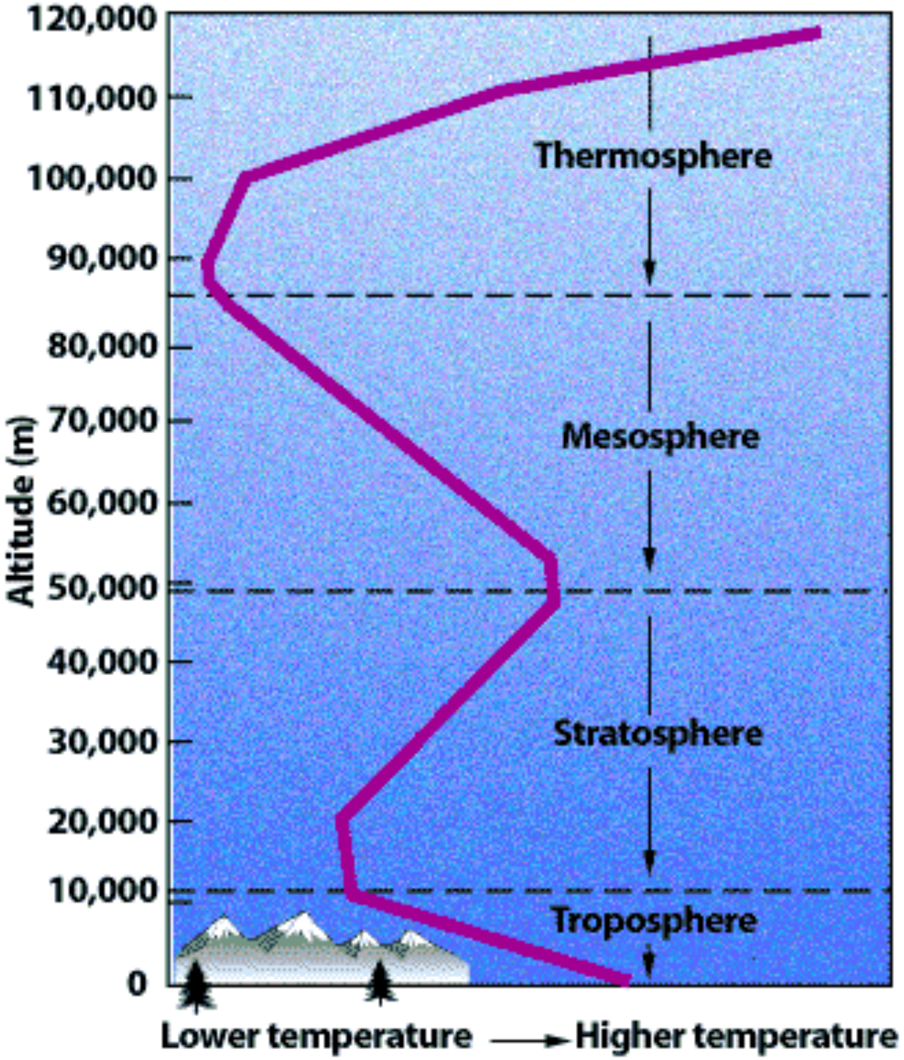
ATMOS_5300 (Fall2020)
Atmospheric Thermodynamics

Dry And Moist Adiabatic Lapse Rate

Xia Li
September 25, 2020



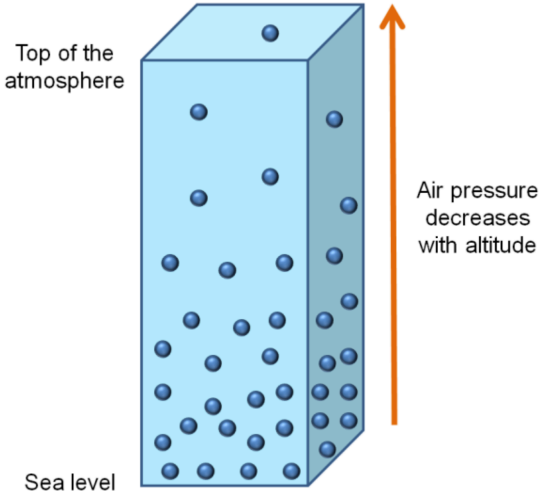
Lapse rate is the rate of temperature ~~change~~ decrease with a ~~change~~ increase in altitude

Three types of lapse rate:

- *Dry adiabatic lapse rate*
  unsaturated air (RH < 100%)
- *Moist (saturation) adiabatic lapse rate*

