12.818: INTRODUCTION TO ATMOSPHERIC DATA AND LARGE-SCALE DYNAMICS

PROJECT THREE: CONVECTION AND ATMOSPHERIC THERMODYNAMICS

ALI RAMADHAN

In this project we will investigate the nature of convection in the lower troposphere, which is the mechanism responsible for transporting heat from terrestrial radiation vertically upward to the upper troposphere where water vapor concentration and thus infrared absorption is much lower, allowing it to be emitted to outer space.

To carry out this investigation, we will used observed temperature profiles from radiosonde soundings to study the onset of convection in the lower atmosphere.

1 Stability to dry processes

Plotting the given temperature profile for standard atmospheric conditions at the midlatitudes on a full-size (29×21.5 in) skew $T \log P$ graph, we can answer the given questions.

1. The tropopause can be identified as the region where an abrupt change in the lapse rate occurs. By inspection, we see this happens somewhere between 300 hPa to 200 hPa with the reference temperature profile indicating that it occurs at around 225 hPa.

2. We see that dry air is unstable only up to the lifted condensation level and then becomes stable, but moist air is unstable all the way up to 525 hPa at which point it becomes stable.

3. The mixing ratio at 1000 hPa is $9.5\,\mathrm{g\,kg^{-1}}$, and at 500 hPa it is just above $1.5\,\mathrm{g\,kg^{-1}}$ indicating drier conditions as expected.

4. If the surface cools radiatively during the night, the air just needs to cool by $2\,^\circ\mathrm{C}$ for it to reach the same temperature as the dew point and for fog to form.

5. If the air is heated the following day and rises adiabatically, condensation will occur above the lifted condensation level (LCL) which occurs where a lifted air parcel reaches 100% relative humidity. For our temperature profile, this happens around

950 hPa (540 m) where the moist adiabat from the dew point crosses the dry adiabat from the surface temperature.

6. Condensation can continue happening until around 525 hPa at which point the atmosphere becomes stable and convection stops.

Given the saturation vapor pressure e_s as a function of T with 4 data points, (6.11 hPa, 0 °C), (13.0 hPa, 10 °C), (23.4 hPa, 20 °C), and (1000 hPa, 100 °C), we can fit the data points to the phenomenological model $e_s(T) = Ae^{\beta T}$. Doing so provides a perfect looking fit ($R^2 = 1$) with parameter values of $A = 8.419\,\text{hPa}$ and $\beta = 0.0477\,\text{K}^{-1}$ although more data would be nice to ensure that this model holds for all physically realizable atmospheric pressures and obtain a more certain fit. From this model, we can calculate the saturation specific humidity $q_\star$ at 850 hPa using

$$q_\star(p, T) = \frac{\epsilon e_s(T)}{p}$$

where $\epsilon = \dfrac{18}{29}$ is the ratio of water vapor's molecular mass to that of air. We can thus obtain $q_\star(850\,\text{hPa}, 4\,°\text{C}) = 7.4\,\text{g/kg}$ where we took 4 °C to be the temperature at 850 hPa according to the skew T log P diagram we were given.

2 Dry convection

Inspecting the dry deserts of the United States, we notice that Arizona may be a good candidate for looking at dry convection. In particular, we see that Tucson, AZ might be a particularly good example. Figure 1 shows a temperature profile for Tuczon at 0Z (16:00 MST) and 2 shows a temperature profile at 12Z (04:00 MST).

1. Looking at figures 1 and 2 it is hard to see any sharp abrupt changes in the lapse rate to signify the height of the tropopause, however, the lapse rare seems to slow down substantially near 200 hPa at 0Z and around 225 hPa to 250 hPa at 12Z.

2. During the day at 0Z dry air appears to be neutral in the lower tropopause up until roughly 650 hPa indicating a rather large dry convective layer, above which it remains stable. At night (12Z), however, we see a temperature inversion near the surface indicating a highly unstable region up until 850 hPa above which it remains rather stable.

