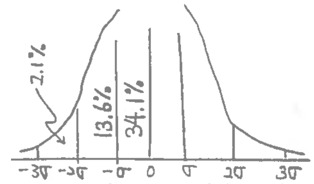
MET5534: Tropical Meteorology II
LaSeur



• Fluxes of momentum, heat & moisture in the tropical boundary layer can be considered from three points-of-view: (1) eddy correlation, (2) mixing-length and (3) bulk-aerodynamic and the sub-cloud boundary layer can be sub-divided into: (1) surface layer of constant fluxes (Prandtl layer), (2) mixed layer (Ekman layer) and (3) transitional layer just beneath cloud base (also part of Ekman layer).

A. Consider Prandtl layer from eddy correlation point-of-view; with density = constant $= 1.0 \text{ kg m}^{-3}$ and wind direction and fluxes constant in the layer.

(1) Show that the stress $\tau = -\rho \overline{u'w'}$ has dimensions of $\left[\dfrac{\text{Force}}{\text{area}}\right] \equiv [\text{momentum flux}]$ and that the appropriate units in SI system = Pascals.

(2) Show that the stress may also be written as: $\tau = -\rho r_{u,w} \sigma_u \sigma_w$ where $r_{u,w}$ = correlation between u and w, σ_u = standard deviation of u, etc.

(3) If $\tau = 0.1 \text{ Pa}$, $r_{u,w} = -1.0$ and $\sigma_u \equiv \sigma_w$, what are values of σ_u and σ_w? If u' and w' are normally distributed what do these values of σ imply about the range in values of u' and w'?

(4) If sensible heat flux $= 10 \text{ W/m}^2$, what would be value for σ_T if σ_w = value from (3) above?

(5) If latent heat flux $F_Q \approx 10^2 \text{ W m}^{-2}$, what is value of σ_q (gm/Kg) for σ_w as in (3) above?

(6) What depth of water (cm per day) must be evaporated from ocean sfc to support $F_Q \approx 10^2 \text{ W m}^{-2}$?

(7) IF all the heat required for $F_H \approx 10 \text{ W/m}^2$ and $F_Q \approx 10^2 \text{ W m}^{-2}$ is supplied by the top one meter of the ocean, what is the cooling rate of the layer in °C per day? (Specific heat of liquid $H_2O = 4.2 \times 10^3 \text{ J kg}^{-1} \text{ deg}^{-1}$)

(8) Observations show that such cooling of the ocean does not occur, discuss briefly why.

B. Consider Prandtl layer from mixing-length point-of-view (K theory).

(1) What form is assumed for u' and w'?

(2) What further assumption is necessary as to dependence of mixing length on z in order to derive "logarithmic wind law"?

(3) Show that these assumptions allow the stress τ_0 be expressed as $\tau = \rho K \dfrac{\partial \bar{u}}{\partial z}$, where K is the "eddy viscosity" coefficient with dimension $\left[\dfrac{\text{m}^2}{\text{sec}}\right]$.

(4) With the assumptions above, how does K depend upon z? What would be values of K @ $z = 10$ m?

(5) If $\tau = 0.1\,\text{Pa}$ and wind obeys logarithmic low, show that $\frac{\partial \bar{u}}{\partial z} = \frac{\bar{u}}{z \ln \frac{z}{z_0}}$ and estimate value of K @ $z = 10$ m if $\bar{u}_{10} = 7$ mps, $z_0 = .025$ cm.

(6) If $F_H = 10\ \text{W/m}^2$, what is value of $\frac{\partial \bar{T}}{\partial z}$?

(7) If $F_Q = 100\ \text{W/m}^2$, what is value of $\frac{\partial \bar{q}}{\partial z}$?

C. Consider Prandtl layer from bulk-aerodynamic point-of-view; which relates fluxes to C_D = drag coeff. And values of T, u, and q at z_a = anemometer height and @ $z = 0$ = sea surface.

(1) Show that stress may be expressed as $\tau = \rho C_{D_a} \bar{u}_a^{2}$ where $C_{D_a} = \frac{k^2}{\left(\ln \frac{z_a}{z_0}\right)}$ and k = 0.4 = von Karman constant.

(2) If $z_0 = 0.4$ cm as given in table 5.1 of Krishnamurti what is value of $C_{D_{10}}$ @ z = 10 m? How does this value compare with value suggested in Krishnamurti text?

