Chapter 6

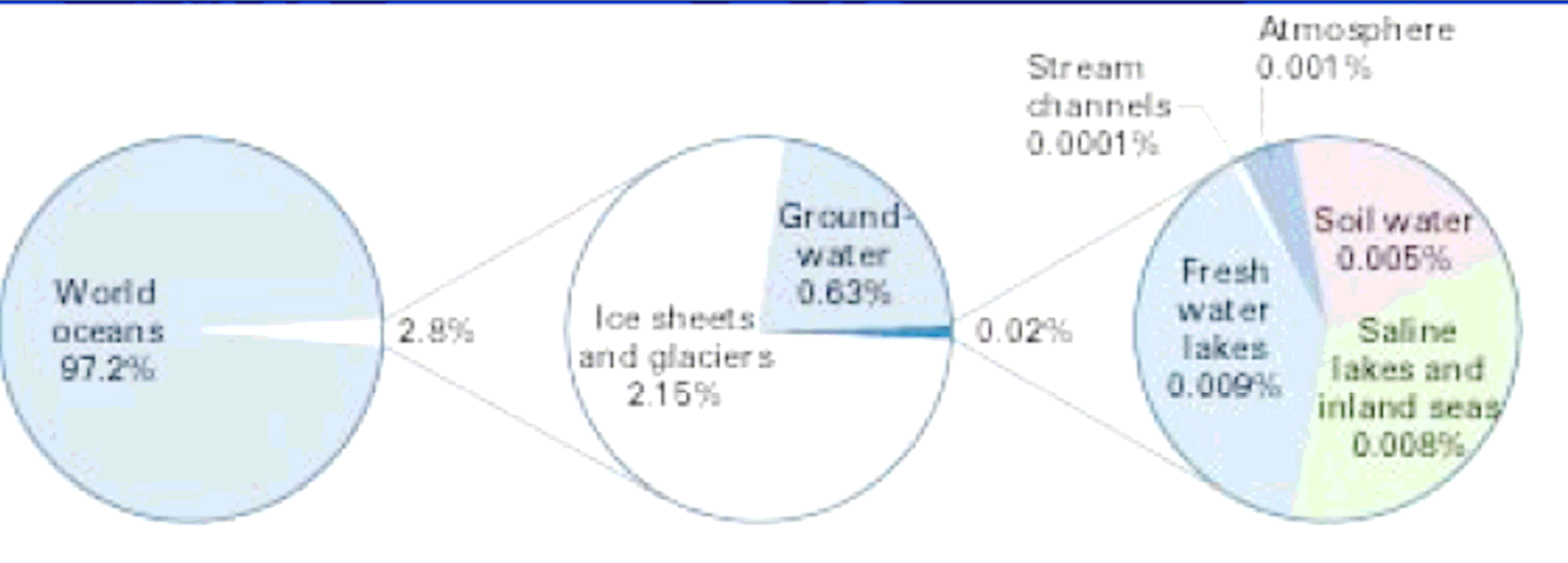
Atmospheric Moisture and Precipitation

The Hydrosphere

- **Hydrosphere** – water in the earth-atmosphere system
  - ***Oceans and Salt Lakes*** ***97.6%***
  - ***Ice Caps and Glaciers*** ***1.9%***

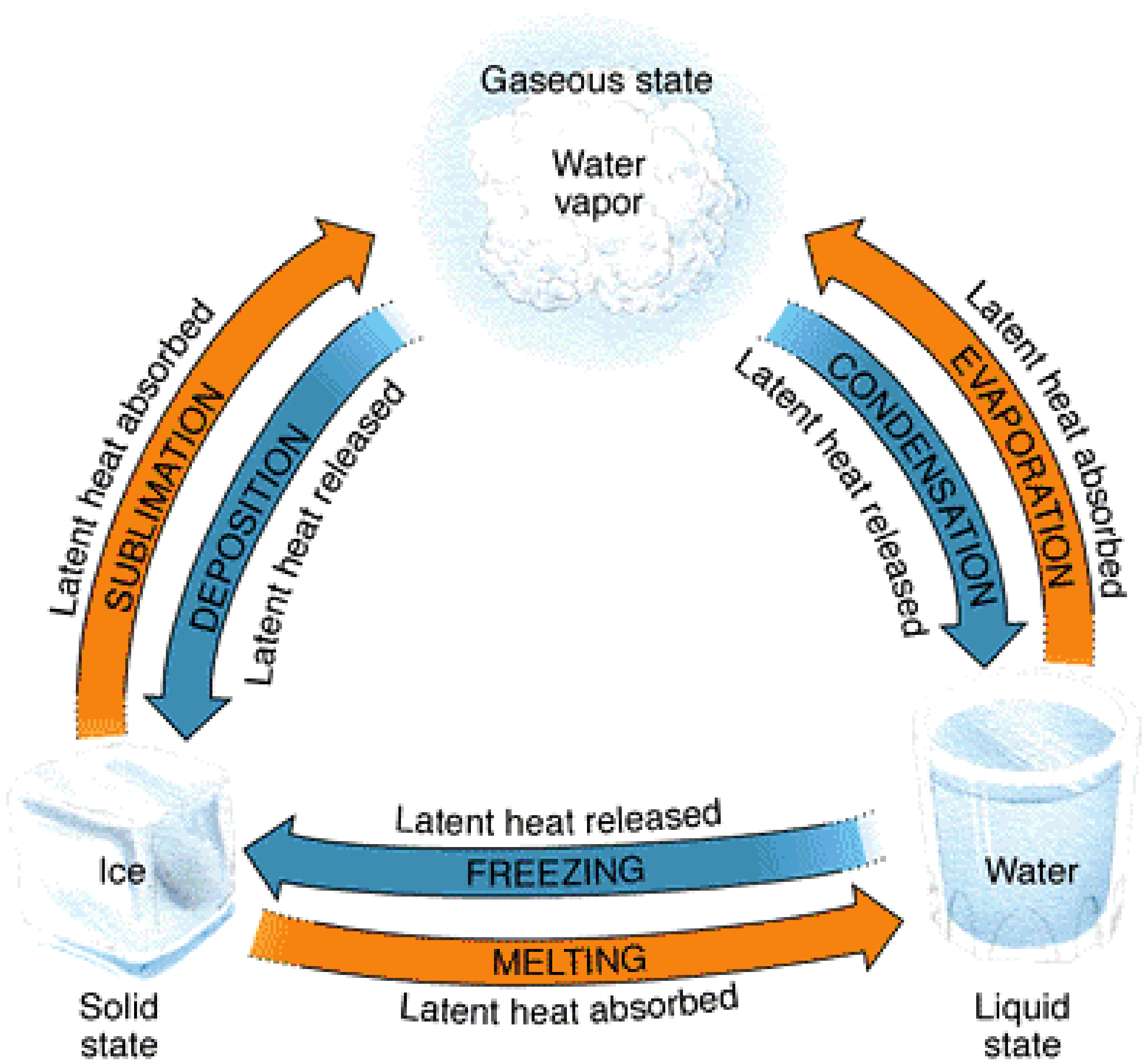
  (Not available for humans) ***99.5%***
  - ***Subsurface Water (soil, groundwater)*** ***0.5%***
  - ***Surface Water (rivers, freshwater lakes)*** ***0.02%***
  - ***Atmosphere*** ***0.0001%***

- If all land were flat, the oceans would cover it to a depth of 3 km
- If all atmospheric water were precipitated, it would cover the earth to a depth of 25 mm (1 inch)
- Holt, MO -- 12 inches of rain in 42 minutes!


World oceans 97.2%
2.8%
Ice sheets and glaciers 2.15%
Ground-water 0.63%
0.02%
Stream channels 0.0001%
Atmosphere 0.001%
Soil water 0.005%
Fresh water lakes 0.009%
Saline lakes and inland seas 0.008%

The Hydrosphere

- Over 70% of the planet is covered by water
- Water is unique in that it can simultaneously exist in all three states (solid, liquid, gas) at the same temperature
- Water is able to shift between states very easily



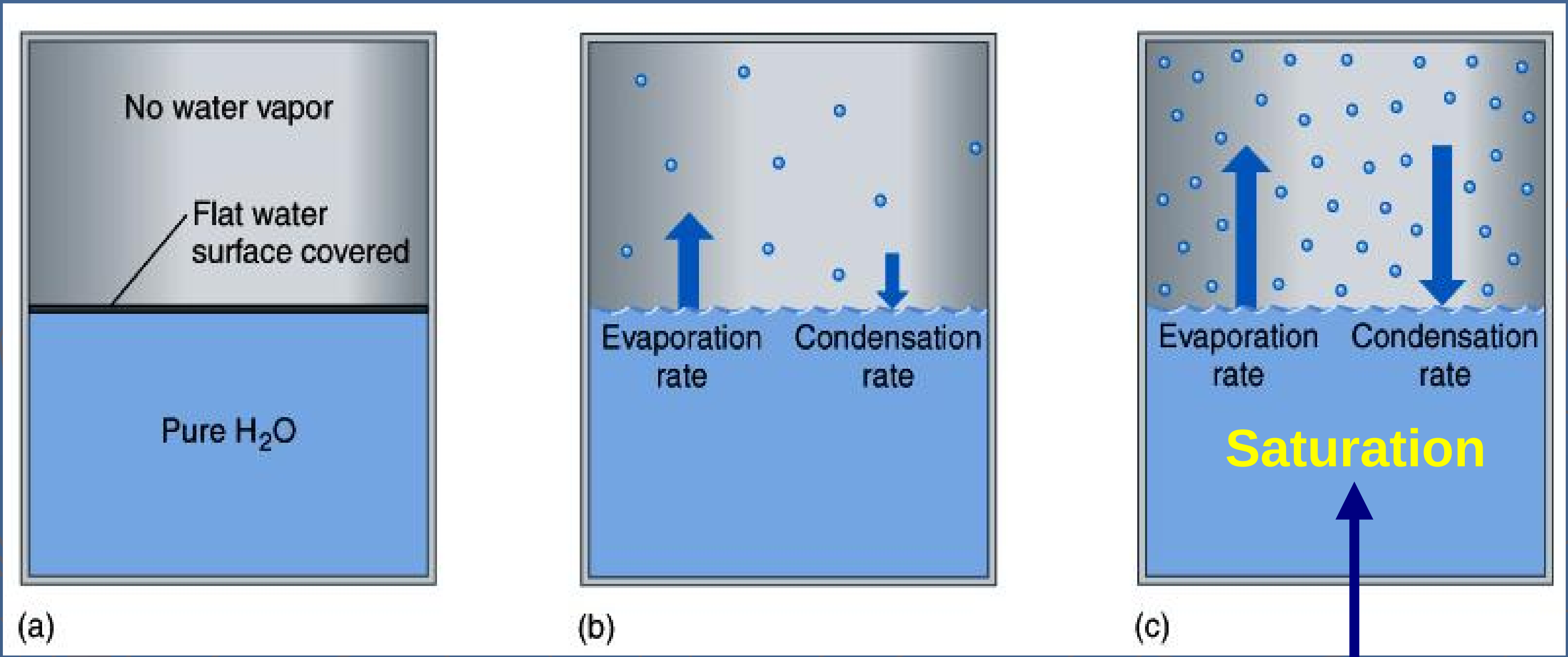
Gaseous state
Water vapor
Latent heat absorbed
SUBLIMATION
DEPOSITION
Latent heat released
CONDENSATION
Latent heat released
EVAPORATION
Latent heat absorbed
Ice
Solid state
Latent heat released
FREEZING
MELTING
Latent heat absorbed
Water
Liquid state

- Hydrologic cycle defines the movement of water among the great global reservoirs

  - Positive balance over land = more precipitation that evaporation
  - Negative balance over water = more evaporation that precipitation

Evaporation

- molecules escape liquid water as water vapor
- Water vapor increases in air as surface water evaporates
- Condensation begins and water returns to the surface
  - Water vapor molecules become liquid



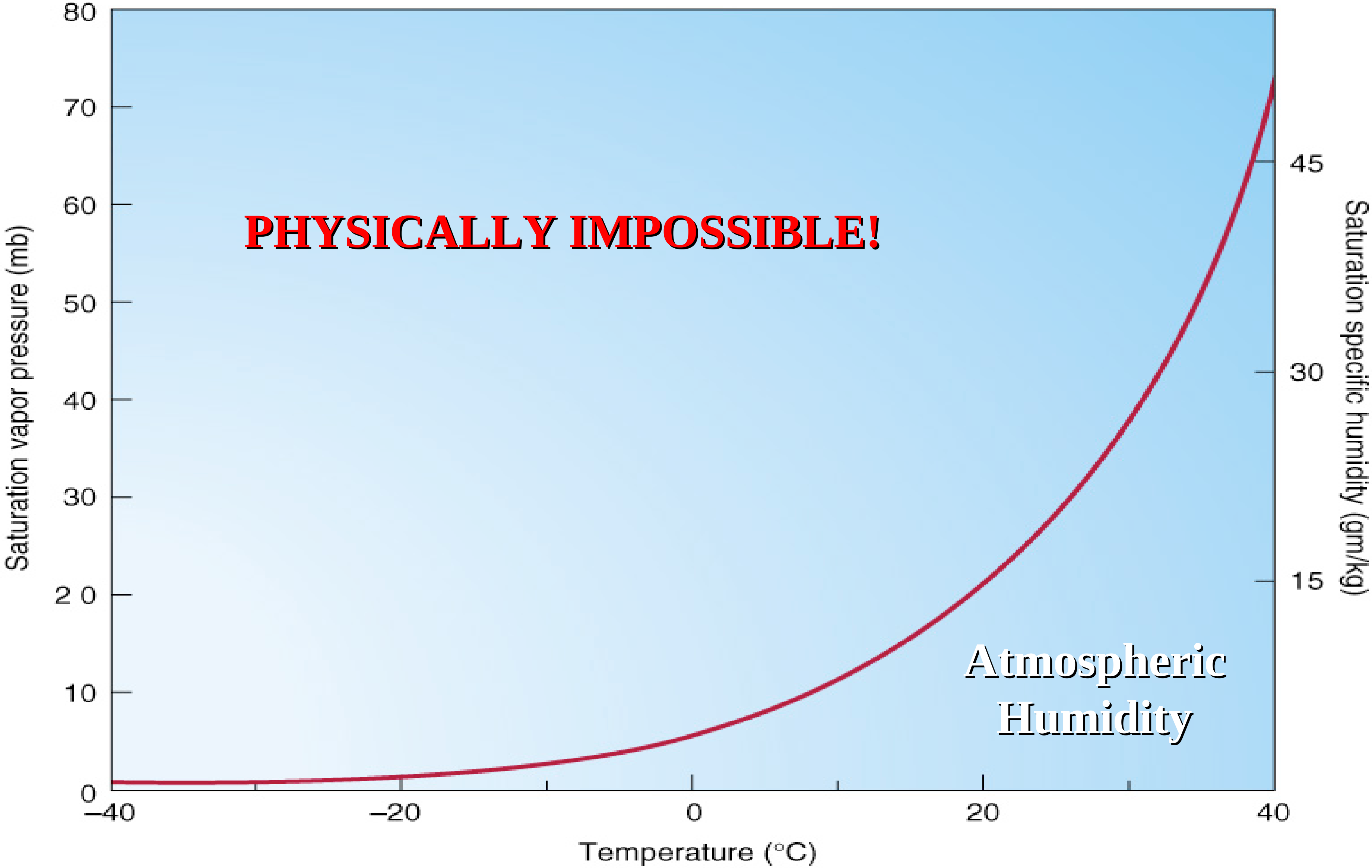
No Evaporation Or Condensation

Evaporation >> Condensation

Evaporation = Condensation

Atmospheric Humidity

- ***Humidity*** – the amount of water vapor in the air
- When saturated, warm air contains more water vapor than cold air
- Thus, we erroneously say that warm air can “hold” more water vapor than cold air
- So, we would expect deserts near the poles due to the cold air temperatures

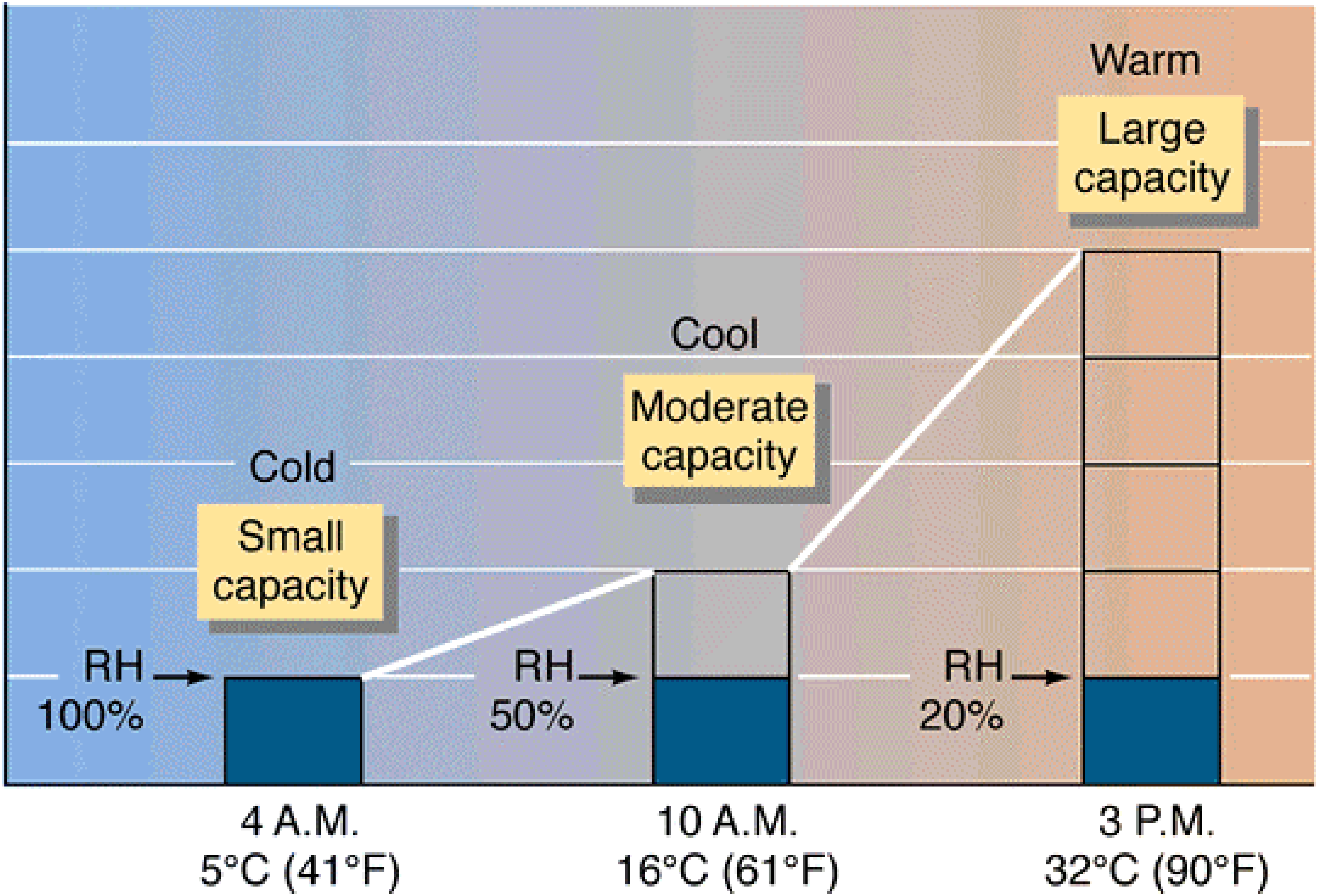

PHYSICALLY IMPOSSIBLE!
Atmospheric Humidity
Saturation vapor pressure (mb)
Saturation specific humidity (gm/kg)
Temperature (°C)
80
70
60
50
40
30
2 0
10
0
45
30
15
–40
–20
0
20
40

