EAS372 Open Book Final Exam 20 April, 2016

Professor: J.D. Wilson Time available: 2 hours Value: 30%

A. Multi-choice (24 x 2/3% → 16 %)

1. Which option best defines the term "precipitable water" associated with an atmospheric column of unit area, as plotted (e.g. in [mm]) on meteorological maps?
   (a) the maximum cumulative precipitation (expressed as a depth) observed from a given storm
   (b) the maximum cumulative precipitation (expressed as a depth) forecast over 24 hours
   (c) the most probable amount of precipitation (expressed as a depth) from a given storm
   (d) instantaneous column water content expressed as depth resulting if water in all its forms were converted to liquid, and collected at the base of the column (also accepted, ✓✓)
   (e) resulting depth if all water vapour were converted to liquid, and collected at the base of the column ✓✓(definition used by the AMS glossary)

2. Which option is a correct verbal interpretation of the formula

$$\mathrm{D} = \frac{1}{\rho_{\ell w}} \int_0^\infty \left[\, \rho_v(x,y,z) \,+\, \rho_w(x,y,z) \,+\, \rho_i(x,y,z) \right]\, dz$$

   where (ρ_v, ρ_w, ρ_i) with unit $[\mathrm{kg\,m^{-3}}]$ are respectively the absolute humidity, the mass of water per unit volume and the mass of ice per unit volume at height z above the surface, and $\rho_{\ell w} = 1000\,\mathrm{kg\,m^{-3}}$ is the density of liquid water?
   (a) D, having the unit of length, is the precipitable water in the column at (x, y) ✓✓
   (b) D, having the unit of mass, is the precipitable water in the column at (x, y)
   (c) D, having the unit of velocity, is the precipitable water in the column at (x, y)
   (d) D, having the unit of length, is the rainfall that will accumulate at (x, y) from a storm
   (e) D, having the unit of velocity, is the rainfall rate at (x, y)

3. Which of the following restrictions or approximations regarding the quasi-geostrophic (QG) model is **false**?
   (a) frictionless, hydrostatic, extra-tropical motion
   (b) linear variation of Coriolis parameter with north-south coordinate y, viz. $f = f_0 + \beta y$
   (c) Geostrophic wind vector, defined $\mathbf{V}_g = (g/f_0)\,\hat{k} \times \nabla_H Z$ where Z is isobaric height, is non-divergent (i.e. $\nabla_H \cdot \mathbf{V}_g = 0$)
   (d) neglects vertical advection, and neglects horizontal advection of and by the ageostrophic wind
   (e) horizontal velocity divergence ($D = \nabla_H \cdot \mathbf{V}_H = -\partial\omega/\partial p$) is evaluated using the geostrophic wind ✗✗

4. A mean virtual temperature $\overline{T}_v$ for the layer spanning $p_1 \geq p \geq p_2$ appears in the hypsometric equation for the layer thickness, and is defined by

$$\overline{T}_v = \frac{\int_{p_1}^{p_2} p^{-1}\, T_v(p)\, dp}{\int_{p_1}^{p_2} p^{-1}\, dp} \ .$$

If $p_1 = 850$ hPa and $p_2 = 700$ hPa, how much bigger/smaller is the weighting for T_v at the 700 hPa level than at the 850 hPa level?

(a) bigger weighting for $T_{v,700}$ by a factor of 700/850
(b) smaller weighting for $T_{v,700}$ by a factor of 700/850
(c) bigger weighting for $T_{v,700}$ by a factor of 850/700 ✓✓
(d) smaller weighting for $T_{v,700}$ by a factor of 2
(e) bigger weighting for $T_{v,700}$ by a factor of 2

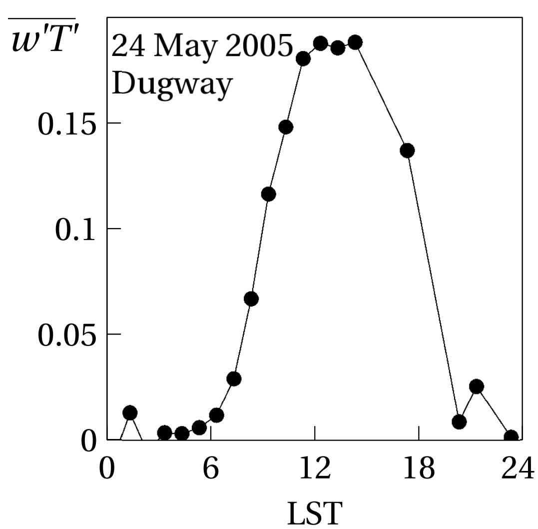
5. The turbulent kinetic energy (TKE) residing in unresolved scales of motion is defined as $k = \left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)/2$, and it is common to write the eddy diffusivity for unresolved transport as $K = \lambda\sqrt{k}$, where λ is a length scale (to be considered *known*) for the unresolved motion. Accordingly, many NWP models employ a simplified conservation equation for k, e.g.

$$\frac{\partial k}{\partial t} = \underbrace{K\left[\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2\right]}_{\text{I}} - \underbrace{\frac{g}{\theta_0}\, K\, \frac{\partial \overline{\theta}}{\partial z}}_{\text{II}} - \underbrace{\frac{k^{3/2}}{\lambda}}_{\text{III}} + \underbrace{\frac{\partial}{\partial z}\left(K\,\frac{\partial k}{\partial z}\right)}_{\text{IV}},$$

where (U, V) are the resolved horizontal velocities and $\overline{\theta}$ is resolved potential temperature (whose mean value for the planet is θ_0). Which interpretive statement is **true**?

