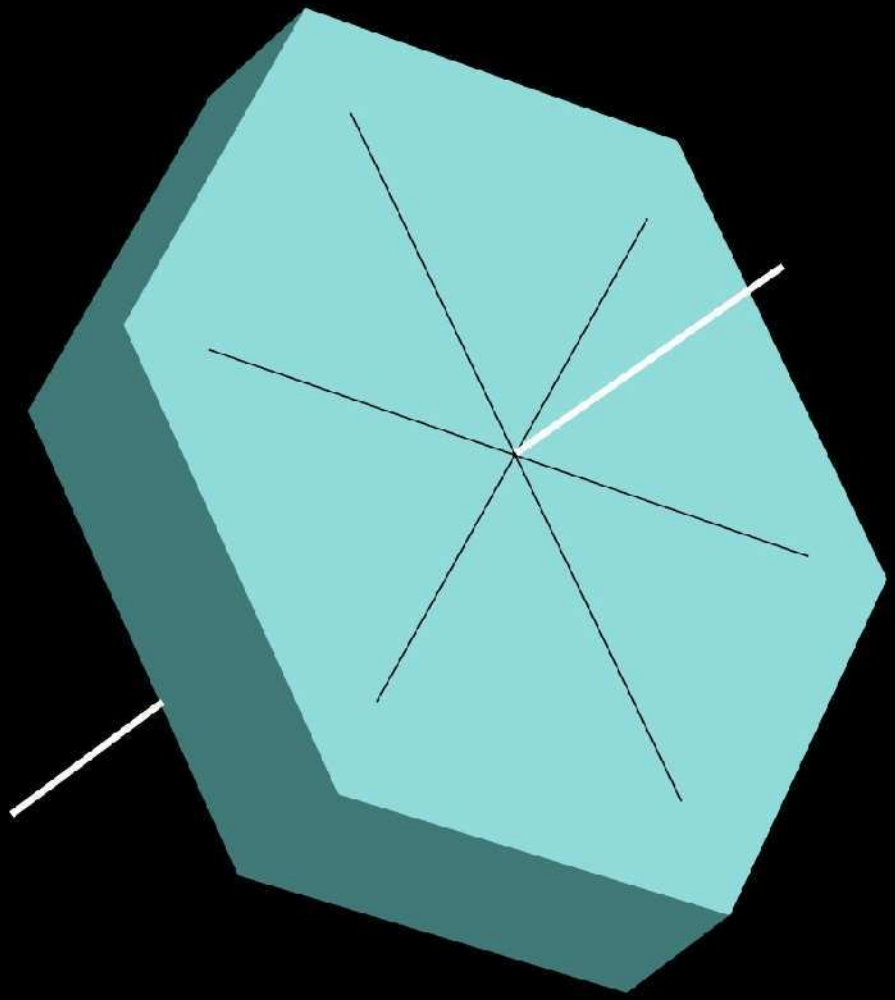


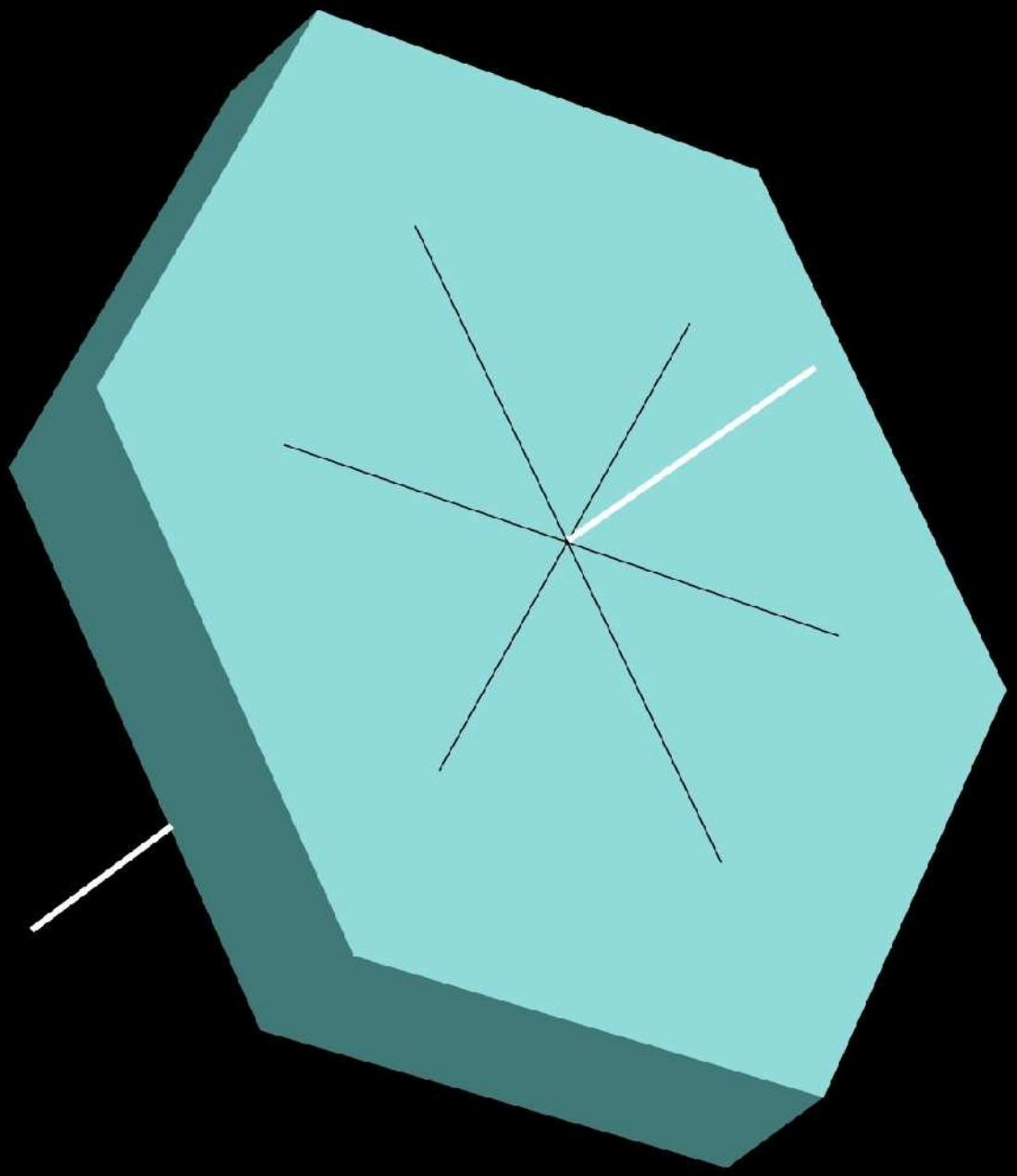


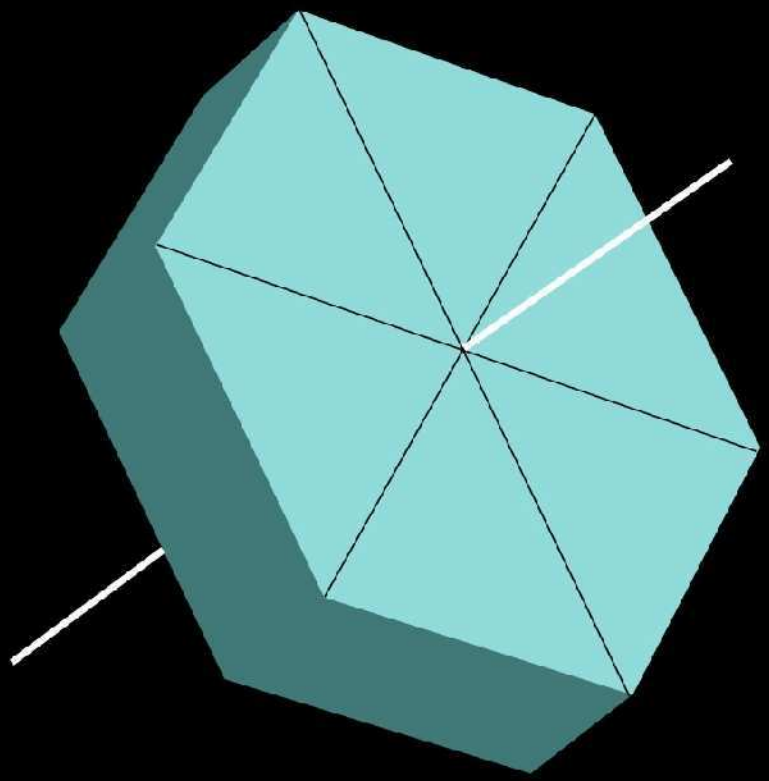


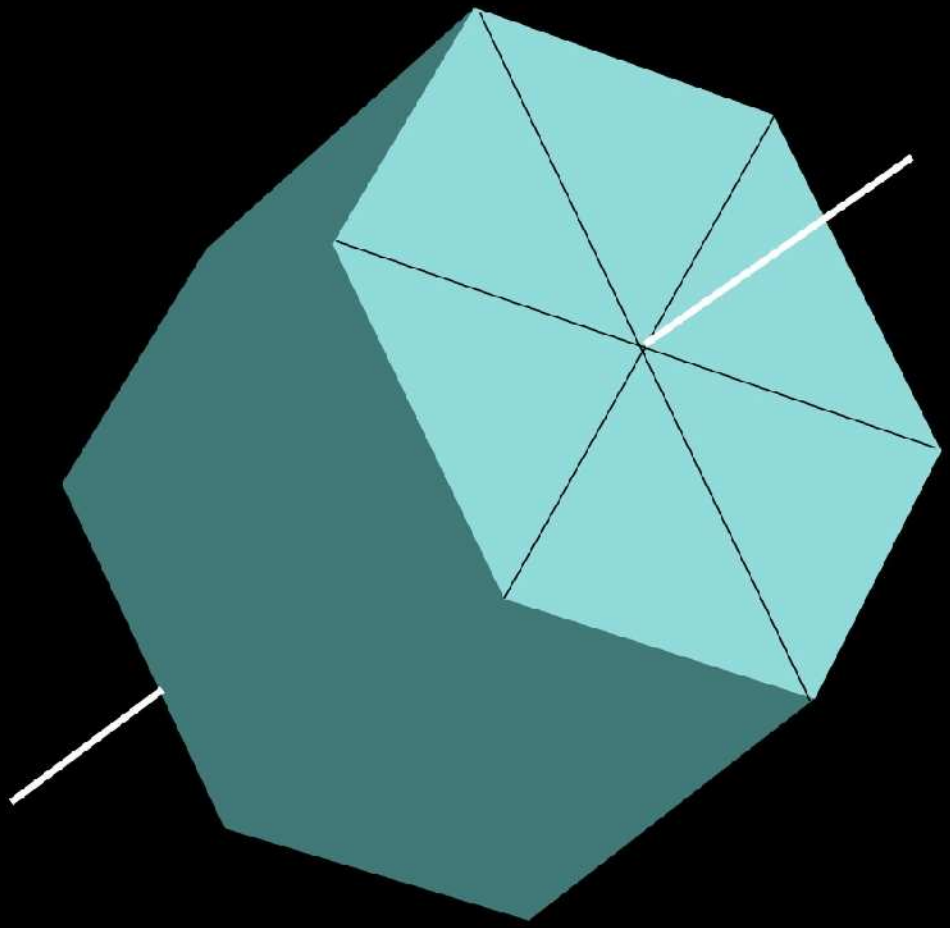

0.2 mm

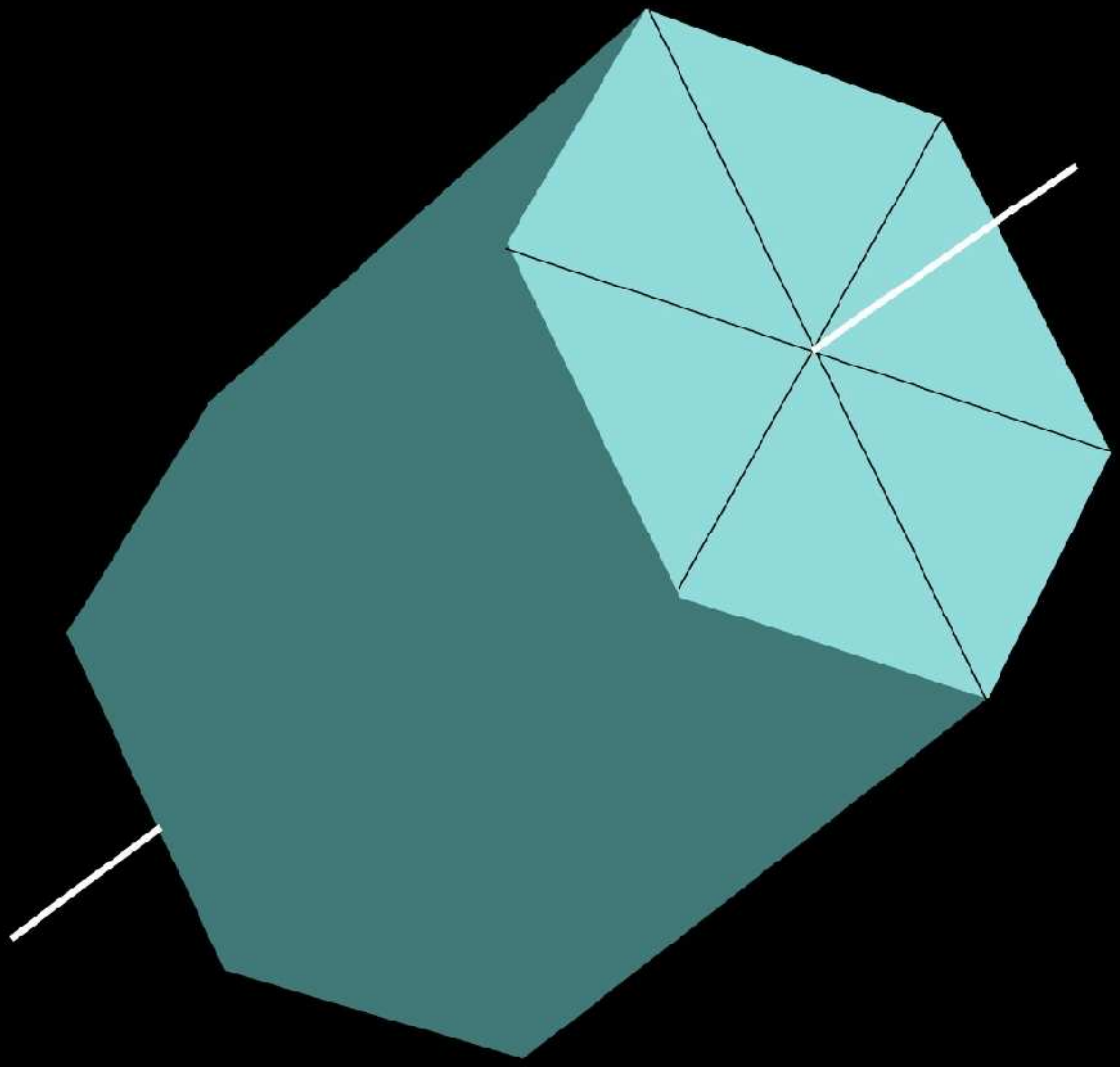



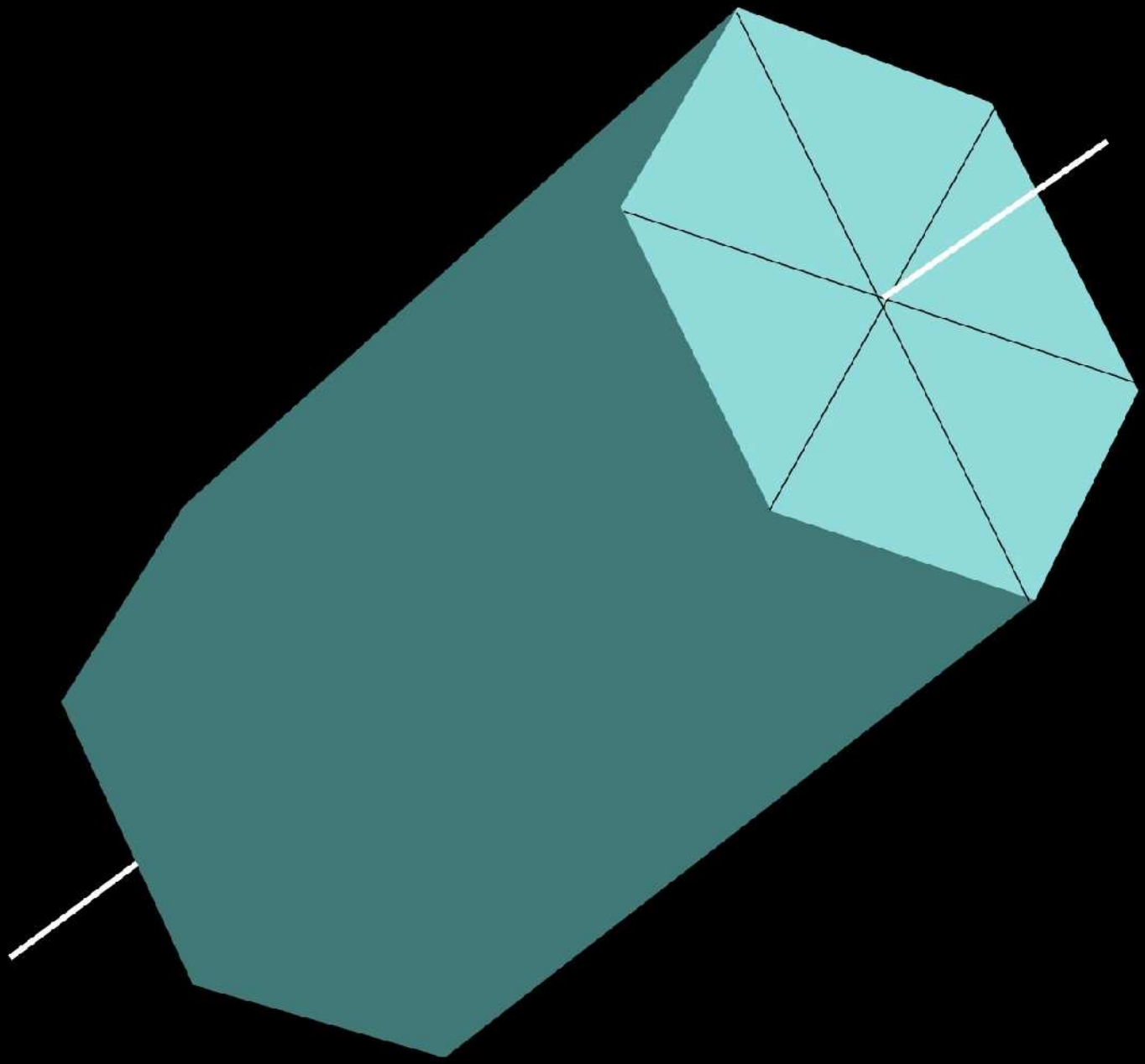


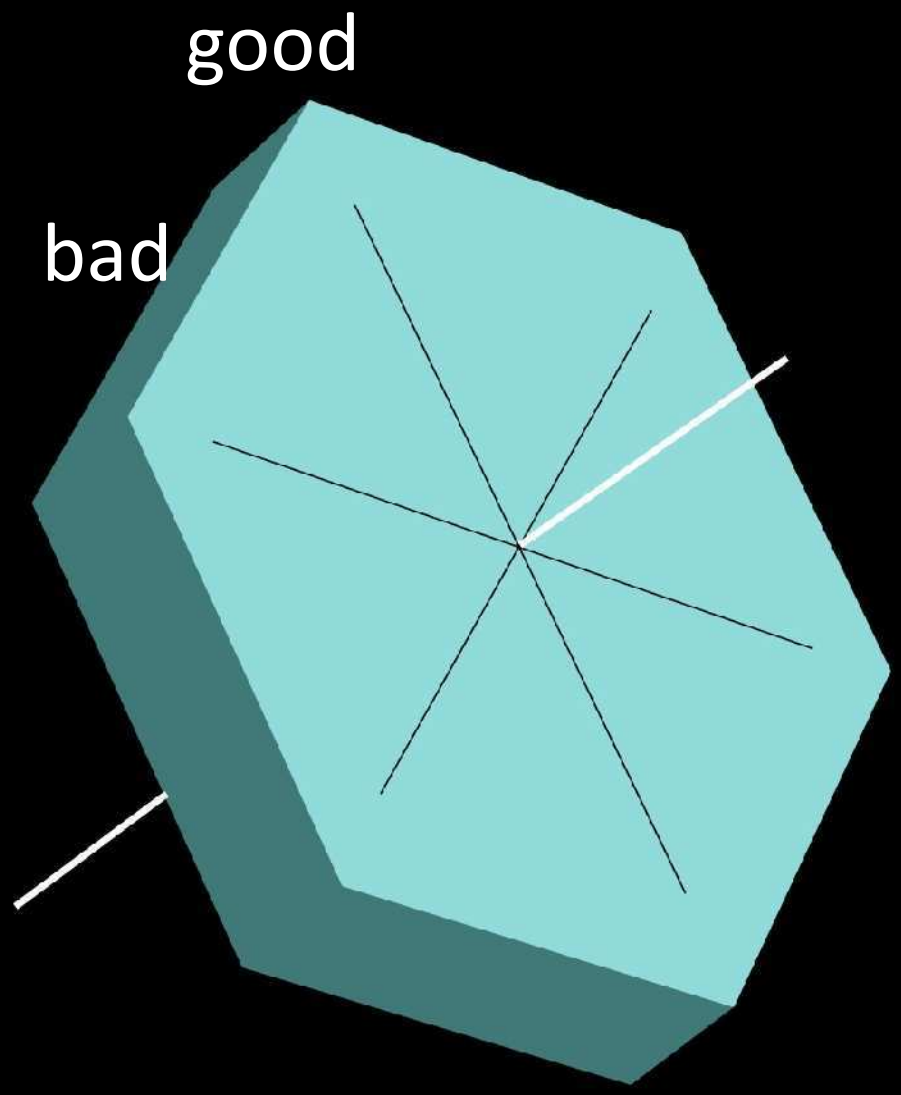




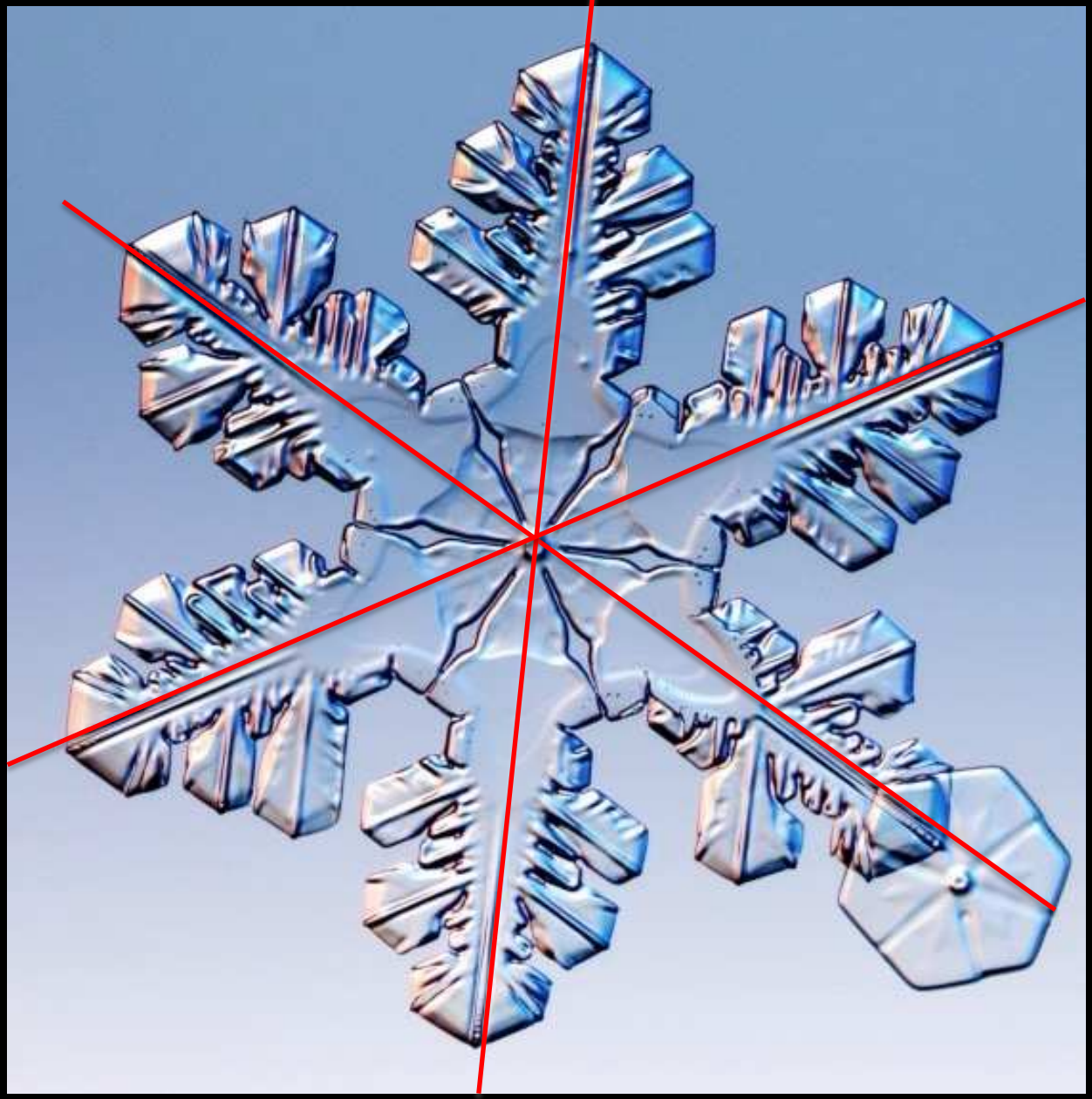




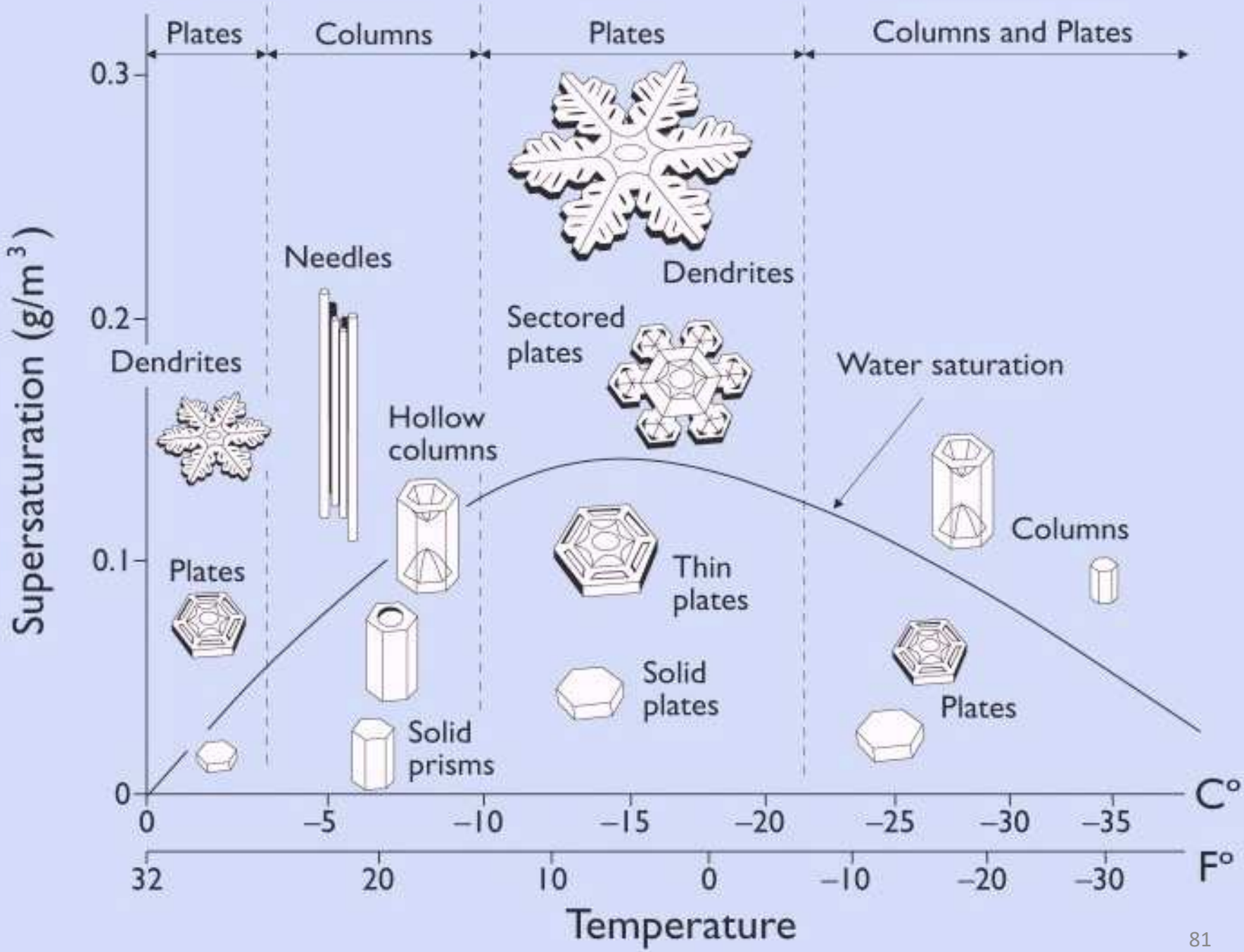



good
bad

Why such “fearful symmetry”?



Ukichiro Nakaya (1900-1962)

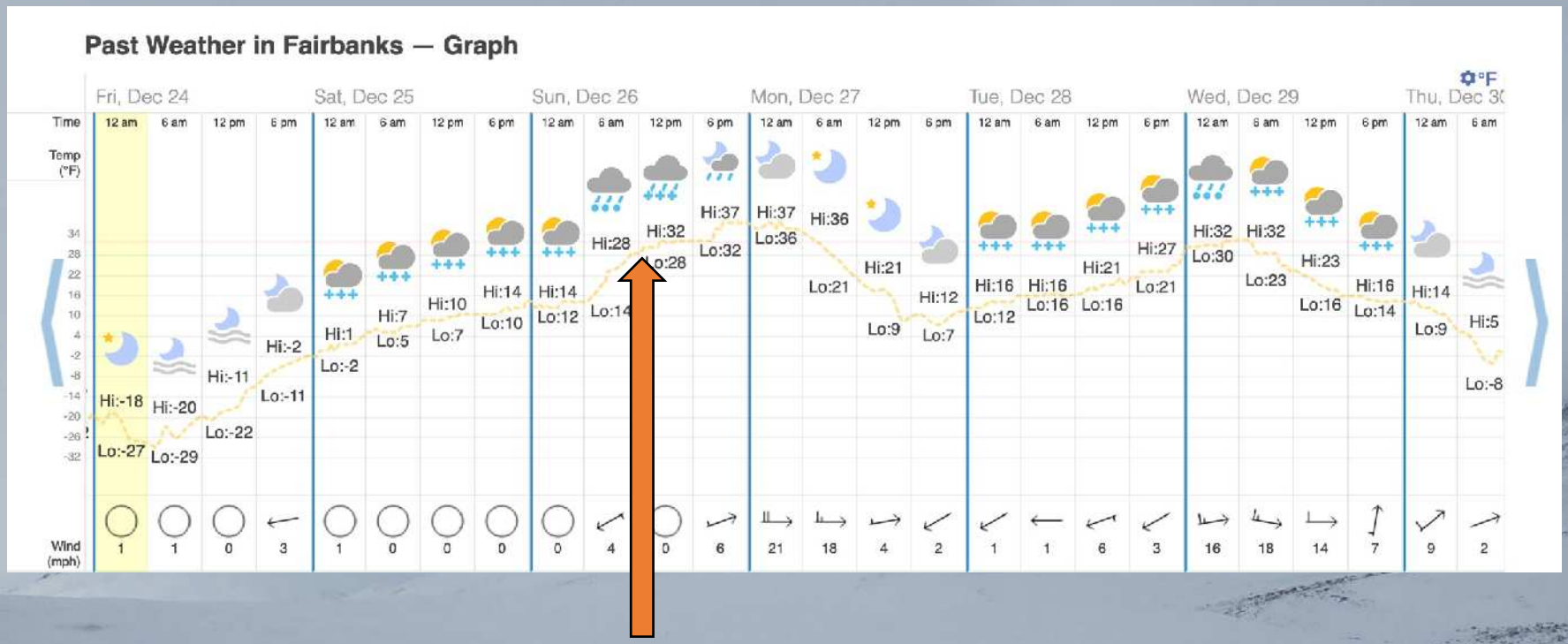

Plates
Columns
Plates
Columns and Plates
0.3
0.2
0.1
0
Supersaturation (g/m³)
Dendrites
Needles
Dendrites
Sectored plates
Water saturation
Hollow columns
Plates
Thin plates
Columns
Solid plates
Plates
Solid prisms
C°
0
–5
–10
–15
–20
–25
–30
–35
F°
32
20
10
0
–10
–20
–30
Temperature

The Christmas Storm of 2021—Fairbanks, Alaska

Many Alaskans will remember Christmas, 2021 as a holiday of big snow, freezing rain, power outages, and roof collapses.

