EAS372 — Open Book Final Exam — 20 April, 2012

Professor: J.D. Wilson   Time available: 2 hours 20 min   Value: 35%

Please answer all questions in the Examination Booklet.

A. Multi-choice (20 x 1/2 → 10 %)

1. In the N. hemisphere the thermal wind vector is oriented ____ the isotherms with cold air ____
   - (a) parallel to; on its right
   - (b) perpendicular to; on its right
   - (c) parallel to; on its left ✓✓
   - (d) perpendicular to; on its left
   - (e) obliquely across; where it is pointing

2. The equation

$$Q_H = \rho\, c_p\, C_H\, U_{10}\, (T_0 - T_a)$$

   is a bulk model for sensible heat exchange between the surface and the atmosphere (ρ, air density; c_p, specific heat of air at constant pressure; U_{10} the 10 m wind speed; T_0, surface temperature; T_a, air temperature). The units of C_H must be
   - (a) m
   - (b) s
   - (c) $\mathrm{J\,m^{-2}\,s^{-1}}$
   - (d) $\mathrm{s\,m^{-1}}$
   - (e) C_H carries no units ✓✓

3. The spatial resolution of the GOES infra-red image on the equator (instantaneous geographic field of view at nadir) is about
   - (a) 40m
   - (b) 400m
   - (c) 4km ✓✓
   - (d) 40km
   - (e) 400km

4. Brightness of each single pixel of the GOES visual image is determined by
   - (a) cloud top temperature
   - (b) shortwave reflectivity (albedo)
   - (c) sum of shortwave and longwave intensities incident at cloud top
   - (d) solar elevation and intensity, and shortwave reflectivity (albedo) ✓✓
   - (e) roughness of the surface seen (cloud, ground or water)

5. If ϕ is a conserved variable (i.e. does not change along trajectories) and $\mathbf{U}$ is the 3D velocity vector, then

   (a) $d\phi/dt = \partial\phi/\partial t$
   (b) $\partial\phi/\partial t = -\mathbf{U} \cdot \nabla\phi$ ✓✓
   (c) $\partial\phi/\partial t = \mathbf{U} \cdot \nabla\phi$
   (d) $\partial\phi/\partial x = \partial\phi/\partial y = \partial\phi/\partial z = 0$
   (e) $\mathbf{U} \cdot \nabla\phi = 0$

6. According to the quasi-geostrophic (QG) model, in mid-latitudes the evolution of the synoptic scale pressure field is primarily determined by ____ advection of ____

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

7. The velocity on a pressure surface may be partitioned into geostrophic and ageostrophic components ($\mathbf{U}_g$, $\mathbf{U}_{ag}$), where $\mathbf{U}_g$ is non-divergent. The QG vorticity equation, which associates a property of the vorticity and motion fields with horizontal divergence D_p, is

$$\frac{d_g\eta}{dt} = -f_0 D_p$$

   where f_0 is the Coriolis parameter evaluated at the reference latitude, and $\eta = f_0 + \zeta_g$ is the absolute vorticity (ζ_g is the relative vorticity evaluated using the geostrophic wind). The operator d_g/dt is

   (a) the local (Eulerian, or fixed-frame) tendency in time
   (b) the time derivative following the total wind $\mathbf{U}_g + \mathbf{U}_{ag}$
   (c) the time derivative following the ageostrophic wind $\mathbf{U}_{ag}$
   (d) the time derivative following the geostrophic wind $\mathbf{U}_g$ ✓✓
   (e) the Laplacian

8. Referring again to the QG vorticity equation, the divergence D_p is evaluated using

   (a) the natural coordinate system
   (b) the hydrostatic approximation
   (c) a non-hydrostatic vertical momentum equation
   (d) the total wind $\mathbf{U}_g + \mathbf{U}_{ag}$ ✓✓
   (e) the β-plane approximation $f(y) = f_0 + \beta y$, y being the meridional coordinate

9. On a Graphical Area Forecast (e.g. Fig. 12) the symbol "P6SM" has what significance?
   (a) predicted visibility exceeds 6 statute miles ✓✓
   (b) probability 0.6 of snow
   (c) precipitation 6 mm (snow depth)
   (d) precipitation 6 mm (water equivalent)
   (e) partial (6/8) cloud cover on synoptic and meso scales

