

- energy = capacity to do work
- neither created nor destroyed, but subject to transformation and transport – law of "conservation of energy"
- familiar forms:
  - kinetic energy (energy of motion; macroscopic or microscopic)
  - potential energy
    - gravitational potential energy
    - chemical potential (bonding) energy
    - nuclear binding energy\*\*
  - radiant energy
- in a given system or process, may neglect energy forms that do not "participate" (undergo transformation), e.g. in connection with weather, air's nuclear binding energy is irrelevant

\*\*mass of atom < sum of masses of its nucleons & electrons

Kinetic energy of a mass  $m$  with velocity  $v$ :

$$KE = \frac{1}{2} m v^2$$

Kinetic energy *per unit volume* of moving air (or any fluid):

$$ke \quad \textcircled{KE} = \frac{1}{2} \rho v^2$$

Grav. ptl. energy of a mass  $m$  at height  $h$  in gravity  $g$ :

$$PE = m g h$$

Gravitational PE per unit volume of air:

$$pe \quad \textcircled{PE} = \rho g h$$

We might analyse the trajectories of baseballs in terms of KE and PE, without any reference to the "internal energy" of the ball, which is constituted by forms of energy at the microscopic (molecular) level

- sensible heat energy and latent heat energy are the two forms of "internal energy" possessed by matter that are of concern to us in atmos. sci.
- the amount of sensible heat energy stored in a given mass of material is proportional to (thus, measured by) temperature

**TABLE 4.1** | Specific heats of various substances.

Substance	Specific Heat ( $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ )
Asphalt	920
Concrete	880
Glass	670
Steel	500
Gold	130
Sand	800
Dry Soil	800
Wet Soil	1480
Granite	790
Basalt	840
Light Wood	1420
Dense Wood	1880
Ice (at $0^\circ\text{C}$ )	2100
Water	4186
Steam	2040

- if the temperature of mass  $m$  of a sample changes by  $\Delta T$  without phase change, the change in the sensible heat content of the sample is

$$Q = m c \Delta T \quad [\text{J}]$$

Eq 4.1

where  $c$  [ $\text{J kg}^{-1} \text{K}^{-1}$ ] is the "specific heat" (or "specific heat capacity") of the material

- latent ("invisible") heat is the energy used to change the phase of a substance

### Evaporation:

- fast moving molecules more likely to "escape" intermolecular bonds
- thus preferentially the most energetic molecules are lost
- thus unless energy is added to compensate, the water cools