But the storm was also a wonderful example of a snowstorm evolving over time, with the snow crystals telling us what was happening in the clouds.

A journey through the Nakaya Snow Crystal Morphology Diagram



Above-freezing temperatures and freezing rain: power outages. At our house, the power was out for 26 hours. The roads went unplowed until December 30th.

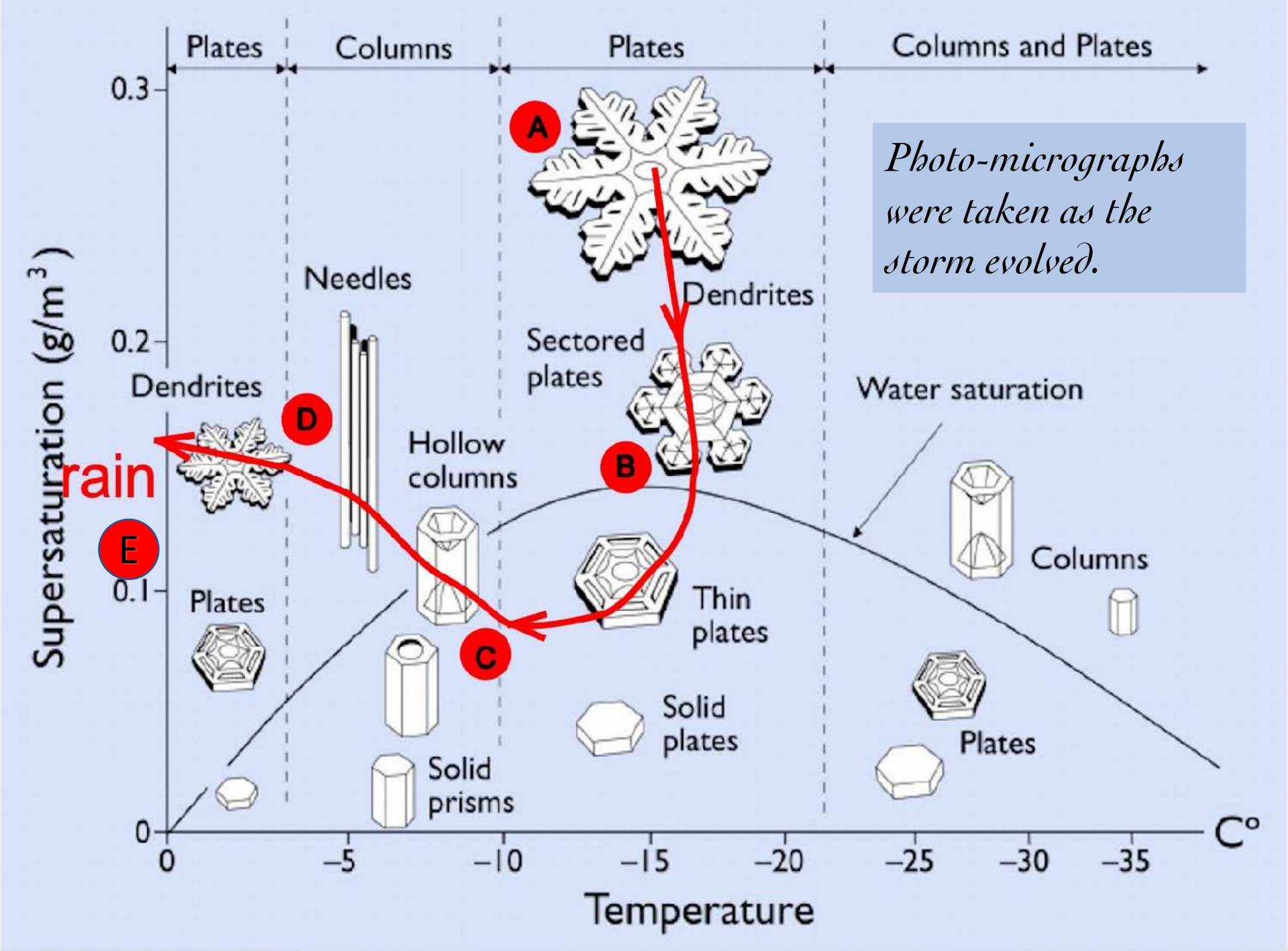


Photo-micrographs were taken as the storm evolved.

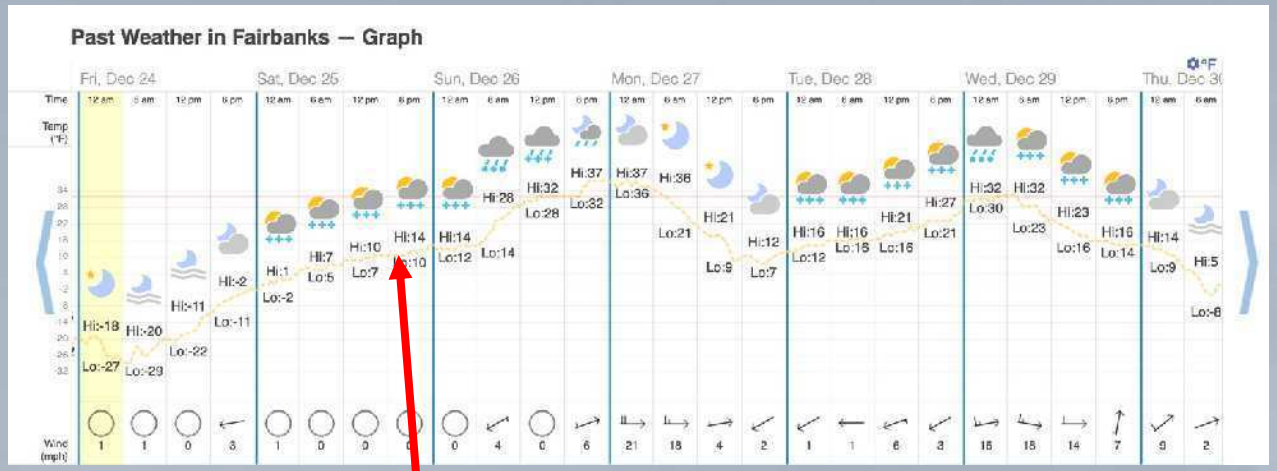

Past Weather in Fairbanks — Graph
Fri, Dec 24
Sat, Dec 25
Sun, Dec 26
Mon, Dec 27
Tue, Dec 28
Wed, Dec 29
Thu, Dec 30
Time
Temp (°F)
Wind (mph)
Hi:-18
Lo:-27
Hi:-20
Lo:-29
Hi:-11
Lo:-22
Hi:-2
Lo:-11
Hi:1
Lo:-2
Hi:7
Hi:10
Lo:7
Hi:14
Lo:10
Hi:14
Lo:12
Hi:28
Lo:14
Hi:32
Lo:28
Hi:37
Lo:32
Hi:37
Lo:36
Hi:36
Lo:21
Hi:21
Lo:9
Hi:12
Lo:7
Hi:16
Lo:12
Hi:16
Lo:15
Hi:21
Lo:16
Hi:27
Lo:21
Hi:32
Lo:30
Hi:32
Lo:23
Hi:23
Lo:16
Hi:16
Lo:14
Hi:14
Lo:9
Hi:5
Lo:-6