3. During the day at 0Z (figure 1) we see the temperature profile follows an almost perfect dry adiabatic in the lower troposphere, while at night (12Z, figure 2) the surface cools and convection has moved the heat vertically upwards leading to a cooler surface with a warmer boundary layer right above it—a temperature inversion.

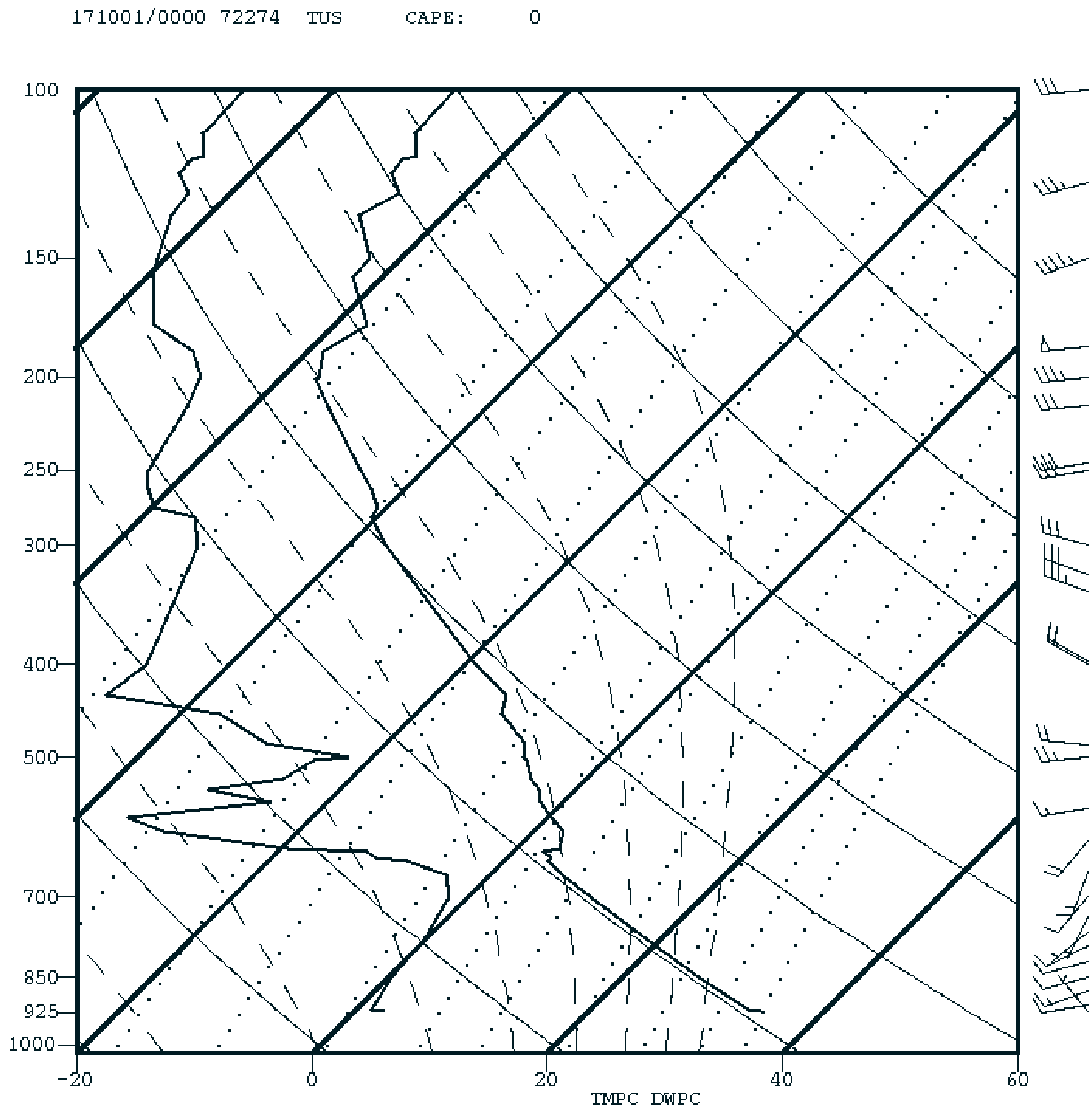

Figure 1: Temperature profile over Tucson, AZ on October 1, 2017 at 0Z (16:00 MST) plotted on a skew T log P graph. Thick solid black lines indicate isotherms or curves of constant temperature. Thin solid black lines indicate dry adiabats, dashed black lines indicate saturated adiabats, and dotted black lines indicate curves of constant saturation mixing ratio.

