Chap. 1

Overview of thermodynamics

What is a simple definition of the laws of thermodynamics?

Answer

Thermodynamics is the study of the inter-relation between heat, work and internal energy of a system.

Thermodynamics defined

Thermodynamics:

- is an empirical science based on a small number of principles
- is concerned only with macroscopic or large-scale properties of matter
- provides general relations between quantities such as coefficients of expansion, compressibilities, specific heat capacities, heats of transformation, and magnetic and dielectric coefficients, and their dependence on temperature.
- indicates which relations must be determined experimentally in order to completely specify the system properties
- is complementary to kinetic theory and statistical thermodynamics.
- provides relationships between physical properties of a system

Areas within physics: Where does thermodynamics fit in?

- Mechanics
- Thermodynamics
- Vibrations and wave phenomena
- Optics
- Electromagnetism
- Relativity
- Quantum mechanics

Source: High School physics text

Areas within Atmospheric Science

- Atmospheric dynamics
- Atmospheric thermodynamics
- Severe storms
- Radiation
- Cloud physics and dynamics
- Physical climatology
- General circulation
- Synoptic meteorology
- Tropical meteorology
- Mesoscale meteorology
- Boundary layer meteor.
- Remote sensing
- Hydrology
- Climate dynamics

- *But there is more:*

http://www.ametsoc.org/stacpages/CommitteeDisplay/CommitteeDisplay.aspx?CC=STAC

Thermodynamics

- deals with energy and the transformations of the nature of energy
- three fundamental laws (principles):
  - the equation of state (ideal gas law),
  - the first law of thermodynamics (conservation of energy),
  - the second law of thermodynamics (degradation of energy, i.e., entropy increases).

"Well then, thermodynamics is simple!"

statistical thermodynamics

- Strives to deduce the average properties of a large number of molecules

Thermodynamics and dynamics: Some end results

- Dynamics/kinematics (momentum equations for u, v; continuity equation)

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - \omega\frac{\partial u}{\partial p} - \frac{\partial \phi}{\partial x} + fv + F_x$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - \omega\frac{\partial v}{\partial p} - \frac{\partial \phi}{\partial y} - fu + F_y$$

$$\frac{\partial \omega}{\partial p} = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$$

- Thermodynamics (equation of state, hydrostatic equation, thermodynamic equation or First Law):

$$\frac{\partial \phi}{\partial p} = -\frac{RT}{p}$$

$$\frac{\partial T}{\partial t} = -u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} + \omega\left(\frac{\kappa T}{p} - \frac{\partial T}{\partial p}\right) + \frac{\dot{H}}{c_p}$$

Equations are complete sentences. Equations convey important information, like any other language

Cloud physics

An equation set used to simulate ice fog, thin stratus, etc.

Aerosols

$$\frac{\partial}{\partial t}m_A(r) = K\frac{\partial^2}{\partial z^2}m_A(r) + S_{A_{\text{cond}}} + S_{A_{\text{depo}}} + S_{A_{\text{coag}}} + S_{A_{\text{sedi}}} + S_{A_{\text{nucl}}}, \quad (1)$$

Ice crystals

$$\frac{\partial}{\partial t}m_I(r) = K\frac{\partial^2}{\partial z^2}m_I(r) + S_{I_{\text{depo}}} + S_{I_{\text{aggr}}} + S_{I_{\text{sedi}}} + S_{I_{\text{nucl}}} + S_{I_{\text{phas}}}, \quad (2)$$

Water droplets

$$\frac{\partial}{\partial t}m_W(r) = K\frac{\partial^2}{\partial z^2}m_W(r) + S_{W_{\text{cond}}} + S_{W_{\text{coal}}} + S_{W_{\text{sedi}}} + S_{W_{\text{nucl}}} + S_{W_{\text{phas}}}, \quad (3)$$

Specific humidity

$$\frac{\partial q}{\partial t} = K\frac{\partial^2 q}{\partial z^2} + S_{I_{\text{depo}}} + S_{W_{\text{cond}}} + S_{A_{\text{cond}}} + S_{A_{\text{depo}}}, \quad (4)$$

Temperature

$$\frac{\partial T}{\partial t} = K\frac{\partial^2 T}{\partial z^2} + \frac{Q_{\text{rad}}}{C_p} + \frac{Q_{\text{cond}}}{C_p} + \frac{Q_{\text{depo}}}{C_p}, \quad (5)$$