10. Referring to Figures (1-2), surface analyses from the Australian Bureau of Meteorology, at a best guess the dashed blue lines represent
    (a) shortwave troughs ✓✓
    (b) shortwave ridges
    (c) occluded fronts
    (d) lee troughs
    (e) storm tracks

11. The west coast of the South Island of New Zealand (NZ) is defined by a narrow chain of high mountains, while the east coast is substantially an erosion plain; the sea-level isobar pattern over the South Island often reflects the influence of that topography. Still in reference to Figures (1-2), westerly winds would have been occurring over the South Island of NZ on
    (a) 9 April and 11 April ✓✓(answer accepted because a flow from west coast to east coast would not be exactly "westerly")
    (b) neither 9 April nor 11 April
    (c) 9 April ✓✓
    (d) 11 April

12. On the basis of Fig. (3), what process or phenomenon might one expect to occur over east-central Manitoba?
    (a) cold advection
    (b) cyclogenesis
    (c) freezing rain
    (d) frontogenesis ✓✓
    (e) severe convection

13. Again referring to Fig. (3), what temperature label attaches to the isotherm designated by an "**X**" in the Yukon at the top of the map? The heavy dashed ring, indicating suspicious data, probably refers to which variable?
    (a) -35; dewpoint
    (b) -35; temperature
    (c) -30; dewpoint
    (d) -30; temperature ✓✓
    (e) -30; height of the 850 hPa surface

14. Referring to Figure (4), the cut-off low in the United States might be termed
    (a) super-geostrophic
    (b) a mesoscale low
    (c) a cold core low ✓✓
    (d) a hurricane
    (e) a tropical storm

15. If vectors $\mathbf{P}, \mathbf{Q}$ respectively have components $(0, p_b, 0)$ and $(1, q_b, 1)$ relative to a basis defined by orthogonal unit vectors $(\hat{\imath}, \hat{\jmath}, \hat{k})$ then the quantity $\mathbf{P} \cdot \mathbf{Q}$ (ie. 'dot product' of the two vectors) is ____

    (a) 0
    (b) $(0, 0, 0)$
    (c) $p_b q_b$ ✓✓
    (d) $(1, p_b + q_b, 1)$
    (e) $p_b + q_b$

16. In a single spatial dimension x, and using a Cartesian coordinate, which is the correct representation of the operator ∇^2 ($\equiv \nabla \cdot \nabla$), variously named the Laplacian/diffusion/curvature operator?

    (a) $\partial/\partial x$
    (b) $\partial^2/\partial x^2$ ✓✓
    (c) $\partial/\partial t$
    (d) $\partial^2/\partial t^2$
    (e) $\partial/\partial t + U\,\partial/\partial x$

17. Suppose that $f(x) = \alpha \exp(-x/x_0)$ is the probability density function (PDF) for a random non-negative real number x. For f to be an accceptable PDF, the constants x_0 and α must satisfy

    (a) $\alpha = 1,\ x_0 < 0$
    (b) $\alpha = \exp(-1)$
    (c) $\alpha = x_0$
    (d) $\alpha = 1/x_0$ ✓✓(required to ensure $\int_0^\infty f(x)\,dx = 1$)
    (e) $\alpha^2 = \sqrt{x_0}$

18. The mean square value of x can be computed from the PDF as

    (a) $\overline{x^2} = \int_0^\infty f(x)\, dx$
    (b) $\overline{x^2} = \int_0^\infty x f(x)\, dx$
    (c) $\overline{x^2} = \int_0^\infty x f^2(x)\, dx$
    (d) $\overline{x^2} = \int_0^\infty x^2 f(x)\, dx$ ✓✓
    (e) $\overline{x^2} = \int_0^\infty x^2 f^2(x)\, dx$

19. Assuming the 250 hPa wind speed $|U|$ is the value reported for Fort Smith (YSM, on the northern border of Alberta) on Figure (9), the Courant number $C = |U|\,\Delta t/\Delta x$ at a 250 hPa-level gridpoint of the GEM (regional config.) model (near Fort Smith) is about

    (a) 1000
    (b) 100
    (c) 10
    (d) 1 ✓✓
    (e) 0.1

20. The mean vertical sensible heat flux density carried by unresolved scales of motion, formally $\overline{w'\theta'}$ (where w', θ' are the fluctuations in vertical velocity and potential temperature), is typically parameterized in an NWP model, by analogy with Fourier's law of conduction, as

$$\overline{w'\theta'} = -K_h\, \frac{\partial \overline{\theta}}{\partial z}$$

    where K_h [$\mathrm{m^2\,s^{-1}}$] is the "eddy diffusivity for heat." Then in a "neutral" (unstratified, i.e. thermally well-mixed) layer of the atmosphere the unresolved vertical heat flux

