

# Lecture 9: Evaporation

## Key Questions

1. What is a evaporation?
2. Why does evaporation cool water?
3. What are the main energy inputs into a lake?
4. What is a vapor pressure deficit?
5. How does wind sustain lake evaporation?
6. What cause lake effect snow?

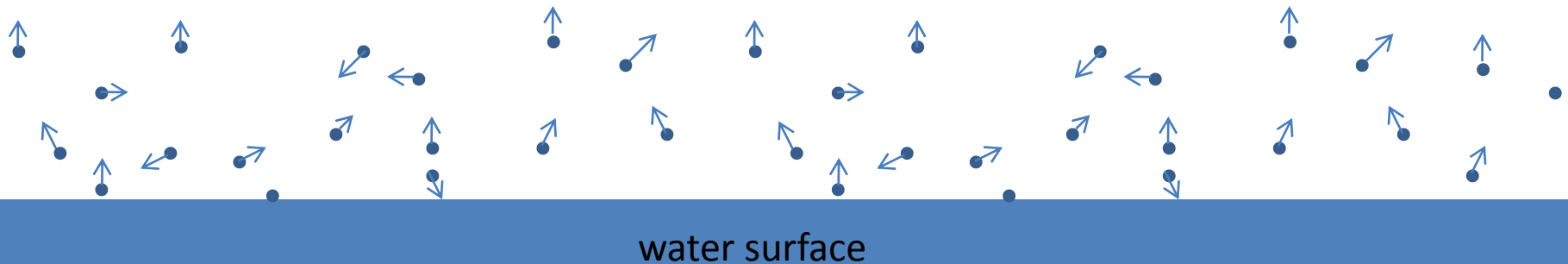
evaporation



**Evaporation** is the net loss of water from a liquid surface that results from a phase change from a liquid to a vapor.

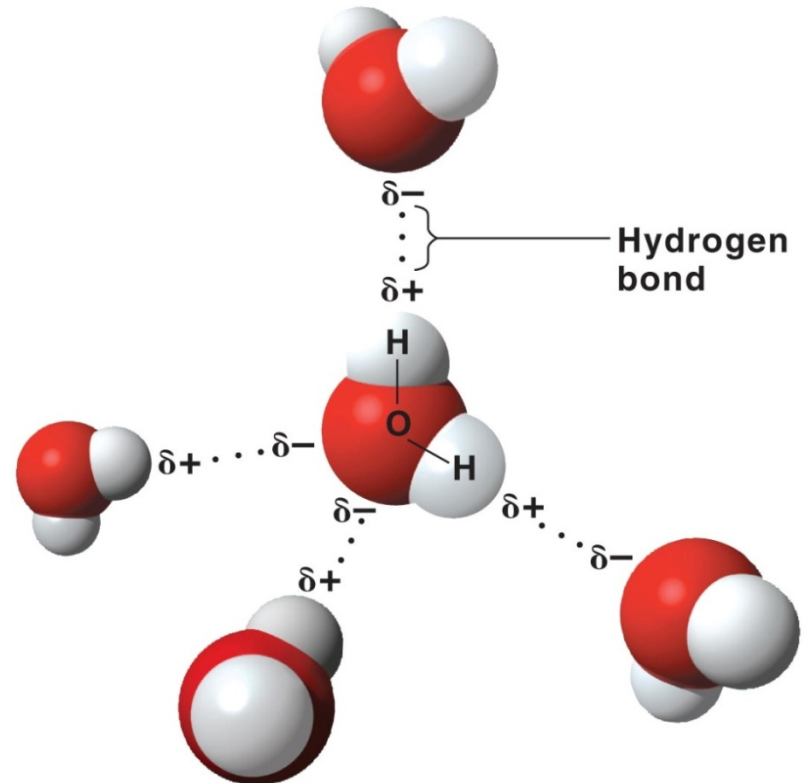
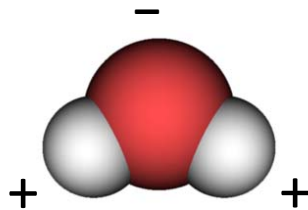
It is a net process because water vapor is constantly moving back and forth from the water surface.

Evaporation occurs when there are more molecules leaving the water surface than entering.



Remember, water is a polar molecule. Liquid water is a collection of molecules connected by hydrogen bonds.

water is polar

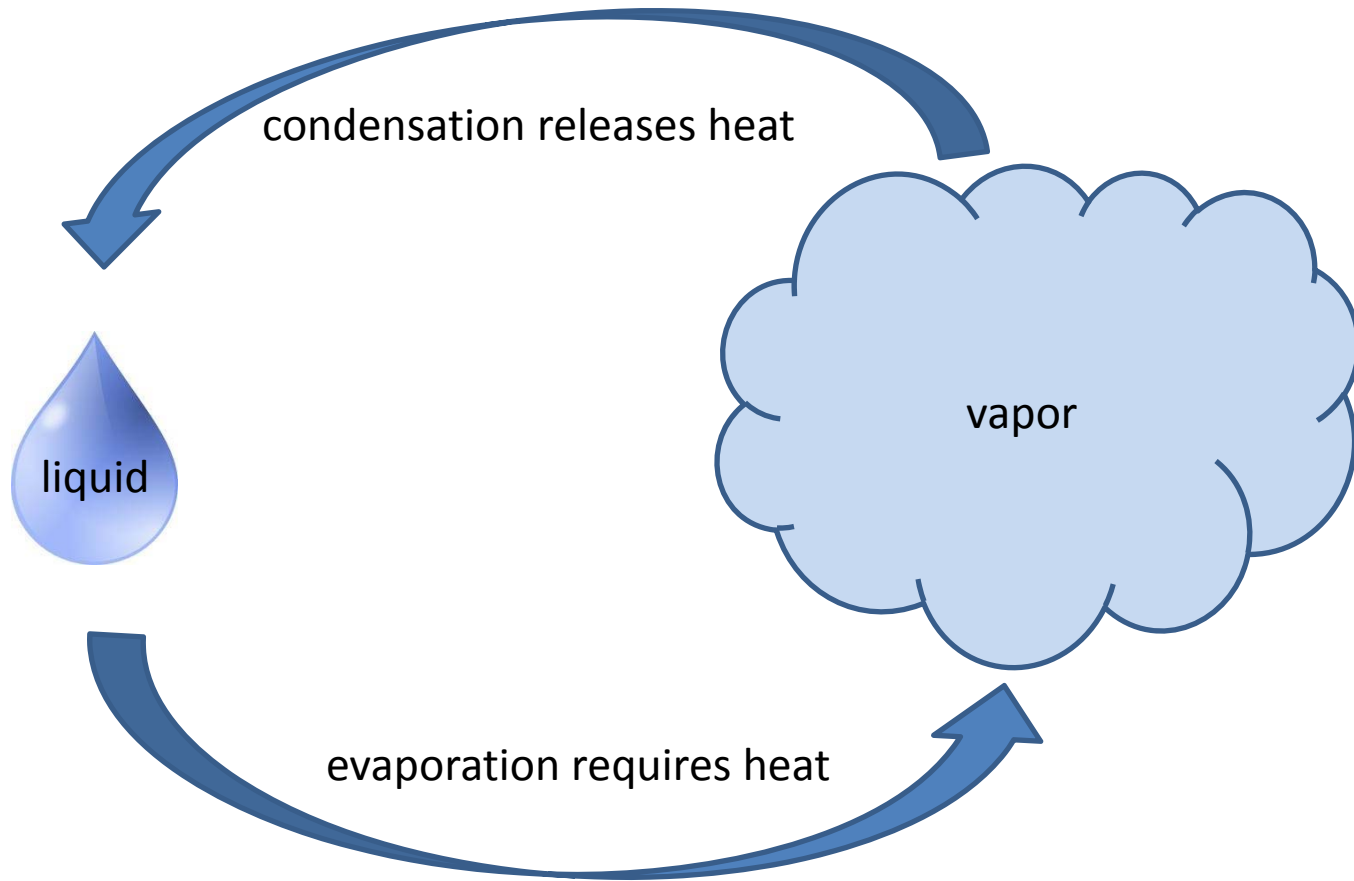


It takes **energy** for a molecule to break a hydrogen bond and escape the water surface.

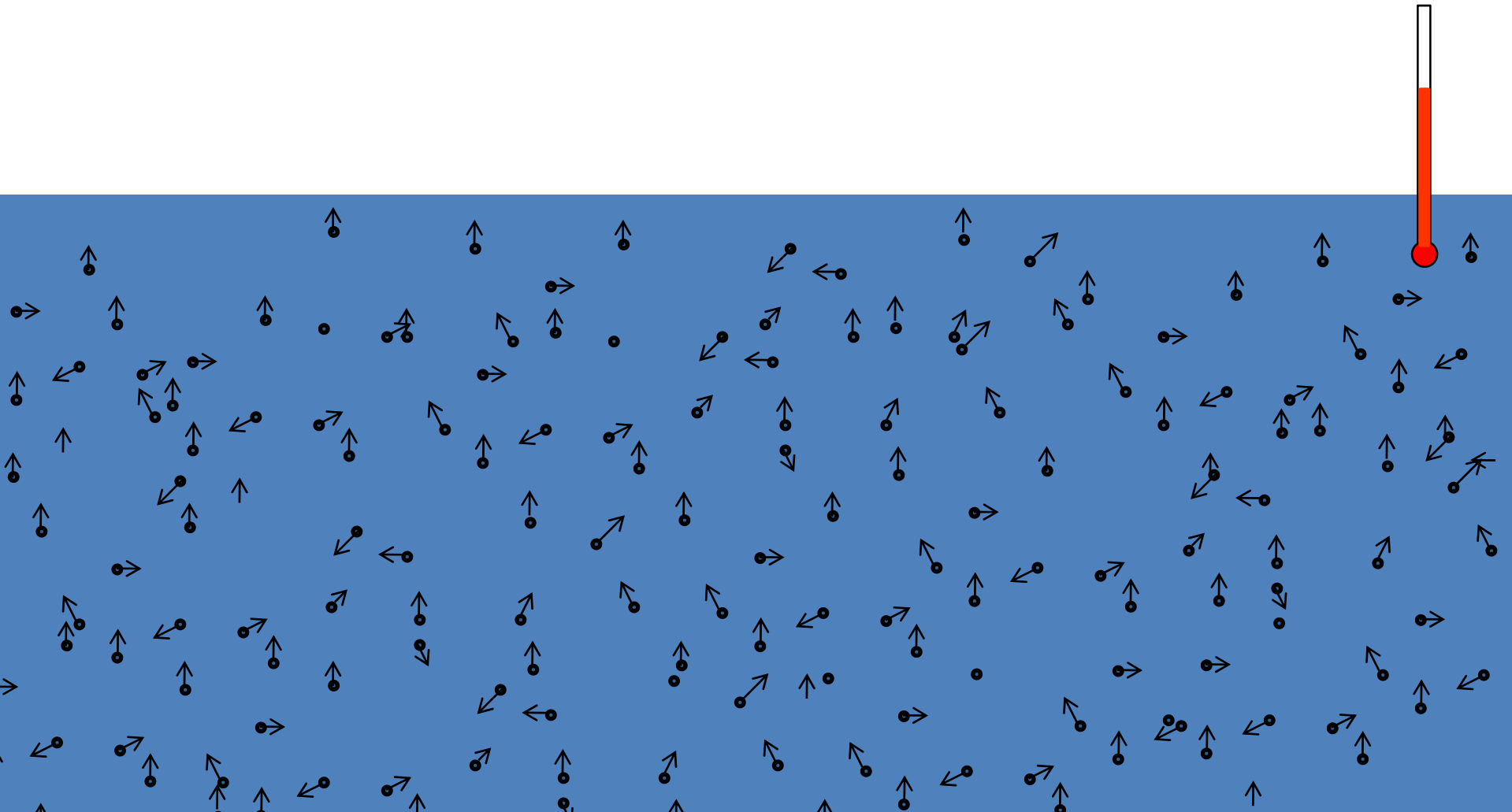


water surface

Phase changes involve heat (energy) exchanges (latent heat )



The collective motion of water molecules in the water is called **kinetic energy**. The average kinetic energy of the molecules quantifies the water **temperature**.



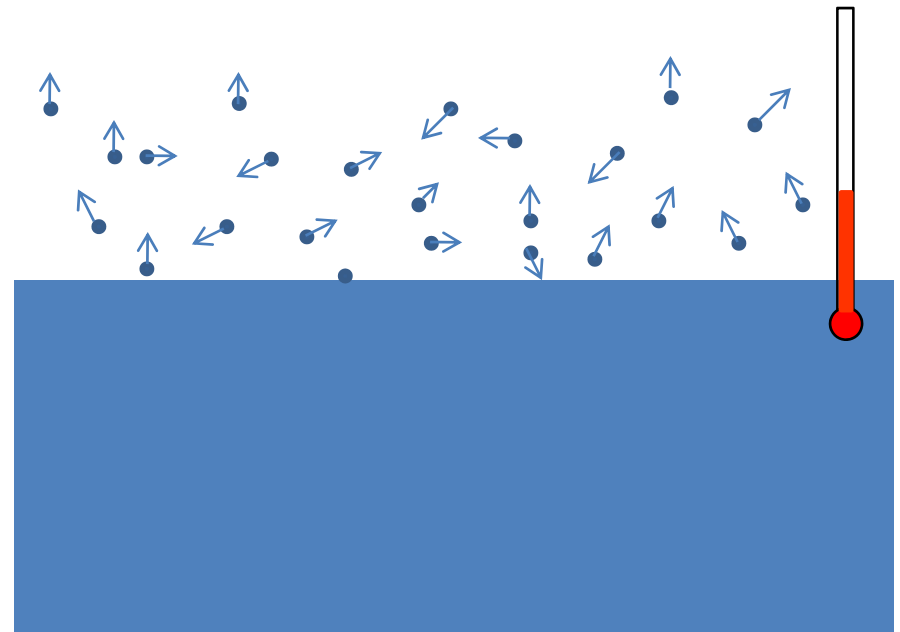
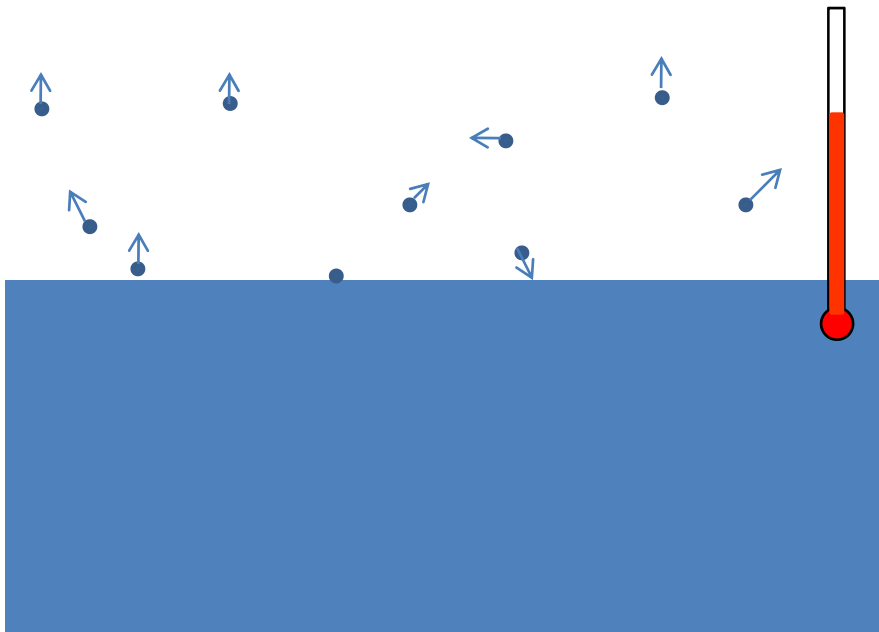
Molecules with the highest kinetic energy can break the hydrogen bonds and escape the water surface.

Thus, reducing the water temperature because the average kinetic energy is reduced (heat is removed).