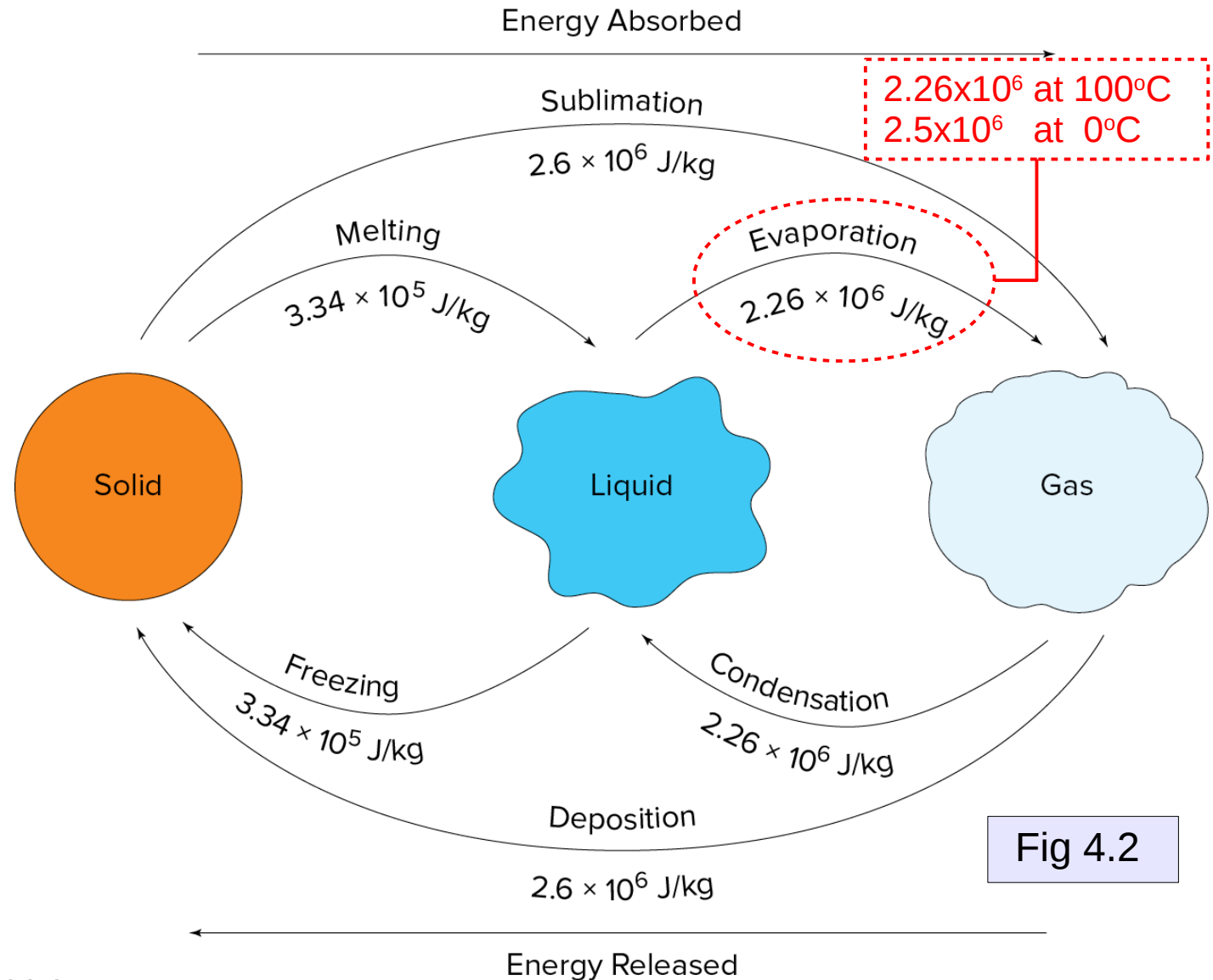


Fig 4.2

### Latent heat of phase change:

$$Q = L m \quad [\text{J}]$$

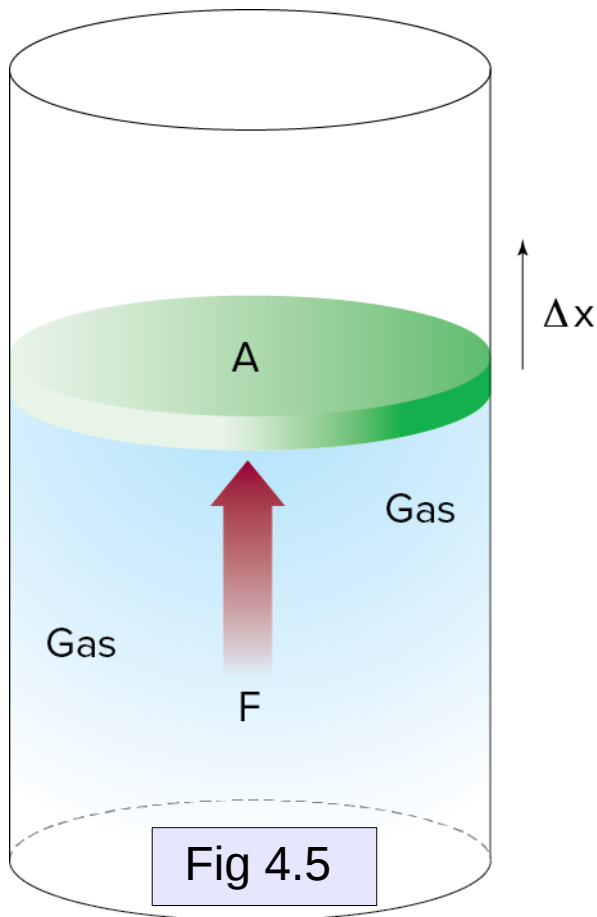
Eqs 4.2a,b

"An expanding (sample of) gas does work because it pushes on its surroundings"

"When a (sample of) gas is compressed, the surroundings have performed work on (it)"

Suppose a fixed mass  $m$  of gas expands by distance  $\Delta x$  – volume change is  $\Delta V = A \Delta x$

The force acting is  $F = P A$  thus the work done is  $W = F \Delta x = P \Delta V$