Saturation ratio

$$\frac{d\delta}{dt} = -\left(\frac{L_v}{R_v T^2}\right)\frac{\partial T}{\partial t} - \left(\frac{p}{\varepsilon e_s}\right) \times [S_{W_{\text{cond}}} + S_{I_{\text{depo}}} + S_{A_{\text{cond}}} + S_{A_{\text{depo}}}], \quad (6)$$

Some definitions

- *Energy*: This is almost impossible to define precisely. It is not the "ability to do work" unless some conditions are carefully defined. Energy is a property and is defined as such by the First Law .of Thermodynamics

System

- *System*: A system is some portion of the universe selected for study. Strictly speaking a system may, or may not, contain matter or energy. For atmospheric applications, systems will always contain both matter and energy. The remainder of the universe is defined as the "surroundings" of the system.

Systems may be classified as *isolated, closed* or *open*.

- *Isolated system*: A system which cannot exchange either matter or energy with its surroundings. The universe is defined by the First Law as an isolated system.
- *Closed system*: A system which can exchange energy, but not matter, with its surroundings.
- *Open system*: A system which can exchange both matter and energy with its surroundings.

The systems in Atmospheric Thermodynamics will be "parcels" of air undergoing transformations in the atmosphere. Thus, these are really open systems, but for the sake of simplicity, they will often be treated as closed systems.

Parcel

- We will often use the concept of a parcel (which is a *closed system*) in our discussions of atmospheric thermodynamic processes. A parcel is often defined as a volume of air which does not interact with its environment, i.e.,
  (a) no compensating motions occur in the environment as a consequence of the parcel motions
  (b) the parcel does not exchange mass with the environment.
- A parcel can do work on the environment. A parcel is therefore an example of a closed system.

Property

- *Property*: A property is an observable. It results from a physical or chemical measurement. A system is characterized by a set of properties. Typical examples are mass, volume, temperature, pressure, moisture content, chemical composition, energy, etc. Properties may be classified as *intensive* or *extensive*.
- *Intensive property*: A property that characterizes the system as a whole, and is not given as the sum of the property for portions of the system. Pressure, temperature, density, water vapor mixing ratio, and specific heat are examples of intensive properties.
- *Extensive property*: A property which is dependent on the extent or physical size of the system, and which is given by the sum of the extensive properties of portions of the system. Examples are mass, volume and energy. [We will avoid this to a large extent by defining *specific volume* and *specific energy*, which have units per unit volume or mass, respectively.]

State of a system

- The state of a system is defined by a set of system properties. A certain minimum number of such properties are required to specify the state. Thus in an ideal gas, any three of the four properties -- pressure, volume, number of moles, and temperature -- define the state of the system. The *equation of state* defines the relation among these properties.

Process

- *Process*: A description in the manner in which a change in state occurs. Four examples are:
  - isothermal process: a change in state occurring at constant temperature;
  - adiabatic process: a change in state involving no transfer of energy between the system and its surroundings;
  - isochoric process: a change in state occurring at constant volume;
  - cyclic process: a change occurring when the system (but not necessarily its surroundings) is returned to its initial state after one or more processes.

Equilibrium

- A necessary, but insufficient, condition for a system to be in equilibrium is that the system *state* must be constant with time. In addition, if the system is perturbed by a small amount, then in an equilibrium state the system would retain its initial properties. We will later further distinguish among, *stable*, *unstable* and *metastable* equilibria.
- Types of equilibria:
  - Physical, dynamical, chemical

Scale and units

- We will generally adhere to the SI (System Internationale) or MKS (meter/kilogram/second) units, but for convenience we will depart from MKS at times. (After all, we can't avoid using calories in a course like this.)
- The appropriate temperature scale will be either Celsius or Kelvin
- Pressure will be expressed in both mb and Pa (or hPa which is numerically identical to mb).

Aside: What quantities are used to describe physical systems?