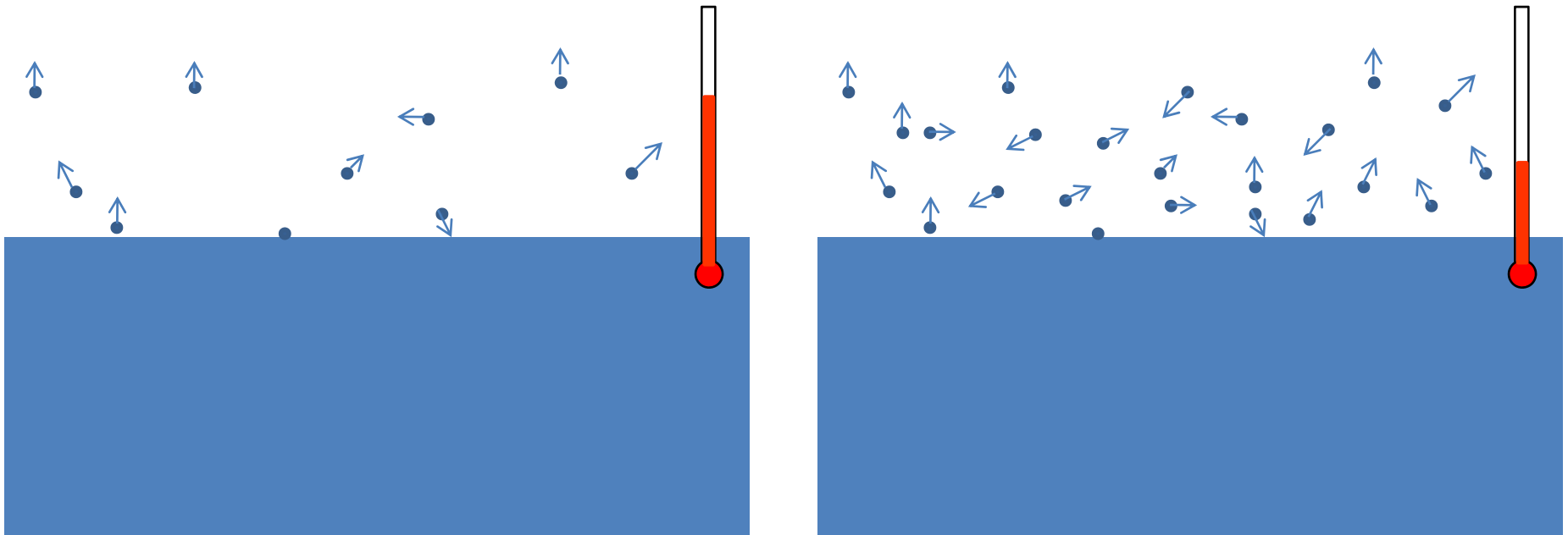


water surface

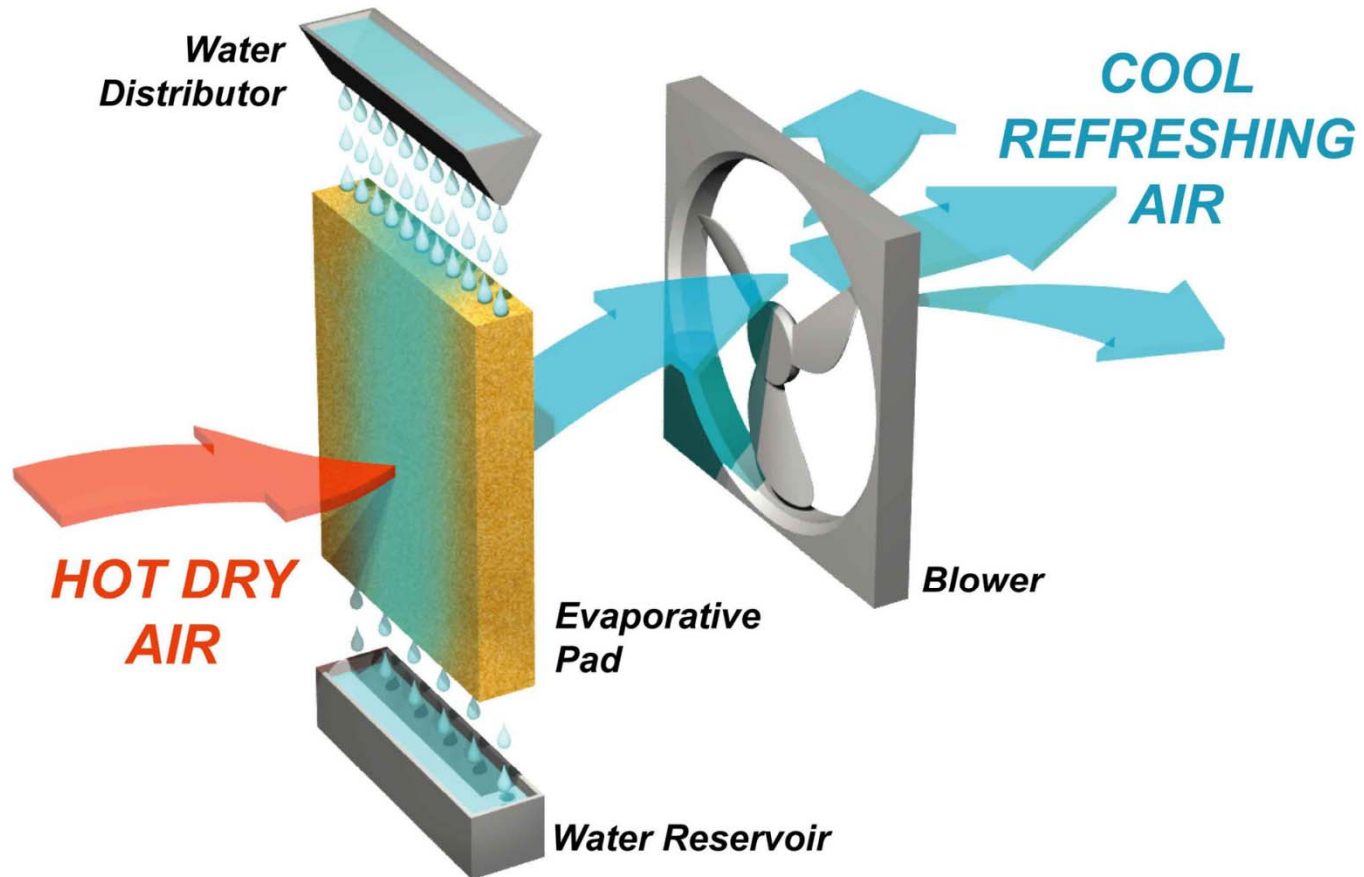
Evaporation cools off the water!

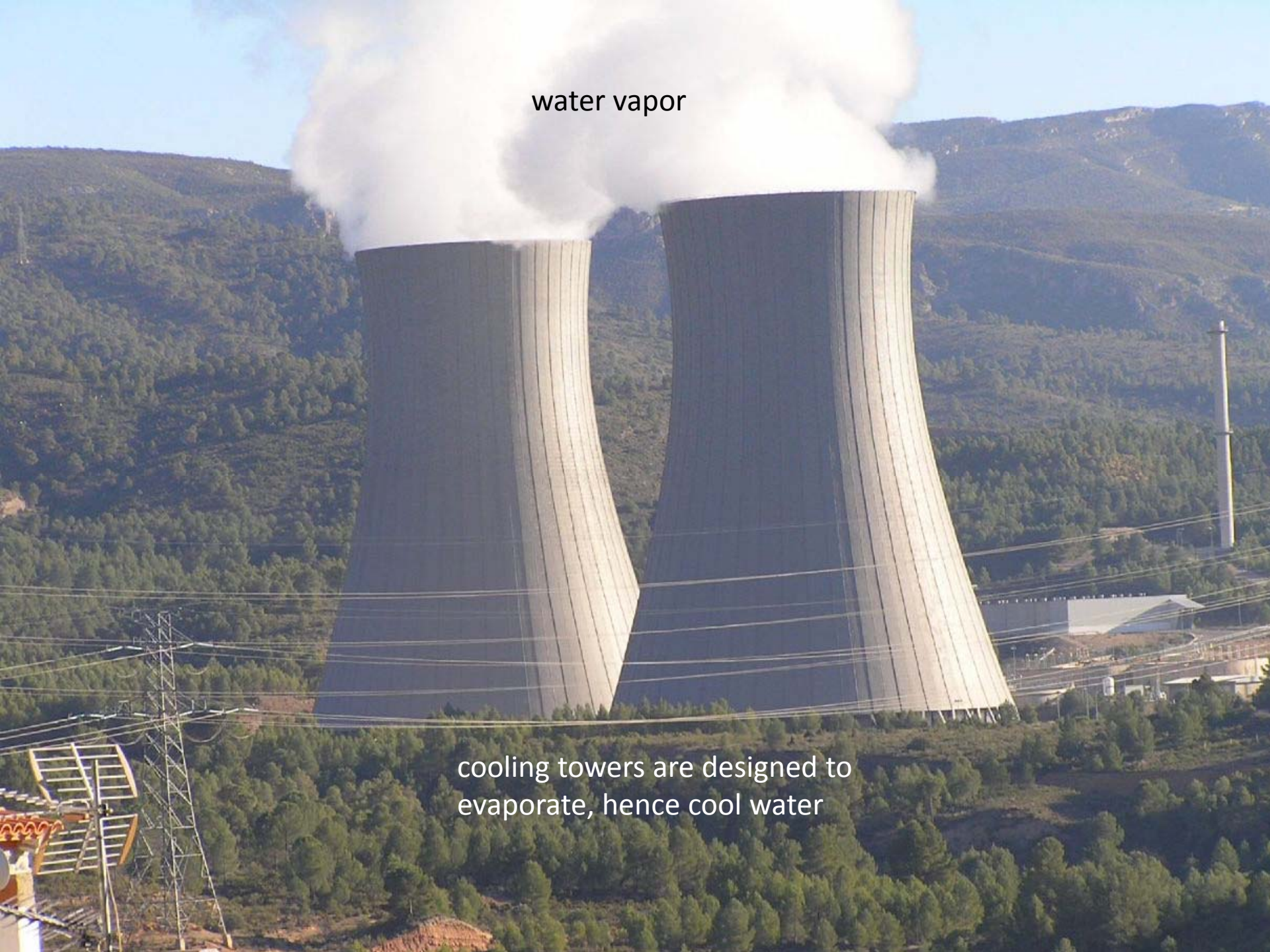


Evaporation cools off the water!



# Swamp Cooler (evaporation cools)



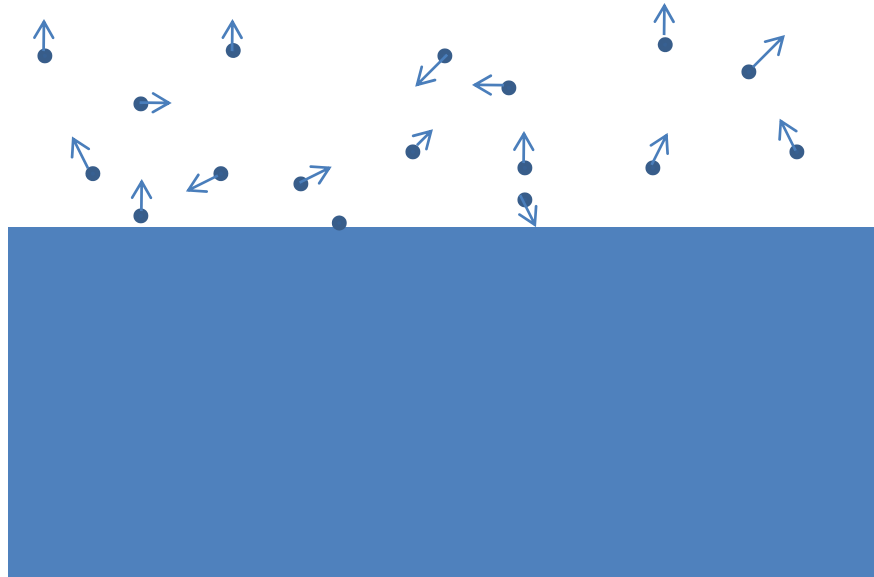
A photograph of two large, hyperboloid cooling towers at a nuclear power plant. The towers are grey and have a flared top. Thick white plumes of water vapor are rising from the top of each tower. The plant is situated in a valley with green trees. In the background, there are rolling hills and mountains under a clear blue sky. To the right, a tall, thin white chimney is visible. In the foreground, there are power lines and a small structure with solar panels.

water vapor

cooling towers are designed to  
evaporate, hence cool water

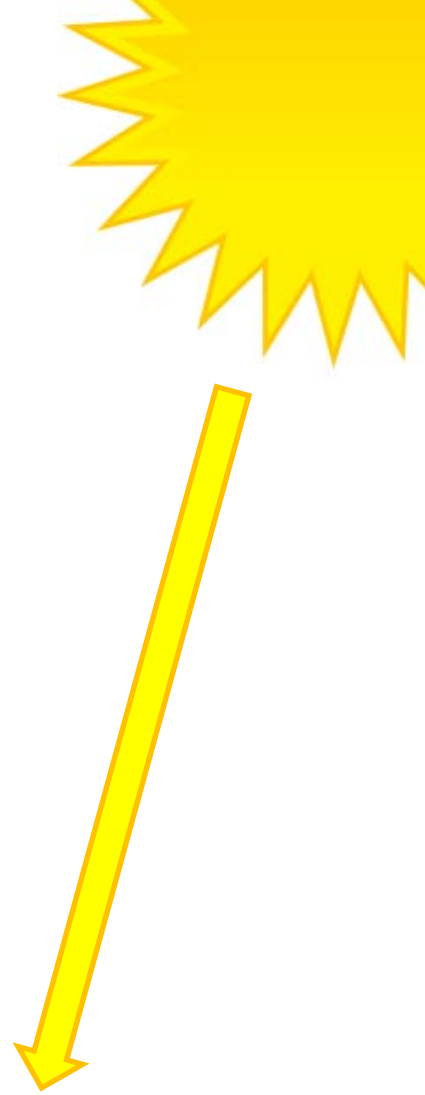
# What drives evaporation?

- 1) Energy input to the water to supply heat (i.e., increase the kinetic energy so molecules can escape).
- 2) Diffusion of water vapor molecules from the water surface to the atmosphere.
- 3) Transport of water vapor molecules away from the water surface.



# Heat Inputs

1. Solar radiation is the main source of heat to a lake.

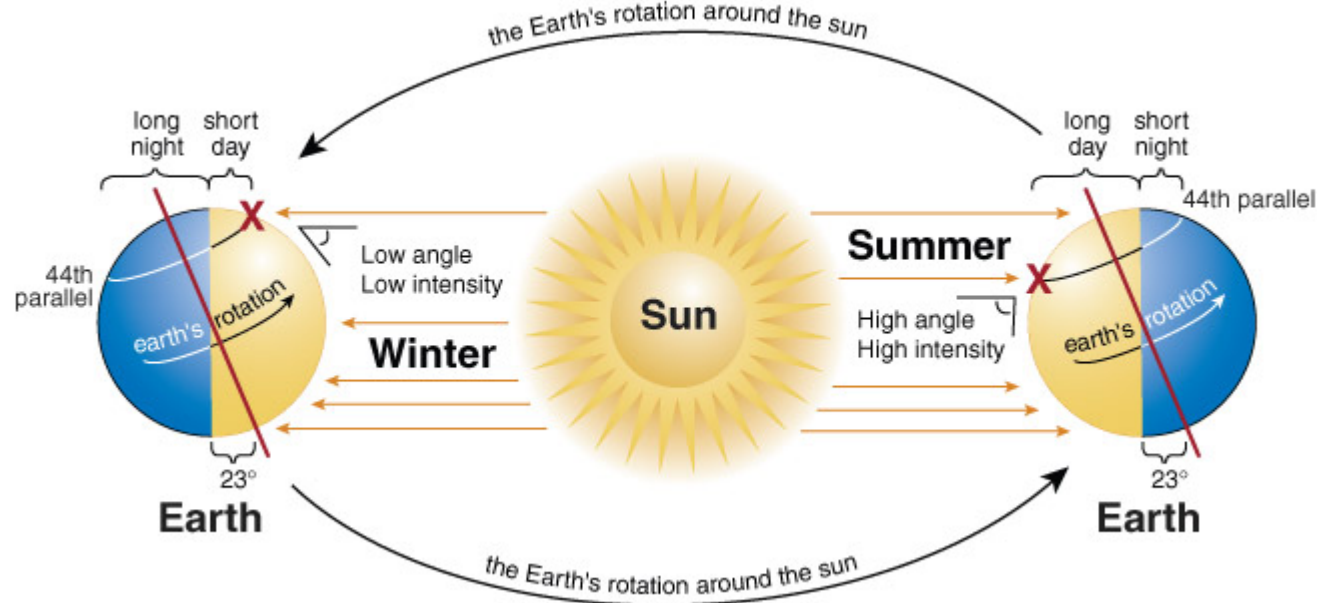


water surface

# Heat Inputs

1. Solar radiation is the main source of heat to a lake.

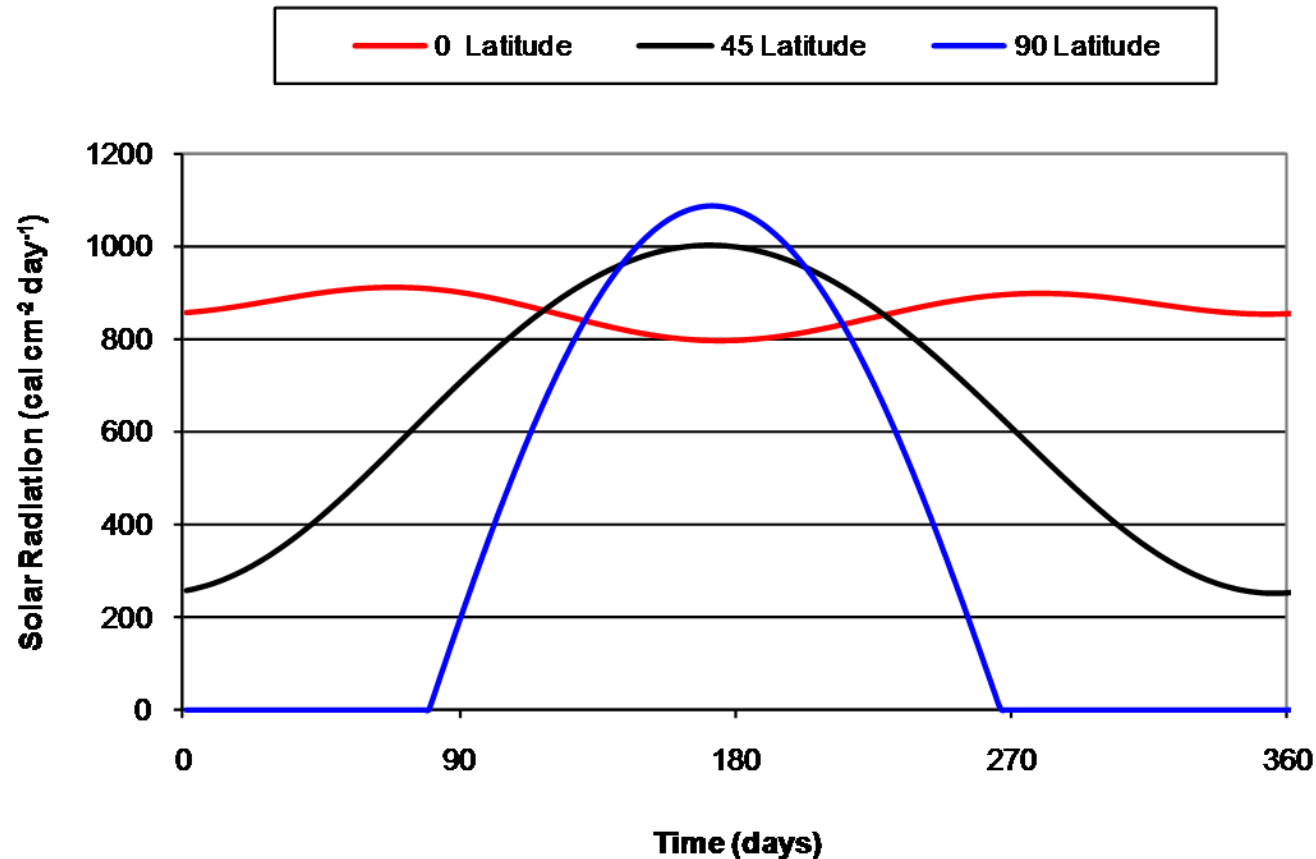
The amount of solar radiation depends on the time of year and latitude.



