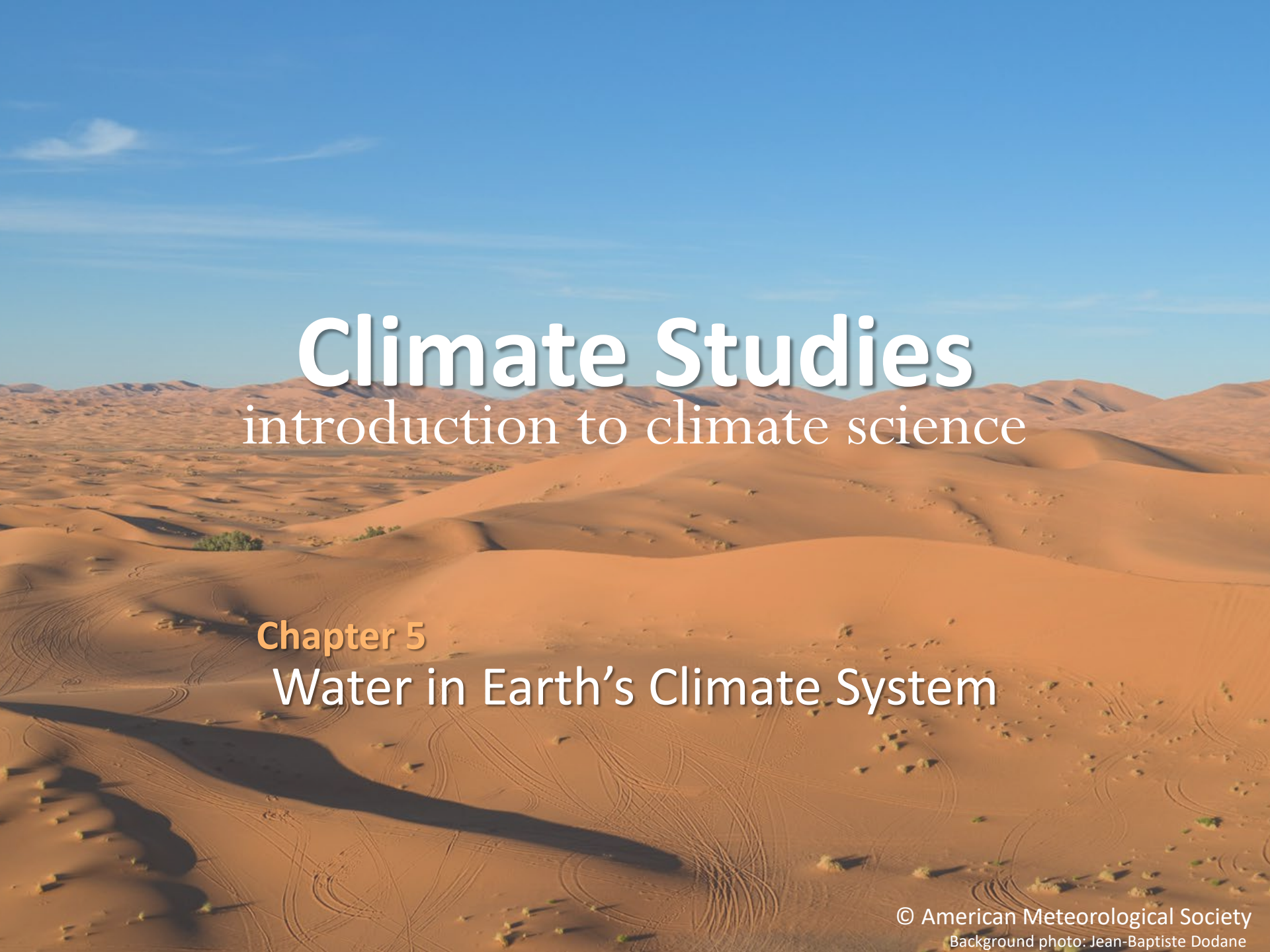


Climate Studies

introduction to climate science

Chapter 5

Water in Earth's Climate System

Background photo: Jean-Baptiste Dodane

Essential Questions

- How is energy related to temperature and phase changes of water?
- How does the presence or absence of water affect the climate character of a region?
- How does the global hydrologic cycle contribute to making Earth's climate habitable?
- Why is it important to budget the distribution of water in the different domains of the climate system?
- Where, geographically, are there greater/lesser concentrations of atmospheric moisture? Why?
- How does atmospheric stability affect cloud formation?
- What mechanisms play a role in forcing air upward to produce a cloud?
- What are the main types of precipitation from the atmosphere?
- What are the different instruments used to measure moisture in the climate system?

Introduction

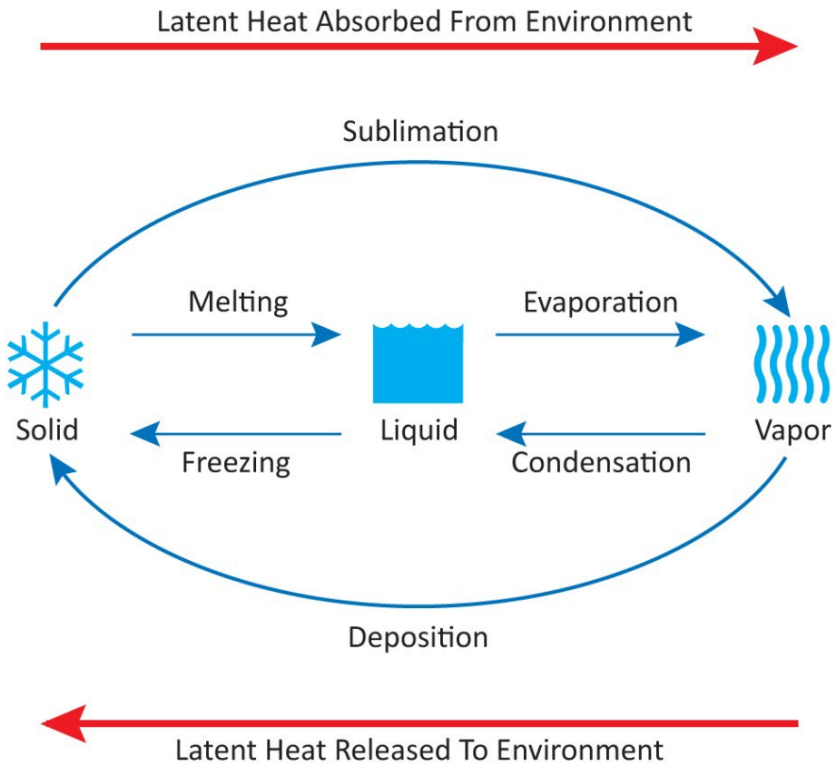
- Water is a liquid, solid and gas on Earth
  - Essential to all life
  - Common medium between the major spheres of the climate system
  - Key in extreme climatic phenomena like seasonal floods and droughts
  - Critical to natural ecosystems and societies
  - Most important greenhouse gas, magnifing the intensity of climate change and causes natural variations
  - As clouds, it influences present and future states of the climate
  - Creates complex interactions within and between climate's sub-systems, and must be examined in the context of the larger climate system
- Water vapor is the most plentiful greenhouse gas, and can potentially reduce or amplify climate
  - Including doubling the climate warming caused by increased levels of carbon dioxide in the atmosphere

Properties of Water
Latent Heating

- Water occurs naturally in all three phases within the temperature and pressure ranges at and near Earth's surface
  - crystalline solid (ice or snow)
  - liquid (liquid water)
  - gas (water vapor)
  - continually changes phase
- **Latent heat -** quantity of heat involved in phase changes of water
  - "latent" refers to heat "hidden" until released

Properties of Water
Latent Heating

- **Melting -** phase change from solid to liquid
- **Evaporation -** phase change from liquid to vapor
- **Sublimation -** phase change directly from solid to vapor
- **Freezing -** phase change from liquid to solid
- **Condensation -** phase change from vapor to liquid
- **Deposition -** phase change directly from vapor to solid



Properties of Water
Specific Heating

- **Specific heat -** amount of heat that will raise the temperature of 1 gram of a substance by 1 Celsius degree

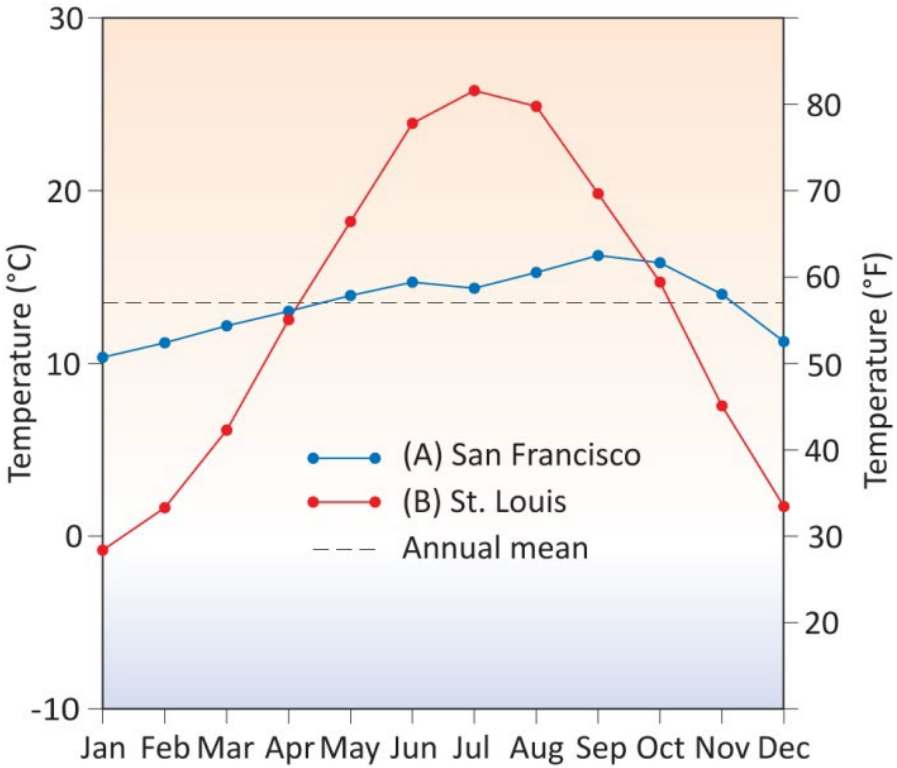
Substance	Specific Heat
Water	1.000
Wet mud	0.600
Ice (at 0 °C)	0.478
Wood	0.420
Aluminum	0.214
Brick	0.200
Granite	0.192
Sand	0.188
Dry air[b]	0.171
Copper	0.093
Silver	0.056
Gold	0.031