Atmospheric Humidity

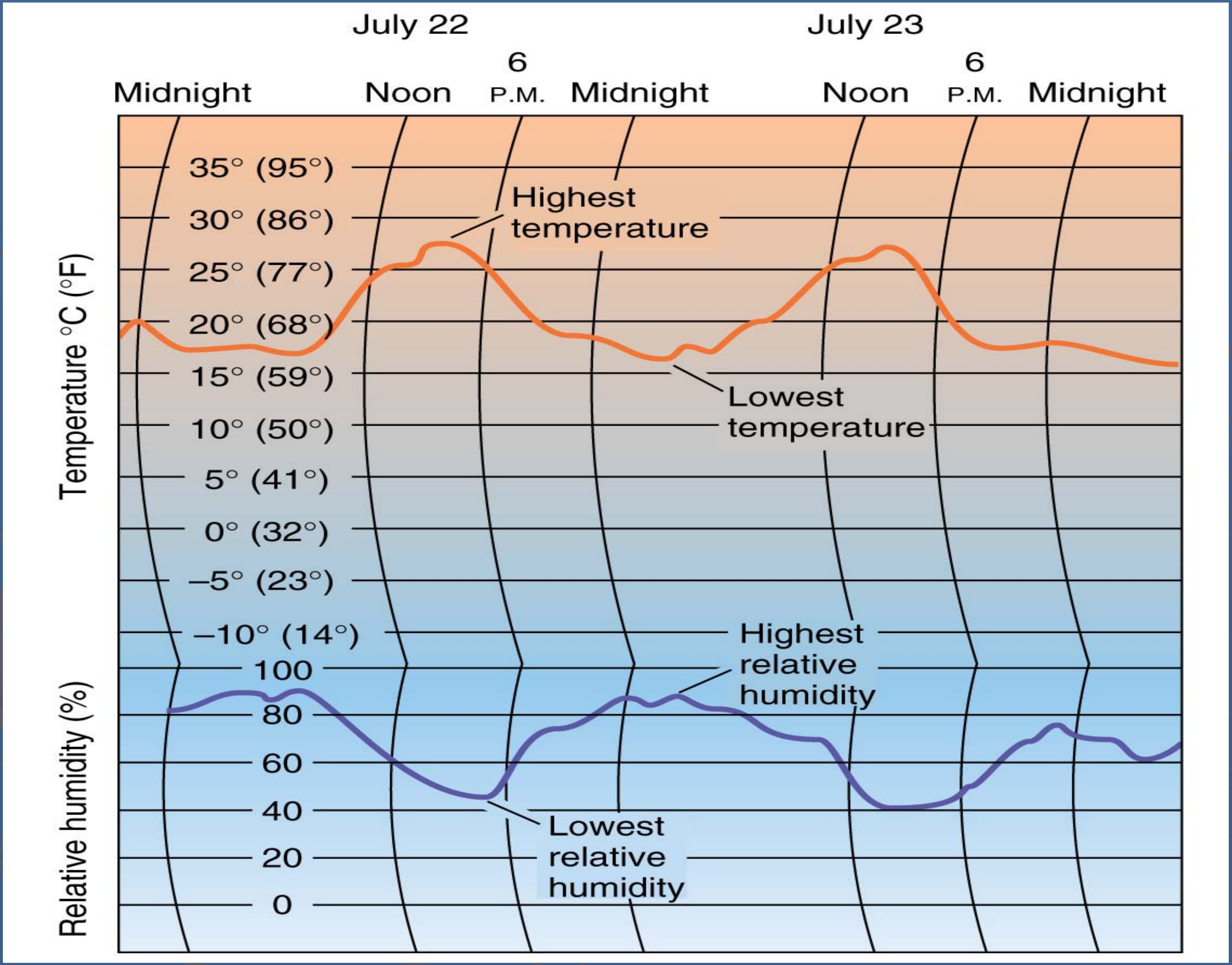
- ***Relative Humidity*** – the amount of water vapor in the air relative to the amount at saturation
- If air is saturated, we say that it has a relative humidity of 100%
- A relative humidity of 50% implies that the air has only half as much water vapor as it would have when saturated

Atmospheric Humidity

- Since at saturation, warm air contains more water vapor than cold air, relative humidity is inversely related to air temperature
- As air temperature rises and the amount of moisture in the air remains the same, the relative humidity decreases
- As air temperature falls and the amount of moisture in the air remains the same, the relative humidity increases

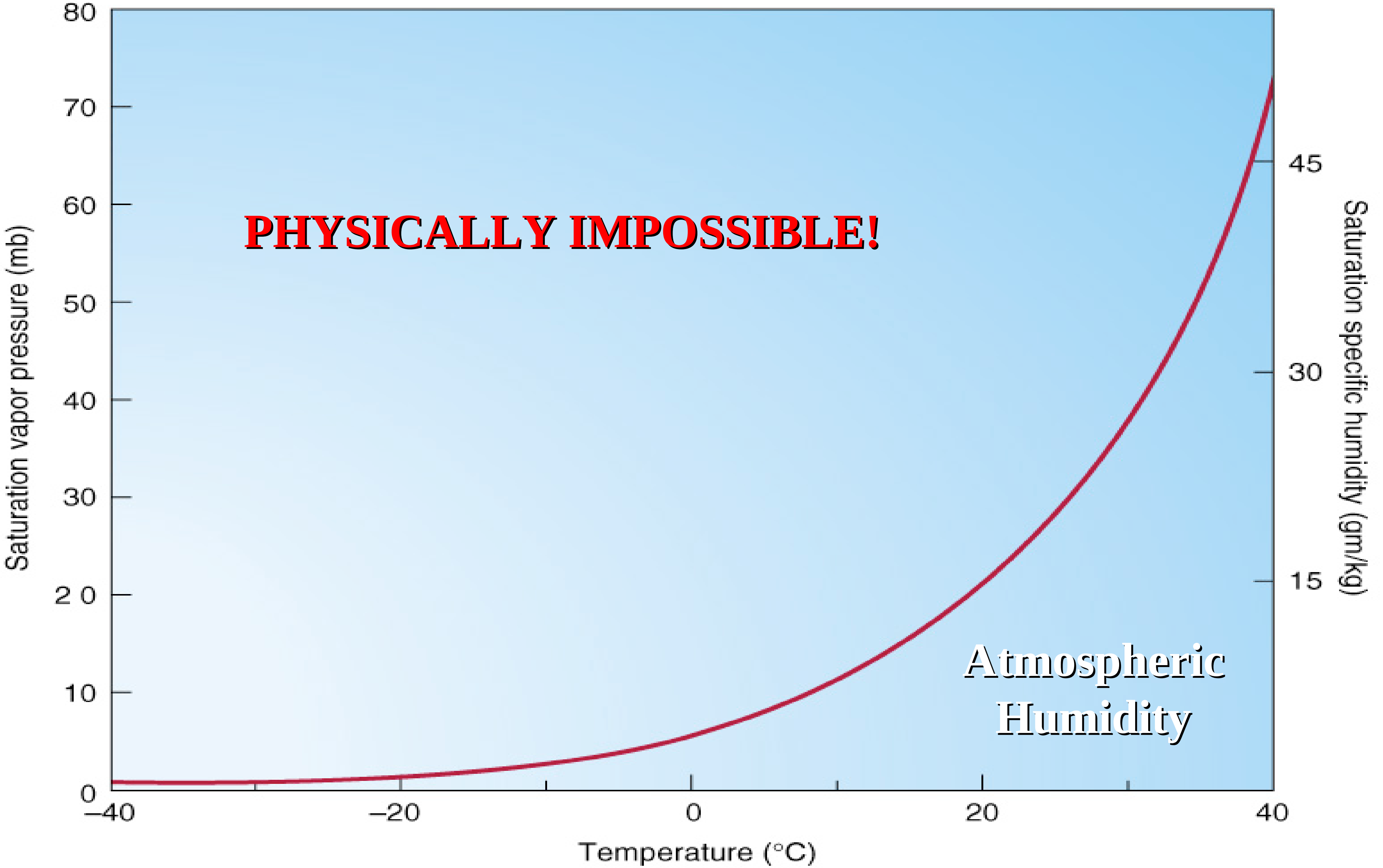

Warm
Large capacity
Cool
Moderate capacity
Cold
Small capacity
RH 100%
RH 50%
RH 20%
4 A.M.
5°C (41°F)
10 A.M.
16°C (61°F)
3 P.M.
32°C (90°F)

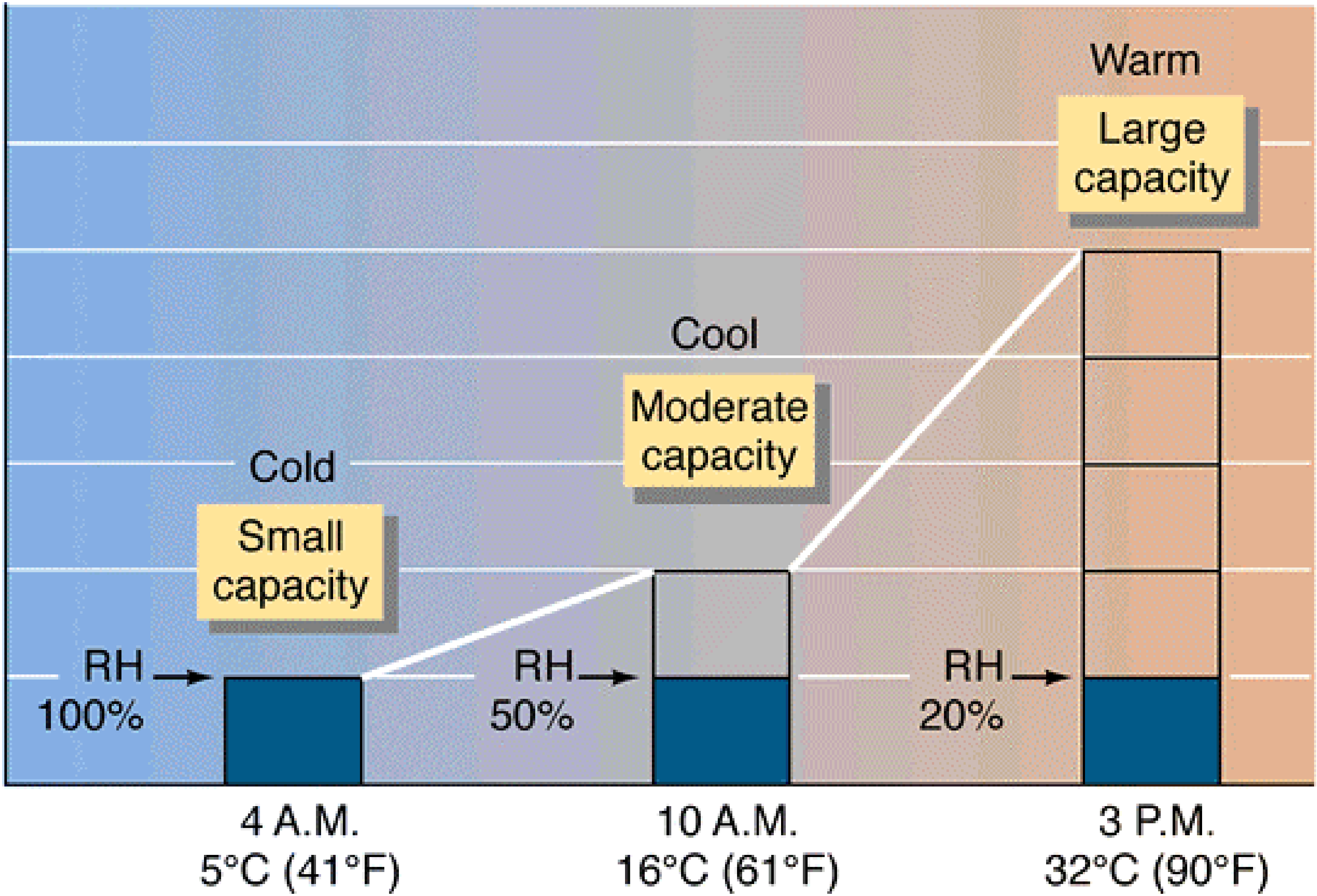
DAILY CYCLES IN RELATIVE HUMIDITY



Atmospheric Humidity

- ***Dew Point*** -- the temperature the air must reach for the air to become saturated. If you lower the air temperature until the relative humidity reaches 100%, you have reached the dew point. Lowering the air temperature below the dew point will result in condensation.


PHYSICALLY IMPOSSIBLE!
Atmospheric
Humidity
Saturation vapor pressure (mb)
80
70
60
50
40
30
2 0
10
0
–40
–20
0
20
40
Temperature (°C)
Saturation specific humidity (gm/kg)
45
30
15

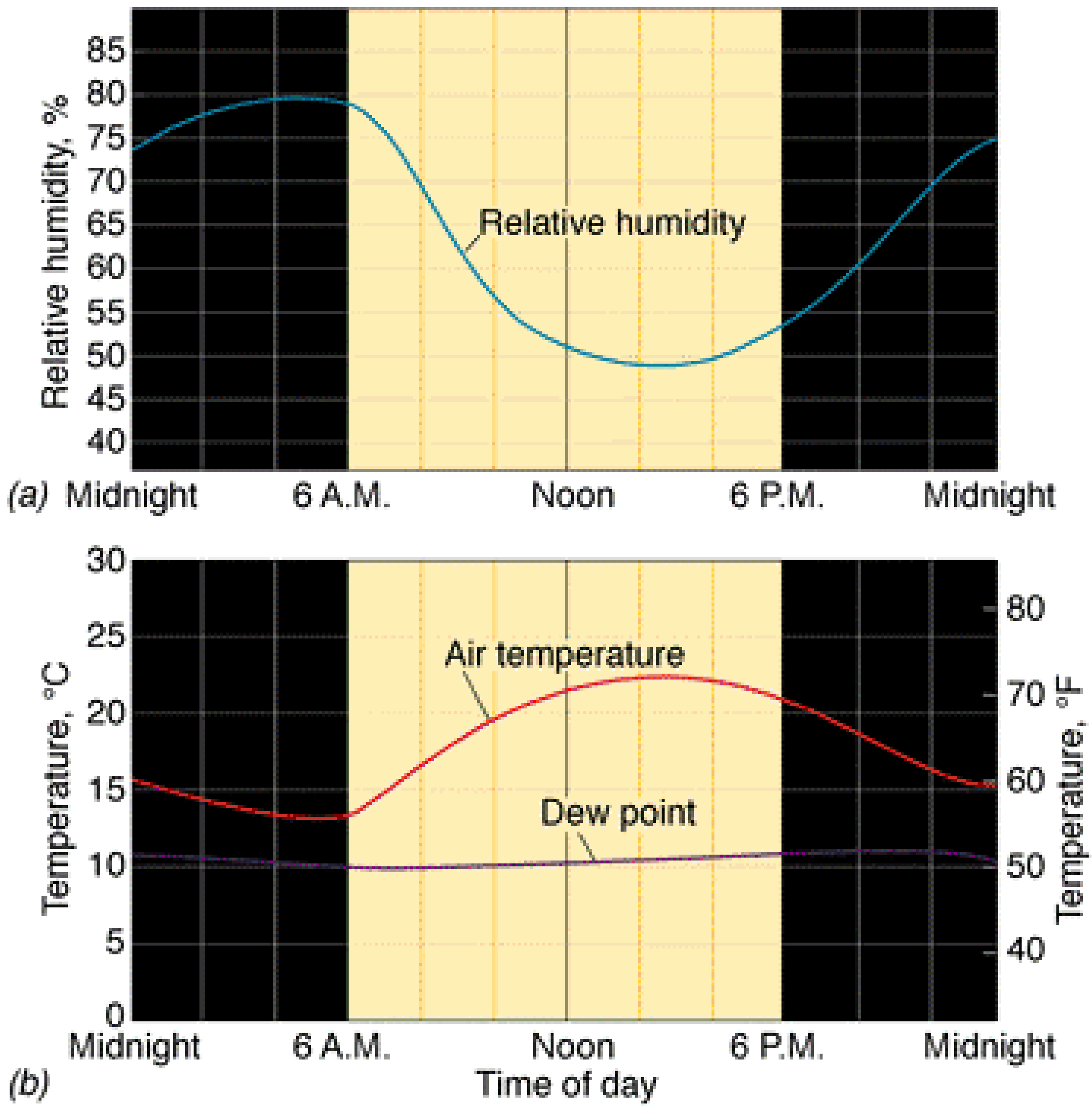

Warm
Large capacity
Cool
Moderate capacity
Cold
Small capacity
RH 100%
RH 50%
RH 20%
4 A.M.
5°C (41°F)
10 A.M.
16°C (61°F)
3 P.M.
32°C (90°F)

Atmospheric Humidity

- Relative humidity is strongly dependent on the air temperature; the dew point is a more conservative measure of the moisture content of the air.
- Therefore, dew point is a better way to represent the moisture content of the air.

Atmospheric Humidity

- Relative humidity is inversely related to air temperature; the dew point is not
- The highest value of relative humidity usually occurs just after sunrise
- The lowest value of relative humidity usually occurs in the mid-afternoon



Data from National Weather Service.