    (a) is positive
    (b) is zero ✓✓
    (c) is negative
    (d) is indeterminate
    (e) is infinite

B. "Live" web weather data (5 x 1 → 5%)

1. What was the total rainfall recording for Edmonton International Airport on 8 July 2011? **11.6 mm**

2. What was the CAPE at 00Z 3 April 2012 at Lamont Oklahoma (74646, LMN)? **Convective Available Potential Energy 1622** $\mathrm{J\,kg^{-1}}$**. CAPE using virtual temperature 1783** $\mathrm{J\,kg^{-1}}$

3. Retrieve and write down the METAR for CYEG for 06Z today

    CYEG 200600Z 14017KT 15SM FEW090 SCT170 BKN240 05/M01 A2985 RMK AC2AC1CI4 SLP126=

4. According to the GEM reg run initialized at 06Z today, what was the 0h value (i.e. analysis) for the maximum value of the precipitable water anywhere over Western Canada (BC-Alberta-Saskatchewan-Manitoba)? **15-20 mm over southern B.C.**

5. According to the MSC analysis valid at 06Z today, what is the maximum value over N. America of the absolute vorticity at the 500 hPa level?

   If one consulted the 4 panel b/w chart, the maximum indicated was $+20 \times 10^{-5}\ s^{-1}$.

   However the 4 panel colour chart picked up a very sharp trough in SW B.C. (probably orogtraphic in origin), and the shading indicated $+32 \rightarrow +50 \times 10^{-5}\ s^{-1}$.

   Either answer was acceptable

C. Interpretation of weather situation. (1 x 10 → 10%)

On 5 April 2012 Edmonton experienced a heavy snowfall, with a high rate of accumulation coinciding with morning rush hour traffic. This storm had been a feature of GEM model progs for at least the previous eight days. Figures (5-12) summarize the prevailing meteorology at 12Z (i.e. 06 MDT).

From the given information, **interpret the meteorological facts** relating to this event. Please present your analysis in point form.

Summary

1. Low pressure system on Ab./Sask. border east of Edmonton, not a particularly deep storm but nevertheless causing strong surface winds
2. Upslope surface wind may have contributed
3. Narrow ridge of warmer air at 850 hPa in S and W. Saskatchewan (roughly coinciding with the warm sector analysed on the GFA); somewhat colder air in Alberta west of the low (i.e. some temperature contrast, but not dramatic)
4. Mild surface air wrapping around the low, but sub-zero aloft — suggesting rain or wet snow would not have been too surprising
5. Strong N. wind at 850 hPa
6. Sounding indicates a nearly saturated atmosphere to almost 500 hPa, and that the temperature profile is *neutral* w.r.t. moist adiabatic motion to about 600 hPa
7. Zone of high values of precipitable water in Sakatchewan and wrapping around the N. of the low
8. Zone of strong ascent at 700 hPa over Edmonton

9. Zone of strong low level (900 hPa) convergence over Edmonton
10. Zone of warm advection at 850 hPa just east of Edmonton
11. Surface storm was situated under the exit from an upper trough (500 hPa and above)
12. 500 hPa vorticity maximum just upwind of Edmonton (probable positive vorticity advection over Edmonton)
13. Southerly 250 hPa jet runs along Alberta-Saskatchewan border
14. GFA indicates region of overcast skies with precipitation covers C. Alberta. Low ceiling (i.e. low cloud base).
15. Altocumulus castellanus noted on GFA (indicative of convection)
16. Overall most elements of the pattern would suggest higher precip east of Edmonton, the vert. velocity being the exception (centred on the city)

D. Short answer (2 x 5 % $\rightarrow$ 10 %)

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

1. Describe the scientific and operational features of Canada's NWP model "GEM"

2. In gridpoint computations the friction term F_u in the mean zonal momentum equation is simplified

$$
\begin{aligned}
F_u \quad &\equiv \quad - \frac{\partial\, \overline{u'^2}}{\partial x} - \frac{\partial\, \overline{u'v'}}{\partial y} - \frac{\partial\, \overline{u'w'}}{\partial z} \\
&\rightarrow \quad - \frac{\partial\, \overline{u'w'}}{\partial z} \\
&\rightarrow \quad - \frac{\partial}{\partial z}\left(- K \frac{\partial U}{\partial z} \right) .
\end{aligned}
$$

Explain the logic and meaning of this simplification.

