EAS372 Final Exam 19 April, 2010

Professor: J.D. Wilson Time available: 2 hours Value: 35%

Please answer all questions in the Examination Booklet.

A. Multi-choice (9 x 1 $\rightarrow$ 9 %)

1. The CMC (Canadian Meteorological Centre) "Global Environmental Multiscale" (GEM) model for Numerical Weather Prediction (NWP) ____

   (a) uses vorticity and divergence in lieu of the horizontal velocity components

   (b) is a "primitive equation" model, i.e. formulated explicitly in terms of the horizontal velocity components (and other necessary variables) ✓✓

   (c) is coupled to a dynamical ocean model

   (d) resolves atmospheric motion on a range of scales from the global down to finer than one kilometer

2. For the regional run, GEM's timestep is ____

   (a) 6 hr

   (b) 3 hr

   (c) 15 min

   (d) 7.5 min ✓✓

3. Suppose the potential temperature of an unsaturated parcel at 730 mb happened to be $\theta = 260$ K. If this parcel were to undergo an adiabatic motion that resulted in its descent to 930 mb, its potential temperature would be ____

   (a) 258 K

   (b) 260 K ✓✓

   (c) 262 K

   (d) insufficient information is given to determine the answer

4. If ϕ is a conserved variable and $\vec{U}$ the 3D velocity vector, then ____

   (a) $d\phi/dt = \partial\phi/\partial t$

   (b) $\partial\phi/\partial t = -\vec{U} \cdot \nabla\phi$ ✓✓

   (c) $\partial\phi/\partial x = \partial\phi/\partial y = \partial\phi/\partial z = 0$

   (d) $\vec{U} \cdot \nabla\phi = 0$

5. In the N. hemisphere the thermal wind vector is oriented ____ to the isotherms with cold air on its ____

   (a) parallel; left ✓✓
   (b) perpendicular; left
   (c) parallel; right
   (d) perpendicular; right

6. Which of the following properties is conserved by an unsaturated parcel undergoing adiabatic, non-entraining vertical motion?

   (a) temperature
   (b) dewpoint
   (c) density
   (d) water vapour mixing ratio ✓✓

7. According to the quasi-geostrophic model, the evolution of mid-latitude, synoptic scale weather fields is primarily determined by ____ advection of ____

   (a) horizontal; vertical vorticity and temperature ✓✓
   (b) horizontal; humidity and temperature
   (c) vertical; horizontal vorticity and temperature
   (d) vertical; humidity and temperature

8. The 'eddy diffusion paradigm' is applied in GEM to parameterize ____

   (a) deep convection
   (b) stratiform cloud
   (c) horizontal heat and vapour transport in the ABL by unresolved eddies
   (d) vertical heat and vapour transport in the ABL by unresolved eddies ✓✓

9. If (over some region) a particular level p of the atmosphere is a 'level of non-divergence' (LND), then at that level ____

   (a) vertical velocity $\omega = 0$
   (b) the magnitude $|\omega|$ of the vertical velocity is a local maximum, i.e. $\partial|\omega|/\partial p = 0$ ✓✓
   (c) atmospheric stratification is unconditionally stable
   (d) relative vorticity $\zeta = 0$

B. “Live” web weather data (7 x 1 $\rightarrow$ 7%)

Please access the internet for today’s 12Z data, i.e. sounding(s), analyses, etc.

1. At 12Z today the height (ASL) of the 850 hPa surface at The Pas (Manitoba, YQD) was: 1533 m

2. At 12Z today the 700 hPa wind direction at Fort Smith (YSM, located near the northern border of Alberta) was: 195 degrees

3. At 12Z today the dominant meteorological feature(s) or weather system(s) affecting western Canada are: *a longwave ridge (visible e.g. at 500 hPa) centred roughly over Saskatchewan, and a more-or-less coincident thickness ridge. The height pattern is broadly that of the Omega block.*

4. At 12Z today the true surface pressure at Kelowna (WLW, in southern British Columbia) was 961 hPa

5. At 12Z today the 1000-500 hPa thickness at Kelowna was: $5630 - 121 = 5509$ m

6. From the 0-hr GEM Regional forecast valid at 12Z today, the largest *magnitude* of the vertical velocity ω [$\mathrm{Pa\,s^{-1}}$] at the 500 hPa level over Newfoundland[1] was: -0.5 to -1.0 $\mathrm{Pa\,s^{-1}}$. This corresponds to: ascent