Properties of Water
Thermal Inertia

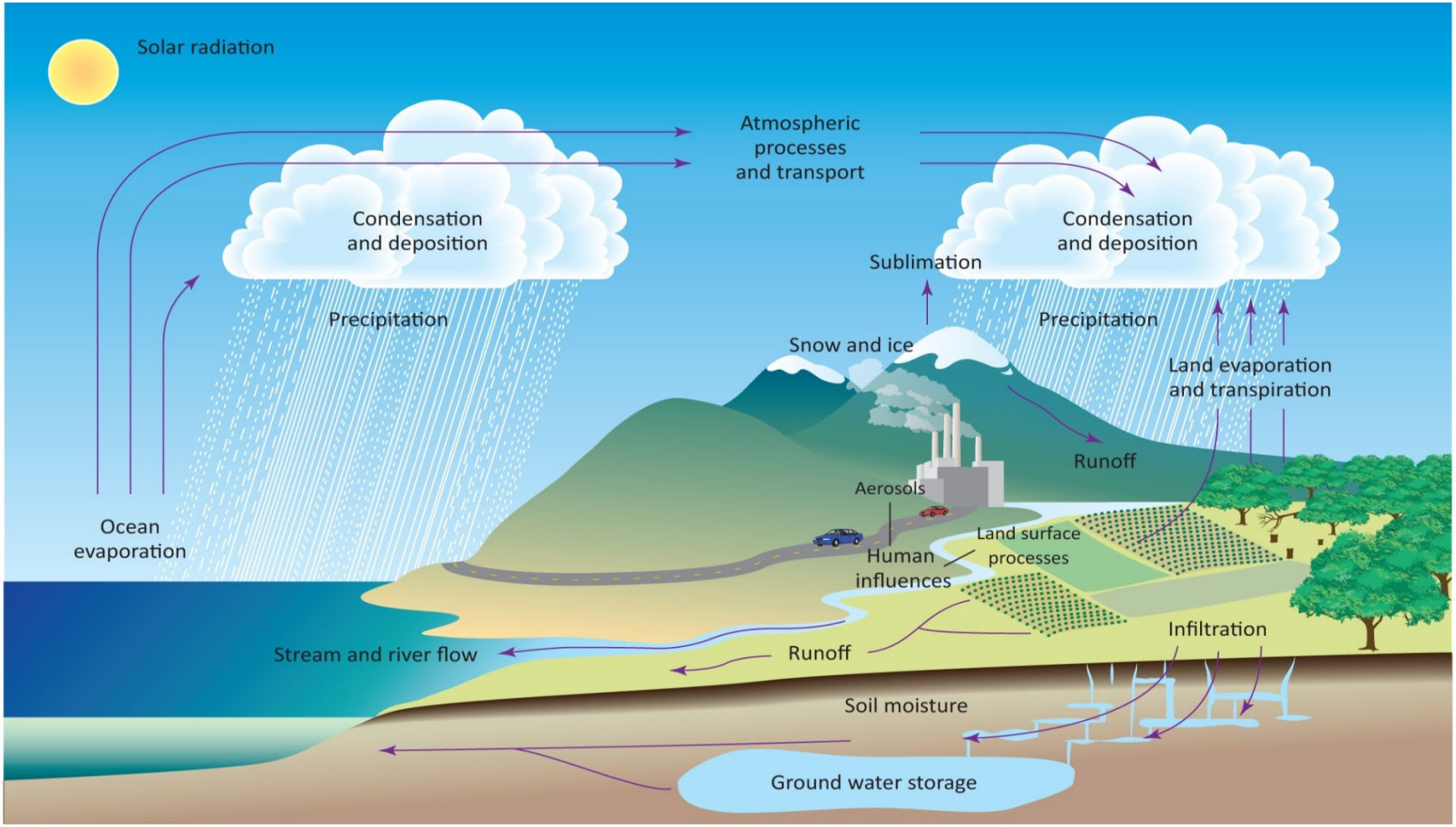
- **Thermal inertia -** resistance to temperature change
- A large body of water influences the climate of downwind localities, especially air temperature
  - Compared to an adjacent landmass, a body of water warms more slowly during the day or in summer and cools more slowly at night or in winter
  - Incoming solar radiation penetrates water to a greater depth and is absorbed while land absorbs solar radiation only within the first few centimeters of the surface
  - Circulation of waters transports heat, whereas heat is conducted only very slowly into soil

Properties of Water
Maritime and Continental Climates

- **Maritime climate -** locations immediately downwind of the ocean experience much less contrast between average winter and summer temperatures
- **Continental climate -** inland locations experiencing a much greater contrast between winter and summer temperatures

