EAS372 | Final Exam | 19 April, 2011

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

Please answer all questions in the Examination Booklet.

A. Multi-choice (15 x 2/3 → 10 %)

1. Let $T_{\text{env}}(z)$ be the environmental temperature profile (sounding) and let $T_{\text{parcel}}(z)$ be a temperature profile corresponding to the adiabatic ascent of a moist parcel from the surface ($z = z_s$), where its temperature and dewpoint are T_s, T_{ds}. The Convective Inhibition (CIN) is defined by the integral

$$\Phi = \int_{z_a}^{z_b} g \, \frac{T_{\text{parcel}} - T_{\text{env}}}{T_{\text{parcel}}} \, dz$$

with

   (a) $z_a = z_s$, $z_b =$LCL
   (b) $z_a =$LCL, $z_b =$LFC
   (c) $z_a = z_s$, $z_b =$LFC
   (d) $z_a = z_s$, $z_b =$LNB
   (e) $z_a =$LFC, $z_b =$LNB

   where LCL denotes the lifting condensation level, LFC the level of free convection and LNB the level of neutral buoyancy.

2. The units of Convectively Available Potential Energy (CAPE) are ____

   (a) CAPE is dimensionless
   (b) Joules
   (c) Watts
   (d) Watts per kilogram
   (e) Joules per kilogram

3. Negative horizontal divergence (D_p, see Equations and Data at back) implies progressive ____ in time of a unit of area on a constant pressure surface

   (a) expansion
   (b) contraction
   (c) distortion
   (d) lifting
   (e) cooling

4. If at all levels beneath a Level of Non-Divergence (pressure $p \geq p_{LND}$) it is true that the horizontal divergence $D_p \leq 0$, then at the LND ____

   (a) air is ascending
   (b) air is descending
   (c) vertical velocity is zero
   (d) $D_p < 0$
   (e) $D_p > 0$

5. If x is a random variable whose probability distribution is Gaussian (or Normal), then the probability density function for x is

$$f(x) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] ,$$

   and $f(x_1)\,dx$ gives the probability that a randomly sampled value of x lies in the range $x_1 \pm dx/2$. The value of the integral

$$\int_{-\infty}^{\infty} f(x)\,dx$$

   evaluates to

   (a) 0.0
   (b) 0.5
   (c) 1.0
   (d) ∞
   (e) x

6. Canada's NWP model "GEM" is a ____ model whose domain is ____

   (a) non-hydrostatic; global
   (b) hydrostatic; global
   (c) non-hydrostatic; the N. hemisphere
   (d) hydrostatic; the N. hemisphere
   (e) non-hydrostatic; North America

7. The semi-logarithmic mean wind profile

$$\overline{u}(z) = \frac{u_*}{k_v} \ln\left(\frac{z}{z_0}\right) \equiv \frac{u_*}{k_v} \left[\ln(z) - \ln(z_0)\right]$$

gives the mean wind speed in the surface layer of the atmosphere under neutral stratification ($k_v = 0.4$ is the von Karman constant and z_0 is the roughness length of the surface). According to this equation the "friction velocity" u_* is numerically equal to

(a) $k_v\, \overline{u}(z)$
(b) $\ln z_0$
(c) 0.4
(d) z
(e) the slope of a plot of $k_v \overline{u}$ versus $\ln z$

8. The quantity $\overline{u'w'}$ is an off-diagonal component of the Reynolds stress matrix (given below), and corresponds to a flow of momentum: $\rho\, \overline{u'w'}$ $[\mathrm{N\,m^{-2}}]$ is the mean rate of vertical transport of u-momentum by unresolved scales of motion, and is equivalent to a force (per unit area) oriented in the x-direction (ρ is the air density). The mean drag τ of the atmosphere on the ground is given by

$$\tau = \lim_{z \to 0} \rho \sqrt{\overline{u'w'}^2 + \overline{v'w'}^2} \qquad \text{Eqn. (A)}$$

and the "friction velocity" u_* is fundamentally defined in terms of this atmospheric drag or "friction" as $u_* = \sqrt{\tau/\rho}$. From Eqn. (A) we see that τ