(3) $z_0 = .025$ cm was suggested by others, what is value of $C_{D_{10}}$ for this z_0?

(4) Give a brief physical argument in support of the hypothesis that C_D should increase with increasing wind speed over the ocean.

(5) If $F_H = 10\ \text{W/m}^2$, $C_{D_a} = 1.4 \times 10^{-3}$, $\bar{u}_a = 7$ mps, what would be value of $(T_0 - T_a)$?

(6) If $F_Q = 10^2\ \text{W/m}^2$, C_{D_a} and $\bar{u}_a$ as above, what would be value of $(q_0 - q_a)$?

D. Above the Prandtl layer, bulk aerodynamic approach is no longer valid. The classical view of this upper layer is Ekman theory which assumes K = constant and $\tau \to 0$ at top of the layer, with $\tau = \rho K \frac{\partial \underline{V}}{\partial z}$.

(1) The eddy correlation approach states $\tau = -\rho \overline{u'w'}$, assuming the Ekman and eddy correlation approaches are consistent what does this imply as to u' and w' at the top of the Ekman layer?

(2) What does Ekman theory predict for the value of vertical wind shear at the top of the layer where $\tau \to 0$ and $V \to V_{\text{geos}}$?

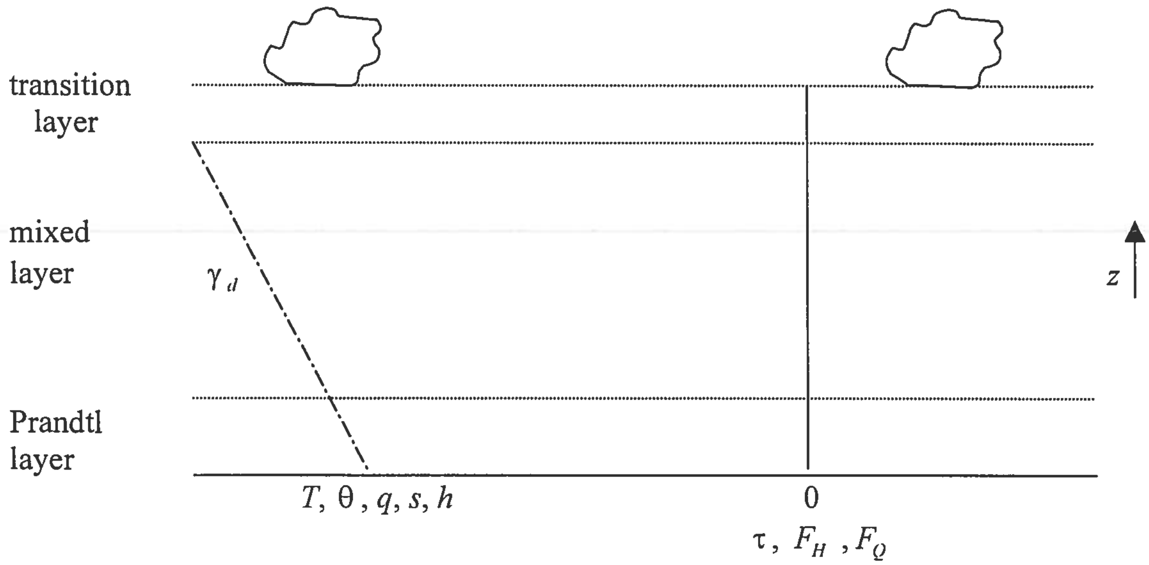
(3) This theory predicts the top of the Ekman layer at $z_{top} = \pi \left(\frac{2K}{f}\right)^{1/2}$, if this is assumed to coincide with cloud base at 700 m what is the implied value of K? (use $f = 5 \times 10^{-5}\,\text{s}^{-1}$)

E. Question

(1) On diagram below sketch typical vertical distributions of T, θ, q, s, and h for the undisturbed tropical boundary layer

(2) Sketch typical vertical distributions of τ, F_H and F_Q for undisturbed trop. BL, indicating typical surface values.

(3) Discuss briefly how the fluxes change in magnitude for "disturbed" conditions.



MET5534 (Tropical II): LaSeur – Mid term

- The lower half of the tropical troposphere is typically convectively and conditionally unstable. As a result the dominant cloud type is cumulus, the development of which involves positive buoyancy forces.

A. Question

(1) Discuss the physical processes that contribute to positive buoyancy in a saturated cloud surrounded by unsaturated environment.