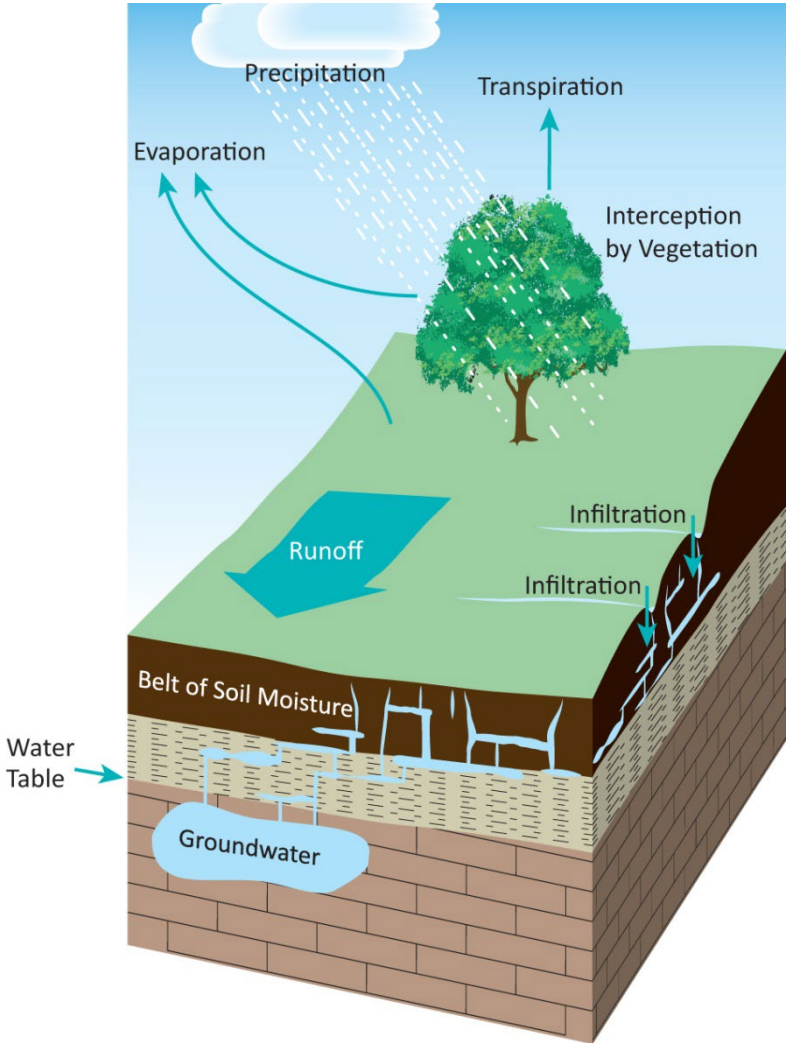


Global Water Cycle



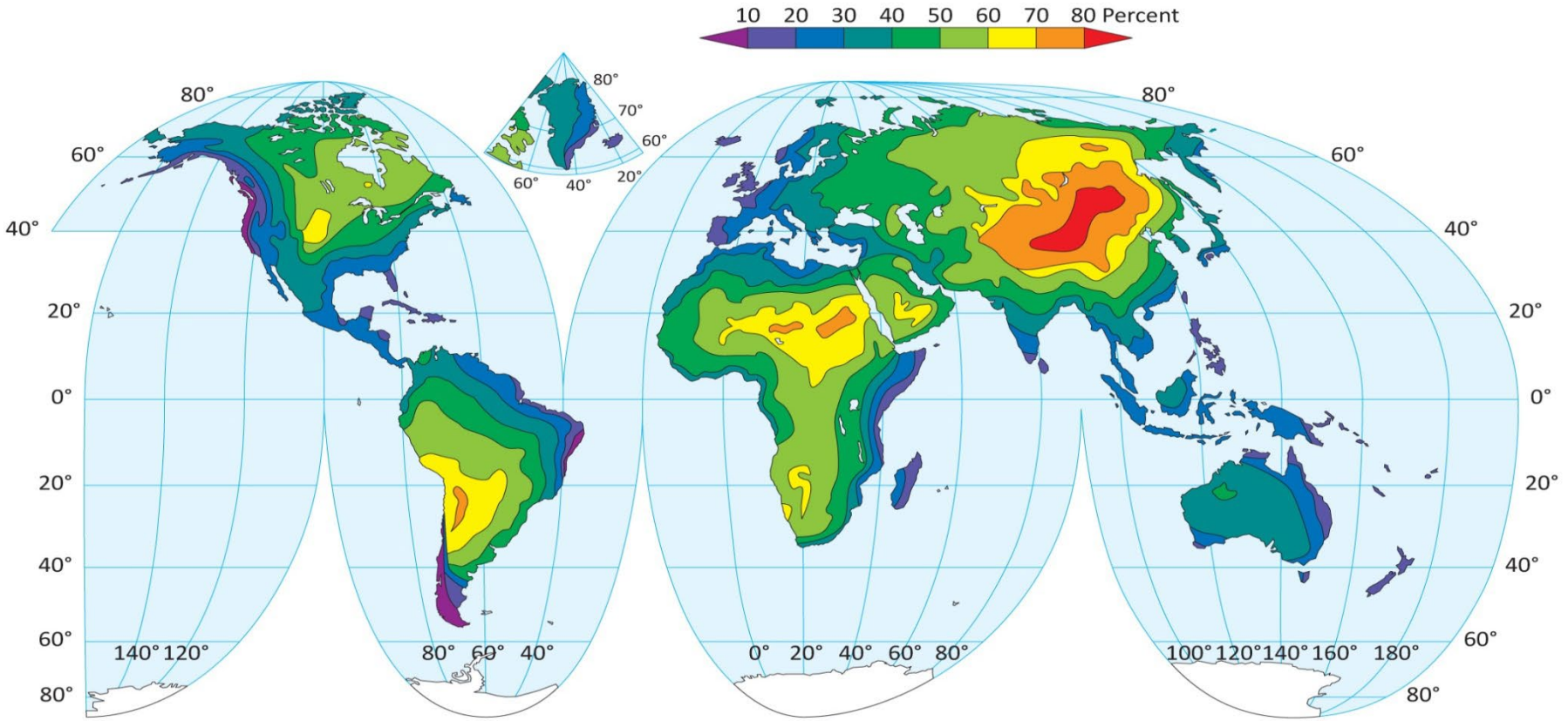
- **Distillation -** when water vaporizes from the Earth's surface, nearly all suspended and dissolved substances, such as sea salts and other contaminants, are left behind
- **Drainage basin -** rivers and streams plus their tributaries, drain a fixed geographical area

Global Water Cycle



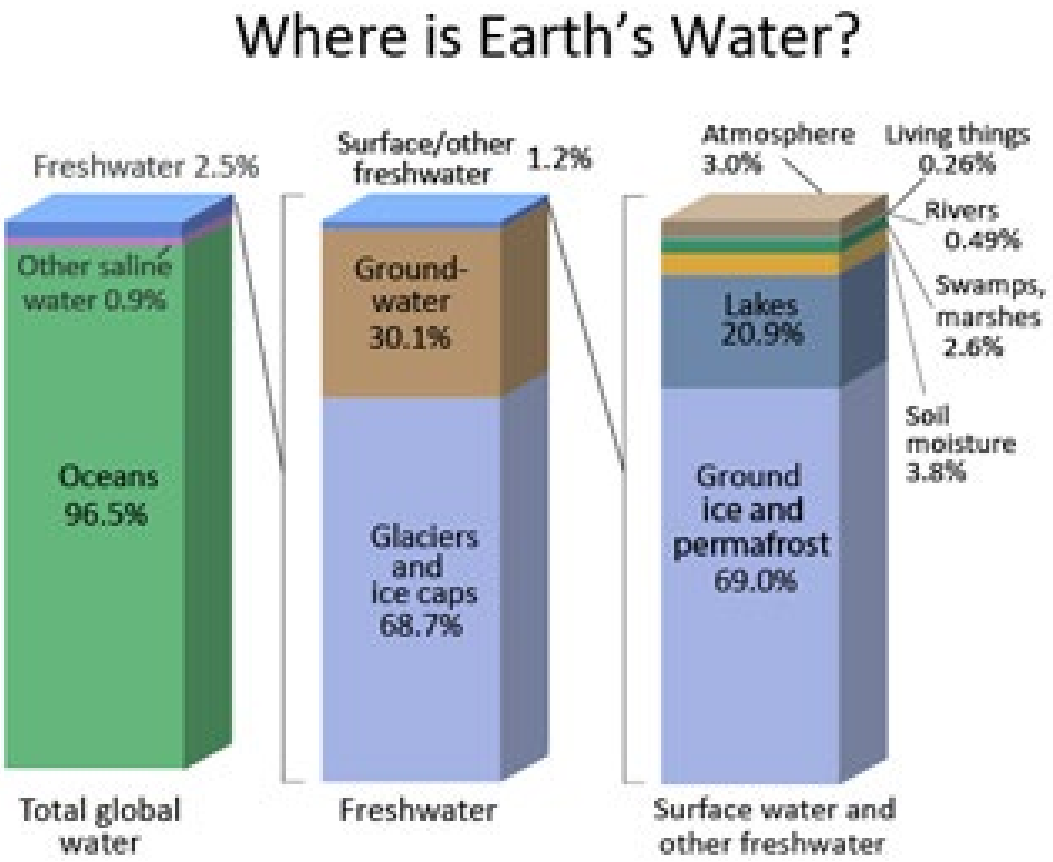
- **Transpiration -** process whereby water taken up from the soil by roots travels through the plant and escapes as vapor through tiny pores (stomata) on the underside of green leaves
- **Evapotranspiration -** direct evaporation from Earth's surface plus transpiration
- **Precipitation -** water in liquid, frozen or freezing form (rain, drizzle, snow, ice pellets, hail and freezing rain) that falls from clouds under the influence of gravity to Earth's surface

Global Water Budget



- The percentage of annual precipitation that falls on land, originating as water that vaporized from the continent

Global Water Cycle



Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources.
NOTE: Numbers are rounded, so percent summations may not add to 100.

Global Water Budget

Source	Cubic meters per year	Gallons per year
Precipitation on the ocean	$+3.24 \times 10^{14}$	$+85.5 \times 10^{15}$
Evaporation from the ocean	-3.60×10^{14}	-95.2×10^{15}
Net loss from the ocean	-0.36×10^{14}	-9.7×10^{15}
Precipitation on land	$+0.98 \times 10^{14}$	$+26.1 \times 10^{15}$
Evapotranspiration from land	-0.62×10^{14}	-16.4×10^{15}
Net gain on land	$+0.36 \times 10^{14}$	$+9.7 \times 10^{15}$

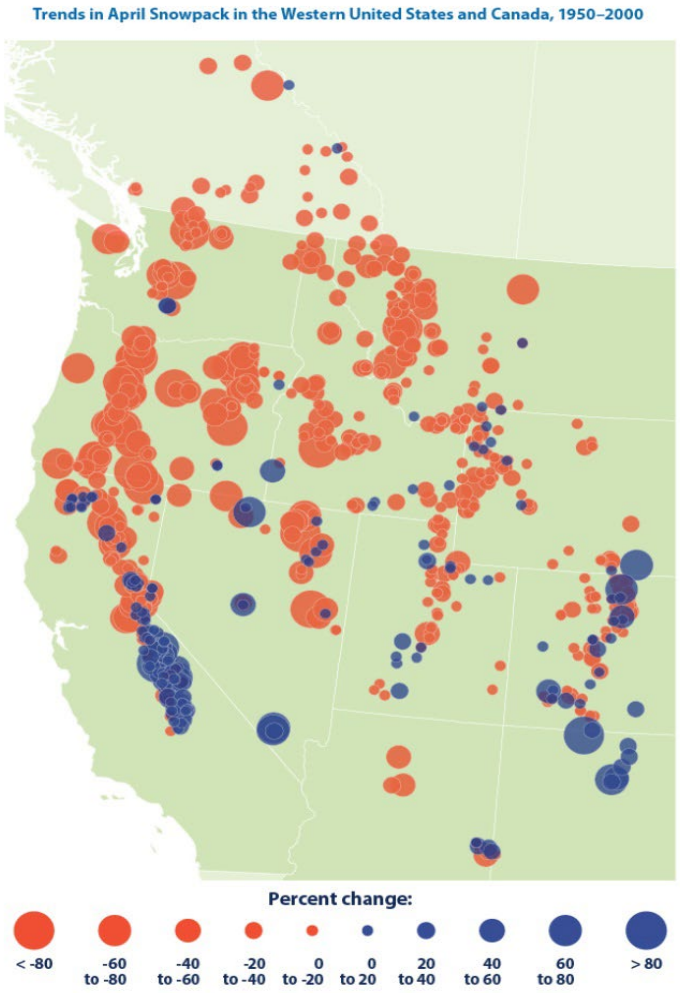
- **Global water budget -** balance sheet for inputs and outputs of water to and from the various global reservoirs

Global Water Budget

	Precipitation (mm)	Evaporation (mm)	Net (mm)
Land	663	419	+244
Ocean	895	944	-49
Global	828	828	0

- Global water budget as depth of liquid water

Global Water Budget



- Ice and snow represent a significant portion of the freshwater in the global water budget
- Current trend is lessening overall snowfall
- Blue circles represent increased snowpack, red circles represent a decrease