(a) is a vertical force
(b) is the magnitude of the resultant of the vector sum of the forces on ground in the x- and y directions
(c) is an imaginary number
(d) is a complex number
(e) has units of velocity

9. The ____ "explains" why it is that over much of the earth's surface the height contours and isotherms tend to run parallel to each other

(a) ideal gas law
(b) hydrostatic equation
(c) hypsometric equation
(d) geostrophic wind equation
(e) thermal wind equation

10. The diagonal elements of the Reynolds stress matrix

$$\mathbf{R} = \mathbf{R}(x, y, z, t) \quad = \quad \begin{pmatrix} \overline{u'^2} & \overline{u'v'} & \overline{u'w'} \\ \overline{v'u'} & \overline{v'^2} & \overline{v'w'} \\ \overline{w'u'} & \overline{w'v'} & \overline{w'^2} \end{pmatrix}$$

give ____

(a) the drag of the mean (resolved) wind on the ground, along each of the three coordinate directions

(b) the mean drag of the unresolved wind on the ground, along each of the three coordinate directions

(c) the standard deviations of the components (U, V, W) of the mean (resolved) wind

(d) the variances of the components (u', v', w') of the unresolved wind

11. In many NWP models, vertical transport by unresolved scales of motion is parameterized using an eddy diffusivity $K = c\sqrt{k}\,\lambda$, where c is an optimized constant, k is the "turbulent kinetic energy" residing in the unresolved motion (defined to be one-half the sum of the three unresolved velocity variances), and λ is an empirical "length scale" of the unresolved scales of motion. Typically k is computed from the equation

$$\frac{\partial k}{\partial t} = K \left[\left(\frac{\partial \overline{u}}{\partial z} \right)^2 + \left(\frac{\partial \overline{v}}{\partial z} \right)^2 \right] - \frac{g}{\theta_0} K \frac{\partial \overline{\theta}}{\partial z} - \frac{k^{3/2}}{\lambda} ,$$

where the overbar denotes resolved properties, K is the eddy viscosity and $\overline{\theta}$ is the resolved potential temperature. The mean rate of input of energy to the subgrid motion field by "mechanical production" (also known as "shear production") is given by

(a) the left hand side (lhs)

(b) first term of the three terms on the rhs

(c) second term on the rhs

(d) third term on the rhs

(e) sum of all terms on the rhs

12. 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; let $p(z)$ be the pressure at an arbitrary height, and $p_\infty (\ll p_h)$ the pressure at the 10 hPa level. Which of the following vertical coordinates is **not** a terrain-following coordinate?

(a) $z - h$

(b) $p(z)/p_h$

(c) $[p(z) - p_\infty]/[p_h - p_\infty]$

(d) $p(z)/p_\infty$

(e) z/h

13. On the "synoptic scale," the free atmosphere is considered to be in a state of "delicate imbalance," i.e. not quite hydrostatic and not quite geostrophic. However modern NWP models typically use a horizontal grid length ($\Delta x, \Delta y$) of the order of 10 km, and accordingly may at least partially resolve "mesoscale" circulations. Constraining the initial state of such a model to be hydrostatic and (above the boundary layer) geostrophic would entail the disadvantage that ____

    (a) the initial state would be *incompatible* with the model dynamics

    (b) excessive vertical and horizontal accelerations would be provoked, early in the forecast

    (c) an oversimplified initial state might hamper proper development, early in the forecast

    (d) the thermodynamic fields of the initial state would not satisfy the ideal gas law

    (e) the initial humidity field would be supersaturated

14. Suppose that at the end of a model time step resolved humidity was supersaturated, and so adjustments were made to the model's resolved temperature (T) and specific humidity (q) fields in a layer spanning $z_B \leq z \leq z_T$ under the constraint

$$
\begin{aligned}
-\int_{z_B}^{z_T} L\,\rho(z)\,\Delta q(z)\,dz &= \int_{z_B}^{z_T} \rho(z)\,c_p\,\Delta T(z)\,dz\,, \\
q(z) + \Delta q(z) &= q_*(T(z) + \Delta T(z))\,,
\end{aligned}
$$

where $\Delta T(z), \Delta q(z)$ are the adjustments ($\Delta q \leq 0$, $\Delta T \geq 0$), L is the latent heat of vapourization, ρ is density and q_* denotes the equilibrium vapour pressure. After the adjustment, which ____ , the layer is ____