(a) term I reflects the tendency of weak winds to result in strong mixing
(b) term II shows that unstable stratification tends to reduce k
(c) term III acts to enhance turbulence (increase k)
(d) a solution for k implies a value for K, enabling flux computations like $\overline{w'\theta'} = -K\partial\overline{\theta}/\partial z$ ✓✓
(e) all terms on the r.h.s. vanish if $K = 0$ (this answer also accepted, as the only reasonable way to have $K = 0$ is to have $k = 0$... thus, ✓✓)

6. The figure plots the kinematic vertical heat flux density $H = \overline{w'T'}$ at $z = 1.4$ m over a desert in Utah. Which inference is **incorrect**?



(a) the sun rose at about 06 LST
(b) the interval 06-18 LST was cloudless
(c) $\rho c_p H$ peaked at roughly 200 W m^{-2}
(d) nocturnally, $|H|$ was small
(e) net radiation switched negative at $\sim$ 15 LST ✗✗

7. Thermal stratification (i.e. a height gradient in mean potential temperature $\overline{\theta}$) exerts a major influence on the state of the atmospheric surface layer (ASL), an influence that is expressed, according to the Monin-Obukhov similarity theory, via the difference from unity of each member of a set of universal functions $\phi_a(z/L), \phi_b(z/L), ...$, where the Obukhov length

$$L = \frac{-\,u_*^3}{k_v\,(g/T_0)\,\overline{w'\theta'}}$$

(symbols have their usual meaning). Which statement is **false**?

(a) to a good approximation the (kinematic) heat flux density $\overline{w'\theta'}$ is height invariant across the ASL (roughly the lowest 50-100 m AGL)

(b) the equation $\overline{w'\theta'} = -\,K_h\,\partial\overline{\theta}/\partial z$, where K_h is the eddy diffusivity for heat, is *empirical* in its origin

(c) the equation $\overline{w'\theta'} = -\,K_h\,\partial\overline{\theta}/\partial z$ is *analogous* to Fourier's law of conduction

(d) the effect of stratification on the state of the ASL is diminished if the wind is strong

(e) in neutral stratification ($\overline{\theta}$ independent of height) the Obukhov length $L = 0$ ✗✗

8. Which option correctly gives the "instantaneous geographic field of view at nadir" for GOES visible and infra-red images, respectively?

(a) 4 km, 1 km

(b) 1 km, 4 km ✓✓

(c) 10 km, 40 km

(d) 40 km, 10 km

(e) 2 km, 8 km

9. Which formula expresses a well-defined (i.e. legitimate) action of the Laplacian operator ∇^2 on an argument? (ϕ is a scalar, and $\mathbf{A}$ a vector.)

(a) $\nabla^2\phi = \nabla\cdot(\nabla\phi)$ ✓✓

(b) $\nabla^2\mathbf{A} = \nabla\cdot(\nabla\mathbf{A})$

(c) $\nabla^2\phi = 2\nabla\phi$

(d) $\nabla^2\phi = \nabla\cdot(\nabla\cdot\phi)$

(e) $\nabla^2\mathbf{A} = \nabla\mathbf{A}\times\nabla\mathbf{A}$

10. Which expression correctly expresses the result ("D") when quantity B with uncertainty range $\pm\epsilon_B$ is subtracted from A (whose uncertainty range is $\pm\epsilon_A$)? (Note: all five symbols carry the same unit.)

(a) $D = (A-B) \pm (\epsilon_A - \epsilon_B)$

(b) $D = (A-B) \pm (\epsilon_A + \epsilon_B)$ ✓✓

(c) $D = (A-B) \times (1 + \epsilon_A/A + \epsilon_B/B)$

(d) $D = (A-B) \pm (\epsilon_A/A + \epsilon_B/B)$

(e) $D = (A-B) \pm (\epsilon_A/A - \epsilon_B/B)$

11. If θ_p is the potential temperature of an air parcel and $\theta(z)$ the potential temperature of the parcel's environment at level z, what quantity is given by the formula

$$W = \int_{\mathrm{LFC}}^{\mathrm{LNB}} g \, \frac{\theta_p - \theta(z)}{\theta(z)} \, dz \; ,$$

where (LFC, LNB) denote the Level of Free Convection and the Level of Neutral Buoyancy?

(a) Convective Inhibition (CIN)
(b) Convectively Available Potential Energy (CAPE) ✓✓
(c) vertical velocity of the parcel in velocity unit
(d) vertical velocity of the parcel in pressure unit ($\mathrm{Pa\,s^{-1}}$)
(e) cloud depth

12. It is considered that on the "synoptic scale," the free atmosphere is in a state of "delicate imbalance." Which option best states what this means?

(a) the pressure profile is almost hydrostatic
(b) the free winds are almost geostrophic
(c) vertical energy fluxes at the base of the atmosphere almost sum to zero
(d) vertical radiative fluxes at the top of the atmosphere almost sum to zero
(e) the pressure profile is almost hydrostatic and the free winds are almost geostrophic ✓✓

13. At mid-latitudes on the synoptic scale the field of vertical motion is controlled by the pattern of advection of which two properties?