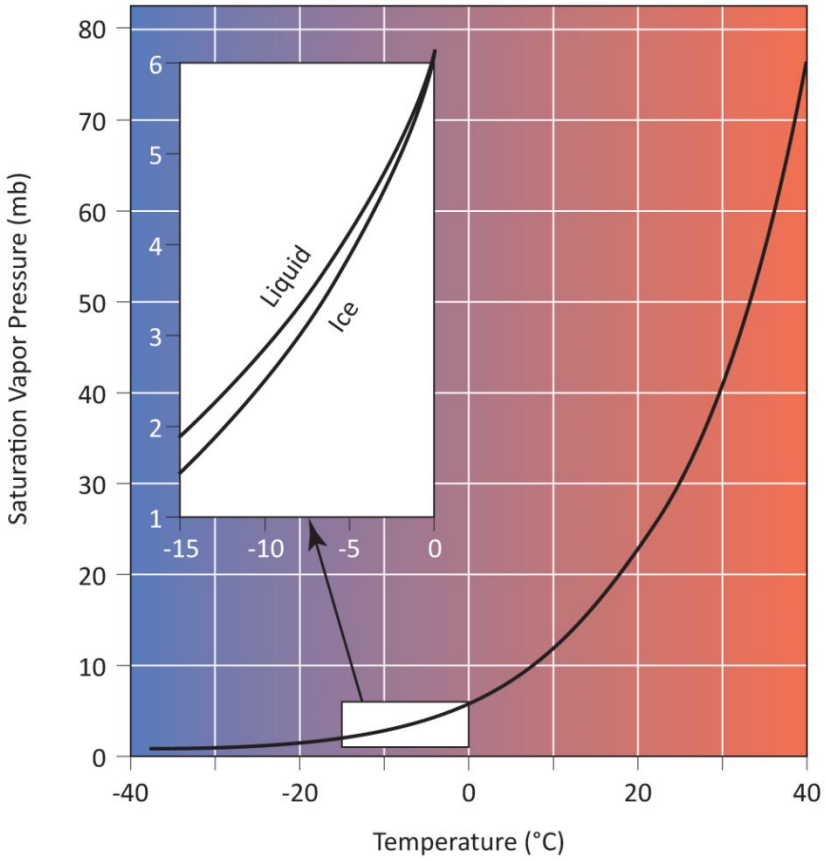
Humidity & Saturation

- It’s not the heat, it’s the humidity”
- **Humidity -** water vapor in the air
  - Varies seasonally, daily, hourly and from one place to another
  - Summer days feel more humid than winter days, especially in cold climates where dry winter air may cause discomfort

Vapor Pressure

- **Pressure -** a force per unit area
- **Air pressure -** forces of a multitude of molecules colliding with a unit surface area of any object in contact with air
- **Dalton's law of partial pressures -** total pressure exerted by a mixture of gases equals the sum of the pressures produced by each constituent gas since each gas acts independently of all the other molecules; each gas exerts a pressure as if it were the only gas present
- **Vapor pressure -** water vapor's contribution to the total air pressure

Saturated Air

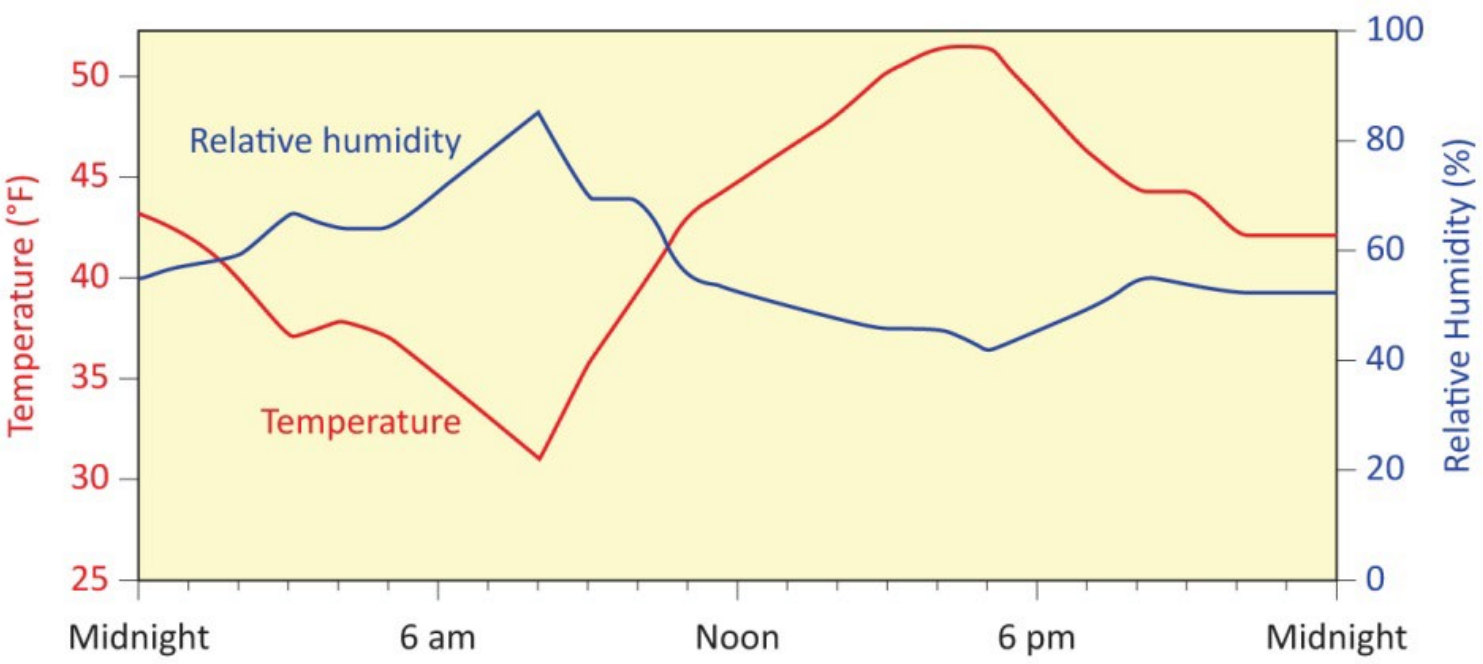


- **Saturation vapor pressure -** the vapor pressure when, above a plane surface of liquid water or ice, the air is saturated with water vapor
  - Raising the air temperature increases the saturation vapor pressure
  - Decreasing the air temperature reduces the saturation vapor pressure

Saturated Air

Temperature °C	°F	Saturation Vapor Pressure over water (mb)	Saturation Vapor Pressure over ice (mb)
50	122	123.40	-
45	113	95.86	-
40	104	73.78	-
35	95	56.24	-
30	86	42.43	-
25	77	31.67	-
20	68	23.37	-
15	59	17.04	-
10	50	12.27	-
5	41	8.71	-
0	32	6.11	6.11
-5	23	4.21[a]	4.02[a]
-10	14	2.86	2.60
-15	5	1.91	1.65
-20	-4	1.25	1.03
-25	-13	0.80	0.63
-30	-22	0.51	0.38
-35	-31	0.31	0.22
-40	-40	0.19	0.13
-45	-49	0.11	0.07

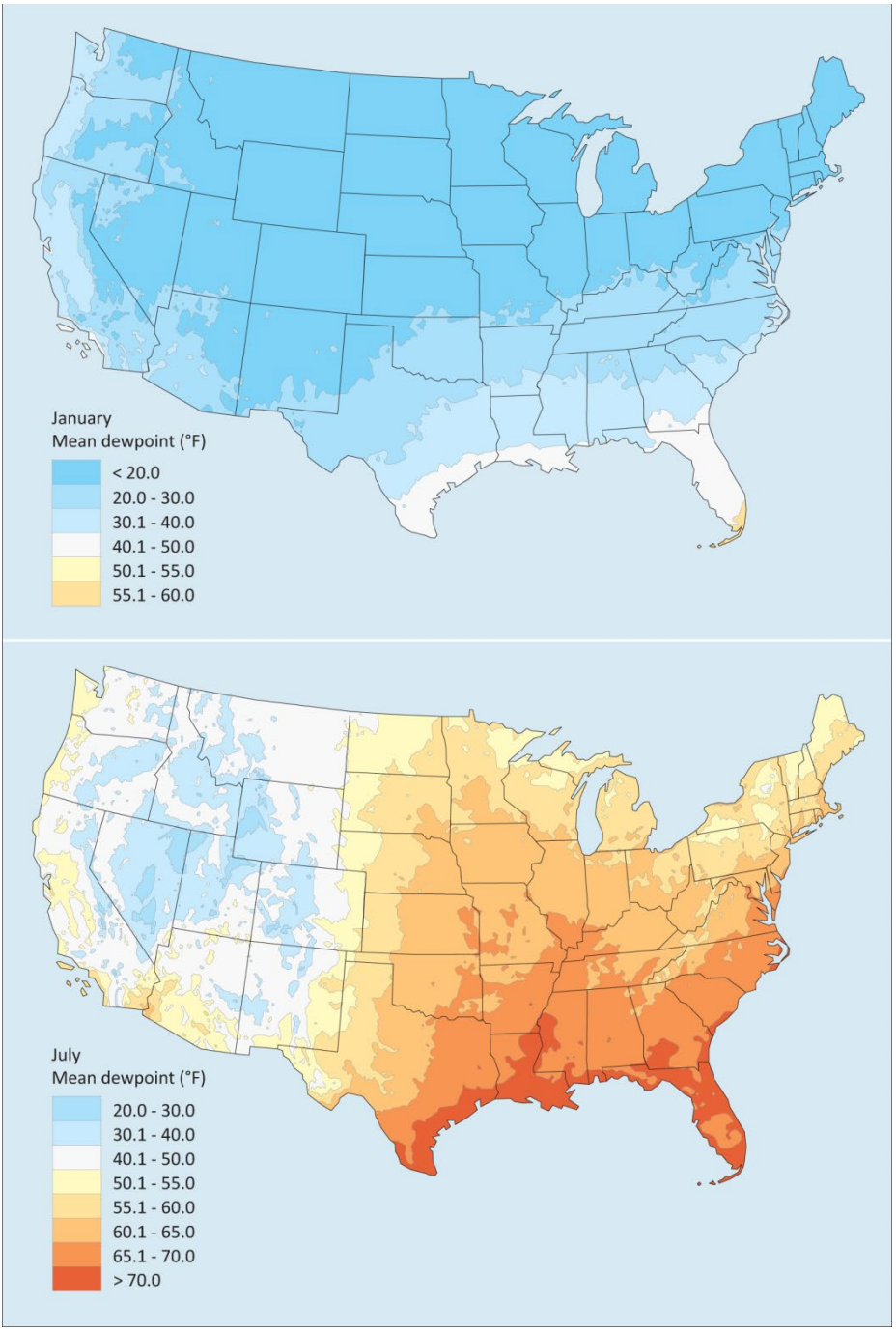
Relative Humidity



- **Relative humidity -** compares the actual amount of water vapor in the air with the amount of water vapor that would be present if that same air were saturated
  - RH = (actual vapor pressure) / (saturation vapor pressure) × 100%