Air Temperature and Height

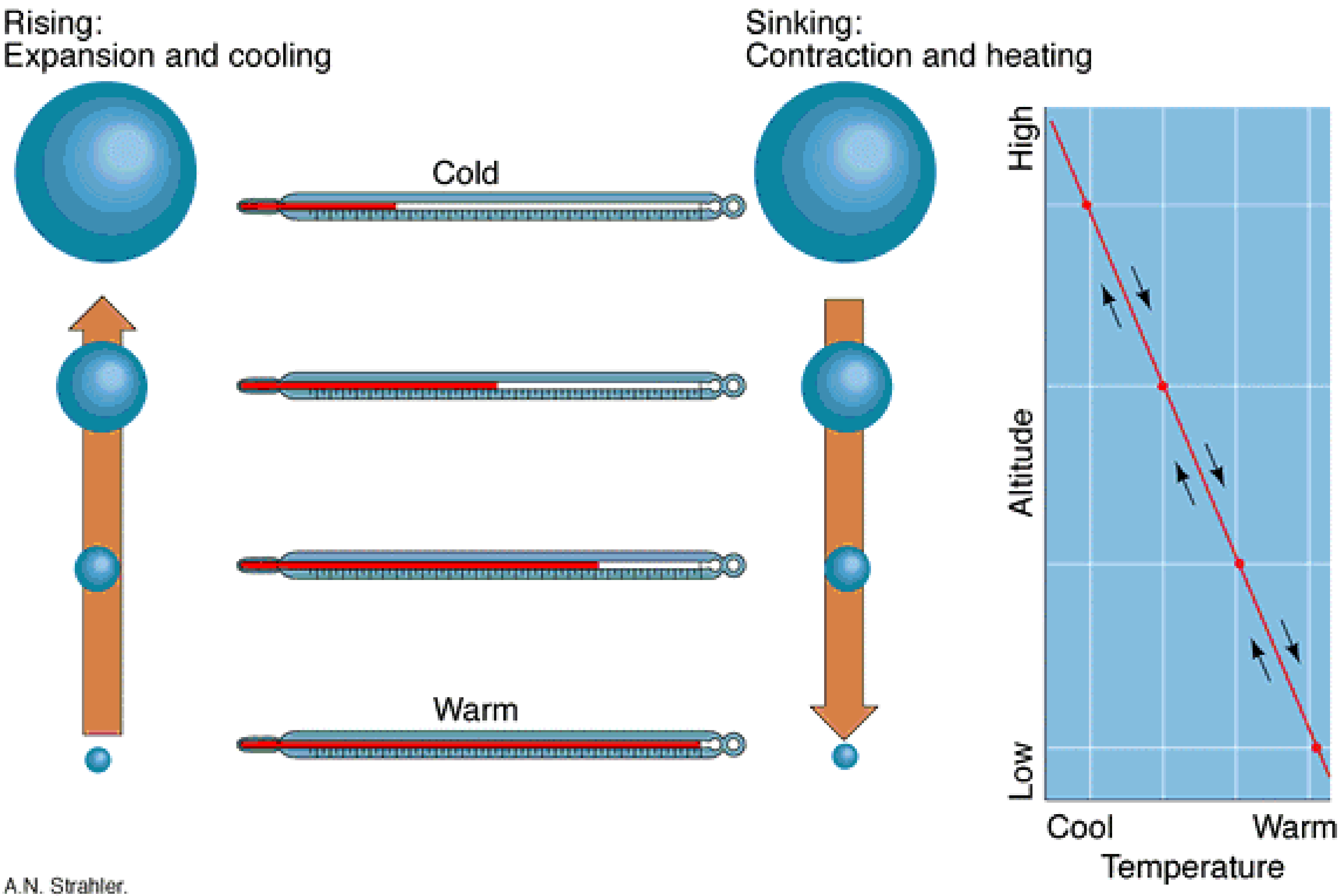
Air Temperature and Height

- In the troposphere, air temperature decreases with height
- Rising air expands due to the decreasing atmospheric pressure and cools as it expands
- Similarly, descending air will warm as it compresses due to the increasing atmospheric pressure

Air Temperature and Height

- The process by which changes in air temperature occur solely as a result of changes in atmospheric pressure is called an ***adiabatic process***

- When air is heated or cooled adiabatically and no condensation occurs, air temperature will follow the ***dry adiabatic lapse rate*** which equals about 10°C per kilometer (or about 5.5°F per 1000 feet)


Rising:
Expansion and cooling
Sinking:
Contraction and heating
Cold
Warm
High
Altitude
Low
Cool
Warm
Temperature
A.N. Strahler.

Air Temperature and Height

- However, rising air will cool and it is possible that it will reach the dew point temperature (a relative humidity of 100%)

- At that point, or the ***lifting condensation level***, moisture will condense from the air and the air temperature will follow the ***wet adiabatic lapse rate*** which ranges from between 4°C and 9°C per kilometer

- The wet adiabatic lapse rate will be lower for warmer air since there is more moisture to condense

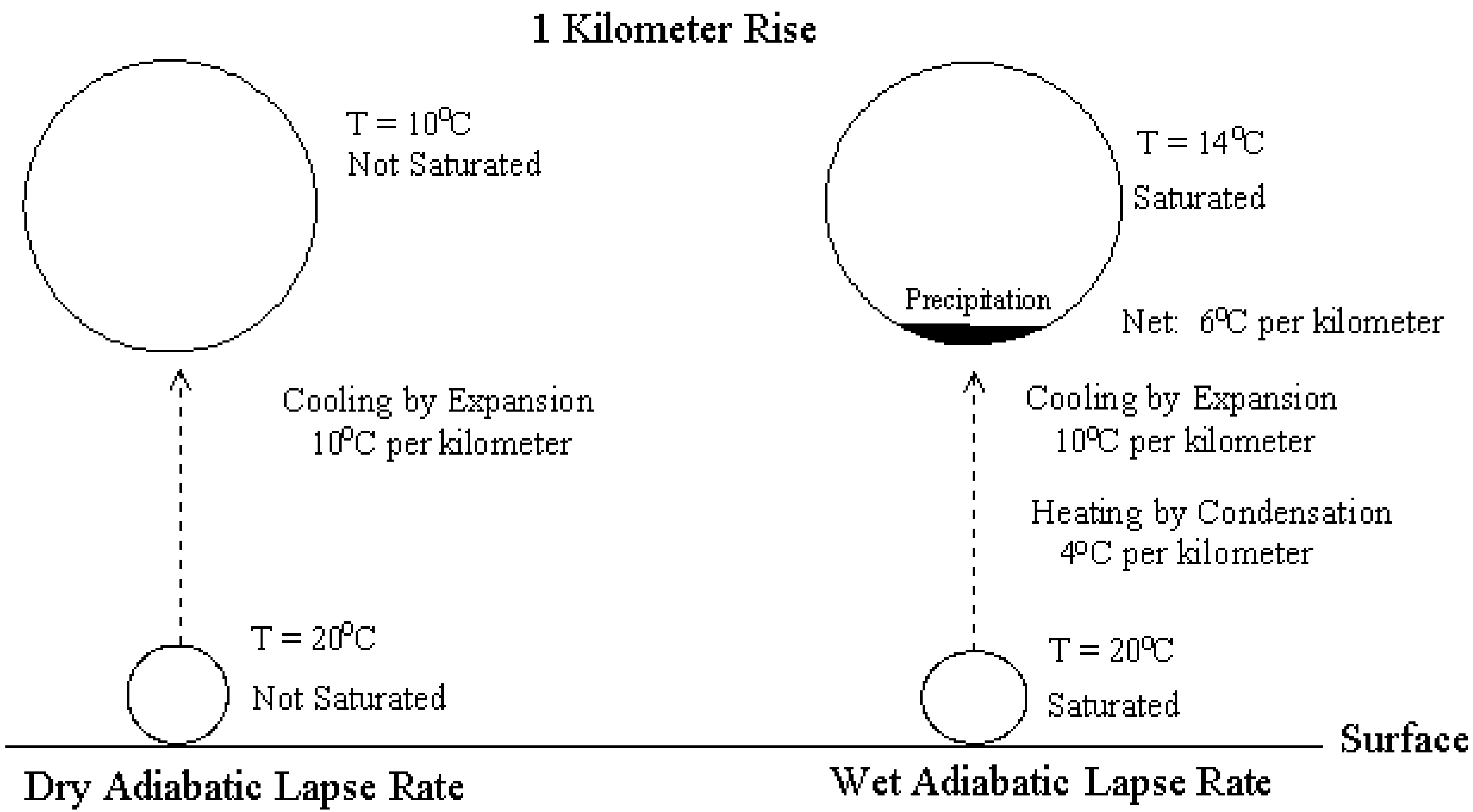
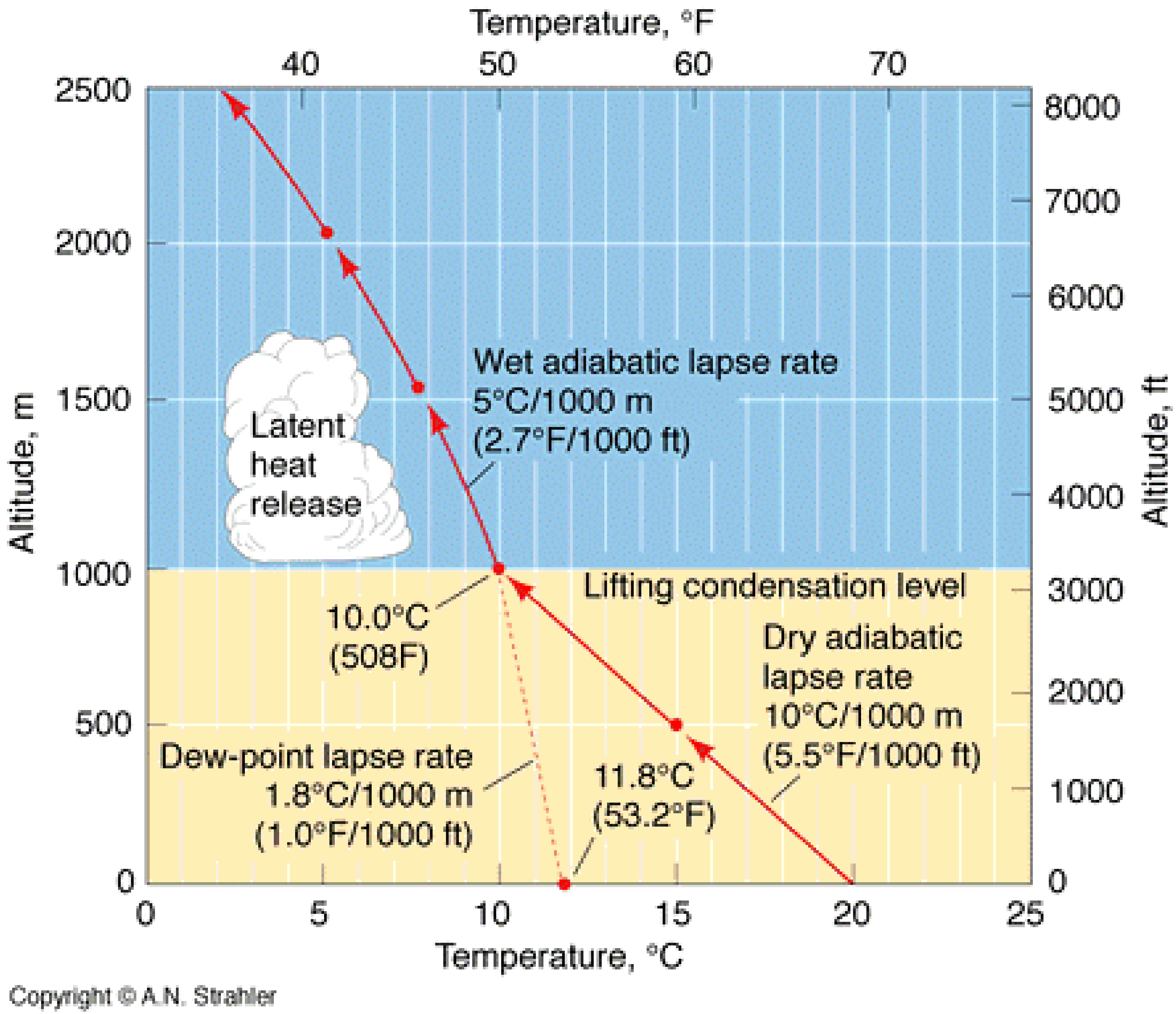
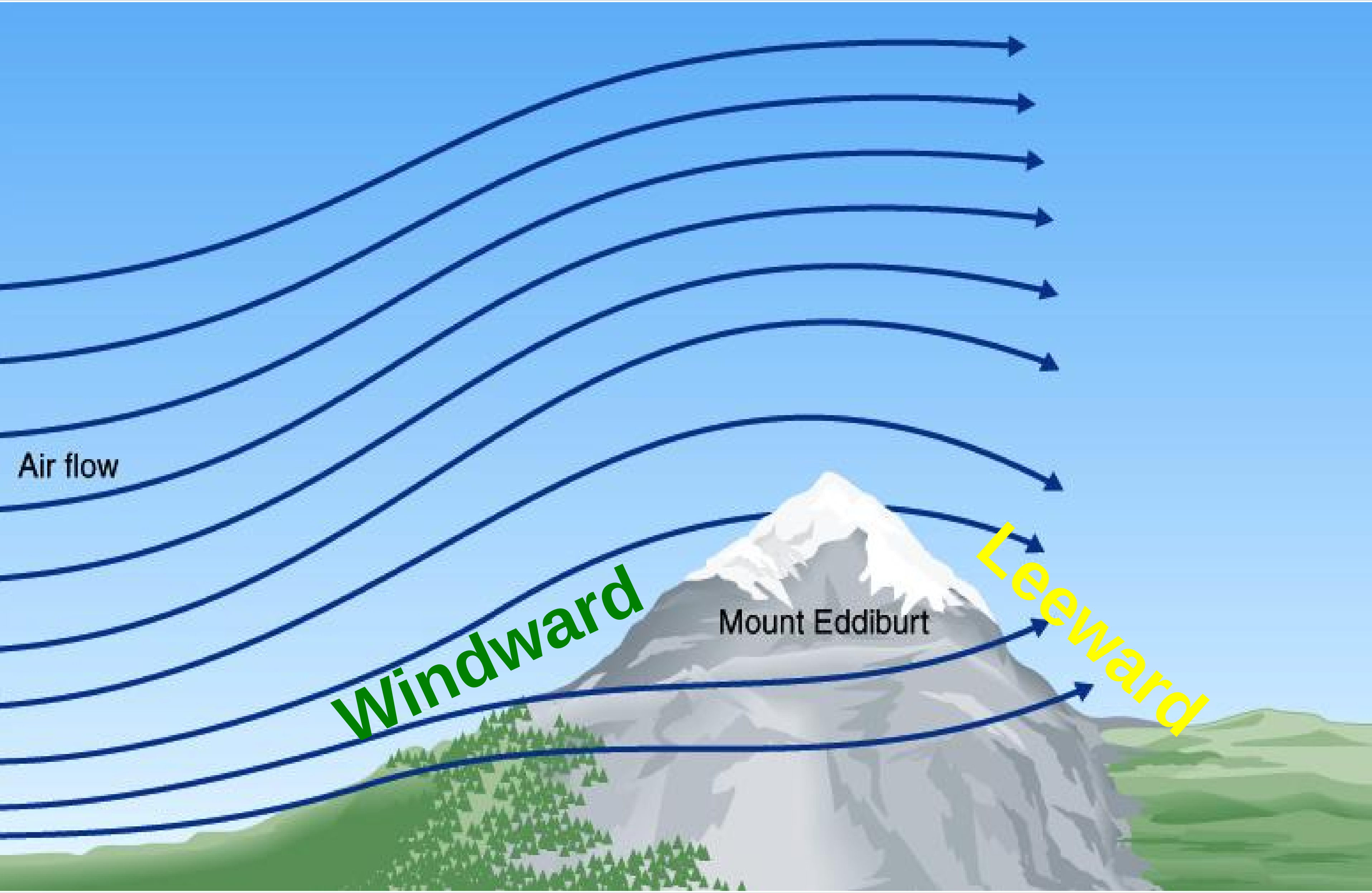


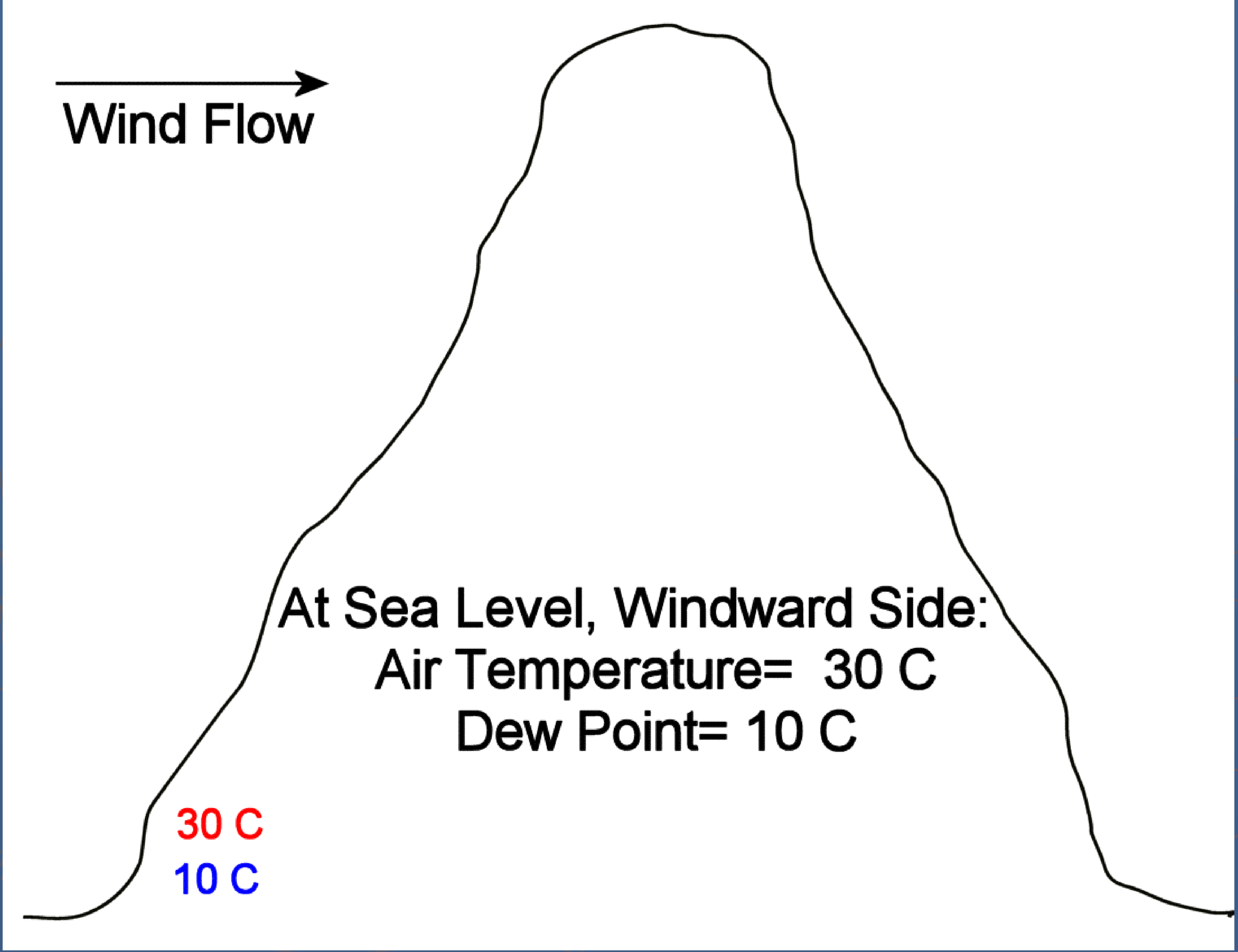
Figure 4-2: A parcel of air which is forced to rise to a height of 1 kilometer when it is not saturated (left) and when it is saturated (right).

