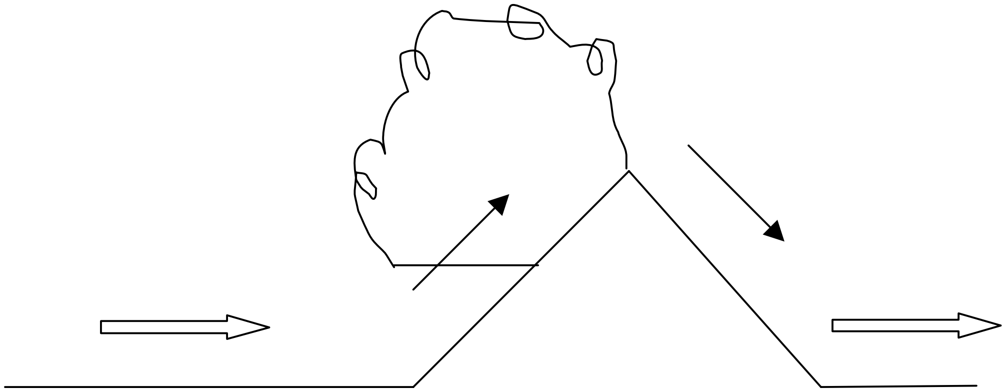
Flow of moist air over a mountain

To understand many of the implications of the moist and dry adiabats, it is useful to examine what happens to moist air as it flows over a mountain.

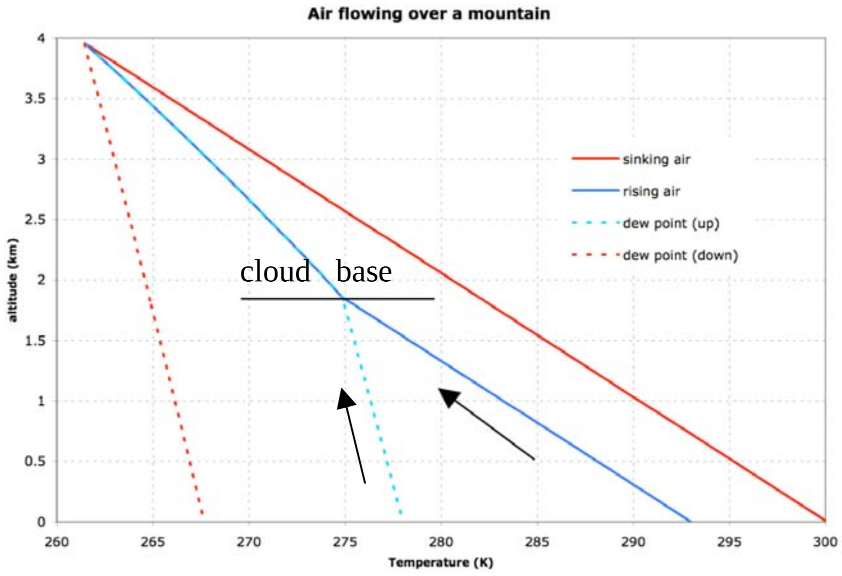


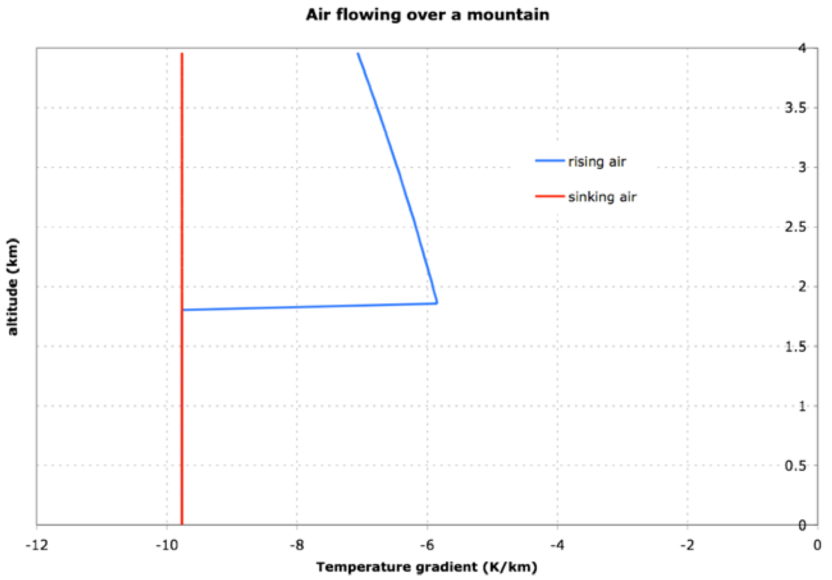
The low level air comes in from the west. It runs into the mountain and is forced up and over the mountain.