Work done per unit mass,  $W/m = P (\Delta V)/m$

Introducing the volume per unit mass ("specific volume"),

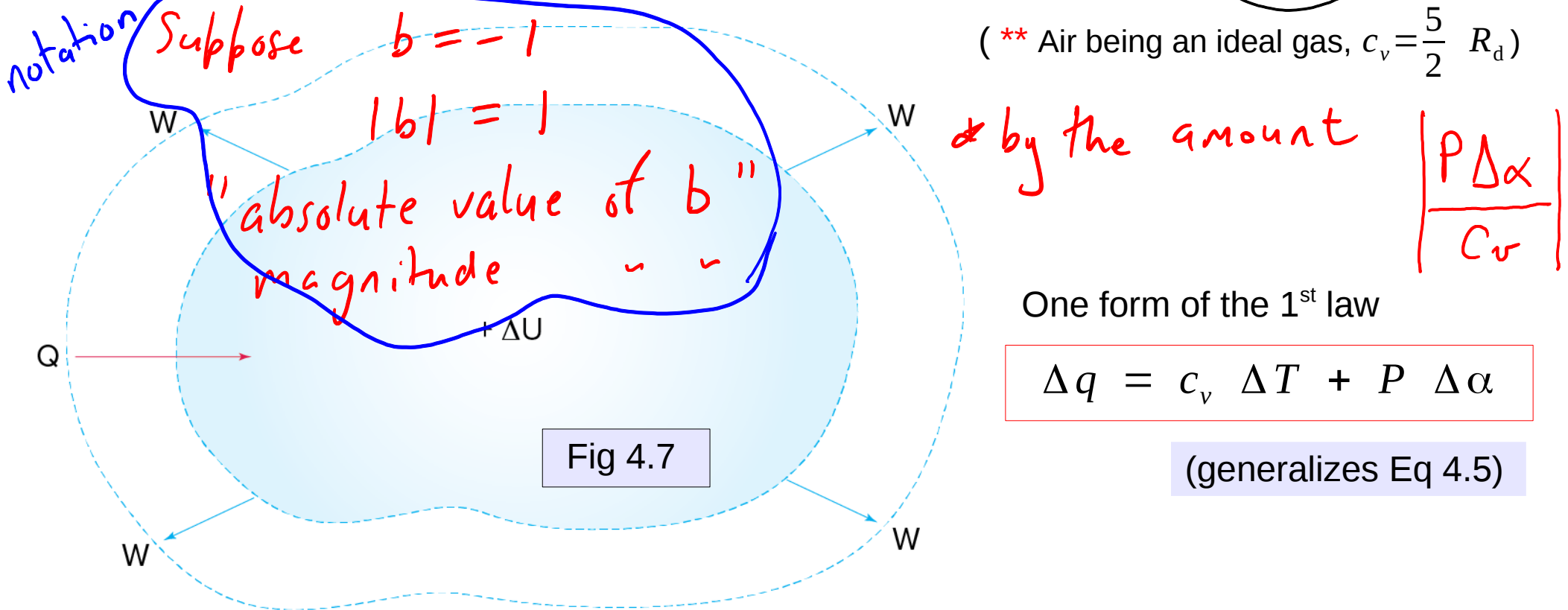
$$\alpha = \frac{V}{m} = \frac{1}{\rho}$$

the work done per unit mass is  $w = P \Delta \alpha$

*Common convention: lower case letters refer to "intensive" quantities (amount per unit mass) and upper case refers to "extensive" quantities (total amount).*

- Let  $\Delta q$  [ $\text{J kg}^{-1}$ ] be heat energy exchanged between a sample of gas ("system") and its "environment"
- Let  $\Delta u = c \Delta T$  be the resulting change [ $\text{J kg}^{-1}$ ] in internal energy of the system. In general, the gas may have expanded (or contracted) in response to  $\Delta q$ , but define  $\Delta q = c_v \Delta T$  as the relationship between  $\Delta q$  and  $\Delta T$  **if** there were no change in volume – then  $c_v$  is (by definition) the specific heat capacity of the gas at constant volume\*\*
- If the sample were allowed to expand, the temperature change would be smaller:

(\*\* Air being an ideal gas,  $c_v = \frac{5}{2} R_d$ )