    (a) conserves water vapour; unsaturated

    (b) allows latent heat at one level to be released as sensible heat at a different level, while conserving total thermodynamic energy of the layer; saturated

    (c) converts latent heat at level z into the same amount of sensible heat at (the same) level z; unsaturated

    (d) converts latent heat at level z into the same amount of sensible heat at (the same) level z; saturated

    (e) conserves water vapour; saturated

15. The instantaneous geographic field of view at nadir (IGFOV) of the GOES satellites' infra-red channels is nominally ____

    (a) 100 m

    (b) 400 m

    (c) 1 km

    (d) 4 km

    (e) 40 km

B. “Live” web weather data (5 x 1 $\rightarrow$ 5%)

Where appropriate, rather than giving an exact value for your answer, you may give a range — e.g. thickness will be “in the range 528-534 dam.”

1. According to the Stony Plain sounding (stn. identifier WSE, stn. number 71119) at 00Z today (Tuesday 19 April) the potential temperatures (“THTA”) of the air at 700 hPa and 850 hPa were ____
2. GEM’s 10 day forecast for the surface temperature at Edmonton, valid 00Z April 29, is ____
3. GEM’s 10 day forecast for sea-level corrected surface pressure and for 1000-500 hPa thickness over Edmonton, valid 00Z April 29, is ____
4. NCEP’s GFS 10 day forecast for 1000-500 hPa thickness over Edmonton, valid 00Z April 29, is ____
5. The minimum, mean and maximum temperatures reported at Edmonton International Airport (CYEG) for 1 March 2011 were ____

C. Interpretation of weather situation. (1 x 10 $\rightarrow$ 10%)

By Wednesday 13 April 2011 sidewalks in Edmonton were finally ice free and mostly dry, for the first time in many months (the day’s high was 5.3°C at Edmonton International Airport, CYEG). During January 64 cm of snow had fallen at the International Airport, and snowpack depth at the end of the month was 38 cm. February brought another 21 cm of snowfall, and at the end of the month snowpack depth was 39 cm. March brought a further 18 cm of snow, and ended with a snowpack 40 cm deep — contrasting with the 8 cm depth that is the 1971-2000 normal for end of March. To general discontentment, Thursday 14 April delivered Edmonton a substantial snowfall. Hourly weather data are given by Figure (1). Morning traffic was disturbed by the quickly accumulating, wet and heavy snow. CYEG reported a daily total of 13.8 cm of snow, and those shovelling their sidewalks could testify to its weight.

From the given information (Figures 1-7), **interpret the salient meteorological facts** relating to this event. Please present your analysis in point form.

D. Short Essay (10 %)

Please answer **one** of the following questions.

1. Describe the purpose and science of Kuo's scheme for the parameterization of unresolved convective clouds

2. Describe the salient scientific and operational features of Canada's NWP model (GEM)

3. Interpret the terms in the Reynolds-averaged humidity conservation equation

$$\begin{aligned}\frac{\partial \overline{\rho}_v}{\partial t} = & - \frac{\partial}{\partial x}\,\overline{u}\,\overline{\rho}_v - \frac{\partial}{\partial y}\,\overline{v}\,\overline{\rho}_v - \frac{\partial}{\partial z}\,\overline{w}\,\overline{\rho}_v \\ & - \frac{\partial}{\partial x}\,\overline{u'\rho_v'} - \frac{\partial}{\partial y}\,\overline{v'\rho_v'} - \frac{\partial}{\partial z}\,\overline{w'\rho_v'} + \overline{Q}\end{aligned}$$

   where ρ_v is the absolute humidity and the overbar denotes the Reynolds average. Identify the origins of the terms, and any assumptions that have been made to arrive at this equation. Relate your discussion to the physics/dynamics terminology of weather models. Note: it can be shown that under the assumptions leading to this momentum equation,