# Heat Inputs

1. Solar radiation is the main source of heat to a lake.

The amount of solar radiation depends on the time of year and latitude.

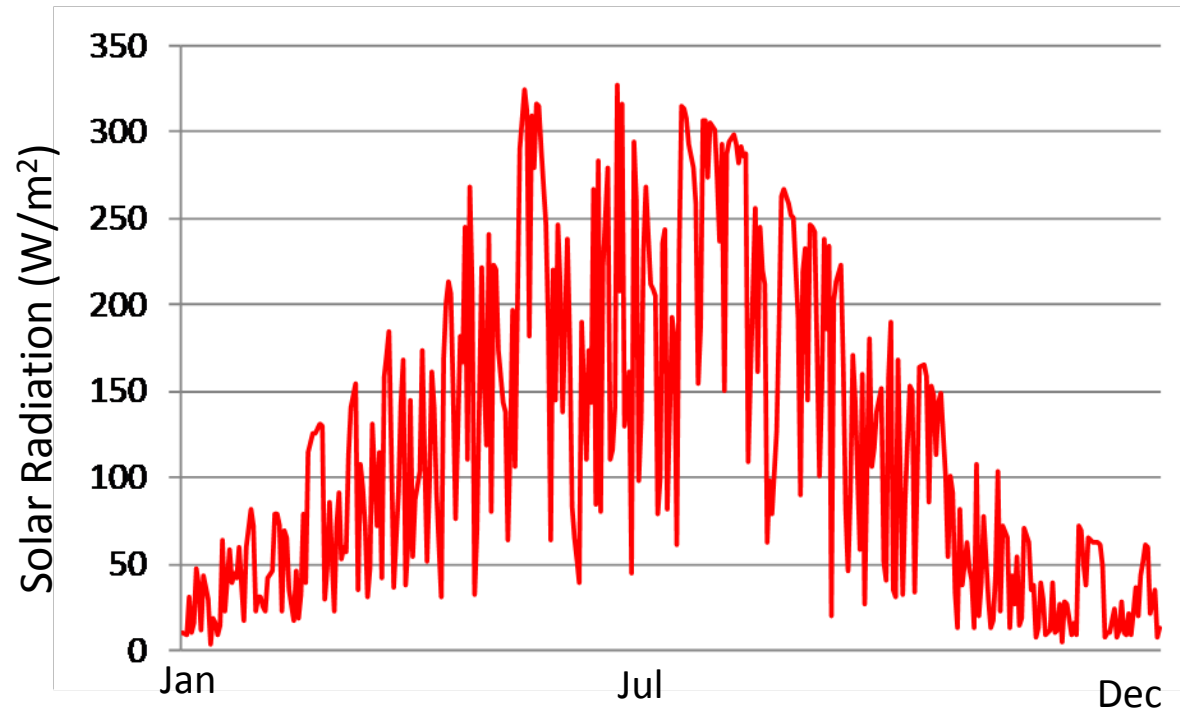


## North Shore Meteorological (MET) Station

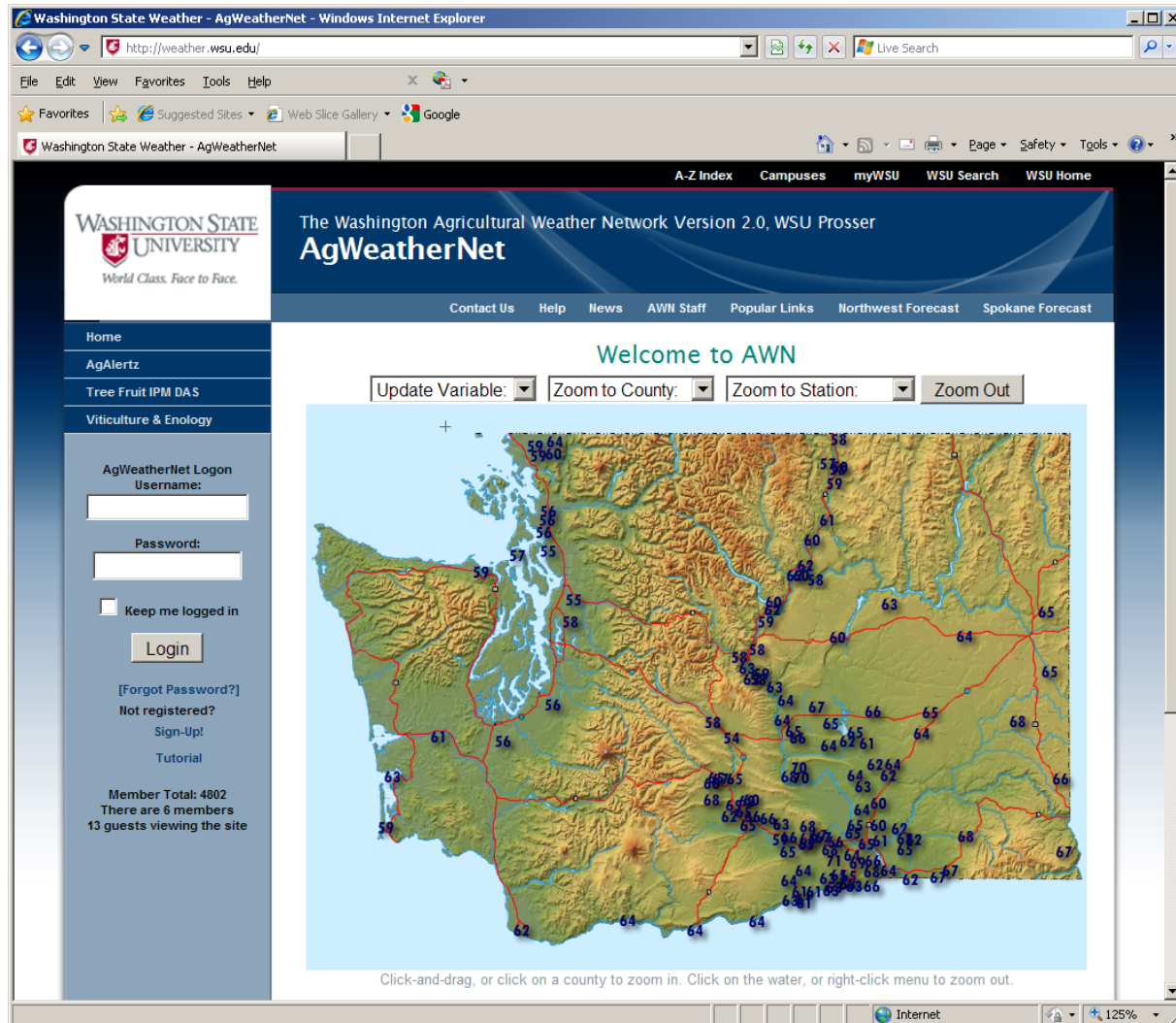


Measures rain, temperature, humidity, wind speed, wind direction, and solar radiation