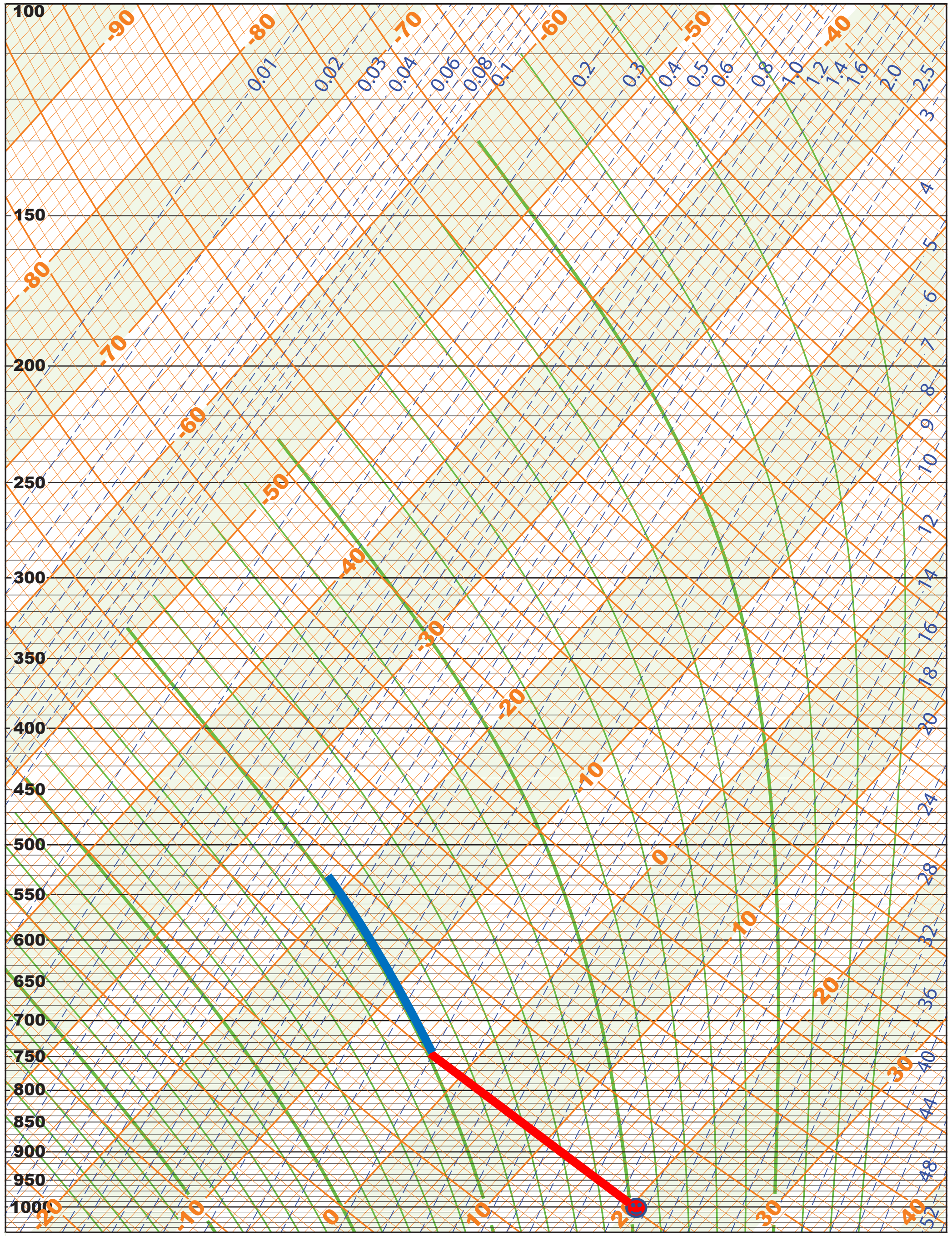
- *Environmental (ambient) lapse rate*

Useful criterion for atmospheric stability



Ascending: expands
Descending: compresses

Check the isothermal lines on Skew T- log P



Skew-T / log p diagram for use with *A First Course in Atmospheric Thermodynamics* ©2008 by G.W. Petty