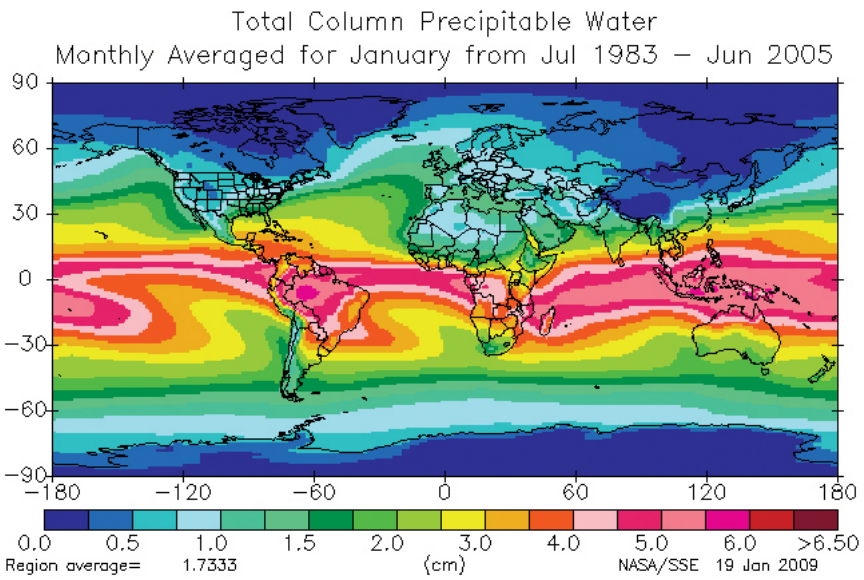
Dewpoint Temperature

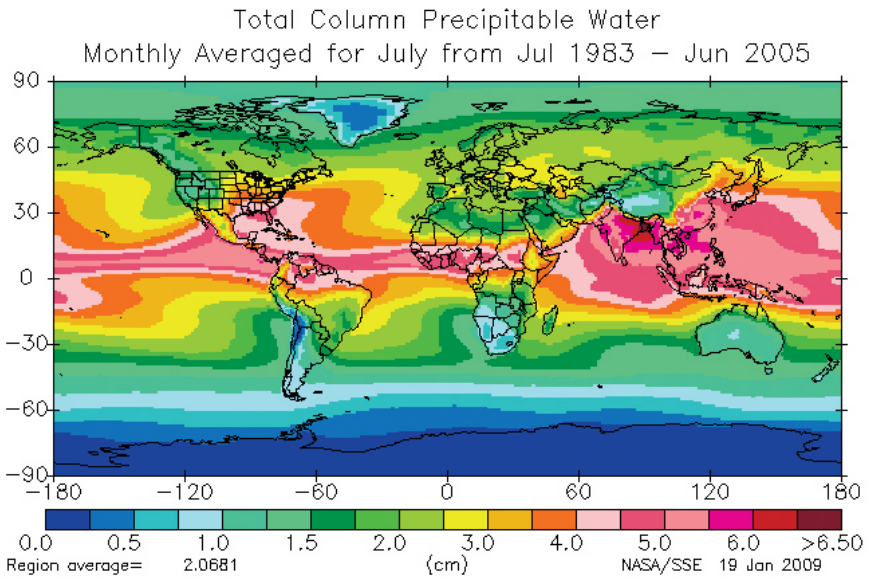
- **Dewpoint temperature - ** the dewpoint temperature is the threshold at which air must be cooled to achieve saturation relative to liquid water, without the addition or removal of water vapor, at constant pressure



- Average surface dewpoint temperatures in the U.S. for January (top) and July (bottom)

Precipitable Water





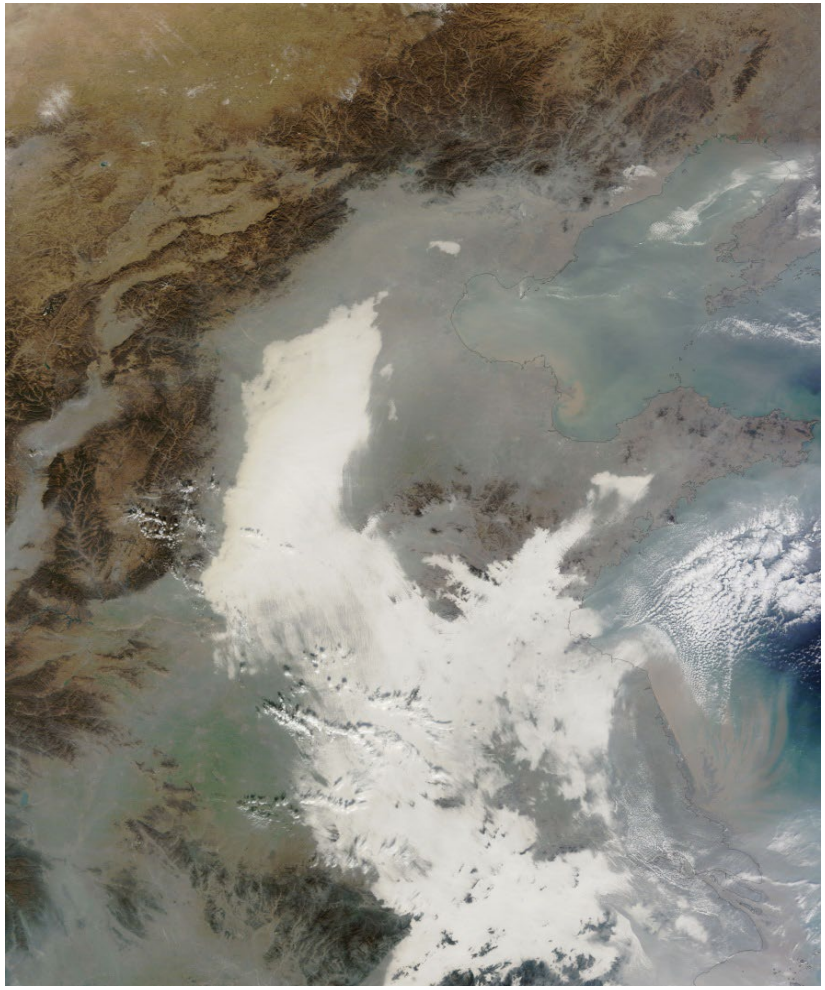
- **Precipitable water -** the depth of liquid water that would be produced by condensing all the water vapor in a vertical column of air

Saturation & Clouds

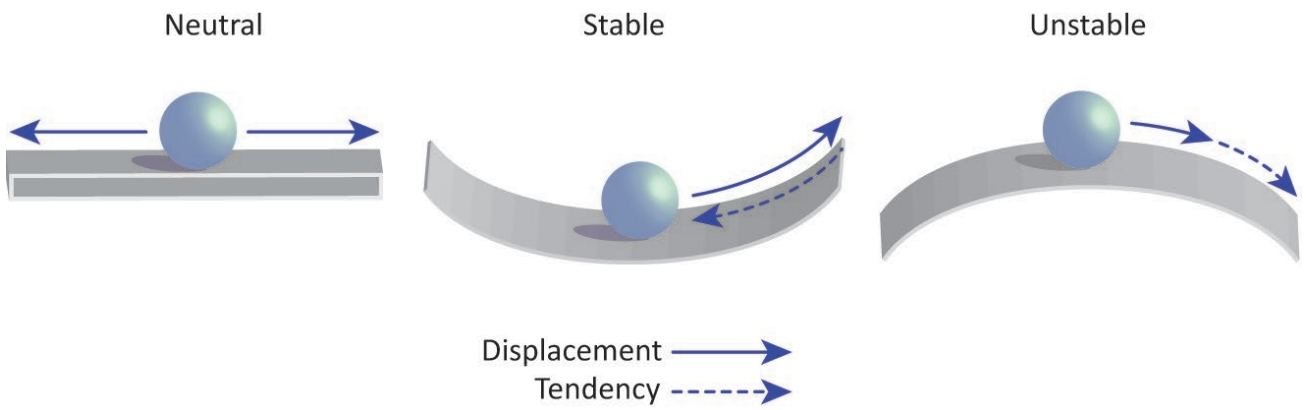
- Probability of cloud development increases as the relative humidity nears saturation
- **Cloud -** visible aggregate of tiny water droplets and/or ice crystals suspended in the atmosphere
  - Affect the incoming and outgoing flux of radiation
  - Critical feedbacks in a changing climate

Atmospheric Stability

- **Boundary layer -** the portion of the troposphere closest to the surface that can undergo a greater variation in heating and cooling
  - Plays a significant role in convective activity, types of clouds formed, likelihood of turbulence for airplanes, and dispersion of pollutants

