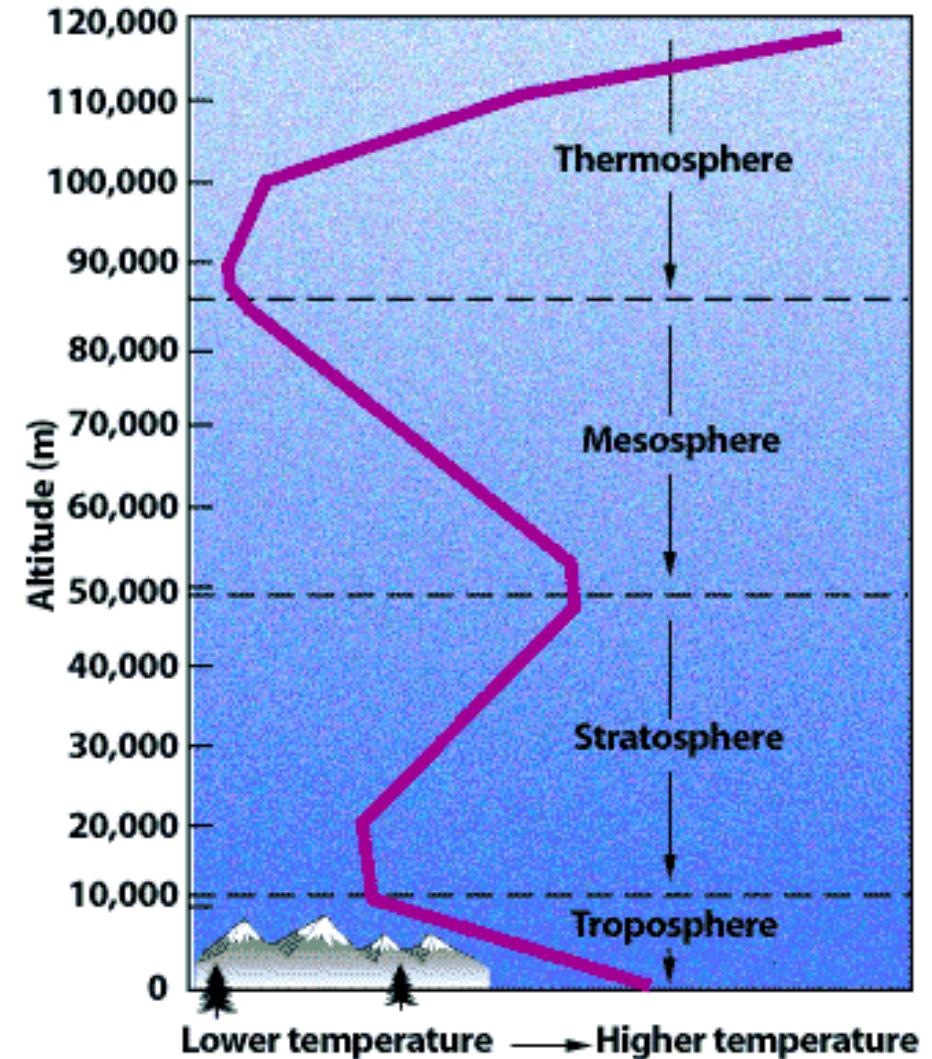


ATMOS_5300 (Fall2020)
Atmospheric Thermodynamics

Dry And Moist Adiabatic Lapse Rate

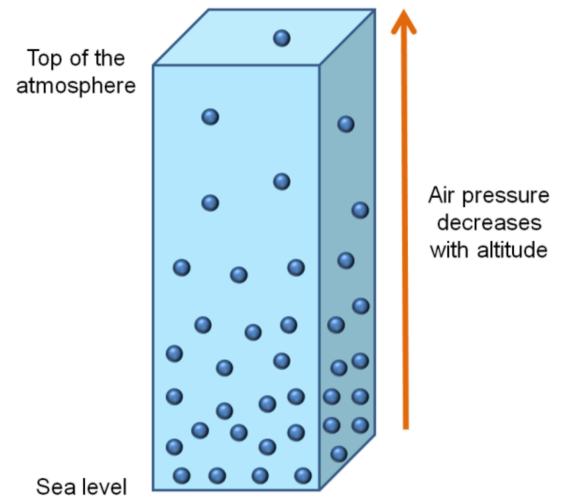
Xia Li
September 25, 2020



Lapse rate is the rate of temperature ~~change~~ with a ~~change~~ in altitude

Three types of lapse rate:

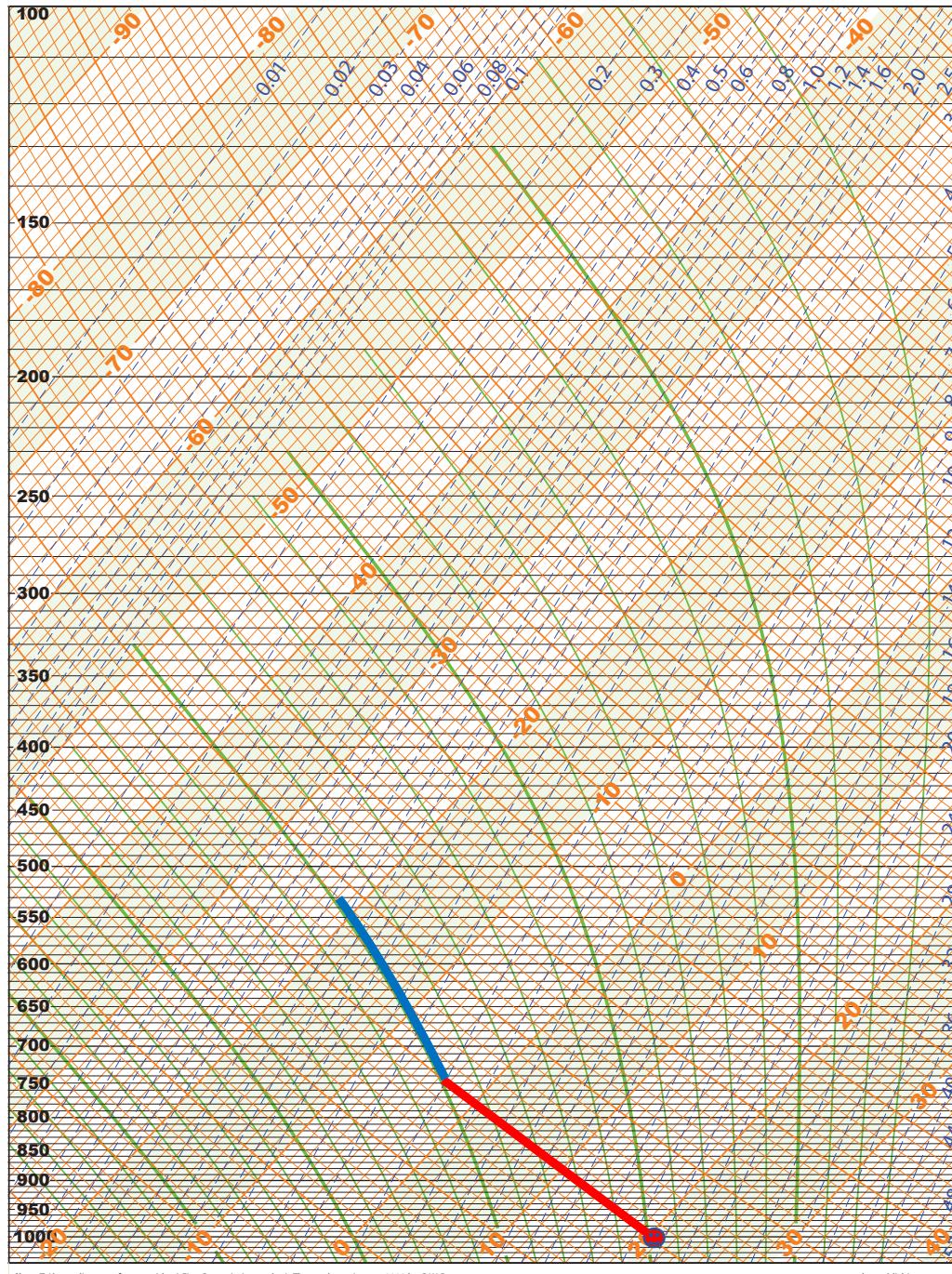
- Dry adiabatic lapse rate
unsaturated air ($RH < 100\%$)
 - Moist (saturation) adiabatic lapse rate
 - Environmental (ambient) lapse rate



Ascending: expands
Descending: compresses

Useful criterion for atmospheric stability

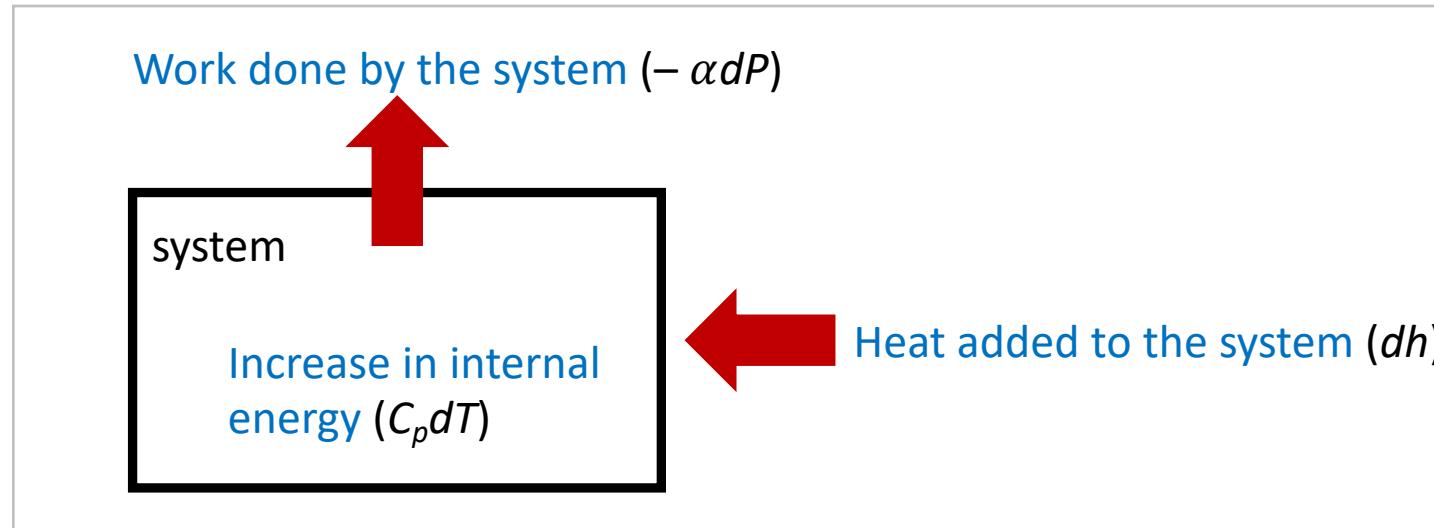
Check the isothermal lines
on Skew T- log P



Where should we start?