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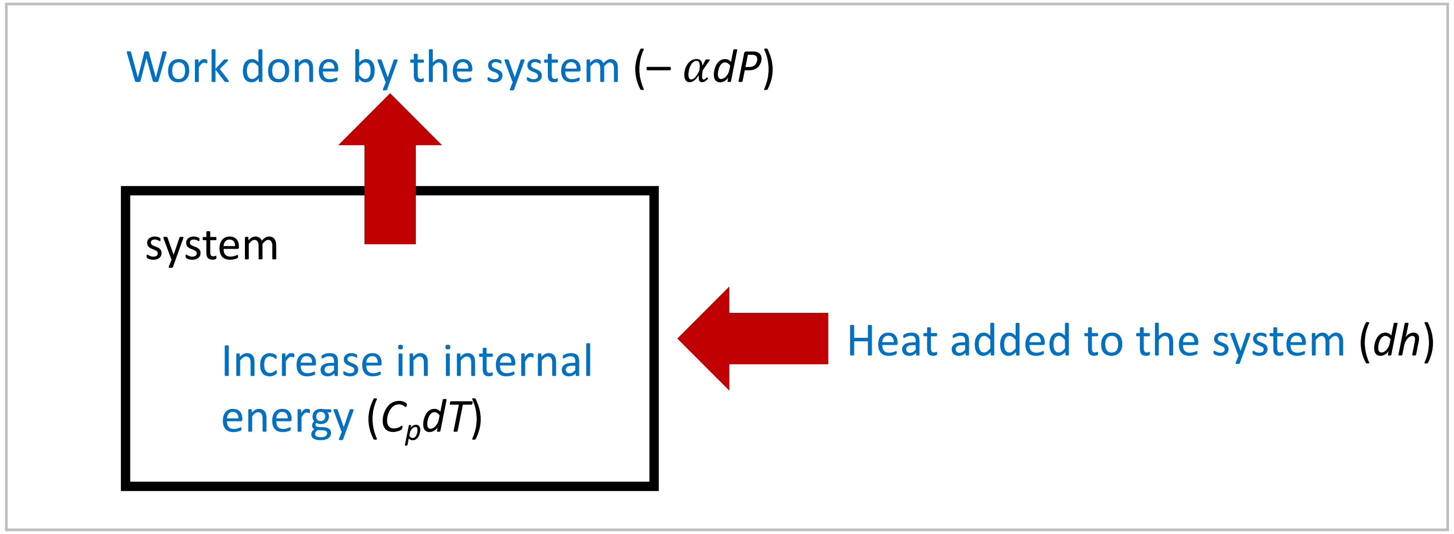
Where should we start?

The fundamental law: the first law of thermodynamics

- Principle of conservation of energy



Work done by the system ($-\alpha dP$)

system

Increase in internal energy ($C_p dT$)

Heat added to the system (dh)

- One form is:

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

Theoretical dry adiabatic lapse rate

The first law of thermodynamics for a parcel is

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

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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 ($\bar{p}$): $p = \bar{p}$

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x: parcel properties
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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:

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

Theoretical dry adiabatic lapse rate

Use Eq.1 in the first law to obtain

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

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To further simply, 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:

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

Theoretical dry adiabatic lapse rate

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

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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$g = 9.81$ m s^{-2}
$c_p = 1004\ J\ kg^{-1}\ K^{-1}$

Lets do the calculation!

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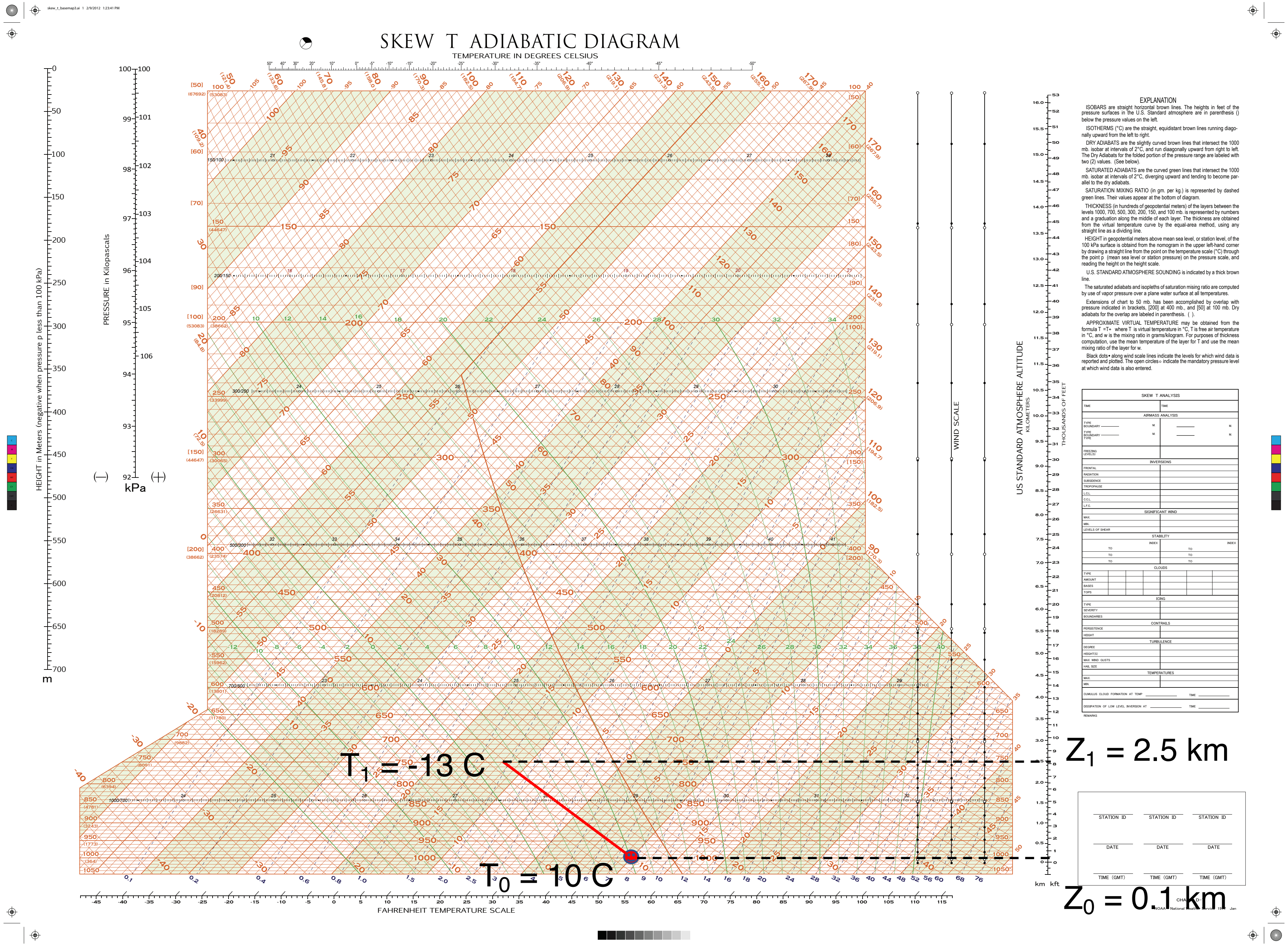
Γ_d for dry air is 9.76 K km^{-1} (5.4 F ~~feet~~ kft^{-1})

