Dr. Hart

General

As the debate over global warming rages, a rather unique proposal has been put forward to reduce and reverse the increase in global temperature. It goes as such: move the Earth to a larger radius orbit around the Sun.

a) Please calculate the approximate radius of orbit to which the Earth should be moved to completely negate the proposed 2C of warming over the next 100 years.

b) Discuss the potential implications on the global climate from moving the Earth to this larger radius, including but not necessarily limited to: General circulation, Hadley circulation, jet stream intensity, and tropical cyclone frequency.

Question 1: A faculty member received this email recently. Please describe how you would reply, using any necessary calculations to prove or disprove their assertions.

I have an unusual question about something that I heard about on The Learning Channel. The announcer stated that a large cumulo-nimbus thunderhead cloud may contain as much as 510 thousand tons of water prior to actually raining. I teach the physical sciences. That amount of weight is a tremendous amount and I can believe it when one sees the pictures of a great rainfall and flood. Can you confirm or deny this great weight. What keeps it up prior to falling? Further, I have read elsewhere that the integrated amount of water vapor (precipitable water) in any given column of the atmosphere rarely exceeds a few cm . How can only a few cm of precipitable water lead to the often 5-20cm of rainfall associated with these thunderstorms? Thanks for your help.

Question 2: How would the climate of the eastern United States differ if the Appalachian Mountains were restored to their peak height (from millions of years ago) of approximately 3000m? Would impacts on the climate extend around the rest of the globe, and if so, how far would they extend and what would the impacts be?

Question 3: While the tilt of the Earth leads to the evolution of seasons at any given location, this tilt also has the effect of altering the mean annual energy balance globally. Please explain how this is so, in terms of both the atmosphere and ocean surface. If the Earth were not tilted, how would the mean energy balance change? Also, how would the details of the climate change (frequency, locations, and intensity of cyclone development both tropical and extratropical, for example) if the Earth were not tilted. Finally, at what angle of planetary tilt would minimize the extremes (warmest coldest) of global temperature? Based upon your answers, comment on the assertion made by one scientists that the current tilt of the Earth has made the planet the most hospitable it could possibly be. Your answers should be presented both qualitatively and quantitatively.

Hart (1hr)

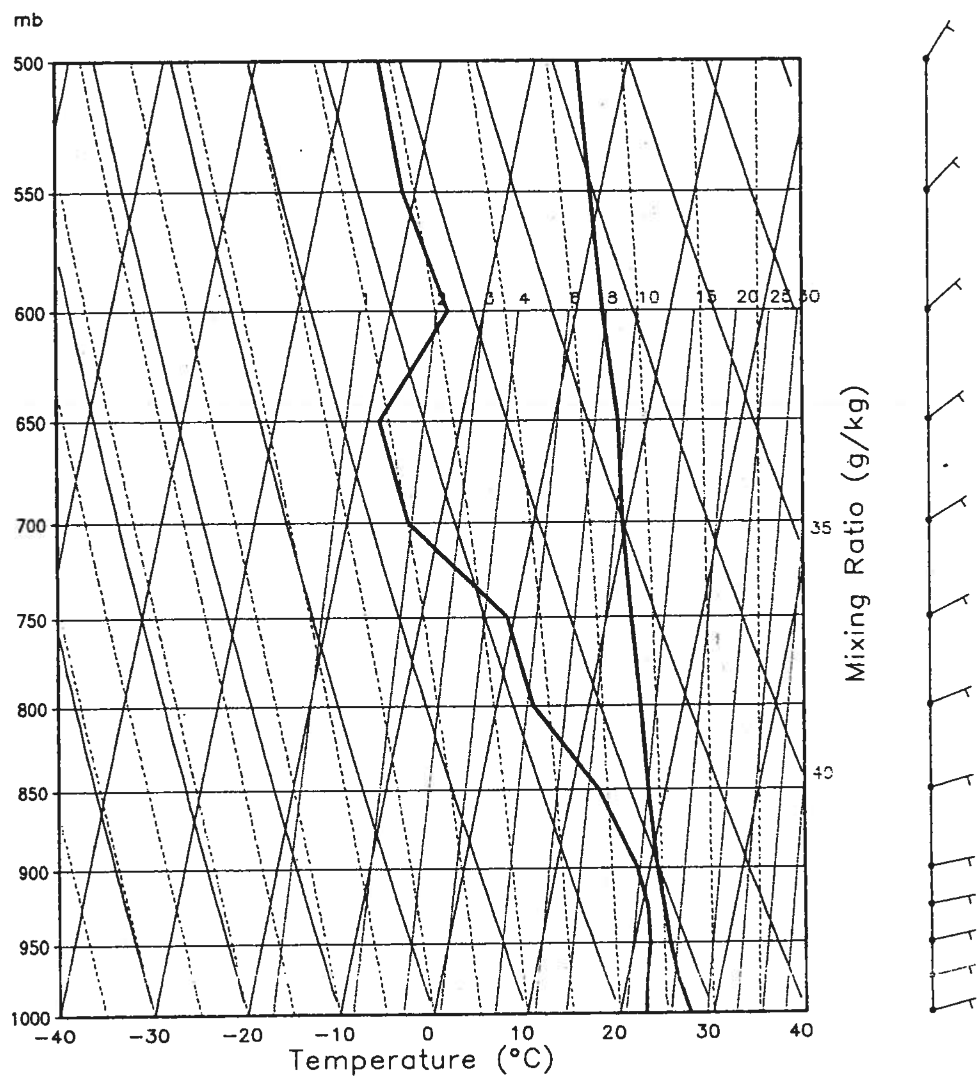
Q2. Although you have yet to begin your PhD research, it might be advantageous to begin to form hypothesis to test. Please speculate, with scientific arguments, on under what conditions you expect the following variables to be conserved. Some of these you should know from your courses, whereas some may require considerable speculation.