The fundamental law: **the first law of thermodynamics**

- Principle of conservation of energy



- One form is:

$$dh = c_p dT - \alpha dp$$

Theoretical dry adiabatic lapse rate

The first law of thermodynamics for a parcel is

$$dh = c_p dT - \alpha dp$$

Our goal: $\frac{dT}{dz} = \dots$

Theoretical dry adiabatic lapse rate

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x : parcel properties

\bar{x} : environmental properties

First, let's try to convert p to z

Assumptions:

- [1] We assume that the pressure of the parcel (p) is always the same as that of the environment (\bar{p}): $p = \bar{p}$

Theoretical dry adiabatic lapse rate

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$$dh = c_p dT - \alpha dp$$

Our goal: $\frac{dT}{dz} = \dots$

x : parcel properties

\bar{x} : environmental properties

First, let's try to convert p to z

Assumptions:

- [1] We assume that the pressure of the parcel (p) is always the same as that of the environment (\bar{p}): $p = \bar{p}$
- [2] The environment is in hydrostatic equilibrium:

$$dp = d\bar{p} = -\frac{1}{\alpha}g dz \quad (1)$$

Theoretical dry adiabatic lapse rate

Use Eq.1 in the first law to obtain

$$dh = c_p dT + \frac{\alpha}{\bar{\alpha}} g dz$$

Theoretical dry adiabatic lapse rate

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$$dh = c_p dT + \frac{\alpha}{\bar{\alpha}} g dz$$

To further simplify, considering that typically, temperature fluctuations in the horizontal are $O(1K)$, at most 10 K, so that

$$P\alpha = RT_v$$

$$\bar{P}\bar{\alpha} = R\bar{T}_v$$

$$\frac{\alpha}{\bar{\alpha}} = \frac{T_v}{\bar{T}_v} \approx 1$$

Now we have a good approximation the first law of thermodynamics for a parcel in a hydrostatic environment:

$$dh = c_p dT + g dz \tag{2}$$

Theoretical dry adiabatic lapse rate $dh = c_p dT + g dz$ (2)

For unsaturated dry air, no heat is added or lost during the adiabatic process,

$$dh = 0$$

Theoretical dry adiabatic lapse rate

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Therefore, the dry adiabatic form of Eq. (2):

$$0 = c_p dT + g dz$$

The lapse rate for a dry-adiabatic process is thus,

$$\Gamma_d \equiv -\frac{dT}{dz} = \frac{g}{c_p}$$

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$$g = 9.81 \text{ m s}^{-2}$$

$$c_p = 1004 \text{ J kg}^{-1} \text{ K}^{-1}$$

Lets do the calculation!

Theoretical dry adiabatic lapse rate

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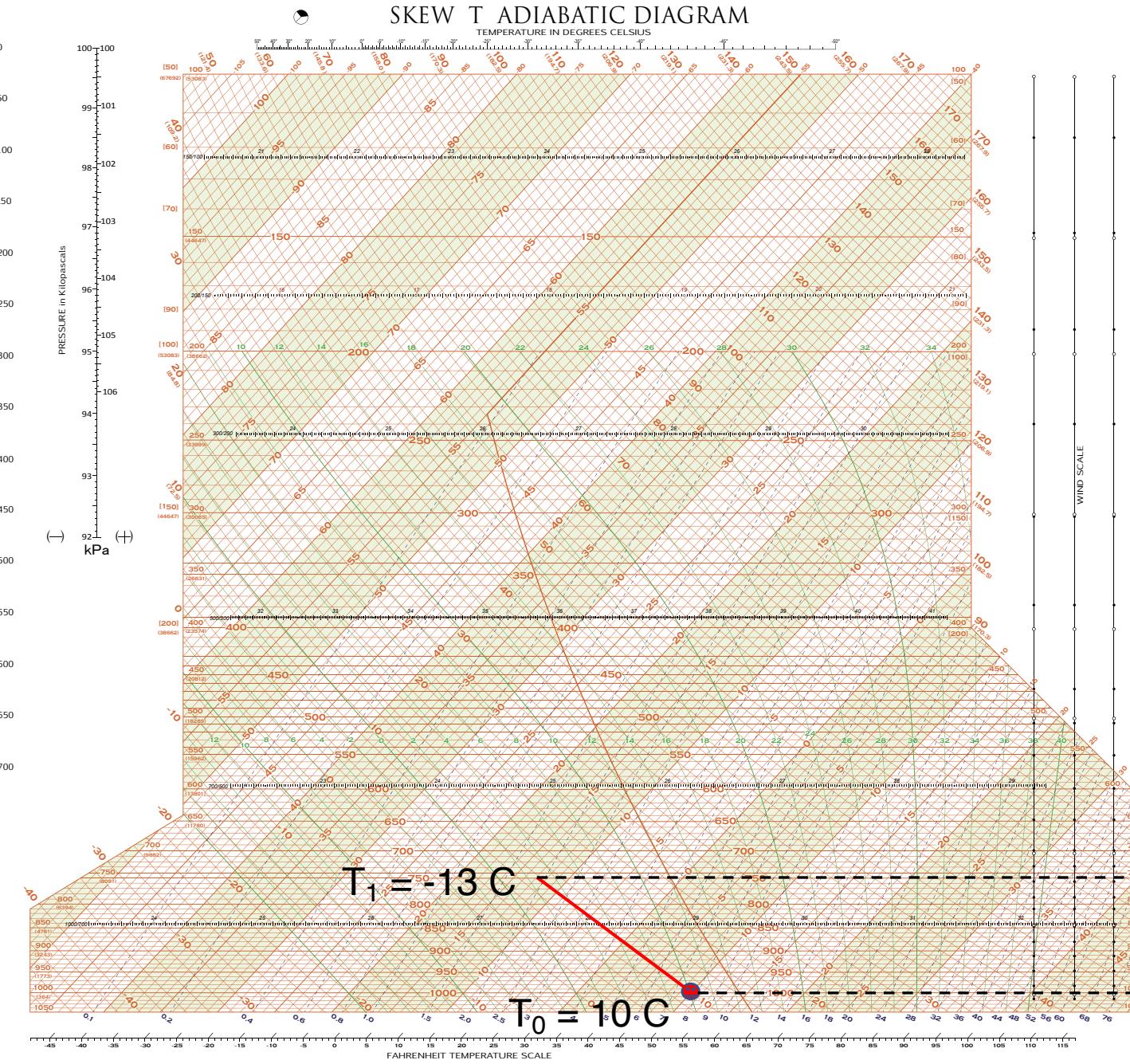
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$$c_p = 1004 \text{ J kg}^{-1} \text{ K}^{-1}$$