$$\Delta q = c_v \Delta T + P \Delta \alpha$$

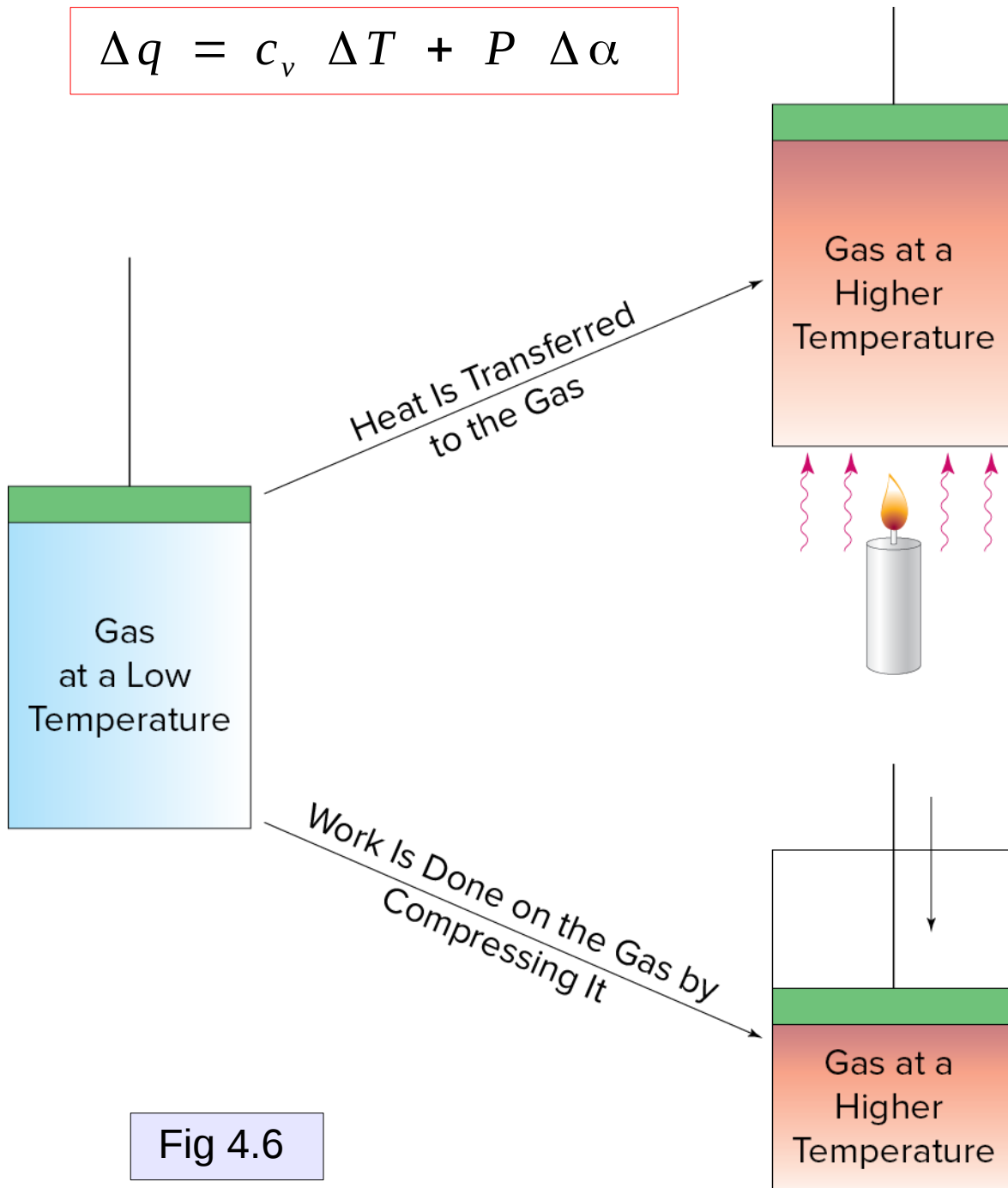


Fig 4.6

Summary: Let  $\Delta q$  [ $\text{J kg}^{-1}$ ] measure (any) energy added/subtracted to/from the system, and let  $\Delta u = c_v \Delta T$  be the change in internal energy. In general, the gas may have expanded (or contracted) in response to  $\Delta q$ , but the diagram represents two special cases:

$$\Delta q > 0, \Delta \alpha = 0 \Rightarrow \Delta T > 0$$

$$\Delta q = 0, \Delta \alpha < 0 \Rightarrow \Delta T > 0$$

Now we will find a second form of the energy conservation law.

There are these two forms of the ideal gas law:

$$P = \rho R_d T$$

$$P \alpha = R_d T$$

Differentiating the second,

$$\Delta(P \alpha) = P \Delta \alpha + \alpha \Delta P = R_d \Delta T$$

Use this result to eliminate  $P \Delta \alpha$  from the 1<sup>st</sup> law,

$$\Delta q = c_v \Delta T + (R_d \Delta T - \Delta P \alpha)$$

But  $c_p$ , the “specific heat capacity of air at constant pressure”, is defined  $c_p = c_v + R_d$  and so we have a second form of the 1<sup>st</sup> law,

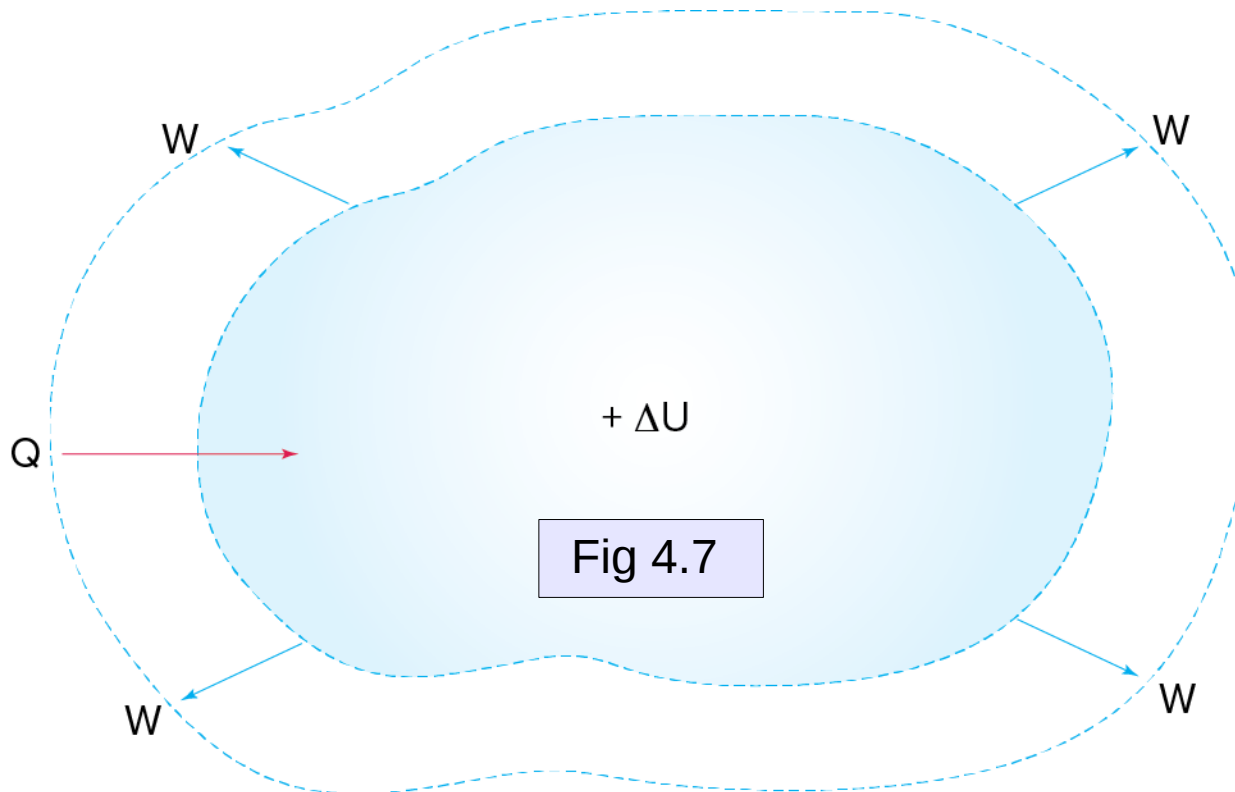
$$\Delta q = c_p \Delta T - \alpha \Delta P$$