Average daily solar radiation collected at  
the North Shore MET station

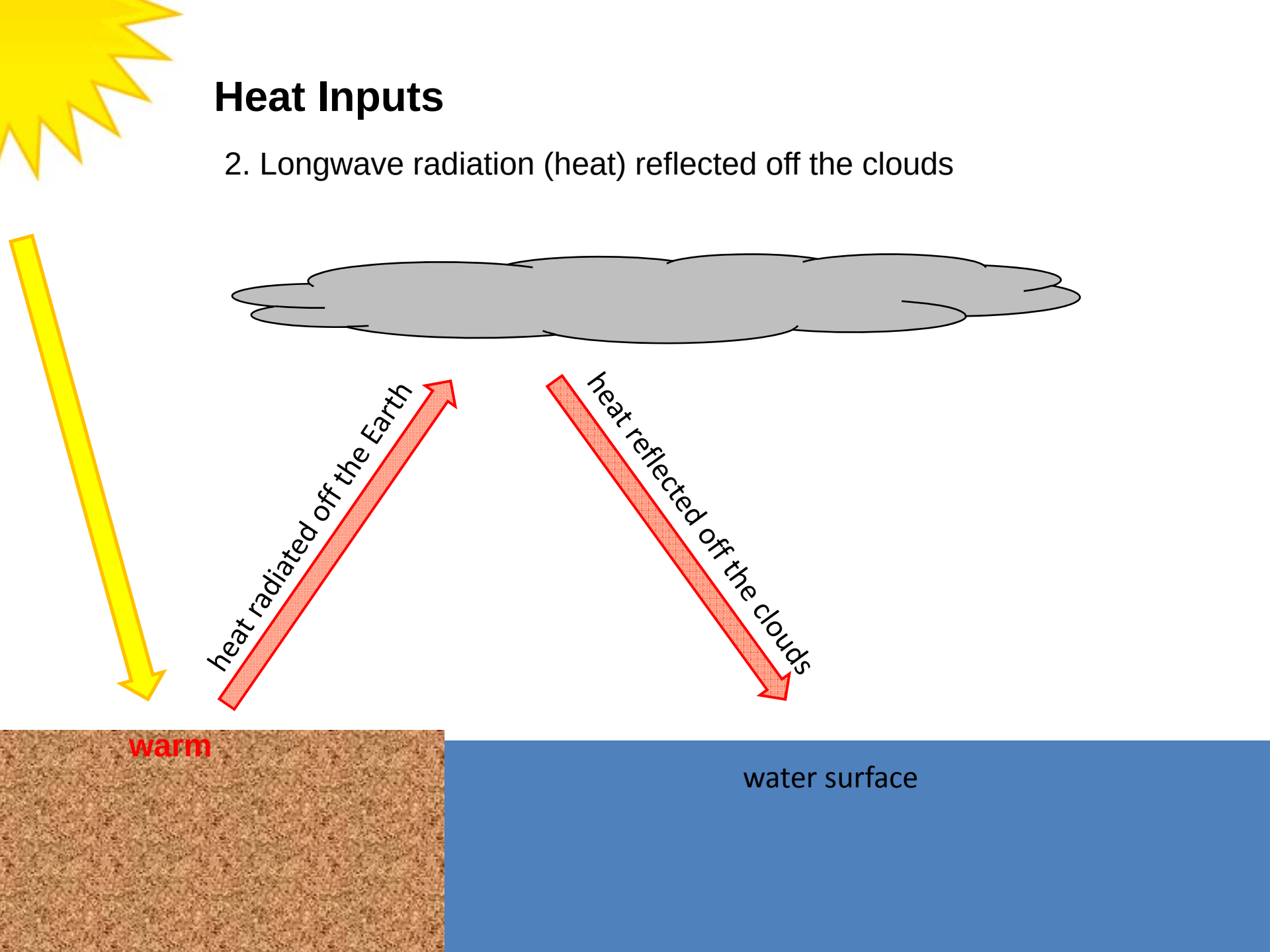


# Ag weather stations collect solar radiation data



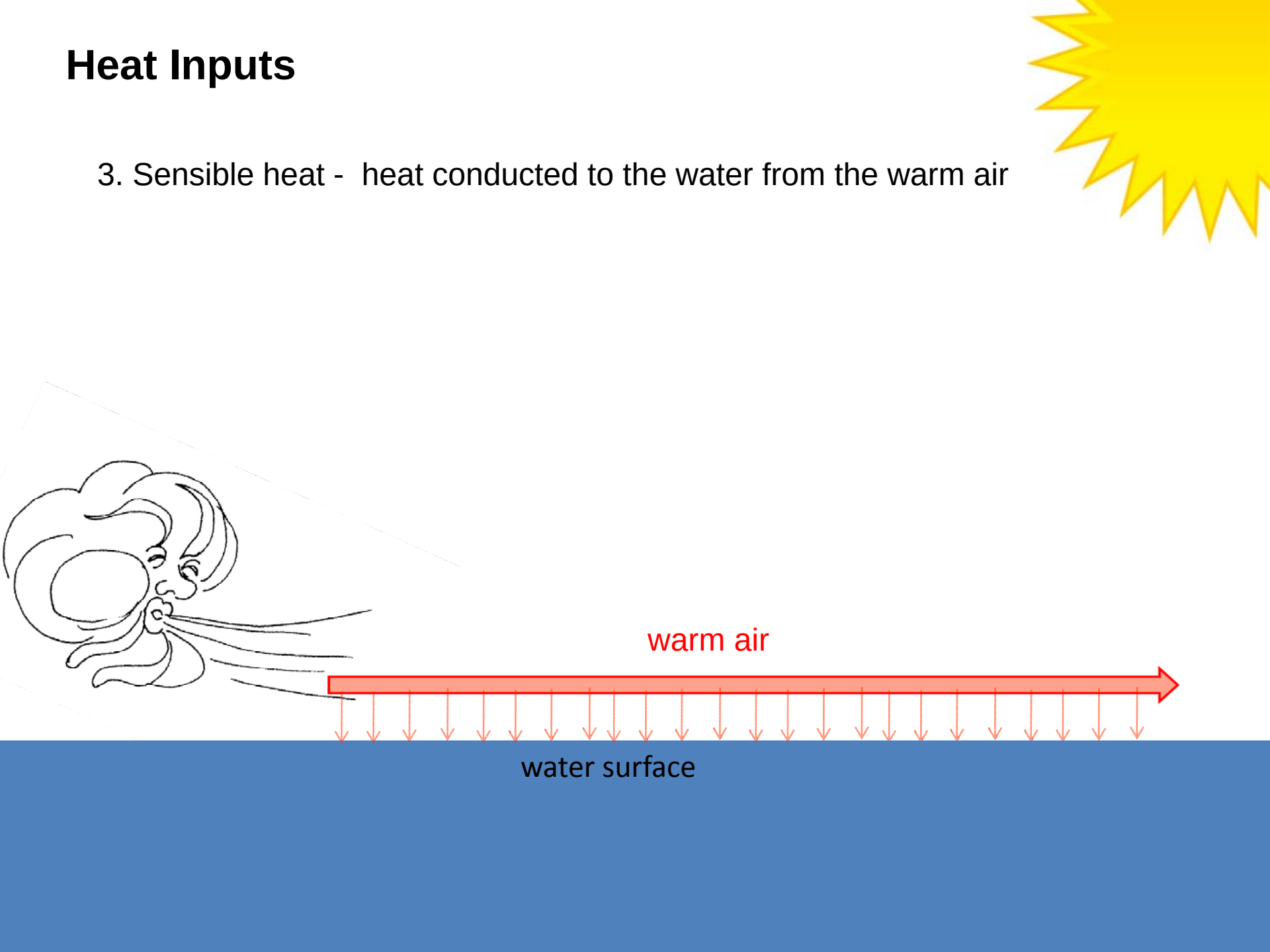
# Heat Inputs

2. Longwave radiation (heat) reflected off the clouds

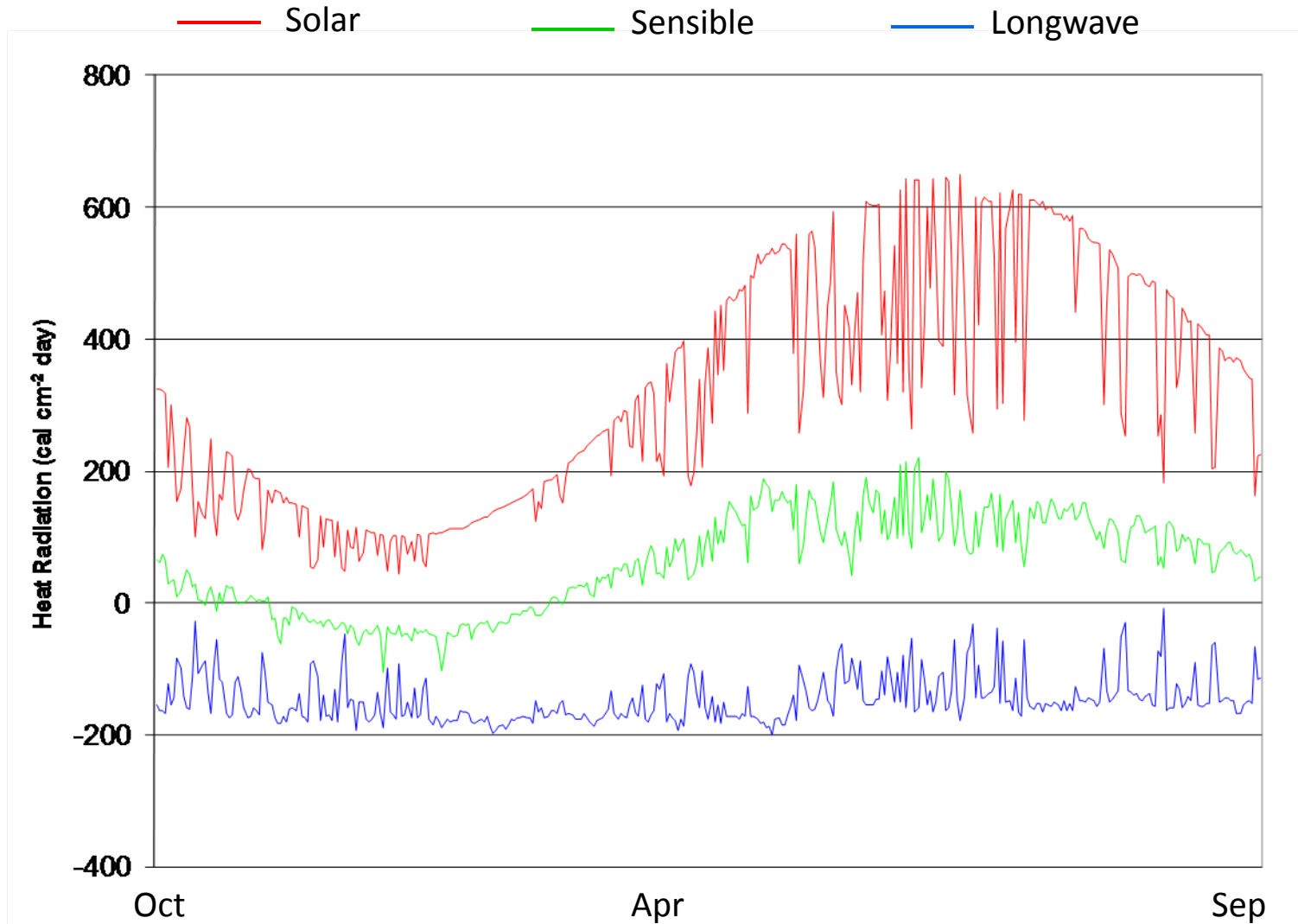


# Heat Inputs

3. Sensible heat - heat conducted to the water from the warm air

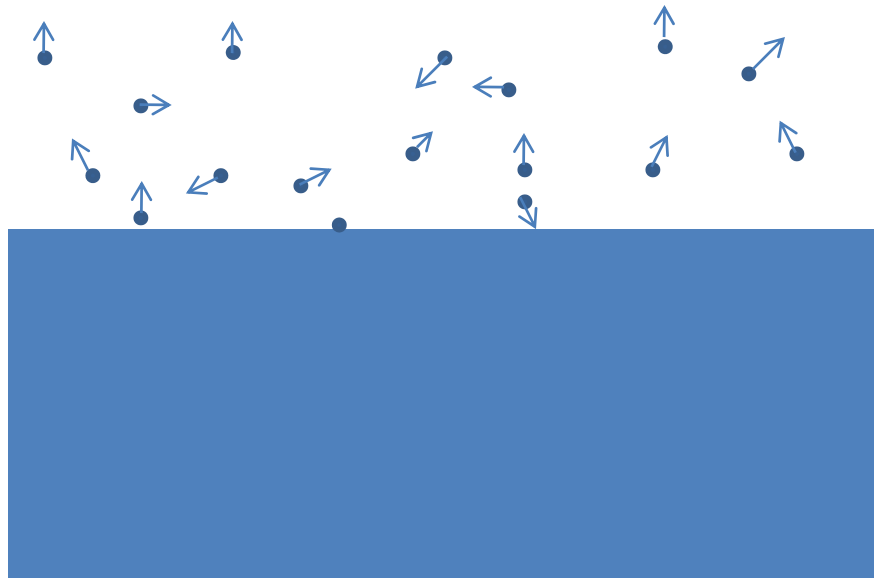


# Modeled Heat Inputs into Lake Whatcom



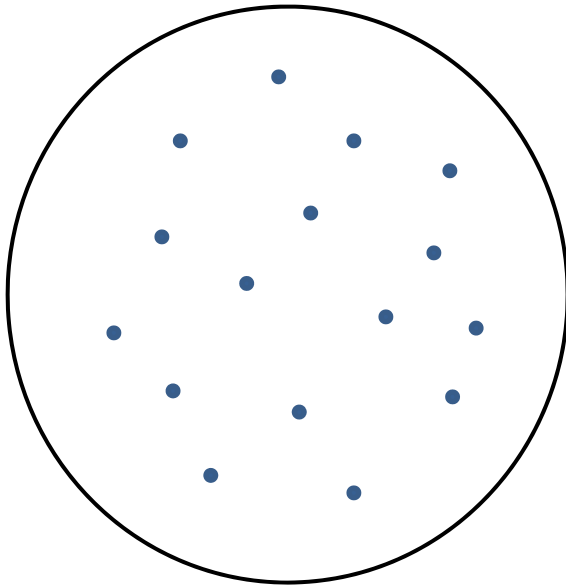
# What drives evaporation?

- 1) Energy input to the water to supply heat (i.e., increase the kinetic energy so molecules can escape).
- 2) Diffusion of water vapor molecules from the water surface to the atmosphere.
- 3) Transport of water vapor molecules away from the water surface.

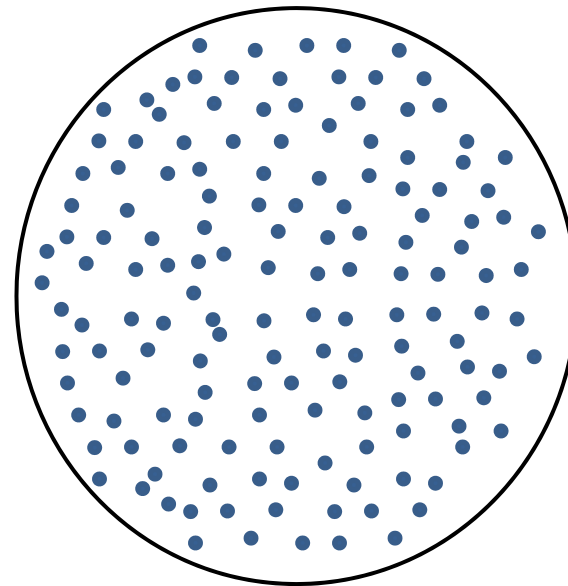


Actual vapor pressure is a measure of the amount of water vapor molecules present in a given parcel of air.

$e_a$  = actual vapor pressure



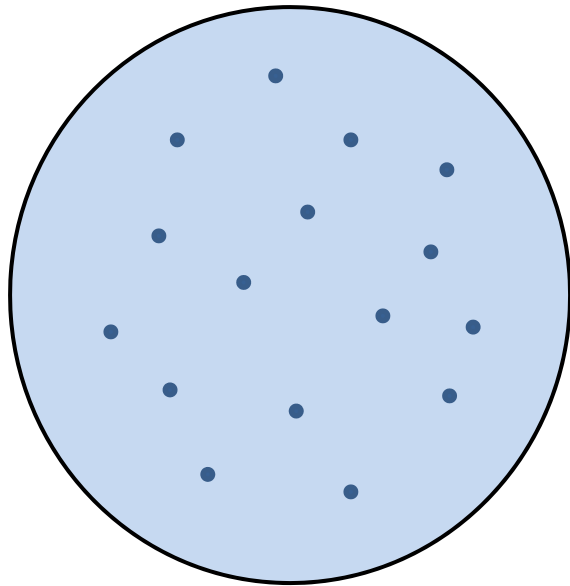
low vapor pressure



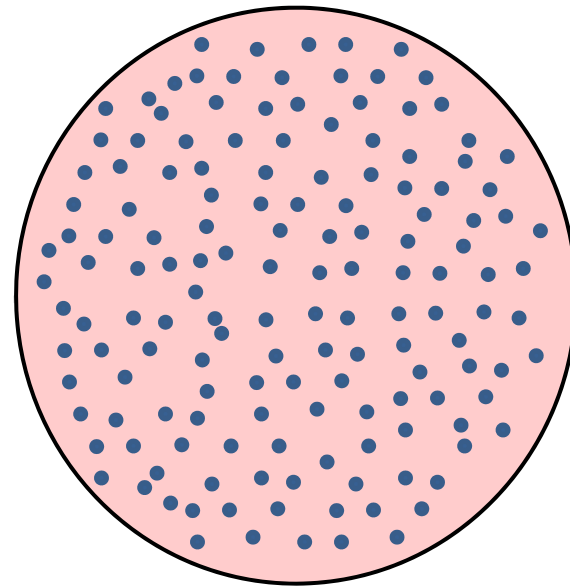
high vapor pressure

Saturation vapor pressure is the maximum amount of water vapor a parcel of air could hold at a specific temperature (which decreases with temperature).

$e_{\text{sat}}$  = saturation vapor pressure

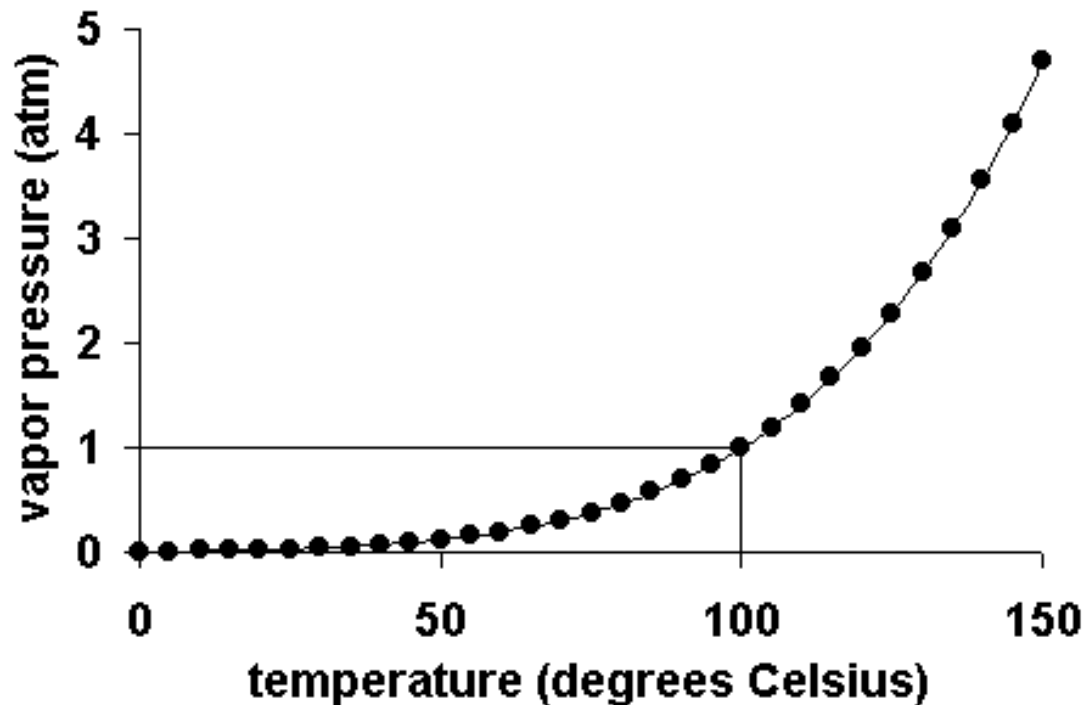


cool air has a low  
saturation vapor pressure

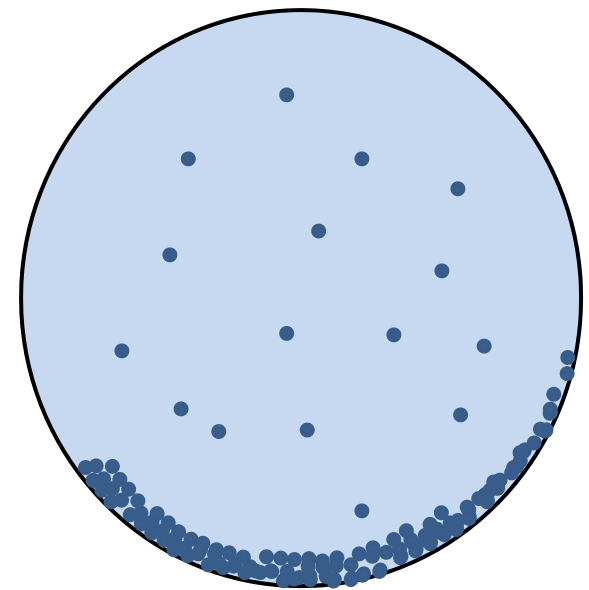
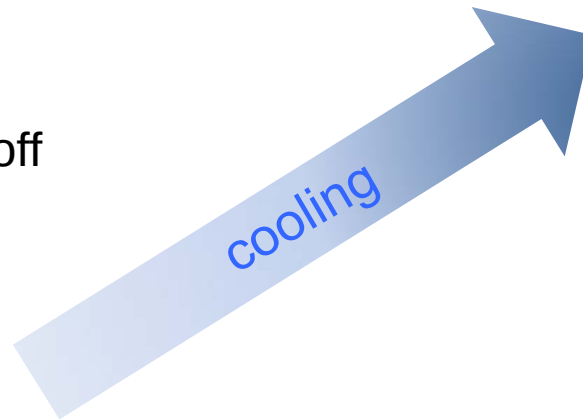
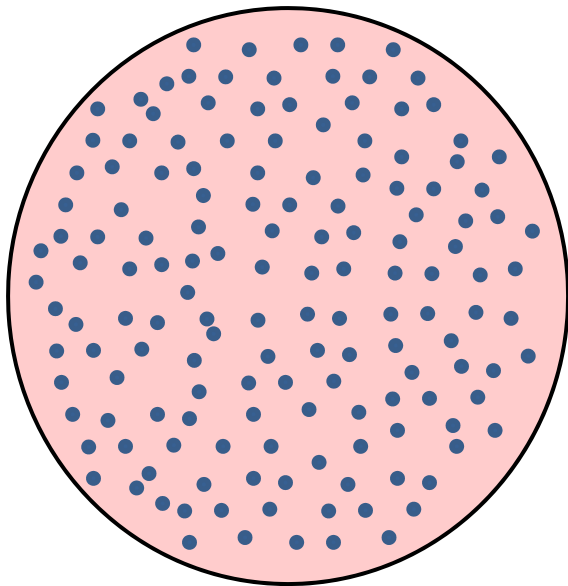


warm air has a higher  
saturation vapor pressure  
(more water molecules)

Saturation vapor pressure is the maximum amount of water vapor a parcel of air could hold at a specific temperature (which decreases with temperature).



If warm, humid air is cooled off



water vapor will condense  
because the saturation  
vapor pressure decreases

Relative humidity is the ratio of the amount of water vapor in a parcel of air (absolute vapor pressure) to how much water vapor the parcel could hold at a given temperature (saturation vapor pressure).

$$\text{relative humidity} = \frac{\text{actual vapor pressure}}{\text{saturation vapor pressure}} \times 100$$

Dew point temperature is the temperature at which a parcel of air reaches saturation.