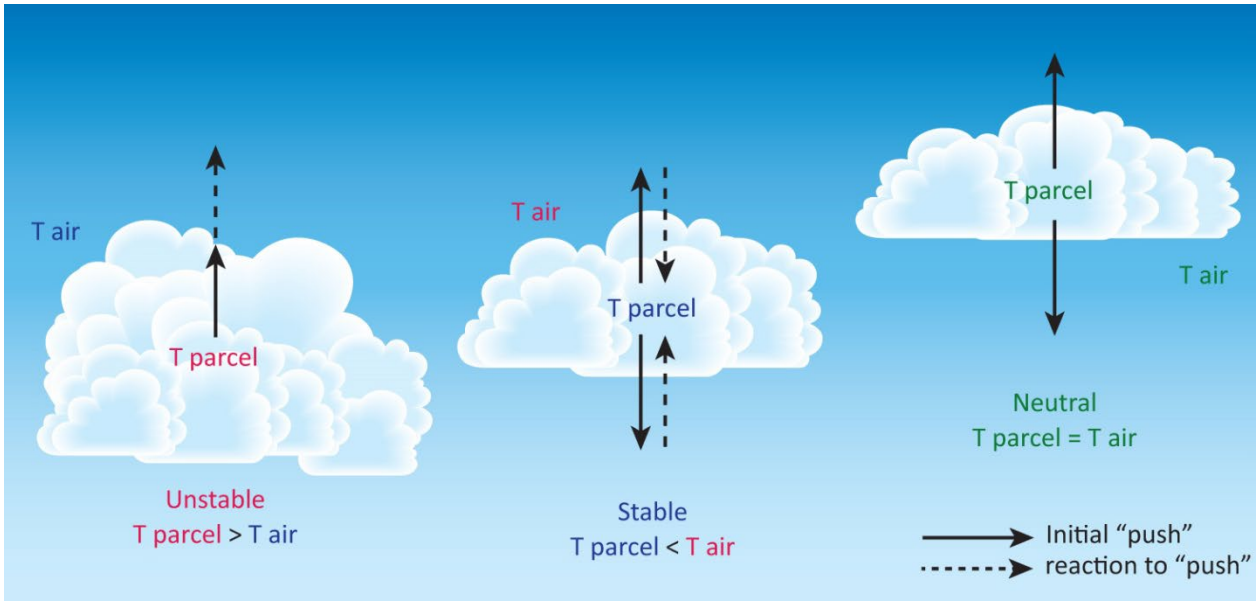


Types of Stability



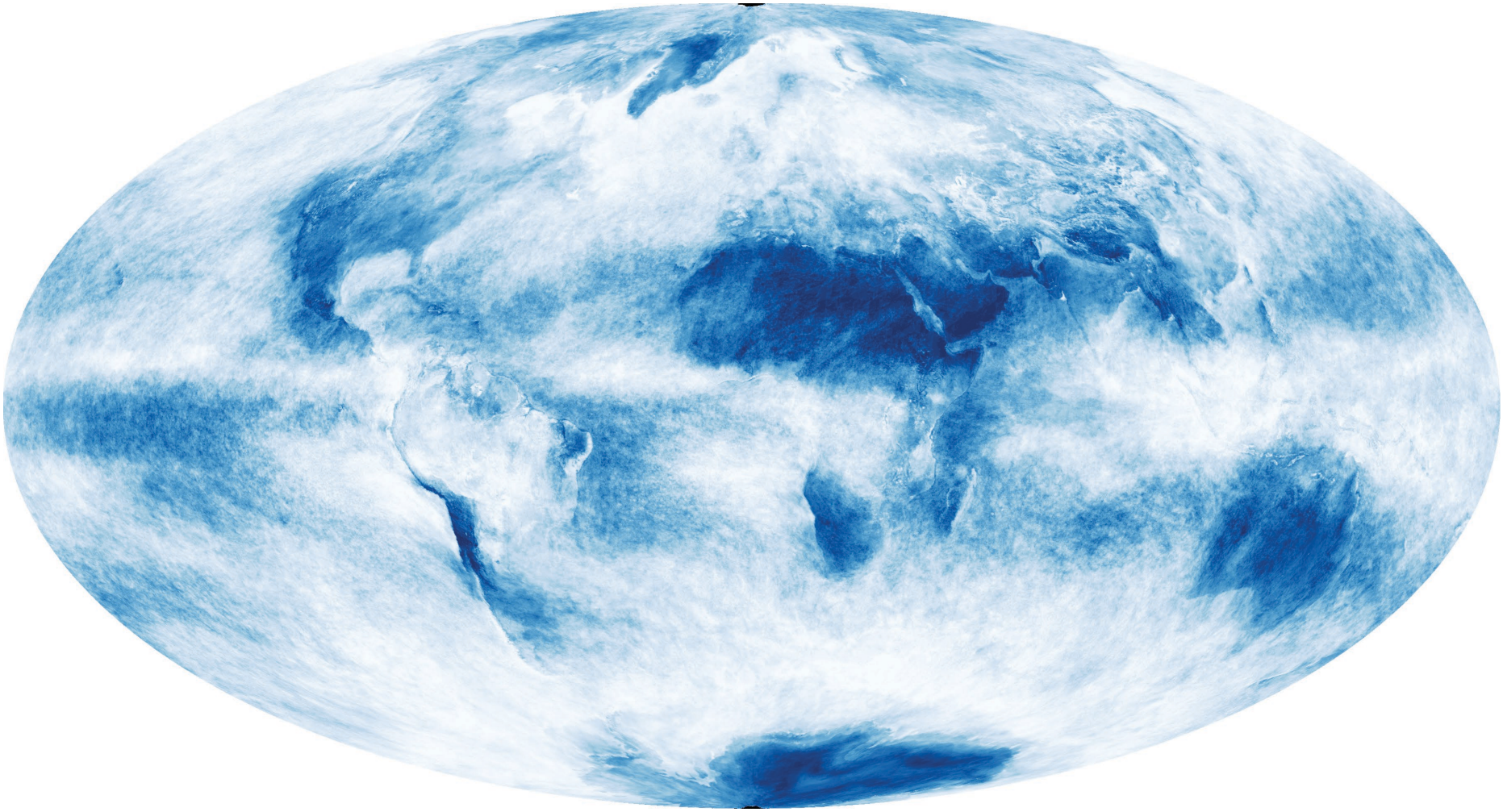
- **Stability -** state of the atmosphere with respect to the reaction of an air parcel to an induced vertical displacement
- **Stable air layer -** where an air parcel forced upward becomes cooler and denser than the ambient air, while a descending air parcel becomes warmer and less dense than the ambient air
- **Unstable air layer -** where an ascending air parcel becomes warmer and less dense than the ambient air and continues to ascend, whereas a descending air parcel becomes cooler and denser than the ambient air and continues to descend

Types of Stability



- The effects of upward and downward displacements on an air parcel in unstable, stable and neutral air layers
  - In an unstable air layer, a displaced parcel will continue in the direction it was "pushed"
  - In a stable layer, an air parcel tends to return to its original altitude
  - In a neutral air layer, there is no tendency for the parcel to continue or return to its original altitude

