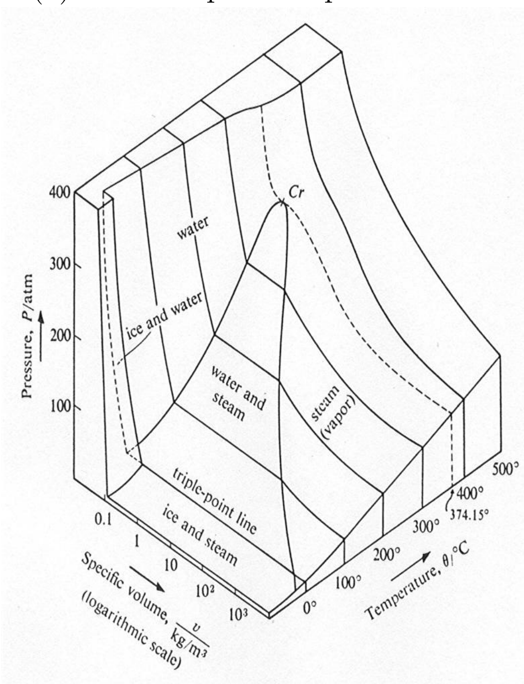
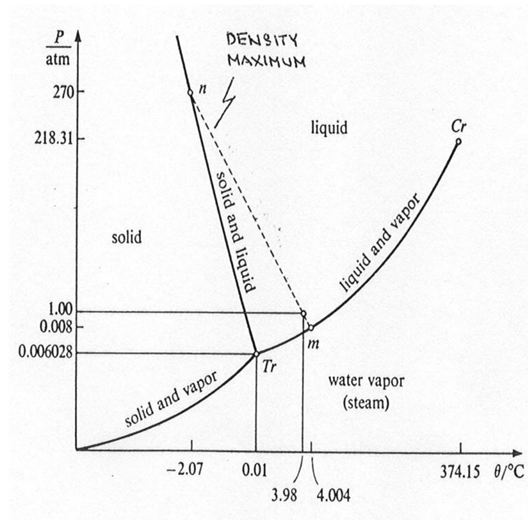
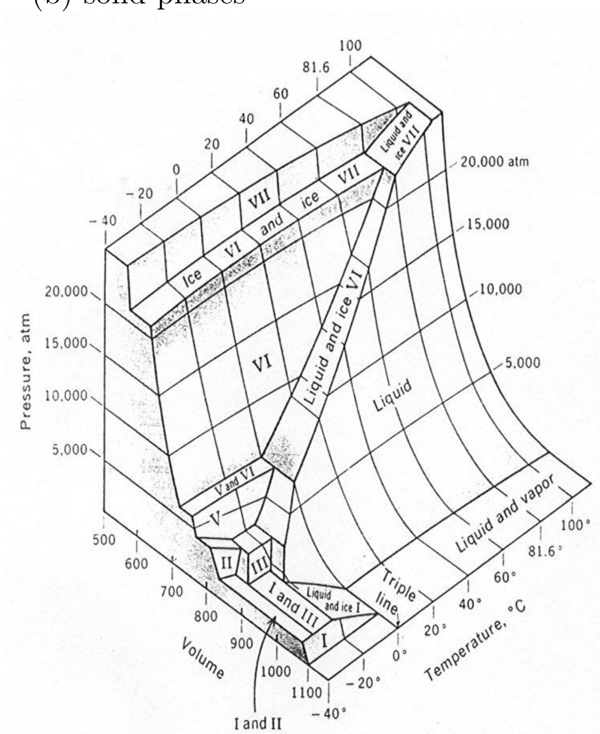
# Phase diagram of $H_2O$ [tsl4]