(2) Discuss the physical processes that trend to reduce such positive buoyancy. What can produce negative buoyancy?

Buoyancy $\equiv B$ may be related to vertical acceleration as follows:

$$\frac{dw}{dt} = gB = \frac{dw}{dz}\frac{dz}{dt} = w\frac{dw}{dz} = \frac{d}{dz}\frac{w^2}{2}$$

(3) Consider the simple case of constant buoyancy B and show that for this case $w = (2gB_0z)^{1/2}$ if $w = 0$ at $z = 0$ at the base of the cloud. If $B_0 = 1/300$ what is the value of w at $z = 1$, 3, and 5 km?

(4) Consider a second case in which buoyancy is assumed to decrease linearly with height, i.e., $B = B_0(1 - az)$ with $a = 1/5$ km. At what height will $B = 0$? What is B @ $z = 10$ km?

Show that for this case $w = \left[2gB_0z\left(1 - \frac{az}{2}\right)\right]^{1/2}$. For $B_0 = 1/300$ as above, what is value of w @ 5 km? At what z is $w = 0$?

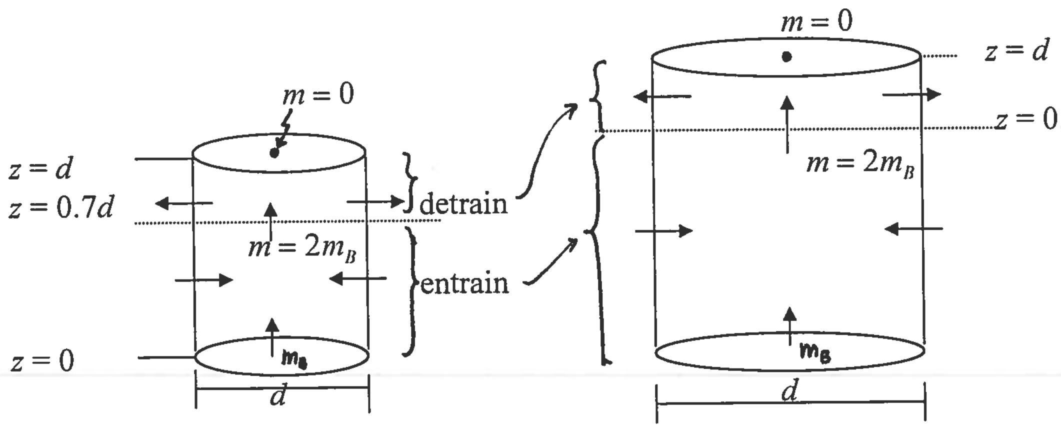
B. Several papers we have read treat cumulus as "entraining plumes" in which the cloud mass flux $= m \equiv \rho w$ is assumed to change by entrainment of environmental mass at a constant rate $= \lambda$, thus

$$\frac{1}{m}\frac{\partial m}{\partial z} = \lambda, \qquad m = \rho w \ \left[\text{Kg m}^{-2}\text{s}^{-1}\right]$$

(1) Show that these assumptions predict that $m = m_B e^{\lambda z}$ where m_B = mass flux at $z = 0$ = cloud base.

Cloud observations suggest that small ☁ have larger values of λ than large ☁, and that ☁ are approx. "square", i.e. that cloud height $\approx$ cloud diameter. Thus assume that $\lambda = 1/d$, d = cloud diameter and that cloud top rises to $z = d$. Further, at $z = 0.7d$ $e^{\lambda z} = e^{z/d} = 2$ so $m = 2m_B$. Assume clouds entrain from $z = 0$ to $z = 0.7d$ and detrain between $z = 0.7d$ and $z = d$. For a small cloud $d = 1$ Km and a larger cloud $d = 10$ km, both with $m_B = 1\ \text{Kgm}^{-2}\text{s}^{-1}$, calculate the cloud scale Divergence = D_c in the entrainment and detrainment layers. To a good approx., $-D_c = \frac{1}{\rho}\frac{\Delta m}{\Delta z}$,

for small cloud use $\bar{\rho} = 1\ \text{Kg m}^{-3}$ for both layers, for large cloud use $\bar{\rho} = 0.5\ \text{Kg m}^{-3}$ for entrain, and $\bar{\rho} = 0.3\ \text{Kg m}^{-3}$ for detrainment.