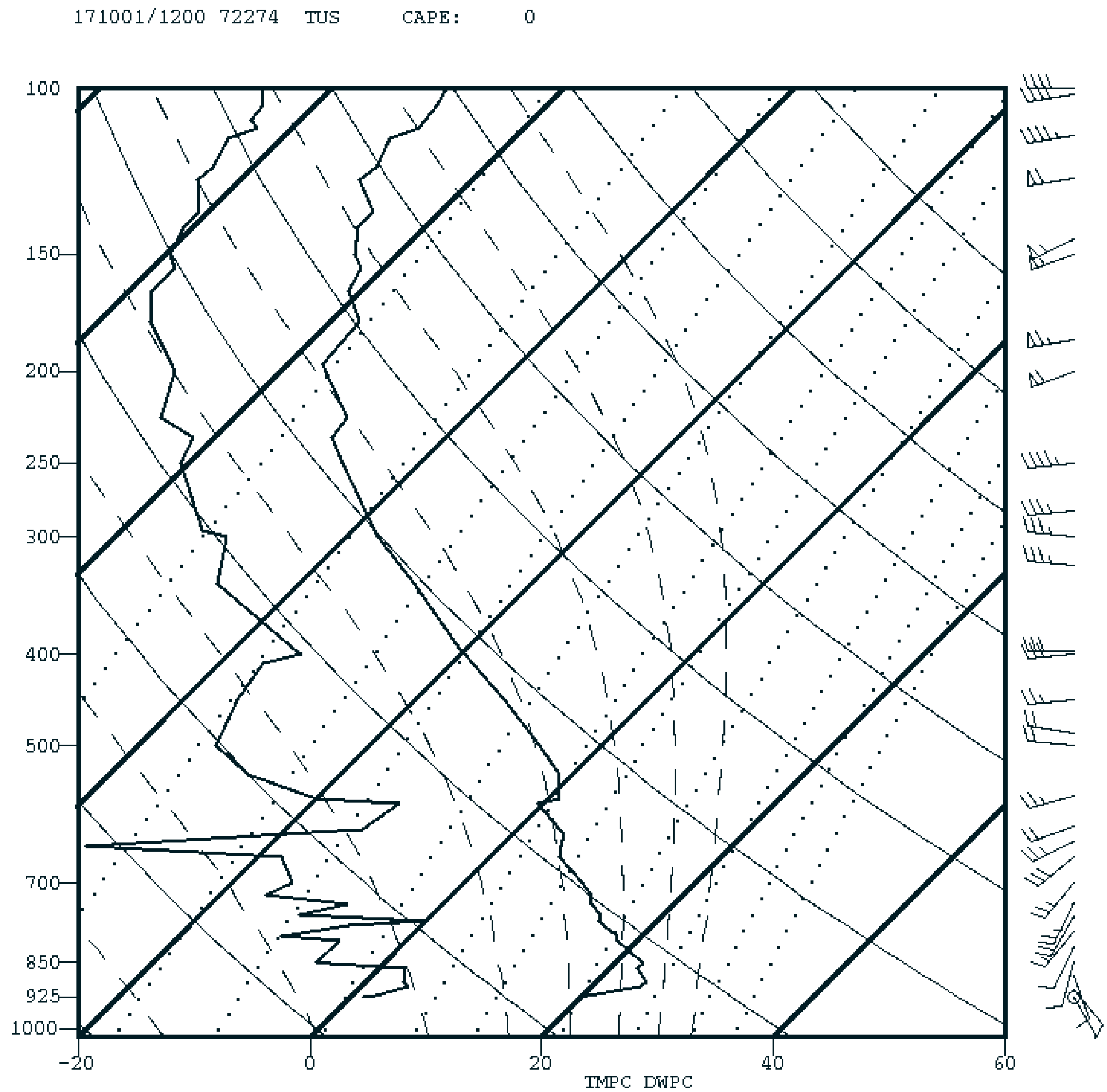

Figure 2: Temperature profile over Tucson, AZ on October 1, 2017 at 12Z (04:00 MST) plotted on a skew T log P graph. Thick solid black lines indicate isotherms or curves of constant temperature. Thin solid black lines indicate dry adiabats, dashed black lines indicate saturated adiabats, and dotted black lines indicate curves of constant saturation mixing ratio.

3 Dry convection case study

Figure 3 shows a temperature profile over Yuma, AZ while figure 4 shows the corresponding potential temperature profile for approximate 2-hour intervals from 11:36 GMT to 21:39

GMT (04:36 to 14:39 MST) on a particular day. $R/c_p = 7/2$ for a dry atmosphere, as it is very closely approximated by an ideal diatomic gas with translation and rotational degrees of freedom, but not vibrational. The potential temperature is expressed as