kft

Γ_d for dry air is 9.76 K km^{-1} (5.4 F feet^{-1})

Let's check it at the Skew ~~T-log~~ P diagram



EXPLANATION
ISOBARS are straight horizontal brown lines. The heights in feet of the pressure surfaces in the U.S. Standard atmosphere are in parentheses () below the pressure values on the left.

ISOTHERMS ($^{\circ}\text{C}$) are the straight, equidistant brown lines running diagonally downward from right to left.

DRY ADIABATS are the slightly curved brown lines that intersect the 1000 mb isobar at intervals of 2°C , and run diagonally upward from right to left. The Dry Adiabats of the folded portion of the pressure range are labeled with their values.

SATURATED ADIABATS are the curved green lines that intersect the 1000 mb isobar at intervals of 2°C , diverging upward and tending to become parallel to the isobars.

SATURATION MOISTURE RATIO (in gm. per kg.) is represented by dashed green lines. Their values appear at the bottom of diagram.

THICKNESS (in hundreds of geopotential meters) of the layers between the levels 1000, 700, 500, 300, 200, and 100 mb is represented by numbers placed near the upper boundary of each layer. The thickness is derived from the virtual temperature curve by the equal-area method, using any straight line as a dividing line.

HEIGHT (in meters above mean sea level, or station level) of the 100 hPa surface is obtained from the nomogram in the upper left-hand corner by drawing a straight line from the point on the temperature scale ($^{\circ}\text{C}$) through the 100 hPa surface to the pressure on the pressure scale, and reading the height on the height scale.

U.S. STANDARD ATMOSPHERE SOUNDING is indicated by a thick brown line.

The saturated adiabats and equations of saturation mixing ratio are computed by use of vapor pressure over a plane water surface at all temperatures.

Extension of chart to 50 mb has been accomplished by overlap with pressure indicated in brackets [200] at 400 mb, and [50] at 100 mb. Dry adiabats of the overlap are shown.