Overview:

- The motivation for making simplifications is approximate unknown statistics of unresolved motion in terms of quantities that are resolved (known)
- The first simplification is to *neglect horizontal gradients* in favour of what is expected to be a much stronger *vertical* gradient
- The quantity $\overline{u'w'}$ represents unresolved convective vertical transport of zonal momentum, i.e. a flux of momentum[1].

[1] Technically, this is named a "kinematic" momentum flux, since the factor ρ does not appear. If we multiply the kinematic flux by air density we have a quantity $\tau = \rho\, \overline{u'w'}$ having units of pressure [Pa]. This is a tangential (i.e. shearing) stress.

- If this momentum flux changes with height, we have "friction"
- The second simplification is to *model* the unresolved momentum flux $\overline{u'w'}$, by analogy with Newton's law of viscous friction

$$\tau = \mu \, \frac{dU}{dz} \, .$$

  Here $\mu \equiv \nu \, \rho$ is the "dynamic viscosity" of air, and ν [$\mathrm{m^2\,s^{-1}}$] is the kinematic viscosity. Taking this as the form for modelling the unresolved convective flux, $\overline{u'w'}$ is expressed as the product of an "eddy viscosity" (K, $\mathrm{m^2\,s^{-1}}$) and the gradient in the resolved velocity, viz.

$$\overline{u'w'} = -K \, \frac{\partial U}{\partial z} \, .$$

- One needs now to specify the K, which can be regarded as being the product of a length scale times a velocity scale, $K = \lambda \, \mathcal{V}$. The velocity scale is often taken as $\mathcal{V} = \sqrt{k}$, where k is the "turbulent kinetic energy"
- Given a prescription for K, one has "closed" the problem, i.e. the impact of unresolved scales of motion on the evolution of resolved zonal velocity U can be computed.

3. The geostrophic wind is

$$\mathbf{U}_g = \frac{g}{f} \, \hat{k} \times \nabla_p Z$$

where Z is the height of a constant pressure surface. Derive an expression for the geostrophic shear $\partial \mathbf{U}_g / \partial p$ in terms of the two components $\partial T/\partial x, \partial T/\partial y$ of the temperature gradient $\nabla_p T$ on the constant pressure surface. (Assume a hydrostatic atmosphere).

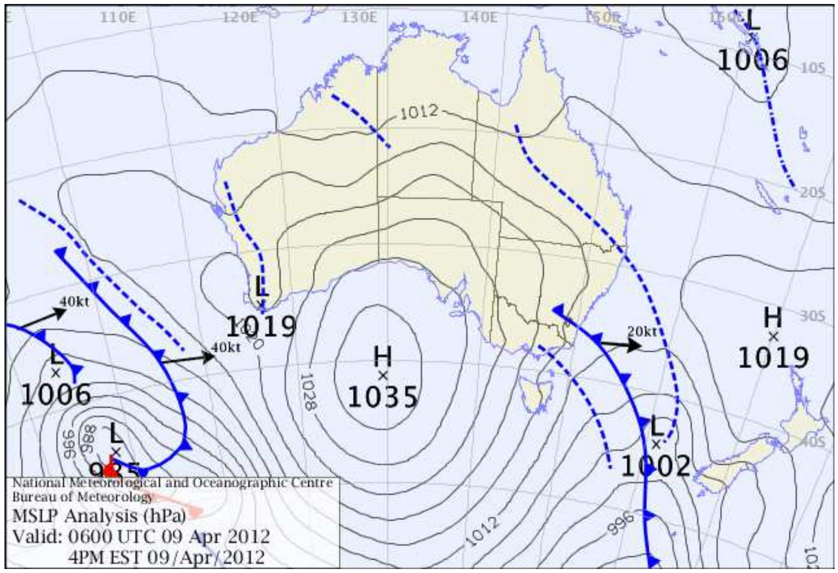

Figure 1: Bureau of Meteorology (Australia) surface analysis, 06Z April 9, 2012.