$$\theta(T,p) = T\left(\frac{p_0}{p}\right)^{R/c_p} \tag{1}$$

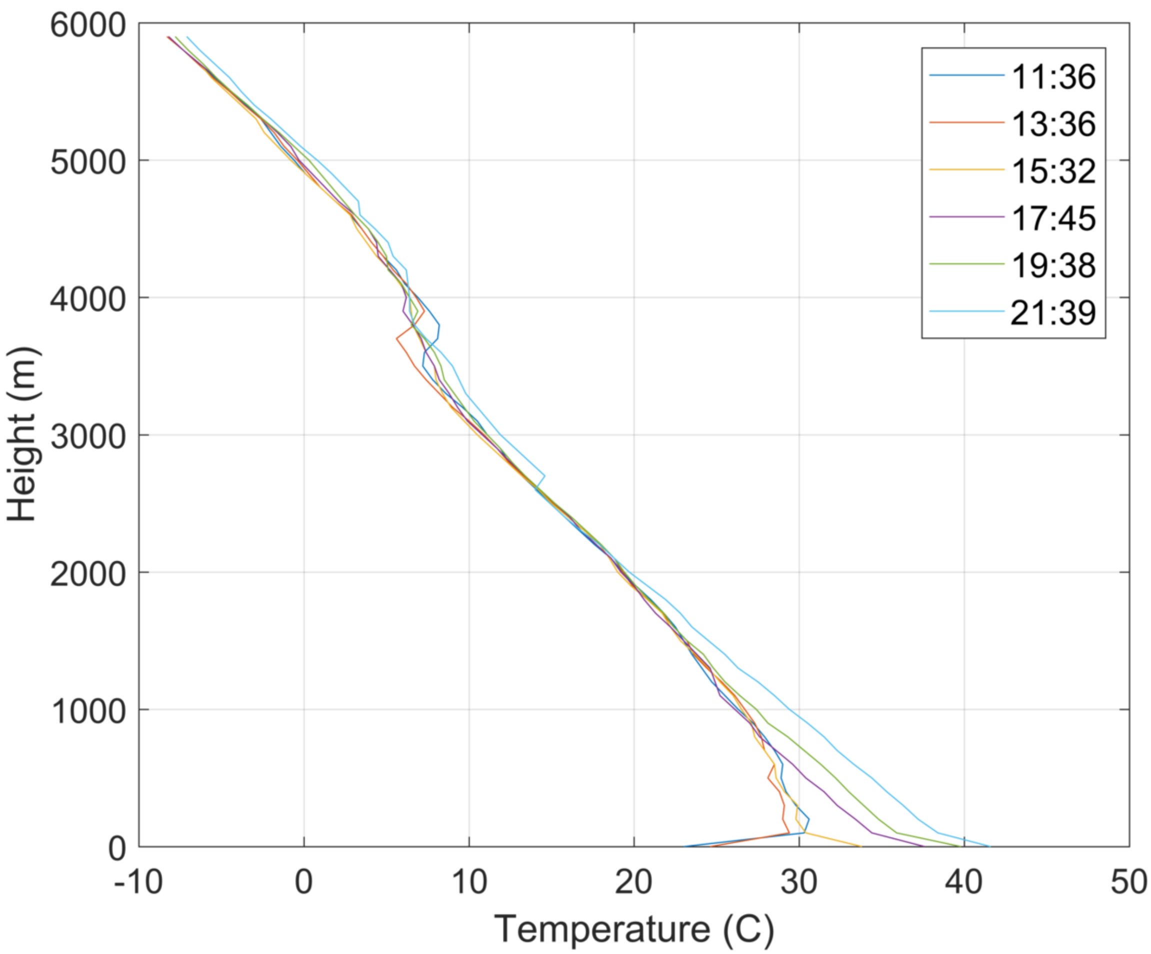

Figure 3: Temperature profile over Yuma, AZ on a particular day from 11:36 GMT to 21:39 GMT (04:36 to 14:39 MST).

Before the sun rises at 11:36 GMT and 13:36 GMT (03:36 and 05:36 MST), we notice a temperature inversion near the surface indicating that radiative cooling has taken place overnight leaving the surface cooler than the warmer air above it. For these two temperature profiles, dry air is highly unstable near the surface but then becomes rather neutral