A

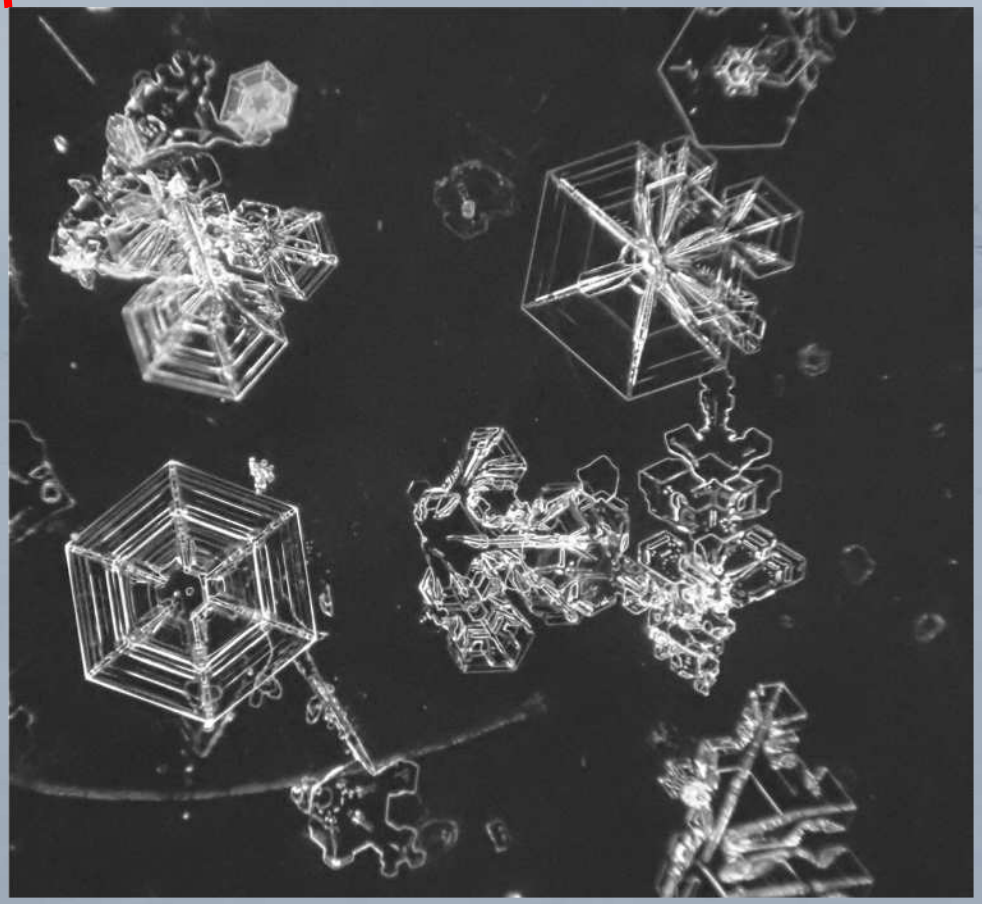

Crystal photos by M. Sturm

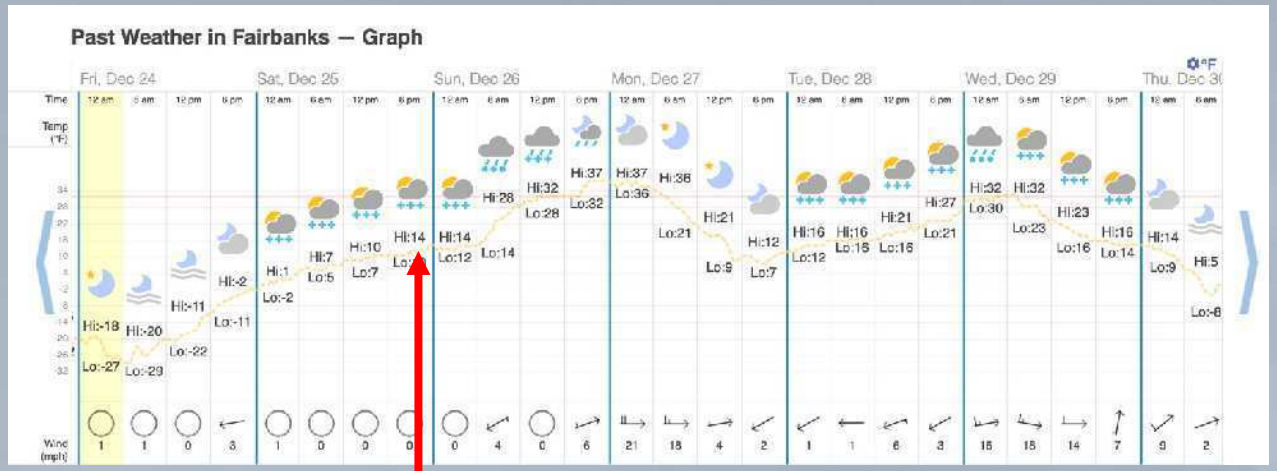

Past Weather in Fairbanks — Graph
Fri, Dec 24
Sat, Dec 25
Sun, Dec 26
Mon, Dec 27
Tue, Dec 28
Wed, Dec 29
Thu, Dec 30
Time
Temp (°F)
Wind (mph)
Hi:-18
Lo:-27
Hi:-20
Lo:-29
Hi:-11
Lo:-22
Hi:-2
Lo:-11
Hi:1
Lo:-2
Hi:7
Lo:5
Hi:10
Hi:14
Lo:10
Hi:14
Lo:12
Hi:28
Lo:14
Hi:32
Lo:28
Hi:37
Lo:32
Hi:37
Lo:36
Hi:36
Lo:21
Hi:21
Lo:9
Hi:12
Lo:7
Hi:16
Lo:12
Hi:16
Lo:15
Hi:21
Lo:16
Hi:27
Lo:21
Hi:32
Lo:30
Hi:32
Lo:23
Hi:23
Lo:16
Hi:16
Lo:14
Hi:14
Lo:9
Hi:5
Lo:-6

A

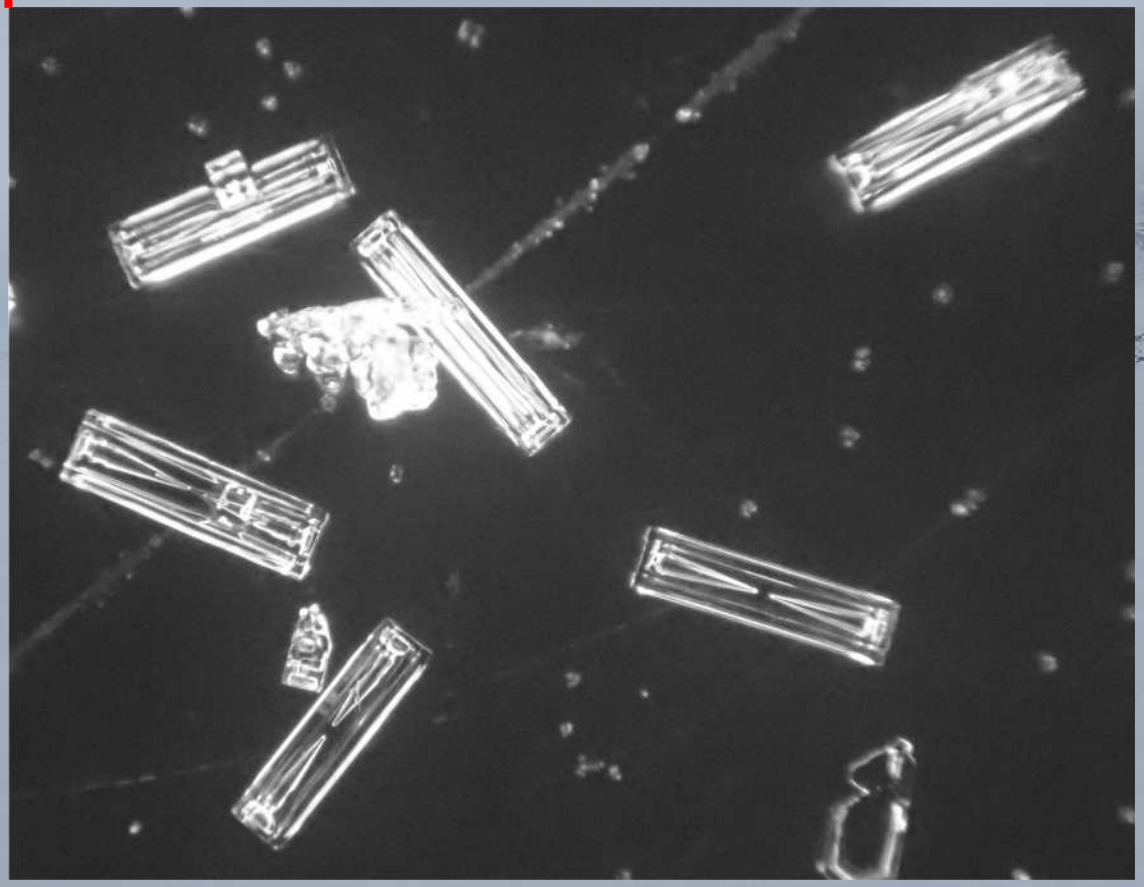

Past Weather in Fairbanks — Graph
Fri, Dec 24
Sat, Dec 25
Sun, Dec 26
Mon, Dec 27
Tue, Dec 28
Wed, Dec 29
Thu, Dec 30
Time
Temp (°F)
Wind (mph)

B



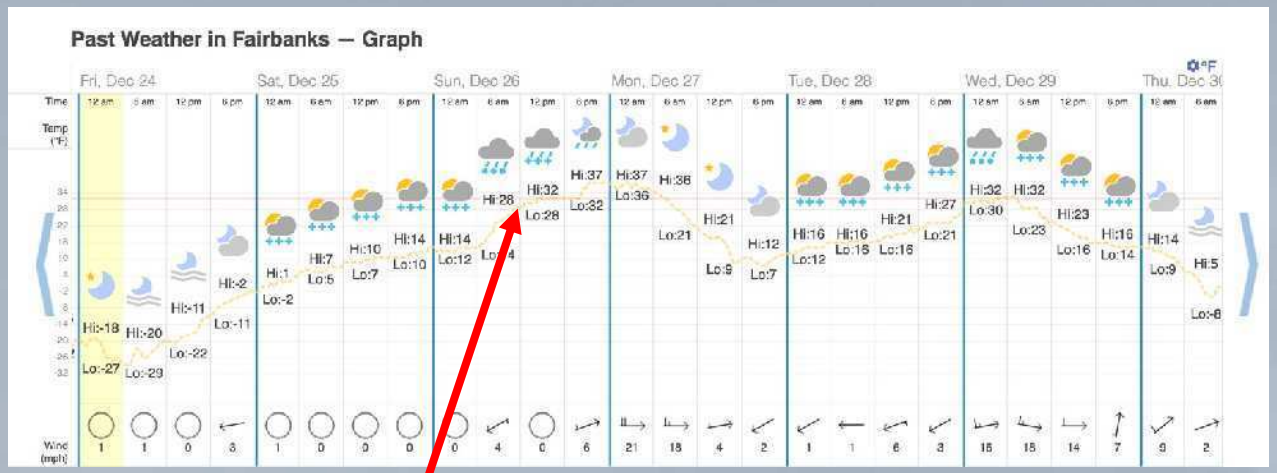

Past Weather in Fairbanks — Graph
Fri, Dec 24
Sat, Dec 25
Sun, Dec 26
Mon, Dec 27
Tue, Dec 28
Wed, Dec 29
Thu, Dec 30
Time
Temp (°F)
Wind (mph)
Hi:-18
Lo:-27
Hi:-20
Lo:-29
Hi:-11
Lo:-22
Hi:-2
Lo:-11
Hi:1
Lo:-2
Hi:7
Lo:5
Hi:10
Lo:7
Hi:14
Hi:14
Lo:12
Hi:28
Lo:14
Hi:32
Lo:28
Hi:37
Lo:32
Hi:37
Lo:36
Hi:36
Lo:21
Hi:21
Lo:9
Hi:12
Lo:7
Hi:16
Lo:12
Hi:16
Lo:15
Hi:21
Lo:16
Hi:27
Lo:21
Hi:32
Lo:30
Hi:32
Lo:23
Hi:23
Lo:16
Hi:16
Lo:14
Hi:14
Lo:9
Hi:5
Lo:-6

C



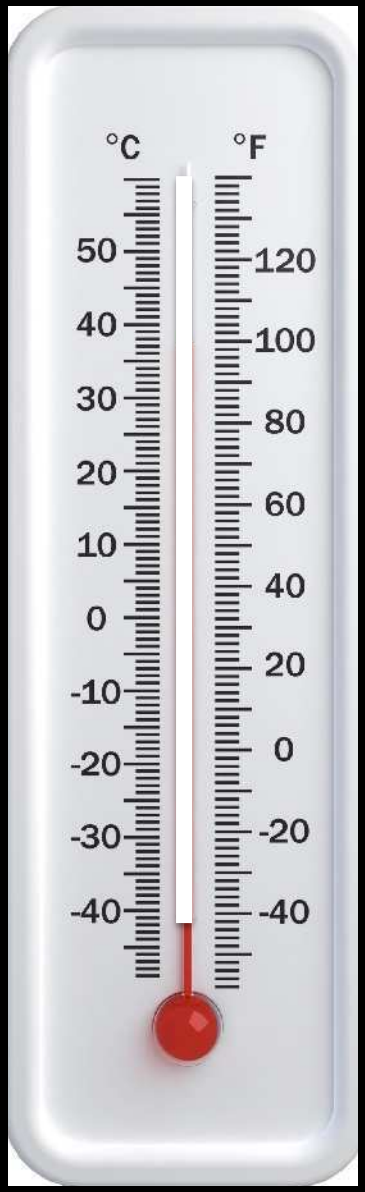

Past Weather in Fairbanks — Graph
Fri, Dec 24
Sat, Dec 25
Sun, Dec 26
Mon, Dec 27
Tue, Dec 28
Wed, Dec 29
Time
Temp (°F)
Wind (mph)

D

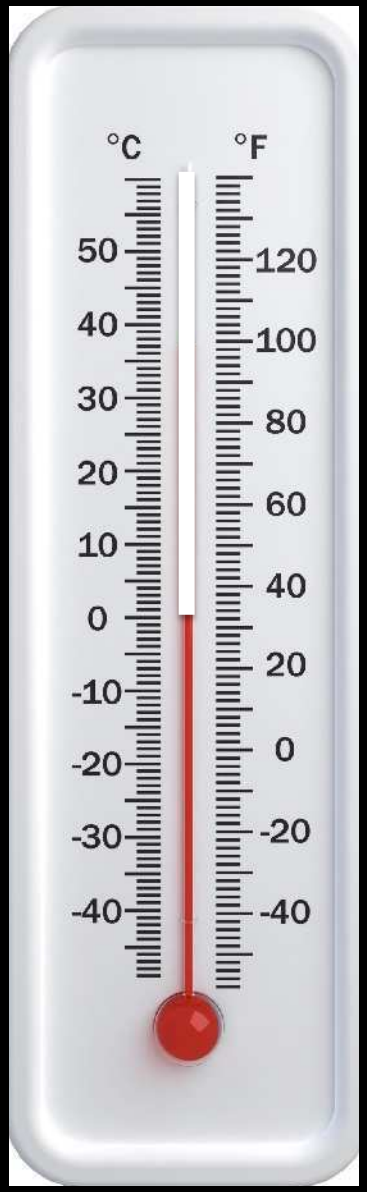

Past Weather in Fairbanks — Graph
Fri, Dec 24
Sat, Dec 25
Sun, Dec 26
Mon, Dec 27
Tue, Dec 28
Wed, Dec 29
Thu, Dec 30
Time
Temp (°F)
Wind (mph)
Hi:-18
Lo:-27
Hi:-20
Lo:-29
Hi:-11
Lo:-22
Hi:-2
Lo:-11
Hi:1
Lo:-2
Hi:7
Lo:5
Hi:10
Lo:7
Hi:14
Lo:10
Hi:14
Lo:12
Hi:28
Hi:32
Lo:28
Hi:37
Lo:32
Hi:37
Lo:36
Hi:36
Lo:21
Hi:21
Lo:9
Hi:12
Lo:7
Hi:16
Lo:12
Hi:16
Lo:15
Hi:21
Lo:16
Hi:27
Lo:21
Hi:32
Lo:30
Hi:32
Lo:23
Hi:23
Lo:16
Hi:16
Lo:14
Hi:14
Lo:9
Hi:5
Lo:-6

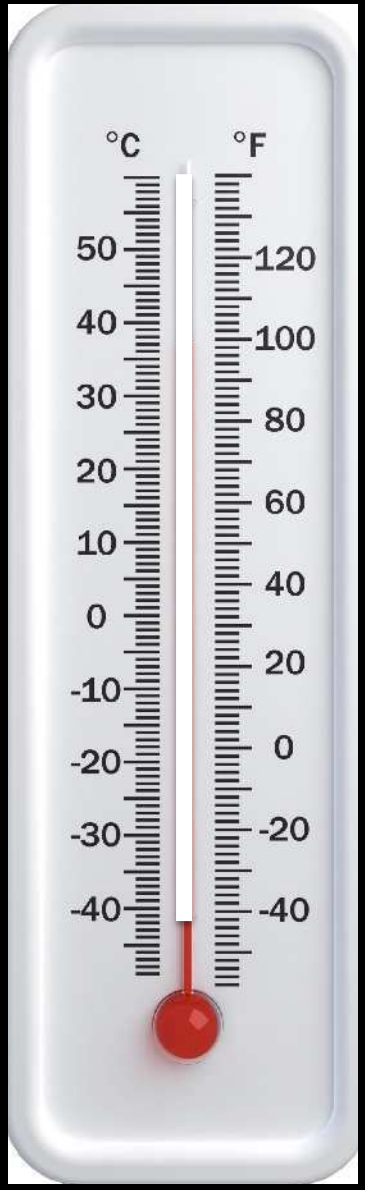
E

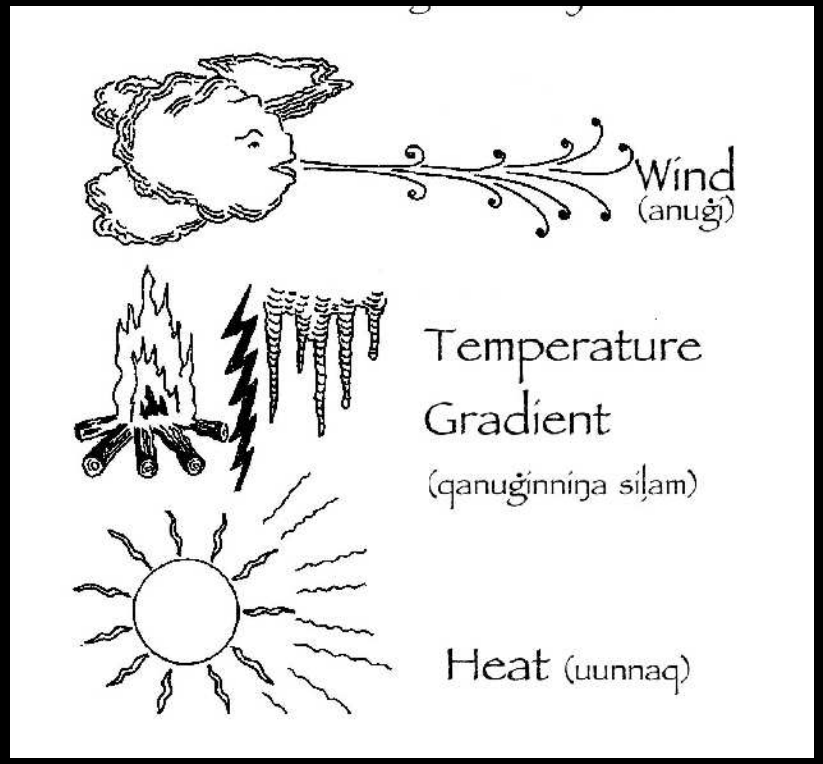
The *white blanket*; the *snow cover* the *snowpack*. *Apun*.
There the global impacts and ramifications arise.

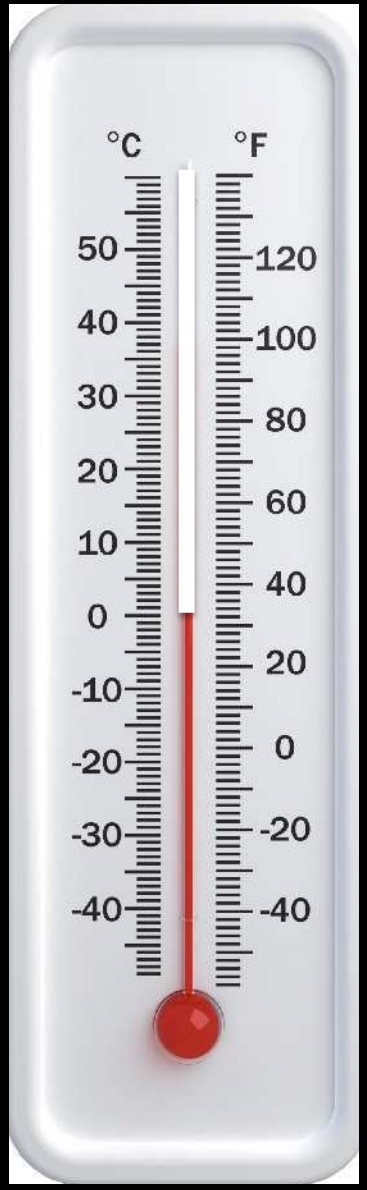


On the ground, conditions are so different than in the clouds.