C. Consider a synoptic-scale area which includes an "ensemble" of many cumulus covering a fractional area = σ with vertical motion = w_c. The "environment" then consists of area = $(1-\sigma)$ with vertical motion $\tilde{w}$. The area-weighted average vertical motion is then = $\overline{w} \equiv \sigma w_c + (1-\sigma)\tilde{w}$.

(1) At cloud base suppose $\overline{w} = 1\ \text{cms}^{-1}$, $w_c = 0.5\ \text{ms}^{-1}$ and $\tilde{w} = 0$, what is value of σ?

If w_c increases upward at rate of 1 ms^{-1} per 2 Km, what are values of $\tilde{w}$ @ 2 and 4 Km if $\overline{w}$ remains constant? Is $\overline{w} = \tilde{w}$ a good approximation?

(2) Similarly, $\overline{q} \equiv \sigma q_c + (1-\sigma)\tilde{q}$ (q = mixing ratio). Show that $\overline{q} \approx \tilde{q}$ is a good approximation.

(3) Also $\overline{qw} \equiv \sigma q_c w_c + (1-\sigma)\tilde{q}\tilde{w}$, using this and $\overline{q} \approx \tilde{q}$ show that the eddy flux $\overline{q'w'} \equiv \overline{qw} - \overline{q}\,\overline{w}$ may be written as $\overline{q'w'} = \sigma w_c\left(q_c - \tilde{q}\right)$ and give a physical interpretation of $\overline{q'w'}$.

(4) The latent heat flux in the cloud layer is mostly accomplished by the cumulus, thus $F_Q = \rho L\overline{q'w'} = \rho L w_c\left(q_c - \tilde{q}\right)$, if $F_Q = 10^2\ \text{Wm}^{-2}$, $\rho = 0.8\ \text{Kgm}^{-3}$, $w_c = 1\ \text{ms}^{-1}$ and $\left(q_c - \tilde{q}\right) = 3\ \text{gm Kg}^{-1}$, what is value of σ?

D. In pressure coordinate ($\omega = dp/dt$), the area-weighted average vertical motion becomes $\overline{\omega} = \sigma\omega_c + (1-\sigma)\tilde{\omega}$ and the continuity equation is $d\omega/dp = -D$ (D = div.). Show that the area-weighted average divergence is then

$$\overline{D} = \sigma D_c + (1-\sigma)\tilde{D}$$

Consider again the small and large cumulus in section B. For the small (shallow) clouds suppose $\overline{D} = -1\times 10^{-5}\ \text{s}^{-1}$ in both the entrainment and detrainment layers. For the large (deep) clouds suppose $\overline{D} = -1\times 10^{-5}\ \text{s}^{-1}$ in the entrainment layer but

$\overline{D} = +1 \times 10^{-5}$ s^{-1} in the detrainment layer. For $\sigma = 1\%$ in both cases, use your values of cloud-scale divergence D_c from section B to estimate values of "environment" divergence for both cases. Is $\overline{D} = \tilde{D}$ a good approximation?

E. Observational studies of actual tropical cumulus ensembles ("cloud clusters") reveal important features not incorporated in the "model" ensembles used in diagnostic studies. Discuss briefly and concisely these important differences between "real" and "model" ensembles including the qualitative differences their inclusion in the models would produce in quantities such as cloud mass flux and environmental heat and moisture changes.
Also discuss briefly important "feed back" interactions with the sub-cloud boundary layer.

MET5534 (Tropical II): LaSeur – Mid term

- The following data have been adapted from the Mean Tropical atmosphere and the GATE composited wave Trough region.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
P (mb)	$\bar{\theta}$ (deg K)	$\bar{q}$ (gm Kg^{-1})	$\frac{\Delta\bar{\theta}}{50\text{m}}$	$\frac{\Delta\bar{q}}{50\text{mb}}$	$\bar{\omega}$ (mb day^{-1})	Q/c_p	Q/c	Q_R	$Q_1 - Q_2 - Q_R$	ΔF $\frac{\text{W}}{\text{m}^2\,50\text{mb}}$	F $\frac{\text{W}}{\text{m}^2}$
						(deg day^{-1})					
200	345.4	0.1			-35			-1.0			
250	341.8	0.2			-45			-1.2			
300	338.7	0.3			-60			-1.3			
350	335.4	0.5			-70			-1.4			
400	332.0	0.9			-85			-1.5			
450	328.3	1.4			-95			-1.5			
500	324.7	2.1			-100			-1.4			
550	321.2	2.8			-100			-1.3			
600	317.8	3.6			-100			-1.3			
650	314.8	4.6			-100			-1.2			
700	312.1	5.8			-100			-1.0			
750	309.4	7.1			-100			-0.9			
800	306.8	8.8			-90			-0.7			
850	304.3	10.8			-65			-0.6			
900	302.0	13.0			-40			-0.7			
950	300.6	15.3									