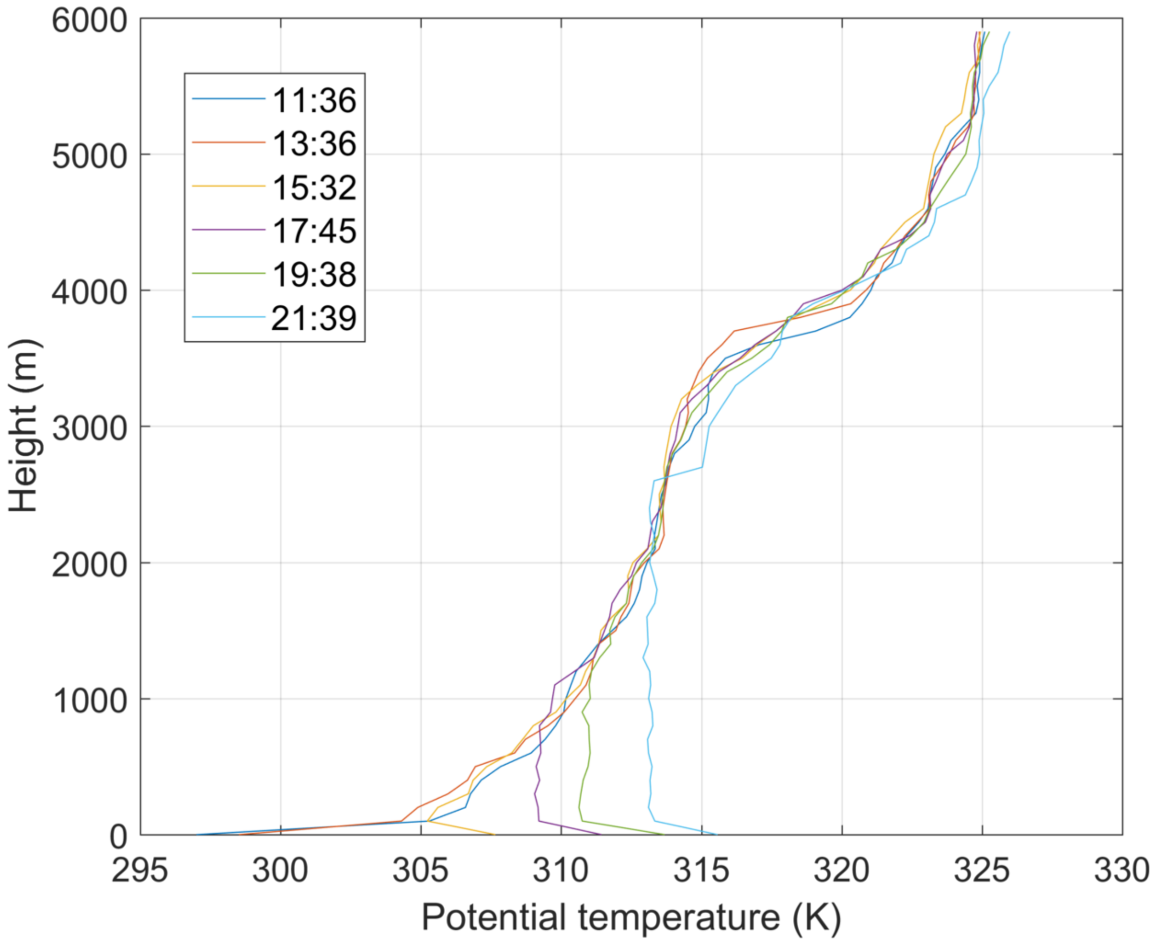

Figure 4: Potential temperature profile over Yuma, AZ on a particular day from 11:36 GMT to 21:39 GMT (04:36 to 14:39 MST).

then stable past the first kilometer.

Once the sun is out at 15:32 GMT (07:32 MST) the surface begins to warm, undoing the temperature inversion that developed overnight. This trend continues throughout the day with the surface getting progressively warmer as indicated by the temperature profiles at 17:45, 19:38, and 21:39 GMT (9:45, 11:38, and 13:39 MST) until the dry air is neutrally buoyant all the way up to 2 km, indicating the presence of large dry convective cells. For these four profiles, we see that dry is still unstable in the lowest layer of the troposphere until it is well past noon with the 21:39 GMT (13:39 MST) profile, at which point the lowest layer is largely neutral. The development of large convective cells during the day increases the thickness of the turbulent boundary layer.

4 Moist convection

For moist convection, we look towards the tropics. In particular, we look at the temperature profile over Cayenne-Félix Eboué Airport in Cayenne, French Guiana (SOCA) just off the Atlantic Ocean in Northern South America bordered by Brazil to the south. Interestingly, French Guiana is a territory that does belong to France and serves as the European Space Agency's primary launch site near the equator.

1. The tropopause height appears to be higher up in the tropics as evidenced by the temperature profiles over Cayenne, French Guiana. At 0Z there is a sharp change in the lapse rate at around 140 hPa and at 12Z it is at around 150 hPa.

2. Moisture drops off exponentially as you go up the atmosphere, however, at 0Z we see some fluctuations between 700 hPa and 500 hPa indicating the presence of moist clouds. At 12Z these fluctuations are gone, instead being replaced by a large dip in dew point at around 500 hPa.

3. At 0Z and 12Z, moist air is unstable all the way up into the tropopause where it becomes stable around 125 hPa.

4. Tracing a saturation adiabat from the lifted condensation level upwards, we can estimate the pressure at the cloud base and cloud top. At 0Z the cloud base is very low, starting at around 925-950 hPa and continuing all the way up to into the tropopause. At 12Z the cloud base is practically at the surface with the cloud top still reaching up into the tropopause.