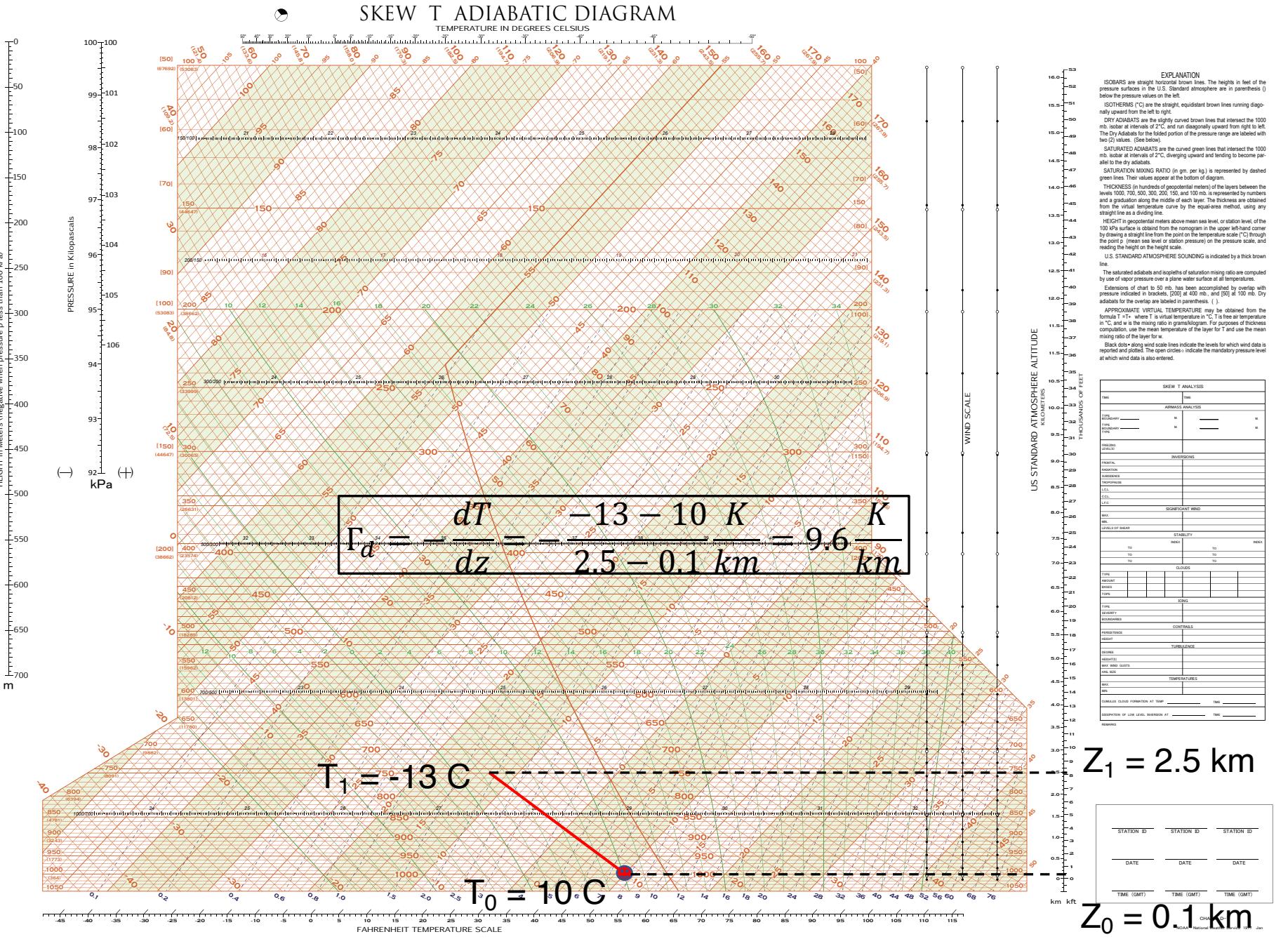
APPROXIMATE VIRTUAL TEMPERATURE may be obtained from the formula $T_v = T + \frac{w}{w+1}$, where T is virtual temperature in $^{\circ}\text{C}$, T is free air temperature in $^{\circ}\text{C}$, and w is the mixing ratio in grams/kilogram. For purposes of thickness computation, virtual temperature of the layer for T_v and the mean mixing ratio of the layer for w .

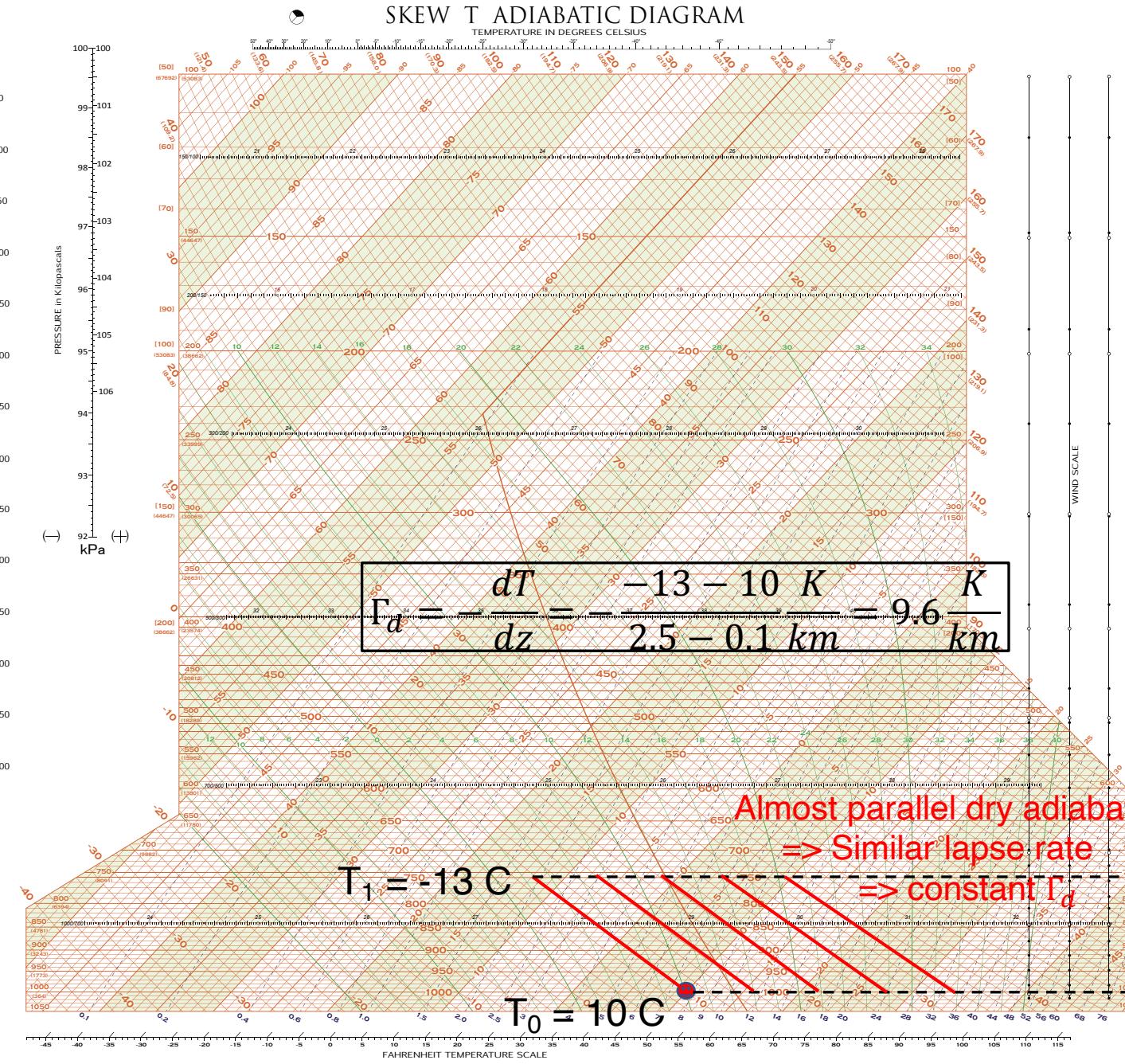
Black dots along wind scale lines indicate the levels for which wind data is reported. Vertical dashed lines indicate the mandatory pressure level at which wind data is also entered.