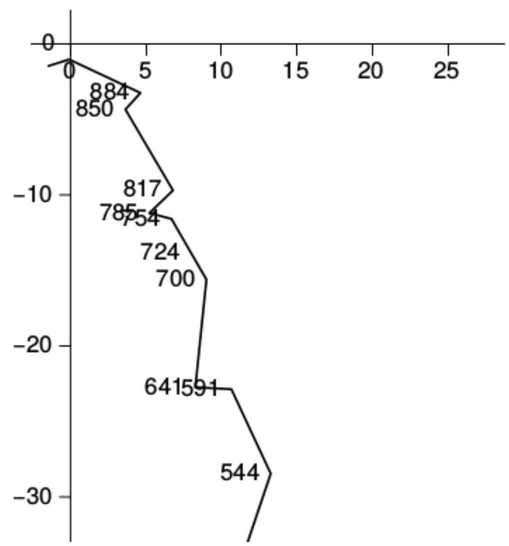
(a) **Q**-vectors and humidity
(b) isobaric height and temperature
(c) vertical vorticity and temperature ✓✓
(d) horizontal vorticity and humidity
(e) temperature and thickness

14. Which pair of properties is conserved in unsaturated, adiabatic, non-entraining parcel motion?

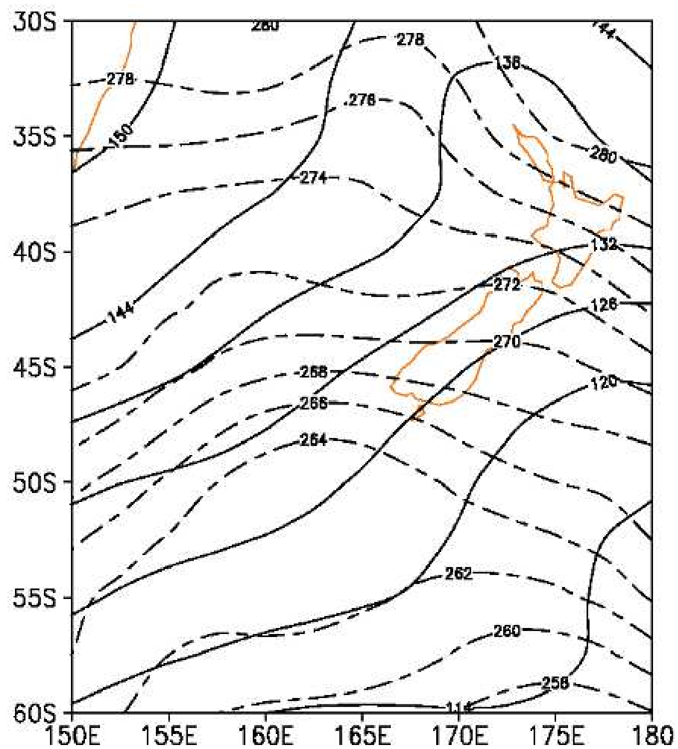
(a) potential temperature and water vapour mixing ratio ✓✓
(b) temperature and dewpoint
(c) potential temperature and dewpoint
(d) density and potential temperature
(e) absolute humidity, and the ratio of pressure over density

15. Suppose that a particular level p of the atmosphere is a 'level of non-divergence' (LND). Which option correctly gives the implication?
    (a) vertical velocity $\omega = 0$
    (b) magnitude $|\omega|$ of the vertical velocity is a local maximum ✓✓
    (c) the horizontal wind is Geostrophic
    (d) on that isobaric plane, stratification is unconditionally stable
    (e) relative vorticity $\zeta = 0$

16. Referring to the hodograph, what name describes the thermal wind for the 700 hPa to 544 hPa layer?
    (a) NNW ✓✓
    (b) SSE
    (c) NNE
    (d) E
    (e) W



17. Referring to this NCEP reanalysis (valid 18 UTC June 30, 1996), which process may one infer was occurring over southern New Zealand?
    (a) frontogenesis
    (b) deformation
    (c) vorticity advection
    (d) cold advection ✓✓
    (e) warm advection



18. Let z be height above sea level; let $h(\theta, \phi)$ be the surface elevation as function of latitude and longitude and p_h be atmospheric pressure at that elevation; $p(z)$ is the pressure at an arbitrary height, and $p_\infty (\ll p_h)$ is the pressure at the 10 hPa level. Which of the following vertical coordinates is **not** a terrain-following coordinate (i.e. **not** constant along $z = h(\theta, \phi)$)?

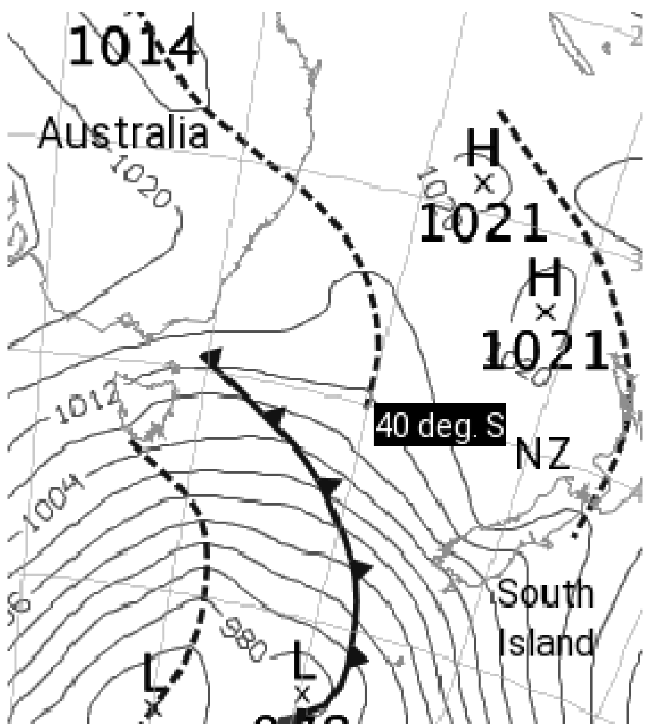
   (a) $z - h$
   (b) $p(z)/p_\infty$ ✗✗
   (c) $p(z)/p_h$
   (d) $[p(z) - p_\infty]/[p_h - p_\infty]$
   (e) z/h

19. Which statement concerning GDPS-GEM (i.e. the twice-daily GDPS runs of the Canadian Meteorological Centre's "Global Environmental Multiscale" model) is correct.