c.f. Eq 4.7

$$\Delta q = c_v \Delta T + P \Delta \alpha$$

c.f. (compare with) Eq 4.6

(We'll neglect the distinction between  $T$  and  $T_v$  for present purposes)



Use the 1st law of thermodynamics to establish the connection between (adiabatic) vertical motion of unsaturated air parcels, and their change in temperature

$$\Delta q = c_p \Delta T - \alpha \Delta P$$

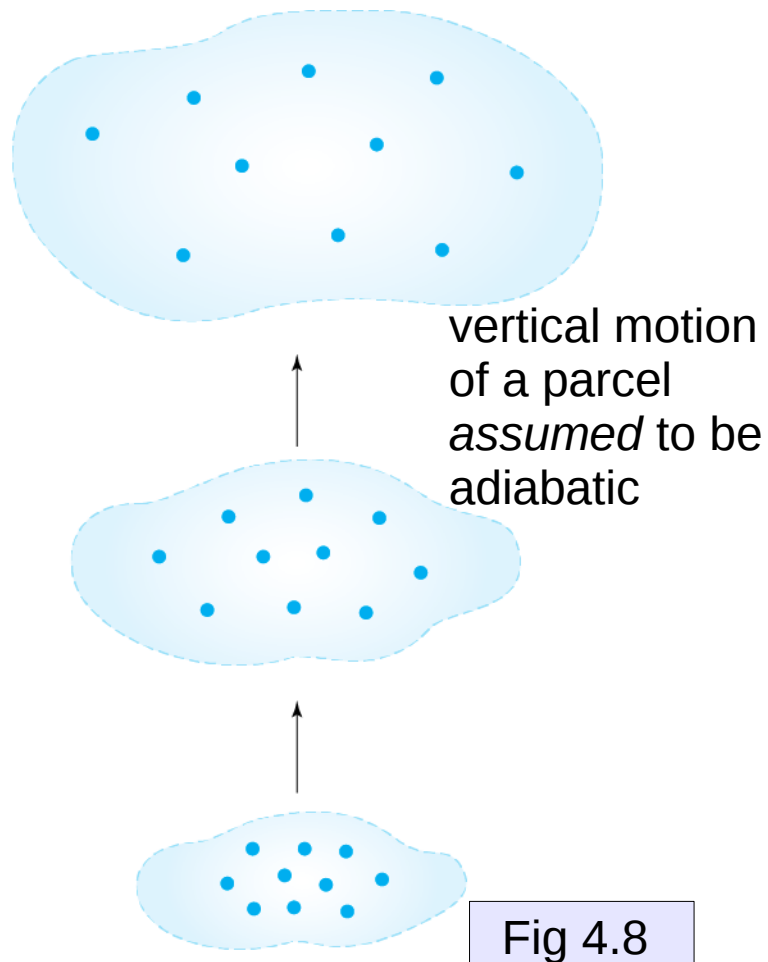


Fig 4.8

$$c_p = c_v + R_d = \frac{7}{2} R_d = 1005 \text{ J kg}^{-1} \text{ K}^{-1}$$

For an adiabatic process ( $\Delta q = 0$ ) with no phase change

$$\Delta q = 0 = c_p \Delta T - \Delta P / \rho$$

Assume hydrostatic relationship between  $P$  and  $z$ :

$$\Delta P = -\rho g \Delta z \quad \left\{ \begin{array}{l} \text{dry} \\ \text{unsaturated} \end{array} \right\}$$

$$0 = c_p \Delta T + g \Delta z \quad \left\{ \begin{array}{l} \text{adiabatic} \\ \text{lapse rate} \end{array} \right\}$$

$$\frac{\Delta T}{\Delta z} = -\frac{g}{c_p} \approx -0.01 \text{ K m}^{-1}$$



If a parcel of air is rising adiabatically, for every increase  $\Delta z = 1 \text{ m}$  in its height, its temperature drops by the amount  $g/c_p \sim 0.01 \text{ K}$

If a parcel at the surface ( $z=700 \text{ m}$ ) has  $T=13^\circ\text{C}$  and it is lifted adiabatically, what is its temperature at  $z=1000 \text{ m}$ ?

And if it sinks again adiabatically to  $900 \text{ m}$ ?