7. From a forecast sounding valid 00Z April 20, based on the NAM forecast initialized at 12Z today (April 19), the temperature and relative humidity at 650 hPa over Calgary (CYYC) are predicted to be: $T = -4.4^{o}$C, RH= 28%

C. Interpretation of weather situation. (2 x 5 $\rightarrow$ 10%)

1. Contrast the two winter weather regimes summarized by Fig.(1).

2. Focusing on the extreme NE corner of Alberta and according to what is conveyed by Fig.(2), how has the weather evolved from 00Z to 12Z that day (11 Jan., 2010) — and by what mechanism?

[1] Newfoundland was substituted here on the day of the exam for Manitoba — vertical velocity over the latter having been negligible at the time of interest.

Answers to C. Interpretation of weather situation.

1. This was an exercise challenging students' skill in seeing the forest instead of the trees, so to speak — in sorting out what is *most important*, or at least, what is *unambiguous* and *most* relevant — what gives the most enlightenment, for minimum expense of words. I ought to have specified *Alberta* or *Western Canadian* weather regimes, and so the question was marked in such a manner as not to favour anyone who tacitly assumed that focus, nor penalize anyone who did not. In the Table below I have not listed every detail that could be found in the maps, for to have done so would undermine my point: we are trying to find the big picture here, and in many cases the specifics are consequences of the big picture (positions of longwaves ridges and troughs, for example), and so, inherently less worthy of being remarked.

   With this sort of question, responding with a torrent of words — and particularly if these do not evidence any obvious ordering principle — may work against you. Five short points would suffice to gain you full marks, here. Thus, focus on the big things, not the details.

Table 1: Salient *differences*

Feature	24 Jan	1 Feb
Flow aloft	Firm W. or SW. over W. Cda.	Strong northerly
Longwave pattern	Trough offshore "ventilates" W. Cda	Ridge offshore blocks air-land flow
Longwave pattern (ctd.)	Tr/Rdg/Tr config. hardly an Ω-blk	Definite Ω-block, centred offshore
Thickness field	Ridge over B.C., Ab.	Trough over entire northern N. Am.
Dominant low-level feature	Ab. lee trough	Arctic ridge
850 hPa thermal field	Mild over Ab.	Cold
" "	Thermal ridge over B.C.	Freezing contour pushed to W. coast
Surface isobar spacing	Tight over B.C. & Rockies	Tight over prairies
Surface temperature	Mild	Less mild
Pattern	Mild – Pacific influence	(Potentially) cold – Arctic influence

   The question invited you to find *contrasts*. Some valid points of similarity were made, too... e.g. that on both days ∇T_{850} is oriented SW↗NE across the prairies, with colder air to the NE. However in this sort of context it is always best to take your cue from the way the question is posed — similarities here contribute less to the coherency of your "story" (i.e. the story the instructor has asked for) than the differences, so you want to concentrate on the latter.

2. The region of interest is very specific, and the radiosonde report for Fort St. John (YSM) is helpful.

   - There is a very strong ∇T_{850} in the area of interest throughout the time period
   - However at 00Z there is no wind in the region of interest, as reported. This is qualitatively consistent with the widely separated 850 hPa height contours at 00Z, whose configuration, moreover, suggests we could get intensification of ∇T (as indeed the maps confirm)

- But overnight the height gradient in the region of interest strengthens, and a SW wind picks up (WSW at 10 $\mathrm{m\,s^{-1}}$ by 12Z at YSM.
- The component of this wind that is perpendicular to the isotherms results in *warm advection* in the area of interest
- The consequence is advective warming, as confirmed by the 15°C increase in T_{850} reported at YSM
- It is not unreasonable to speak of a warm front, although there isn't a lot of definite guidance on that — just the strong ∇T and (at 12Z) a trough running roughly W-E over the region
- In summary, it got windier and (consequently, by virtue of the pre-existing ∇T) warmer in the area of interest
- Hard to tell on the given evidence *why* ∇p strengthened in the area of interest — one student suggested incipient lee cyclogenesis in the (undoubted) lee trough. This was speculation, but insightful and relevant speculation

D. Calculations (3 x 3 → 9 %)

1. Estimate the height above ground of the GEM model's $\eta = 0.995$ surface, given that at the surface $p = p_S = 910$ hPa and $T = 20$°C. Compute also the density ρ at $\eta = 0.995$, assuming the $1 \leq \eta \leq 0.995$ layer is neutrally stratified
2. Referring to Fig.(2), compute the rate of temperature advection at 12Z on the 850 hPa surface at the extreme NE corner of Alberta
3. Referring to Fig.(3), and taking the reference pressure as being 1000 hPa, determine the potential temperatures of parcels of air at the 700 hPa and the 500 hPa level. Compute the absolute humidity and the relative humidity of surface parcels.