In the case we will work through, the air at the surface initially has a temperature of 293 K, 20°C and a dew point temperature of 278 K, 5°C and a pressure of 1000 mb. We'll use a 4 km tall mountain similar to many of the mountains near the west coast of the US. This example will show us why the western sides of these mountains in California, Oregon and Washington are quite wet while the eastern sides are deserts.

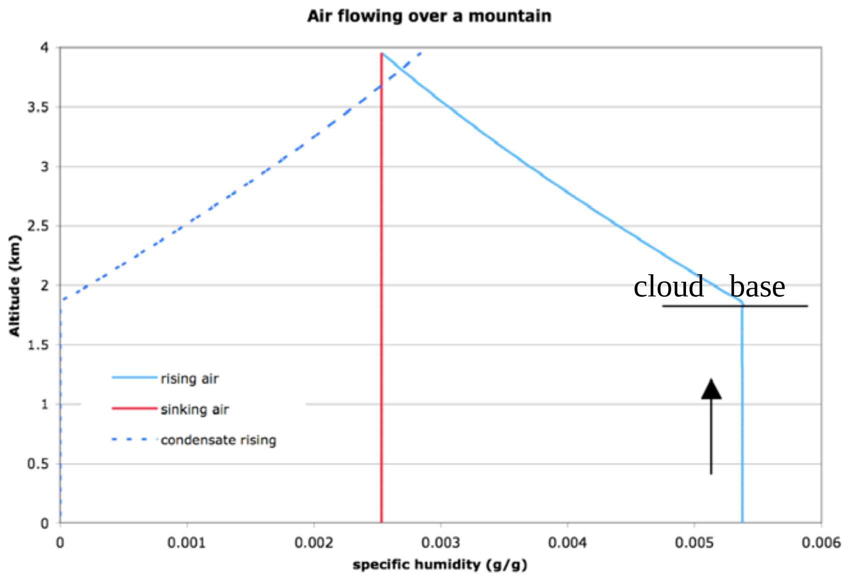
Rising air below the cloud

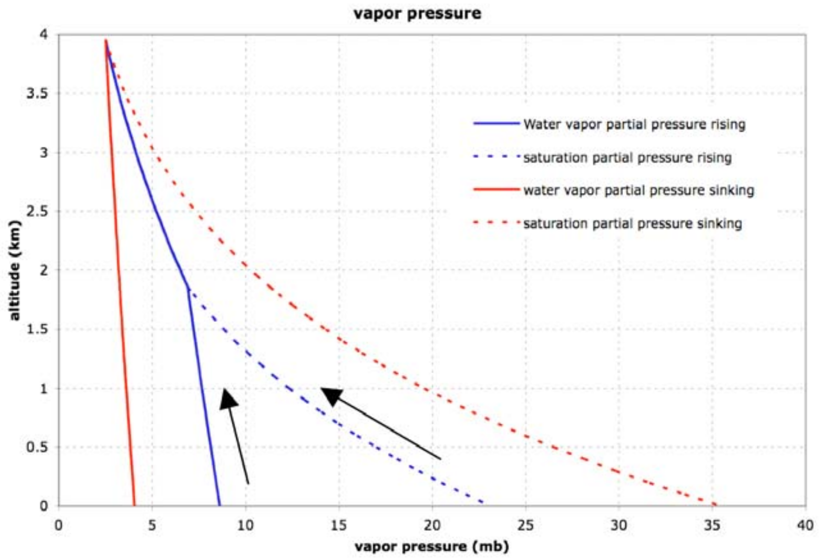
- The air runs into the mountain and begins to rise.
- As the air rises, it decompresses and cools.
- The rising motion is rapid so the air cools according to the dry adiabat
  - o $\frac{\partial T}{\partial z} = -\frac{g}{C_p}$
  - o ~10^oC cooling for every km of rise