If you decide to ascend a mountain, climbing (say)  $2000 \text{ m}$  from your camp where  $T=5^\circ\text{C}$ , what is a best first guess for  $T$  at the top?  
[Guess is best on a cloudy, windy day]

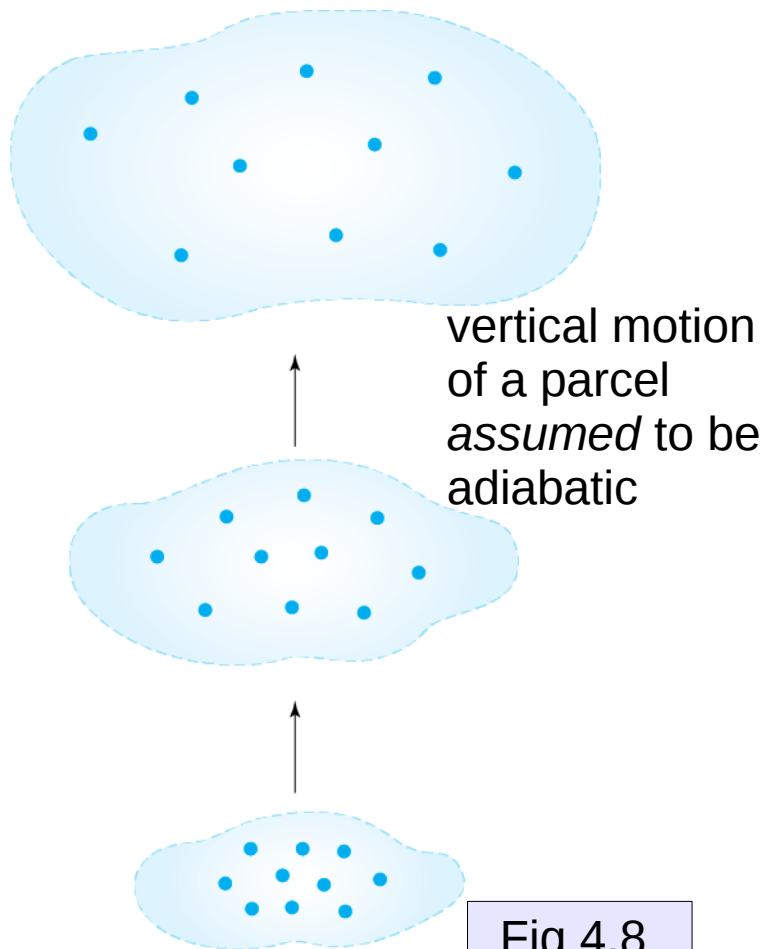