Answers to D. Calculations.

1. Properties at an η surface. This entailed:

   - correctly extracting p for the $\eta = 0.995$ surface, mostly an exercise in the understanding of English and conventions of English usage in science: answer, $p_\eta = 905.5$ hPa
   - application of the hydrostatic law to deduce over what distance Δz the pressure drops from the surface value (910 hPa) to 905.5 hPa, and this application necessitated estimating the density.

     This is most appropriately done for the level where you *do* know both pressure and temperature, viz., at the surface: $\rho_{sfc} = 1.082\ \mathrm{kg\,m^{-3}}$

     Then, $\Delta z = 42.4$ m
   - To get the density at the $\eta = 0.995$ level you need the temperature, and this is obtained by assuming an adiabatic lapse rate (you were given that the layer is neutrally stratified): $T_\eta = 20 - 0.01 \times \Delta z = 19.58$°C. The resulting density is very slightly lower than surface density, $\rho_\eta = 1.078\ \mathrm{kg\,m^{-3}}$

2. Rate of temperature advection:

   - Estimate the strength of the temperature gradient. For example, I took the distance between the freezing contour and the -15^{o}C contour, measured normal to the freezing contour and passing through the NE corner of Alberta. My ruler distance was $d = 14$ mm. The corresponding true distance can be taken from the length of the eastern border of saskatchewan (which happily, was not cropped off the diagram). My ruler distance for this was $D = 75$ mm, while the true distance is $D_{true} = 11 \times 111,000$ m.
   - Thus, $\Delta T/\Delta s \approx -15 \times (d/D \times 11 \times 111,000)^{-1} \approx \frac{-15\text{ K}}{2.28\times10^5\text{ m}}$. Of course one makes arbitrary choices in the above calculation, and there is not a uniquely correct answer.
   - For the needed wind speed, I expected you would take the value from the nearby Fort St. John radiosonde, viz. $10\ m\, s^{-1}$, however, I applied a penalty of $\frac{1}{2}$ mark if you did not at least indicate the necessity in principle to take the component normal to the isotherms. I estimated that $v = 10 \cos\alpha$ where $\alpha \sim 40^{o}$ was my guesstimate for the angle of the wind relative to the normal — giving about $v \approx 8\text{ m s}^{-1}$.

     Some of you chose to compute the Geostrophic wind speed. Again, this entails arbitrary choices. So long as there was no obvious error in the calculation, this was fine, and I did not fuss over the specific value obtained, so long as it was reasonable.
   - The resulting rate of advection, according to my calculation, was

$$A_T \equiv -v\,\frac{\Delta T}{\Delta s} \approx +5 \times 10^{-4}\text{ K s}^{-1} \approx 2\text{ K hr}^{-1}$$

   - A $\frac{1}{2}$ mark penalty was implied if the wrong sign was given; a 1 mark penalty was assigned if the mistake was made of adding 273.16 to the ΔT between chosen isotherms

3. Thermodynamic properties computed for sounding.

   - Read off temperatures as $T_{500} \approx -26 \pm 1^{o}$C or 247K, and $T_{700} \approx -7 \pm 1^{o}$C or 266K. Then apply the formula for potential temperature: answers, $\theta_{500} \approx 302$ (or 29 Celcius), and $\theta_{700} \approx 295$ K (or 22 Celcius). *I also accepted the (arguably less accurate) estimates one could obtain by following a dry adiabat down to 1000 hPa level.*
   - Read off surface temperature and dewpoint as $T \approx 14 \pm 1^{o}$C and $T_d \approx 1^{o}$C. Use given tabulation of $e_s(T)$ to infer that the actual vapour pressure $e = e_s(T_d) = 6.57$ hPa, while the benchmark value $e_s(T) = 15.98$ hPa
   - Thus RH$= 6.57/15.98 = 0.41$ and $\rho_v = 657/(462 \times (273.16 + 14)) \approx 5 \times 10^{-3}\text{ kg m}^{-3}$ (units mandatory).