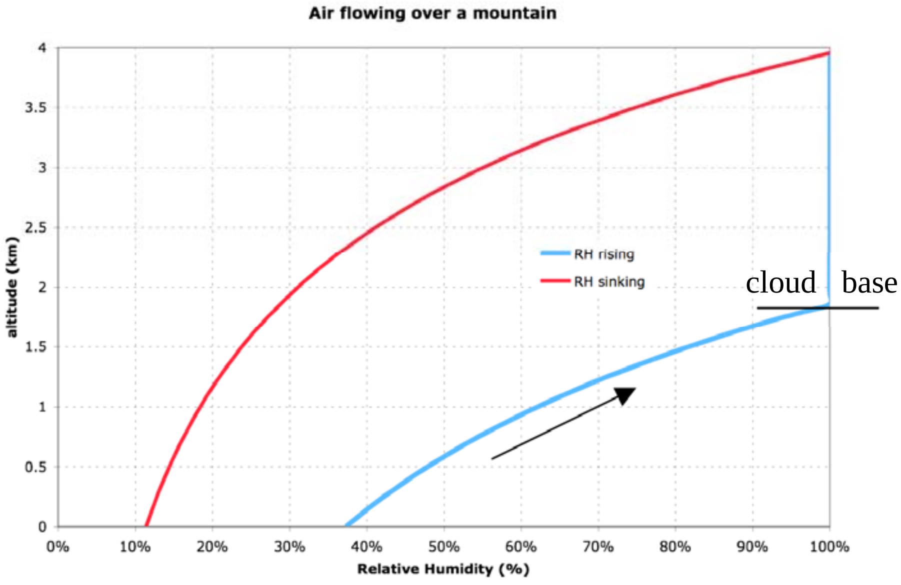
- The water vapor mixing ratio or specific humidity remains constant (below cloud base)
  - q = constant
  - because there are no sources adding water vapor to the air
  - or sinks removing water vapor from the air





- The water vapor partial pressure of the air decreases with height at the same rate as the air pressure decreases (because the volume mixing ratio = e/P is constant below cloud base).
- The dew point temperature decreases about 1.7 K/km in a well mixed layer (constant mixing ratio) as you showed in your homework
  - $$\frac{dT_d}{dz} = -\frac{g}{L}\frac{m_d T_d^2}{m_v T} \sim -\frac{g}{L}\frac{m_d T_d}{m_v}$$
- In the rising air, the temperature and dew point temperatures are converging at about 8 K/km (the difference between the dry adiabat and the dew point lapse rates.
- Because the air is cooling rapidly with height, the saturation vapor pressure of the air decreases rapidly with height,

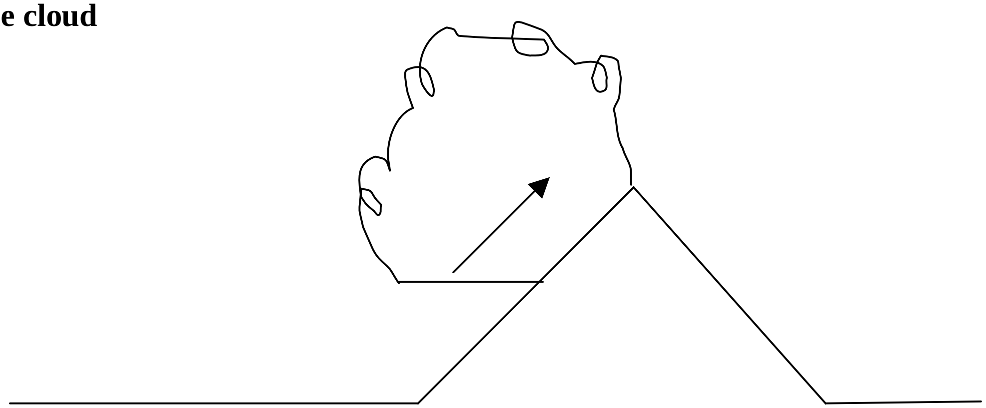
  - Roughly a factor of 2 for every km of rise because, at typical surface temperatures, the saturation vapor pressure decreases by about a factor of 2 for every 10^{o}C decrease in temperature
- The relative humidity ($=e/e_s$) of the rising air therefore ***increases*** because even though the vapor pressure of the air is decreasing with altitude, the saturation vapor pressure is decreasing far more rapidly with height