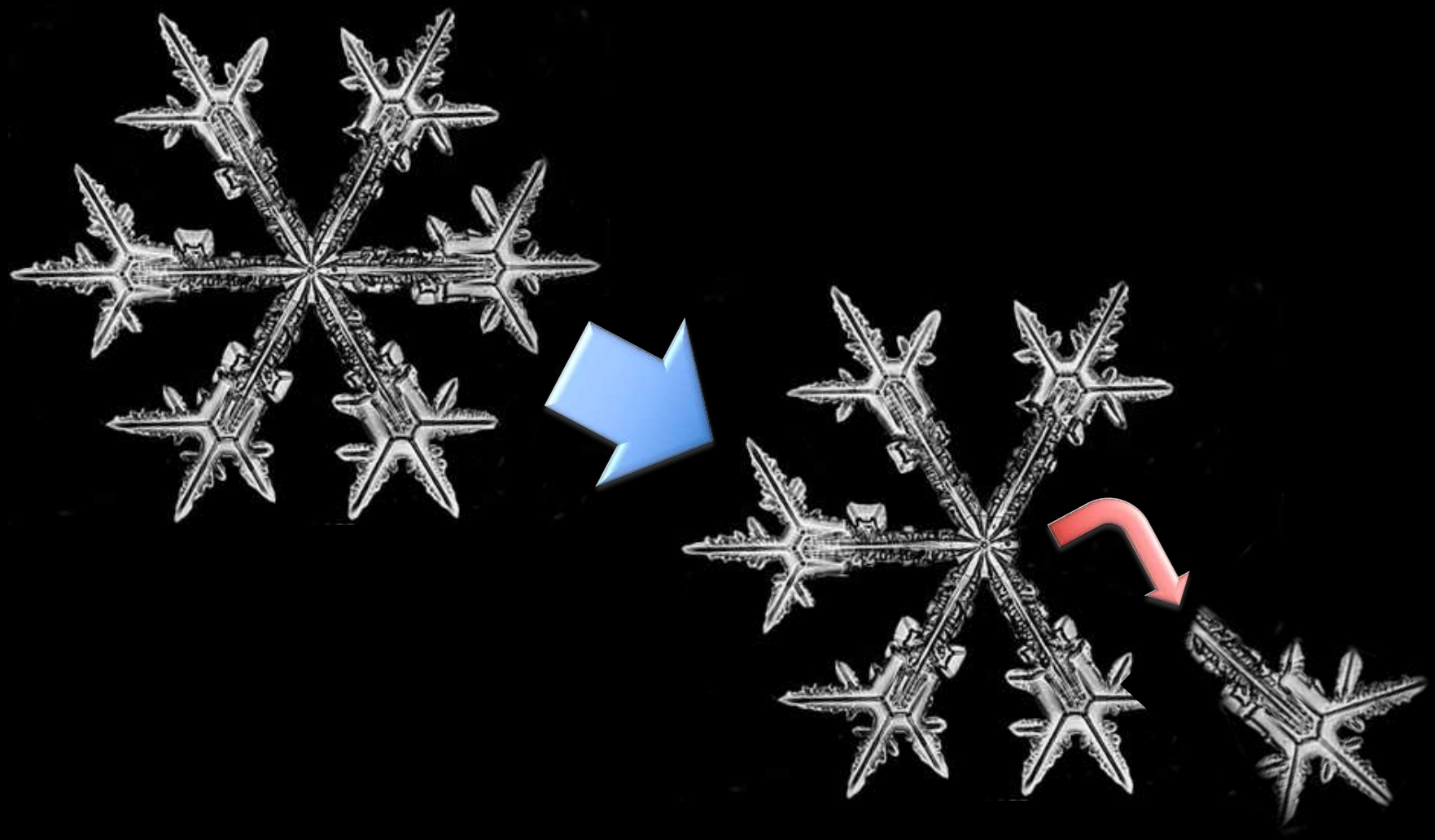



°C
°F
50
40
30
20
10
0
-10
-20
-30
-40
120
100
80
60
40
20
0
-20
-40

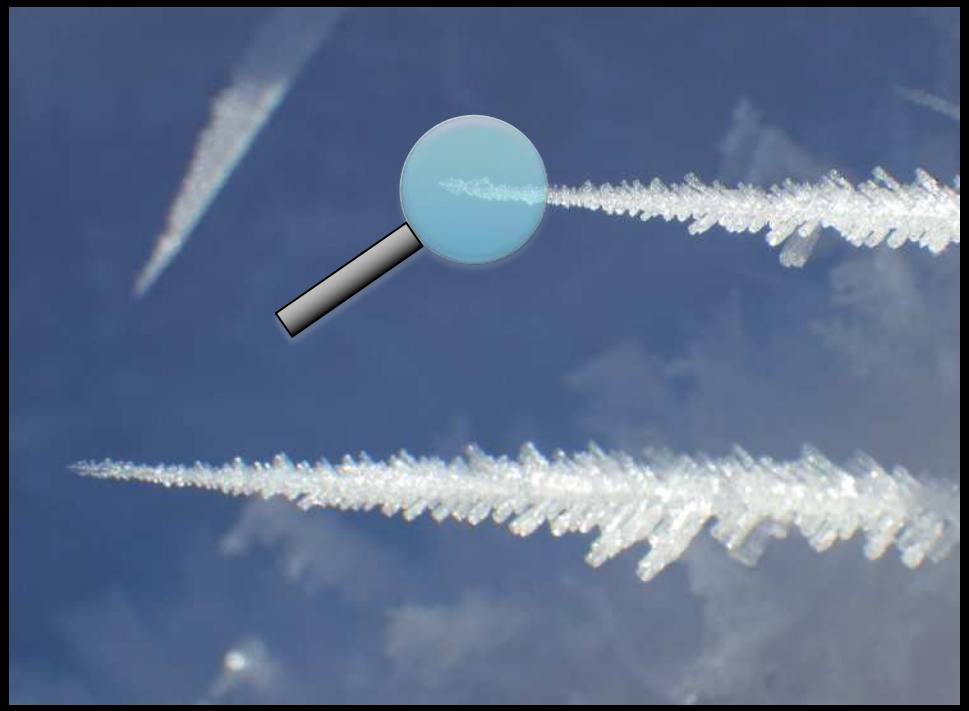

Wind
(anugi)
Temperature
Gradient
(qanuginniŋa siḷam)
Heat (uunnaq)


°C
°F
50
40
30
20
10
0
-10
-20
-30
-40
120
100
80
60
40
20
0
-20
-40

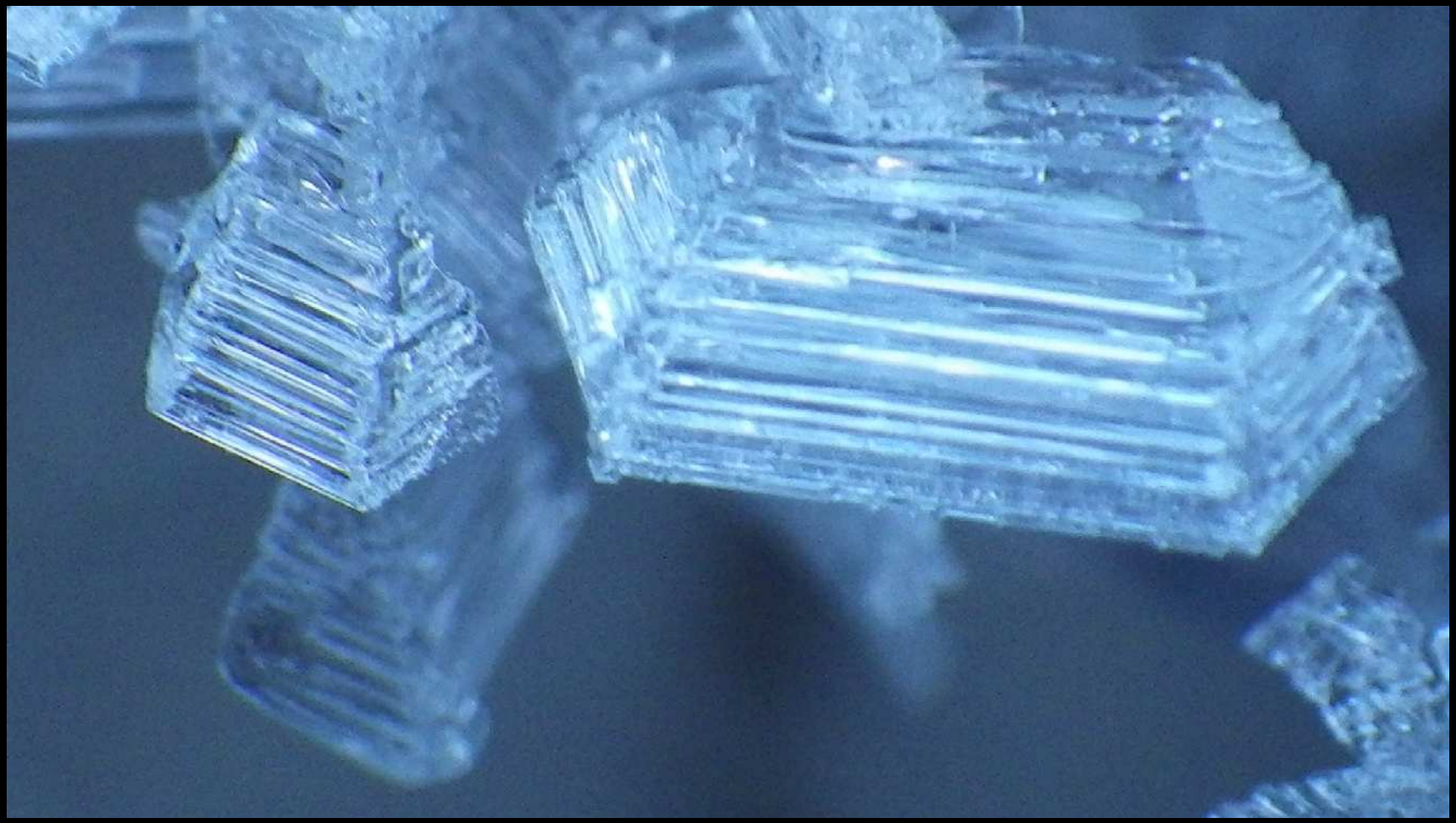
They break apart due to gravity.

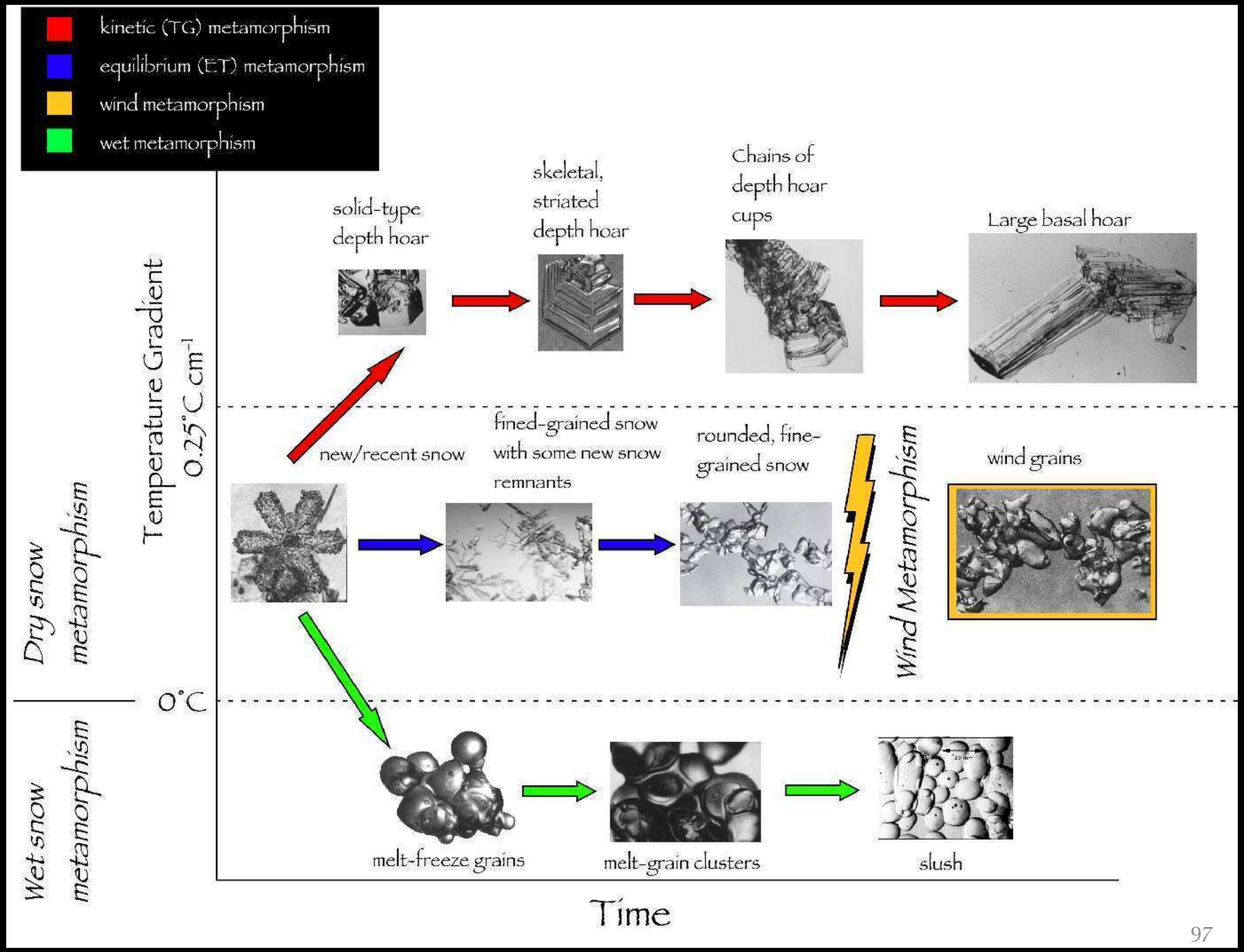


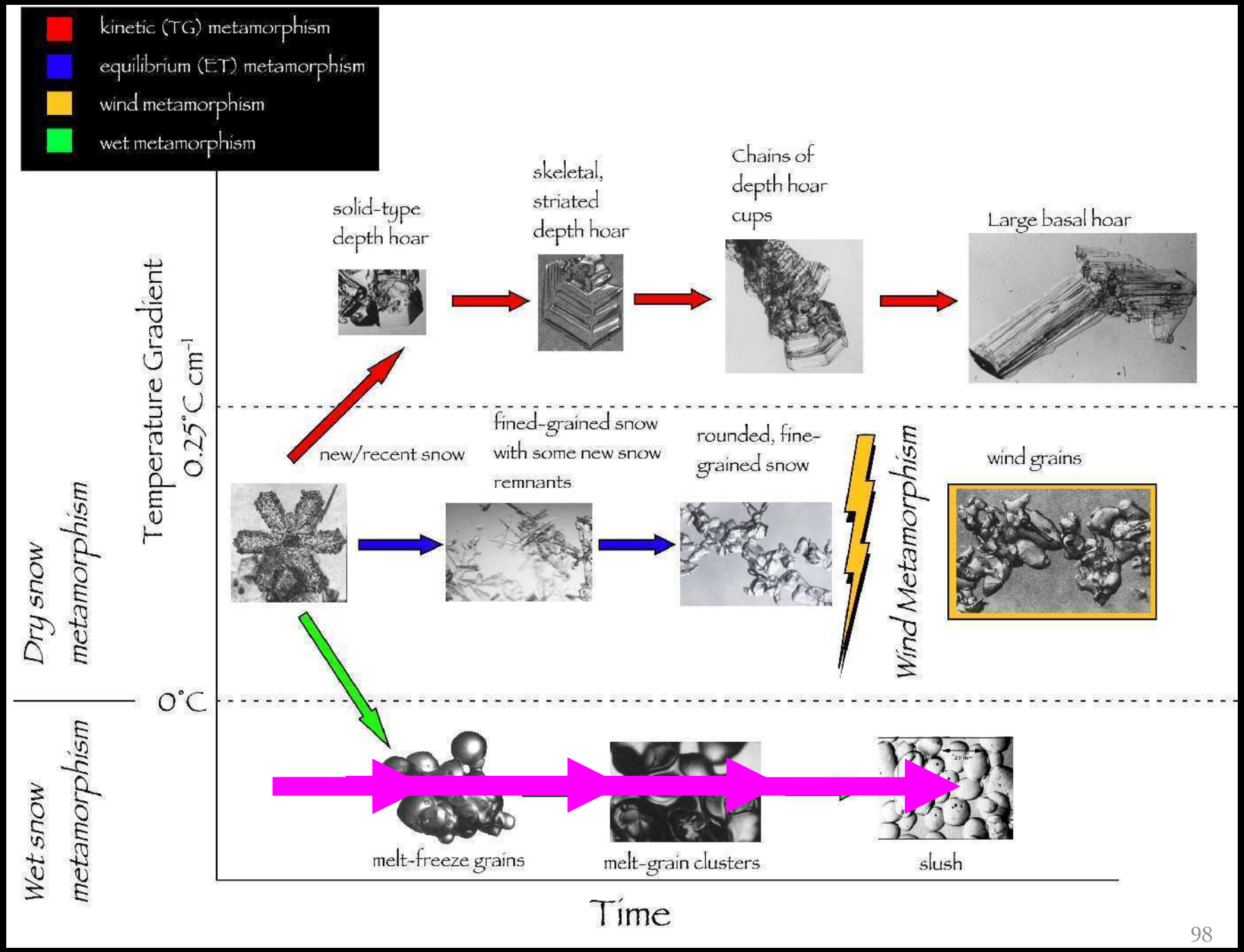
They round due to the Kelvin Effect.

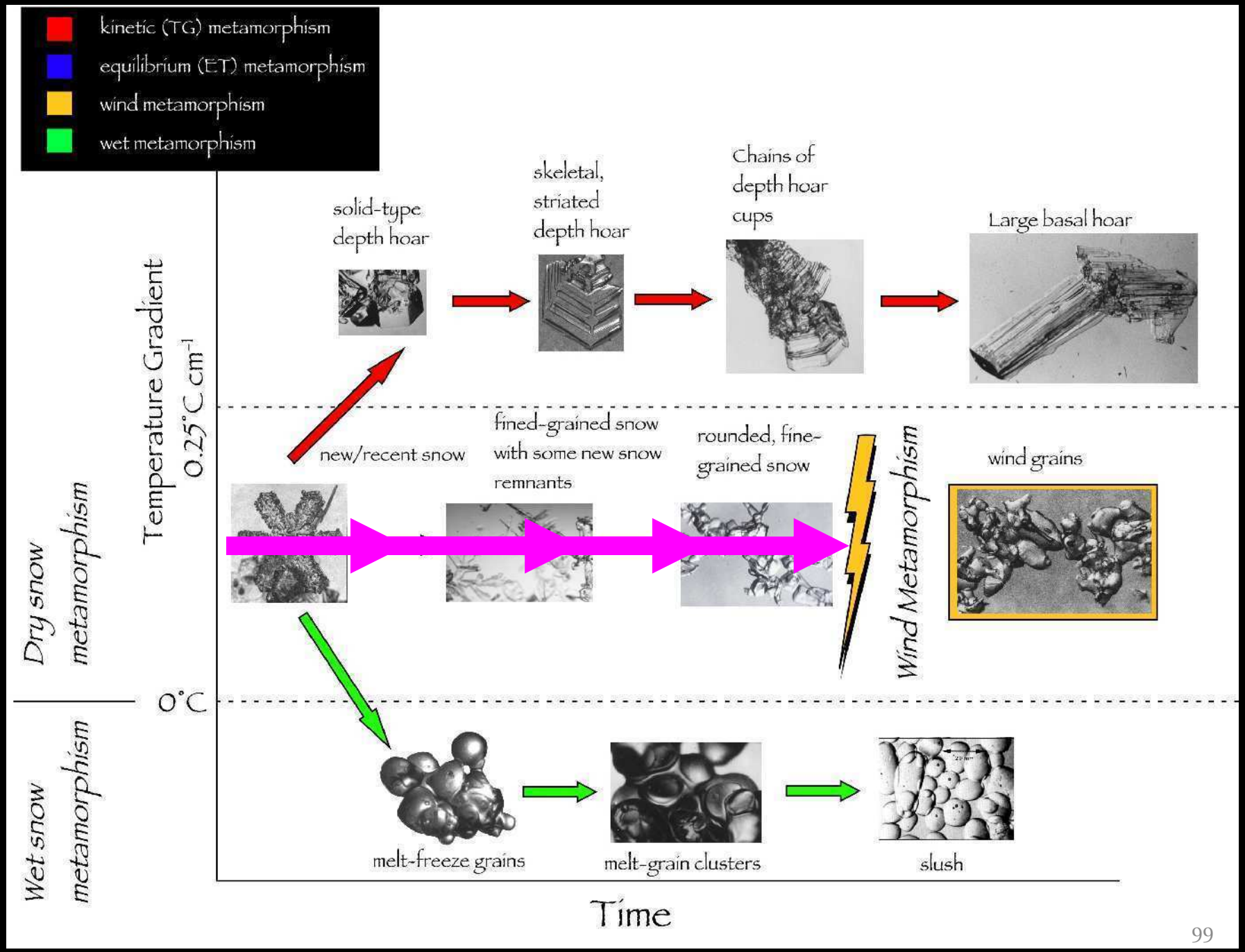


They become re-faceted and striated due to strong temperature gradients across the pack.




