1.) One way of deducing past climate changes and present climate trends is to examine variations in the mountain snowline altitude, which is roughly indicative of the height of the freezing level. Paleoclimate evidence suggests that tropical mountain snowlines were about 1 km lower at the Last Glacial Maximum (LGM) than at present. How much cooler the oceans were is controversial, with estimates ranging from 1.5-6.5°C; see Greene et al. (2002, *JGR* **107, D8**, ACL 4-1) for an excellent review of the situation. For our purposes, let's take an intermediate value of 2.8°C based on analysis of planktonic foraminifera (Lea et al., 2000, *Science* **289,** 1719) as a good guess. Assume that in the tropics, $\Gamma = \Gamma_m$, and consider a typical current-day surface temperature of 25°C.

a.) Estimate the height of the freezing level in the tropics. Take the value of the moist adiabatic lapse rate at 800 mb (15°C) as being indicative of its mean value over the lower half of the troposphere to simplify your calculations.

b.) The actual freezing level in the tropics is a little lower than 5 km. What does this imply (qualitatively) about the actual lapse rate in the tropical lower troposphere relative to what we have assumed? Offer a specific explanation for the sign of the discrepancy (based on concepts we have discussed).

c.) Ignoring the complication of part (b), derive an expression for the change in freezing height ΔH_f that would accompany a change in surface temperature ΔT_s. If the 800 mb level was 3.5°C cooler at the LGM than at present, is the observed snowline descent consistent with the surface LGM cooling inferred by Lea et al.?

d.) Read the article by Gaffen et al. (2000, *Science* **287**, 1242) to see what has been happening to tropical surface temperatures, lapse rates, and freezing levels in the last two decades. Are recent changes consistent with the ideas used to reconcile inferred changes at the LGM? Are climate changes in the atmospheric thermodynamic structure on decadal time scales controlled strictly by changes in moist convection?

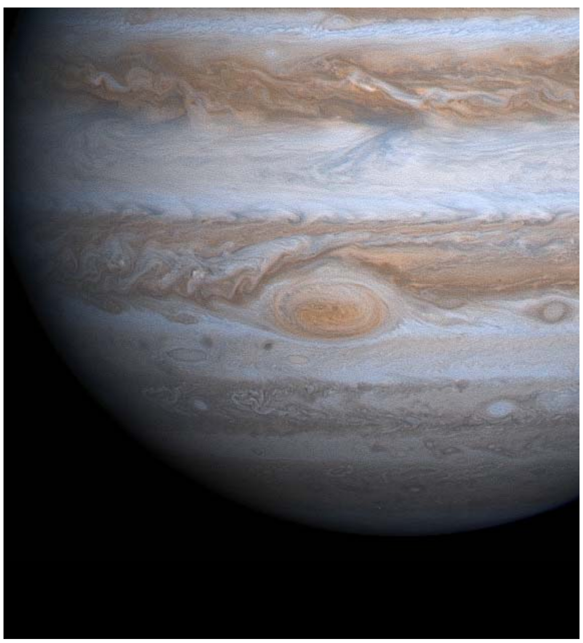
2.) Jupiter's clouds are organized into an alternating pattern of dark bands, called belts, and bright bands, called zones (left figure below). Spacecraft observations suggest that at the level of the visible clouds, a zone-belt horizontal temperature difference of ~ 2K exists. This is difficult to understand, since Jupiter has a strong internal heat source (thought to be mostly primordial heat remaining from gravitational contraction at the time of the planet's formation) and therefore is thought to have ubiquitous convection at levels below the cloud deck, so that θ should be the same everywhere due to the convective mixing rather than varying from one latitude to another. Absorption of sunlight is not the answer, because that would produce primarily a global equator-pole temperature difference. It has been suggested that latent heat release associated with cloud formation is responsible for the 2K contrasts, i.e., it's warmer in regions where the clouds form. But Jupiter's clouds are quite complex, with at least 2 different gases condensing to form clouds: ammonia (NH_3), which forms high-altitude cirrus at ~ 750 mb that are thought to account for much of the cloudiness we see in the images, at least in the bright zones, and water, which condenses at much deeper levels (~5 bar) mostly hidden from view but occasionally becomes visible as deep moist convective storms, usually in the belts; for an example see the right figure below documenting the time evolution of a jovian thunderstorm (the small white feature) near the Great Red Spot (Porco et al., 2003, *Science*, **299**, 1541).