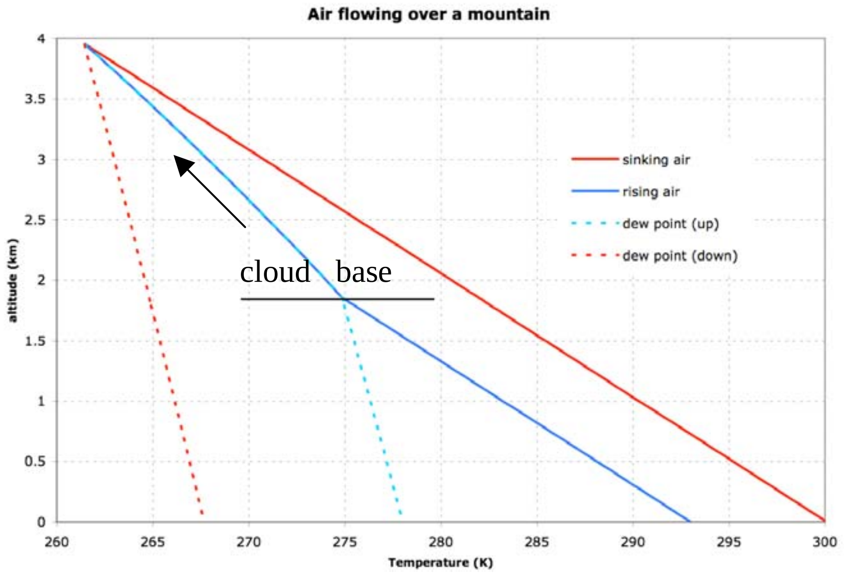
At cloud base

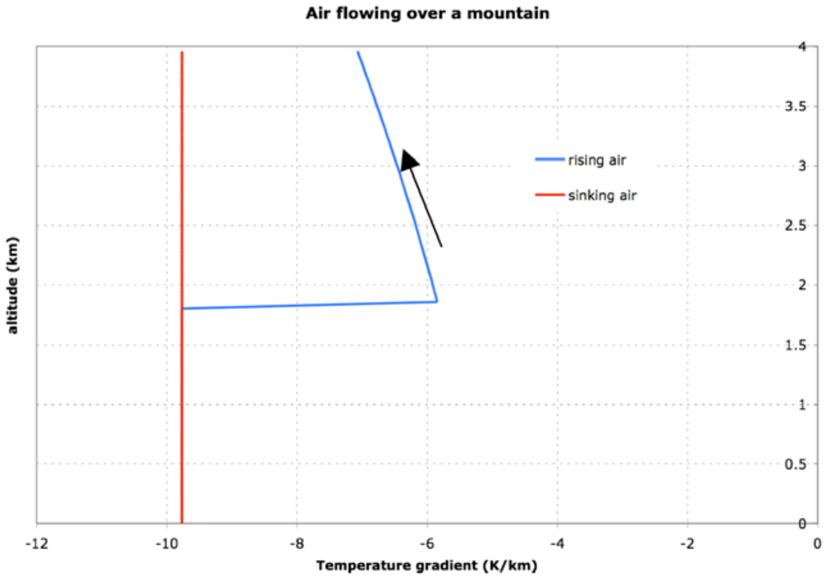
- the water vapor partial pressure equals the saturation vapor pressure
- The dew point temperature equals the air temperature
- The relative humidity reaches 100%
- Water vapor begins to condense out into cloud droplets
- Cloud base occurs at 1.86 km altitude.
  - This can be estimated from $z_{cloudbase} = -\frac{(T-T_d)_{surface}}{\left(-\frac{g}{C_p}-\left(\frac{\partial T_d}{\partial z}\right)_{mixed}\right)} \approx \frac{(T-T_d)_{surface}}{8K/km}$ in km = 1.875 km which is very close