Equations and Data.

- one full barb on the wind vector corresponds to about 5 m s^{-1}, and 1 degree of latitude corresponds to a distance of 111 km

- $v = \frac{g}{f} \frac{\Delta h}{\Delta n}$

  The Geostrophic wind equation. Δh [m], the change in height of a constant pressure surface over distance Δn [m] normal to the height contours; $f = 2\Omega \sin\phi$ [s^{-1}] the Coriolis parameter (where Ω is the angular velocity of the earth, and ϕ is latitude); g acceleration due to gravity.

- $\frac{dA}{dt}$ and $\frac{\partial A}{\partial t}$

  Respectively the Lagrangian (or "material") time derivative (time derivative following the motion) and the local (fixed-point) time derivative ("local tendency") of an arbitrary atmospheric property A. The two time derivatives are related by the equation

$$\frac{dA}{dt} \equiv \frac{\partial A}{\partial t} + \vec{U} \cdot \nabla A \equiv \frac{\partial A}{\partial t} + U \frac{\partial A}{\partial x} + V \frac{\partial A}{\partial y} + W \frac{\partial A}{\partial z}$$

  where U, V, W are the three velocity components in a Cartesian coordinate frame

- $D_p \equiv \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$

  The horizontal divergence, expressed in Cartesian coordinates (x parallel to lines of latitude, increasing towards the east; y parallel to lines of longitude).

- $D_p \equiv \frac{\partial v}{\partial s} + v \frac{\partial \beta}{\partial n}$

  The horizontal divergence, expressed in natural coordinates. The unit vector $\hat{s}$ points downstream, i.e. it is parallel to height contours in the free atmosphere. The unit vector $\hat{n}$ is normal to $\hat{s}$ and points to its left. The angle β is the inclination of flow relative to lines of latitude, with $\beta = 0^o$ being a zonal flow and $\beta = 90^o$ being a meridional flow. The first term is the stretching term. The second term is the diffluence term, and is positive if the channel widens downstream (ie. widens with increasing s).

- $\frac{\partial p}{\partial z} = -\rho g$

  The hydrostatic law, giving the rate of change of pressure p [Pascals] with height; ρ [kg m^{-3}] the density; $g = 9.81$ [m s^{-2}] acceleration due to gravity.

- $p = \rho R T$

  The ideal gas law. p [Pascals], pressure; ρ, [kg m^{-3}] the density; T [Kelvin], the temperature; and $R = 287$ [J kg^{-1} K^{-1}], the specific gas constant for air.

- $e = \rho_v R_v T$

  The ideal gas law for water vapour. e [Pascals], vapour pressure; ρ_v, [kg m^{-3}] the absolute density; T [Kelvin], the temperature; and $R_v = 462$ [J kg^{-1} K^{-1}], the specific gas constant for water vapour.

- $\theta = T \left(\frac{p_0}{p}\right)^{R/c_p}$

  The potential temperature θ [K] of air whose actual pressure and temperature are (p, T), ie. the temperature that air would have if compressed adiabatically to pressure p_0. The exponent involves the gas constant for air ($R = 287$ J kg^{-1} K^{-1}) and the specific heat of air at constant pressure ($c_p \approx 1000$ J kg^{-1} K^{-1}). Temperatures must be expressed in the Kelvin unit.

- $\eta = \frac{p - p_T}{p_S - p_T}$

  Terrain following coordinate used in the GEM model, where $p_T = 10$ hPa is pressure at the top of the model domain, p_S is the pressure at ground-level (n.b. not sea-level corrected), and p is the pressure at the η level.

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  $$\frac{\partial \eta}{\partial t} + \vec{V} \cdot \nabla_p \eta + \omega \frac{\partial \eta}{\partial p} = - D_p \eta + \hat{k} \cdot \left(\frac{\partial \vec{v}}{\partial p} \times \nabla_p \omega \right)$$

  The vorticity equation in isobaric coordinates; η is the vertical component of the absolute vorticity; D_p is the horizontal divergence; ∇_p is the grad operator in a constant pressure surface; $\vec{V} = (U, V)$ is the 'horizontal' wind vector (strictly, the component in the constant pressure surface); $\omega \equiv dp/dt$ the vertical 'velocity'; $\hat{k}$ the unit vector normal to the constant pressure plane.