SKEW T ANALYSIS	
ARMED FORCES	
TYPE	W
TYPE	W
TYPE	W
PHASES	
WINDS	
INVERSIONS	
FRONTAL	
RADIATION	
CONVECTION	
TROPOPAUSE	
LCL	
LFC	
LIFC	
WIND	
MAX	
MIN	
LEVELS OF SHEAR	
STABILITY	
INDEX	
TO	
TO	
TO	
TO	
CLOUDS	
AMOUNT	
TYPE	
SEVERITY	
BOULDERS	
PERSISTENCE	
HEIGHT	
DEBRIS	
FLASH FLOODS	
WHL. WINDS	
MAX	
MIN	
CUMULUS CLOUD FORMATION AT TEMP	
TIME	
DETECTION OF LOW LEVEL INVERSION AT	
TIME	
REMARKS	

STATION ID	STATION ID	STATION ID
DATE	DATE	DATE
TIME (GMT)	TIME (GMT)	TIME (GMT)

$Z_0 = 0.1 \text{ km}$





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SKEW T ANALYSIS	
AMBIENT ANALYSIS	
TYPE	
TEMP.	
HUMIDITY	
WIND	
PHYSICAL	
WIND	
INVERSIONS	
FRONTAL	
RADIATIONAL	
CONVECTIVE	
ADIABATIC	
STABILITY	
LCL	
LFC	
LIFC	
SIGNIFICANT WIND	
MAX.	
MIN.	
LEVELS OF SHEAR	
STABILITY	
INDEX	INDEX
T0	T0
T1	T1
T2	T2
CLOUDS	
TYPE	
AMOUNT	
TYPE	
TYPE	
TYPE	
SEVERITY	
BOULDER	
PERSISTENCE	
HEIGHT	
DEGREE	
ASPECT	
MIL. DIST.	
MAX.	
MIN.	
CUMULUS CLOUD FORMATION AT TEMP	TEMP
DETECTION OF LOW LEVEL INVERSION AT	TEMP
REMARKS	

STATION ID	STATION ID	STATION ID
DATE	DATE	DATE
TIME (GMT)	TIME (GMT)	TIME (GMT)

km kft

$Z_0 = 0.1 \text{ km}$

Moist adiabatic lapse rate

Theoretical moist adiabatic lapse rate

Back to the first law of thermodynamics for a parcel in a hydrostatic environment:

$$dh = c_p dT + g dz$$

As saturated air ascends \Rightarrow water vapor begins to condense and release the latent heat of condensation \Rightarrow rate of cooling changes

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As saturated air ascends \Rightarrow water vapor begins to condense and release the latent heat of condensation \Rightarrow rate of cooling changes

Therefore, $dh \neq 0$, and released latent heat is added to the parcel:

$$dh = -Ldw = -Ldw_s$$

Theoretical moist adiabatic lapse rate

$$dh = c_p dT + g dz \quad (2)$$

Therefore, $dh \neq 0$, and released latent heat is added to the parcel:

$$dh = -Ldw = -Ldw_s$$

$$L = 2.5 \times 10^6 \text{ J kg}^{-1}$$

dw mass changes in water vapor

Eq. (2) changes to:

$$-L dw_s = c_p dT + g dz. \quad (3)$$

Theoretical moist adiabatic lapse rate

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Now, the main problem is dw_s

We know that w_s is a function of pressure and temperature, $w_s = w_s(p, T)$.