Rising air in the cloud

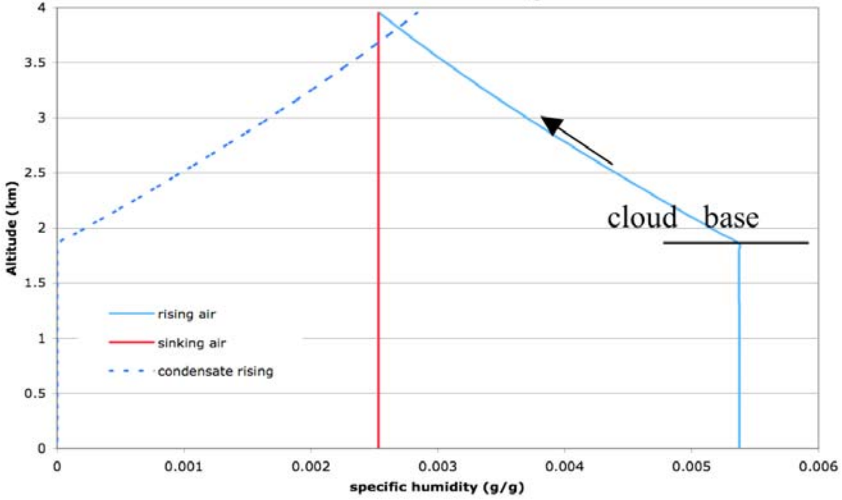


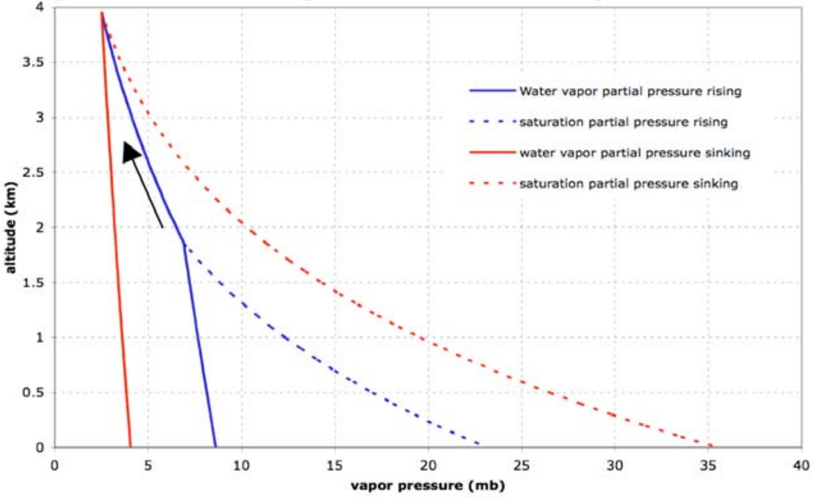
- Water vapor continues to condense out as the air rises
- Latent heat release from the condensation warms the air as it rises
- the resulting moist adiabatic lapse rate is significantly smaller in magnitude than the dry adiabatic lapse rate
    - In this case, -5.8 to -7.1 K/km vs. -9.8 K/km for the dry air below
- Such that the air temperature does not decrease nearly as fast with altitude in the cloud as it did below the cloud.