A. Question

(1) Show that $\bar{s} \equiv \left(c_p\bar{T} + g\bar{z}\right) \approx c_p\bar{\theta}$, and thus that

$$Q_1 \equiv \frac{\partial \bar{s}}{\partial t} + \left(\nabla \cdot \bar{s}\bar{\mathbf{V}}\right) + \frac{\partial}{\partial p}\left(\bar{s}\bar{\omega}\right) \approx c_p\left[\frac{\partial \bar{\theta}}{\partial t} + \left(\nabla \cdot \bar{\theta}\bar{\mathbf{V}}\right) + \frac{\partial}{\partial p}\left(\bar{\theta}\bar{\omega}\right)\right].$$

(2) If $\left(\frac{\partial \bar{\theta}}{\partial t} + \bar{\mathbf{V}} \cdot \nabla\bar{\theta}\right) << \bar{\omega}\frac{\partial \bar{\theta}}{\partial p}$ and can be neglected show that $\frac{Q_1}{c_p} \approx \bar{\omega}\frac{\partial \bar{\theta}}{\partial p}$.

A similar argument (not asked for) gives:

$$\frac{Q_2}{c_p} = -\frac{L}{c_p}\bar{\omega}\frac{\partial \bar{q}}{\partial p}$$

B. For data given above, calculate:

(1) $\frac{\Delta\bar{\theta}}{50\text{ mb}}$, enter values in column 4.

(2) $\frac{\Delta\bar{q}}{50\text{ mb}}$, enter values in column 5.

(3) $\frac{Q_1}{c_p} \approx \bar{\omega}\left(\frac{\text{mb}}{\text{day}}\right)\frac{\Delta\bar{\theta}\text{ (deg)}}{50\text{ mb}} = \left(\frac{\text{deg}}{\text{day}}\right)$, enter values in column 7. (use from column 6)

(4) $\frac{Q_2}{c_p} \approx -\frac{L}{c_p}\bar{\omega}\left(\frac{\text{mb}}{\text{day}}\right)\frac{\Delta\bar{q}}{50\text{ mb}} = \left(\frac{\text{deg}}{\text{day}}\right)$, enter values in column 8. (use from column 6)

(5) $\frac{Q_1 - Q_2 - Q_2}{c_p}\left(\frac{\text{deg}}{\text{day}}\right)$ enter values in column 10. (use from column 9)

(6) Given that the change in cloud "eddy" flux of energy $\Delta F = -\frac{\partial}{\partial p}\left(\overline{w'h'}\right)$ is equal to

$6\ \mathrm{W/m^2}$ per 50mb per $\left(\frac{\text{deg}}{\text{day}}\right)$, convert column 10 to ΔF in column (11).

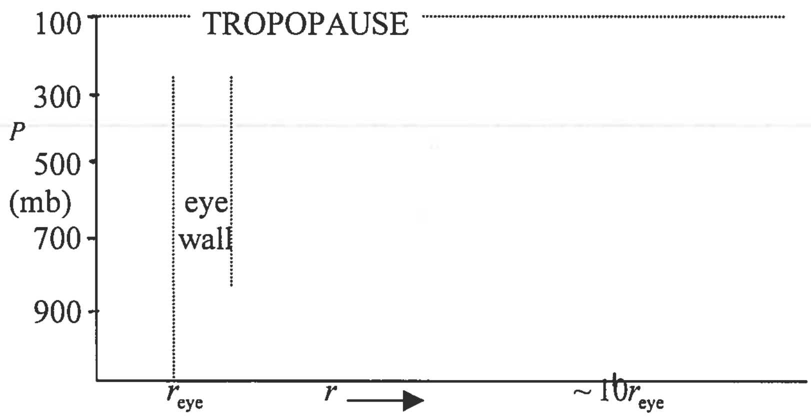
(7) Assuming $F \equiv 0$ at 200mb, accumulate ΔF downward to get F in col. (12). Is the value you obtain at 950mb (cloud base and ~ top of BL) in reasonable agreement with BL turbulent fluxes in convectively "disturbed" regions?