   (a) it uses spectral representation of the horizontal variation in properties
   (b) it uses vorticity and divergence in lieu of the horizontal velocity components
   (c) it is a "primitive equations" model ✓✓
   (d) it is coupled to a dynamical ocean model
   (e) it resolves motion on scales ranging from the global down to about 1 km

20. Which statement is **false**? (Note: the west coast of the South Island of New Zealand — NZ — is defined by a narrow chain of high mountains).

   (a) this is a surface analysis
   (b) dashed lines represent troughs
   (c) a cold front is approaching the South Island
   (d) a lee trough runs along the east coast of NZ's South Island
   (e) another lee trough runs along the South Island's west coast ✗✗



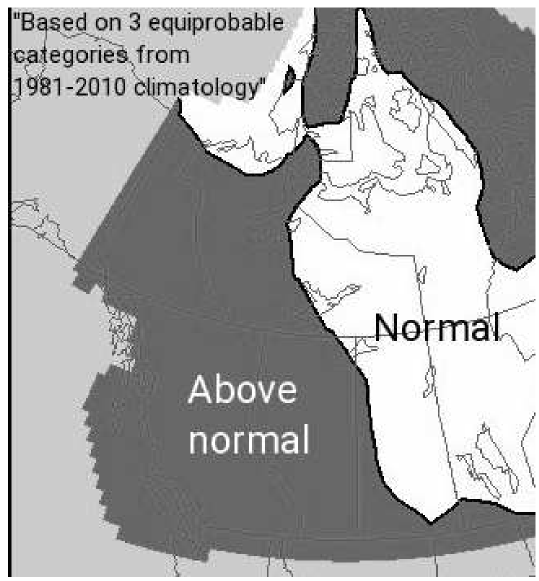
21. Neglecting friction, the horizontal momentum equations in the isobaric coordinate system may be written in the vector form

$$\frac{D}{Dt}\,(u,v) = -\,g\,\left(\frac{\partial}{\partial x},\,\frac{\partial}{\partial y}\right)\,Z\,-\,f\,\,(-v,\,u)\,\,,$$

where f is the Coriolis parameter. Which statement is **false**?

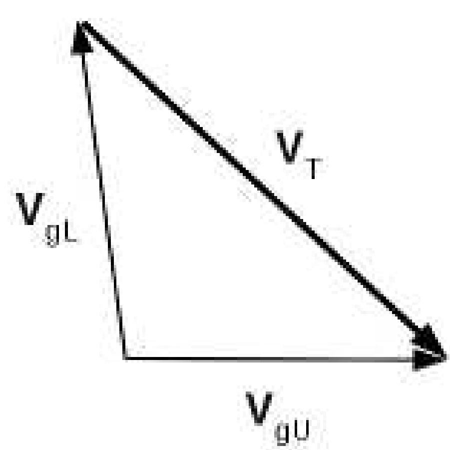
(a) $D/Dt \equiv \partial/\partial t \,+\, (u,v)\,\cdot\,(\partial/\partial x,\,\partial/\partial y)$
(b) Z is the height of the isobaric surface
(c) in "balanced" flow, by definition the left hand side vanishes
(d) the zonal component of the Geostrophic wind is $u_g = (-\,g/f)\,\partial Z/\partial x$ ✗✗
(e) the term involving Z encodes the slope of an isobaric surface

22. This figure is the Environment Canada deterministic categorical surface temperature anomaly forecast for April-May-June 2016, produced 31 March 2016 (ensemble forecast from coupled dynamical atmosphere-ocean-land climate model). Which statement is **false**?



(a) at any point on the map, above-normal, normal and below-normal seasonal temperatures occurred with equal frequency over (1981–2010)
(b) this is a *climate* anomaly forecast
(c) this forecast method would be considered skillful if it proved correct on at least 33% of occasions (in a very long record)
(to make this response *unconditionally* true, the wording should have been "more than 33%")
(d) coupling to an ocean model probably has little impact on skill, for a forecast of the 3-mo anomaly in land surface temperature ✗✗

23. Here $(\mathbf{V}_{\rm gL}, \mathbf{V}_{\rm gU})$ denote the geostrophic wind vector at lower and upper levels of the N. hemisphere free troposphere. Which statement is true?



(a) horizontal divergence is occurring
(b) shearing deformation is occuring
(c) warm advection is occurring ✓✓
(d) isotherms are perpendicular to $\mathbf{V_T}$
(e) thickness contours are perpendicular to $\mathbf{V_T}$

24. Suppose the kinematic vertical heat flux $\overline{w'\theta'}$ decreased linearly to zero at the top ($\delta = 1$ km) of a horizontally-homogeneous ABL, from a surface value of $0.3\,\mathrm{K\,m\,s^{-1}}$. Which option correctly gives the rate of warming $\partial\overline{\theta}/\partial t$ $\left(\equiv -\partial\overline{w'\theta'}/\partial z\right)$?

   (a) $1080\,\mathrm{K\,hr^{-1}}$
   (b) $1.1\,\mathrm{K\,hr^{-1}}$ ✓✓
   (c) $3\times10^{-3}\,\mathrm{K\,hr^{-1}}$
   (d) $3\times10^{-4}\,\mathrm{K\,hr^{-1}}$
   (e) $1.1\times10^{-4}\,\mathrm{K\,hr^{-1}}$

B. Live weather/Short answer (3 x 2 % → 6 %)

1. Record the 1000-500 hPa thickness over the NE corner of Alberta for 12Z today (20 April), as per (i) CMC's 0h RDPS prog [e.g. via Vizaweb: username=vizaweb, password=Bewaziv16!], (ii) NCEP's 0h NAM prog, (iii) the Fort Smith (YSM) sounding. Answers: (i) ≈ 524 dam; (ii) ≈ 524 dam; (iii) 525 dam. (For (i), (ii) answers differing by up to ±2 dam from those stated here were accepted.)