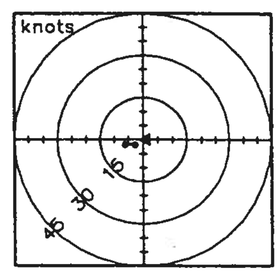
a. Potential temperature – conserved for dry adiabatic ascent
b. Equivalent potential temperature – ″
c. Angular momentum – conserved in flow of ~~type~~ air ascending in the eyewall of a hurr.
d. Dry potential vorticity – Conserved for no advection of temp, or heating ↑.
e. Moist potential vorticity ?

Are there any situations you can think of when all of the above are conserved? How would you formulate experiments to test your hypotheses above?

Hart (45 mins)

Q1. The figure below is the average SkewT (below 500mb) for June-September in the central Gulf of Mexico region. Using this SkewT, and your thorough understanding of WISHE, please explain why, on average, a 26°C SST is required for tropical cyclone formation and intensification. Please now also repeat the process, except for CISK. Now having defended both approaches, explain which of the two (or some combination thereof) you view as valid for explaining tropical cyclone formation and intensification.





K	13
TT	41
PW(cm)	3.15
Surface	
Temp(°C)	27.5
Dewp(°C)	22.8
θ_e(K)	352
LI	−4
CAPE(J)	488
CIN(J)	7
Most Unstable	
Press(mb)	1000
θ_e(K)	352
LI	−4
CAPE(J)	488
CIN(J)	7
Hodograph	
EH	−1
SREH	−1
StmDir	87°
StmSpd(kt)	1

Q3. Hart (1hr)

1. Sketch two cross sections (east-west / height) of an extratropical cyclone. Include contours of potential temperature, wind speed, and the 1 PVU contour for:

   a. A developing extratropical cyclone

   b. A mature (peak intensity) extratropical cyclone

2. Explain the role, quantitatively and qualitatively, that static stability plays in modifying the intensification rate of an extratropical cyclone.

3. Please explain the relationship between surface pressure and temperature & moisture above that point.

4. Based upon your answer in (3), if an extratropical cyclone is cold-core, please explain why it is there is a low pressure in the first place.

5. It has been argued in a global warmed environment that the troposphere will warm and the stratosphere will cool. Please argue how you believe this will lead to a change in the frequency of occurrence of extratropical cyclones, and their intensity distribution. If you do not believe you have enough info to answer this question, state what other information you would need.

a) Numerical modeling has advanced markedly in the past two decades. Resolution has decreased by nearly two orders of magnitude. Computer power has increased by a phenomenal amount. Yet, forecast accuracy of hurricane track has increased by only a factor of 3 or 4. Further, intensity forecasts of hurricanes have only marginally improved given the amazing increase in computer power. Please explain what thermodynamic and dynamic aspects of hurricanes make them so much more challenging to forecast than extra-tropical cyclones. While your answer should be largely qualitative, please attempt to include as much quantitative support of your arguments as possible. Where do you see hurricane track and intensity forecasting in 100 years? Do you expect the current slow rate of accuracy increase to continue, or do you expect a rapid increase in accuracy – or leveling off? Justify your arguments.

b) The predictability of the entire long-wave patter in the northern hemisphere often becomes greatly decreased when a hurricane is recurving from the tropics into the westerlies. Using your understanding of tropical cyclone structure, baroclinic cyclogenesis, QG theory, and teleconnections, please explain why this situation would lead to a rapid decrease in the predictability of the entire long wave pattern.

c) Please explain qualitatively and quantitatively why the surface pressure falls when you warm the troposphere. Please then explain what role this plays in the formation of a tropical cyclone.