log

Let’s check it at the Skew T~~-lop~~ 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 parenthesis () below the pressure values on the left.

ISOTHERMS (°C) are the straight, equidistant brown lines running diagonally upward from the left to right.

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

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 dry adiabats.

SATURATION MIXING 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, 150, and 100 mb. is represented by numbers and a graduation along the middle of each layer. The thickness are obtained from the virtual temperature curve by the equal-area method, using any straight line as a dividing line.

HEIGHT in geopotential meters above mean sea level, or station level, of the 100 kPa surface is obtaind from the nomogram in the upper left-hand corner by drawing a straight line from the point on the temperature scale (°C) through the point p (mean sea level or station 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 isopleths of saturation mising ratio are computed by use of vapor pressure over a plane water surface at all temperatures.

Extensions 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 for the overlap are labeled in parenthesis. ( ).

APPROXIMATE VIRTUAL TEMPERATURE may be obtained from the formula T =T+ where T is virtual temperature in °C, T is free air temperature in °C, and w is the mixing ratio in grams/kilogram. For purposes of thickness computation, use the mean temperature of the layer for T and use the mean mixing ratio of the layer for w.

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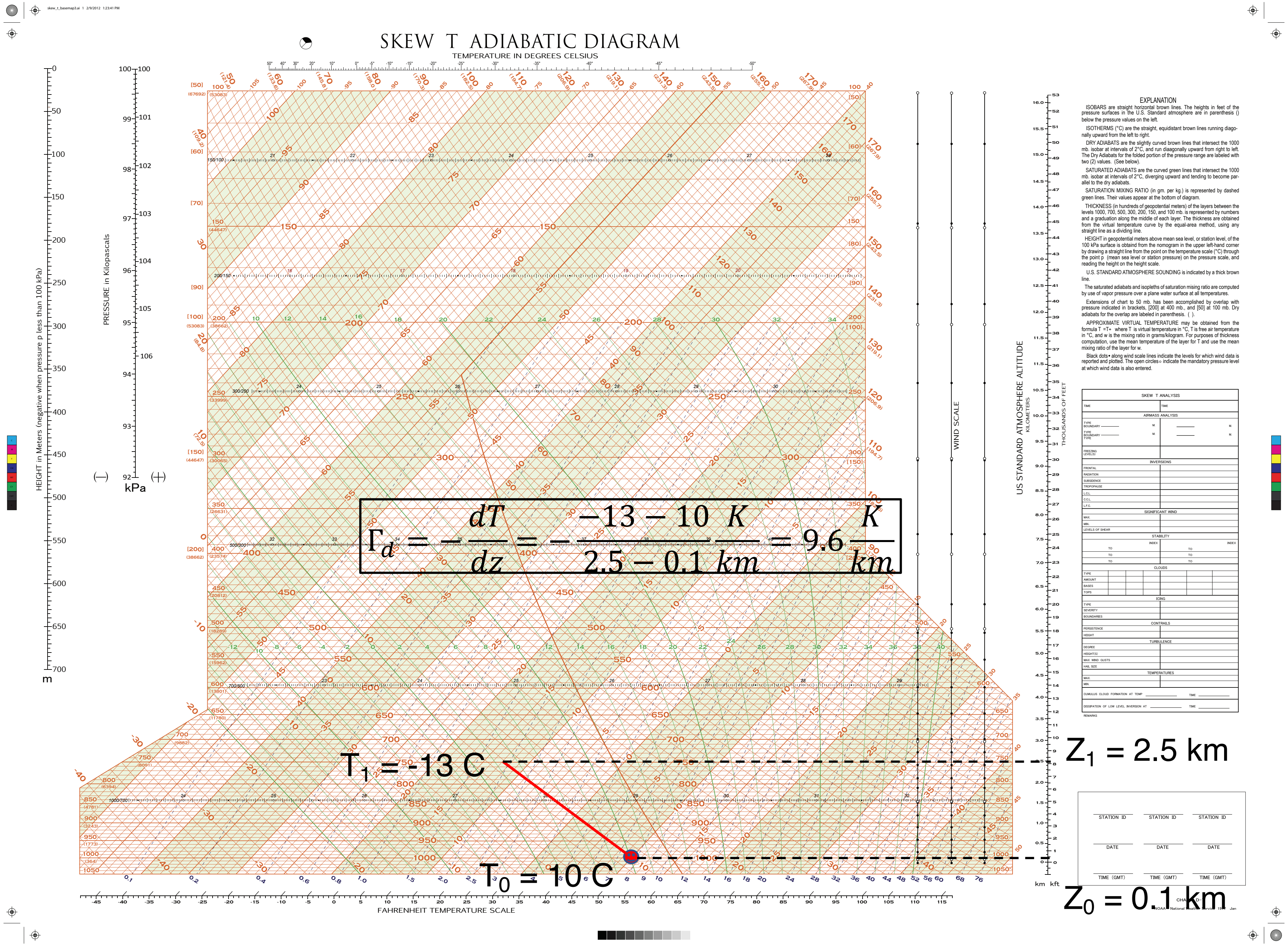