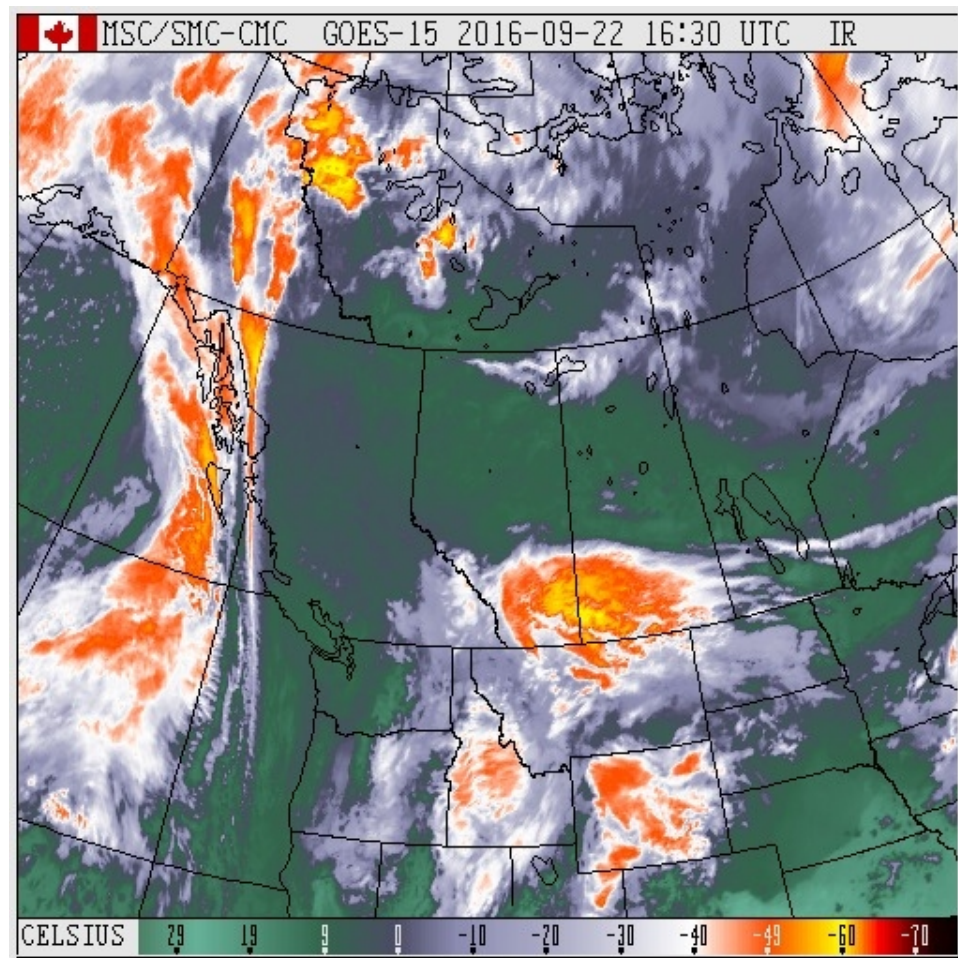
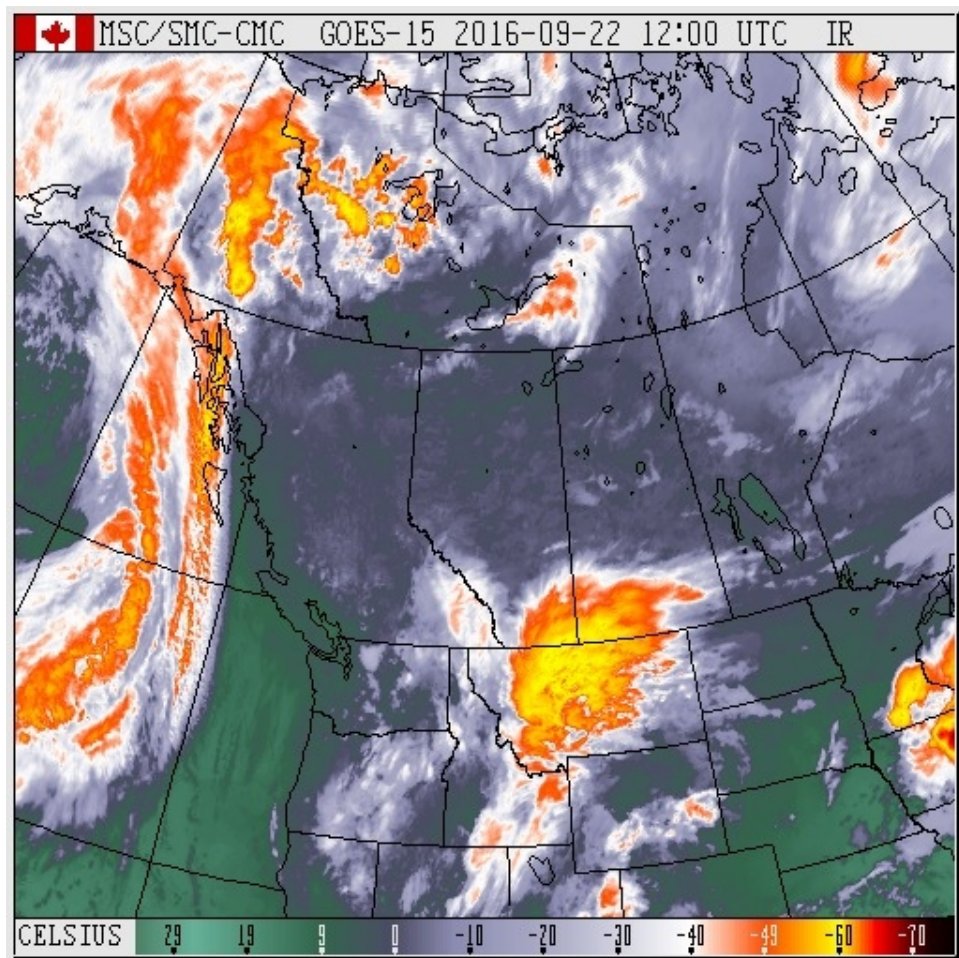
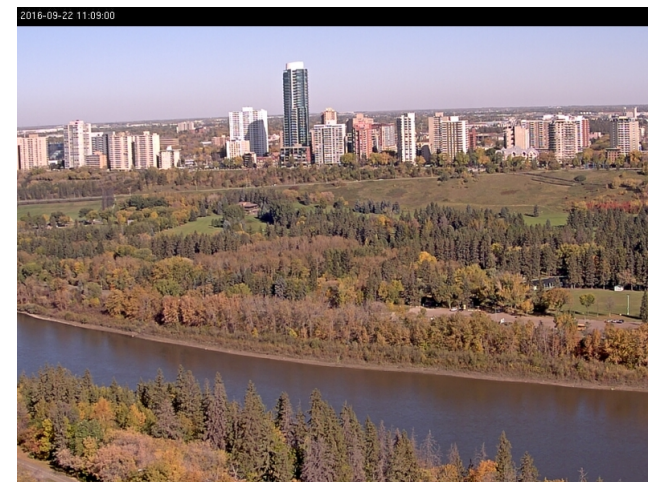
Fig 4.8

# Weather – Thursday 22 Sept. 2016

SIGNIFICANT WEATHER DISCUSSION EC AT 7:00 AM CDT THURS SEPT 22 2016.