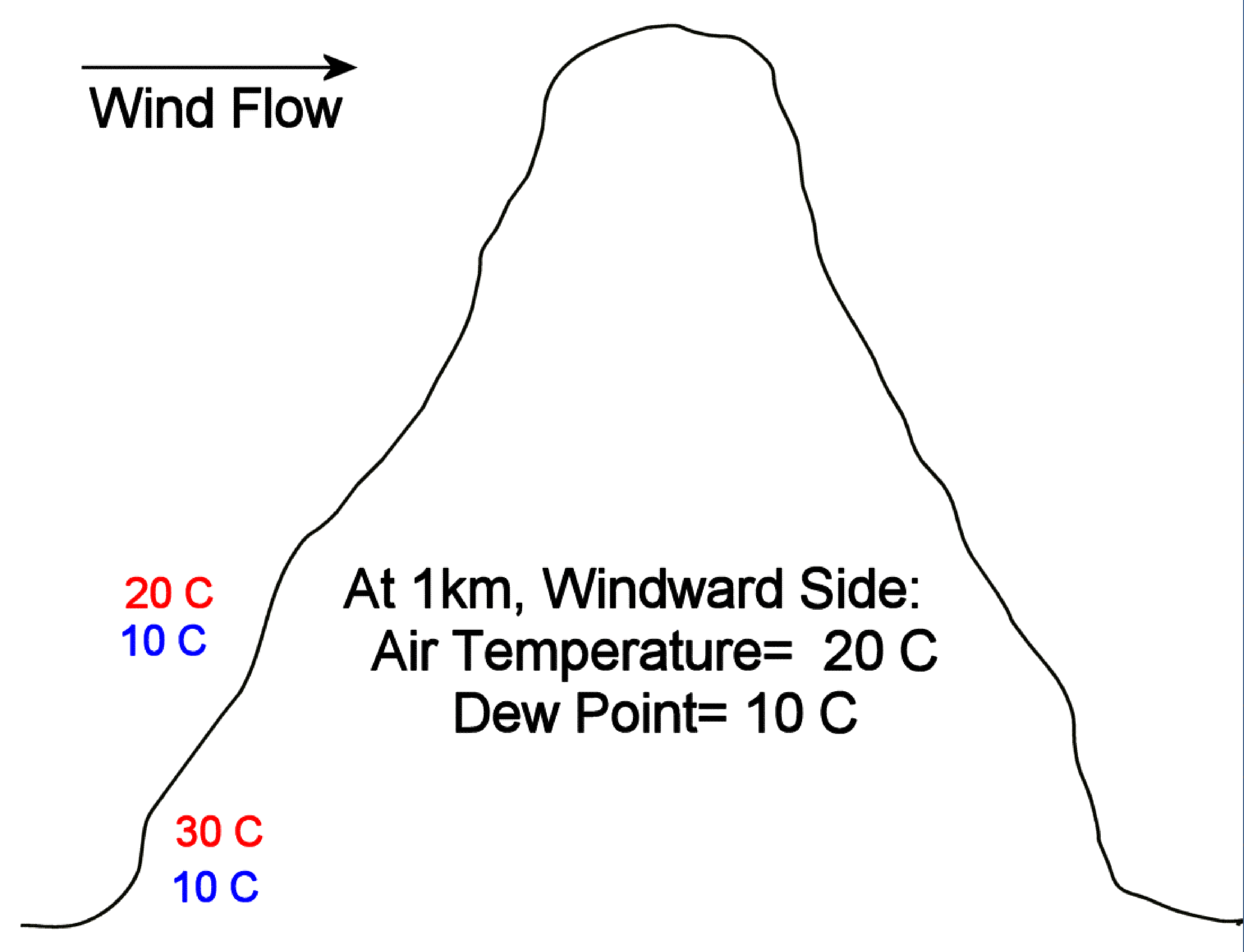

Temperature, °F
40
50
60
70
2500
2000
1500
1000
500
0
Altitude, m
8000
7000
6000
5000
4000
3000
2000
1000
0
Altitude, ft
Wet adiabatic lapse rate
5°C/1000 m
(2.7°F/1000 ft)
Latent
heat
release
Lifting condensation level
10.0°C
(508F)
Dry adiabatic
lapse rate
10°C/1000 m
(5.5°F/1000 ft)
Dew-point lapse rate
1.8°C/1000 m
(1.0°F/1000 ft)
11.8°C
(53.2°F)
0
5
10
15
20
25
Temperature, °C
Copyright © A.N. Strahler

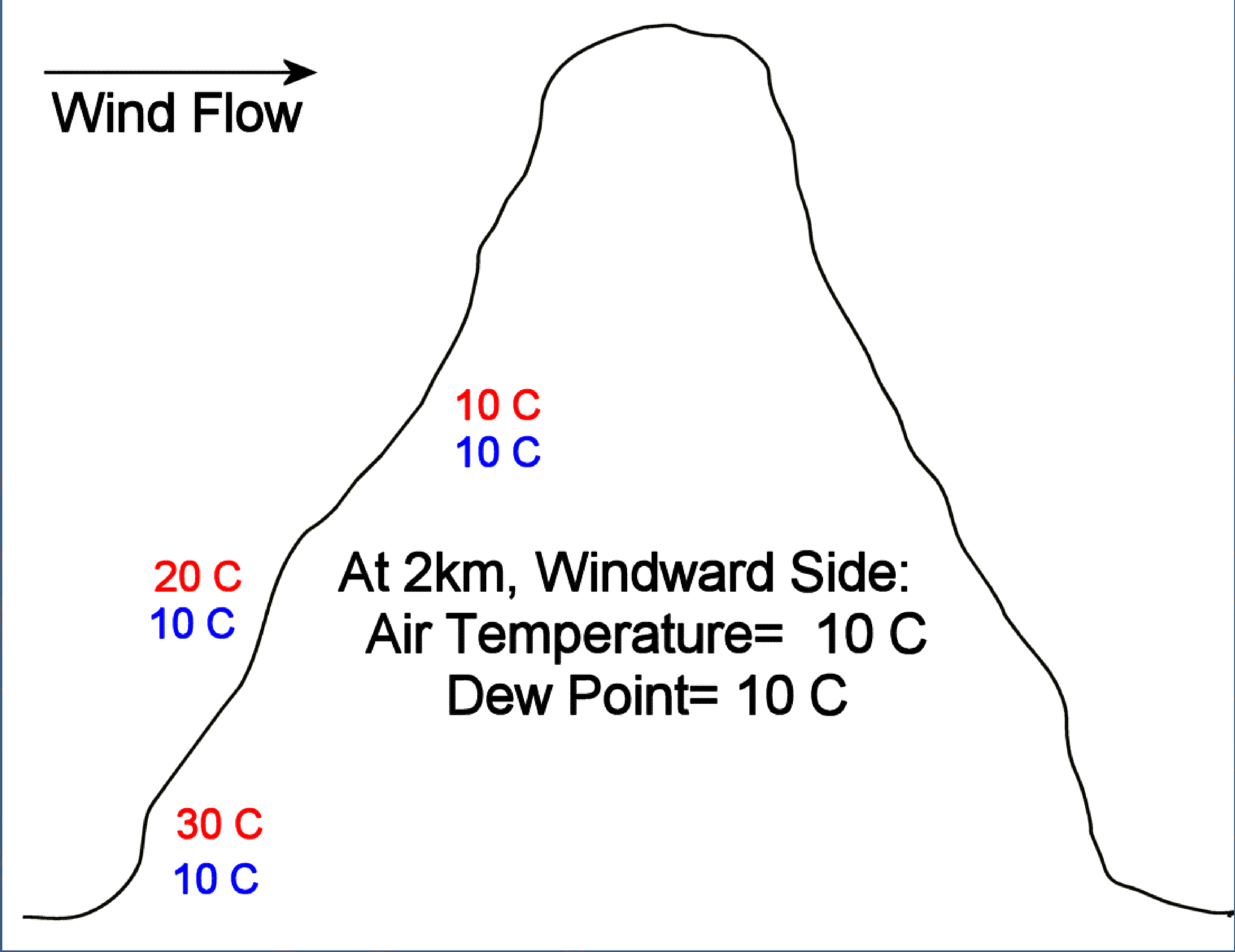
Air Temperature and Height

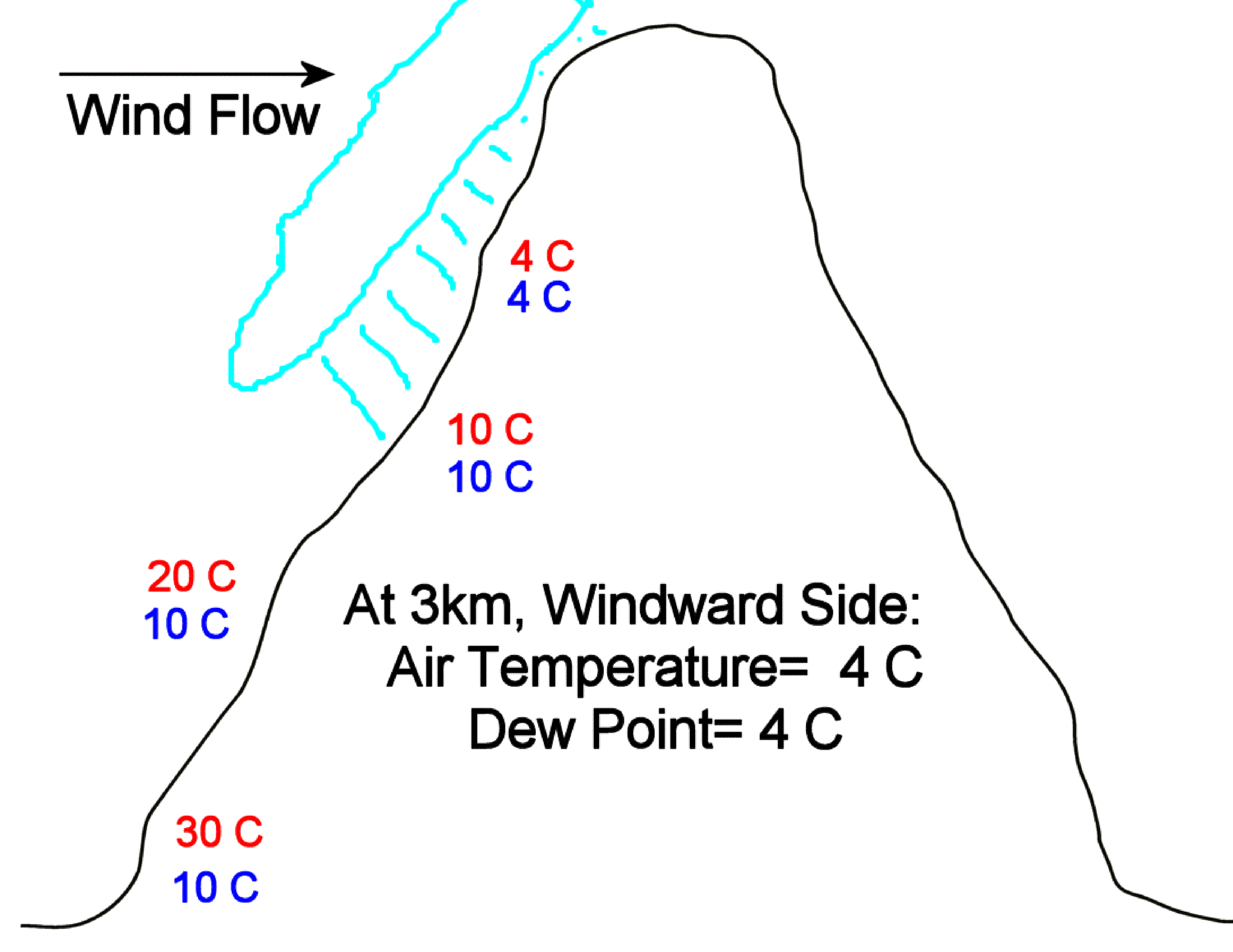
- Consider air flowing over a mountain that is 4 kilometers high (13,123 feet)
- For simplicity, we will assume the wet adiabatic lapse rate is 6°C per kilometer
- At sea level on the windward side of the mountain, the air temperature is 30°C and the dew point is 10°C

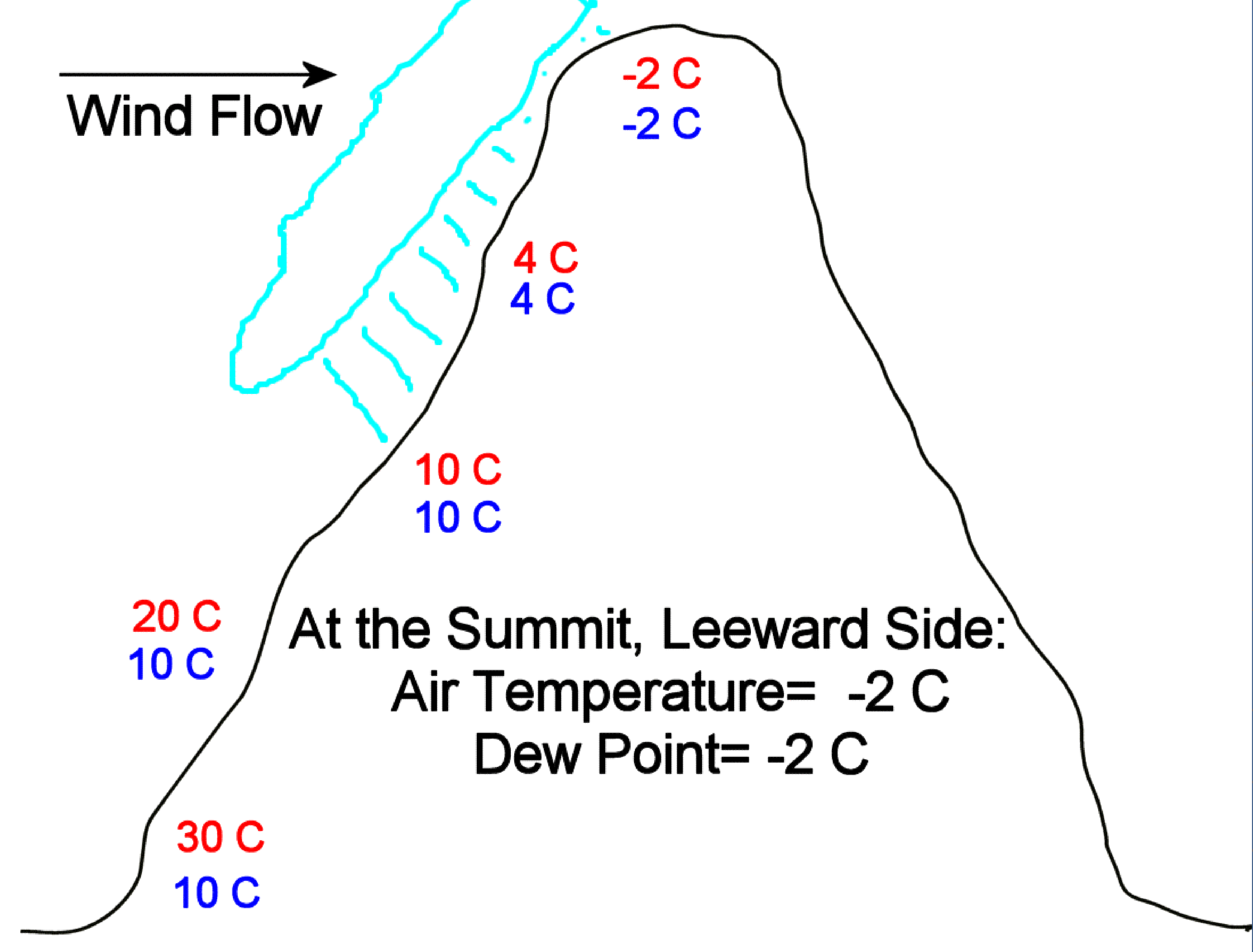

Air flow
Windward
Mount Eddiburt
Leeward


Wind Flow
At Sea Level, Windward Side:
Air Temperature= 30 C
Dew Point= 10 C
30 C
10 C

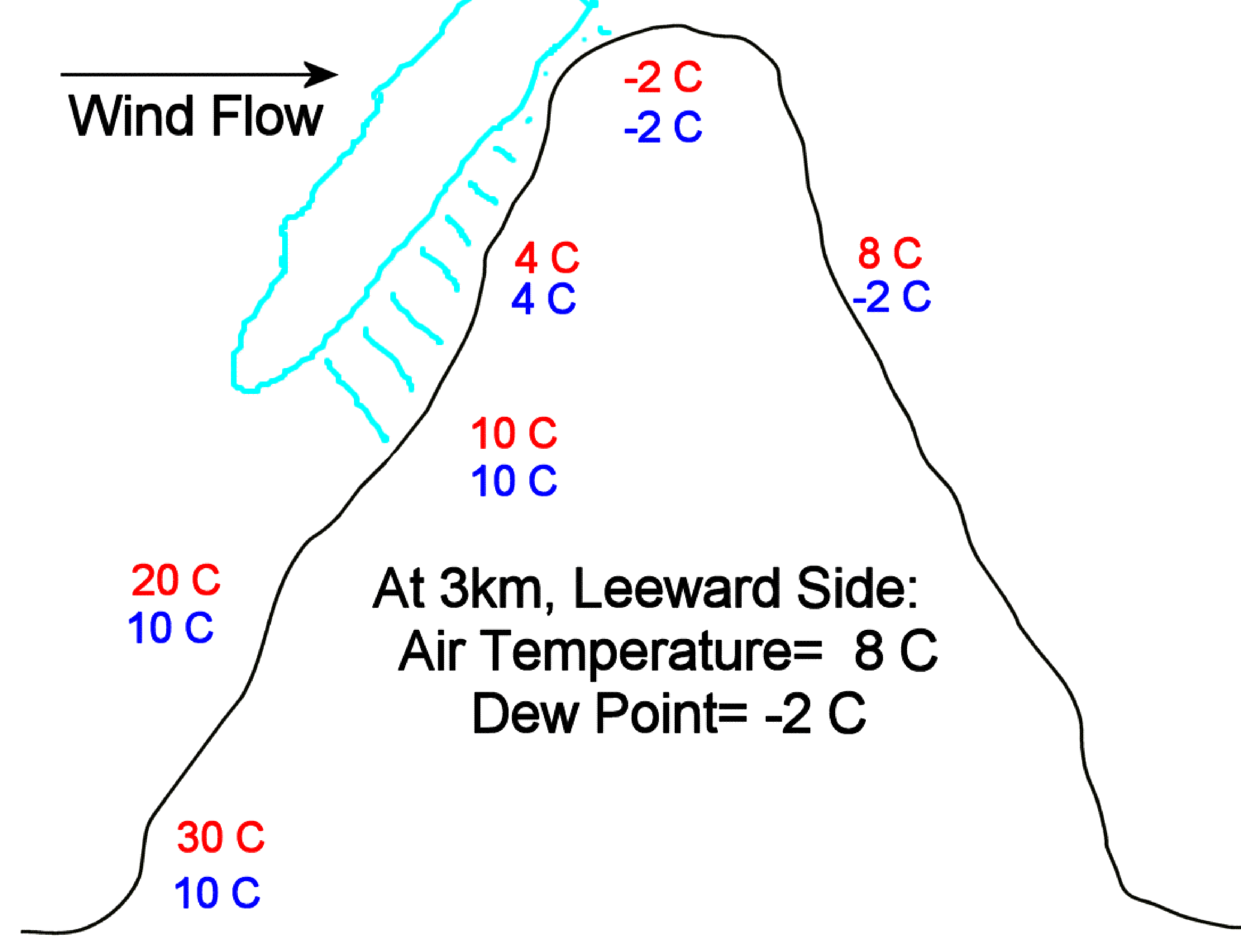

Wind Flow
20 C
10 C
30 C
10 C
At 1km, Windward Side:
Air Temperature= 20 C
Dew Point= 10 C