kinetic (TG) metamorphism
equilibrium (ET) metamorphism
wind metamorphism
wet metamorphism
Temperature Gradient
0.25°C cm⁻¹
solid-type depth hoar
skeletal, striated depth hoar
Chains of depth hoar cups
Large basal hoar
new/recent snow
fined-grained snow with some new snow remnants
rounded, fine-grained snow
Wind Metamorphism
wind grains
Dry snow metamorphism
0°C
Wet snow metamorphism
melt-freeze grains
melt-grain clusters
slush
Time


kinetic (TG) metamorphism
equilibrium (ET) metamorphism
wind metamorphism
wet metamorphism
Temperature Gradient
0.25°C cm⁻¹
solid-type depth hoar
skeletal, striated depth hoar
Chains of depth hoar cups
Large basal hoar
new/recent snow
fined-grained snow with some new snow remnants
rounded, fine-grained snow
Wind Metamorphism
wind grains
Dry snow metamorphism
0°C
Wet snow metamorphism
melt-freeze grains
melt-grain clusters
slush
Time


kinetic (TG) metamorphism
equilibrium (ET) metamorphism
wind metamorphism
wet metamorphism
Temperature Gradient
0.25°C cm⁻¹
solid-type depth hoar
skeletal, striated depth hoar
Chains of depth hoar cups
Large basal hoar
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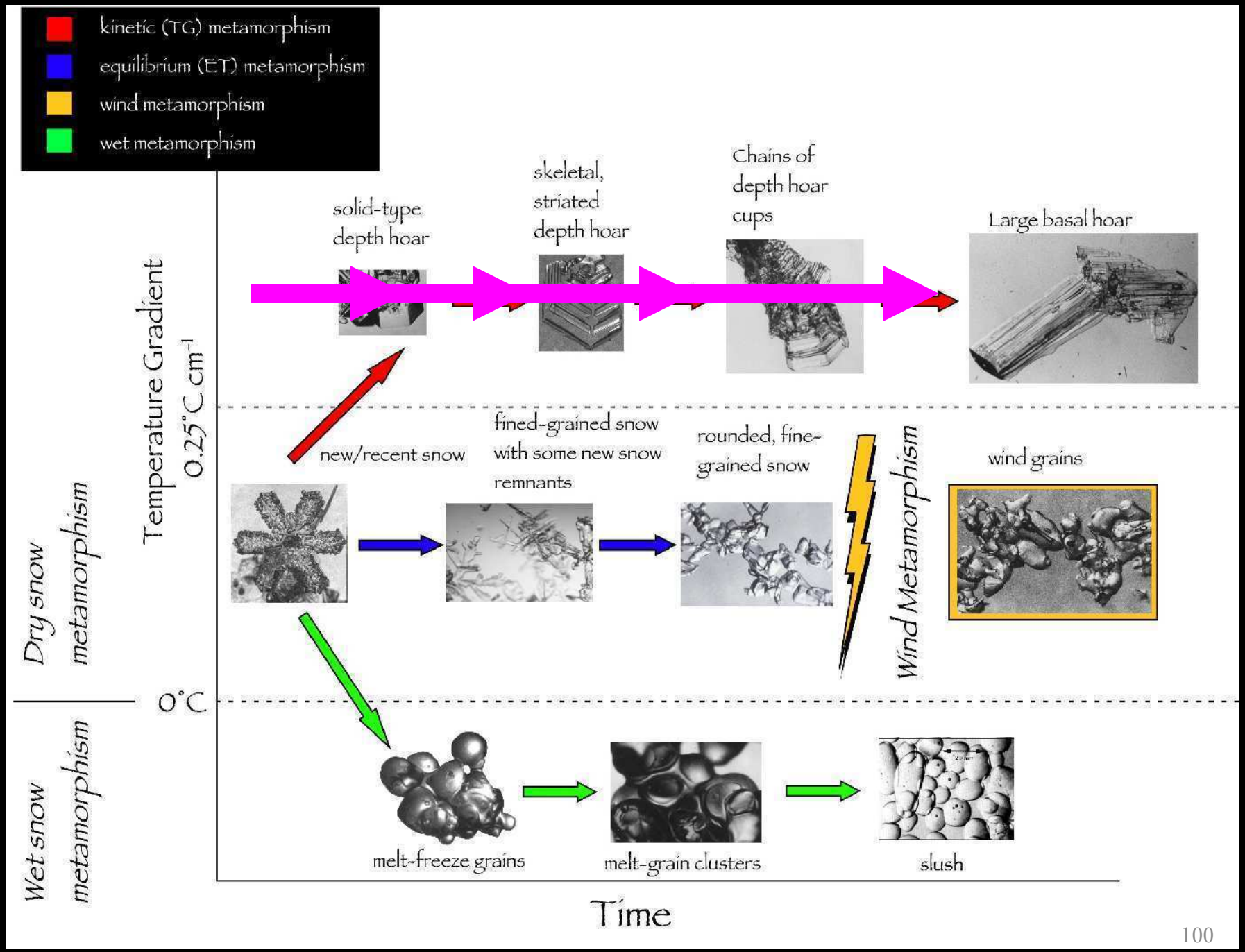
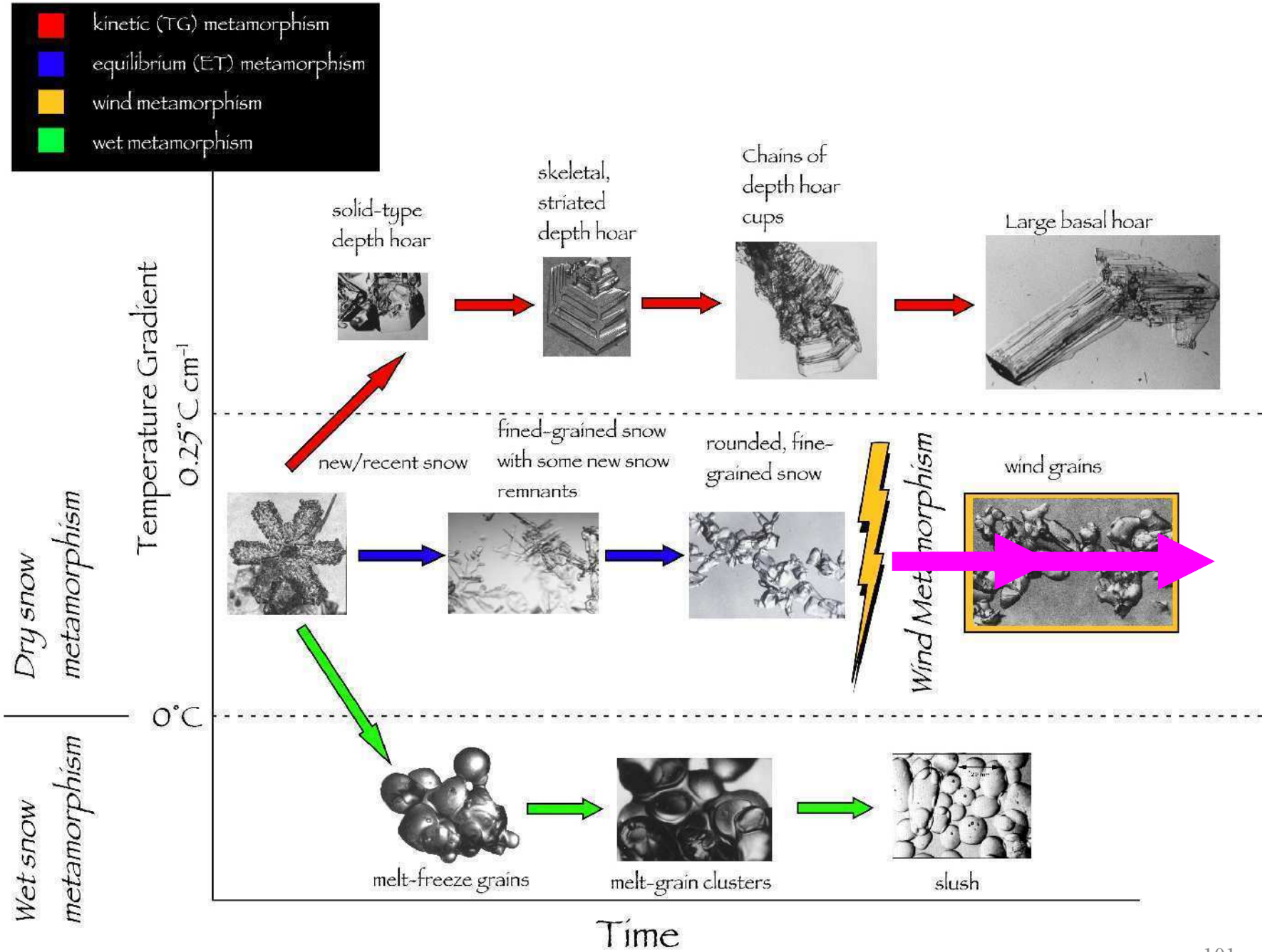
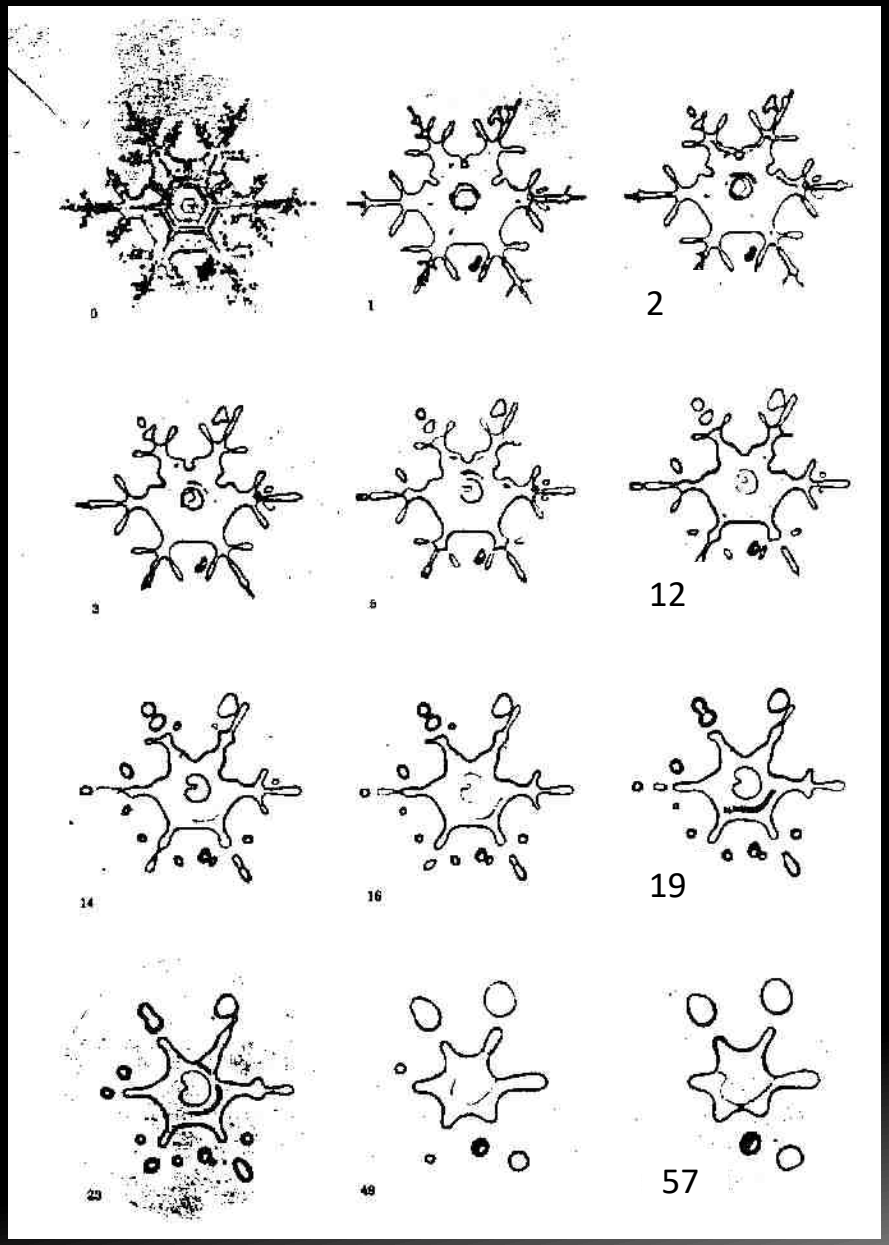
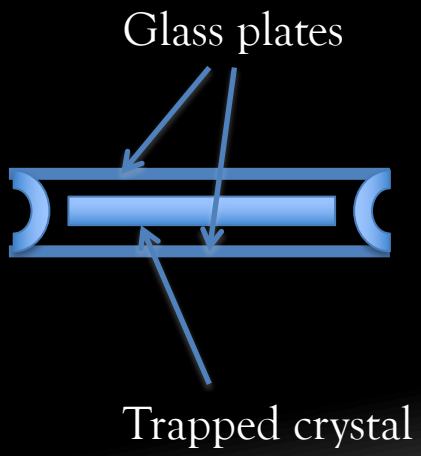
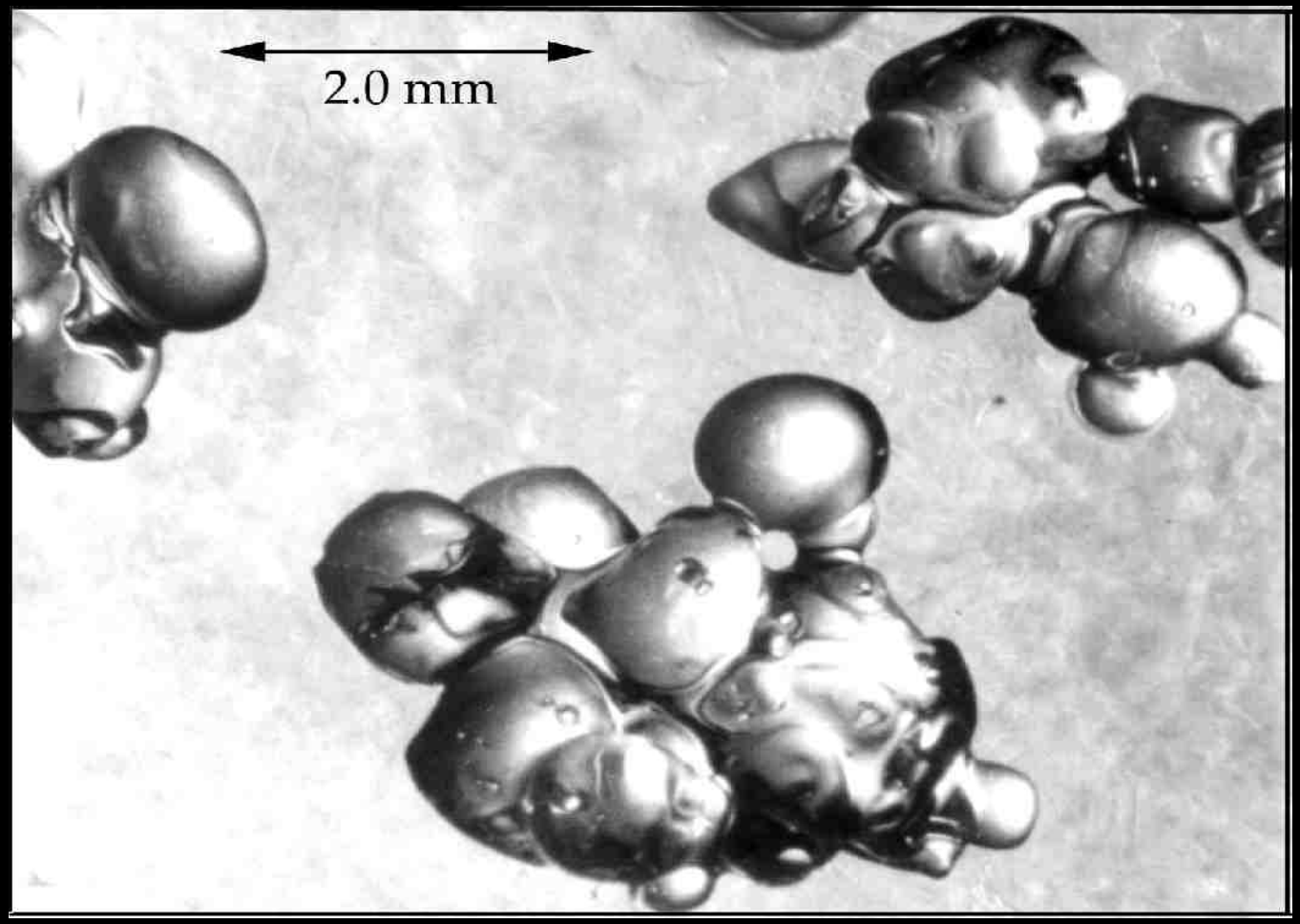
fined-grained snow with some new snow remnants
rounded, fine-grained snow
Wind Metamorphism
wind grains
Dry snow metamorphism
0°C
Wet snow metamorphism
melt-freeze grains
melt-grain clusters
slush
Time

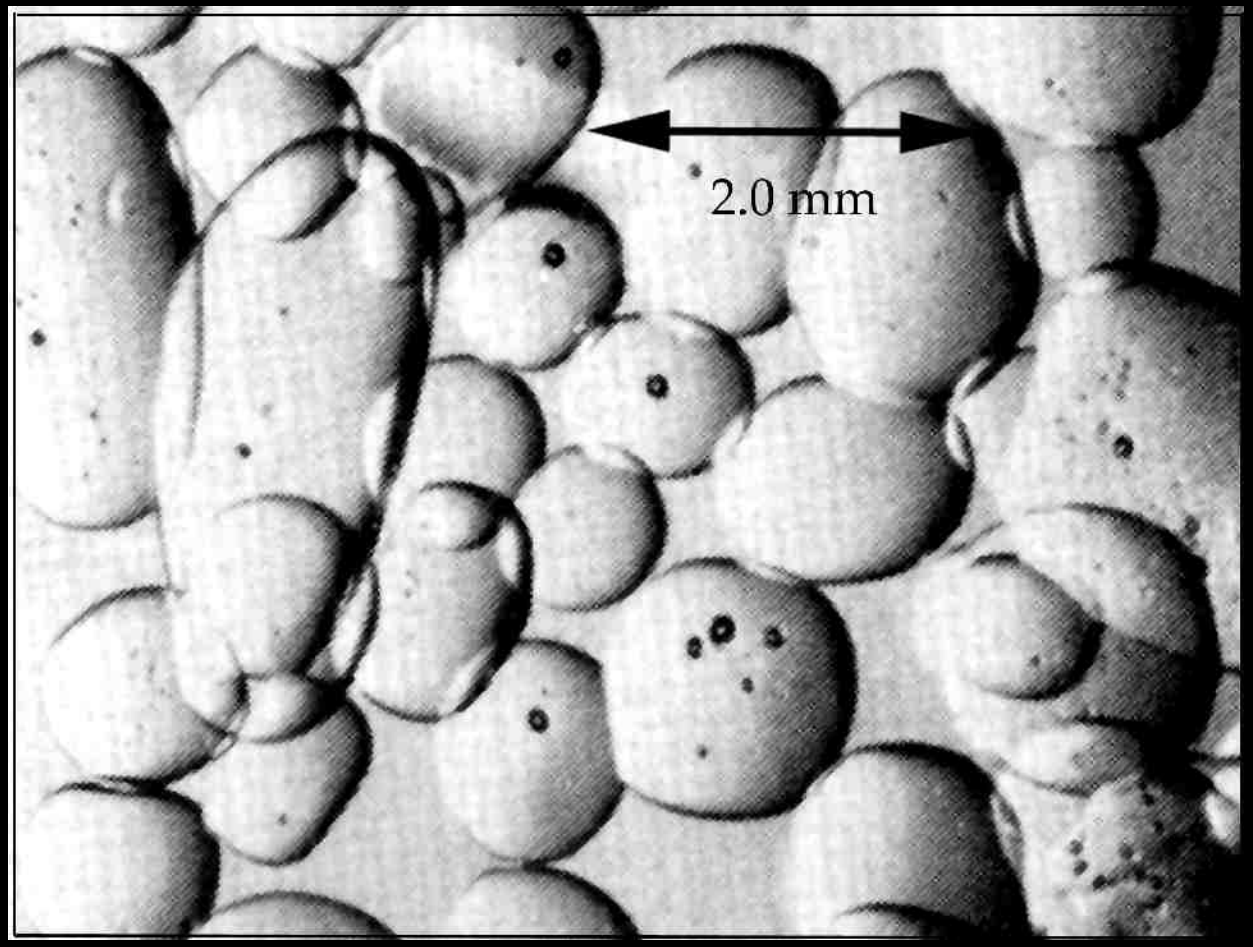

kinetic (TG) metamorphism
equilibrium (ET) metamorphism
wind metamorphism
wet metamorphism
solid-type depth hoar
skeletal, striated depth hoar
Chains of depth hoar cups
Large basal hoar
Temperature Gradient 0.25°C cm⁻¹
new/recent snow
fined-grained snow with some new snow remnants
rounded, fine-grained snow
Wind Metamorphism
wind grains
Dry snow metamorphism
0°C
Wet snow metamorphism
melt-freeze grains
melt-grain clusters
slush
Time