Theoretical moist adiabatic lapse rate

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Let's first expand dw_s to:

$$dw_s = \left(\frac{\partial w_s}{\partial p} \right)_T dp + \left(\frac{\partial w_s}{\partial T} \right)_p dT$$

Theoretical moist adiabatic lapse rate

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$$dw_s = \left(\frac{\partial w_s}{\partial p} \right)_T dp + \left(\frac{\partial w_s}{\partial T} \right)_p dT$$

Substitute this into (3),

$$-L \left[\left(\frac{\partial w_s}{\partial p} \right)_T dp + \left(\frac{\partial w_s}{\partial T} \right)_p dT \right] = c_p dT + g dz$$

Theoretical moist adiabatic lapse rate

Recall that

$$-L \left[\left(\frac{\partial w_s}{\partial p} \right)_T dp + \left(\frac{\partial w_s}{\partial T} \right)_p dT \right] = c_p dT + gdz$$

$$dp = d\bar{p} = -\frac{1}{\bar{\alpha}} g dz$$

$$\frac{\alpha}{\bar{\alpha}} \approx 1$$

Substitute the above two and divide the result by $c_p dz$ to obtain:

Need your help!

Theoretical moist adiabatic lapse rate

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Substitute the above two and divide the result by $c_p dz$ to obtain:

$$-\frac{L}{c_p} \left[- \left(\frac{\partial w_s}{\partial p} \right)_T \rho g + \left(\frac{\partial w_s}{\partial T} \right)_p \frac{dT}{dz} \right] = \frac{dT}{dz} + \frac{g}{c_p}$$

Theoretical moist adiabatic lapse rate

Then solve for dT/dz to obtain the lapse rate for a saturation-adiabatic process,

$$\Gamma_s \equiv -\frac{dT}{dz} = \frac{g}{c_p} \frac{1 - \rho L \left(\frac{\partial w_s}{\partial p} \right)_T}{1 + \frac{L}{c_p} \left(\frac{\partial w_s}{\partial T} \right)_p} \quad (4)$$

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and the *Clausius-Clapeyron equation* for e_s ,

$$\frac{de_s}{dT} = \frac{Le_s}{R_v T^2}$$

Only a function of Temperature
Nice!

Then solve for dT/dz to obtain the lapse rate for a saturation-adiabatic process,

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$$\frac{de_s}{dT} = \frac{Le_s}{R_v T^2}$$

where R_v is the gas constant of water vapor ($461.5 \text{ J kg}^{-1} \text{ K}^{-1}$), $R = R_d$ is gas constant of dry air ($287 \text{ J kg}^{-1} \text{ K}^{-1}$)

$$\epsilon = R_d/R_v \approx 0.622$$

Then solve for dT/dz to obtain the lapse rate for a saturation-adiabatic process,

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The lapse rate for moist-adiabatic process is

$$\Gamma_s \equiv -\frac{dT}{dz} = \frac{g}{c_p} \frac{1 + \frac{L w_s}{R T}}{1 + \frac{\epsilon L^2}{c_p R} \frac{w_s}{T^2}}$$

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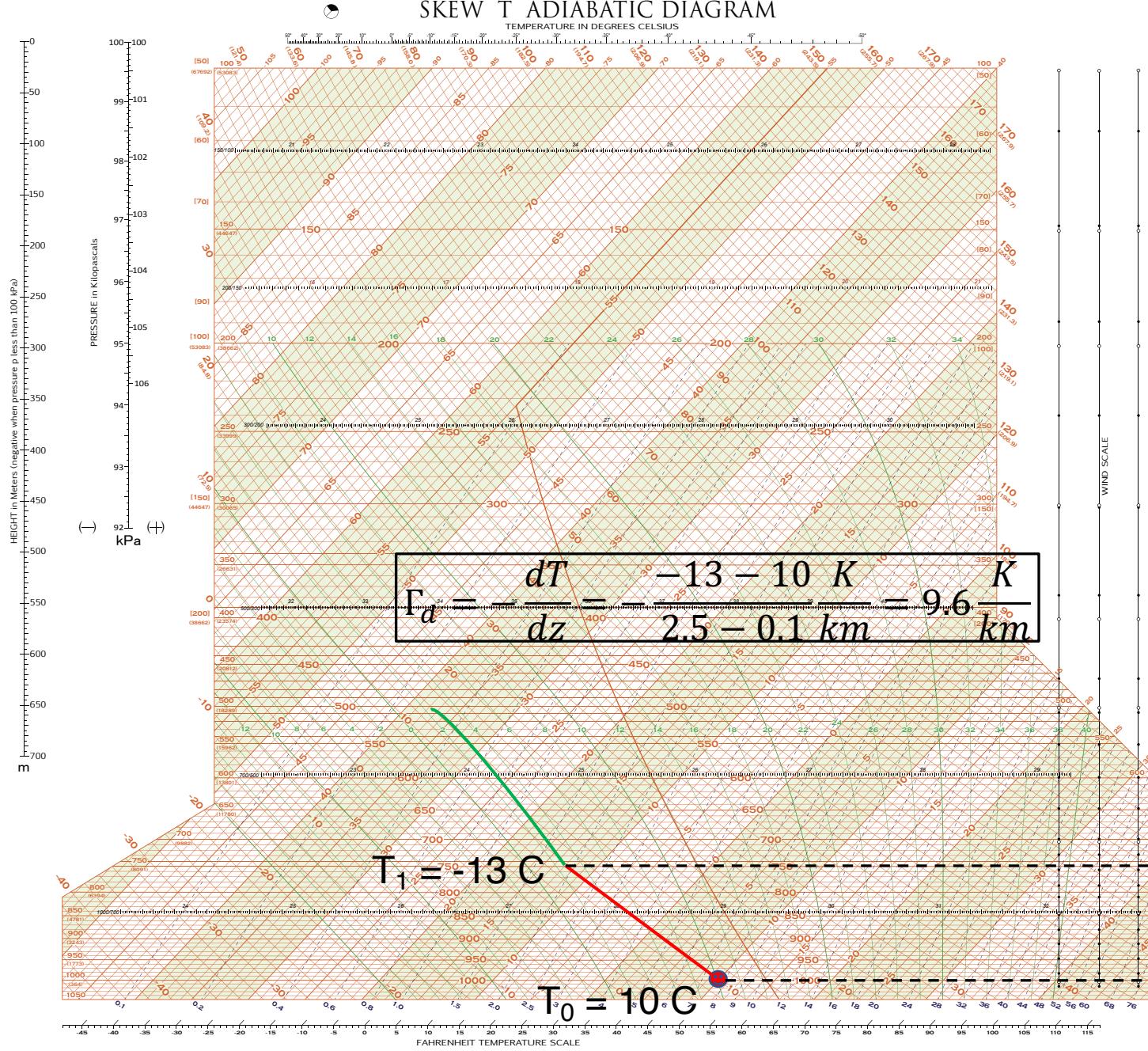
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Γ_s is not a constant