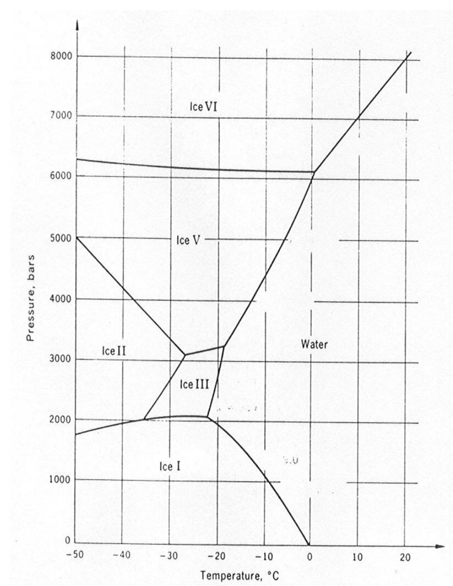
(a) solid – liquid – vapor




(b) solid phases



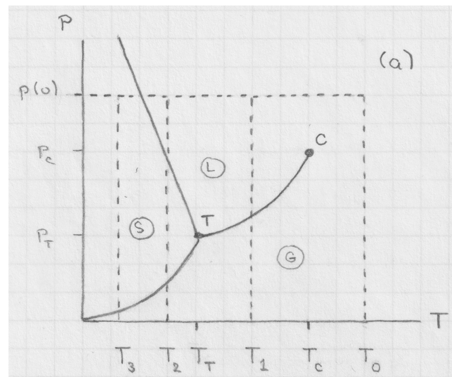



**Effects of a uniform gravitational field:**

Here we briefly discuss density profiles of an infinitely high column of $H_2O$ in a uniform gravitational field.

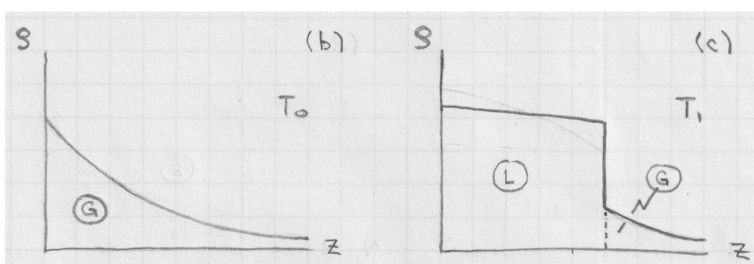
The phase diagram of $H_2O$ in the $(T,p)$-plane is redrawn in panel (a) with additional landmarks.

With coordinate $z$ measuring altitude, the pressure $p(0)$ at the bottom is independent of $T$, here assumed to be larger than $p_C$.




Mechanical stability requires that $p(z)$ is continuous and monotonically decreasing. Otherwise, fluid phases are unstable against convective flow and solid phases against motion propelled by buoyancy.

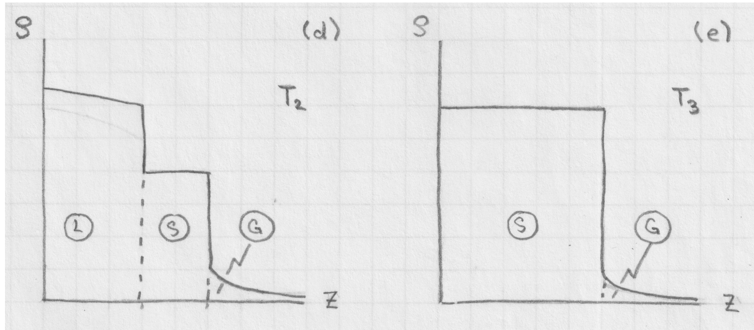
Continuity of density does not follow from continuity of pressure. Discontinuities in density are a common occurrence at phase boundaries. They are caused by cohesive molecular interactions, here the hydrogen bonds between $H_2O$ molecule.




At sufficiently high temperature, e.g. at $T_0$, the column exhibits the standard exponential profile of the isothermal atmosphere as sketched in panel (b).

Upon quasistatic cooling, the density profile changes gradually down to $T_C$. A phase boundary nucleates at the elevation of critical pressure: $p(z) = p_C$. A discontinuity emerges in the density profile, but not in the pressure profile.

Further cooling makes the fluid phase near the bottom look more like a liquid and the fluid phase near the top more like a gas as indicated in panel (c).




At the triple-point temperature $T_\mathrm{T}$, the liquid-gas phase boundary splits into a solid-liquid phase boundary and a solid-gas phase boundary.

A layer of ice of increasing thickness emerges, floating on top of the liquid with the gas on top of the ice. The density at $T_2 < T_\mathrm{T}$, sketched in panel (d), is discontinuous at both phase boundaries.

Further quasistatic heat extraction drives two phase changes: vapor freezes at the upper interface and water freezes at the lower interface. The freezing of water ceases when the latter phase boundary hits bottom.

At yet lower temperatures, e.g. $T_3$, the remaining vapor condenses and freezes into ice as indicated in panel (e).

All these processes are perfectly reversible when we start from $T = 0$ and add heat quasistatically.

Noteworthy points:

- Multiple phase changes can be in process simultaneously.
- Discontinuities can emerge in the middle of smooth density profiles.
- The temperature of coexisting phases (in general) varies while (quasistatic) phase changes are in process.