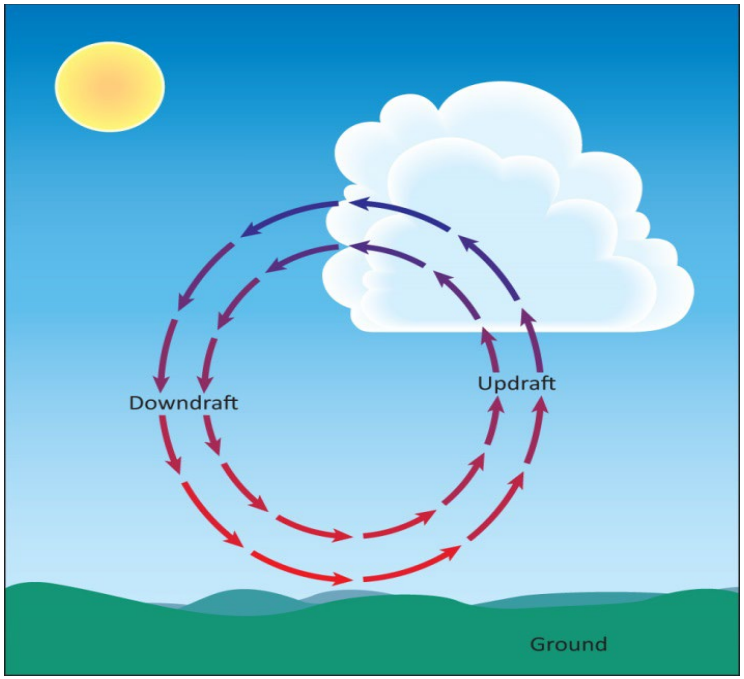
Clouds



Clouds

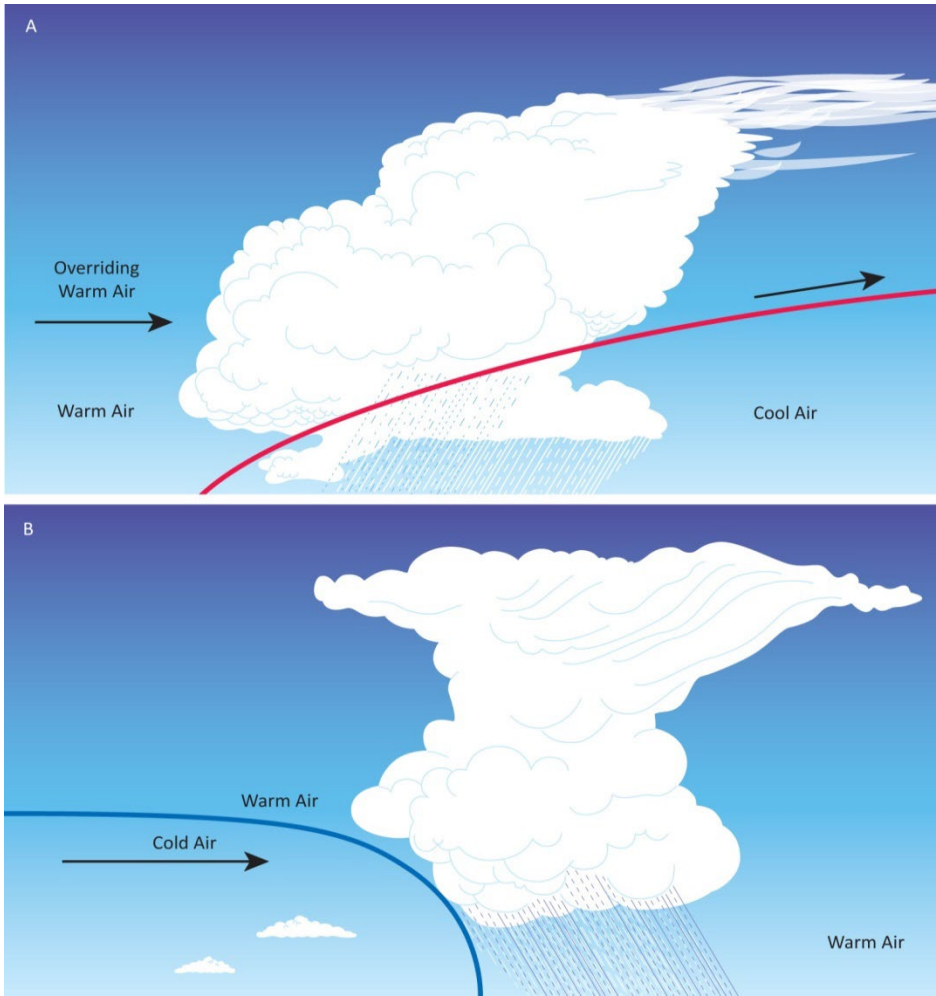
- Cloud droplets and ice crystals form on tiny solid and liquid particles, known as nuclei, suspended in the atmosphere
  - **Cloud condensation nuclei (CCN) -** aerosols that promote condensation of water vapor at temperatures both above and below the freezing point of water
  - Ice-forming nuclei (IN) - less common, promote formation of ice crystals only at temperatures far below 0 °C
  - Natural CCN from volcanic eruptions, wind erosion of soil, forest fires or ocean spray
  - Urban-industrial areas also a major source

Mechanisms of Cloud Formation



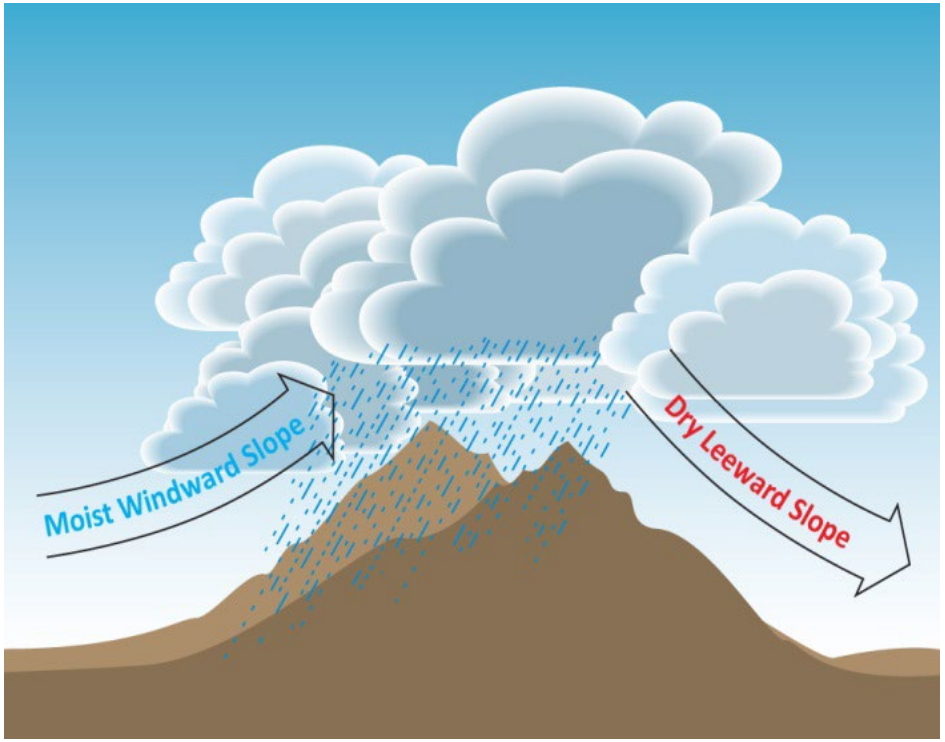
- Cumulus clouds form where convection currents ascend,
  - The sky is generally clear where convection currents descend
- The higher ascending convection currents reach, the greater their cooling by expansion, and the greater likelihood that clouds and precipitation will form

- **Front -** narrow zone of transition between two air masses that differ in temperature, humidity or both
  - Warm front – warm, humid air mass is less dense than a cold, dry air mass, as a cold air mass retreats, the warm air flows up and over the cold air (top)
  - Cold front – cold, dry air displaces warm, humid air by sliding under it and forcing the warm air upward (bottom)

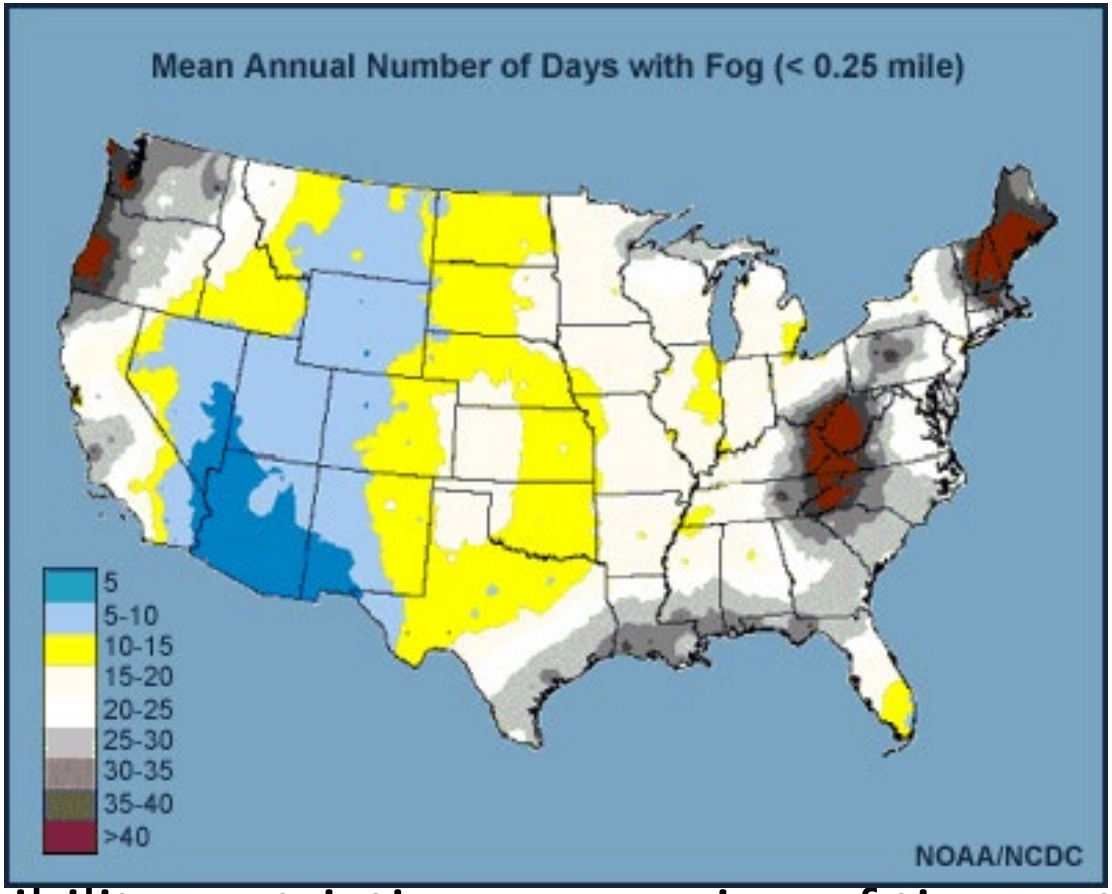


Mechanisms of Cloud Formation

- **Orographic lifting -** where air is forced upward by topography, the physical relief of the land
- **Rain shadow -** dry conditions extending many hundreds of kilometers downwind of a prominent mountain range