2. Compute the 12Z (today, 20 April) vapour pressure and absolute humidity at the 850 hPa level from (T, T_d) based on the Stony Plain (WSE) sounding. Answers: with $T_\mathrm{d} = -16.8$°C, $e = e_*(-16.8°\mathrm{C}) = 1.646$ hPa (following the EC convention). This implies the absolute humidity $\rho_v = 165/(462\times(273.15+5.2)) = 1.28\times10^{-3}\,[\mathrm{kg\,m^{-3}}]$

3. The Table below gives values of mean wind speed $\overline{u}$ at several heights z. Plot this wind profile on the blank graph paper at the back of the exam, and deduce the friction velocity u_* on the assumption that

$$\frac{\Delta\overline{u}}{\Delta z} = \frac{u_*}{k_v}$$

   where the von Karman constant $k_v = 0.4$. Typo here: formula **should** have been $\Delta\overline{u}/\Delta(\ln z) = u_*/k_v$, which would (correctly) have implied $u_* = 0.45\,\mathrm{m\,s^{-1}}$. However answers based on the given (wrong) formula, which yields $u_* = 0.31\,\mathrm{m\,s^{-1}}$, were also accepted.

z [m]	$\overline{u}$ [$\mathrm{m\,s^{-1}}$]
10.0	7.00
5.0	6.22
2.0	5.19
1.0	4.41
0.5	3.63
0.2	2.59

C. Weather chart interpretation. ($\rightarrow$ **8%**)

On 17 July 2015 Edmonton International Airport (YEG) reported 37.4 mm of rain, the rainfall being continuous from midnight through 11 MDT and the rainfall rate being qualified as "moderate" for six of those hours and "heavy" at 03 MDT (or 09Z). Edson, roughly 200 km west of Edmonton, reported 10.5 mm of rain that day, while Lloydminster, roughly 200 km east of Edmonton on the Saskatchewan border, reported 10.8 mm.

Figures (1 – 9) are valid at (or near) 12Z July 17th ("t_0"), while Figures (10 – 13) give a sequence of 500 hPa analyses bracketing t_0. Based on this information, **interpret the meteorology underlying this event**. Your response may be either in point or in essay form.

In hindsight, it's a pity the rainfall figures for Edson and Lloydminster were given: it was not intended that the analysis should go so far as to cover why they might have received less rain than YEG, and with the limited information provided this was a tall order. Be that as it may....

Some key points:

1. surface trough extends into east-central AB from Saskatchewan; closed low aloft (seen at every mandatory level)
2. in effect, a deep low pressure system, centred broadly over C. Saskatchewan and without systematic tilt (can be called a cutoff low)
3. temperature and thickness gradients over Alberta rather weak: would be hard to argue this was frontal rain
4. sounding shows an atmosphere nearly saturated to the tropopause, and neutrally stratified w.r.t. moist adiabatic motion (i.e. no energy penalty preventing deep vertical motion)
5. broad area of ascent, with YEG away from the max but seeing $\omega_{700} \sim -0.2\,\mathrm{Pa\,s^{-1}}$ (roughly $2\,\mathrm{cm\,s^{-1}}$)
6. sequence of 500 hPa charts shows a slowly moving system, i.e. prolonged event
7. convergent surface winds in YEG region (see triangle of three nearest stations) due to the trough
8. some high cloud tops embedded in the shield of cloud over C. and S. Alberta, forecasters commenting on convection – thus cores of stronger vertical motion
9. strong 850 hPa northerly over C. Alberta, weaker wind aloft – low level jet
10. despite the strong 850 hPa wind, weak (if any) thermal advection at that level; a hint of (weak) wrap-around warm thickness/temp. advection over north-central Ab (Figs. 2, 5)
11. as a summative statement: precip resulting from the lifting of a deep layer of saturated air, the lifting mechanism being not altogether clear, not frontal, but certainly *associated* with the disturbances engendered by a deep, slow-moving low pressure system

Lesser or less definite points, or points whose implication (relative to the rainfall amount) is uncertain:

1. low temperature-dewpoint spread at 700 hPa over Ab is consistent with the sounding (but this is the kind of consistency we expect, so barely worth a mention)

2. tight isobar packing in C. Alberta, resulting in a strong NW surface wind (e.g. $10 \mathrm{m\,s^{-1}}$ at Red Deer)
3. Edson, west of YEG, would perhaps not have seen as much ascent as YEG — though this is speculation as we don't have a full time history
4. complicated wind profile
5. in terms of "setting" for the closed low, the jetstream rounds a ridge offshore from B.C. then dives steeply south though eastern BC into the U.S. (Highly meridional pattern).
6. based on the single closed thermal contour (thickness or T_{500}) associated with the low (evident respectively on Figs. 2,6), it might be justifiable to apply the term "cold core low"