$$\frac{\partial \overline{u}\,\overline{\rho}_v}{\partial x} + \frac{\partial \overline{v}\,\overline{\rho}_v}{\partial y} + \frac{\partial \overline{w}\,\overline{\rho}_v}{\partial z} \equiv \overline{u}\,\frac{\partial \overline{\rho}_v}{\partial x} + \overline{v}\,\frac{\partial \overline{\rho}_v}{\partial y} + \overline{w}\,\frac{\partial \overline{\rho}_v}{\partial z}\ .$$

4. Discuss the impact of weather satellites on weather analysis and forecasting

Equations and Data.

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

  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).

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Edmonton Int'l Airport
Past 24 Hour Conditions

Imperial Units

Date / Time (MDT)	Conditions	Temp (°C)	Humidity (%)	Dew Point (°C)	Wind (km/h)	Pressure (kPa)	Vis (km)	Wind Chill
14 April 2011								
21:00	Cloudy	-2	100	-2	N 9	101.7	19	-5
20:00	Light Snow	-1	100	-1	NNW 8	101.6	4	-4
19:00	Light Snow	-1	96	-2	E 5	101.6	5	-3
18:00	Light Snow	-1	95	-2	ESE 21	101.6	2	-7
17:00	Light Snow	-1	96	-2	E 21 gust 30	101.6	2	-7
16:00	Light Snow	-1	96	-2	E 26	101.6	2	-7
15:00	Light Snow	-2	98	-2	E 26	101.6	1	-9
14:00	Light Snow	-2	92	-3	E 28	101.6	2	-9
13:00	Light Snow	-2	94	-3	ESE 32 gust 45	101.6	2	-9
12:00	Light Snow	-2	96	-3	ESE 33 gust 45	101.6	1	-9
11:00	Light Snow	-3	95	-3	E 32	101.7	2	-11
10:00	Light Snow	-2	94	-3	E 33 gust 45	101.7	2	-9
9:00	Light Snow	-2	98	-2	E 35	101.7	1	-10
8:00	Light Snow	-2	98	-2	E 28 gust 37	101.7	1	-9
7:00	Light Snow	-2	93	-3	E 22 gust 32	101.8	2	-8
6:00	Light Snow	-1	84	-3	ESE 24	101.8	10	-7
5:00	Cloudy	-1	83	-3	ESE 24	101.9	24	-7
4:00	Cloudy	0	81	-3	ESE 26 gust 39	101.9	24	-6
3:00	Cloudy	0	80	-3	ESE 30	101.9	24	-6
2:00	Cloudy	1	80	-2	ESE 32	102.0	24	*
1:00	Cloudy	1	81	-2	ESE 32 gust 41	102.0	24	*
00:00	Cloudy	2	79	-2	ESE 32	102.0	24	*

Figure 1: Hourly weather data for Edmonton International Airport (CYEG) on 14 April, 2011. The snowfall accumulation for the day was 13.8 cm.