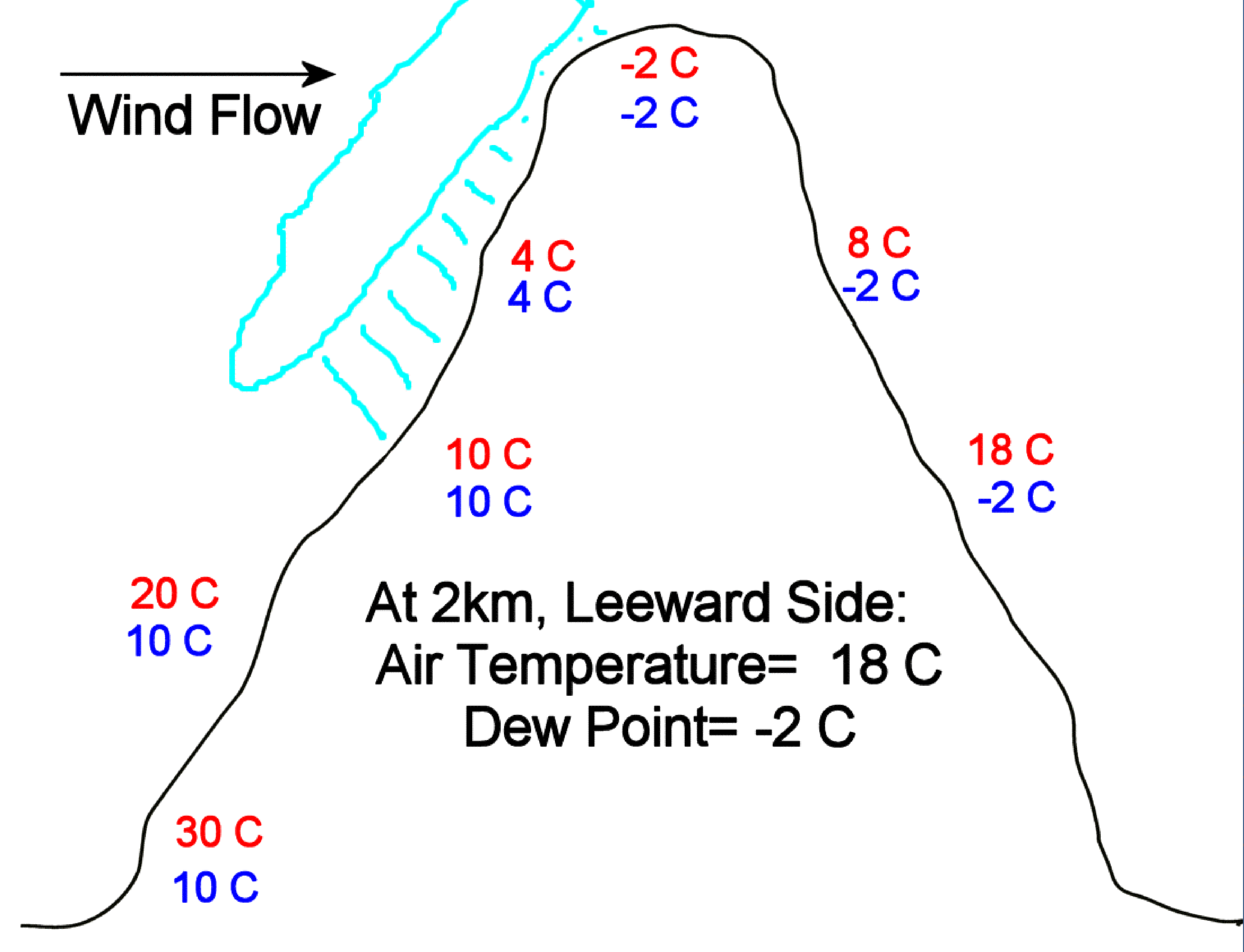

Wind Flow
10 C
10 C
20 C
10 C
At 2km, Windward Side:
Air Temperature= 10 C
Dew Point= 10 C
30 C
10 C

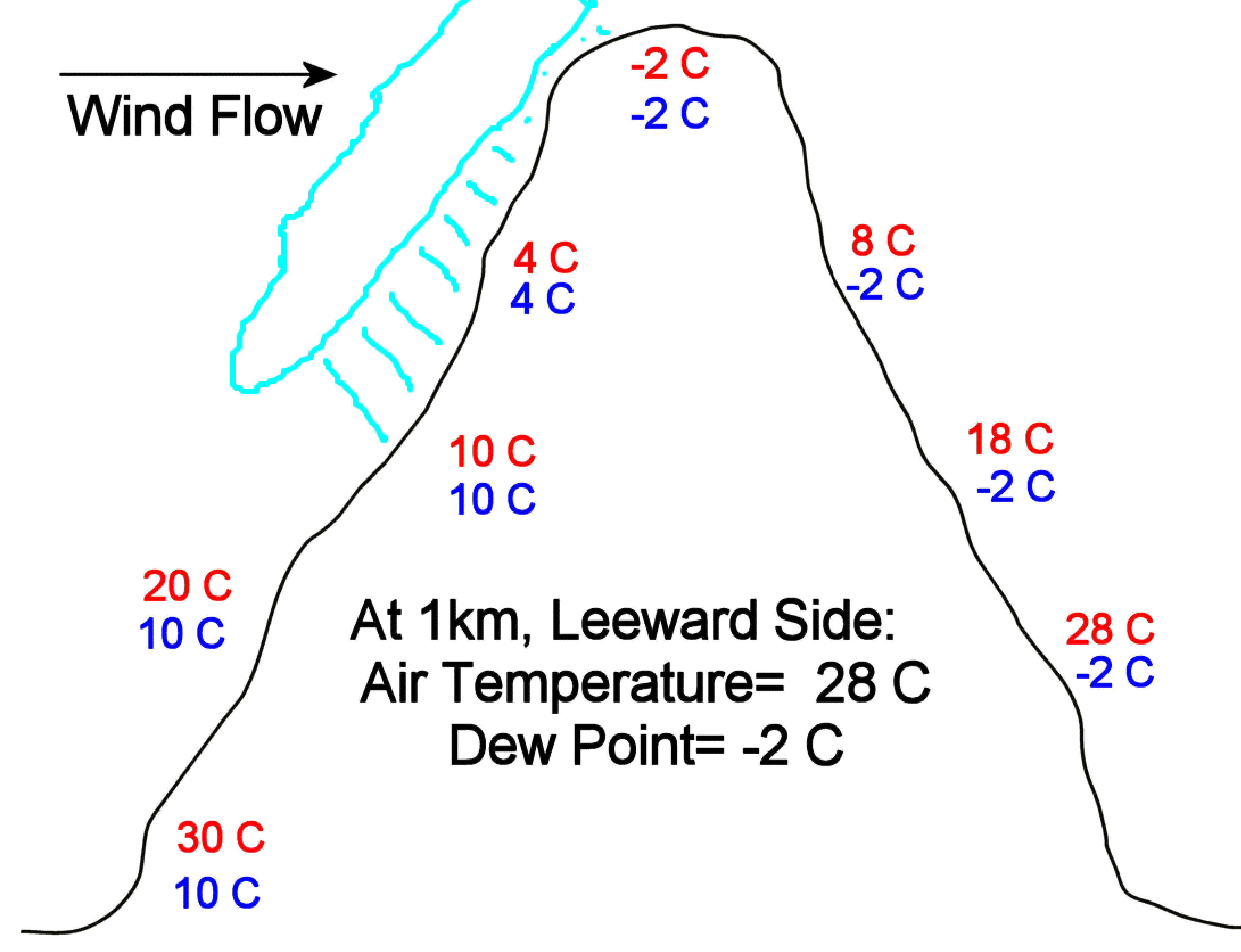

Wind Flow
4 C
4 C
10 C
10 C
20 C
10 C
30 C
10 C
At 3km, Windward Side:
Air Temperature= 4 C
Dew Point= 4 C

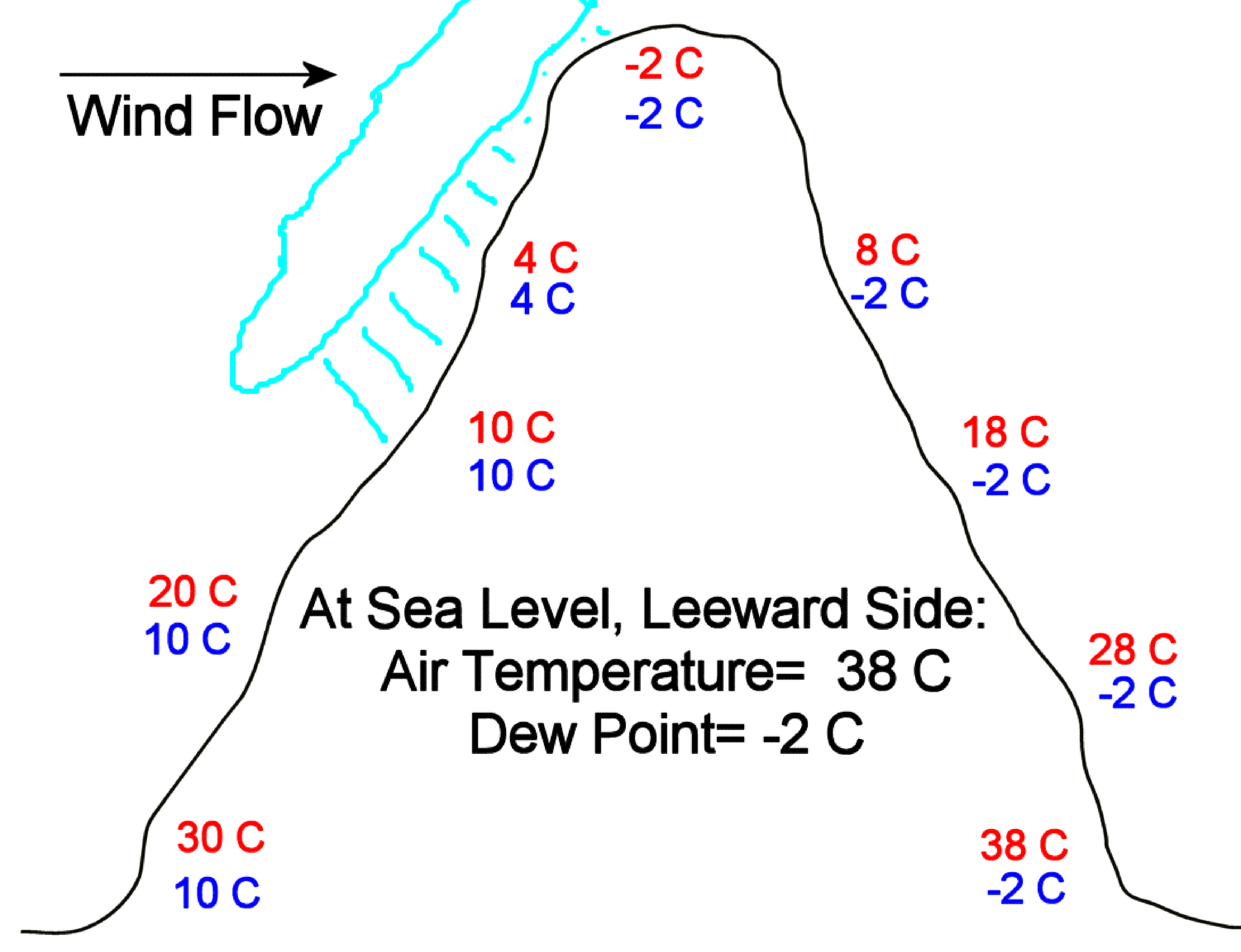


Wind Flow
-2 C
-2 C
4 C
4 C
10 C
10 C
20 C
10 C
30 C
10 C
At the Summit, Leeward Side:
Air Temperature= -2 C
Dew Point= -2 C


Wind Flow
-2 C
-2 C
4 C
4 C
8 C
-2 C
10 C
10 C
20 C
10 C
At 3km, Leeward Side:
Air Temperature= 8 C
Dew Point= -2 C
30 C
10 C


Wind Flow
-2 C
-2 C
4 C
4 C
8 C
-2 C
10 C
10 C
18 C
-2 C
20 C
10 C
30 C
10 C
At 2km, Leeward Side:
Air Temperature= 18 C
Dew Point= -2 C

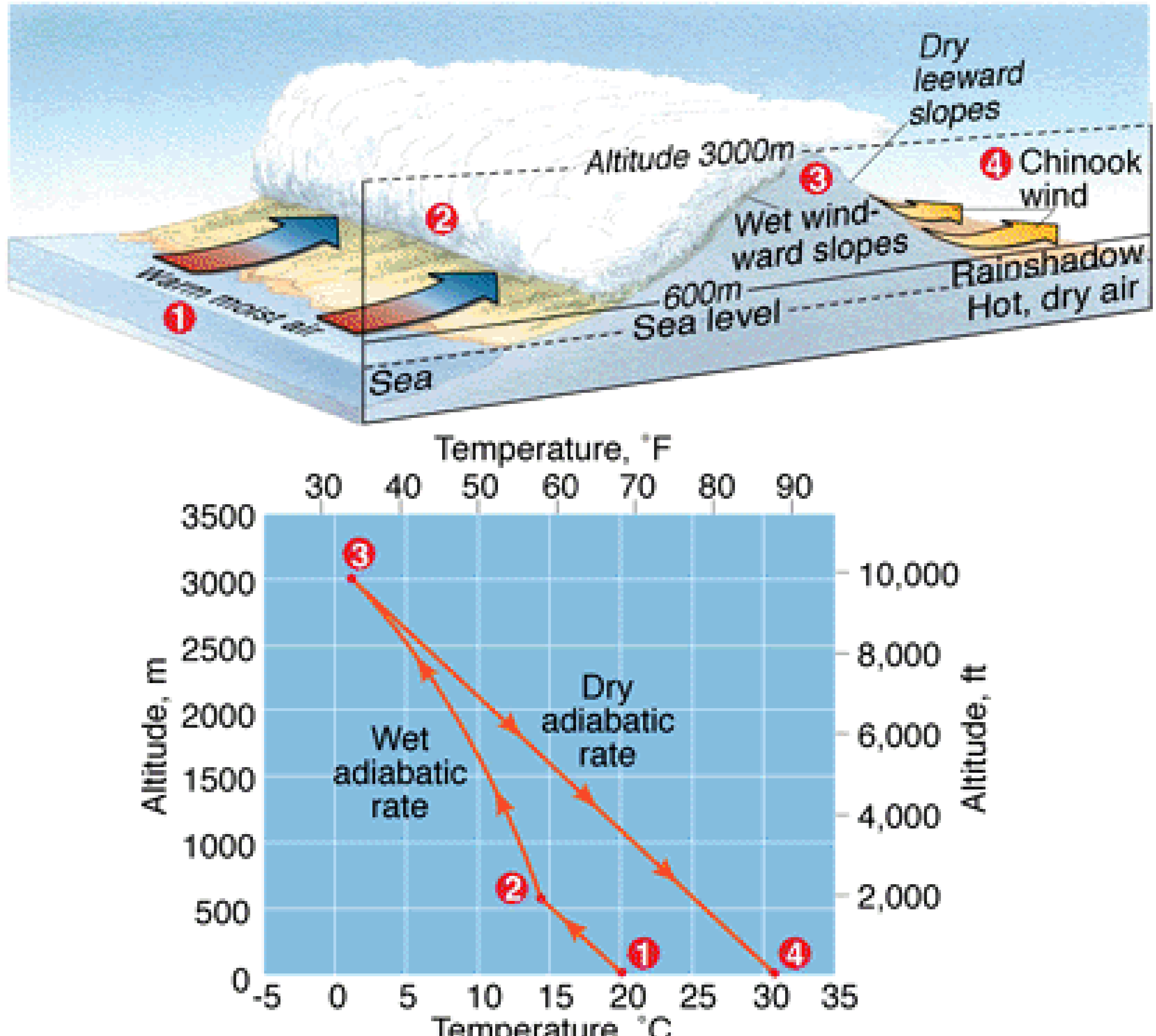

Wind Flow
-2 C
-2 C
4 C
4 C
10 C
10 C
20 C
10 C
30 C
10 C
8 C
-2 C
18 C
-2 C
28 C
-2 C
At 1km, Leeward Side:
Air Temperature= 28 C
Dew Point= -2 C



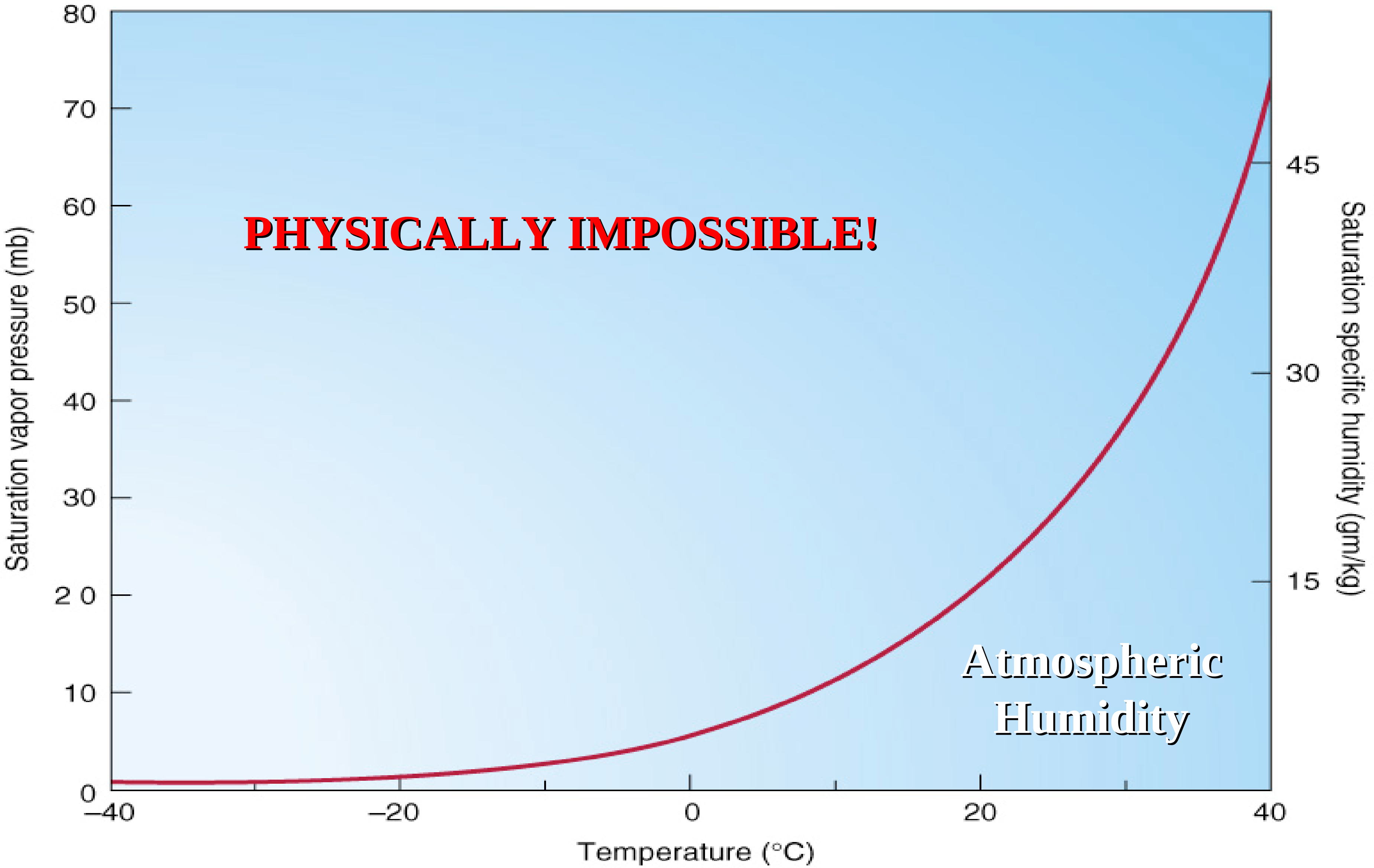
Wind Flow
-2 C
-2 C
4 C
4 C
10 C
10 C
20 C
10 C
30 C
10 C
8 C
-2 C
18 C
-2 C
28 C
-2 C
38 C
-2 C
At Sea Level, Leeward Side:
Air Temperature= 38 C
Dew Point= -2 C