Thermal Wind (Hart)

(a) Define the thermal wind mathematically using geostrophic wind vectors, $\mathbf{V}_{g,UL}$ and $\mathbf{V}_{g,LL}$ for arbitrary upper-level and lower-level pressures p_{UL} and p_{LL}.

(b) Write the equation that expresses the geostrophic wind vector, $\mathbf{V}_g$, as a function of the gradient of a pressure surface. (That is, write the geostrophic wind equation.)

(c) Substitute (b) into (a) to express the thermal wind as a function of the gradient of the thickness field, $z_{UL} - z_{LL}$, where z_{UL} and z_{LL} represent the height of arbitrary upper-level and lower-level pressures p_{UL} and p_{LL}.

(d) Write the hypsometric equation for $z_{UL} - z_{LL}$.

(e) Substitute (d) into (c) and derive the thermal wind equation,

$\mathbf{V}_T = (R/f) \ln(p_{LL}/p_{UL})$ **k x grad**(avg(T)),

where R is the gas constant, f is the Coriolis parameter, "ln" is the natural logarithm, **k** is the upward unit vector, "x" is the cross product, "**grad**" is the horizontal gradient operator (commonly represented by an upside-down Delta), and avg(T) is the vertically-averaged temperature between p_{UL} and p_{LL}.

(f) Use the thermal wind equation in (e) to discuss why the westerly wind in middle latitudes typically becomes faster with increasing height in the troposphere. Make a drawing as part of your answer.

(g) Use the thermal wind equation in (e) to explain the location and altitude of jet streams. Why is there a level above which the speed of the jet decreases?

Mid-latitude Synoptics (Hart)

(a) Sketch vertical cross sections showing isobars and isotherms at various levels for:
- (i) A cold-core developing extratropical cyclone
- (ii) A cold-core occluded extratropical cyclone
- (iii) A warm-core tropical cyclone
- (iv) A hybrid (warm-core low-level and cold-core upper level) cyclone

(b) Explain dynamically and thermodynamically how (a) transitions to (b)
(c) Explain dynamically and thermodynamically how (b) transitions to (d)

Synoptic-Physical Meteorology

(a) The dry adiabatic lapse rate is derived from a balance of what two energy types? Under what conditions is this balance valid, and when is it invalid?
(b) Derive the dry adiabatic lapse rate.
(c) A SkewT/LogP diagram contains isobars, isotherms, dry adiabats, saturated adiabats, and nomograms for computing the thickness of standard atmospheric layers. If Earth's gravity were doubled, what about the SkewT/LogP diagram would be altered and what would stay the same?
(d) What does "scale height" mean physically?
(e) If gravity were to double, what would happen to the scale height, assuming that nothing else were to change?

1. Sketch and label well a cross section of the Hadley Cell circulation from the surface to the lower stratosphere from the equator to 30N.

a) Draw and label the tropopause

b) For each of the four "legs" of the Hadley circulation, discuss the conversions among kinetic energy, internal energy, latent heat, and potential energy, all per unit mass.

c). Given approximate magnitudes for each of these components for each of the four legs

d) Why are there easterlies in the tropics and westerlies in the midlatitudes?

2. According to the *Hitchiker's Guide to the Galaxy*, a second version of Earth was created after the Vogons destroyed the original Earth to make way for the Hyperspace Expressway. Although this piece of trivia is entirely irrelevant, it does provide a much more exciting introduction to this problem. This second version of Earth is identical to the original, except for one aspect: The Earth was accidentally set rotating in the opposite direction and at twice the rate as the original. Please discuss the potential changes to:

a) The size and structure of the Hadley Cell

b) Location and intensity of the subtropical jet

c) Atlantic TC genesis

3. Consider a cyclonic vortex in which V/r = A from just off the center out to a radius of 30km (where V = 80m/s). From r=30km outwards, $Vr^{0.5} = B$. Both A and B are constants. V is wind speed and r is radius. Assume that $f = 10^{-4}s^{-1}$.

a. What is the formula for wind speed and vorticity for each segment?

b. What is the formula for Rossby number for each of the two segments?