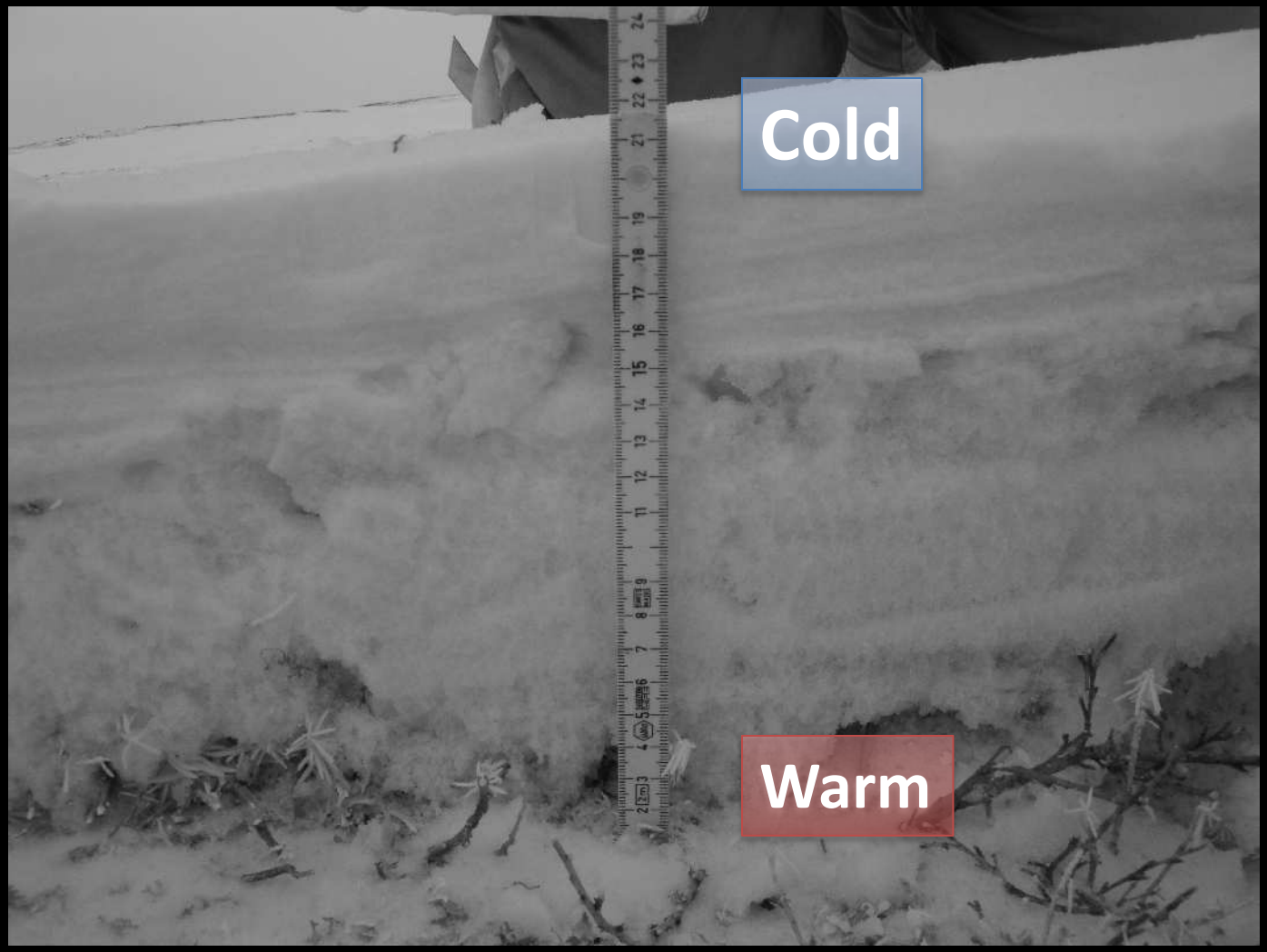

kinetic (TG) metamorphism
equilibrium (ET) metamorphism
wind metamorphism
wet metamorphism
Temperature Gradient
0.25°C cm⁻¹
solid-type depth hoar
skeletal, striated depth hoar
Chains of depth hoar cups
Large basal hoar
new/recent snow
fined-grained snow with some new snow remnants
rounded, fine-grained snow
Wind Metamorphism
wind grains
Dry snow metamorphism
0°C
Wet snow metamorphism
melt-freeze grains
melt-grain clusters
slush
Time

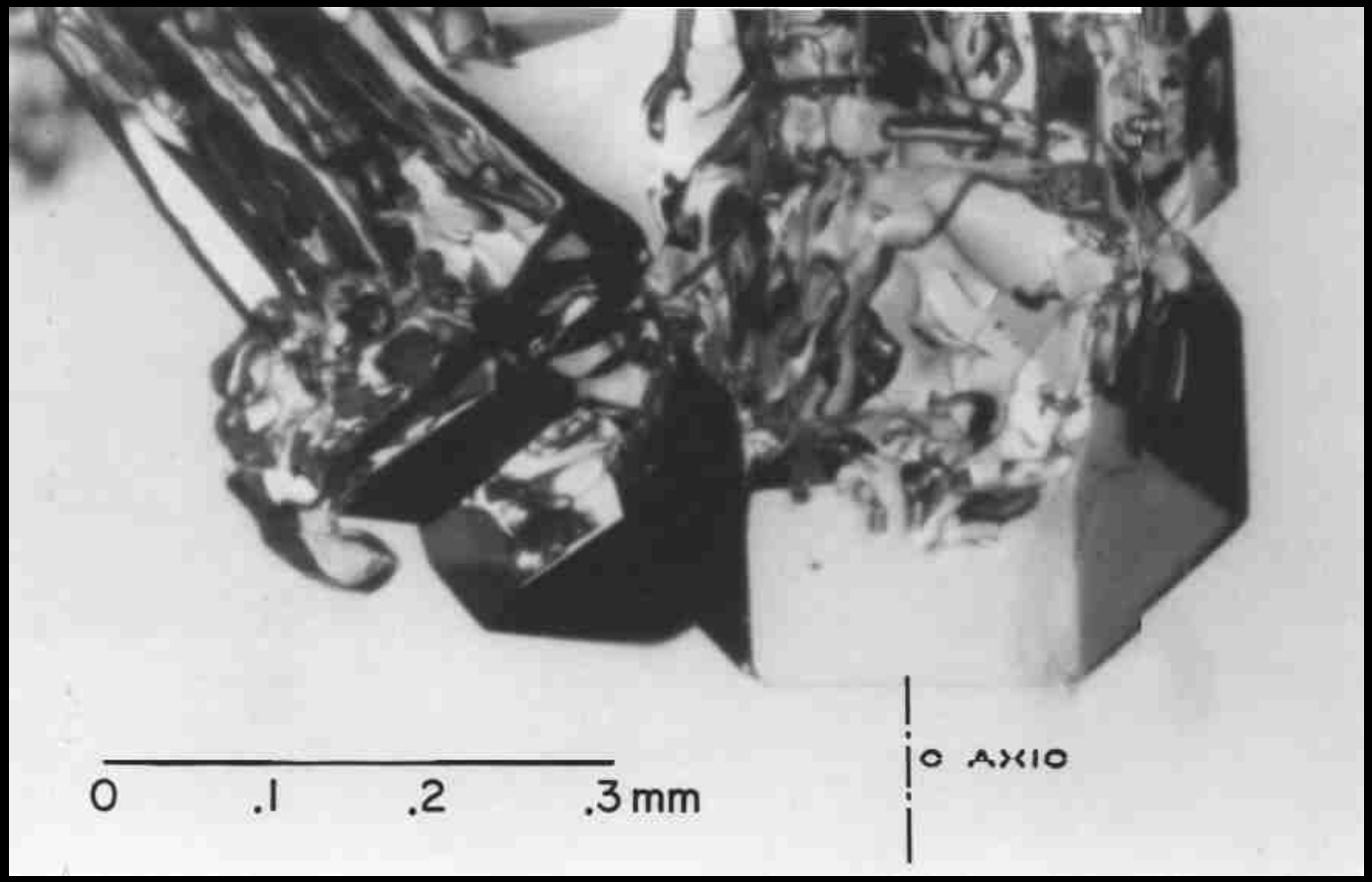

0
1
2
3
5
12
14
16
19
23
49
57


Glass plates
Trapped crystal

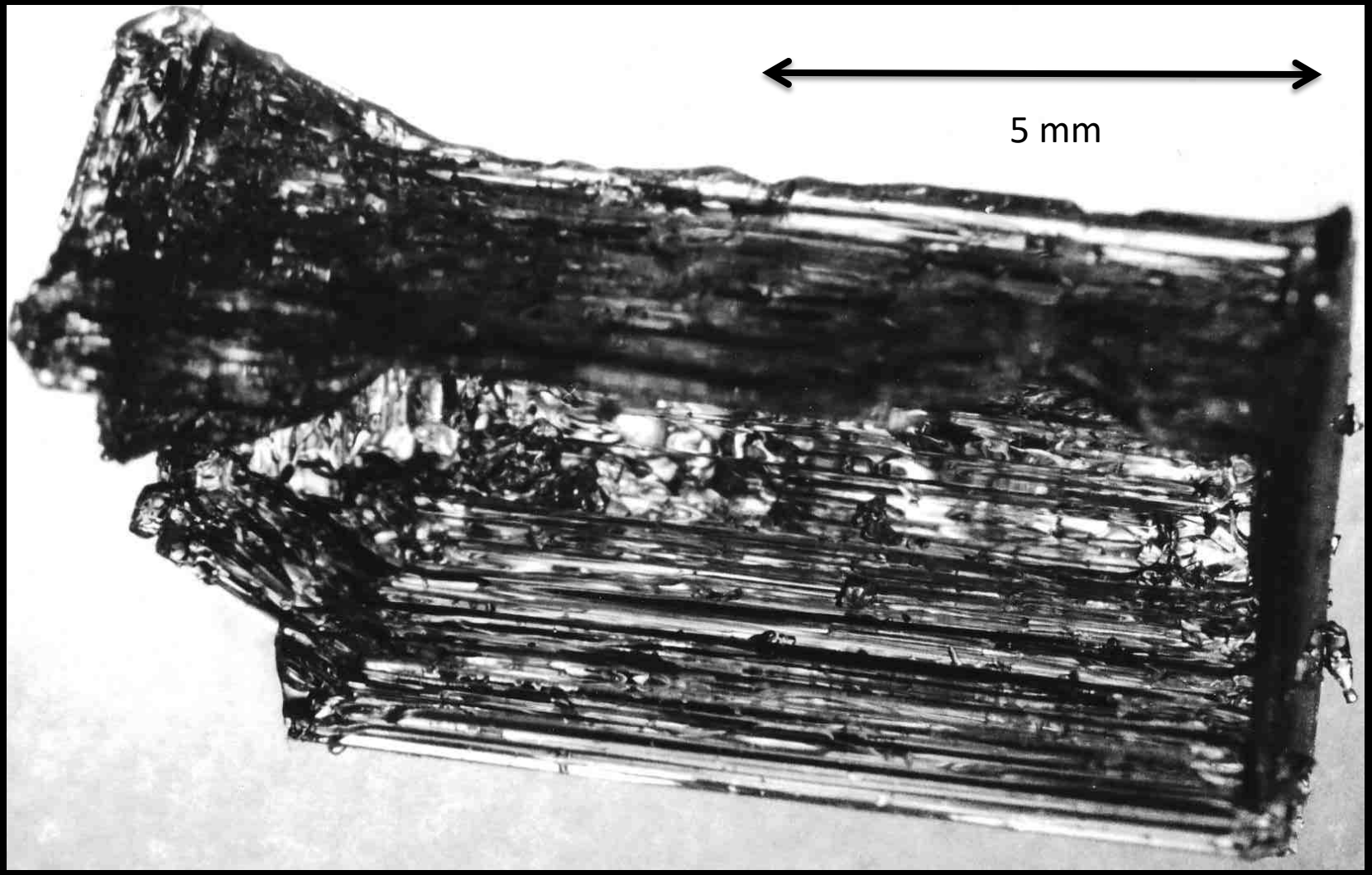

2.0 mm


2.0 mm


Cold
Warm


0 .1 .2 .3 mm
c AXIS

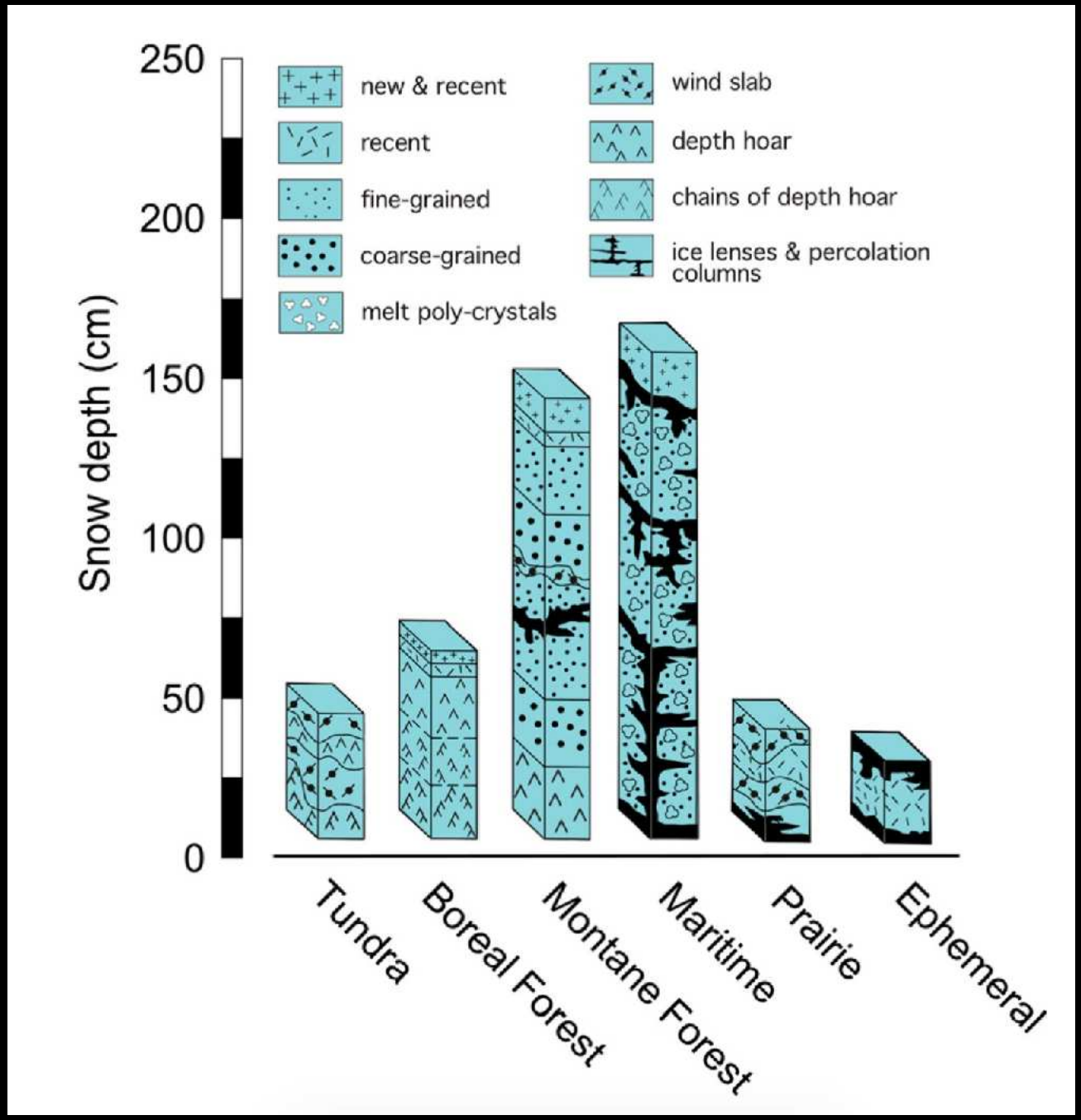
5 mm

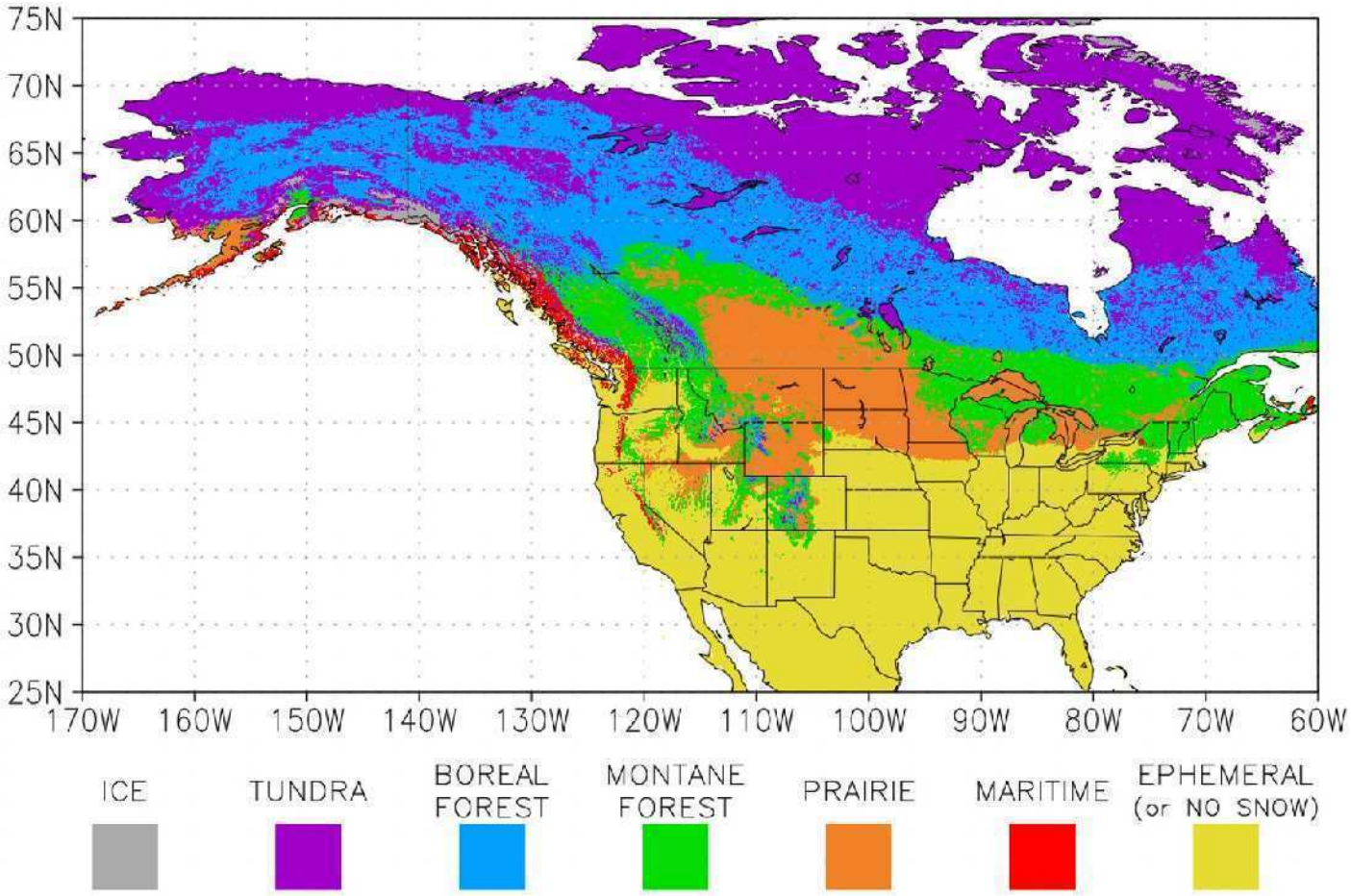

5 mm

Lastly, they can be pulverized and packed together by the wind then fused (sintered) into a solid mass.