Base quantity	***Name***	***Symbol***
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

Source: http://physics.nist.gov/cuu/Units/units.html

Quantity	Unit
Length	m (or cm, mm, μm)
Mass	kg (g)
Acceleration	m s^{-2}
Density	kg m^{-3}
Force	newton (N) $\rightarrow$ N = kg m s^{-2}
Temperature	Kelvin (K) or Celsius (C) K = °C + 273.15 °F = 1.8 °C + 32
Pressure	pascal (Pa) [1 mb = 10^3 dyne cm^{-2} = 102 Pa] Pressure is force per unit area, so the unit of Pa is Pa = N m-2 = kg m^{-1} s^{-2} (1 mb = 10^2 Pa = 1 hPa) Also:1 atm = 1013.25 mb = 101.325 kPa = 14.696 PSI (lb in-2) = 760 mm Hg (29.92 in)
Energy	joule (J) $\rightarrow$ J = N m = kg m^2 s^{-2} [1 cal = 4.1868 J]

calorie

- *calorie* or the gram-calorie (cal). This is defined as the heat necessary to raise by 1 K the temperature of one gram of water at a temperature of 15 °C.
- In terms of the MKS units, 1 cal = 4.1868 J.
- The international calorie was introduced in engineering, in relation to characteristics of water.
- The thermochemical calorie was formulated by physical chemists and is defined as above.
- We will at times use the IT cal in this course.

kilogram molecular weight

- kilogram molecular weight, or kilomole (kmol) is defined as the molecular weight (M) of a material in kg. Thus, one kmol of water is 18.016 kg. The number of kmol n in a mass m is given by

$$n = m/M.$$

- The number of molecules in one kmol of any material is constant and equal to 10^3 x Avogadro's number (6.022×10^{23}).

Recommendation

- Refer to this material frequently throughout the course.

Have any of you been following the developments in redefining planets in our solar system?

- Size criterion: 500 mi diameter (this would have sufficient mass to force the planet into a quasi-spherical shape)
- What about an atmosphere criterion? This implies a mass large enough to hold gas molecules (relation to escape velocity)

Atmospheric Composition

We will consider the atmosphere to be composed of:

- a mixture of gases as defined in Tables 1 and 2;
- water substance in the gaseous, liquid, or ice phase;
- and solid/liquid (aerosol) particles of very small size (10^{-7} to 10^{-4} m).

Table 1.1 Main gas components of the dry atmosphere

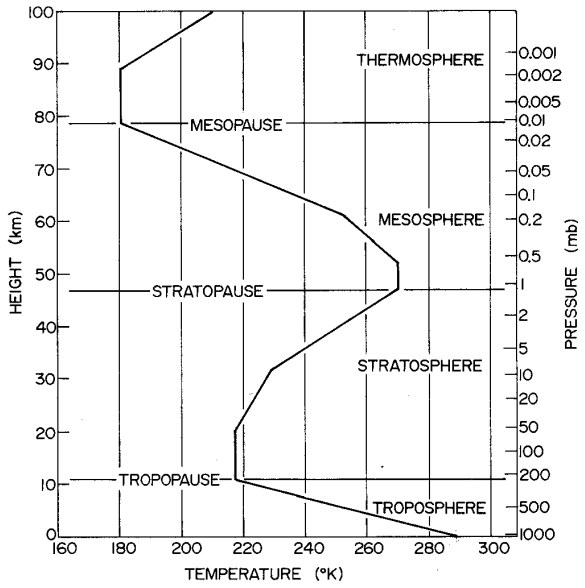
(U.S. Standard Atmosphere, 1976)

Gas	Molecular Weight	Molar (or volume) fraction	Mass fraction (m_i)	Specific gas constant (R_i, J kg^{-1} K^{-1})	$m_i R_i/m$
N_2	28.013	0.78084	0.7552	296.80	224.15
O_2	31.999	0.20948	0.2315	259.83	60.15
Ar	39.948	0.00934	0.0128	208.13	2.66
CO_2	44.010	0.00033 (variable)	0.0005	188.92	0.09
H_2O	18.016	0 – 0.07 (highly variable)			
Sum	***Avg = 28.964***	Sum = 1.00000	Sum = 1.0000		**287.05**

Table 1.2 Minor gas components of the dry atmosphere (U.S. Standard Atmosphere, 1976)

Gas	*Abbreviation*	*Molar (volume) fraction*
Neon	Ne	18.18×10^{-6}
Helium	He	5.24×10^{-6} (?)
Methane	CH_4	2×10^{-6}
Krypton	Kr	1.14×10^{-6}
Nitrous Oxide	N_2O	2.5×10^{-7}
Hydrogen	H_2	0.5×10^{-6}
Xenon	Xe	0.087×10^{-6}
Ozone	O_3	$0 – 10^{-4}$
Sulfur dioxide	SO_2	variable
Nitrogen dioxide	NO_2	$0\text{-}2 \times 10^{-6}$
Carbon monoxide	CO	

Vertical temperature profile for the U.S. Standard Atmosphere. From Wallace and Hobbs (1977).