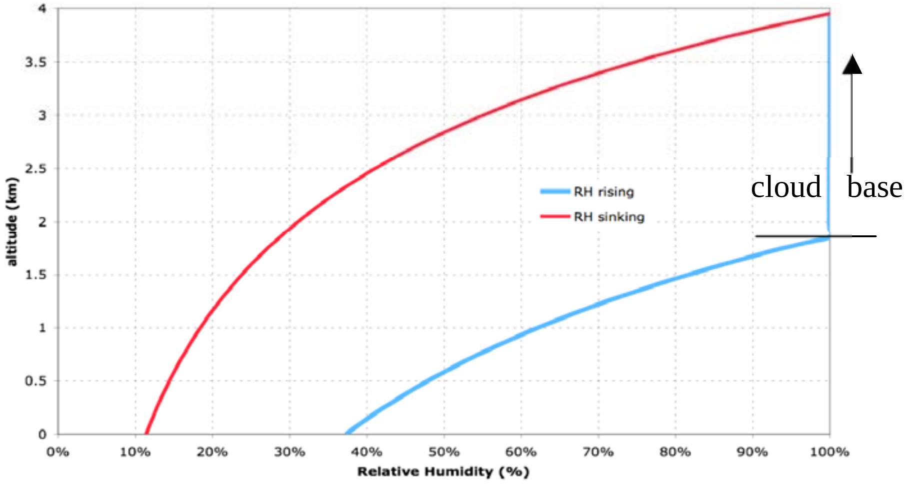




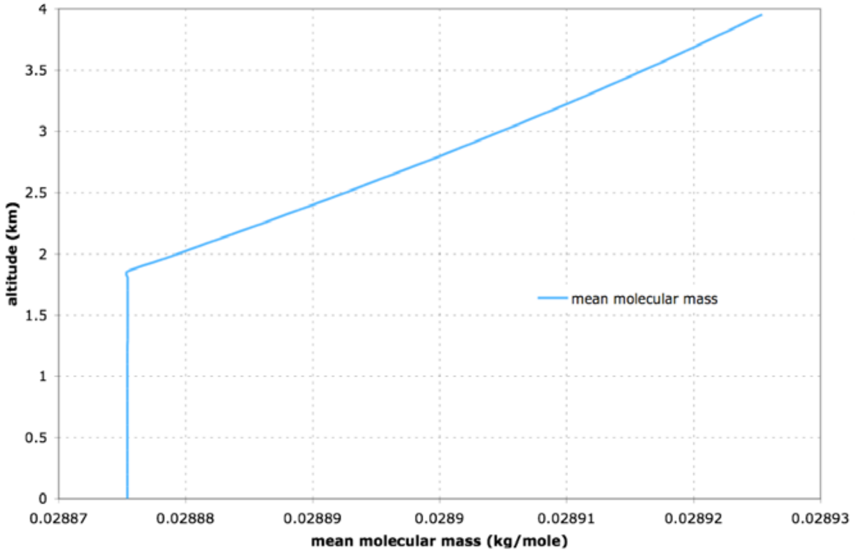
- The water vapor partial pressure in the cloud is equal to the saturation vapor pressure
    - which depends on the temperature which depends on the moist adiabat
- Relative humidity is (approximately) equal to 100% in the cloud
- The mixing ratio decreases with altitude according to the saturation vapor pressure divided by the air pressure.
- The difference between the mixing ratio at cloud base and mixing ratio in the cloud goes into condensed liquid in the cloud.

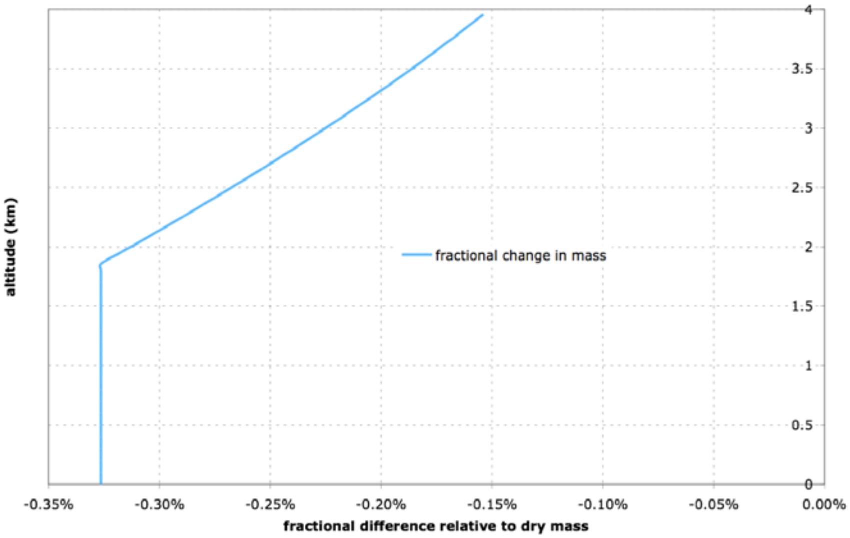






- The mean molecular mass **increases** with height as water condenses out of the air parcel