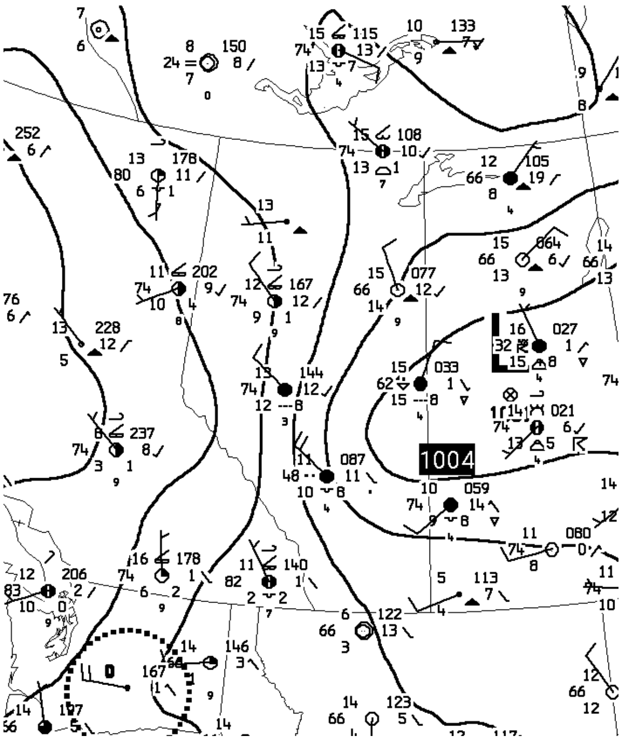


Figure 1: CMC surface analysis.

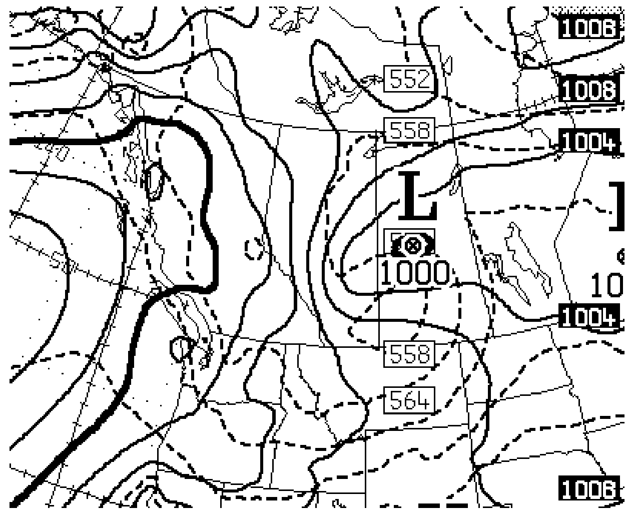


Figure 2: MSLP and thickness (GEM 0h prog).

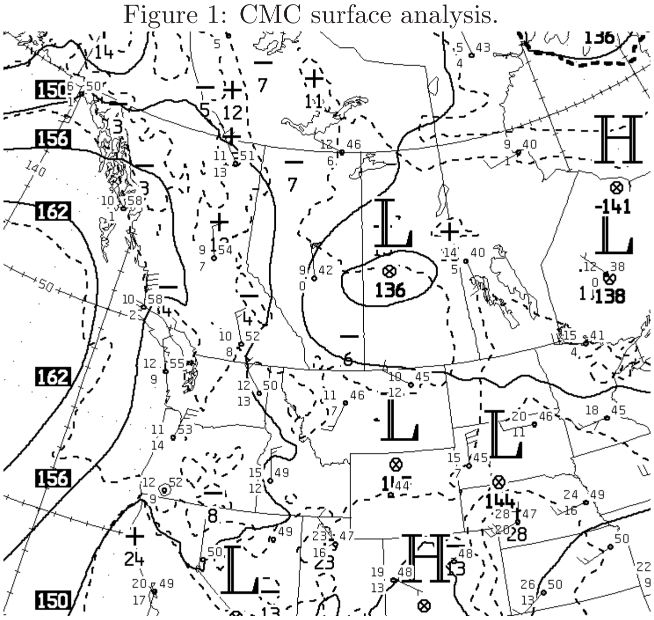


Figure 3: CMC 850 hPa analysis. (Edmonton's 850 hPa wind: northerly, 51 knots.)

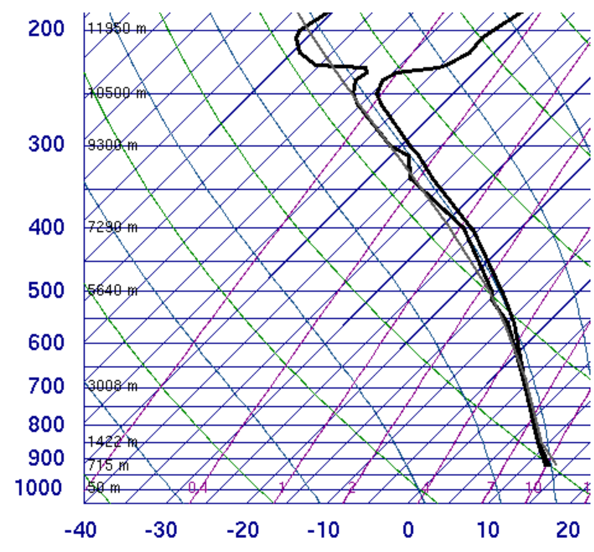


Figure 4: Stony Plain (WSE) sounding.

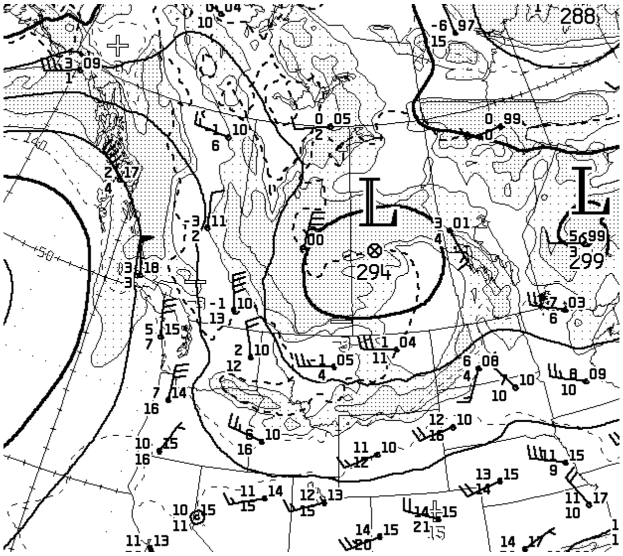


Figure 5: CMC 700 hPa analysis (dense stippling, $T - T_\mathrm{d} \leq 2°$).