# Diffusion or Vapor Transfer

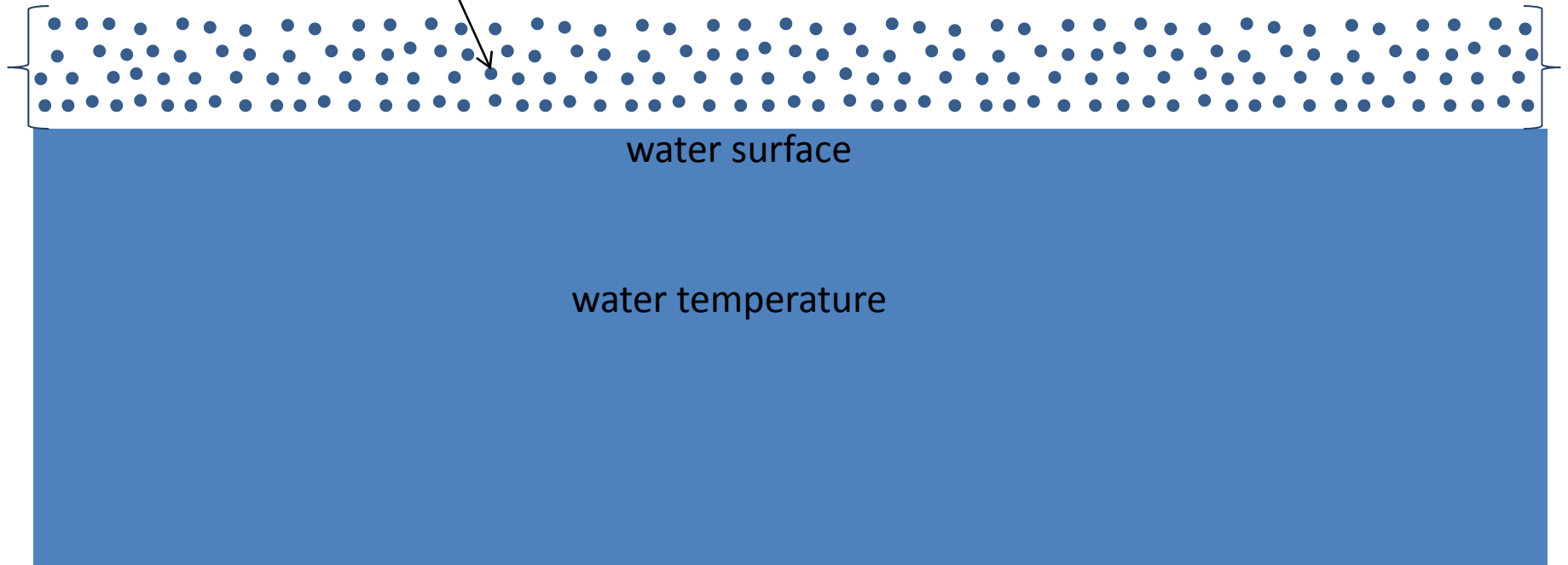
thin boundary layer of air that is fixed at the water temperature

water surface

water temperature

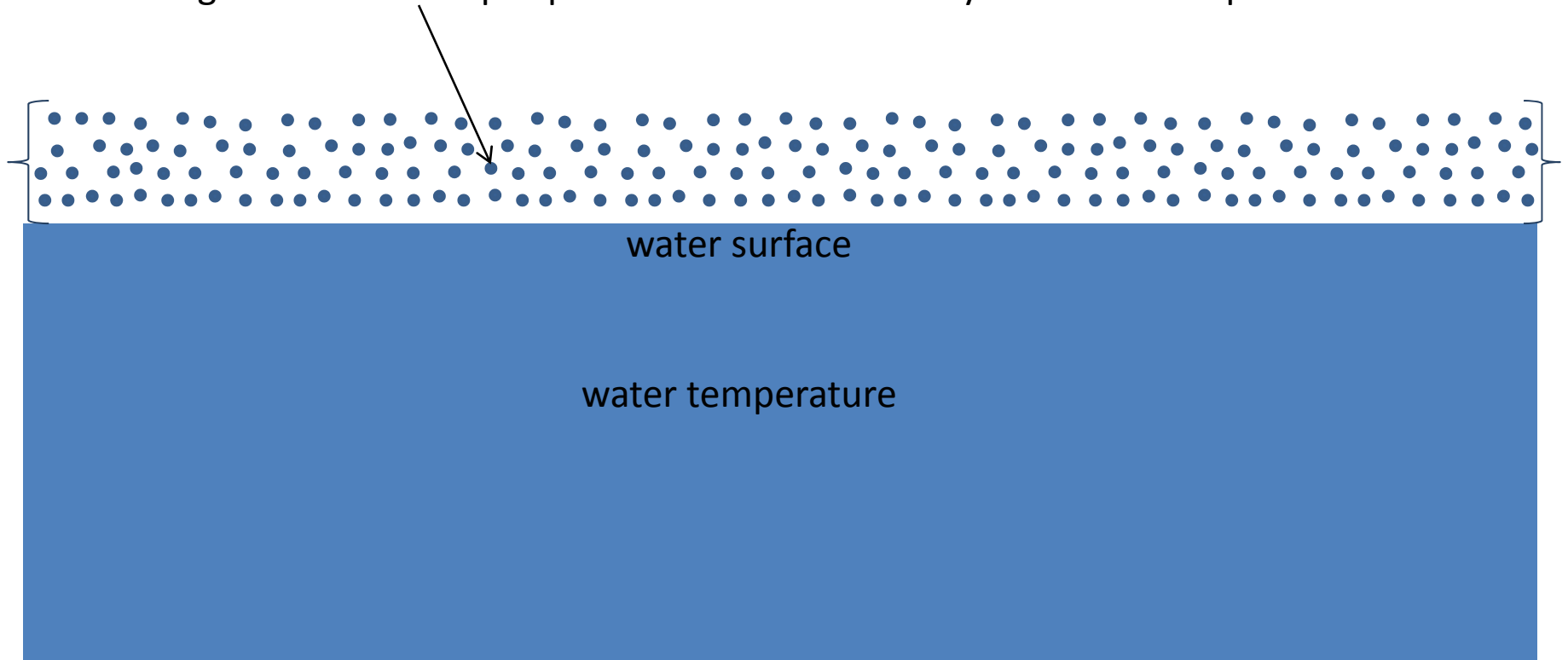
# Diffusion or Vapor Transfer

the boundary layer is always saturated with water vapor



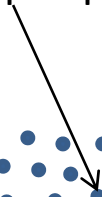
# Diffusion or Vapor Transfer

the magnitude of the vapor pressure is determined by the water temperature



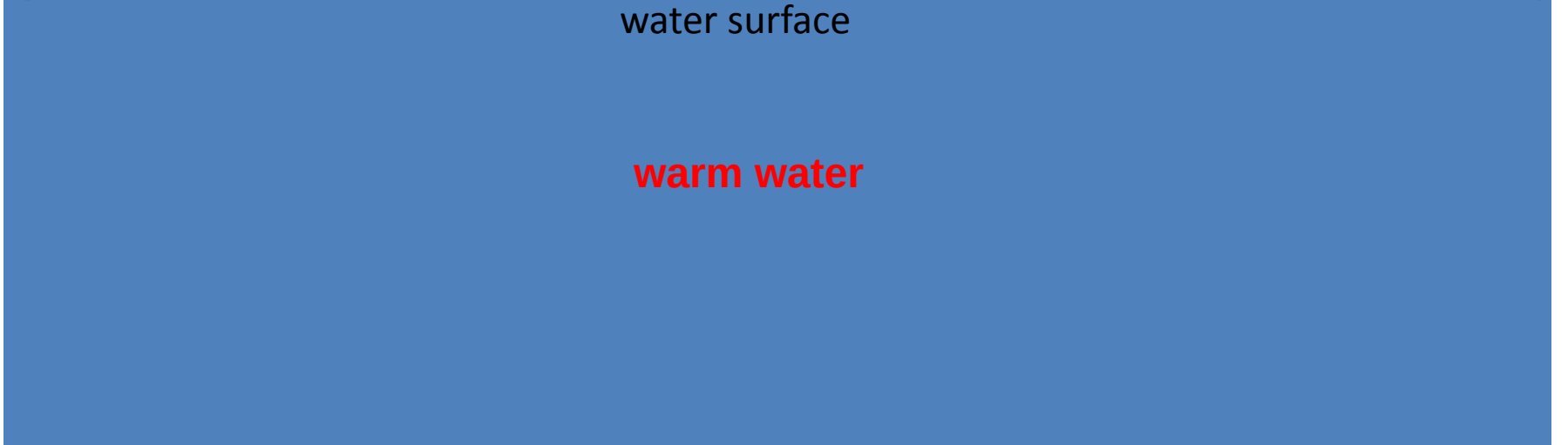
# Diffusion or Vapor Transfer

higher vapor pressure



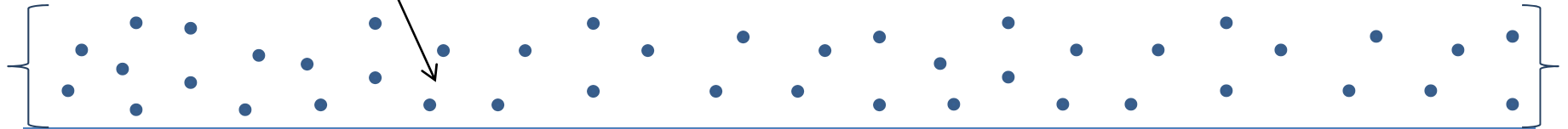
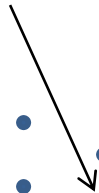
water surface

**warm water**



# Diffusion or Vapor Transfer

low vapor pressure



water surface

cool water

# Variables

---

$T_{\text{air}}$  = temperature of the air

$T_w$  = temperature of the water

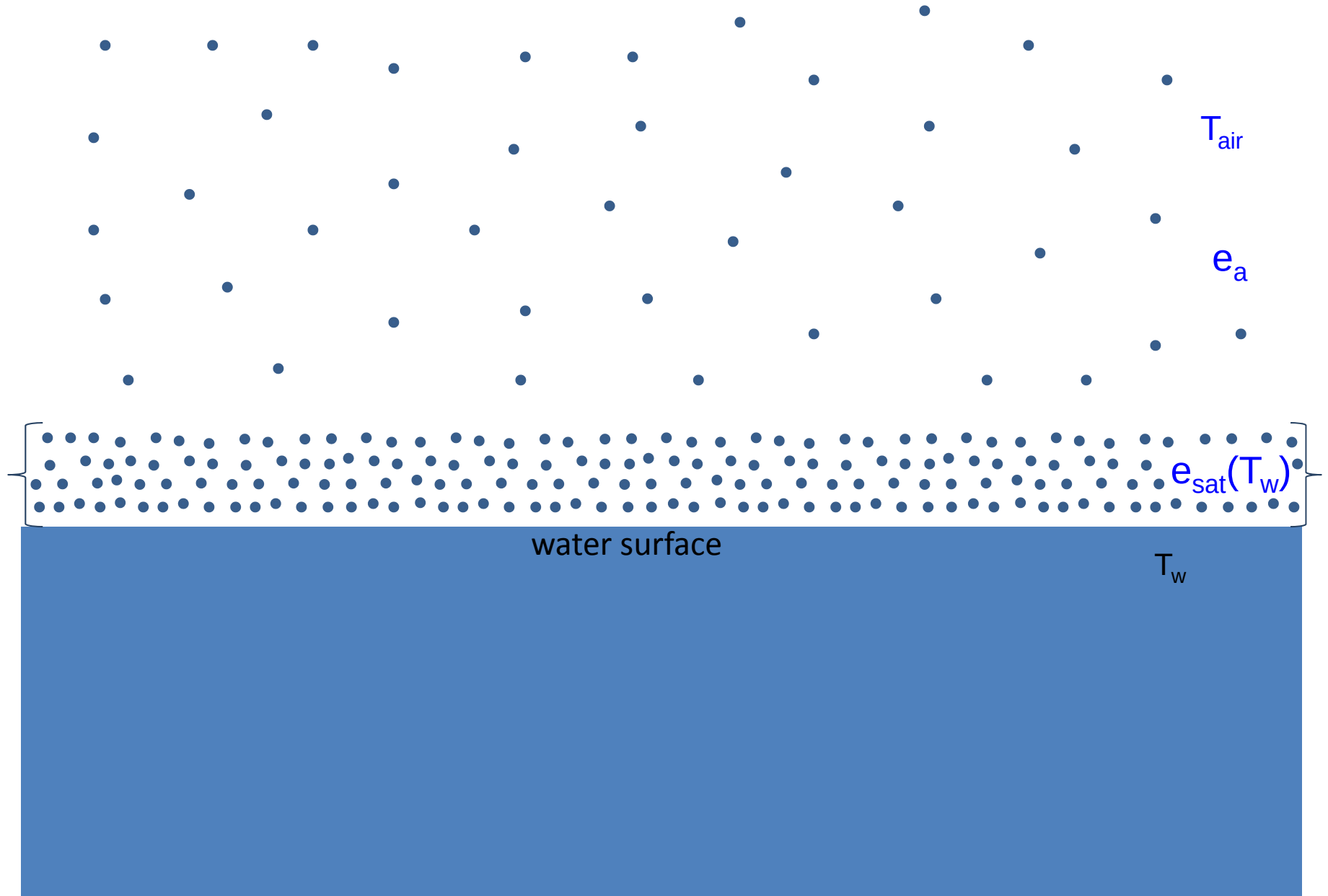
$e_a$  = actual vapor pressure of the air

$e_{\text{sat}}(T_{\text{air}})$  = saturation vapor pressure of the air

$e_{\text{sat}}(T_w)$  = saturation vapor pressure of the boundary layer

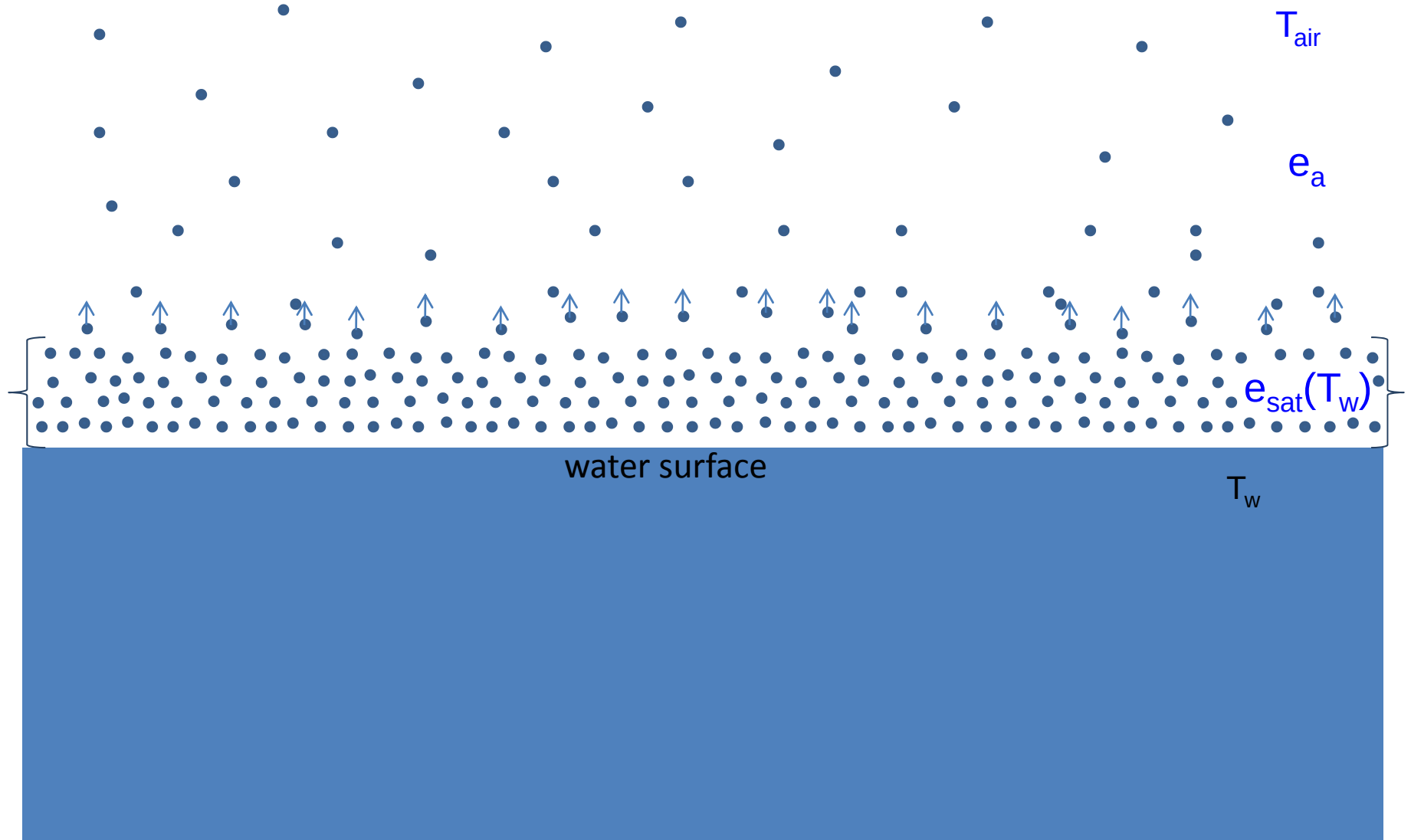
$e_{\text{sat}}(T_w) - e_a$  is called the vapor pressure deficit