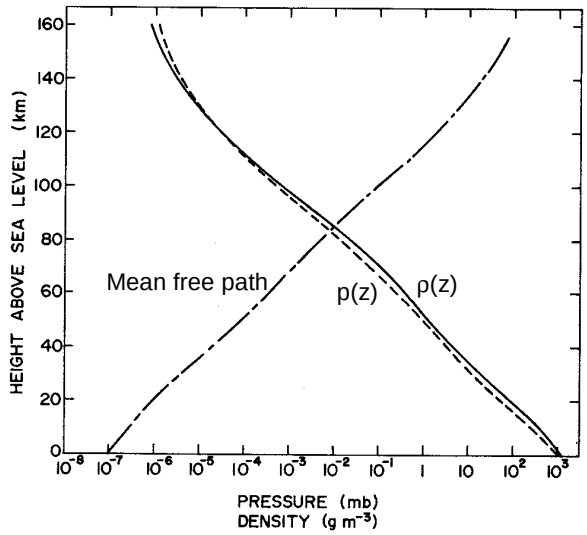


Vertical profile of pressure in mb (dashed), density in g m^{-3} (solid) and mean free path in m (dot-dashed) for the U.S. Extension to International Civil Aviation Organization (ICAO) Standard Atmospere.

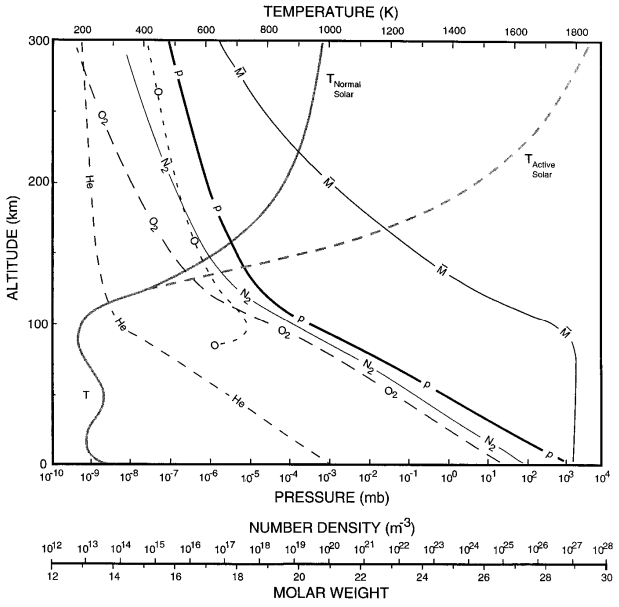
$p(z) = p_0 \exp(-z/H)$

$\rho(z) = \rho_0 \exp(-z/H)$

H is the atmospheric scale height (H ~7-8 km)



Global mean pressure (bold), temperature (shaded), mean molar weight (solid) and number densities of atmospheric constituents, as functions of altitude. Source: U.S. Standard Atmosphere. Taken from Salby (1996).



A standard atmosphere calculator

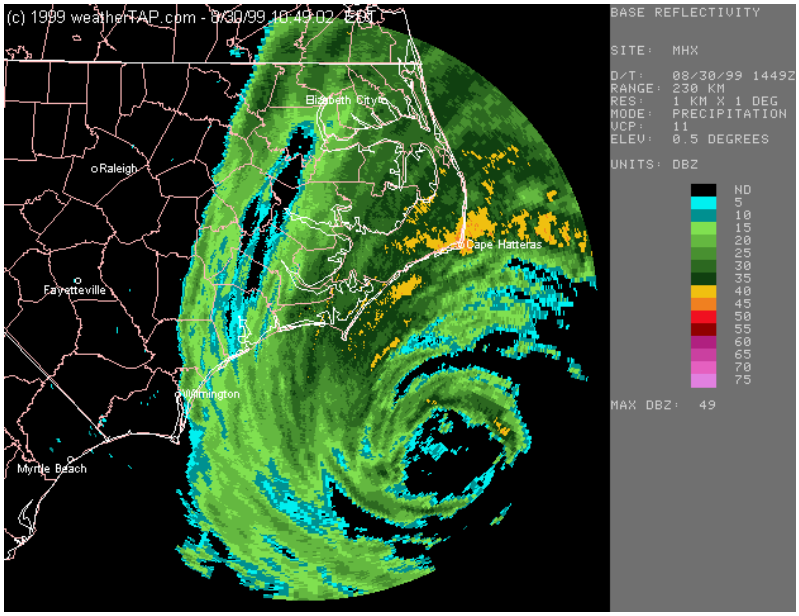
- http://www.digitaldutch.com/atmoscalc/
- relationships among height, pressure, density, temperature, and the speed of sound for a dry atmosphere
- http://aero.stanford.edu/StdAtm.html