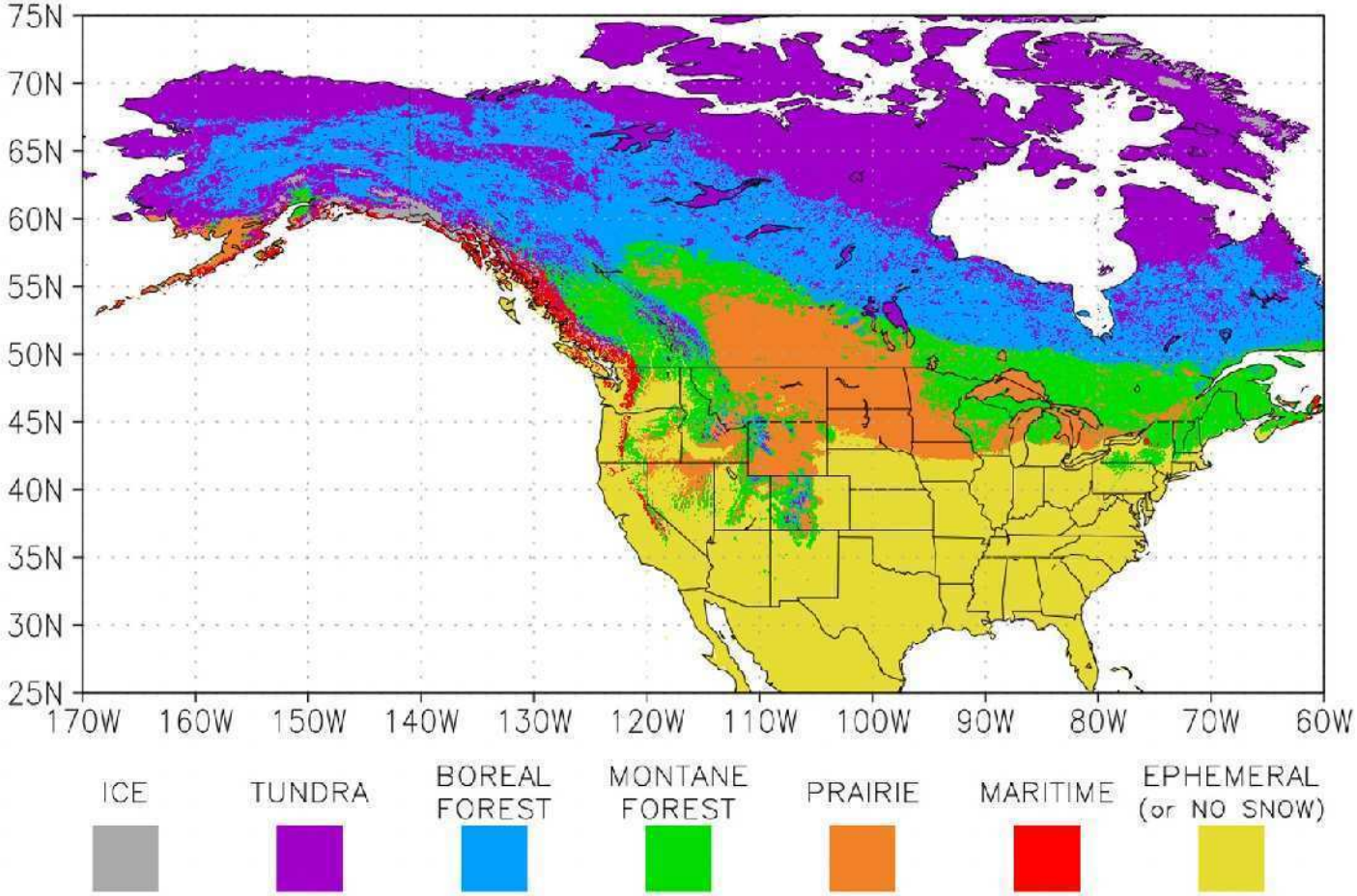

80x
1.0mm

What next for snow?


Snow depth (cm)
250
200
150
100
50
0
new & recent
recent
fine-grained
coarse-grained
melt poly-crystals
wind slab
depth hoar
chains of depth hoar
ice lenses & percolation columns
Tundra
Boreal Forest
Montane Forest
Maritime
Prairie
Ephemeral


75N
70N
65N
60N
55N
50N
45N
40N
35N
30N
25N
170W
160W
150W
140W
130W
120W
110W
100W
90W
80W
70W
60W
ICE
TUNDRA
BOREAL FOREST
MONTANE FOREST
PRAIRIE
MARITIME
EPHEMERAL (or NO SNOW)

889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150W
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120W
110W
100W
90W
80W
70W
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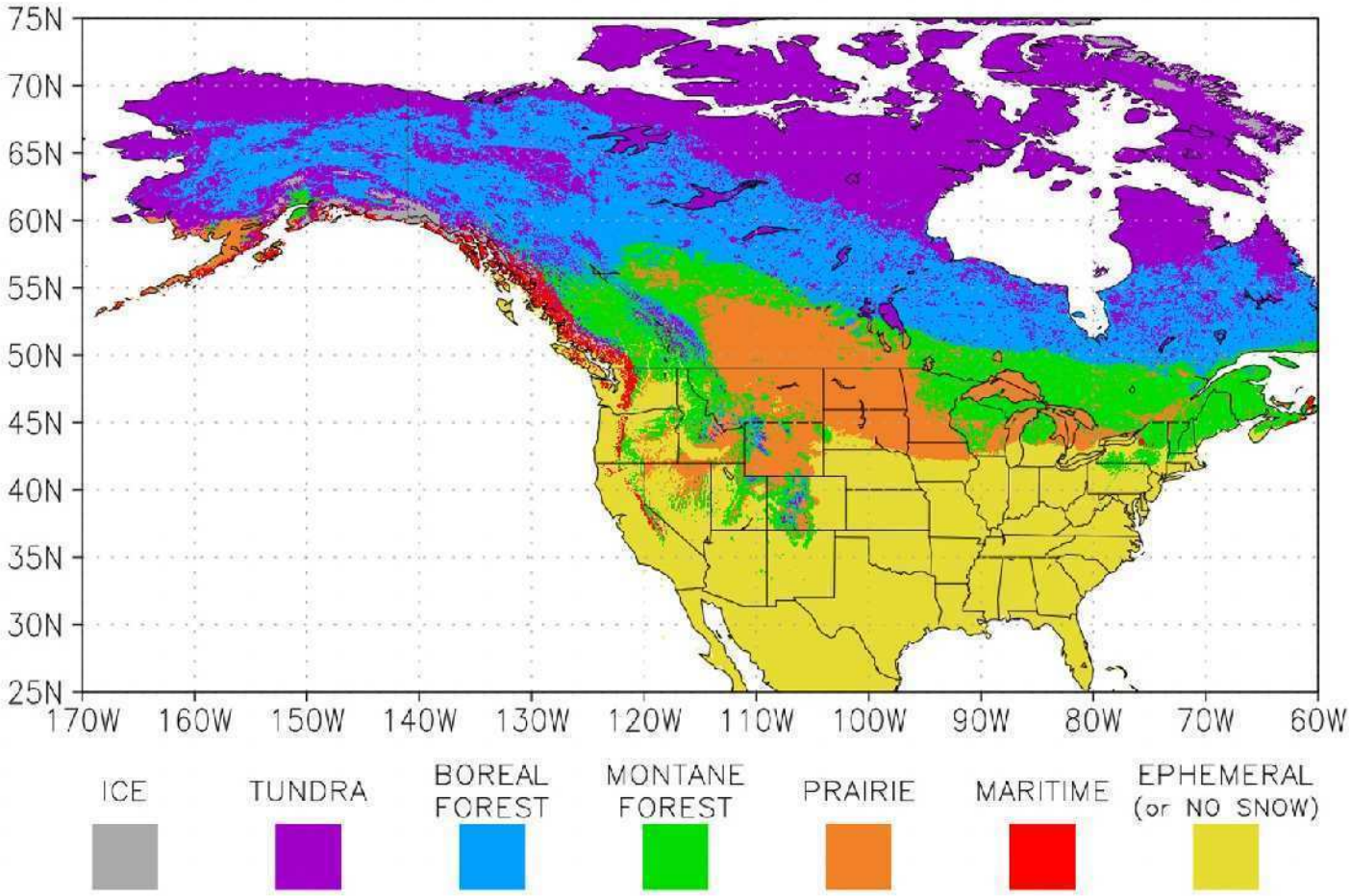
ICE
TUNDRA
BOREAL FOREST
MONTANE FOREST
PRAIRIE
MARITIME
EPHEMERAL (or NO SNOW)

889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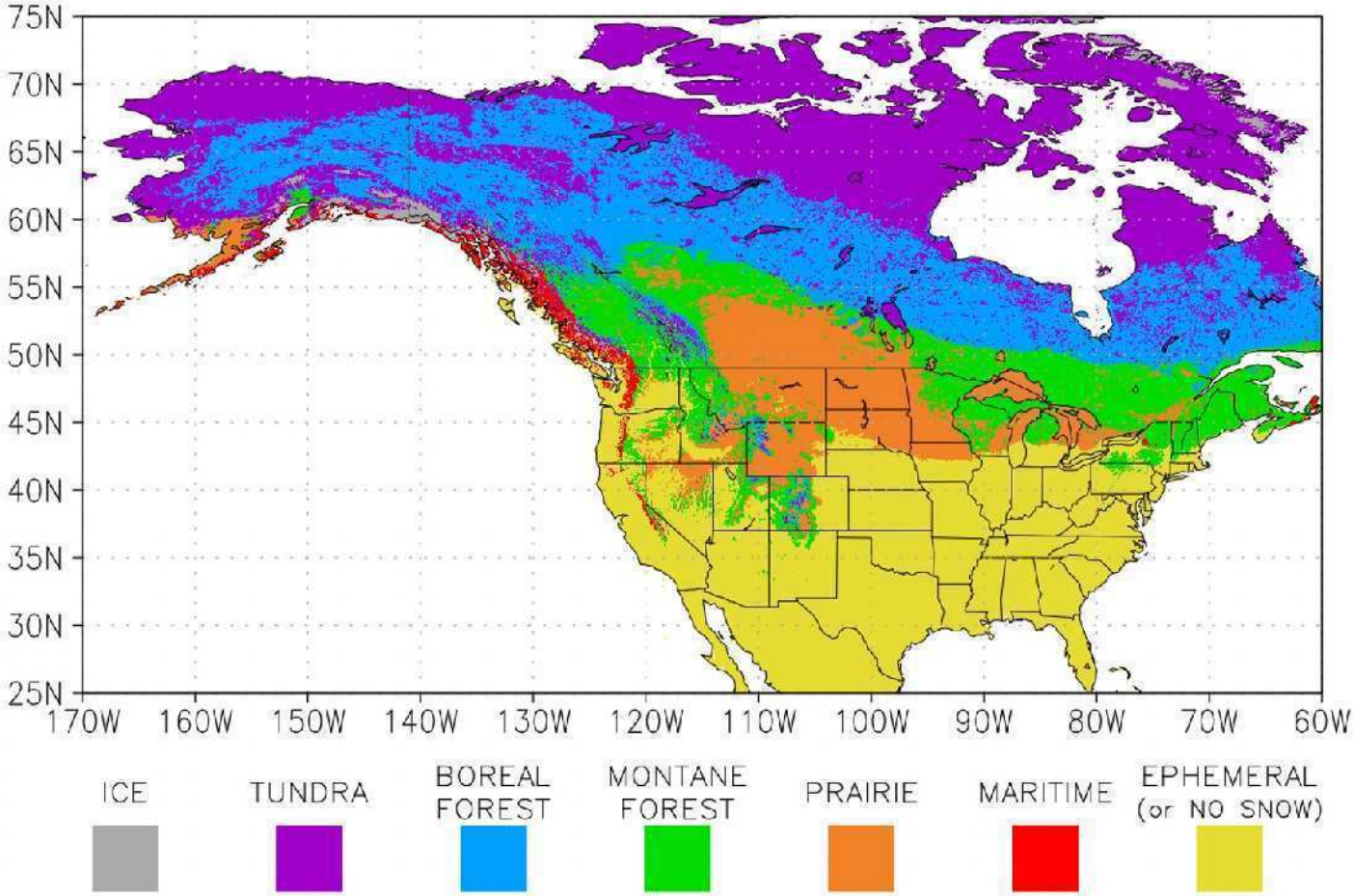
ICE
TUNDRA
BOREAL FOREST
MONTANE FOREST
PRAIRIE
MARITIME
EPHEMERAL (or NO SNOW)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ICE
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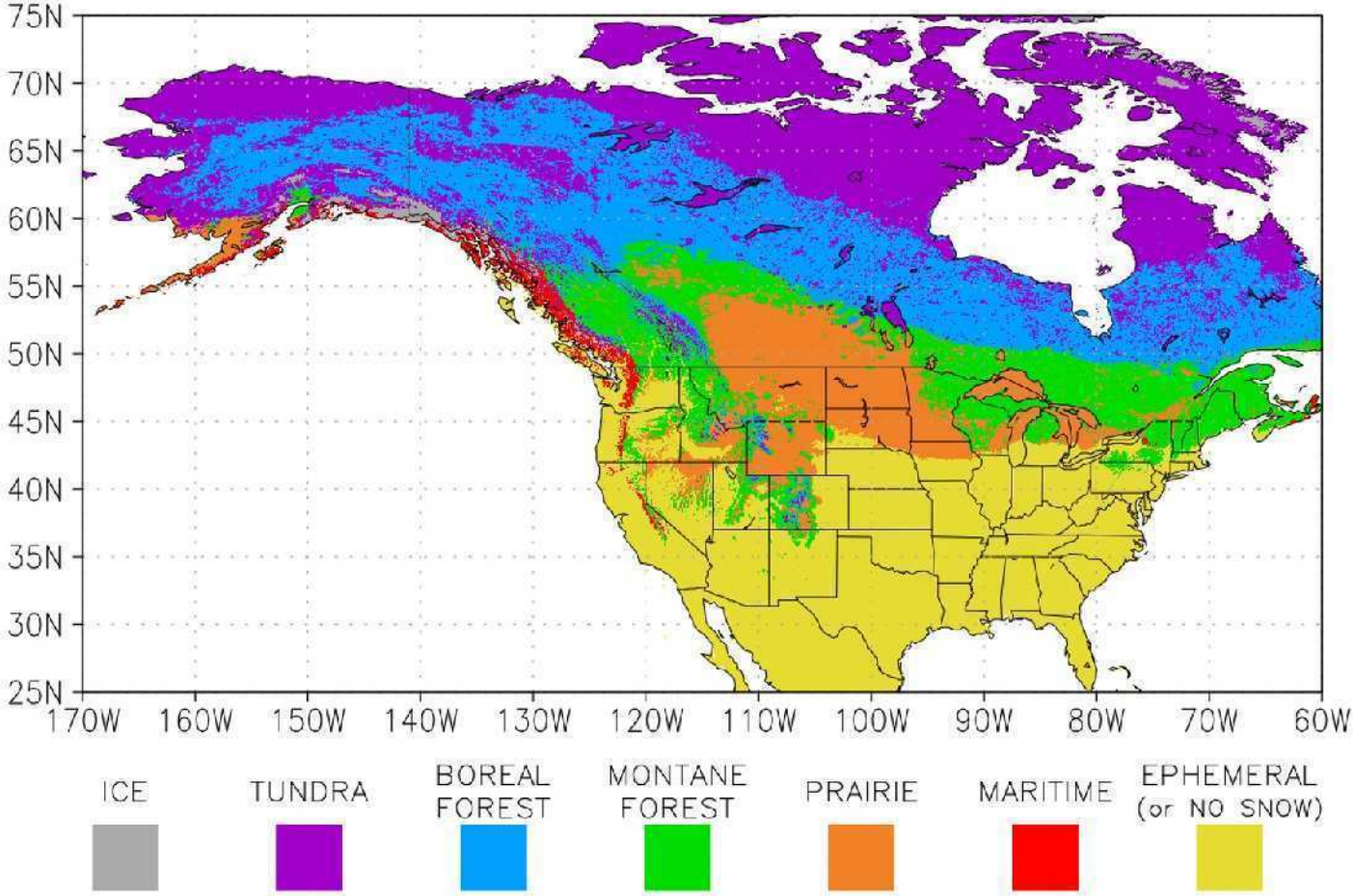
BOREAL FOREST
MONTANE FOREST
PRAIRIE
MARITIME
EPHEMERAL (or NO SNOW)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ICE
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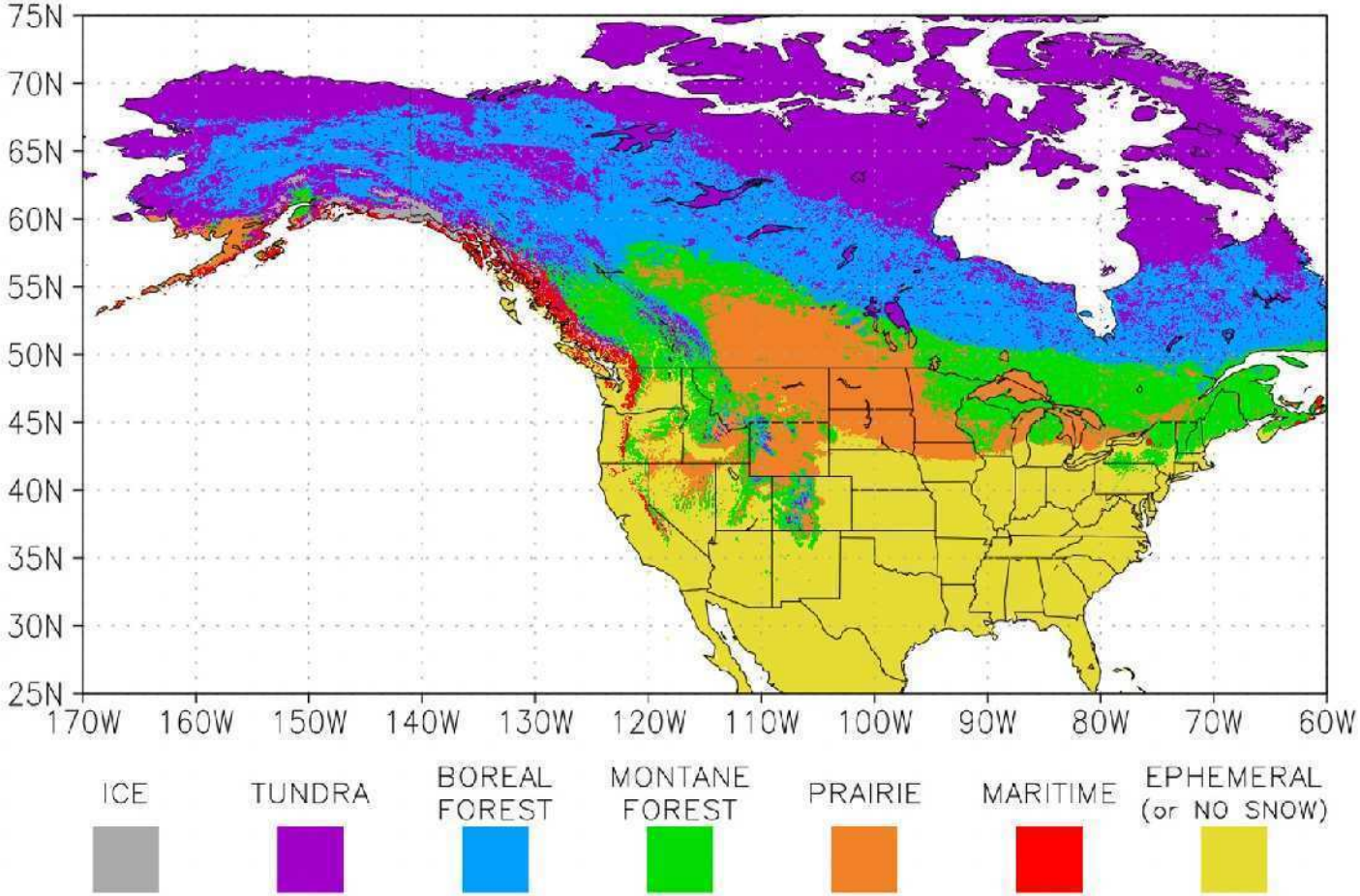
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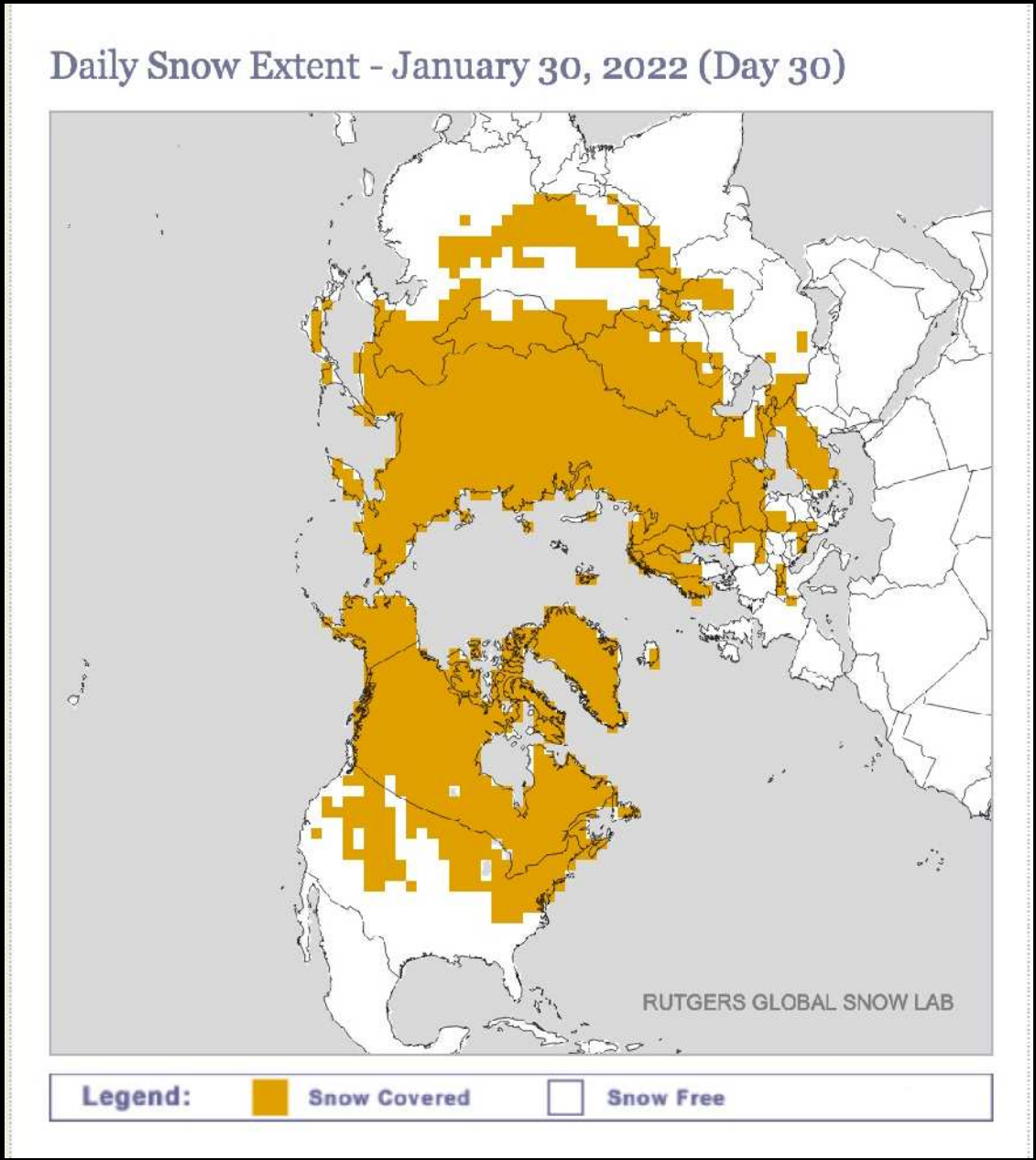
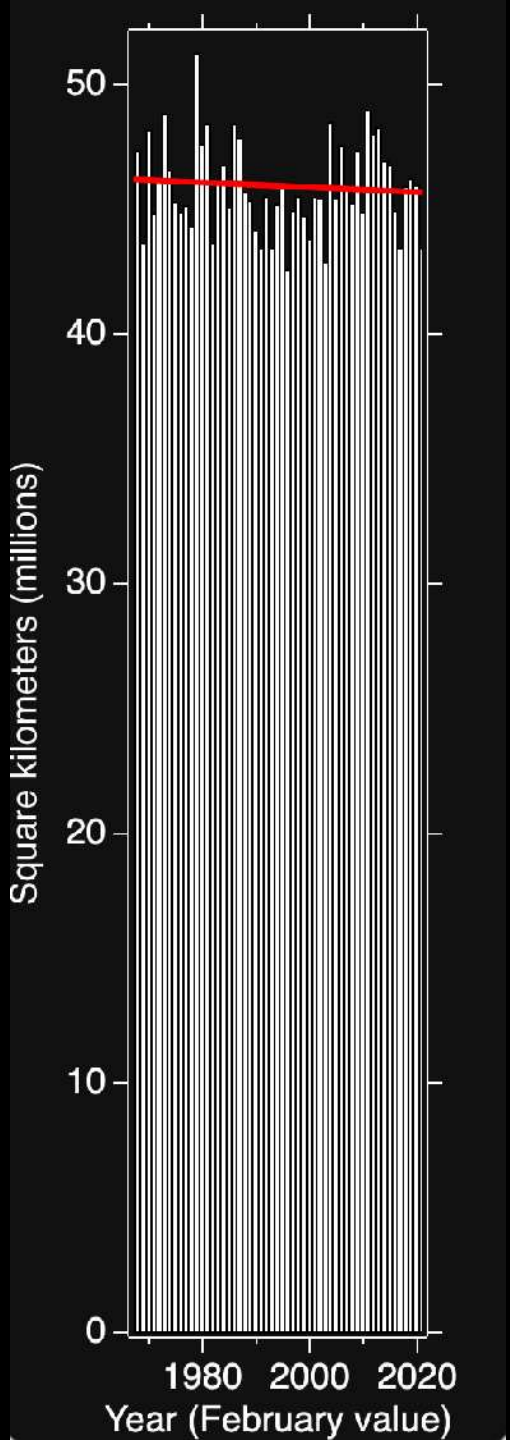
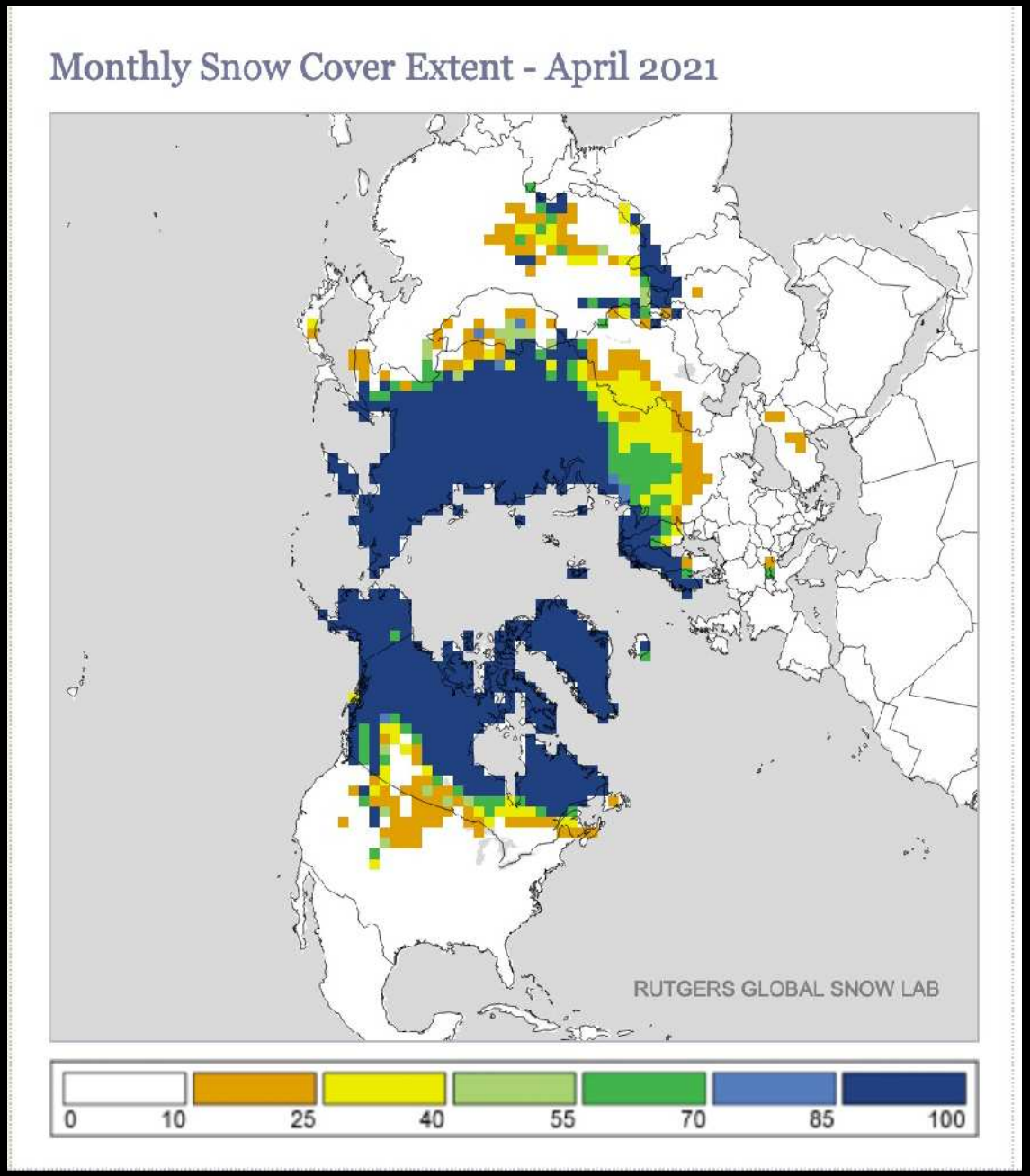
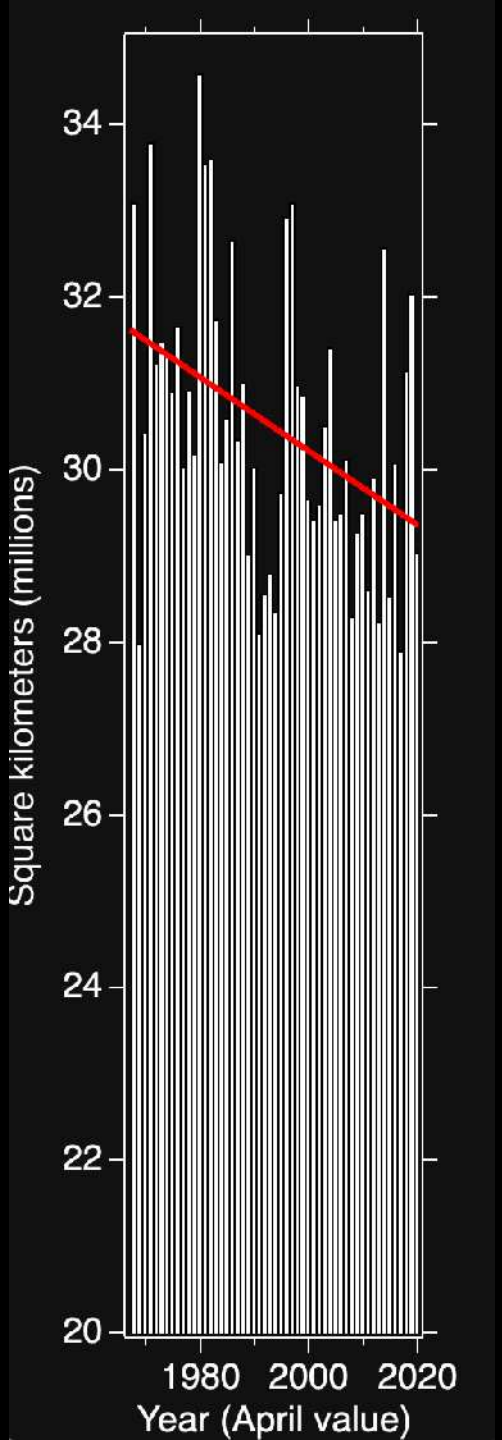
ICE
TUNDRA
BOREAL FOREST
MONTANE FOREST
PRAIRIE
MARITIME
EPHEMERAL (or NO SNOW)