(8) Plot $\frac{Q_1}{c_p}$, $\frac{Q_2}{c_p}$ and F on graph paper provided.

MET5534 (Tropical II): LaSeur – Final exam

- Question

(1) Hurricane temps. are observed to depart significantly from the "mean tropical" atmosphere vales. On the diagram sketch a typical pattern of $\Delta T = (T_{hurr} - T_s)$, the anomaly of hurricane temps. from the mean.



(2) The temp anomalies is (1) are created by diabatic and/or adiabatic processes acting upon initially "mane tropical" air. Discuss these processes responsible for the <u>maximum</u> ΔT shown in (1).

(3) Given that: hydrostatic balance is valid, and that the Tropopause remains undisturbed at $p = 100$mb, and $z = H_T$; show that the height of any pressure sfc z_p is given by:

$$z_p = H_T - \frac{R\overline{T}_v}{g}\ln\left(\frac{p}{100}\right), \quad \overline{T}_v = \text{mean virtual temp } (p \to 100)$$

(4) Further, show that the departure (anomaly) of z_p from its value in the "mean tropical" atmos. $(z_p)_s$ (this departure is called the D value) is given by:

$$D \equiv \left(z_p - z_{ps}\right) = -\frac{R}{g}\ln\left(\frac{p}{100}\right)\left(\overline{\Delta T_v}\right)$$

(5) From your result in (4) and your sketch in (1), explain where you expect the largest magnitude of D values to occur in hurricanes.

(6) The "standard" height of the 900mb sfc in the "mean tropical" atmos = $(z_{900})_s$ = 1054 meters, if the surface (sea-level) pressure in the center of a hurricane is observed to equal 900mb, what must be the average mean virtual temperature departure from the mean (from sfc to tropopause) inside the hurricane eye? What would you estimate the maximum anomaly to be in this case?

MET5534 (Tropical II): LaSeur – Final exam

• Cyclostrophic balance between the wind and pressure fields is a good approximation in the region of maximum winds of hurricanes. Thus:

$$V_{max} \approx V_{cyclo} \approx V_{obs} = V$$

and $K_T V^2 = +\frac{1}{\rho}\frac{\partial p}{\partial r} = +g\frac{\partial D}{\partial r} = fV_g$; V_g = geos. wind.

(1) Given: $V_c \approx V = 50\ \mathrm{ms^{-1}}$, $f = 5\times10^{-5}\ \mathrm{s^{-1}}$, $K_T = \frac{1}{R_T} = \frac{1}{20\mathrm{km}}$; what are the corresponding values of $V_g\ (\mathrm{ms^{-1}})$ and $\frac{\partial D}{\partial r}\left(\frac{\mathrm{m}}{\mathrm{Km}}\right)$?

(2) At the same latitude as in (1) what values of V_g would correspond to the same wind if $K_T = \frac{1}{R_T} = \frac{1}{40\mathrm{km}}$?

(3) Given cyclostrophic balance in a hurricane that is a "permanent type" system (i.e., no change in hurricane structure with time) that translates with a constant speed C along a constant direction, and constant V_g and K_S are around the hurricane then

$$K_T = K_S\left(\frac{V - C_S}{V}\right) \qquad K_S = \text{streamline curv.}$$

Show that under these circumstances the wind speed on the Right-hand side of the hurricane exceeds that on the Left-hand side by an amount = C; i.e. show that:

$$(V_R - V_L) \equiv C$$

(4) The validity of cyclostrophic balance for the wind suggests that the vertical wind shear should correspond to $\frac{\partial V_C}{\partial z}$, the vertical shear of the cyclostrophic wind, show that:

$$\frac{\partial V_C}{\partial z} = \frac{V_C}{2}\left(\frac{1}{V_g}\frac{\partial V_g}{\partial z} + \frac{1}{R_T}\frac{\partial R_T}{\partial z}\right); \qquad \left(\frac{1}{R_T} \equiv K_T\right)$$

(5) The vertical shear of the geostrophic wind is given by: $\frac{\partial V_g}{\partial z} = \frac{g}{fT}\left(\frac{\partial T}{\partial r}\right)_p$; given that $\left(\frac{\partial T}{\partial r}\right)_p = \frac{-3^\circ\mathrm{C}}{10\ \mathrm{km}}$, $T = 300\ \mathrm{K}$, $f = 5\times10^{-5}\ \mathrm{s^{-1}}$, $g \approx 10\ \mathrm{ms^{-2}}$, what is $\frac{\partial V_g}{\partial z}$ in $\left(\frac{\mathrm{ms^{-1}}}{\mathrm{km}}\right)$?