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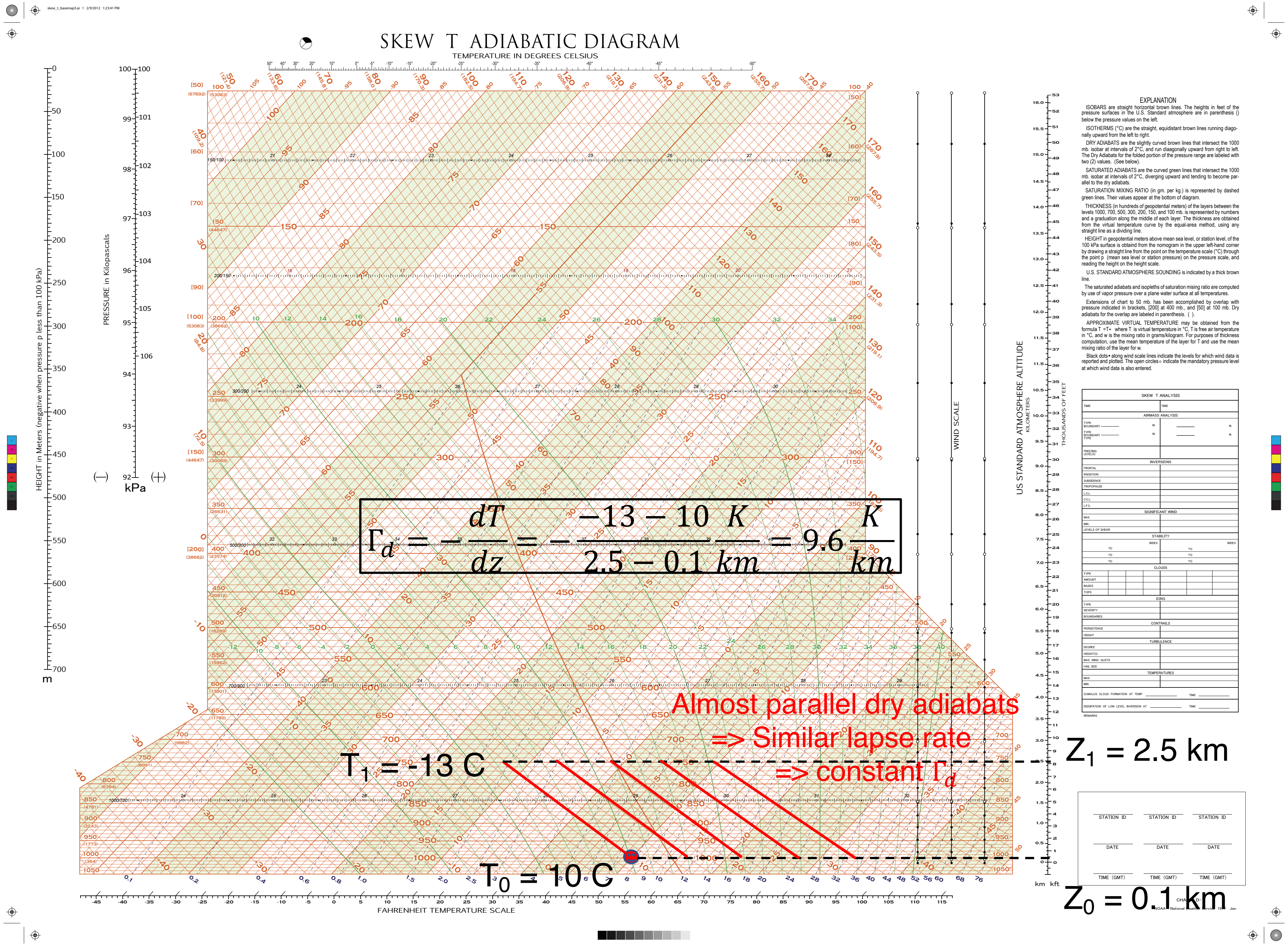
SKEW T ADIABATIC DIAGRAM