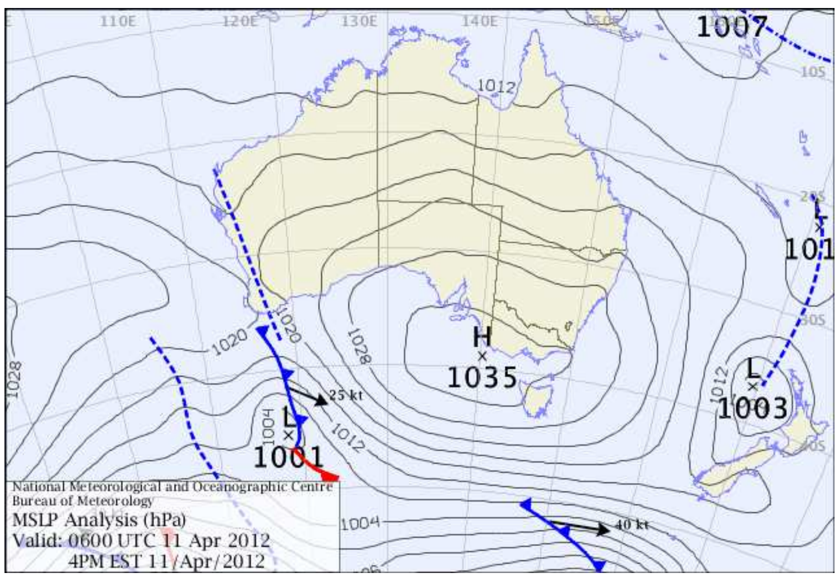

Figure 2: Bureau of Meteorology (Australia) surface analysis, 06Z April 11, 2012.

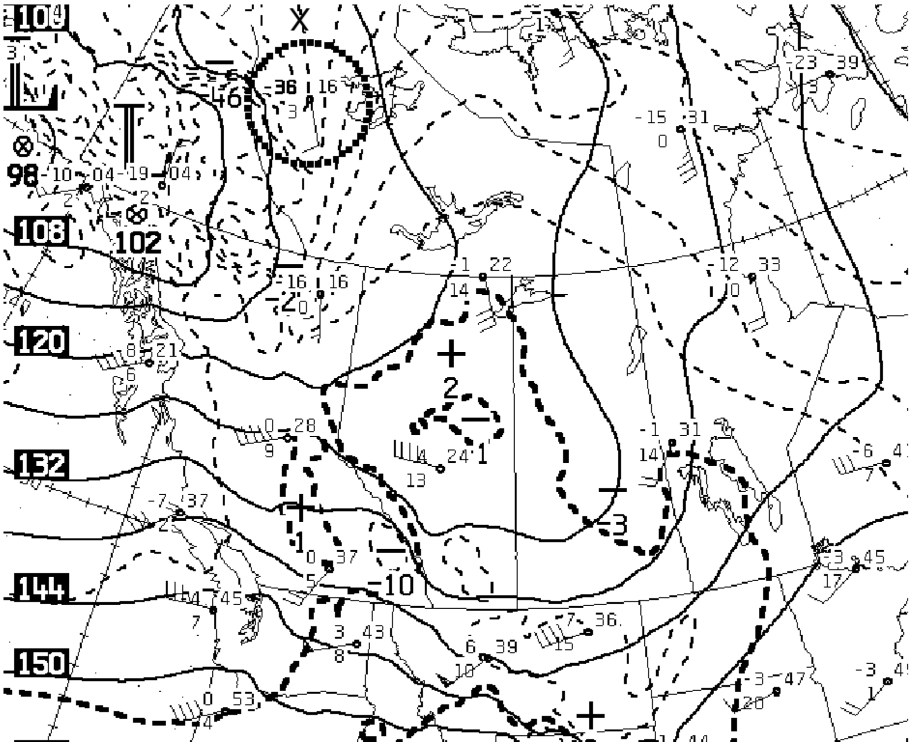

Figure 3: MSC 850 hPA analysis, 12Z January 25, 2012.