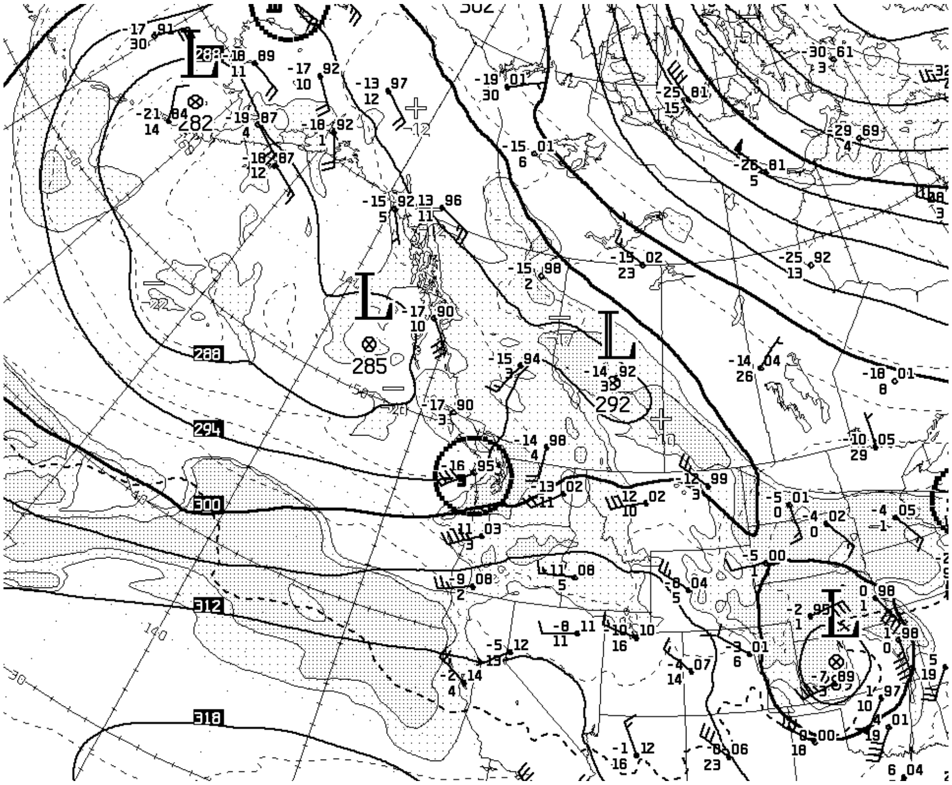

Figure 2: CMC 700 hPa analysis for 18 MDT Thurs 14 April (i.e. 00Z Apr. 15th, 2011).

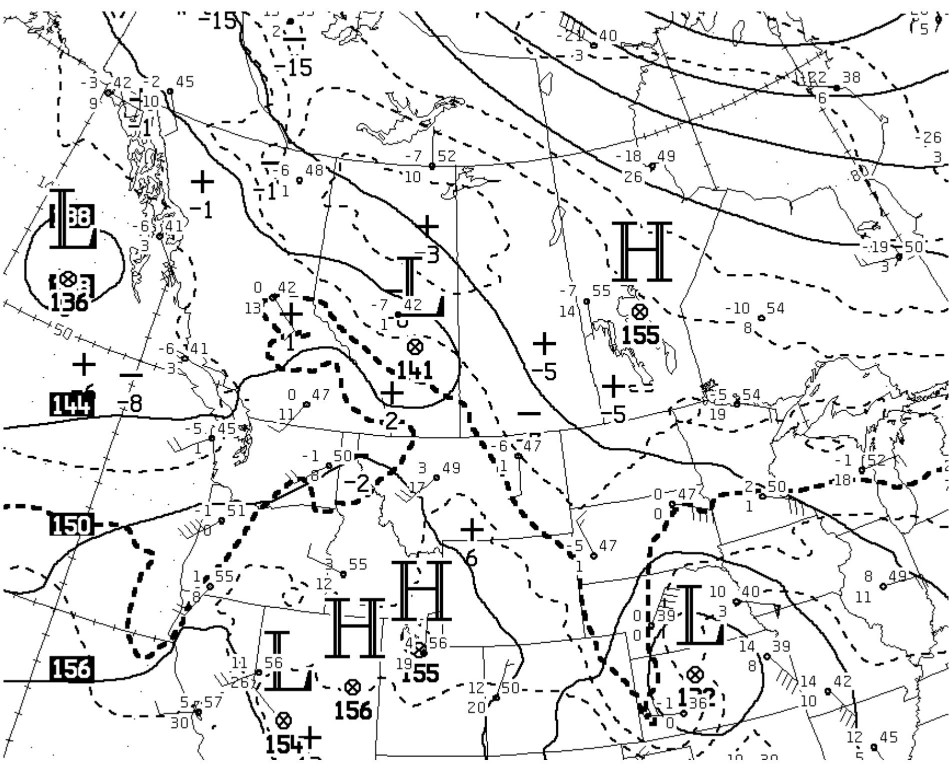

Figure 3: CMC 850 hPa analysis for 18 MDT Thurs 14 April (i.e. 00Z Apr. 15th, 2011).