Table 2: Equilibrium vapour pressure $e_s(T)$ [hPa] versus temperature T [C].

T	$e_s(T)$	T	$e_s(T)$	T	$e_s(T)$	T	$e_s(T)$	T	$e_s(T)$	T	$e_s(T)$
0	6.11	5	8.72	10	12.27	15	17.04	20	23.37	25	31.67
1	6.57	6	9.35	11	13.12	16	18.17	21	24.86	26	33.61
2	7.05	7	10.01	12	14.02	17	19.37	22	26.43	27	35.65
3	7.58	8	10.72	13	14.97	18	20.63	23	28.09	28	37.80
4	8.13	9	11.47	14	15.98	19	21.96	24	29.83	29	40.06

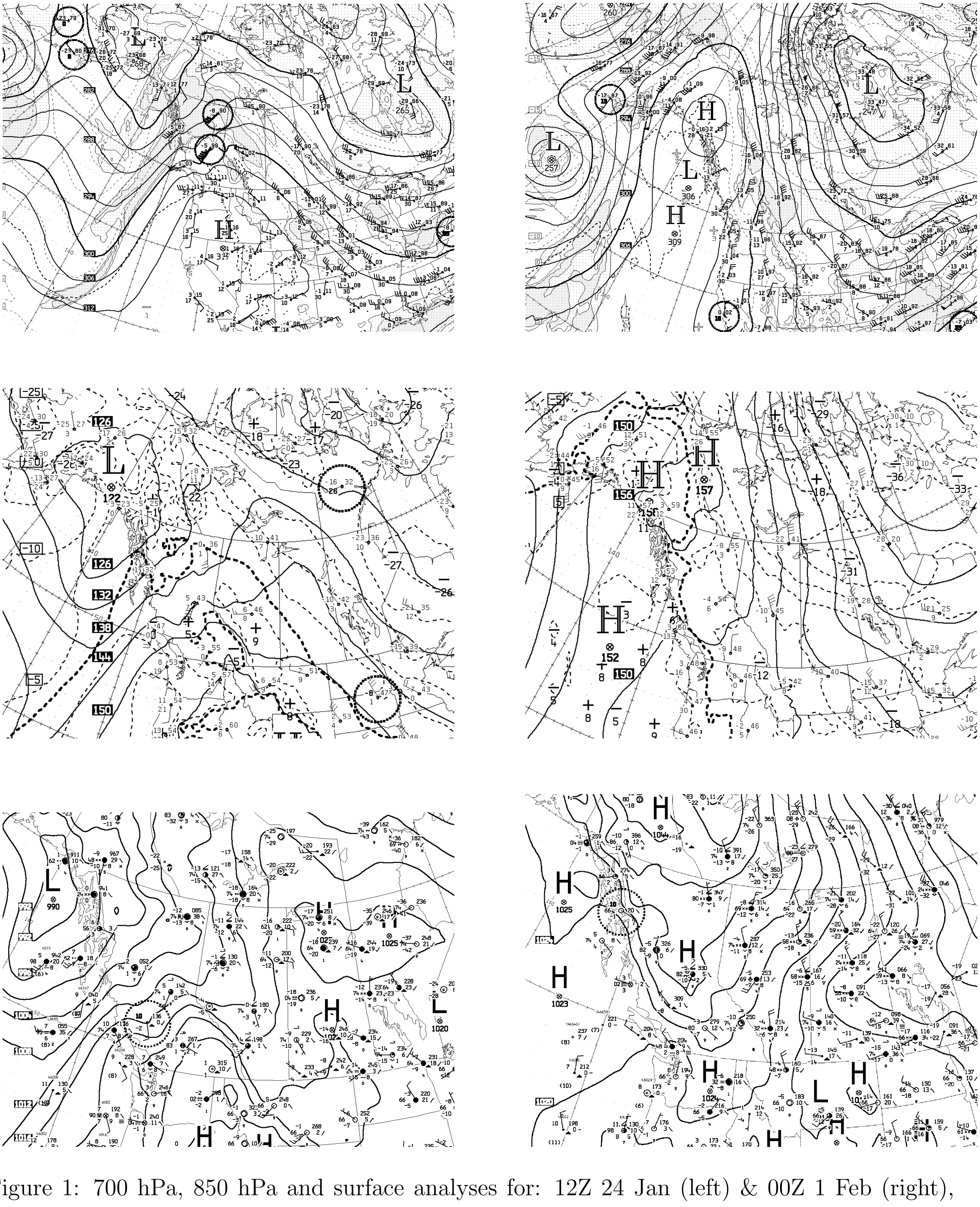

Figure 1: 700 hPa, 850 hPa and surface analyses for: 12Z 24 Jan (left) & 00Z 1 Feb (right), 2007.

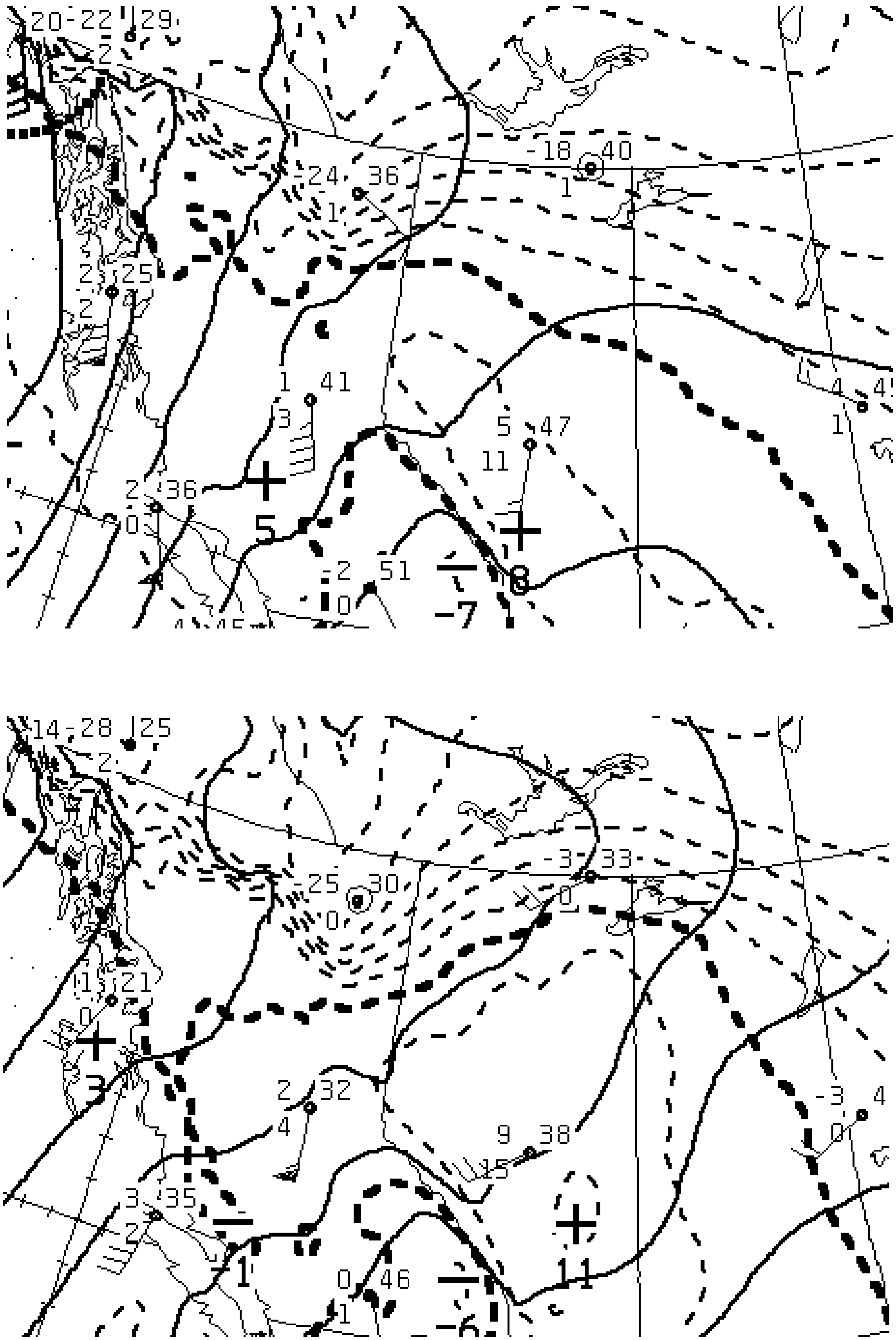

Figure 2: CMC 850 hPa analyses for 00Z (top) and 12Z on 11 Jan., 2010.