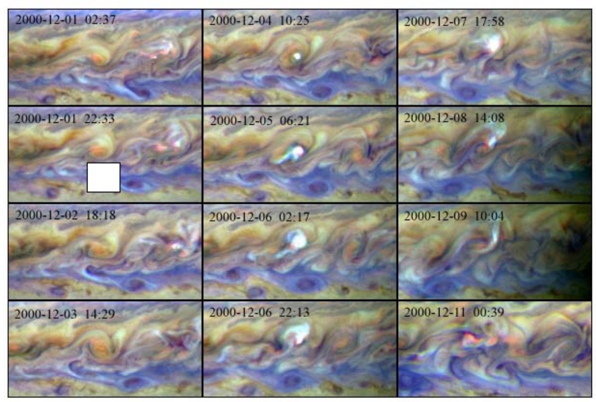
a.) How many scale heights separate the water cloud base and the ammonia clouds at the visible cloud level?

b.) Which of the two types of cloud is more likely to be capable of producing the observed temperature contrasts? Answer this by calculating the maximum possible warming due to condensation of available water vapor or deposition of available ammonia. We don't know the actual abundances of these gases on Jupiter that well, so assume a "solar composition" atmosphere (i.e., abundances consistent with the abundance of the elements N and O in the Sun), implying mass mixing ratios of 9.0 x 10^{-3} (H_2O) and 1.3 x 10^{-3} (NH_3) relative to the dominant H_2-He composition of most of Jupiter's atmosphere. The latent heat of deposition for NH_3 is 1.9 x 10^6 J/kg.

c.) I told you the approximate water cloud base pressure in the introduction to this problem. Now I want you to calculate it yourselves. Estimate the cloud base pressure for the assumed water cloud if the cloud base temperature is 275 K. If the actual abundance of water on Jupiter is enhanced above that for a solar atmosphere ("supersolar"), would you expect the cloud base to be at the same, lower, or higher pressure? Explain.

d.) What is the virtual temperature at the water cloud base? Do virtual effects make water convective clouds more or less buoyant on Jupiter?





3.) The picture below shows vertical profiles of potential temperature and mixing ratio (using the symbol w for what we call ω; the unit g/kg means grams of water vapor per kilogram of dry air, hence ω = .01 is the same as 10 g/kg) observed by radiosondes during various subtropical and tropical ocean field experiments (Albrecht et al., 1995, *JGR*, **100, D7**, 14,209). The altitude scale is normalized by z_i, the height of a temperature inversion (i.e., a thin layer of very small or even negative lapse rate) measured at each location. For this problem focus on the dash-double dot curves labeled "TIWE" that were acquired over the equatorial Pacific. For this location z_i = 1.685 km, corresponding to a pressure of 840 mb. Assume that the surface is at a pressure of 1000 mb and serves as the reference for θ.

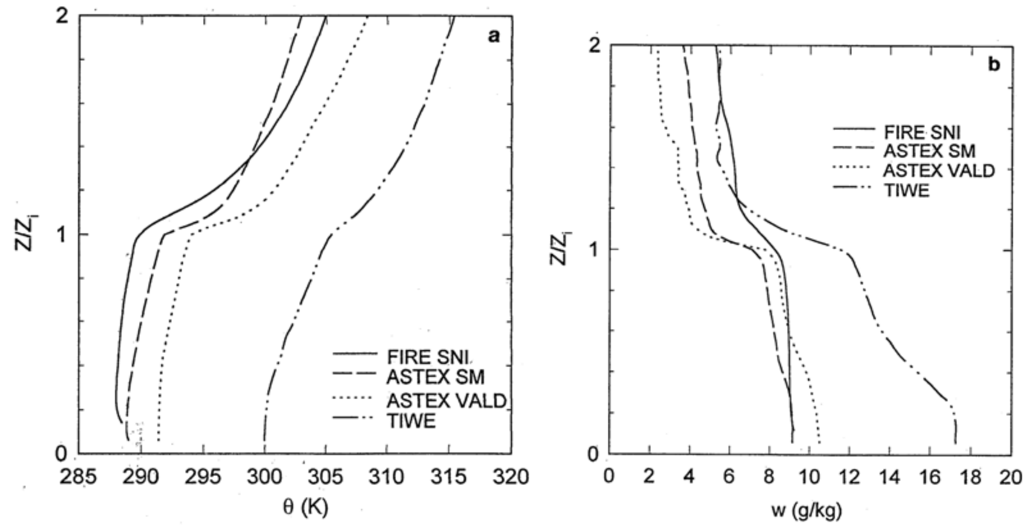


Figure 1. Composite vertical profiles of (a) potential temperature and (b) mixing ratio for San Nicolas Island, Santa Maria, R/V *Valdivia*, and Tropical Instability and Waves Experiment using height scales normalized by the height of the inversion.

a.) Is dry, moist, or no convection happening over the altitude range $z/z_i \sim 0\text{-}0.2$? Explain, and offer an explanation as well for the vertical gradient of w observed over this altitude range.

b.) Repeat part (a) but for the altitude range $z/z_i \sim 0.2\text{-}1.0$. (Assume that p = 965 mb at $z/z_i = 0.2$.)

c.) What is the relative humidity at the inversion level?

d.) Without doing any calculations, would you guess that there is dry, moist, or no convection occurring above the inversion level?