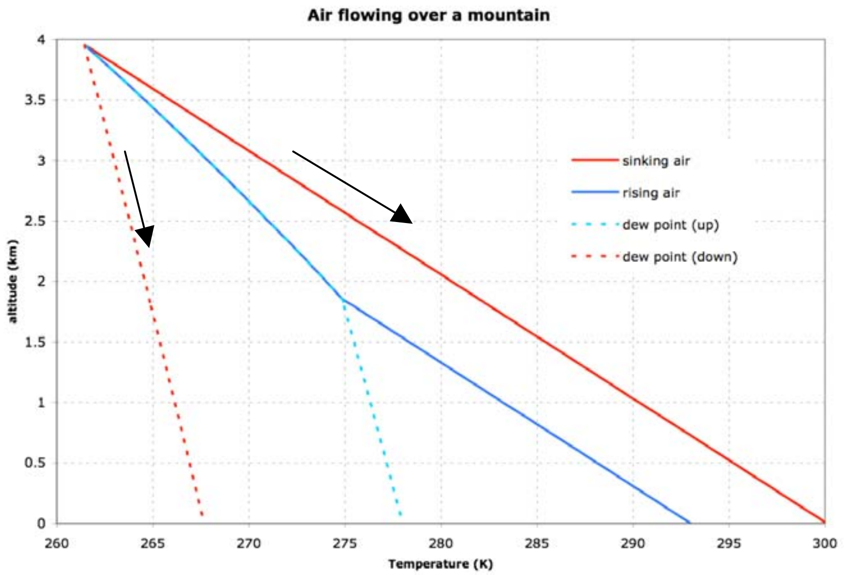


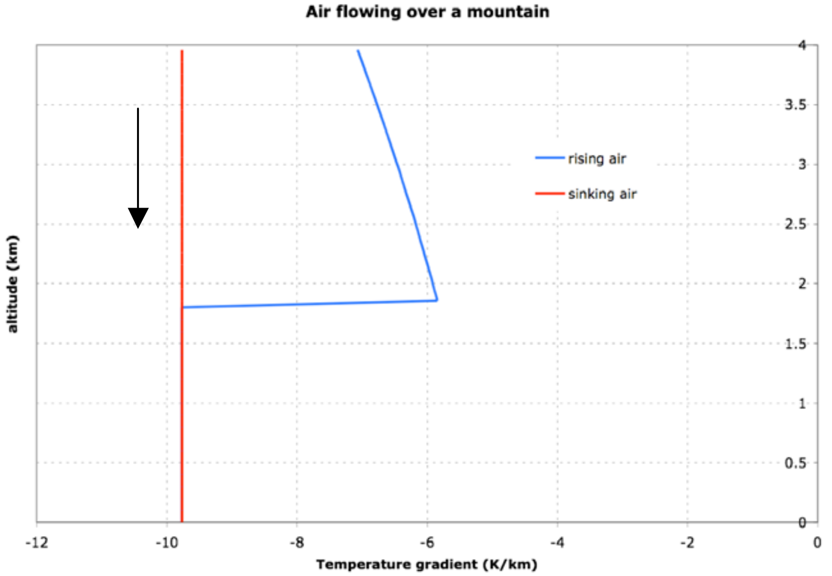


- Increasing the mean molecular mass increases the mass density and is equivalent to decreasing the air parcel temperature.
- This is where the virtual temperature concept comes from.

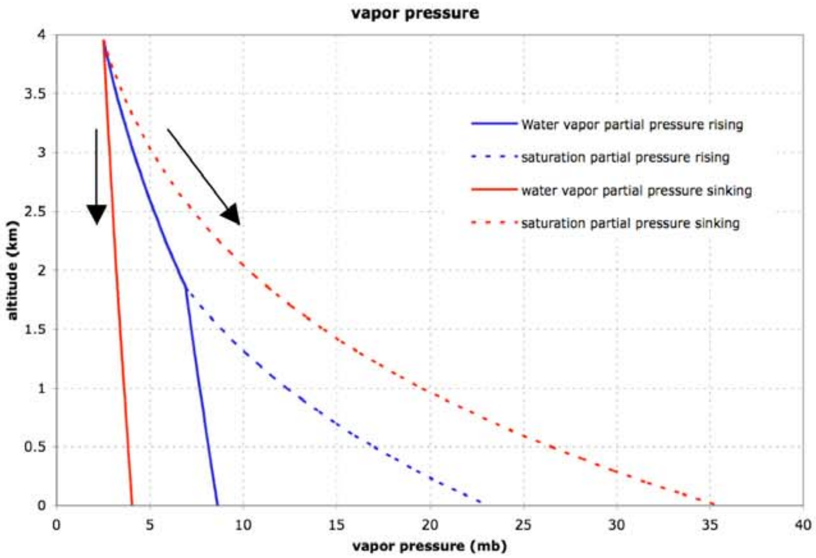
Sinking air

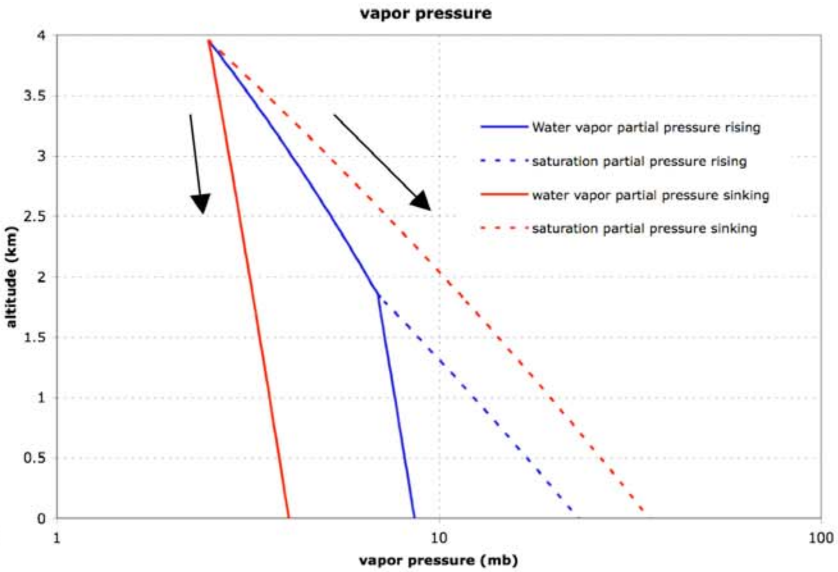
- To make thing simple, we will assume none of the condensed moisture in the cloud makes it over the mountain.
- The sinking air will compress and warm because the environment is doing work on it
- The relatively rapid sinking motion in the absence of condensed droplets means the air will warm along the dry adiabat as it sinks
- Temperatures will therefore increase at about 10^{o}C per km of sinking motion.