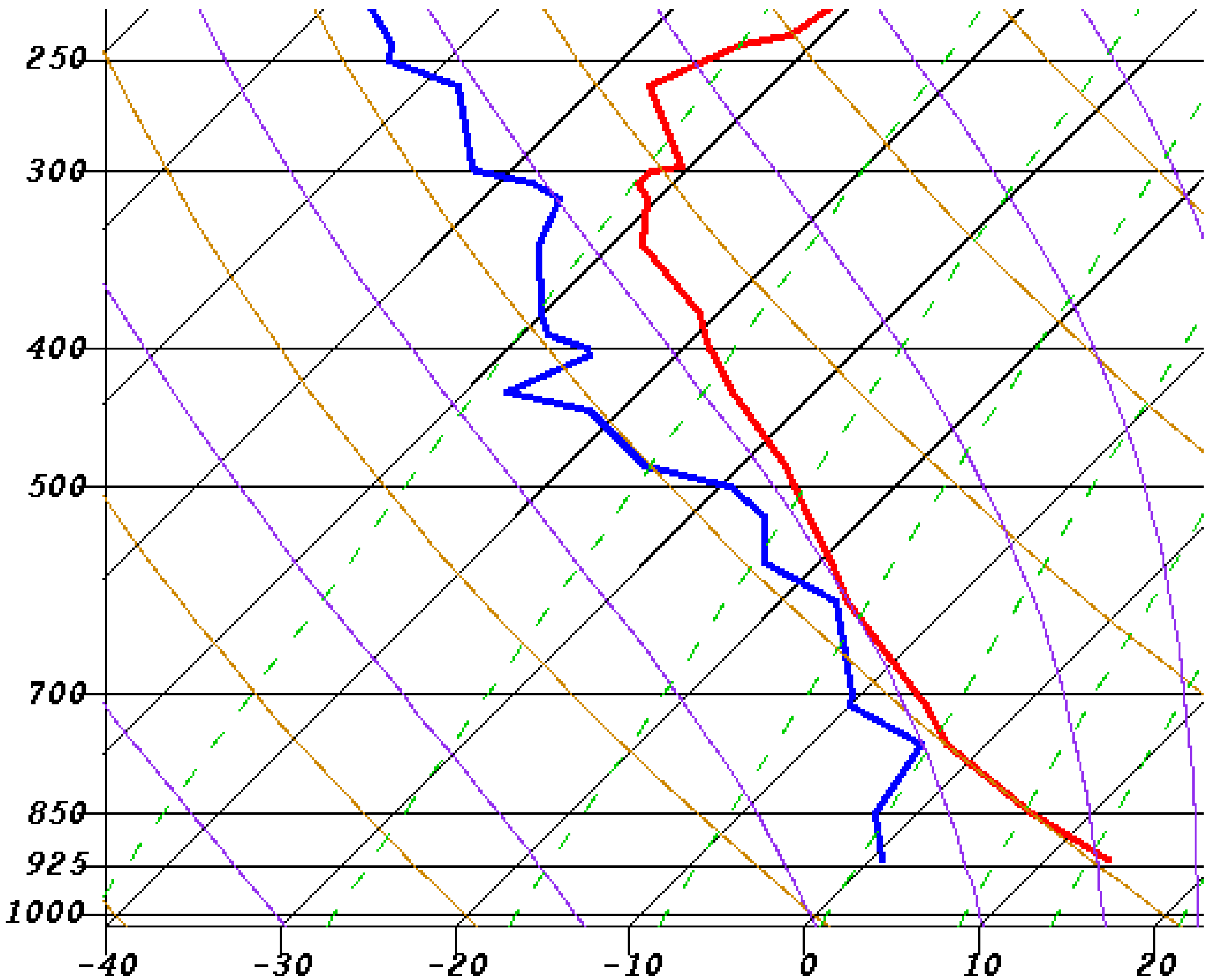

Figure 3: 00Z sounding at Edmonton (wse) on 7 May, 2009.