Daily Snow Extent - January 30, 2022 (Day 30)
RUTGERS GLOBAL SNOW LAB
Legend:
Snow Covered
Snow Free


Square kilometers (millions)
0
10
20
30
40
50
1980
2000
2020
Year (February value)

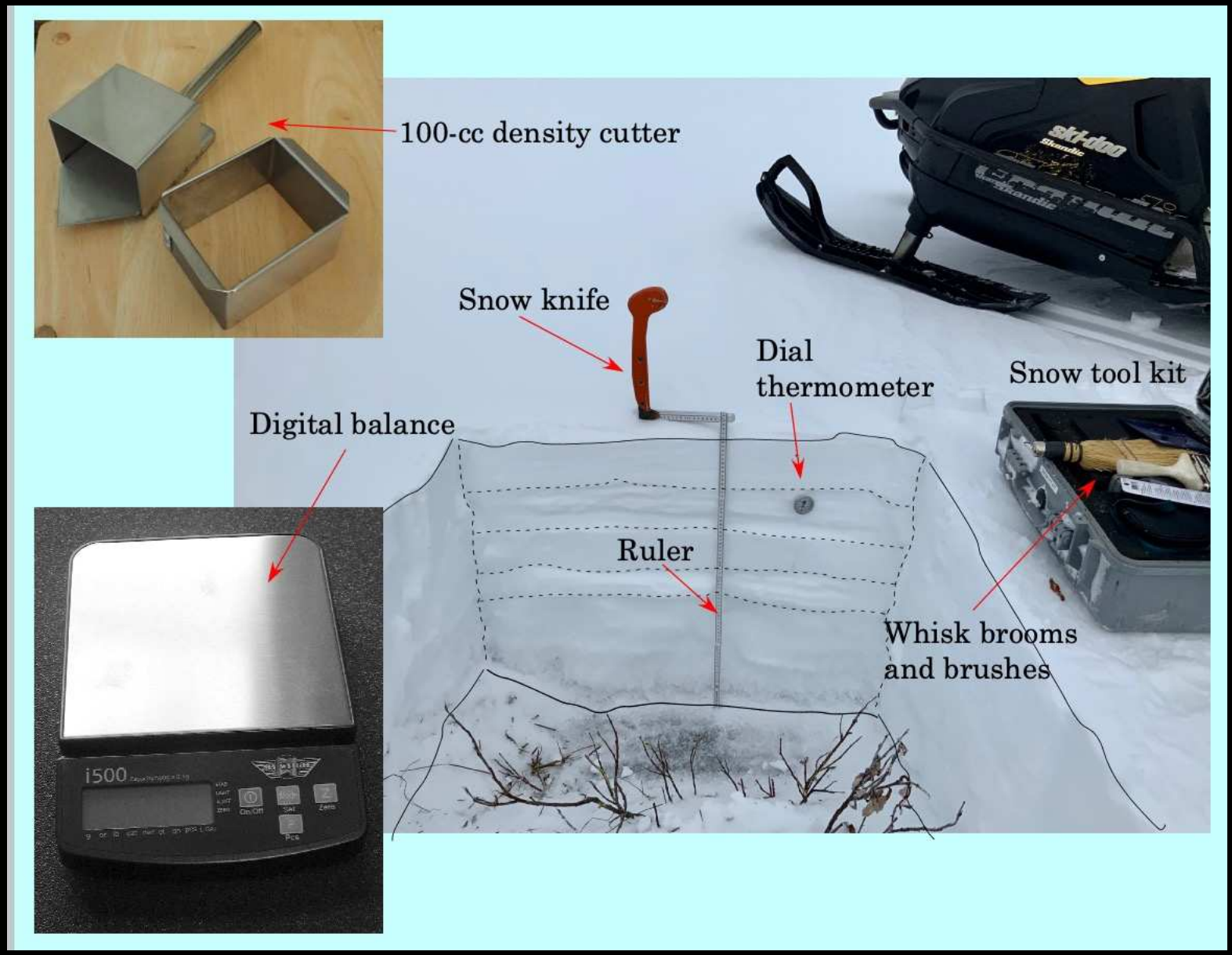

Monthly Snow Cover Extent - April 2021
RUTGERS GLOBAL SNOW LAB
0
10
25
40
55
70
85
100

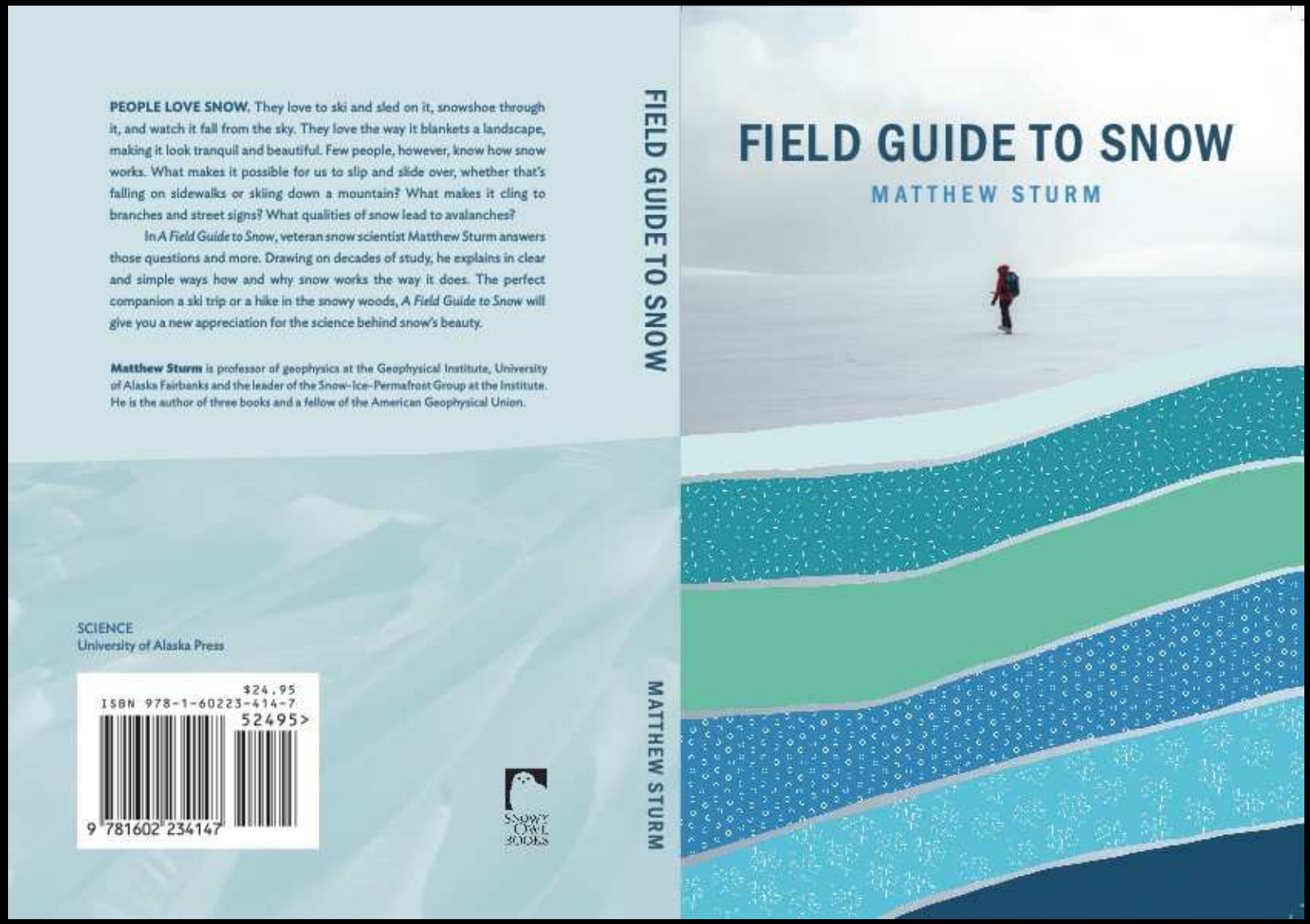

Square kilometers (millions)
34
32
30
28
26
24
22
20
1980
2000
2020
Year (April value)


TRIPLET
10X-18mm


KRYLON
Workable
Fixatif 1306
• Protects pencil, pastel and chalk drawings
• Prevents smudging and wrinkling
• Allows easy rework
• Acid-free/archival-safe
DANGER! EXTREMELY FLAMMABLE - VAPORS MAY CAUSE FLASH FIRE
CONTENTS UNDER PRESSURE. VAPOR HARMFUL.
Before using, carefully read CAUTIONS on back panel.
Net Wt. 11 oz • 311 g


OLYMPUS
Tough
2.1m / 7ft SHOCKPROOF
15m / 50ft WATERPROOF
F2.0


100-cc density cutter
Snow knife
Dial thermometer
Snow tool kit
Digital balance
Ruler
Whisk brooms and brushes
i500



https://www.alaska.edu/uapress/browse/detail/field-guide-to-snow.php

Thank you!