TEMPERATURE IN DEGREES CELSIUS



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Almost parallel dry adiabats

=> Similar lapse rate

=> constant Γ_d

T_1 = -13 C

Z_1 = 2.5 km

T_0 = 10 C

Z_0 = 0.1 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 ⇒ water vapor begins to condense and release the latent heat of condensation ⇒ rate of cooling changes

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🙁 ??

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As saturated air ascends ⇒ water vapor begins to condense and release the latent heat of condensation ⇒ 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

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$L = 2.5 \times 10^6\ J\ kg^{-1}$
dw mass changes in water vapor

Eq. (2) changes to:

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

Theoretical moist adiabatic lapse rate

$$-L\,dw_s = c_p\,dT + g\,dz. \tag{3}$$

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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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

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

Recall that

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

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

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

Theoretical moist adiabatic lapse rate

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

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

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Use assumption for w_s:

$$w_s \approx \epsilon \frac{e_s}{p}$$

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!

Theoretical moist adiabatic lapse rate

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

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

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The lapse rate for moist-adiabatic process is

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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.

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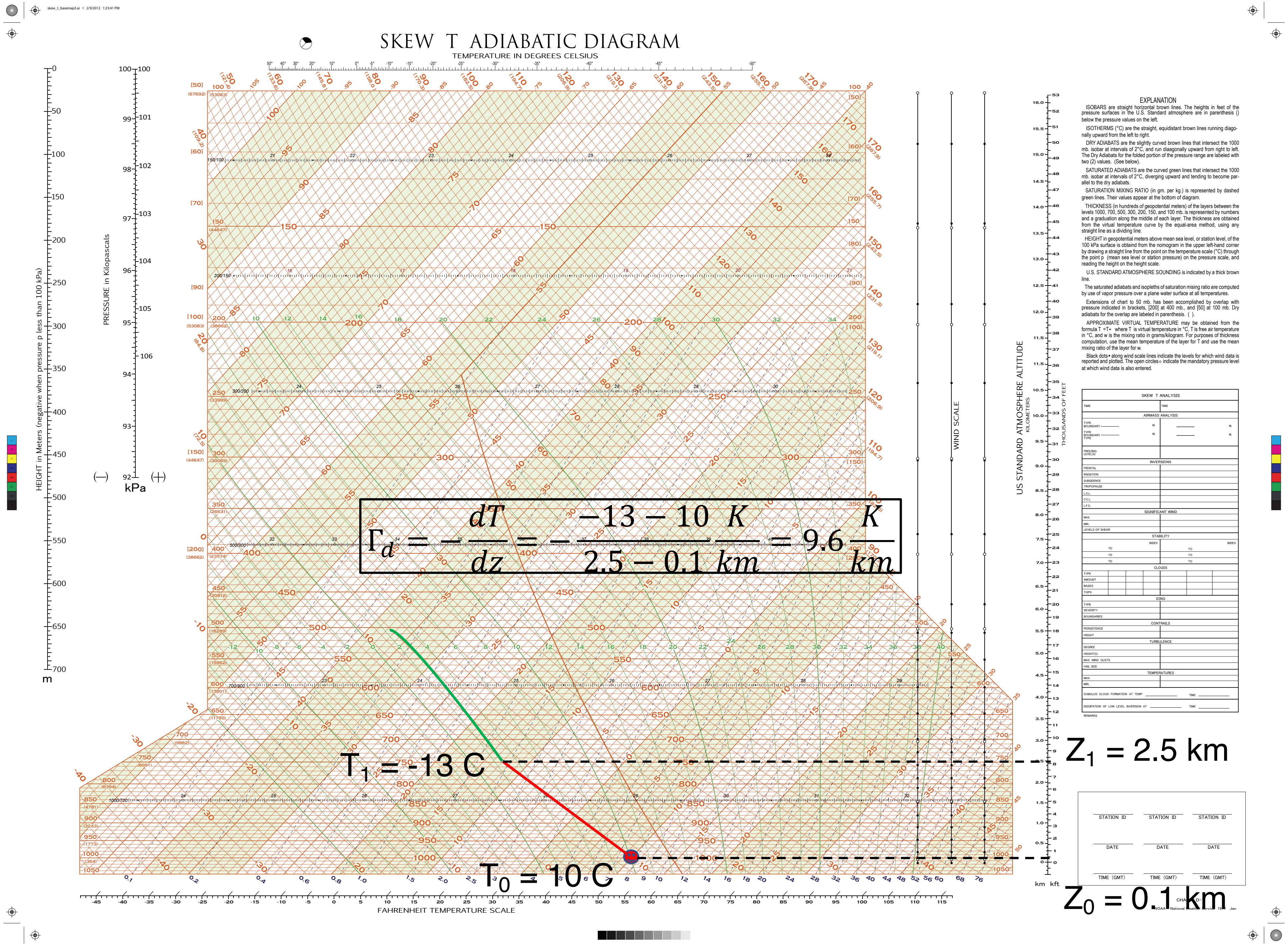