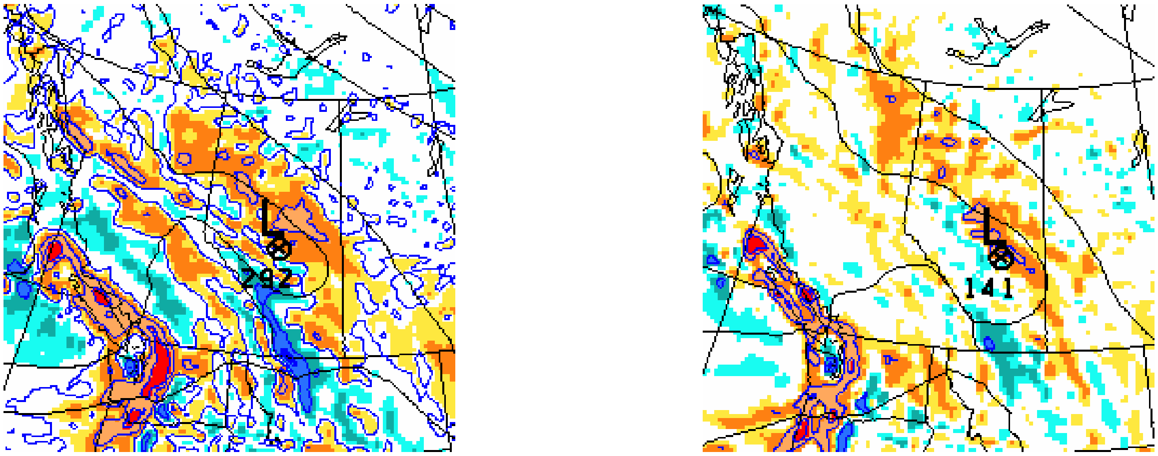

Figure 4: GEM 0h progs for Omega at 700 hPa (left) and 850 hPa (right), valid 18 MDT Thurs 14 April (i.e. 00Z Friday 15 April, 2011). (Yellow, $-0.25 \geq \omega \geq -0.5$ [Pa s^{-1}]. Dark orange, $-0.5 \geq \omega \geq -1.0$ [Pa s^{-1}]. Light orange $-1.0 \geq \omega \geq -2.0$ [Pa s^{-1}]).