Pictures that tell (or imply) a “story” (about thermodynamics)

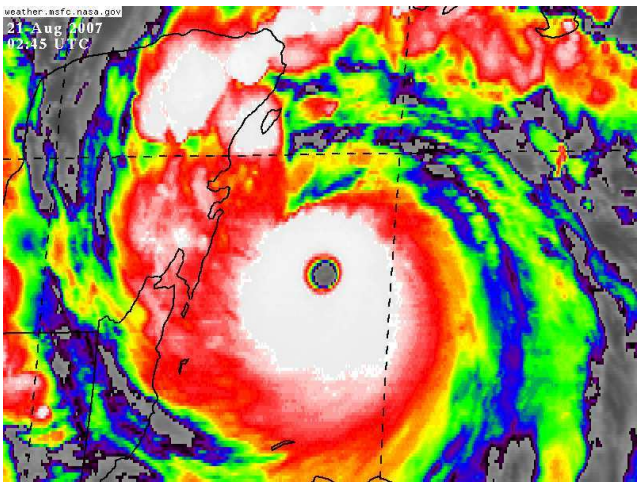
- Example pictures
- Atmospheric thermodynamics in everyday living

Thermodynamics?

Thermodynamics?

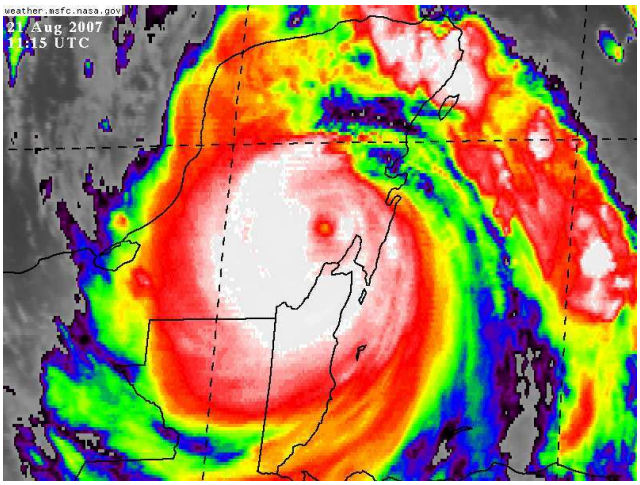


Hurricane Dean, 0245 UTC 21 Aug



http://www.aoml.noaa.gov/hrd/Storm_pages/dean2007/wind.html

Hurricane Dean, 1115 UTC 21 Aug



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HURRICANE DEAN DISCUSSION NUMBER 33

NWS TPC/NATIONAL HURRICANE CENTER MIAMI FL AL042007 500 AM EDT TUE AUG 21 2007

DEAN MADE LANDFALL ON THE EAST COAST OF THE YUCATAN PENINSULA NEAR THE CRUISE SHIP PORT OF COSTA MAYA AROUND 0830 UTC...AND THE EYE IS NOW JUST INLAND. OBSERVATIONS FROM AN AIR FORCE HURRICANE HUNTER PLANE INDICATE THAT THE HURRICANE WAS INTENSIFYING RIGHT UP TO LANDFALL. A PEAK FLIGHT-LEVEL WIND OF 165 KT WAS MEASURED JUST NORTH OF THE EYE. MAXIMUM SURFACE WINDS FROM THE SFMR WERE 124 KT...BUT IT IS HIGHLY LIKELY THAT THE MAXIMUM SURFACE WIND SPEED WAS NOT REPORTED BY THE SFMR INSTRUMENT. A GPS DROPSONDE IN THE NORTHERN EYEWALL MEASURED A WIND SPEED OF 178 KT AVERAGED OVER THE LOWEST 150 METERS OF THE SOUNDING. BASED ON THE DROPSONDE AND THE FLIGHT-LEVEL WINDS...THE INTENSITY IS SET AT 145 KT. A DROPSONDE IN THE EYE MEASURED A CENTRAL PRESSURE OF 906 MB JUST PRIOR TO LANDFALL.