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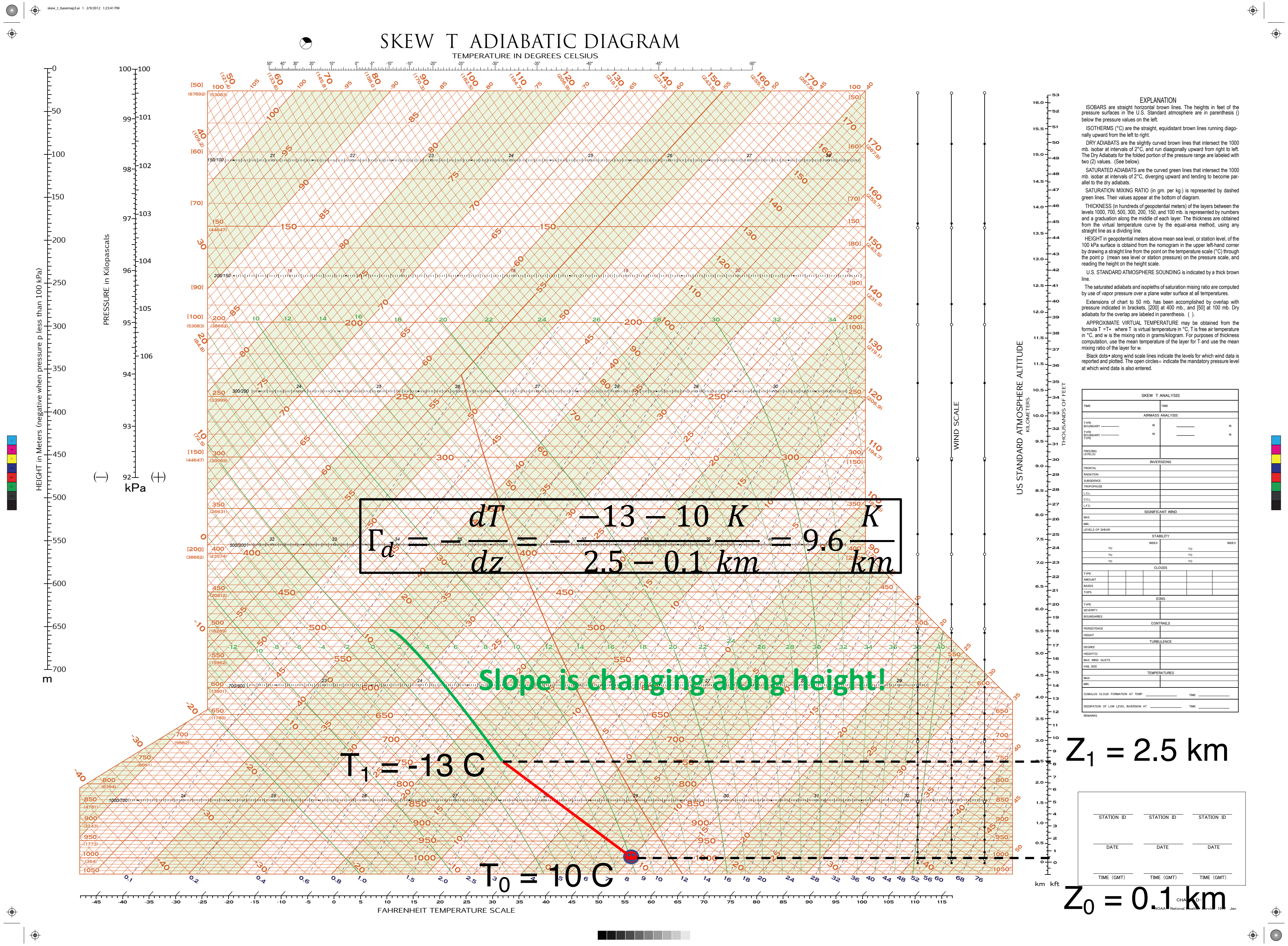

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Slope is changing along height!