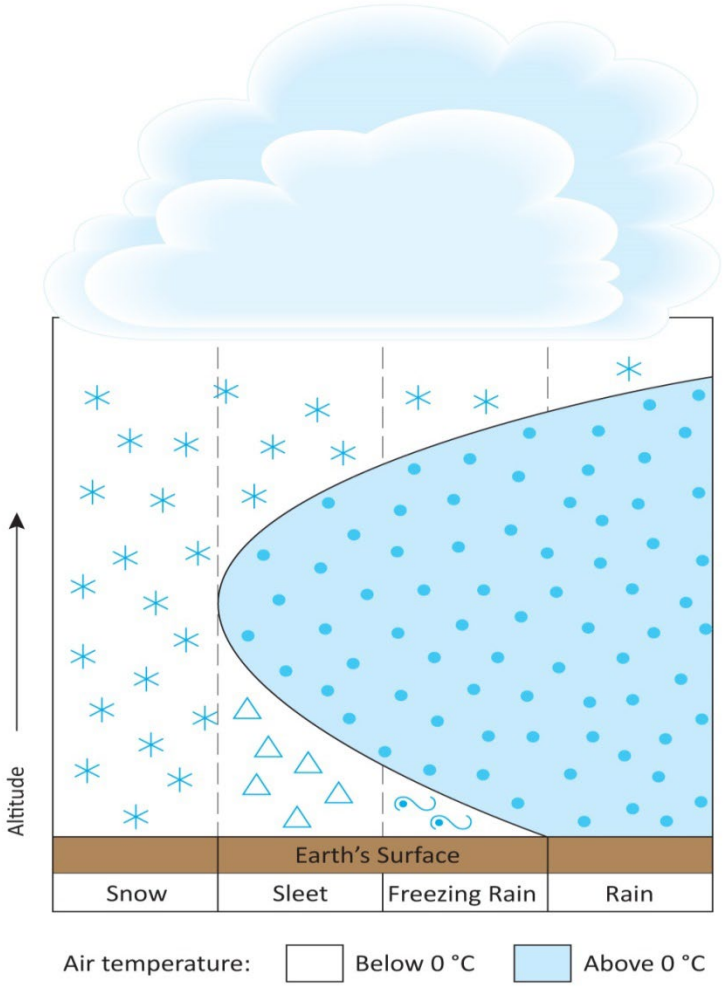
Fog



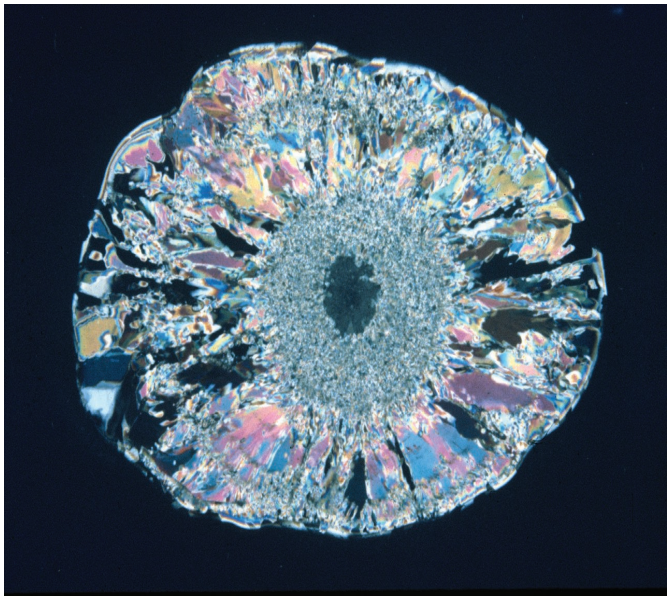
- **Fog -** a visibility-restricting suspension of tiny water droplets or ice crystals (ice fog) in an air layer next to Earth's surface
  - a cloud in contact with the ground

Precipitation Types

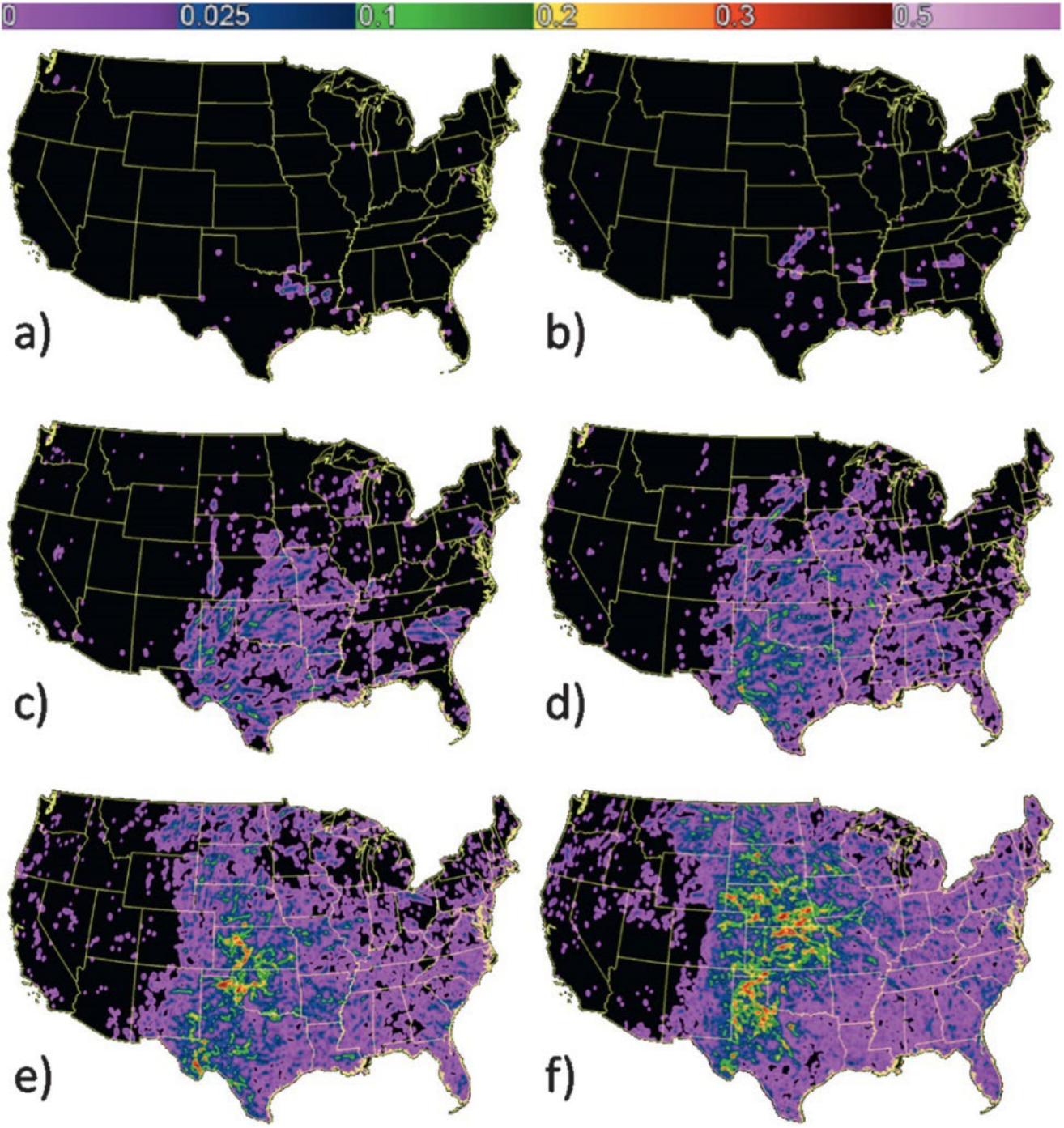
- **Rain -** liquid water drops with diameters generally ranging from 0.5 to 6 mm (0.02 to 0.2 in.), falling mostly from nimbostratus and cumulonimbus clouds
- **Drizzle -** smaller liquid water drops, with diameters between 0.2 and 0.5 mm (0.01 and 0.02 in.), drifts very slowly to Earth's surface
- **Snow -** agglomeration of hexagonal ice crystals, varying in shape and size



Precipitation Types



- **Sleet -** ice pellets, spherical or irregularly shaped, transparent or translucent particles of ice that are 5 mm (0.2 in.) or less in diameter.
- **Freezing rain -** rain drops that become supercooled and partially freeze on contact with cold surfaces at subfreezing temperatures, forming a coating of ice (glaze)
- **Hail -** a ball or jagged lump of ice, often characterized by concentric internal layering resembling an onion



- Average (2007-2010) monthly severe hail days for
  - (a) January
  - (b) February
  - (c) March
  - (d) April
  - (e) May
  - (f) June

Monitoring Moisture in the Atmosphere: Instrumental Arrays

- **Rain gauge -** cylinder equipped with a cone-shaped funnel at the top that directs rainwater into a narrower cylinder seated inside the larger outer cylinder

Snowfall Measures

- Taken when new snowfall accumulates on a wooden board placed on top of the old snow cover and snow depth is measured to the board
  - The board is then swept clean and moved to a new location

Remote Sensing of Precipitation

- **Tropical Rainfall Measuring Mission (TRMM) -** satellite technology that measures rainfall between 40° N and 40° S
- **Snow pillow -** device filled with antifreeze solution and fitted with a manometer, which measures pressure changes, calibrated to give the water equivalent from the weight of the overlying snow cover

Big Ideas

- Water's unique physical properties make it especially important in Earth's climate system
  - Can co-exist in all three phases
  - As it changes phase large amounts of heat energy are absorbed or released
- As air nears saturation, water vapor begins condensing or depositing on airborne nuclei
  - Clouds form with continued cooling, due to expansion of rising air
- Precipitation occurs as rain, drizzle, snow, ice pellets (sleet), freezing rain (or freezing drizzle) and hail
  - Precipitation type depends upon cloud conditions and the temperature of the air column through which the precipitation falls
- Fog, by similar processes, except constrained next to surface

Big Ideas

- The global water cycle transports water and heat energy within and among the reservoirs of the global water cycle, which affects and is affected by climate change
  - A net flow of water is directed from the continents to the ocean
  - A net flow of water vapor occurs from over the ocean to land
- Atmospheric circulation plays a key role in
  - Bringing air to saturation
  - Triggering cloud and precipitation development
- To predict changes, climate scientists monitor rainfall and snowfall
  - A variety of in situ and remote sensing techniques are employed to monitor and measure precipitation
  - Instruments onboard Earth-orbiting satellites estimate rainfall over large expanses of the globe

Key Terms

- Latent heat
- Melting
- Evaporation
- Sublimation
- Freezing
- Condensation
- Deposition
- Specific heat
- Thermal inertia
- Maritime climate
- Continental climate
- Transpiration
- Evapotranspiration
- Precipitation
- Distillation
- Drainage basin
- Global water budget
- Humidity
- Pressure
- Air pressure
- Dalton's law of partial pressure
- Vapor pressure
- Saturation vapor pressure
- Relative humidity
- Dewpoint temperature
- Precipitable water
- Cloud
- Boundary layer
- Stability
- Stable air layer
- Unstable air layer
- Cloud condensation nuclei (CCN)
- Front
- Orographic lifting
- Rain shadow
- Fog
- Rain
- Drizzle
- Snow
- Sleet
- Freezing rain
- Hail
- Rain gauge
- Tropical Rainfall Measuring Mission (TRMM)
- Snow pillow