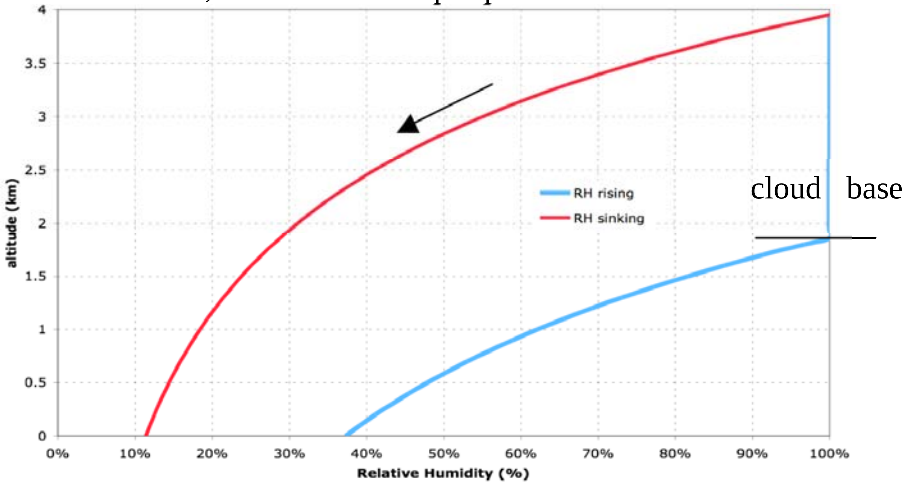
- The water vapor mixing ratio will remain constant during the sinking motion
- The dew point temperature therefore increases about 1.7 K/km during descent in a well mixed layer (constant mixing ratio)
  - $\frac{dT_d}{dz} = -\frac{g}{L}\frac{m_d T_d^2}{m_v T} \sim -\frac{g}{L}\frac{m_d T_d}{m_v}$
- In the sinking air, the temperature and dew point temperatures are diverging at about 8 K for every km of sinking motion (the difference between the dry adiabat and the well mixed dew point lapse rates.
- The water vapor partial pressure will increase in proportion with the pressure as it sinks (because of the constant mixing ratio)
- The saturation vapor pressure will increase rapidly with the sinking motion because of the rapid adiabatic increase in the air temperature as it sinks
  - The saturation vapor pressure will increase approximately a factor of 2 for every km of sinking motion





On the semi-log plot to the right, the nearly straight lines indicate the water vapor dependence on altitude is nearly an exponential

- Relative humidity decreases rapidly with decreasing altitude because while the water vapor partial pressure increases at lower altitudes, the saturation vapor pressure increases much faster



So the air loses a large amount of water going over the mountains. This tremendously reduces evaporative cooling on the descending side of the mountain. As a results, air temperatures to the west of the mountain are much cooler and the humidity is much higher in both absolute and relative humidity sense. In contrast, air to the east of the mountain is hotter and drier in both an absolute and relative humidity sense.   Specifically in the case we examined,

	west	**east**
Surface temperature (K)	293	300
Surface dew point (K)	278	268
Surface specific humidity (g/kg)	5.4	2.5
Surface relative humidity	37%	11%
Surface pressure (mb)	1000	993

The surface pressure reduction is a result of the air being hotter and therefore lighter than the air ont eh west side of the mountain. Therefore the hydrostatic air pressure must be lower on the eastern side of the mountain. This is responsible in part for the intensification of winter storms as they cross the Rocky mountains.

Had we increased the initial dew point of the air, the differences between the west and east sides of the mountain would be even greater.