It is equal to Γ_d multiplied by a factor that depends on temperature and pressure.

Again, let's check it at the Skew T-~~log~~^{log} P diagram



$$Z_1 = 2.5 \text{ km}$$

kft | TIME (GMT) | TIME (GMT) | TIME (GMT)
 $Z_0 = 0.1 \text{ km}$

US STANDARD ATMOSPHERE

THICKNESS KILOMETERS	TEMP. DEGREES CELSIUS	TEMP. DEGREES FAHRENHEIT	PRESSURE KILOPASSAURE	PRESSURE INCHES OF MERCURY	DENSITY KILOGRAMS PER CUBIC METER	DENSITY POUNDS PER CUBIC FEET
0.0 - 10.0	15.0	59.0	1013.2	29.92	1.225	0.0760
10.0 - 20.0	14.5	58.1	1012.2	29.86	1.229	0.0757
20.0 - 30.0	14.0	57.2	1011.2	29.80	1.233	0.0754
30.0 - 40.0	13.5	56.3	1010.2	29.74	1.237	0.0751
40.0 - 50.0	13.0	55.4	1009.2	29.68	1.241	0.0748
50.0 - 60.0	12.5	54.5	1008.2	29.62	1.245	0.0745
60.0 - 70.0	12.0	53.6	1007.2	29.56	1.249	0.0742
70.0 - 80.0	11.5	52.7	1006.2	29.50	1.253	0.0739
80.0 - 90.0	11.0	51.8	1005.2	29.44	1.257	0.0736
90.0 - 100.0	10.5	50.9	1004.2	29.38	1.261	0.0733
100.0 - 110.0	10.0	50.0	1003.2	29.32	1.265	0.0730
110.0 - 120.0	9.5	49.1	1002.2	29.26	1.269	0.0727
120.0 - 130.0	9.0	48.2	1001.2	29.20	1.273	0.0724
130.0 - 140.0	8.5	47.3	1000.2	29.14	1.277	0.0721
140.0 - 150.0	8.0	46.4	999.2	29.08	1.281	0.0718
150.0 - 160.0	7.5	45.5	998.2	29.02	1.285	0.0715
160.0 - 170.0	7.0	44.6	997.2	28.96	1.289	0.0712
170.0 - 180.0	6.5	43.7	996.2	28.90	1.293	0.0709
180.0 - 190.0	6.0	42.8	995.2	28.84	1.297	0.0706
190.0 - 200.0	5.5	41.9	994.2	28.78	1.301	0.0703
200.0 - 210.0	5.0	41.0	993.2	28.72	1.305	0.0700
210.0 - 220.0	4.5	40.1	992.2	28.66	1.309	0.0697
220.0 - 230.0	4.0	39.2	991.2	28.60	1.313	0.0694
230.0 - 240.0	3.5	38.3	990.2	28.54	1.317	0.0691
240.0 - 250.0	3.0	37.4	989.2	28.48	1.321	0.0688
250.0 - 260.0	2.5	36.5	988.2	28.42	1.325	0.0685
260.0 - 270.0	2.0	35.6	987.2	28.36	1.329	0.0682
270.0 - 280.0	1.5	34.7	986.2	28.30	1.333	0.0679
280.0 - 290.0	1.0	33.8	985.2	28.24	1.337	0.0676
290.0 - 300.0	0.5	32.9	984.2	28.18	1.341	0.0673
300.0 - 310.0	0.0	32.0	983.2	28.12	1.345	0.0670

SKEW T ANALYSIS

ALTIMETER ANALYSIS

FRICTION LAYER

INVERSIONS

SIGNIFICANT MILD

STABILITY

CLOUDS

ICING

CONTROLS

TURBULENCE

TEMPERATURES

DETAILED INFORMATION

DESCRIPTION OF LOW LEVEL INVERSION AT