# Diffusion or Vapor Transfer



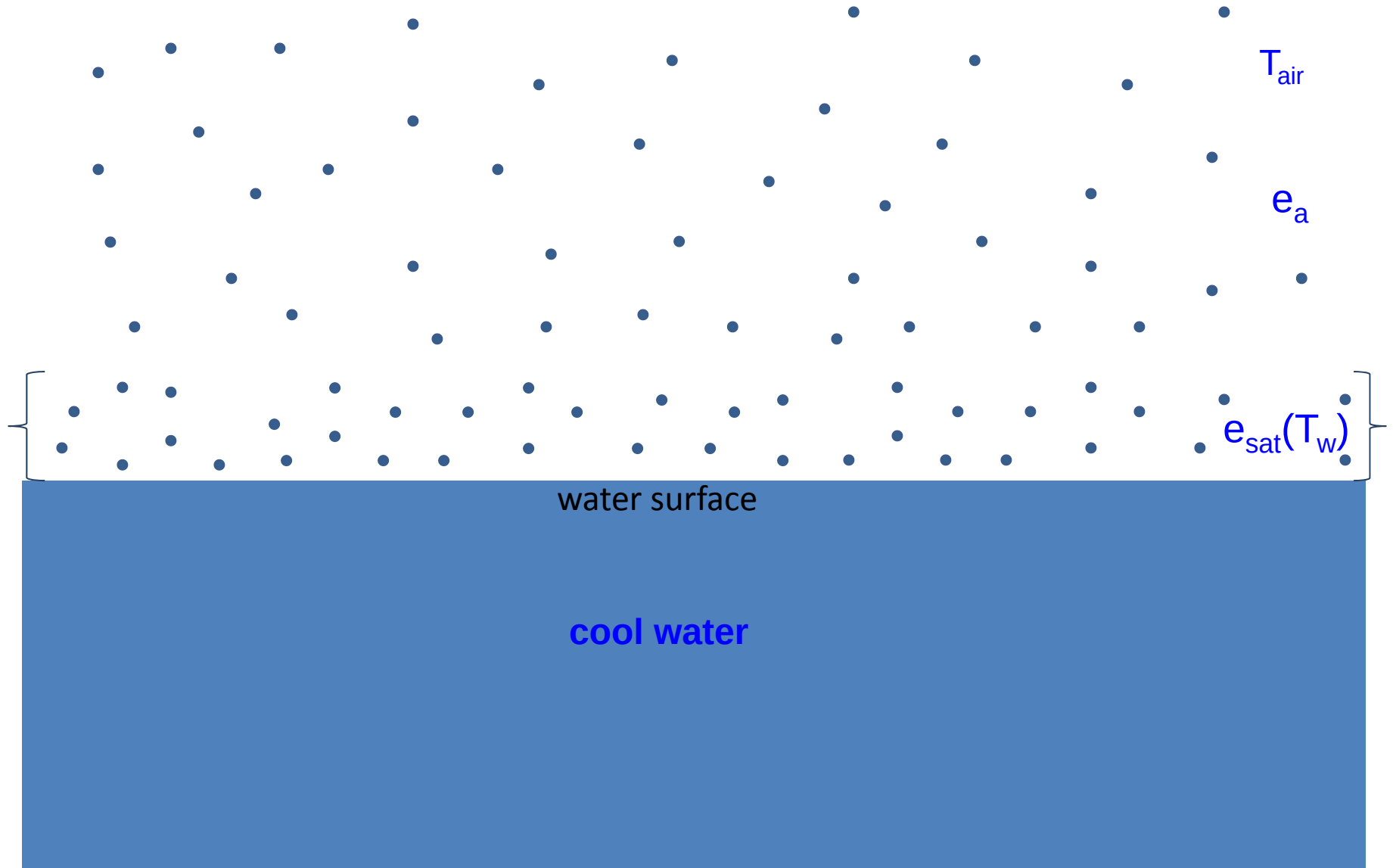
# Diffusion or Vapor Transfer (**evaporation**)

If  $e_a < e_{\text{sat}}(T_w)$  then molecules will diffuse from the boundary layer to the air



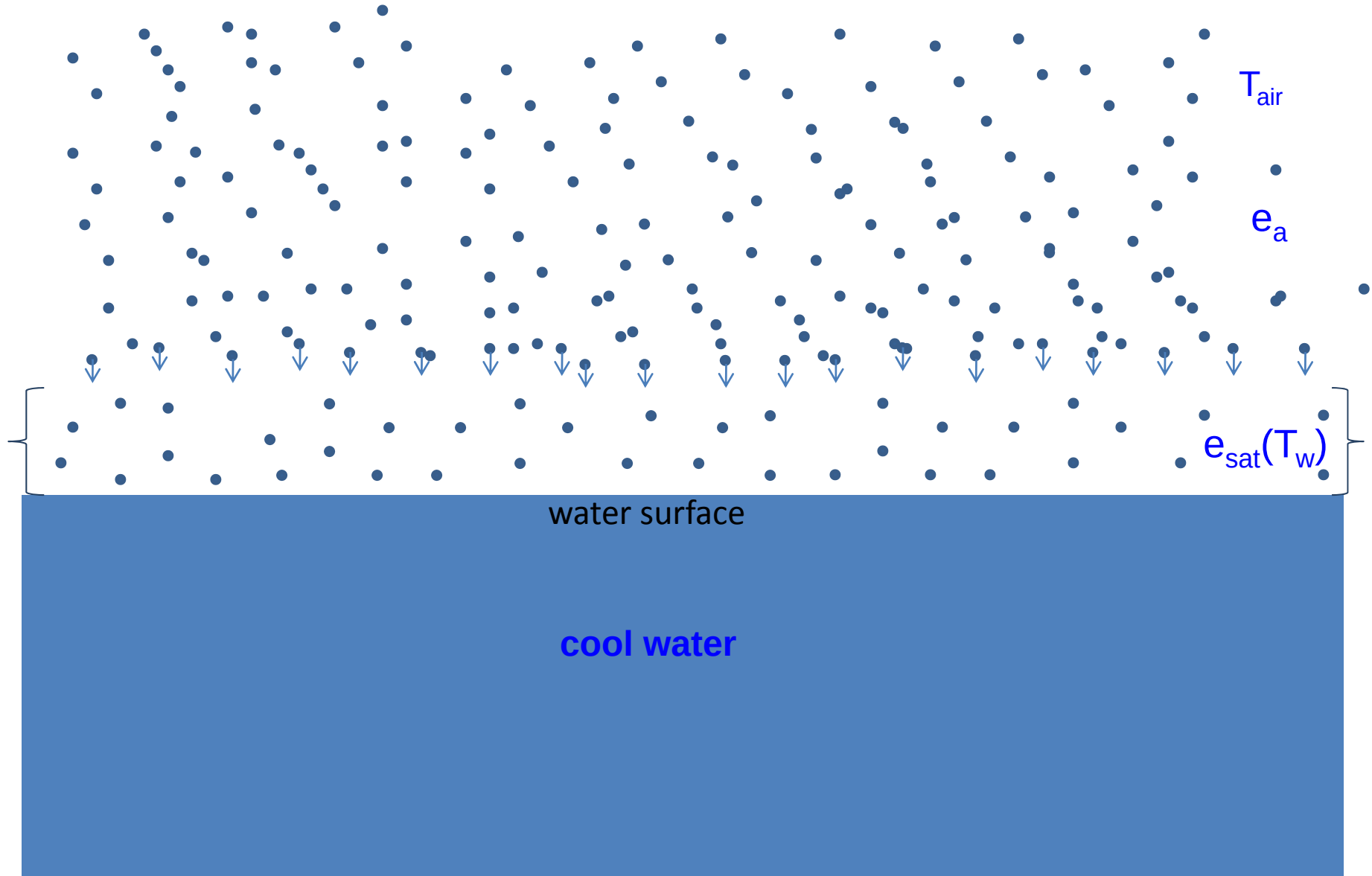
# Diffusion or Vapor Transfer (**no net evaporation**)

If  $e_a = e_{\text{sat}}(T_w)$  then molecules will diffuse back and forth



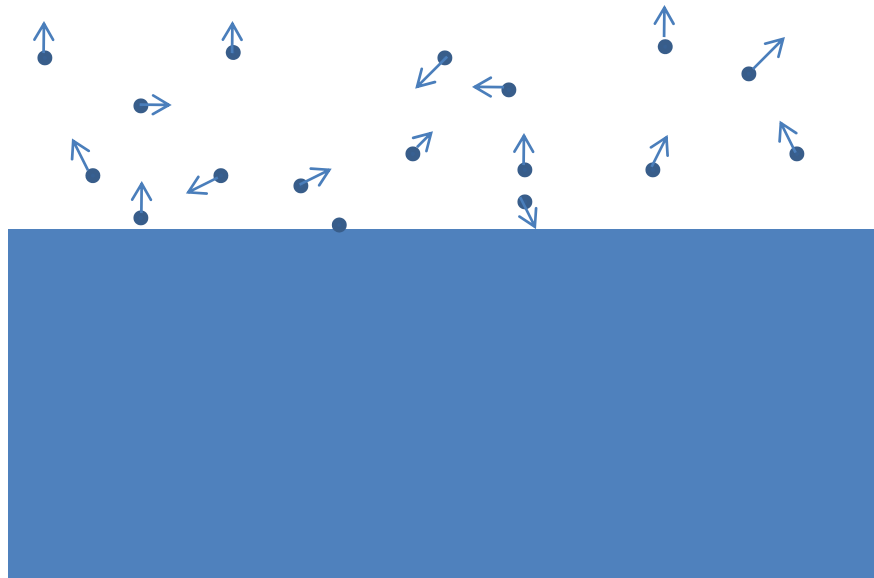
# Diffusion or Vapor Transfer (**condensation**)

If  $e_a > e_{\text{sat}}(T_w)$  then molecules will diffuse from the air to the boundary layer



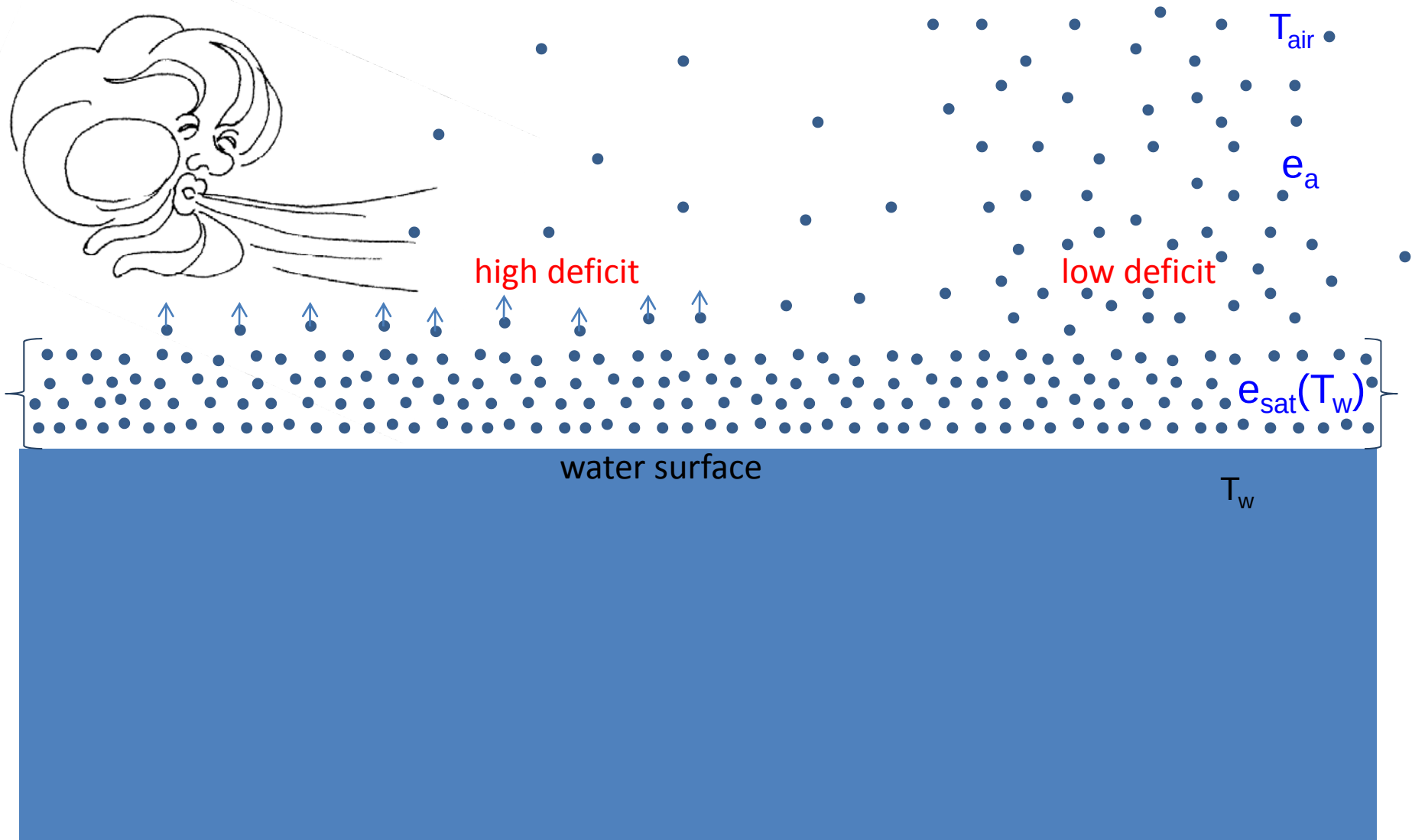
# What drives evaporation?

- 1) Energy input to the water to supply heat (i.e., increase the kinetic energy so molecules can escape).
- 2) Diffusion of water vapor molecules from the water surface to the atmosphere.
- 3) Transport of water vapor molecules away from the water surface.