c. Sketch the Rossby number a function of radius out to 1000km.

d. At what radii is the flow in cyclostrophic balance? Geostrophic balance? Gradient wind balance?

e. What is the angular momentum function for the wind field described by the wind field.

f. Plot the angular momentum out to 1000km radius.

g. Is this vortex field inertially stable? Explain your answer.

h. The thermal wind relationship in the Sawyer-Eliassen balance is:

$$\left(\frac{2v}{r}+f\right)\frac{\partial v}{\partial z}=\frac{g}{\theta_0}\frac{\partial \theta}{\partial r}$$

Discuss how the thermal wind equation above illustrates how an eyewall must tilt outward with height, even without accounting for friction.

i. Please draw an r-z cross section through a hurricane of:
   1. Wind
   2. Angular momentum
   3. Temperature anomaly

4. The dry adiabatic lapse rate is derived from a balance of what two energy types? Derive the lapse rate. Explain during what conditions this balance is valid (and invalid). Next describe how a SkewT/LogP diagram would be different if the gravity of the Earth were doubled. How would this change in gravity influence the scale height of the atmosphere? What does scale height physically mean?

5. Is the coldest temperature at the surface on the planet more extreme (from the mean) than the warmest temperature on the planet? Why is this so? Is a largest percentage of surface area warmer or colder than the mean temperature? Explain your answer.

6. Sketch distance-height cross sections of height and temperature for:
   a. Cold core developing extratropical cyclone
   b. Cold-core occluded extratropical cyclone
   c. Warm-core tropical cyclone
   d. Hybrid (warm-core low-level and cold-core upper level) cyclone

   e. Explain dynamically and thermodynamically how (a) transitions to (b)
   f. Explain dynamically and thermodynamically how (b) transitions to (d)

7. Estimate the total kinetic energy of a typical tropical cyclone. Estimate the total latent heat release in a typical tropical cyclone. Explain why these are different and what this difference quantitatively represents.

9. Explain physically the following typical characteristics of a sounding on a SkewT:
   a. Moist adiabats become parallel to dry adiabats at cold temperatures and low pressure
   b. Moist adiabats are increasingly upright at warm temperatures and high pressure
   c. Even in saturated environment, a temperature sounding often separates from a dewpoint sounding at subfreezing temperatures

10. Derive the thermal wind relationship. Explain how this relationship explains the location and altitude of jet streams.

2. Estimate the total kinetic energy of a typical tropical cyclone. Estimate the total latent heat release in a typical tropical cyclone. Explain why these are different, and what this difference quantitatively represents.

3. Fully compare and contrast CISK and WISHE as mechanisms for tropical cyclone genesis. For a really good answer, include a discussion of the role of vortex Rossby deformation radius in the CISK and WISHE process. Calculate typical values of the radius for a TD, TS, and major hurricane. How does this radius vary vertically within the TC? What does this radius physically tell you?

1. Energetics and Global TC Count

   a. Define each of the terms in moist static energy. Explain how changes in each term are manifested physically.

   b. Explain under what conditions MSE is conserved, and under what conditions MSE is not conserved.

   c. Using reasonable values for the structure of the tropical troposphere, calculate the change in each adiabatic component of MSE between the surface and the tropopause for the entire tropical belt (20S to 20N) in 1 year.

   d. Assuming that MSE is conserved, and the results found in (b), calculate the total diabatic generation necessary to balance MSE during the ascent.

   e. Calculate the mean latent heat release of a tropical cyclone of average lifespan, stating all assumptions.

   f. Using the calculations performed, estimate the annual number of tropical cyclones that are necessary between 20S and 20N to balance MSE.

   g. Compare your result to reality and explain all sources of differences.

2. A field experiment to fill the gaps in CISKE vs. WISHE

   a. Explain the strengths and deficiencies in the CISK and WISHE theories for tropical cyclone intensification.

   b. Design a detailed field experiment that would seek to answer the deficiencies. What would you measure and at what resolution (time and space). What calculations would you perform to seek an answer to resolve the deficiencies in the theories that have not yet been resolved?

   c. Tropical cyclone intensity forecasting has improved barely 10% in 30 years, while track forecasting has improved at least an order of magnitude greater. How much of this 10% to you see as a result of track prediction improvements, and how much do you see as a result of improved understanding of intensification and model physics/resolution improvement. Explain your answer.

   d. What do you predict for the change in intensity forecasting skill over the next 30 years, and why? You will be reminded of your forecast in 40 years at your retirement party, wherever it is, so think hard before answering.