(6) For values of $V \approx V_C$, and V_g from (1), what is $\frac{\partial V_C}{\partial z}$ in $\left(\frac{\mathrm{ms^{-1}}}{\mathrm{km}}\right)$ if $\frac{\partial R_T}{\partial z} = 0$? What change in R_T per km would yield $\frac{\partial V_C}{\partial z} \equiv 0$?

MET5534 (Tropical II): LaSeur – Final exam

• Absolute angular momentum about the axis of a hurricane is defined as $M = vr + f_2 r^2$. Consideration of this quantity illustrates some important aspects of hurricane.

(1) Suppose at an outer radius $r_o = 400\,\text{km}$, $v_o = 8\ \text{ms}^{-1}$ and $f = 6 \times 10^{-5}\ \text{s}^{-1}$, what is the value of M_o @ r_o?

(2) Show that the tangential eqn of motion in cylindrical coord may be written as $\frac{dM}{dt} = 0$ (i.e. M is conserved) if there is no friction and $\frac{\partial p}{\partial \lambda} \equiv 0$.

(3) If air with M_o as in (1) flows into a hurricane in the sfc inflow layer with conservation of M_o to a radius of max wind $r_m = 20\,\text{km}$ what would be the max wind v_m? What does this result imply about $\frac{dM}{dt}$ in actual hurricane inflow?

(4) What change in M_o must occur between $r_o = 400\,\text{km}$ and $r_m = 20\,\text{km}$ if v_m is actually observed to be $= 50\ \text{ms}^{-1}$? If $v_m = 50\ \text{ms}^{-1}$ at $r_m = 40\,\text{km}$?

(5) Suppose the air with $v_m = 50\ \text{ms}^{-1}$ and $r_m = 20\,\text{km}$ at sfc now rises in the eyewall to 200mb with an increase in r_m to 30km but no further change in M, what is the value of v_m @ 200mb?

(6) Now suppose the air @ 200mb in (5) flows outward in the outflow layer with no change in M (i.e. $\frac{dM}{dt} = 0$ in outflow), what will be the value of v when air reaches $r_o = 400\,\text{km}$? At what value of r will $v \equiv 0$ in the outflow under these approximations?

MET5534 (Tropical II): LaSeur – Final exam

• Hawkin's budgets for HILDA give following values for sfc. stress τ, sensible heat flux Q_s and latent heat transfer Q_e for annular areas:

	10-20 nmi	60-70 nmi
τ (dynes cm^{-2})	52	8
Q_s (Joules sec^{-1})	2×10^{12}	2.4×10^{12}
Q_e (Joules sec^{-1})	10×10^{12}	13.5×10^{12}

(1) Convert stress to Pascals, and Q_s & Q_e to Watts m^{-2} and compare these hurricane values to those of the undisturbed tropical boundary layer.

(2) If your values in (1) for hurricanes are interpreted as consistent with the "eddy correlation" point-of-view, what must be the corresponding values of σ_v & σ_w? of σ_T and σ_q?

(3) Consider a column of air in the hurricane inflow layer with a cross-sectional area of $1\ \mathrm{m}^2$, containing 10^3 kg of air that flows inward from a radius r_o where the mean pressure of the column is 975mb to an inner radius r_e with mean pressure = 925mb, with <u>no change of temperature</u> = $25°\mathrm{C}$. How much heat in Joules must be added to the column?

(4) If the added heat is assumed to be entirely due to sensible heat flux from the sea surface what must be the average Q_s in (Watts m^{-2}) if the column moves from $r_o \rightarrow r_e$ in 4×10^4 sec (~11hrs)? How does your value compare with the HILDA values above?

(5) If the average mixing ratio of the column increases by (5 gm Kg^{-1}) from $r_o \rightarrow r_e$, what is the increase in latent heat of the column in Joules? What is the average latent heat flux Q_e in (Watts m^{-2}) necessary to account for this increase? How does this value compare with HILDA budget values?

(6) What is the <u>change</u> in the average potential temperature θ of the column from $r_o \rightarrow r_e$? of the average equivalent potential temperature θ_e?