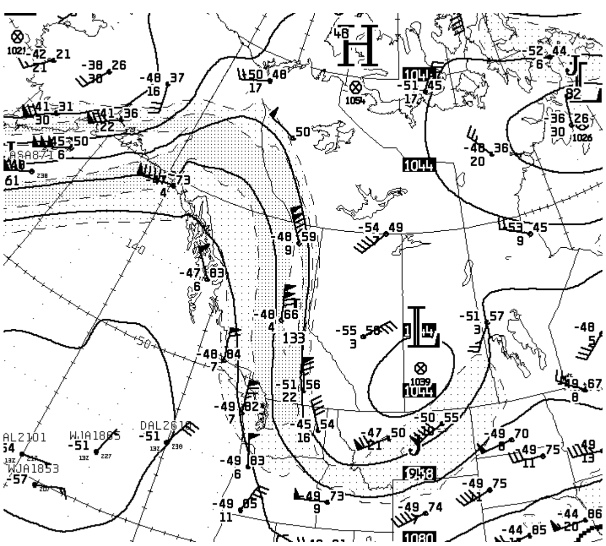


Figure 7: CMC 250 hPa analysis.

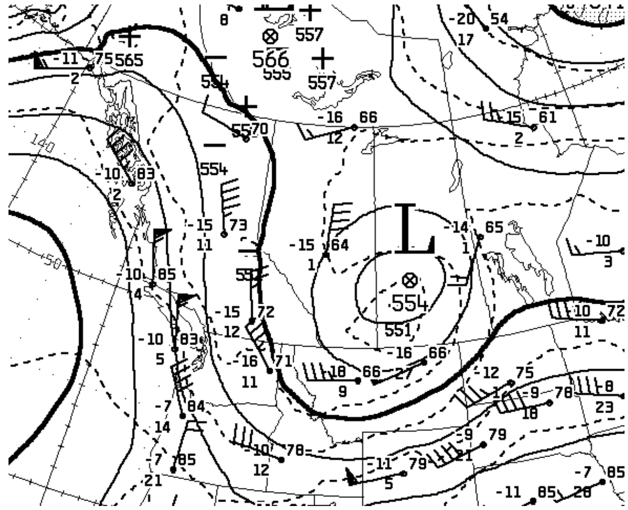


Figure 6: CMC 500 hPa analysis 12Z.

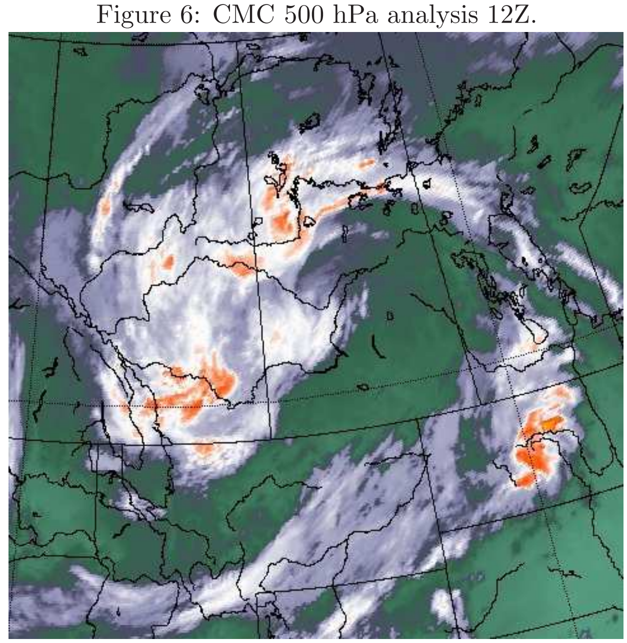


Figure 8: GOES ir image 1430Z, 17 July 2015. (EC forecasters at 12Z: "ir imagery shows a lot of convection associated with the system".)

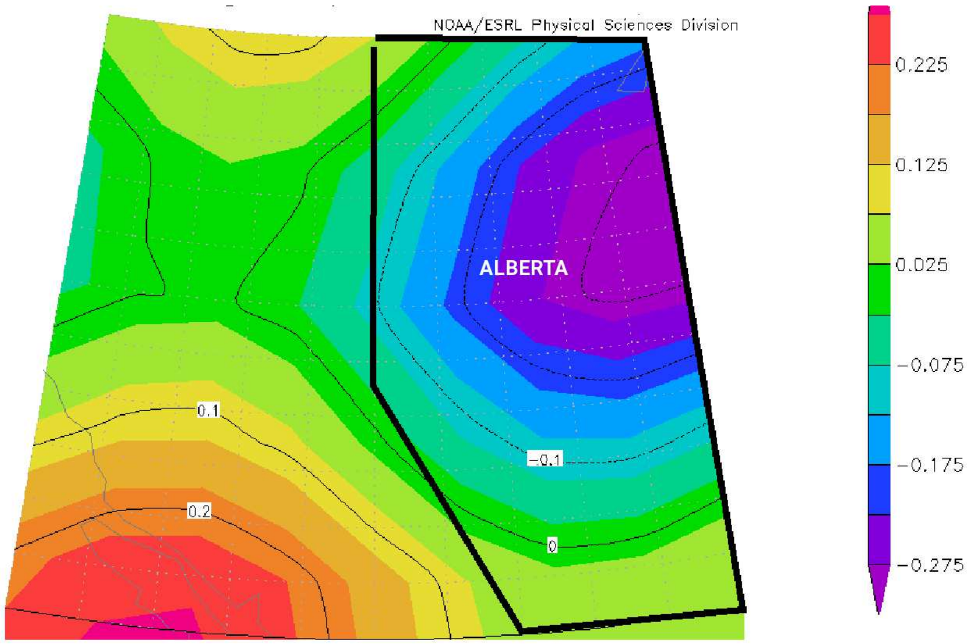


Figure 9: Omega at 700 hPa [$\mathrm{Pa\,s^{-1}}$], 12Z 17 July 2015 (NCEP1 reanalysis).