SOME HISTORIC NOTES ARE IN ORDER HERE. THE 906 MB CENTRAL PRESSURE IS THE NINTH LOWEST ON RECORD FOR AN ATLANTIC BASIN HURRICANE...AND THE THIRD LOWEST AT LANDFALL BEHIND THE 1935 LABOR DAY HURRICANE IN THE FLORIDA KEYS AND HURRICANE GILBERT OF 1988 IN CANCUN MEXICO. DEAN IS ALSO THE FIRST CATEGORY FIVE HURRICANE TO MAKE LANDFALL IN THE ATLANTIC BASIN SINCE ANDREW OF 1992. DEAN WILL WEAKEN AS IT TRAVERSES THE YUCATAN PENINSULA AND THE AMOUNT OF WEAKENING WILL DEPEND ON HOW LONG THE CENTER REMAINS OVER LAND. OUR CURRENT THINKING IS THAT THE CYCLONE WILL STILL BE A BORDERLINE CAT 1/2 HURRICANE WHEN IT EMERGES OVER THE BAY OF CAMPECHE...BUT THERE IS CONSIDERABLE UNCERTAINTY IN THIS FORECAST. ASSUMING THAT THE INNER CORE IS NOT TOO DISRUPTED BY ITS INTERACTION WITH LAND...DEAN SHOULD REGAIN MAJOR HURRICANE STATUS BEFORE ITS FINAL LANDFALL IN MAINLAND MEXICO.

FORECAST POSITIONS AND MAX WINDS

INITIAL 21/0900Z 18.7N 87.8W 145 KT (167 MPH)

12HR VT 21/1800Z 19.1N 90.4W 85 KT...INLAND

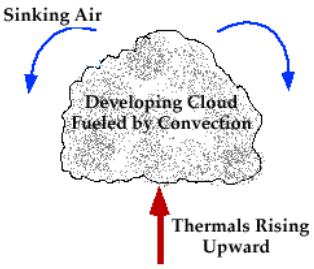
24HR VT 22/0600Z 19.6N 93.9W 95 KT...OVER BAY OF CAMPECHE

36HR VT 22/1800Z 20.1N 96.8W 105 KT...INLAND

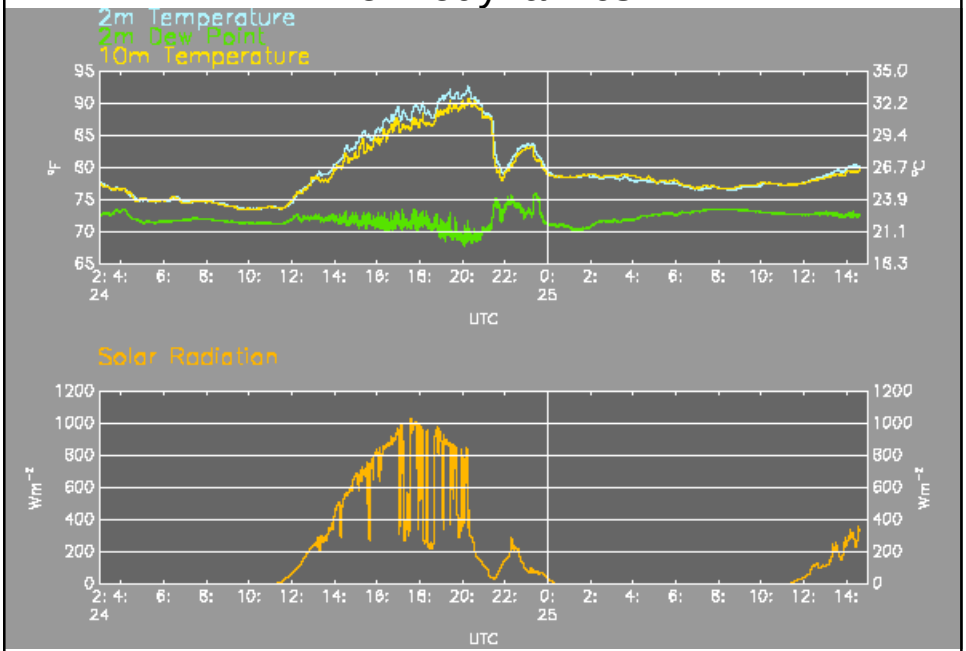
48HR VT 23/0600Z 20.5N 100.0W 25 KT...INLAND...DISSIPATING

72HR VT 24/0600Z...DISSIPATED

Thermodyamics?



Thermodynamics?



http://vortex.nsstc.uah.edu/mips/data/current/surface/

Assignment

- Solve problems 1-3 (notes, p. 8)
- Due date: one week, 8/28