Air Temperature and Height

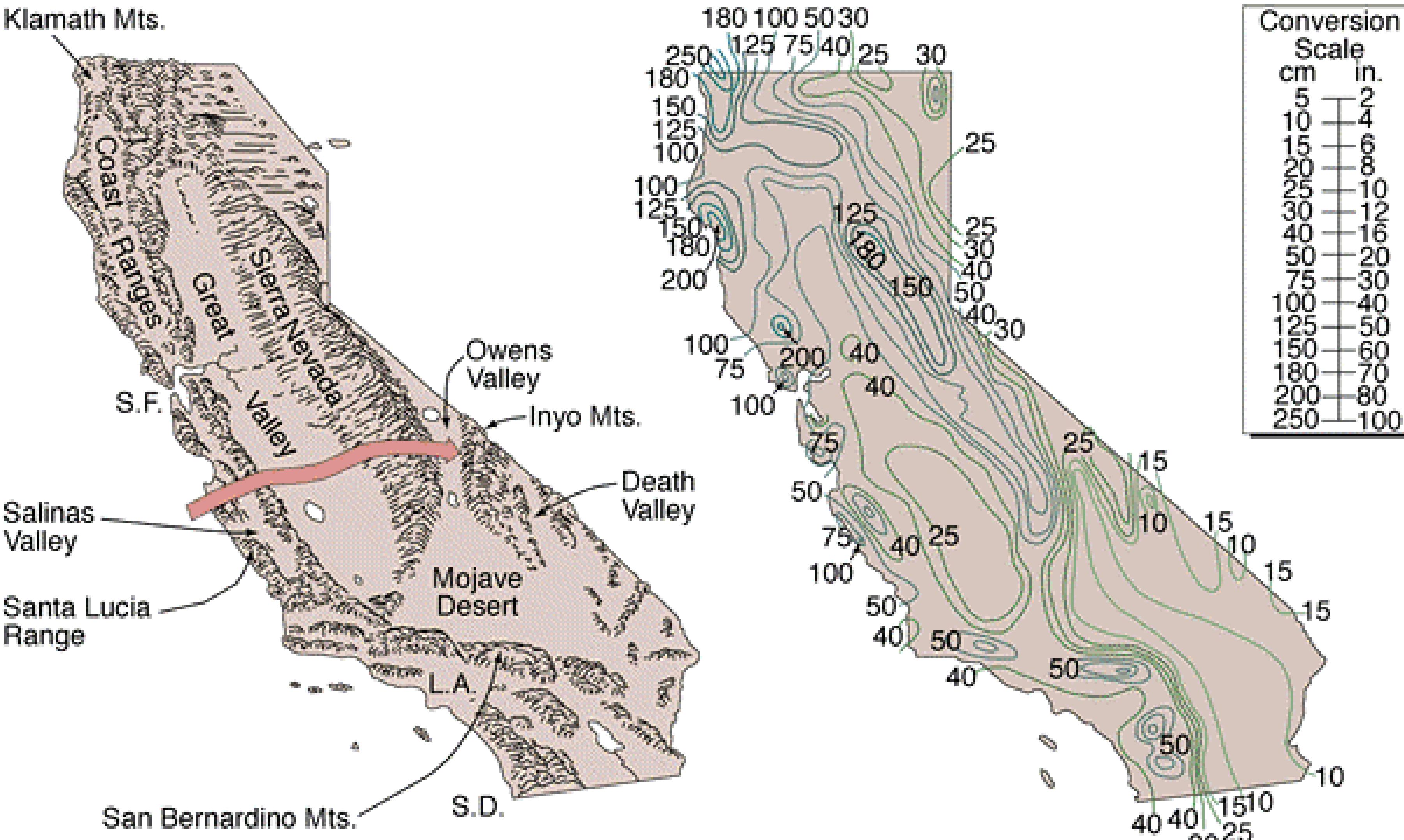
- This demonstrates the ***rainshadow effect*** of mountain ranges
- Precipitation occurs on the windward side
- Warmer and drier conditions are found on the leeward side of the mountain range (*e.g.*, Washington, Oregon, California)
- Downslope winds can be warm and dry – sometimes called ***Chinook Winds***



Dry leeward slopes
Altitude 3000m
4 Chinook wind
3
2
Wet wind-ward slopes
Rainshadow
Hot, dry air
600m
Sea level
1
Warm moist air
Sea
Temperature, °F
30 40 50 60 70 80 90
3500
3000
2500
2000
1500
1000
500
0
Altitude, m
10,000
8,000
6,000
4,000
2,000
Altitude, ft
Dry adiabatic rate
Wet adiabatic rate
-5 0 5 10 15 20 25 30 35
Temperature, °C



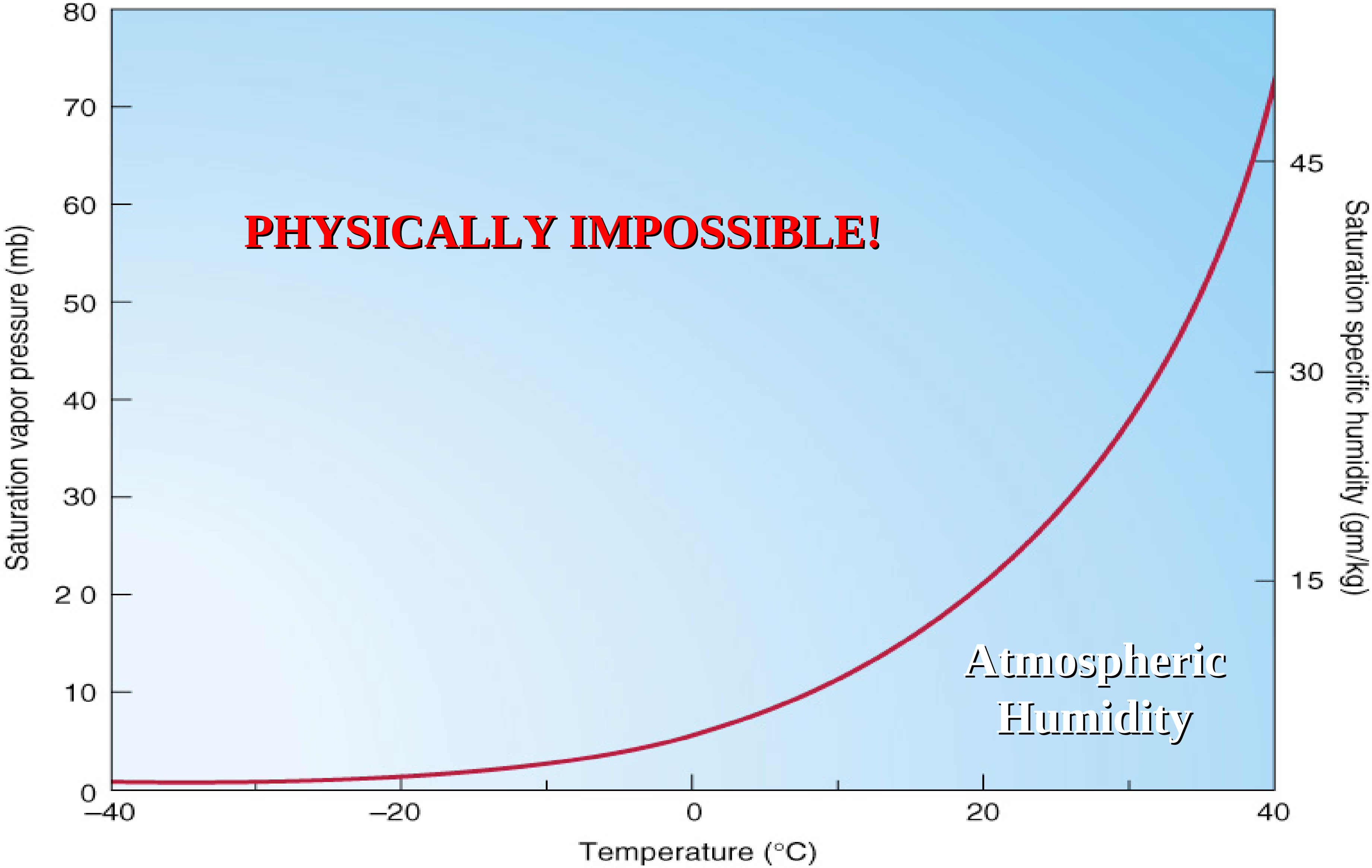
PHYSICALLY IMPOSSIBLE!
Atmospheric
Humidity
Saturation vapor pressure (mb)
80
70
60
50
40
30
2 0
10
0
Saturation specific humidity (gm/kg)
45
30
15
–40
–20
0
20
40
Temperature (°C)


Klamath Mts.
Coast Ranges
Great Valley
Sierra Nevada
S.F.
Owens Valley
Inyo Mts.
Death Valley
Salinas Valley
Santa Lucia Range
Mojave Desert
L.A.
San Bernardino Mts.
S.D.
Conversion Scale
cm in.
5 2
10 4
15 6
20 8
25 10
30 12
40 16
50 20
75 30
100 40
125 50
150 60
180 70
200 80
250 100

Precipitation

To get precipitation, you need:

- Moisture in the Atmosphere
- Mechanism to Release the Moisture
  - Every Mechanism Causes Air to Cool Below the Dew Point Temperature



PHYSICALLY IMPOSSIBLE!
Atmospheric Humidity
Saturation vapor pressure (mb)
80
70
60
50
40
30
2 0
10
0
Saturation specific humidity (gm/kg)
45
30
15
–40
–20
0
20
40
Temperature (°C)

To get precipitation, you need:

- Moisture in the Atmosphere
- Mechanism to Release the Moisture
  - Every Mechanism Causes Air to Cool Below the Dew Point Temperature
  - The Easiest Mechanism is to Force Air to Rise
  - There are 4 Basic Mechanisms for Precipitation and 1 for Condensation

To get precipitation, you need:

1) Moisture in the Atmosphere
   - Clouds are the source of precipitation
   - In warm clouds, liquid droplets condense and collide
   - When the droplets become large enough, they fall as rain

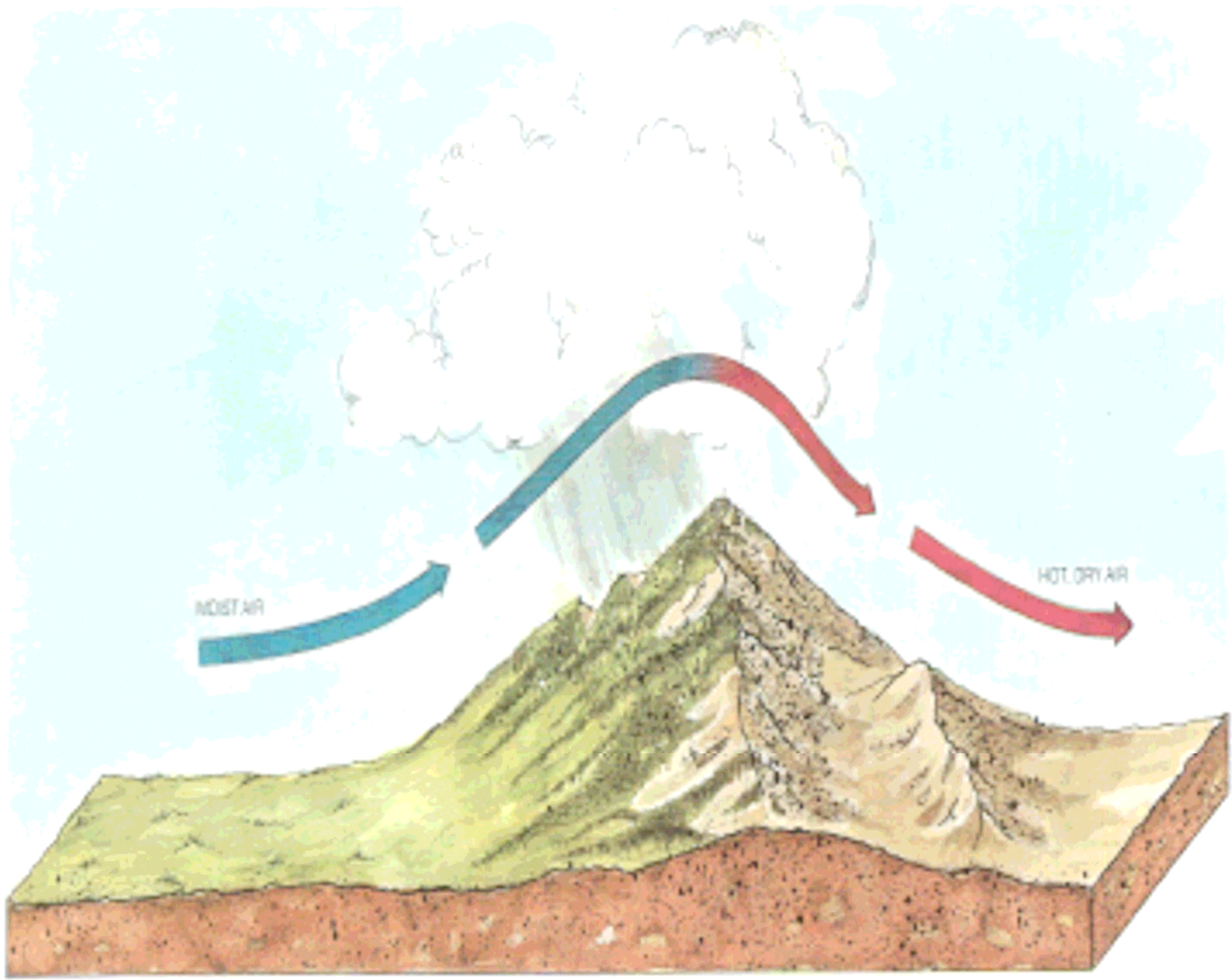
Precipitation Causing Mechanisms

Precipitation Causing Mechanisms

- Orographic Precipitation
-
-
-

1) Orographic Precipitation

- Warm moist air is forced over a mountain barrier
- It cools adiabatically
- At the LCL condensation (and often precipitation occurs


MOIST AIR
HOT, DRY AIR

Precipitation Causing Mechanisms

- Orographic Precipitation
- Convective Precipitation
-
-

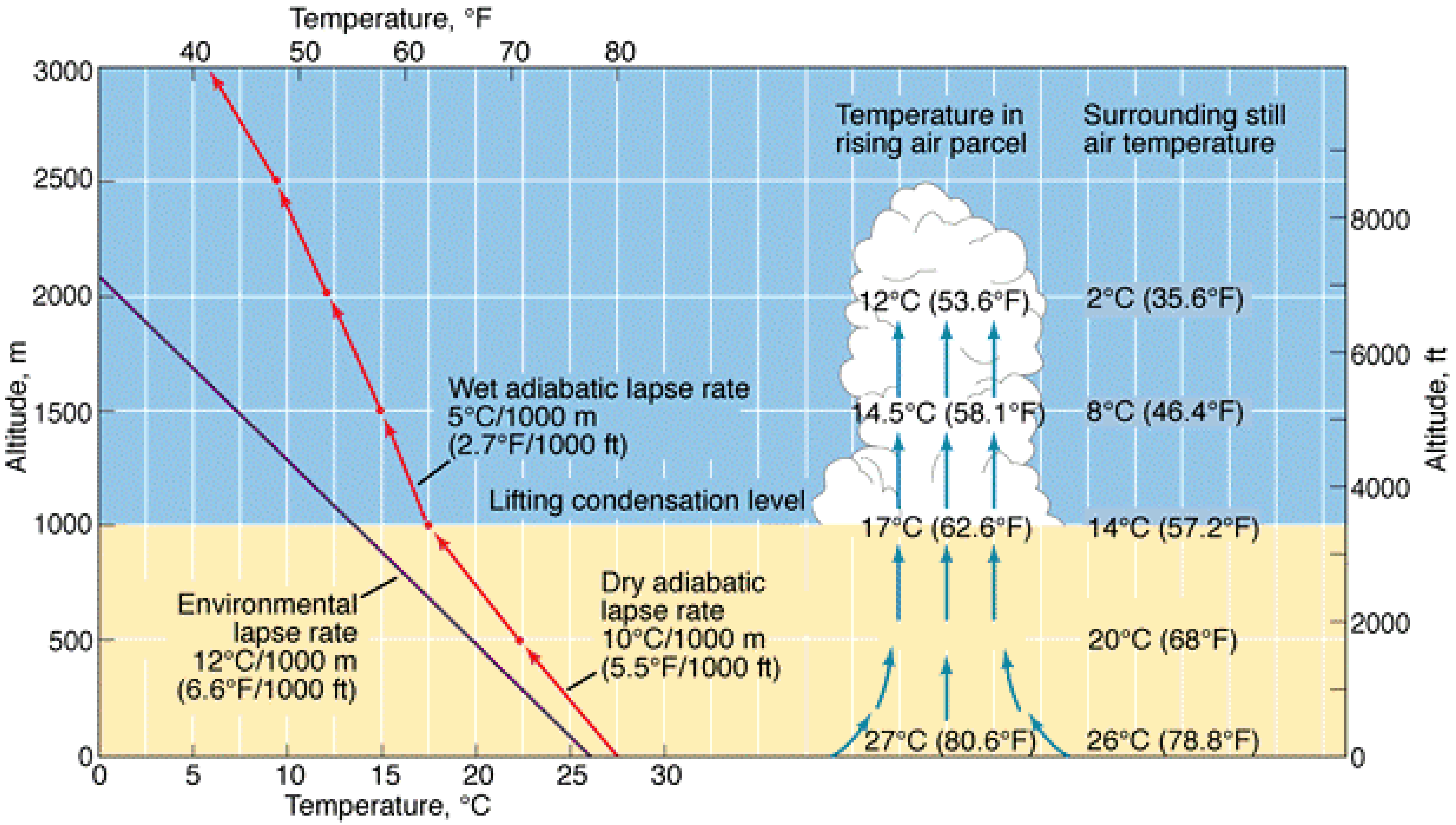
2) Convective Precipitation

- Convection = upwards motion of heat air (convection cells)
- Caused by uneven surface heating
- Parcel of warmer, less dense air rises
- As the parcel rises, it cools