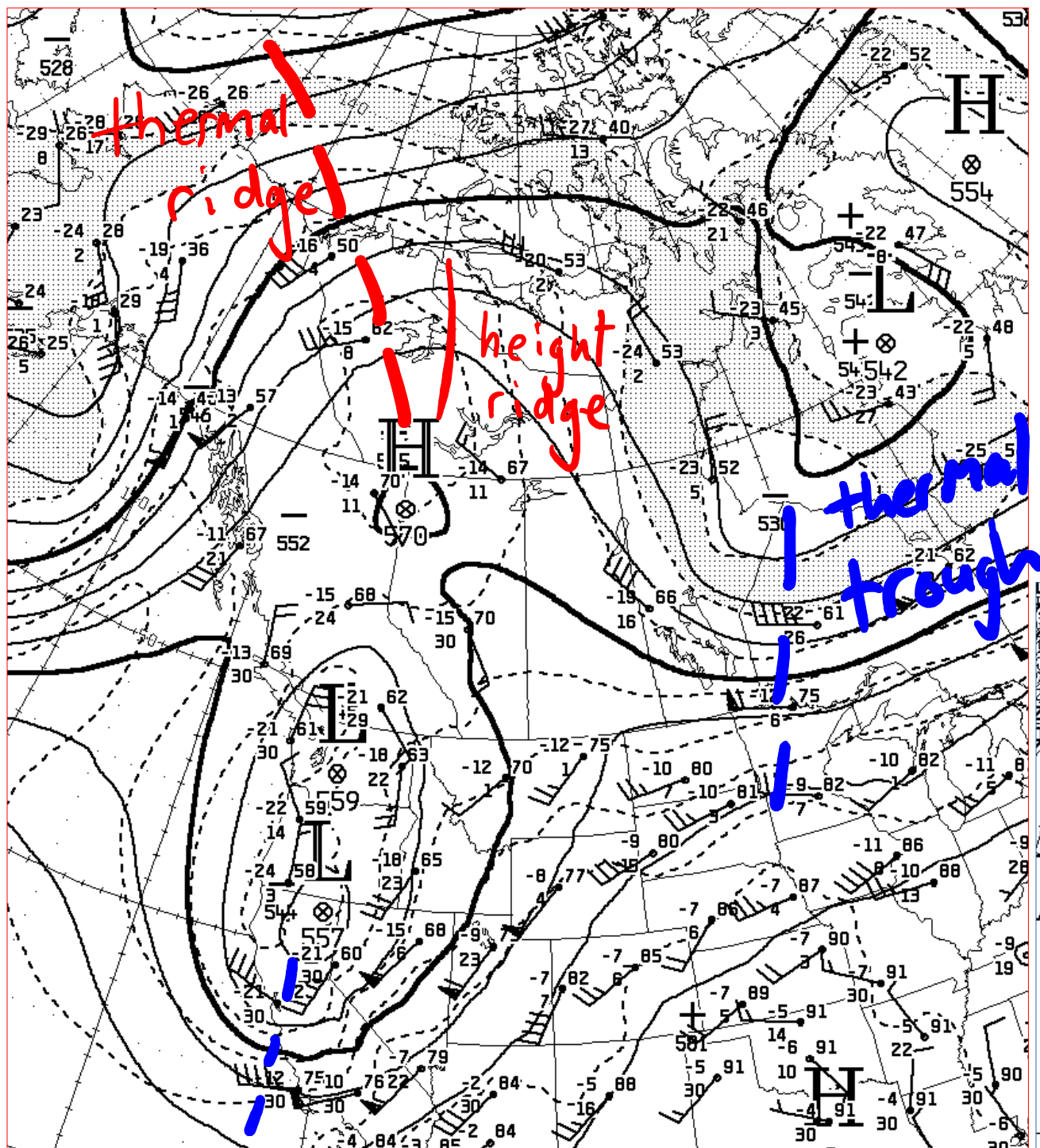
SYNOPTIC OVERVIEW... **UPPER RIDGE** FROM NORTHERN BC AND TO THE NWT MAINLAND. HIGH LEVEL JET FROM IDAHO NORTHEAST ALONG INTL BORDER. DIGGING **UPPER LOW OVER OREGON** WILL... MOVE INTO MONTANA BY SATURDAY.

WESTERN PRAIRIES... MAINLY CLEAR SKIES IN NORTHERN AND CENTRAL ALBERTA OVERNIGHT GAVE BOTH PATCHY FROST AND SOME FOG PATCHES OVERNIGHT. FOG PATCHES SHOULD DISSIPATE BY MID MORNING AND GENERALLY CLEAR AND FAIR CONDITIONS EXPECTED FOR TODAY FOR THE NORTHERN HALF OF ALBERTA WITH RAINFALL EXPECTED TO CONTINUE IN THE EXTREME SOUTH.





# Cropped CMC analyses (500, 700 hPa) for 12Z Thursday 22 Sept. 2016



## Lecture of 23 Sept.

- relevant forms of energy; energy transformations
- two expressions of the first law of thermodynamics covering constant volume and constant pressure processes undergone by ideal gases
- adiabatic processes
- the unsaturated adiabatic lapse rate\*\* of temperature – providing an idealization or "benchmark" for the lapse rate of the observed temperature,  $T=T(z)$  or  $T=T(p)$

\*\* also commonly termed the "dry" adiabatic lapse rate