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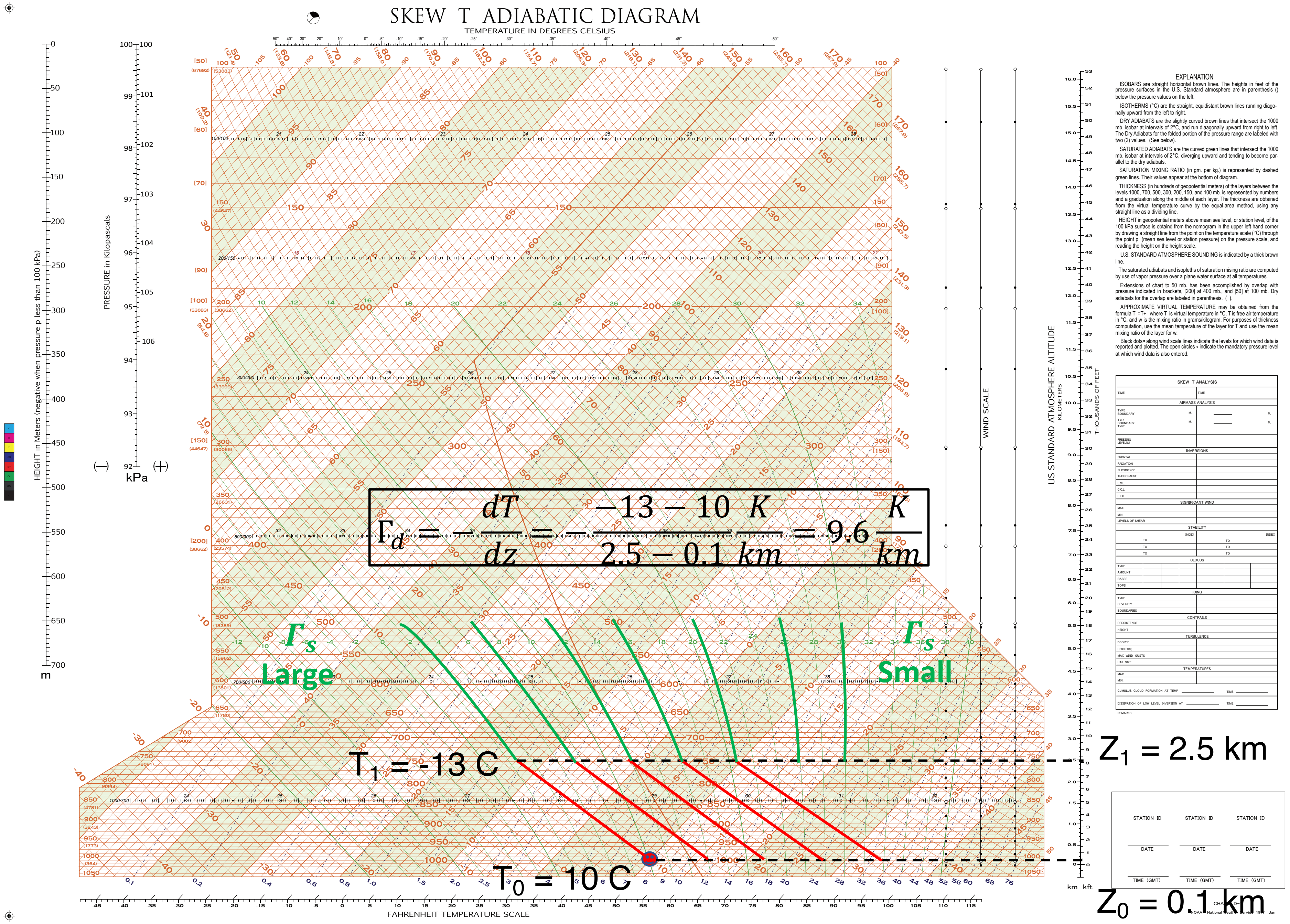

$$\Gamma_d = -\frac{dT}{dz} = -\frac{-13-10\ K}{2.5-0.1\ km} = 9.6\,\frac{K}{km}$$

EXPLANATION

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

ISOTHERMS (°C) are the straight, equidistant brown lines running diagonally upward from the left to right.

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

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 dry adiabats.

SATURATION MIXING 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, 150, and 100 mb. is represented by numbers and a graduation along the middle of each layer. The thickness are obtained from the virtual temperature curve by the equal-area method, using any straight line as a dividing line.

HEIGHT in geopotential meters above mean sea level, or station level, of the 100 kPa surface is obtaind from the nomogram in the upper left-hand corner by drawing a straight line from the point on the temperature scale (°C) through the point p (mean sea level or station 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 isopleths of saturation mising ratio are computed by use of vapor pressure over a plane water surface at all temperatures.

Extensions 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 for the overlap are labeled in parenthesis. ( ).

APPROXIMATE VIRTUAL TEMPERATURE may be obtained from the formula T =T+ where T is virtual temperature in °C, T is free air temperature in °C, and w is the mixing ratio in grams/kilogram. For purposes of thickness computation, use the mean temperature of the layer for T and use the mean mixing ratio of the layer for w.

Black dots • along wind scale lines indicate the levels for which wind data is reported and plotted. The open circles ○ indicate the mandatory pressure level at which wind data is also entered.