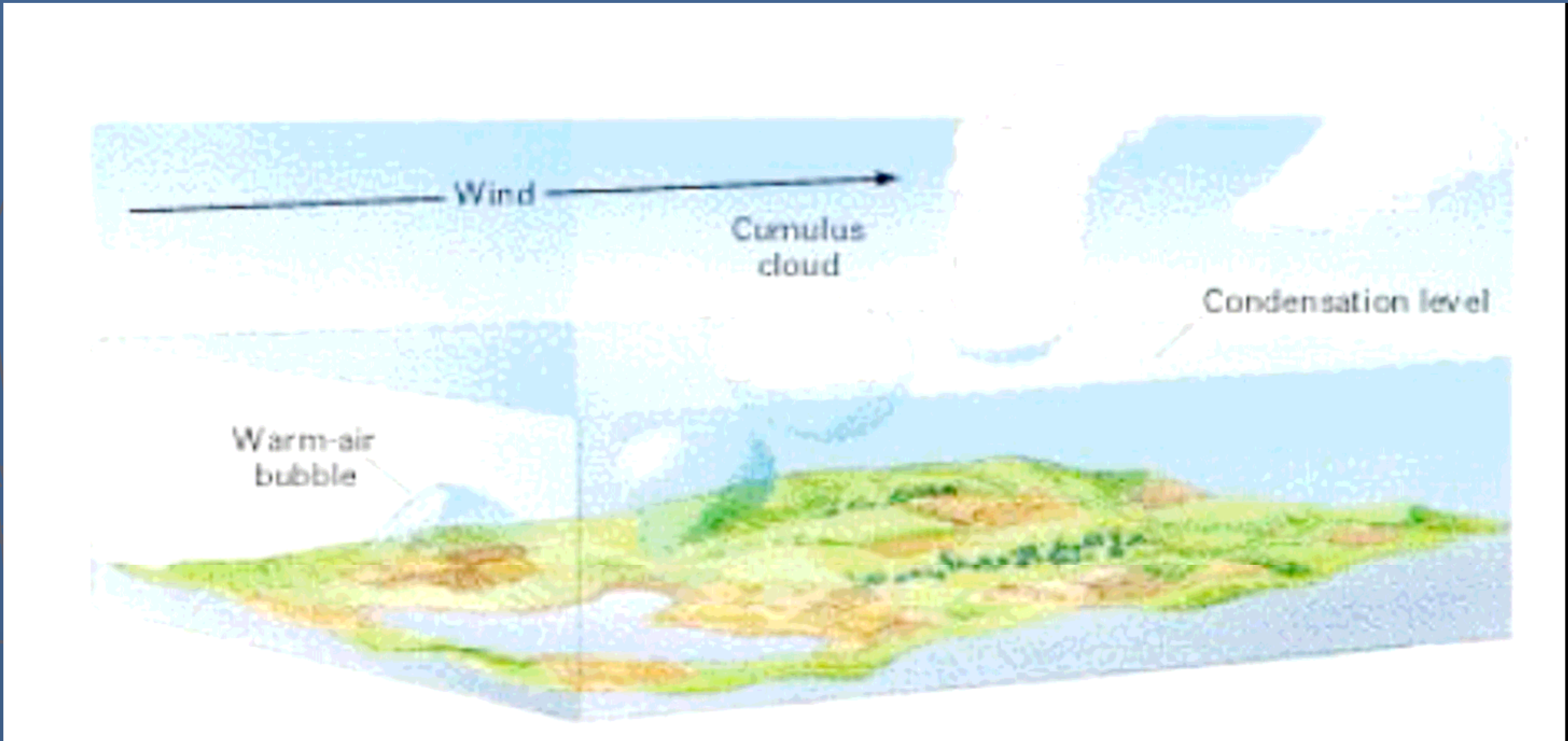
2) Convective Precipitation

- If the air is quite moist, the release of latent heat will ensure that the parcel of air remains warmer than the surrounding air

- If conditions remain favorable, the rising thermal will grow into a thunderstorm



Temperature, °F
40
50
60
70
80
3000
2500
2000
1500
1000
500
0
Altitude, m
Temperature in rising air parcel
Surrounding still air temperature
8000
6000
4000
2000
0
Altitude, ft
12°C (53.6°F)
2°C (35.6°F)
Wet adiabatic lapse rate
5°C/1000 m
(2.7°F/1000 ft)
14.5°C (58.1°F)
8°C (46.4°F)
Lifting condensation level
17°C (62.6°F)
14°C (57.2°F)
Dry adiabatic lapse rate
10°C/1000 m
(5.5°F/1000 ft)
Environmental lapse rate
12°C/1000 m
(6.6°F/1000 ft)
20°C (68°F)
27°C (80.6°F)
26°C (78.8°F)
0
5
10
15
20
25
30
Temperature, °C

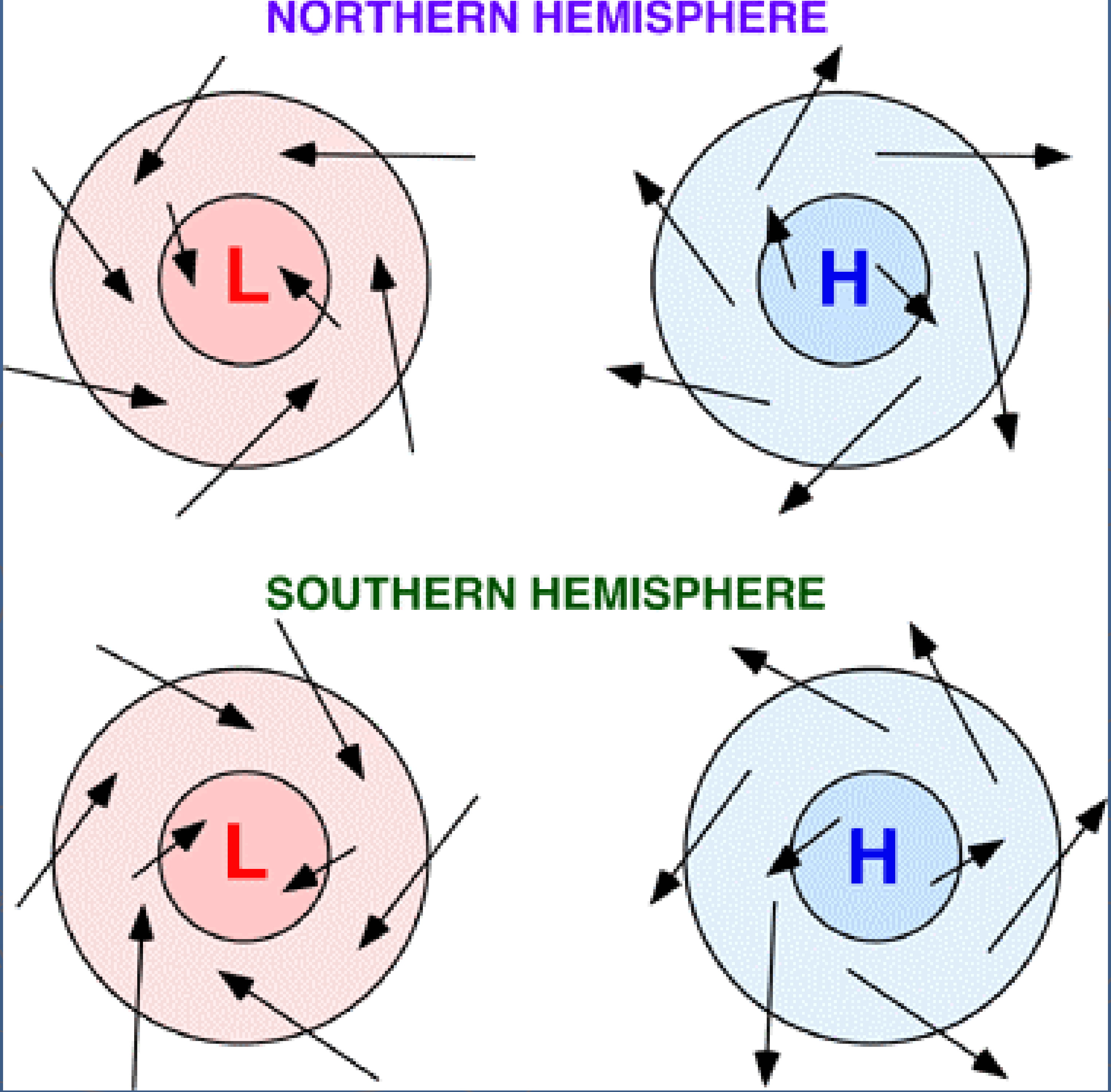

Wind
Cumulus
cloud
Condensation level
Warm-air
bubble

Precipitation Causing Mechanisms

- Orographic Precipitation
- Convective Precipitation
- Cyclonic Precipitation
-

3) Cyclonic Precipitation

- Pressure differences cause air motion (wind)
- A low pressure cell at the surface causes convergence
- Low level convergence causes upward vertical motion, and therefore precipitation


NORTHERN HEMISPHERE
L
H
SOUTHERN HEMISPHERE
L
H

Precipitation Causing Mechanisms

- Orographic Precipitation
- Convective Precipitation
- Cyclonic Precipitation
- Frontal Precipitation

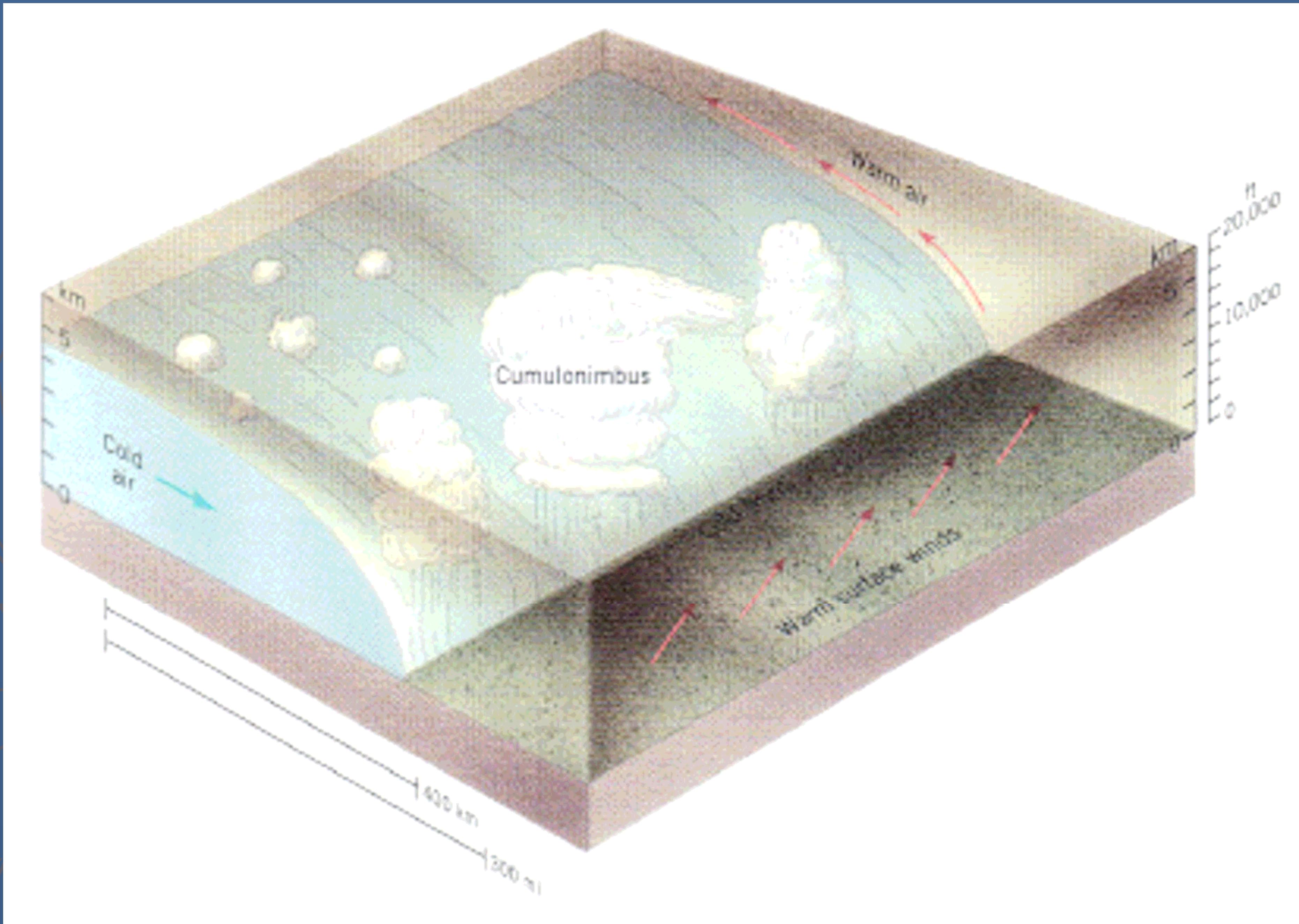
4) Frontal Precipitation

- Frontal uplift – air can be forced upward through the movement of air masses

- Air masses = a large body of air, with a set of relatively uniform temperature and moisture properties

4) Frontal Precipitation

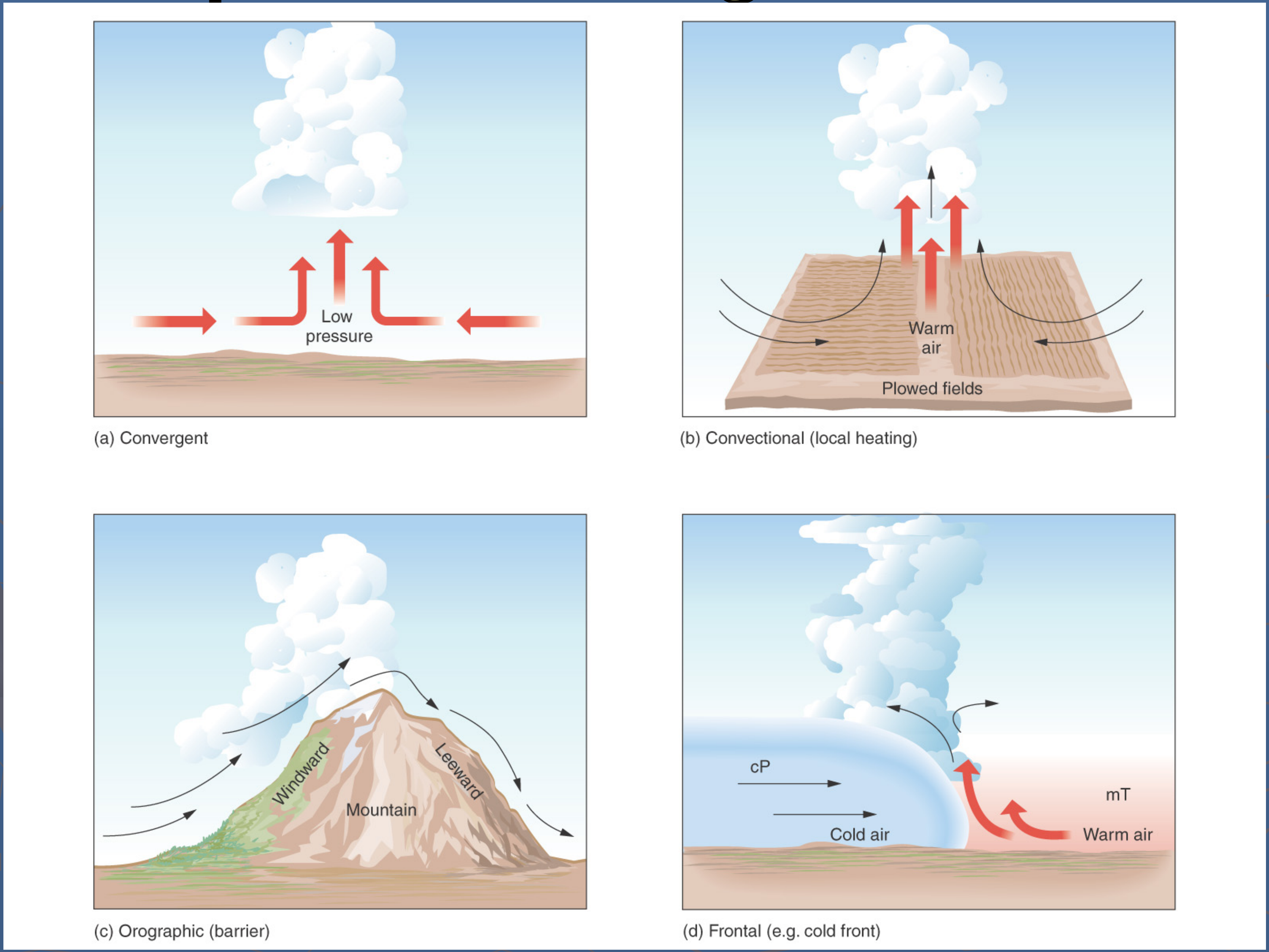
- When a colder, more dense air mass advances on a warmer, less dense air mass (a cold front), it is forced to rise over the cold air mass


Warm air
ft
20,000
10,000
0
km
5
0
Cumulonimbus
Cold air
Warm surface winds
400 km
300 mi

Precipitation Causing Mechanisms

- Orographic Precipitation
- Convective Precipitation
- Cyclonic Precipitation
- Frontal Precipitation

Atmospheric Lifting Mechanisms



Clouds

Clouds and Cloud Formation

- Clouds are instrumental to the Earth's energy and moisture balances
- Most clouds form as air parcels are lifted and cooled to saturation
- Different lifting mechanisms exist to lift air and form clouds through condensation
- In the 1700s, a British Pharmacist developed a cloud classification scheme that we still use today

Clouds and Cloud Formation

- Clouds are classified on the basis of the presence or absence of vertical development
- ***Cumuloform*** clouds exhibit significant vertical development
- ***Stratiform*** clouds do not exhibit significant vertical development