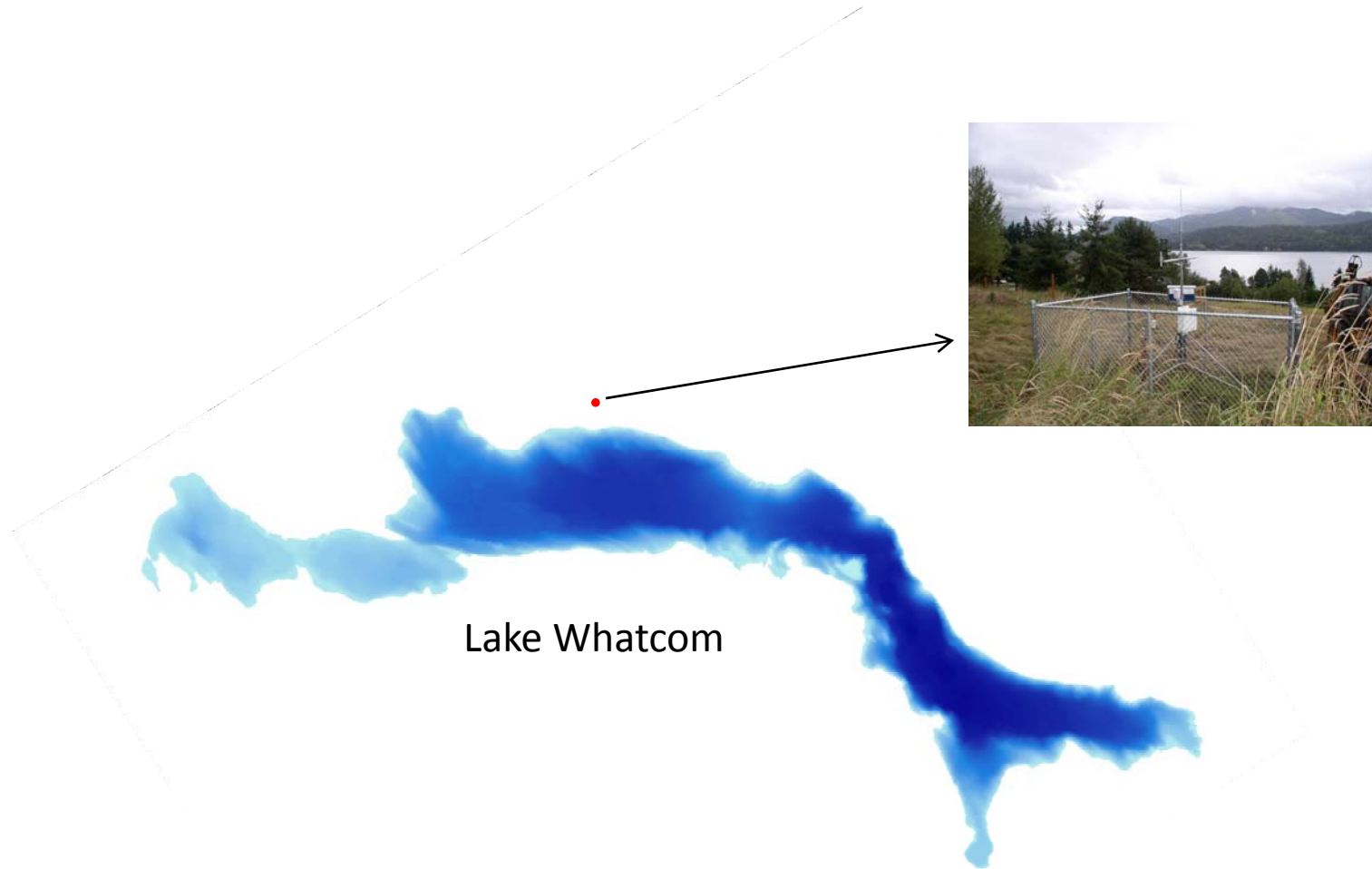


# Diffusion or Vapor Transfer

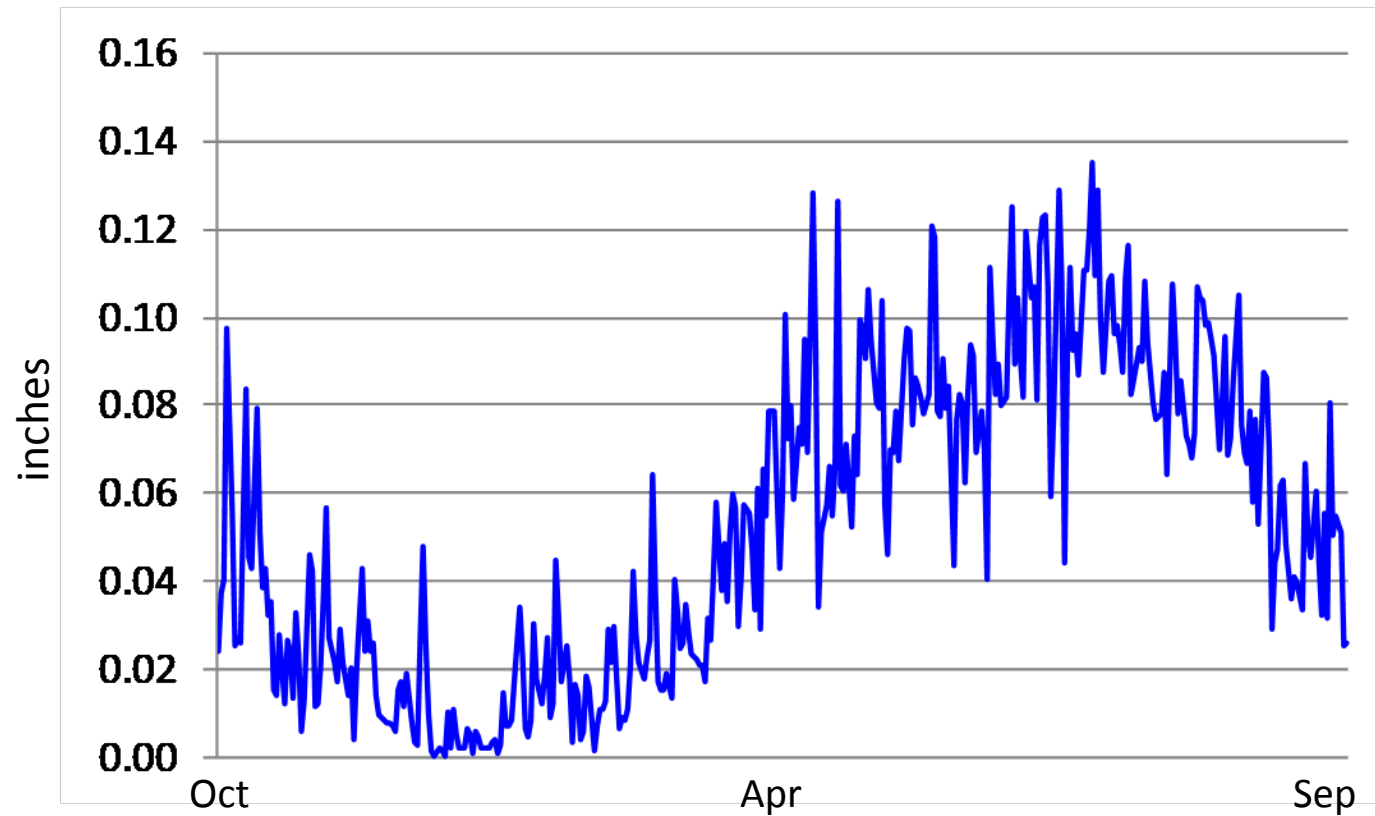
Wind sustains the deficit by sweeping moist air away from the water surface  
if  $e_a < e_{\text{sat}}(T_w)$  then evaporation continues



I use a numerical model based on the Penman method and data from the MET station to estimate the evaporation off of Lake Whatcom each year.



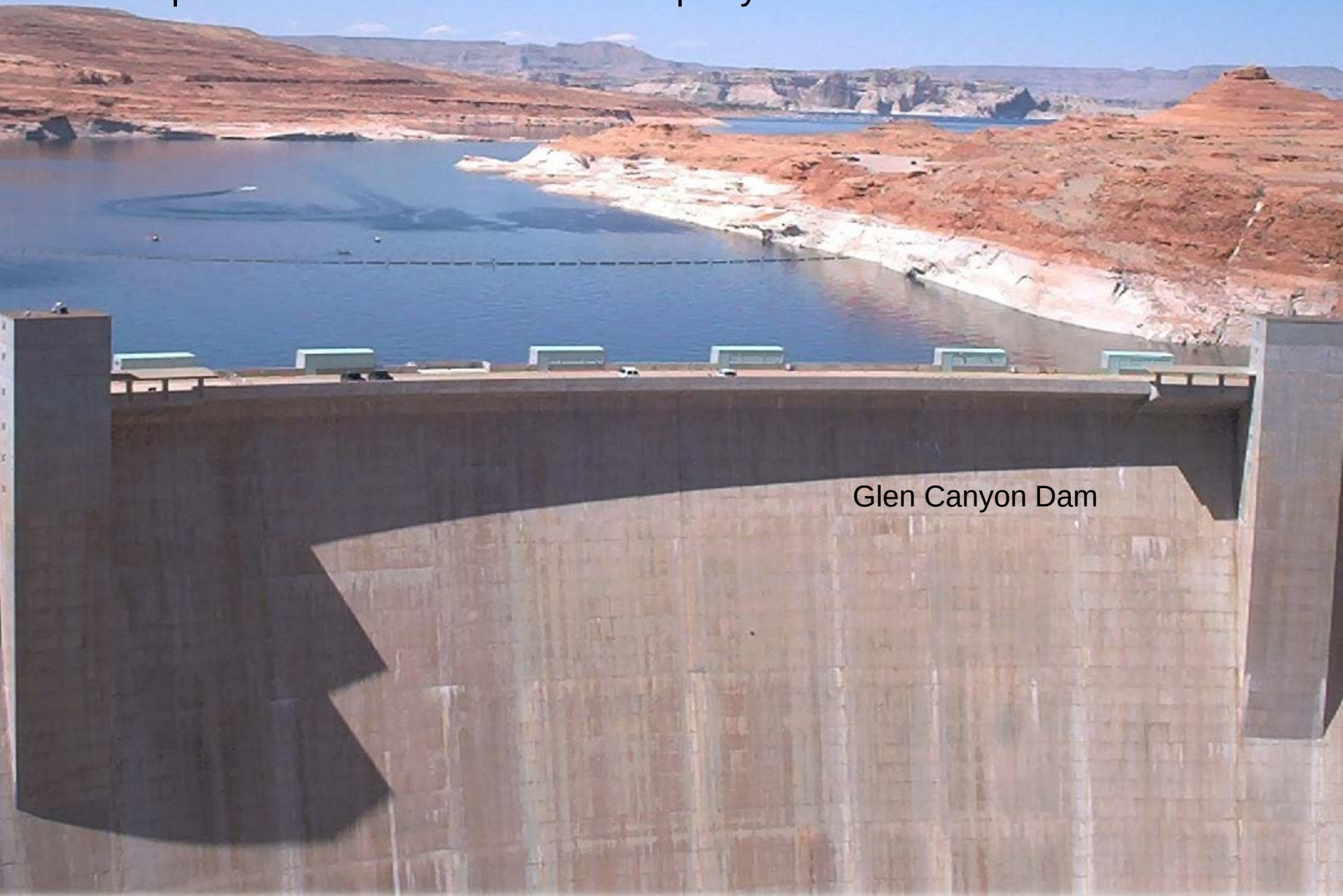
Modeled evaporation from Lake Whatcom in 2009-2010  
(about 20 inches total)



On a sunny summer day, the lake evaporates about as much water as the City of Bellingham withdrawals in a given day - about 20 million gallons!

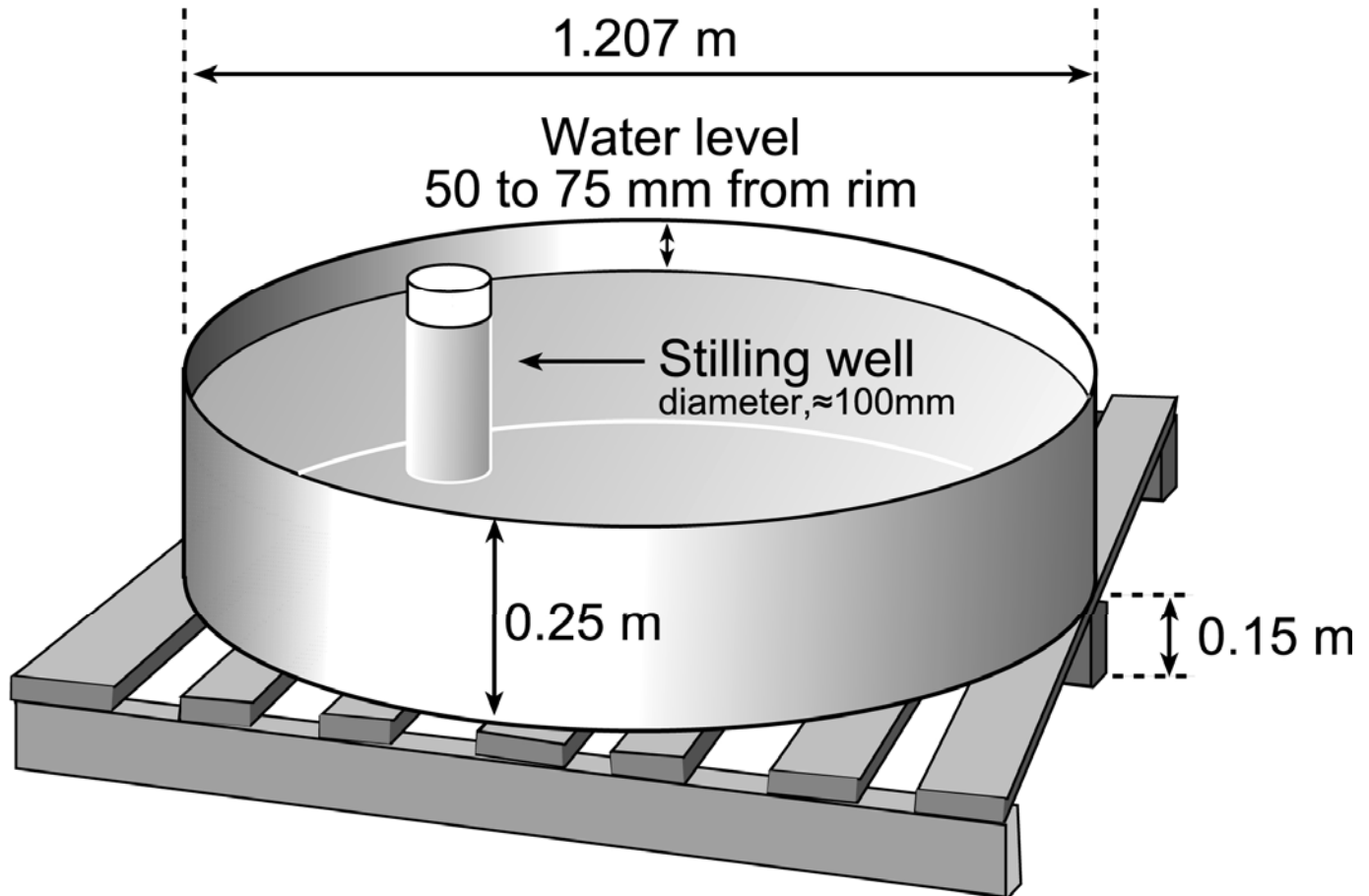


Lake Powell (Utah/Arizona) is a reservoir on the Colorado River. It evaporates about 10 feet of water per year.