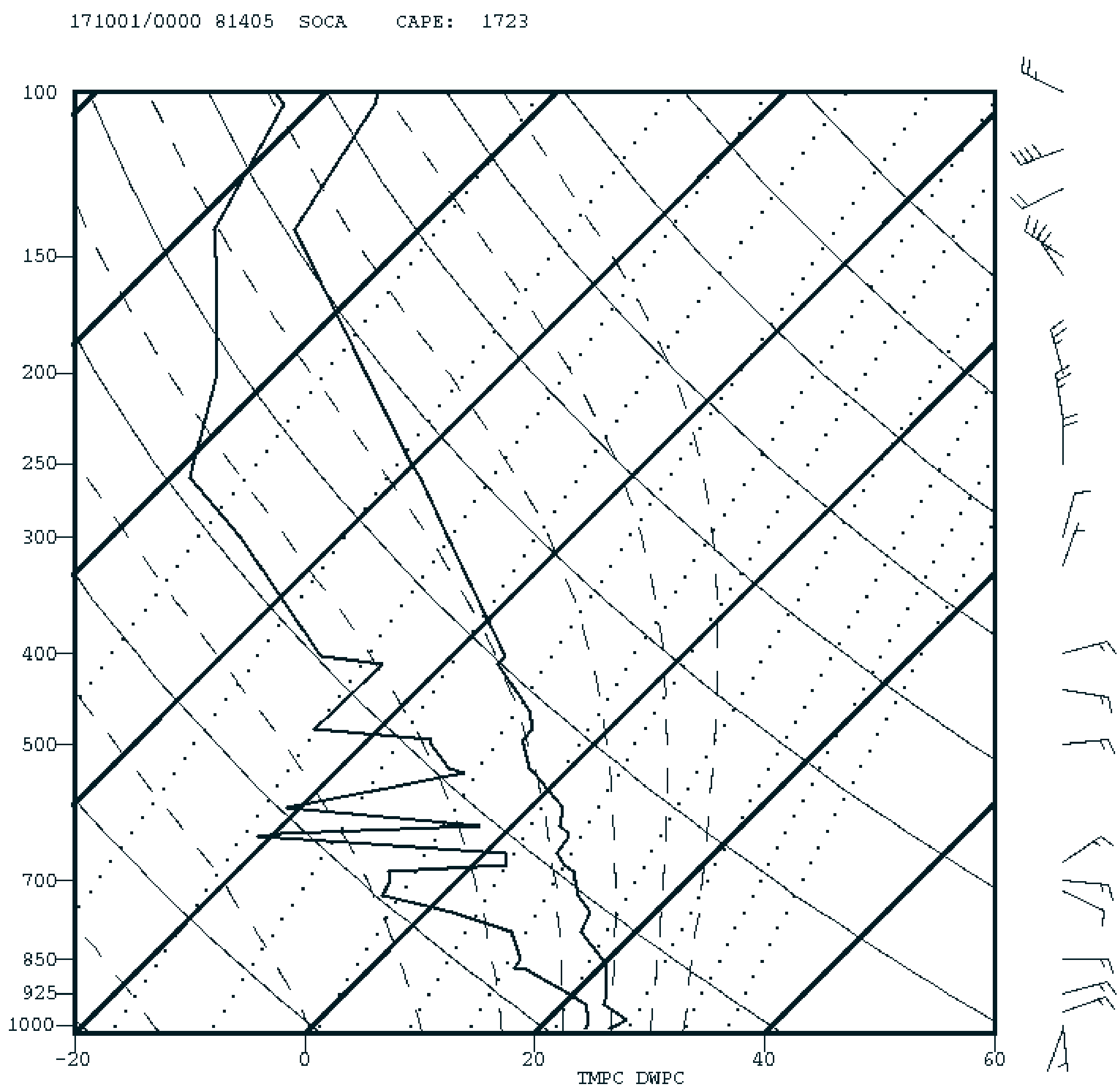

Figure 5: Temperature profile over Cayenne, French Guiana on October 1, 2017 at 0Z (21:00 GFT) plotted on a skew T log P graph. Thick solid black lines indicate isotherms or curves of constant temperature. Thin solid black lines indicate dry adiabats, dashed black lines indicate saturated adiabats, and dotted black lines indicate curves of constant saturation mixing ratio.