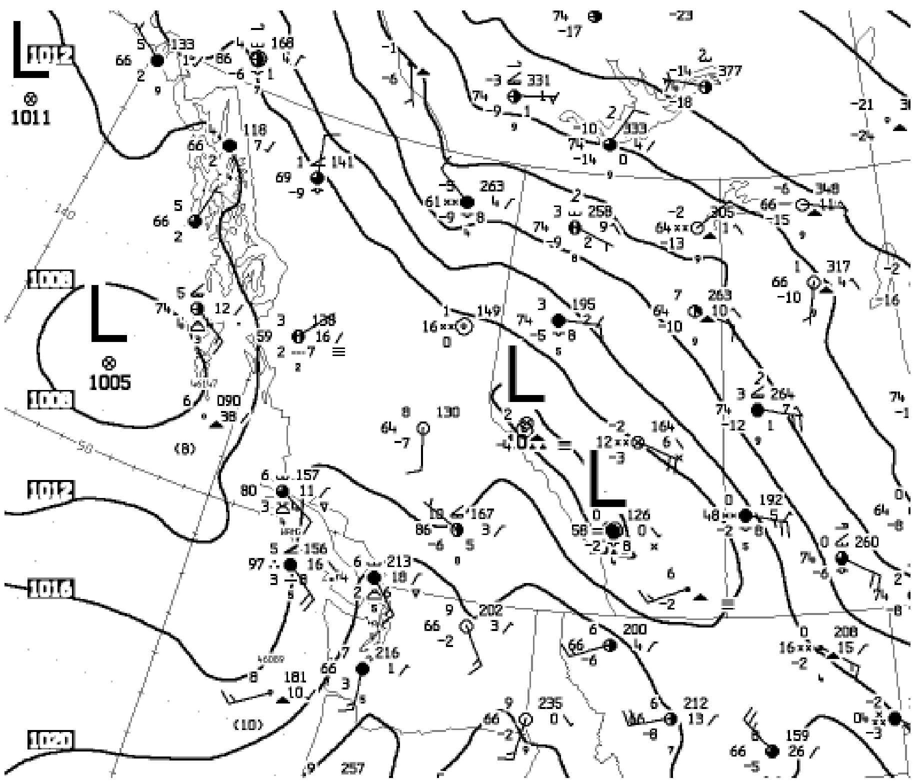

Figure 5: CMC surface analysis for 12 MDT Thurs 14 April (i.e. 18Z Thurs 14 April, 2011).

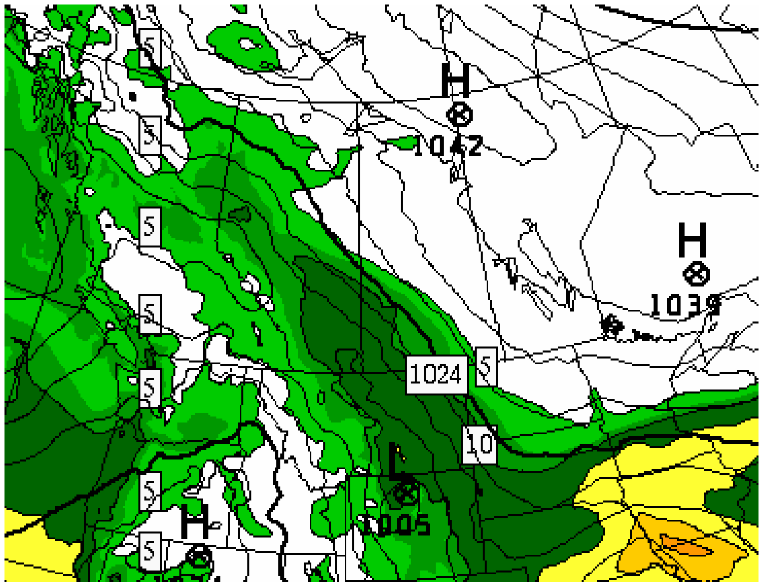

Figure 6: GEM 0h prog for precipitable water, valid 06 MDT Thurs 14 April (i.e. 12Z Thurs 14 April, 2011). (Light green, $5 \leq \text{PW} \leq 7.5$ [mm]. Medium green, $7.5 \leq \text{PW} \leq 10$ [mm]. Dark green, $10 \leq \text{PW} \leq 15$ [mm]).

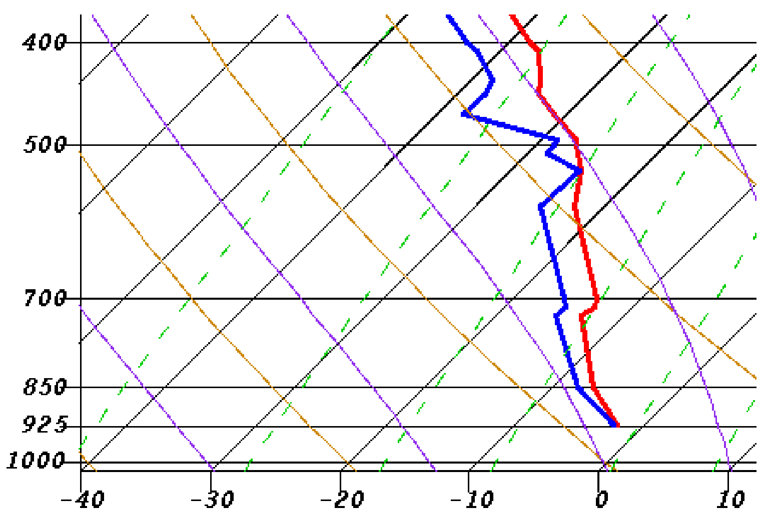

Figure 7: Stony Plain sounding, 18 MDT Thurs 14 April (i.e. 00Z Friday 15 April, 2011).