Glen Canyon Dam

Evaporation pans are used to estimate lake evaporation

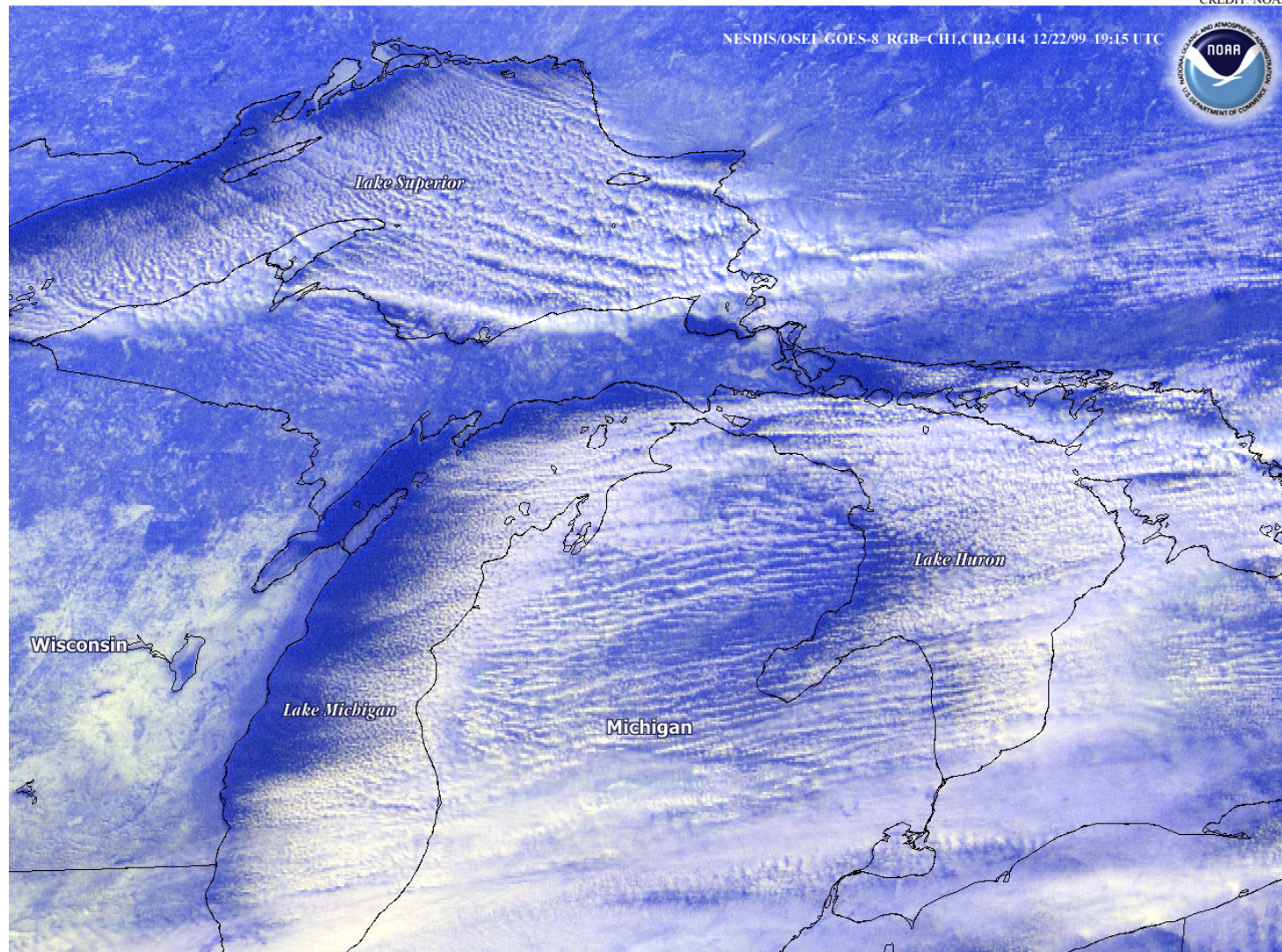




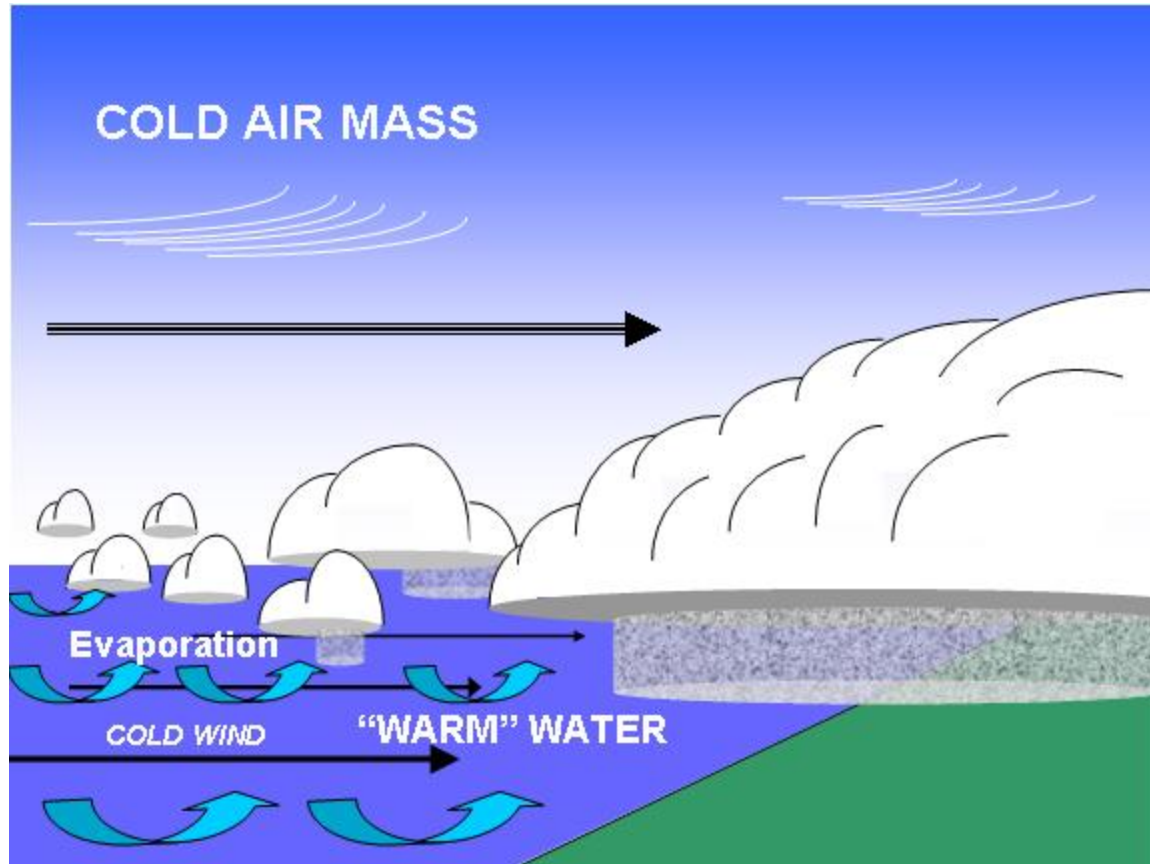
| Station<br>Bellingham 3SSW |                                      |      | County<br>Whatcom |          |              | State<br>WA                       |          | Date (Month & Yr.)<br>Oct 2010 |                      | Time of Complete Observation<br>(Local time) 17:00 |                      | Standard Time in Use |                                                 | RECORD OF EVAPORATION AND<br>CLIMATOLOGICAL OBSERVATIONS |                                                                       |                                               |                     |                                               |                                                             |                               |                            |      |                                   |      |  |
|----------------------------|--------------------------------------|------|-------------------|----------|--------------|-----------------------------------|----------|--------------------------------|----------------------|----------------------------------------------------|----------------------|----------------------|-------------------------------------------------|----------------------------------------------------------|-----------------------------------------------------------------------|-----------------------------------------------|---------------------|-----------------------------------------------|-------------------------------------------------------------|-------------------------------|----------------------------|------|-----------------------------------|------|--|
| DATE                       | AIR TEMPERATURE °F                   |      |                   |          |              |                                   |          |                                | PRECIPITATION        |                                                    |                      |                      |                                                 | WIND                                                     |                                                                       | EVAPORATION<br>(Inches & hundredths)          |                     |                                               | WATER<br>TEMP. °F                                           |                               | ADDITIONAL<br>DATA/REMARKS |      |                                   |      |  |
|                            | 24 Hours<br>Ending at<br>Observation |      | At Observation    |          |              | Supplemental Readings<br>of _____ |          |                                | Time of<br>beginning | Time of<br>ending                                  | Time of<br>beginning | Time of<br>ending    | 24 Hour Amounts                                 |                                                          | At Obsn.<br><br>Snow, Ice<br>Pellets, Hail,<br>Ice on<br>ground (in.) | Ane-<br>mometer<br>dial<br>Reading<br>(miles) | 24 Hour<br>Movement | Gage<br>Reading<br>or<br>Amount<br>Added<br>+ | Reading<br>When<br>Tank Filled<br>or Amount<br>Removed<br>- | Amount of<br>Evapora-<br>tion |                            |      | 24 Hours Ending at<br>Observation |      |  |
|                            | Max.                                 | Min. | Dry-bulb          | Wet-bulb | Dew<br>Point | Dry-bulb                          | Wet-bulb | Dew<br>Point                   |                      |                                                    |                      |                      | Rain, Melted<br>snow, etc. (in<br>& hundredths) | Snow, Ice<br>Pellets,<br>Hail (in. &<br>tenths)          |                                                                       |                                               |                     |                                               |                                                             |                               |                            |      | Max.                              | Min. |  |
|                            |                                      |      |                   |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 |                                                          |                                                                       |                                               |                     |                                               |                                                             |                               |                            |      |                                   |      |  |
| 1                          | 68                                   | 47   | 66                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1369                |                                               |                                                             |                               | 0.03                       | 62   | 46                                |      |  |
| 2                          | 66                                   | 48   | 61                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1385                |                                               |                                                             |                               | 0.05                       | 62   | 55                                |      |  |
| 3                          | 61                                   | 53   | 58                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1399                |                                               |                                                             |                               | 0.06                       | 60   | 54                                |      |  |
| 4                          | 59                                   | 48   | 54                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.05                                                     |                                                                       |                                               | 1415                |                                               |                                                             |                               | 0.00                       | 58   | 48                                |      |  |
| 5                          | 60                                   | 42   | 56                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1424                |                                               |                                                             |                               | 0.04                       | 57   | 42                                |      |  |
| 6                          | 61                                   | 41   | 58                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1432                |                                               |                                                             |                               | 0.00                       | 58   | 43                                |      |  |
| 7                          | 60                                   | 44   | 59                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1440                |                                               |                                                             |                               | 0.01                       | 59   | 44                                |      |  |
| 8                          | 69                                   | 56   | 66                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.02                                                     |                                                                       |                                               | 1466                |                                               |                                                             |                               | 0.03                       | 60   | 52                                |      |  |
| 9                          | 66                                   | 57   | 61                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.33                                                     |                                                                       |                                               | 1515                |                                               |                                                             |                               | 0.00                       | 60   | 54                                |      |  |
| 10                         | 67                                   | 51   | 59                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.48                                                     |                                                                       |                                               | 1562                |                                               |                                                             |                               | 0.00                       | 62   | 55                                |      |  |
| 11                         | 59                                   | 44   | 55                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1584                |                                               |                                                             |                               | 0.07                       | 59   | 45                                |      |  |
| 12                         | 60                                   | 46   | 56                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.02                                                     |                                                                       |                                               | 1603                |                                               |                                                             |                               | 0.02                       | 56   | 44                                |      |  |
| 13                         | 60                                   | 41   | 56                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.01                                                     |                                                                       |                                               | 1609                |                                               |                                                             |                               | 0.03                       | 56   | 44                                |      |  |
| 14                         | 58                                   | 43   | 53                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1625                |                                               |                                                             |                               | 0.02                       | 55   | 43                                |      |  |
| 15                         | 57                                   | 40   | 52                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1643                |                                               |                                                             |                               | 0.03                       | 53   | 41                                |      |  |
| 16                         | 54                                   | 33   | 50                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1654                |                                               |                                                             |                               | 0.03                       | 51   | 36                                |      |  |
| 17                         | 56                                   | 33   | 50                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1665                |                                               |                                                             |                               | 0.03                       | 48   | 36                                |      |  |
| 18                         | 52                                   | 41   | 50                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1667                |                                               |                                                             |                               | 0.00                       | 61   | 39                                |      |  |
| 19                         | 61                                   | 40   | 55                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1673                |                                               |                                                             |                               | 0.00                       | 64   | 39                                |      |  |
| 20                         | 59                                   | 39   | 53                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1679                |                                               |                                                             |                               | 0.01                       | 52   | 40                                |      |  |
| 21                         | 54                                   | 39   | 54                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1686                |                                               |                                                             |                               | 0.01                       | 51   | 40                                |      |  |
| 22                         | 60                                   | 54   | 57                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.02                                                     |                                                                       |                                               | 1729                |                                               |                                                             |                               | 0.01                       | 56   | 49                                |      |  |
| 23                         | 65                                   | 45   | 61                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1735                |                                               |                                                             |                               | 0.00                       | 51   | 45                                |      |  |
| 24                         | 61                                   | 50   | 52                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.45                                                     |                                                                       |                                               | 1793                |                                               |                                                             |                               | 0.00                       | 54   | 48                                |      |  |
| 25                         | 54                                   | 48   | 49                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.38                                                     |                                                                       |                                               | 1864                |                                               |                                                             |                               | 0.00                       | 50   | 44                                |      |  |
| 26                         | 50                                   | 46   | 48                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.09                                                     |                                                                       |                                               | 1922                |                                               |                                                             |                               | 0.00                       | 48   | 42                                |      |  |
| 27                         | 59                                   | 45   | 56                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.01                                                     |                                                                       |                                               | 1933                |                                               |                                                             |                               | 0.00                       | 50   | 43                                |      |  |
| 28                         | 56                                   | 46   | 52                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.05                                                     |                                                                       |                                               | 1937                |                                               |                                                             |                               | 0.03                       | 52   | 45                                |      |  |
| 29                         | 60                                   | 46   | 55                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.01                                                     |                                                                       |                                               | 1950                |                                               |                                                             |                               | 0.00                       | 52   | 46                                |      |  |
| 30                         | 61                                   | 38   | 54                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.00                                                     |                                                                       |                                               | 1955                |                                               |                                                             |                               | 0.00                       | 54   | 39                                |      |  |
| 31                         | 57                                   | 47   | 52                |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 0.29                                                     |                                                                       |                                               | 2003                |                                               |                                                             |                               | 0.29                       | 52   | 44                                |      |  |
| Sum.                       |                                      |      |                   |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 | 2.21                                                     |                                                                       |                                               | 51316.00            |                                               |                                                             |                               | 0.80                       |      |                                   |      |  |
| Avg.                       | 59.7                                 | 44.9 |                   |          |              |                                   |          |                                |                      |                                                    |                      |                      |                                                 |                                                          |                                                                       |                                               | 1655.4              | Adjusted Total                                |                                                             |                               | 0.0                        | 55.6 | 44.7                              |      |  |

Lake effect snow continues for the second day on the eastern shores of Lake Superior, Lake Michigan and Lake Huron. Lake effect snow occurs when cold air flows over the relatively warm surfaces of the lakes causing lifting and condensation.

CREDIT: NOAA



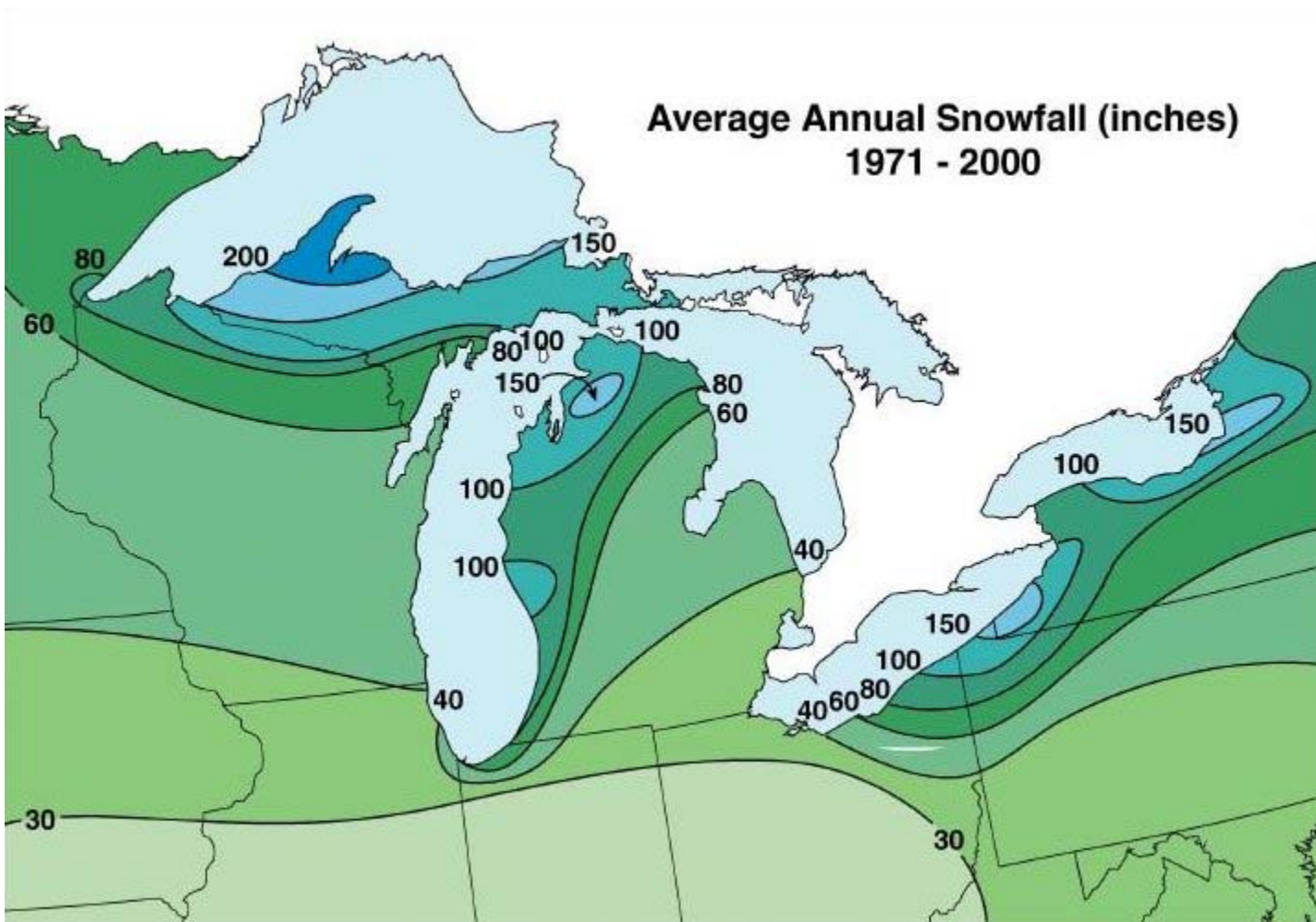
# Lake Effect Snow



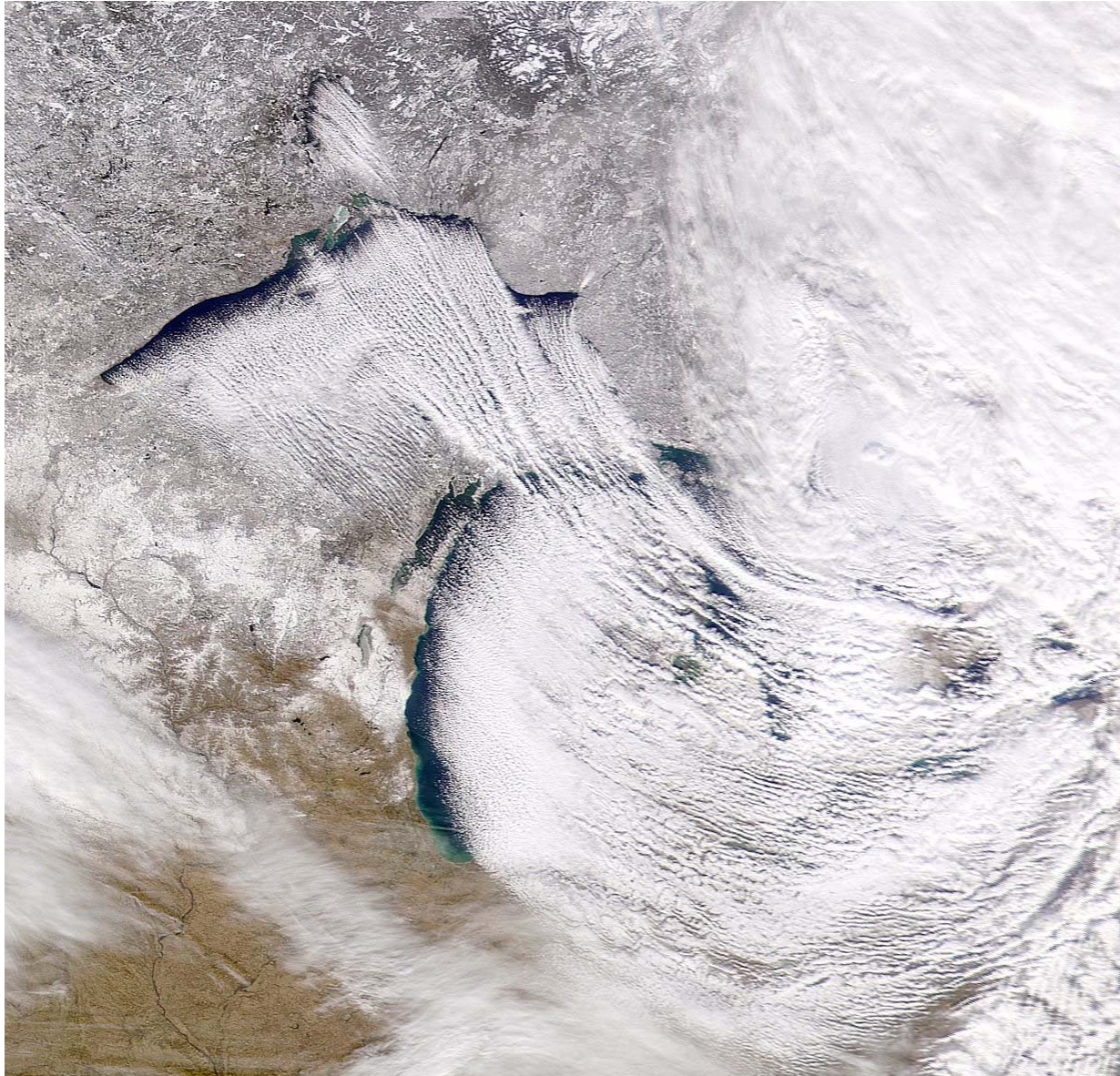
# Lake Effect Snow



# Lake Effect Snow



# Lake Effect Snow



Evaporation is the phase change from liquid to a vapor

Which beaker evaporates more water and why?