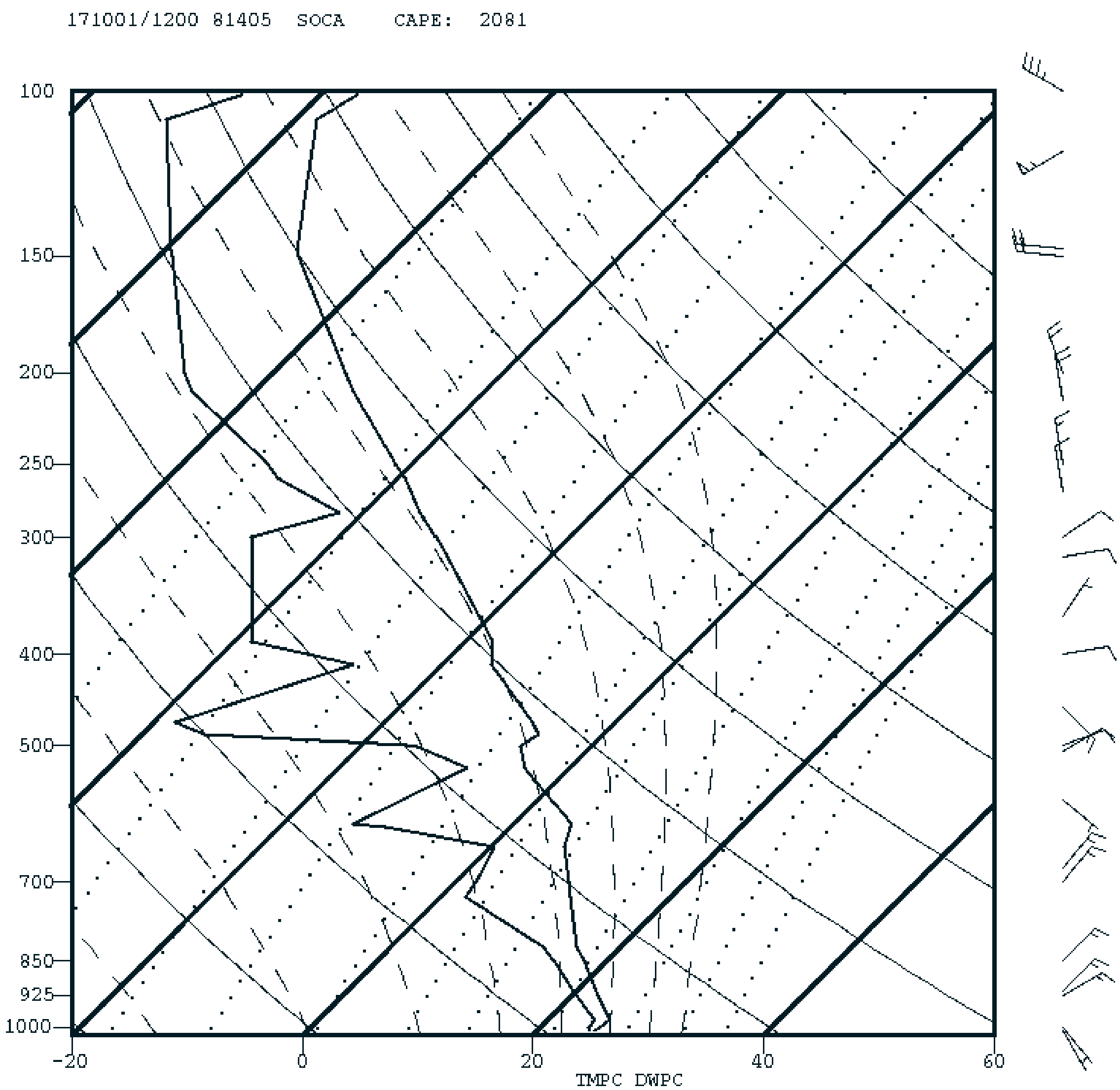

Figure 6: Temperature profile over Cayenne, French Guiana on October 1, 2017 at 12Z (09:00 GFT) plotted on a skew T log P graph. Thick solid black lines indicate isotherms or curves of constant temperature. Thin solid black lines indicate dry adiabats, dashed black lines indicate saturated adiabats, and dotted black lines indicate curves of constant saturation mixing ratio.