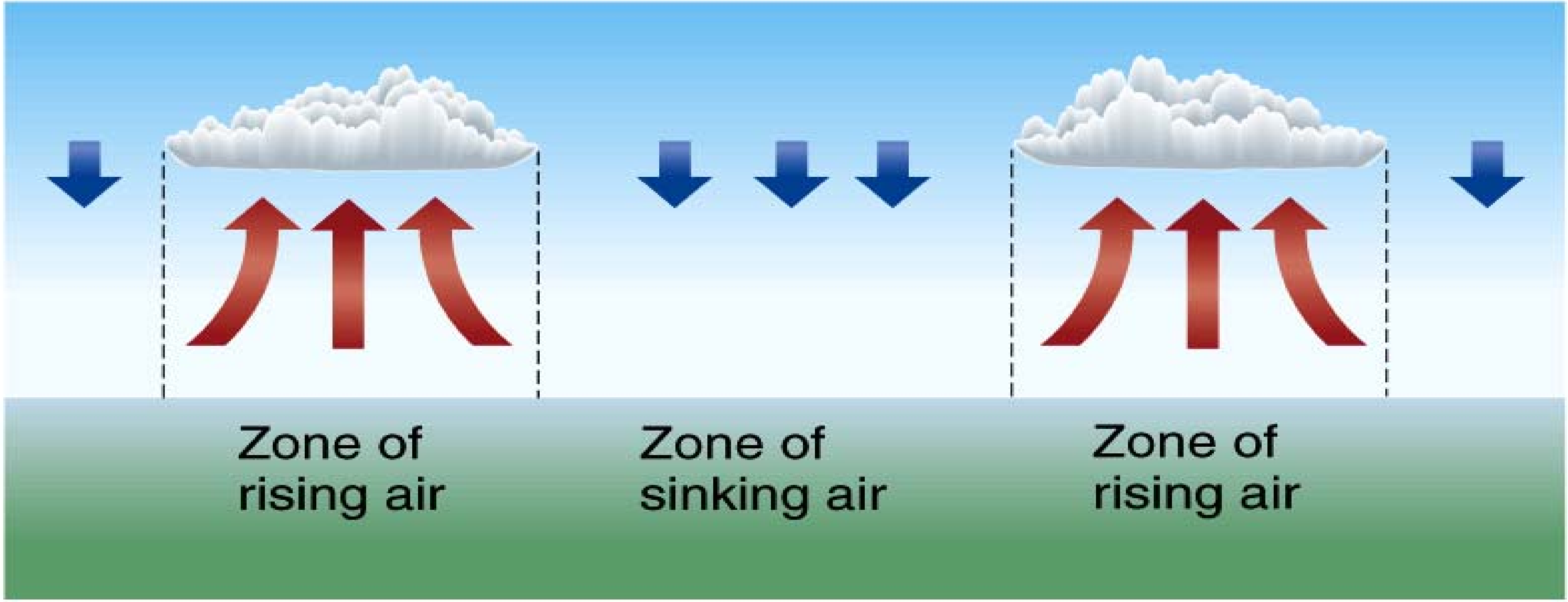
Clouds and cloud formations

- Cirrus – thin, wispy clouds of ice
- Nimbus – rain producing clouds

Cumuloform Clouds

- ***Cumulus*** Clouds
  - 1-2 km thick, 600-1200 meters high

Formation of fair weather cumulus



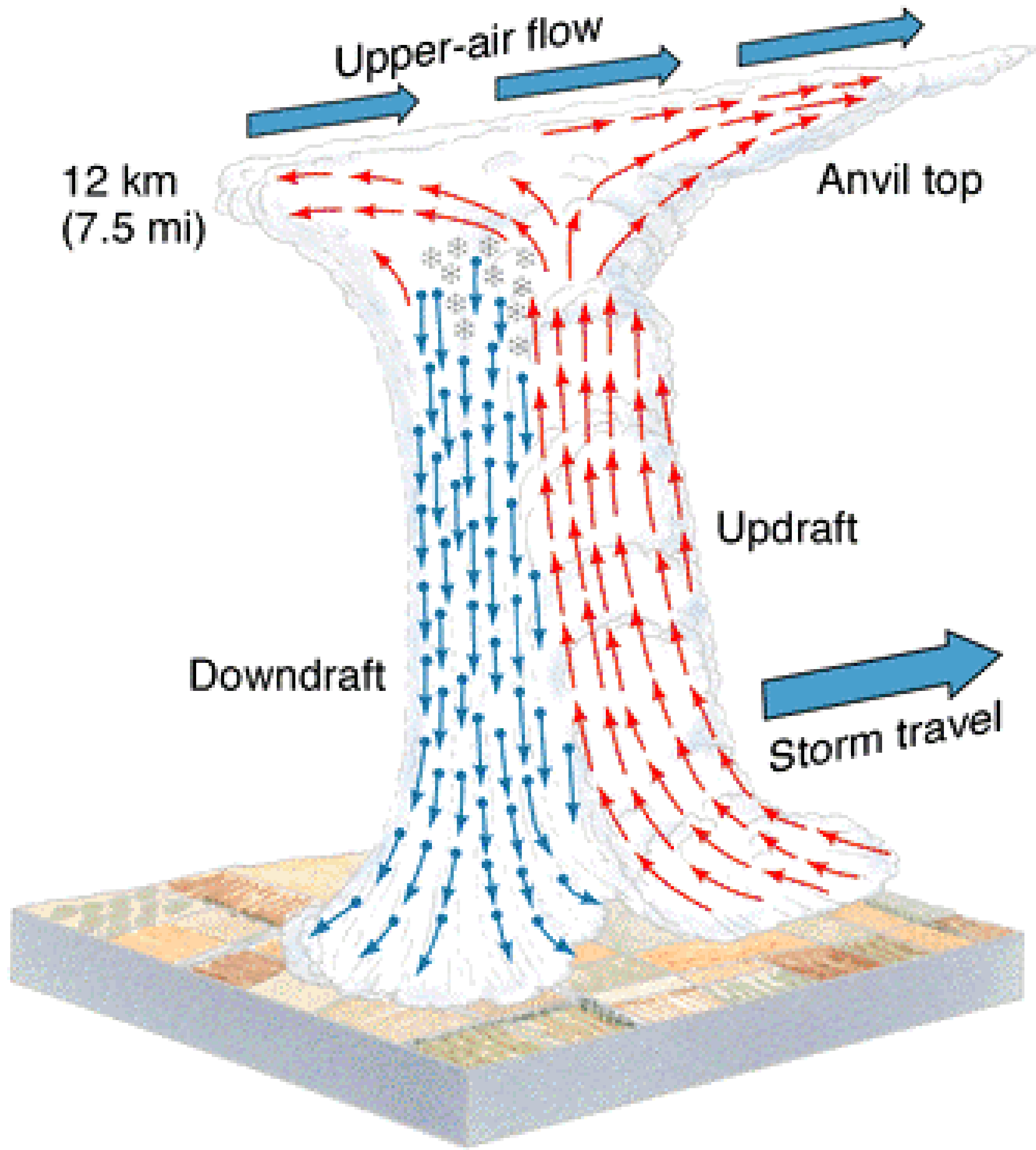
Cumuloform Clouds

- ***Cumulus*** Clouds
  - 1-2 km thick, base is 600-1200 meters high
- ***Cumulus Congestus***
  - 3-5 km thick

Cumuloform Clouds

- ***Cumulus*** Clouds
  - 1-2 km thick, base is 600-1200 meters high
- ***Cumulus Congestus***
  - 3-5 km thick
- ***Cumulonimbus***
  - 6-12 km thick – thunderstorm clouds

- Progression occurs with development


Upper-air flow
12 km
(7.5 mi)
Anvil top
Updraft
Downdraft
Storm travel

Stratiform Clouds

- Classified on the basis of height

High Clouds – more than 6 km high
Middle Clouds – between 2 and 6 km high
Low Clouds – less than 2 km high

Stratiform Clouds

High Clouds – more than 6 km high

- Composed entirely of ice crystals
- Whitish appearance
- Temperature is around -35 C
- Little water vapor (0.025 g/m^3)

- High clouds –
  - Cirrus: fine and wispy

Cirrus clouds with fall streaks

Stratiform Clouds

High Clouds – more than 6 km high

- Composed entirely of ice crystals
- Whitish appearance
- ***Cirrus*** – fine and wispy
- ***Cirrostratus*** – forming a complete layer

Cirrostratus

When viewed through a layer of cirrostratus, the Moon or Sun has a whitish, milky appearance but a clear outline. A characteristic feature of cirrostratus clouds is the *halo*, a circular arc around the Sun or Moon formed by the refraction (bending) of light as it passes through the ice crystals.

Stratiform Clouds

High Clouds – more than 6 km high

- Composed entirely of ice crystals
- Whitish appearance
- ***Cirrus*** – fine and wispy
- ***Cirrostratus*** – forming a complete layer
- ***Cirrocumulus*** – light puffy clouds
  - "Mackerel Sky"

Stratiform Clouds

Middle Clouds – between 2 and 6 km high

- Composed of a combination of ice crystals and water droplets
- Thicker due to higher temperatures
- ***Altostratus*** – forming a near complete layer


Altostratus

Stratiform Clouds

Middle Clouds – between 2 and 6 km high

- Composed of a combination of ice crystals and water droplets
- Thicker due to higher temperatures
- ***Altostratus*** – forming a near complete layer
- ***Altocumulus*** – rows of puffy clouds

Stratiform Clouds

Low Clouds – less than 2 km high

- Composed primarily of water droplets
- Thicker and somewhat darker
- ***Stratus*** – a nearly unbroken layer of gray

Stratiform Clouds

Low Clouds – less than 2 km high

- Composed primarily of water droplets
- Thicker and somewhat darker
- ***Stratus*** – a nearly unbroken layer of gray
- ***Stratocumulus*** – rows of puffy clouds

Cumulus or Stratocumulus?

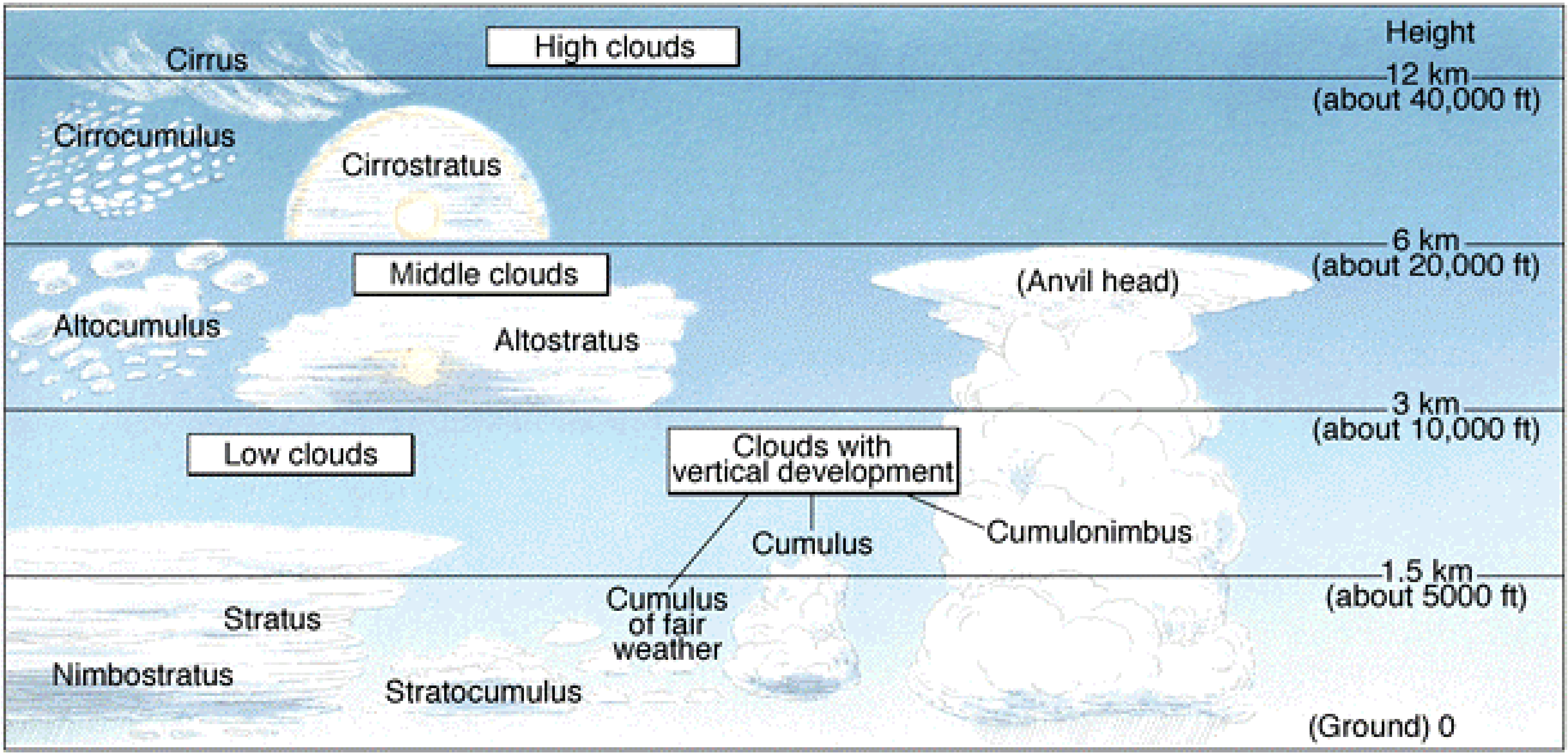
- Cumulus
  - flat bottoms
  - occur when significant lifting is present
- Stratocumulus
  - rounded bottoms
  - occur when vertical motions are minimal

Stratiform Clouds

Low Clouds – less than 2 km high

- Composed primarily of water droplets
- Thicker and somewhat darker
- ***Stratus*** – a nearly unbroken layer of gray
- ***Stratocumulus*** – rows of puffy clouds
- ***Nimbostratus*** – stratus cloud from which rain is falling

Classification of clouds according to height and form



Lenticular Clouds

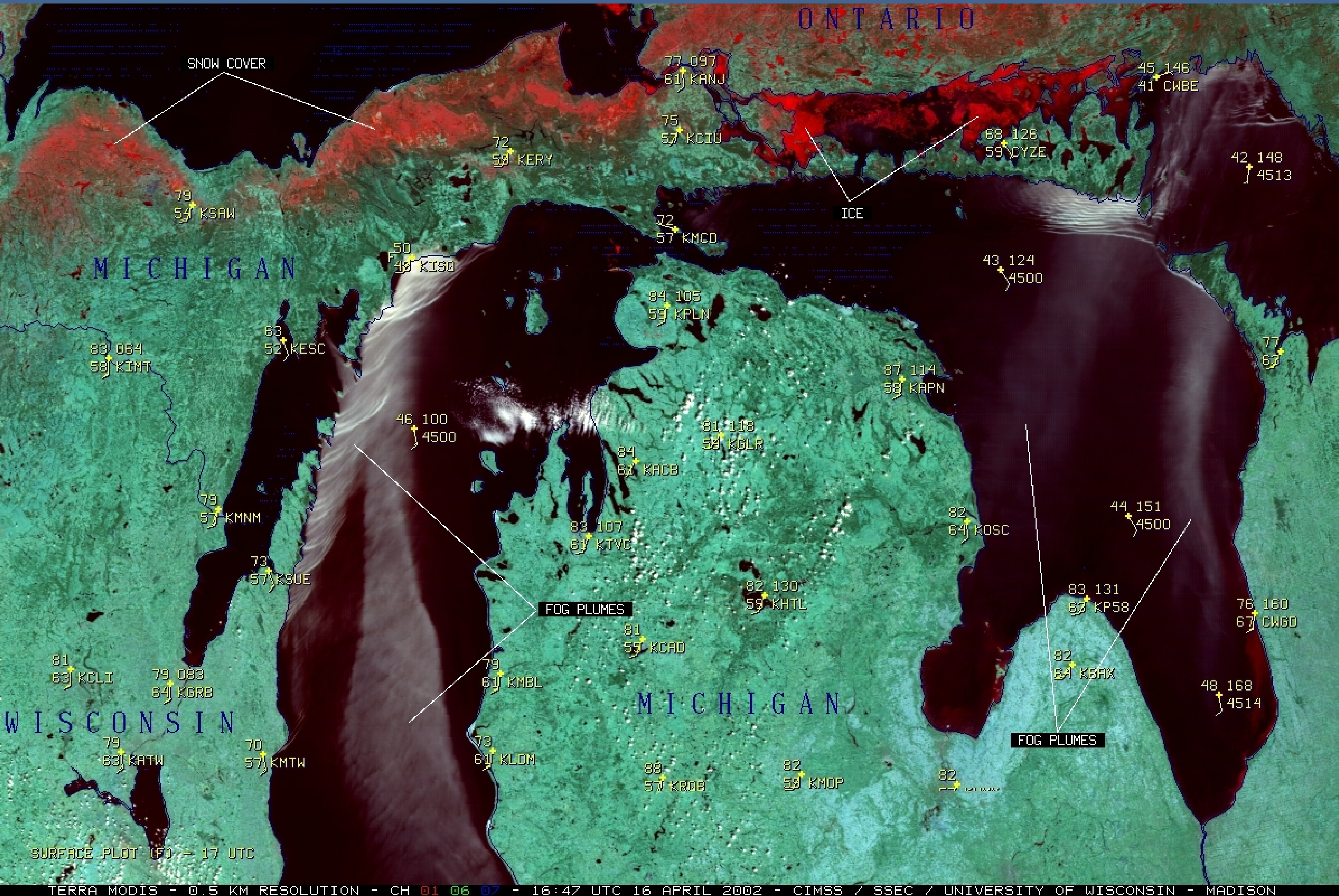
- Form downwind on mountain barriers
- Have a curved (lense-like) shape

altocumulus standing lenticularus

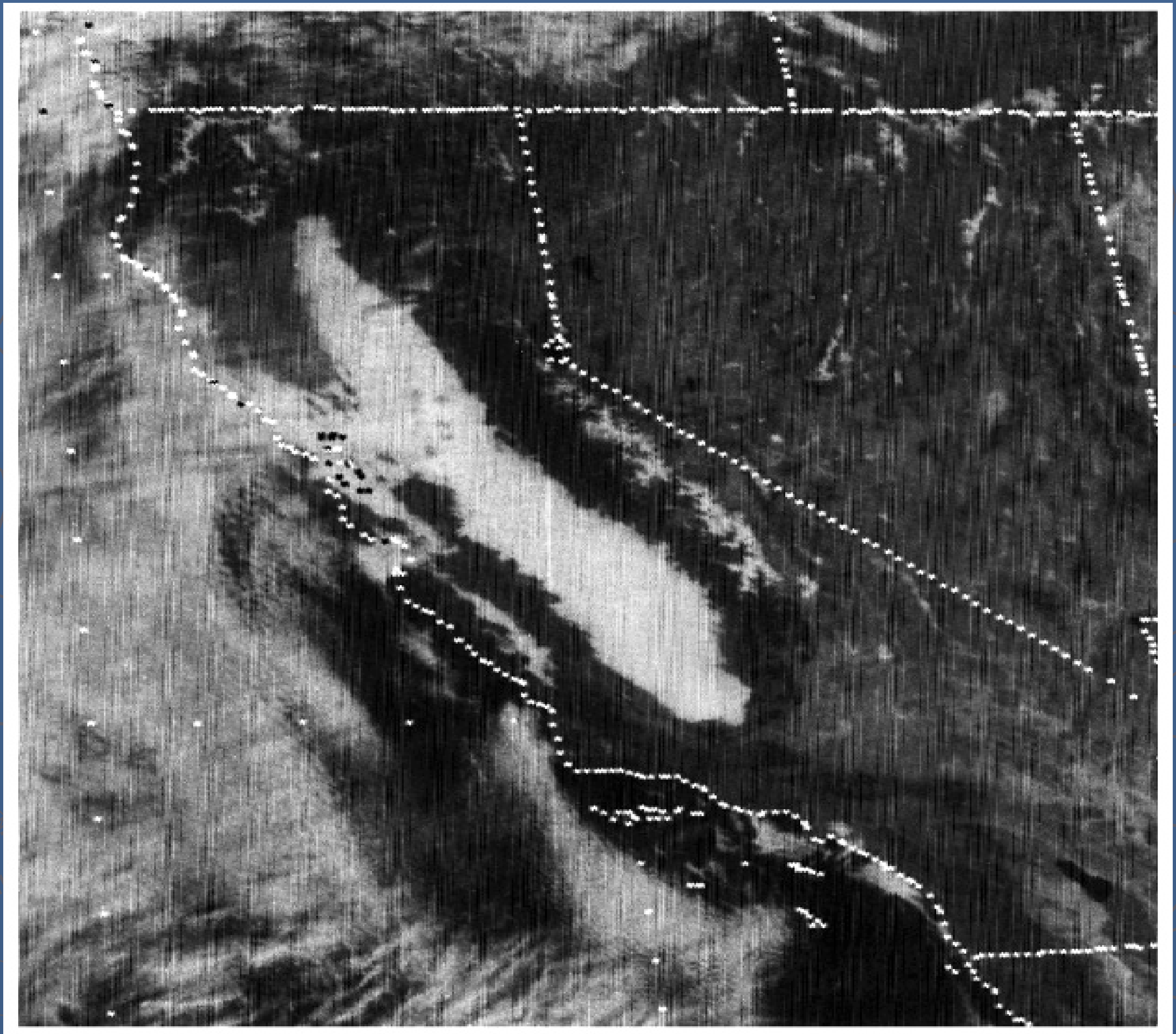
Lenticular Clouds

Stratiform Clouds

- ***Fog*** – stratus cloud at the ground
- ***Advection Fog*** – moving air over a colder surface
  - (e.g., the Grand Banks of Newfoundland)
- ***Radiation Fog*** – motionless air that cools below the dew point due to longwave radiation loss at night


ONTARIO
SNOW COVER
ICE
MICHIGAN
FOG PLUMES
MICHIGAN
FOG PLUMES
WISCONSIN
SURFACE PLOT (F) - 17 UTC
TERRA MODIS - 0.5 KM RESOLUTION - CH 01 06 07 - 16:47 UTC 16 APRIL 2002 - CIMSS / SSEC / UNIVERSITY OF WISCONSIN - MADISON

Radiation Fog in the Central Valley of California



Stratiform Clouds

- ***Fog*** – stratus cloud at the ground
- ***Sea Fog*** – forms when a cool moist air parcel comes in contact with cold ocean

Occurs along the coasts of continents where cold currents move toward the equator (e.g. California, Peru)


Copyright A.N. Strahler

What is the difference between the environmental lapse rate and the dry adiabatic lapse rate?

Environmental Lapse Rate vs. DALR/WALR

- Is the average temperature lapse rate, an expression of how temperature of still air varies with altitude

- This rate will vary from time to time and from one place to another, depending on the state of the atmosphere

- No motion if air is implied for the environmental lapse rate (both DALR and WALR rely on motion)