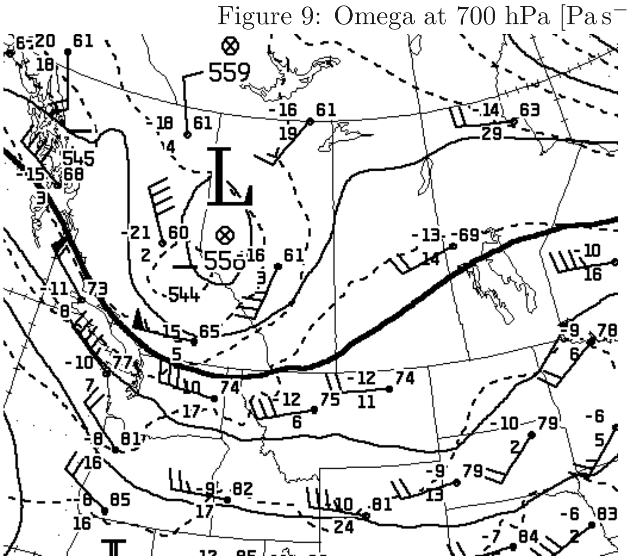


Figure 10: CMC 500 hPa analysis 12Z 16 July.

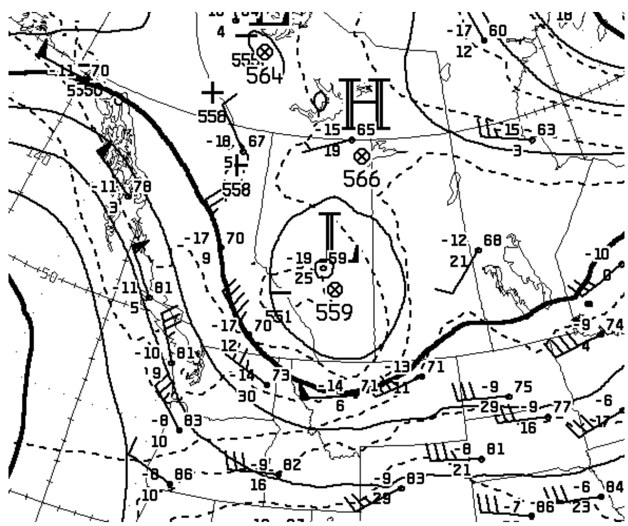


Figure 11: CMC 500 hPa analysis 00Z 17 July.

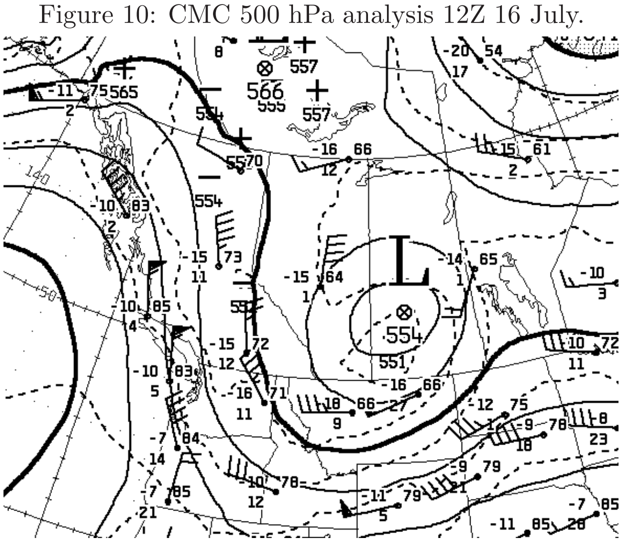


Figure 12: CMC 500 hPa analysis 12Z 17 July.

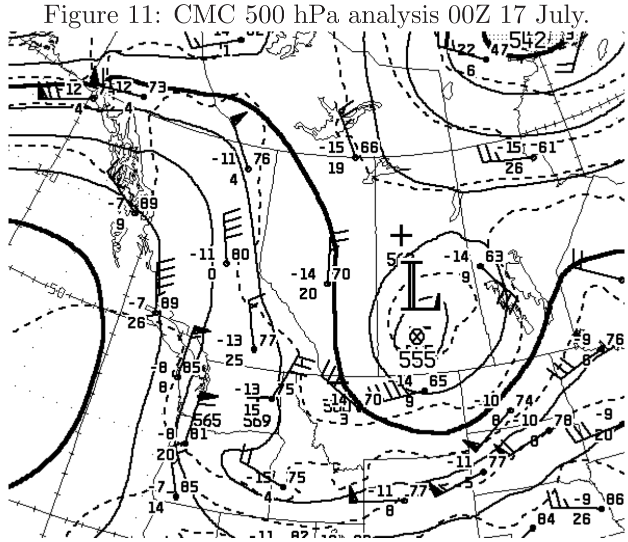


Figure 13: CMC 500 hPa analysis 00Z 18 July.