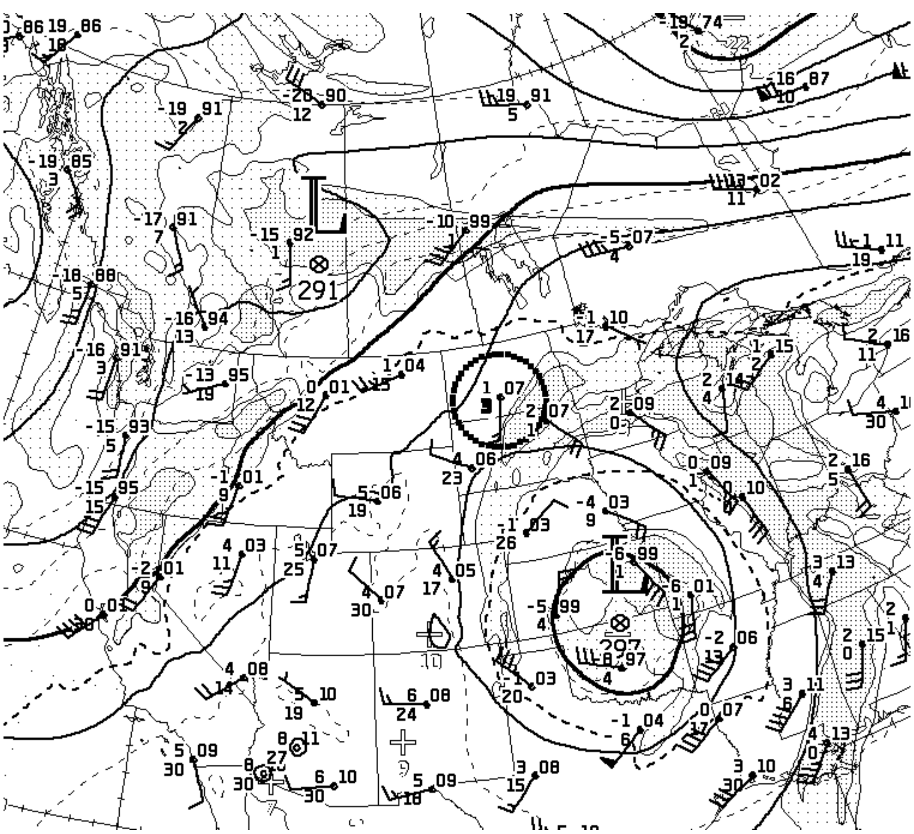

Figure 4: MSC 700 hPA analysis, 00Z March 23, 2012.

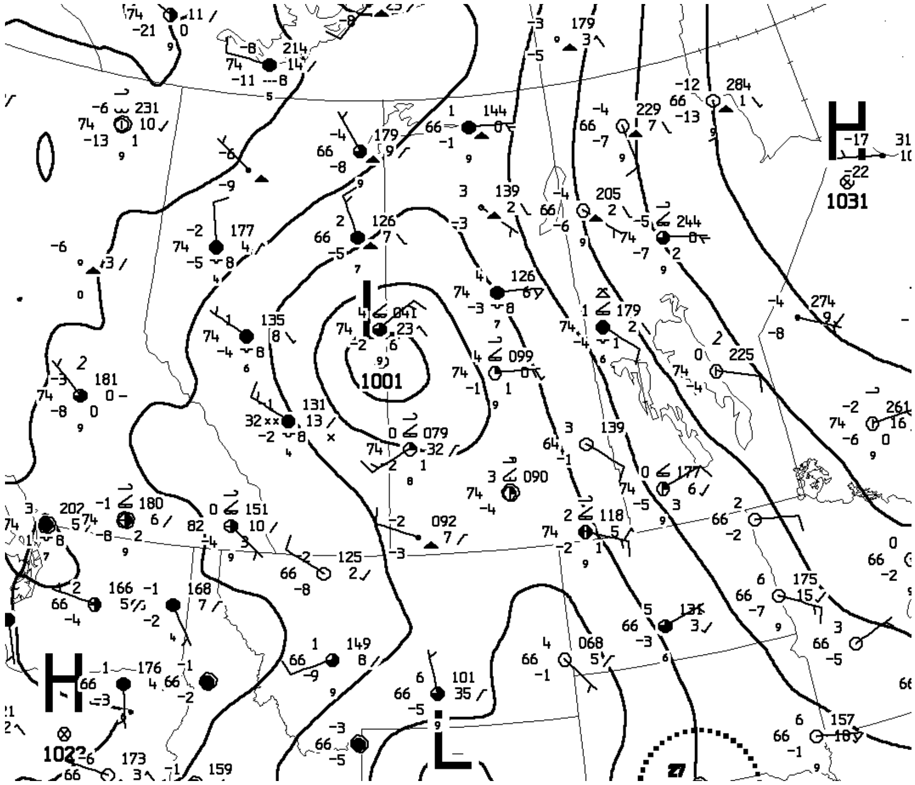

Figure 5: MSC surface analysis, 12Z Thurs 5 April 2012.

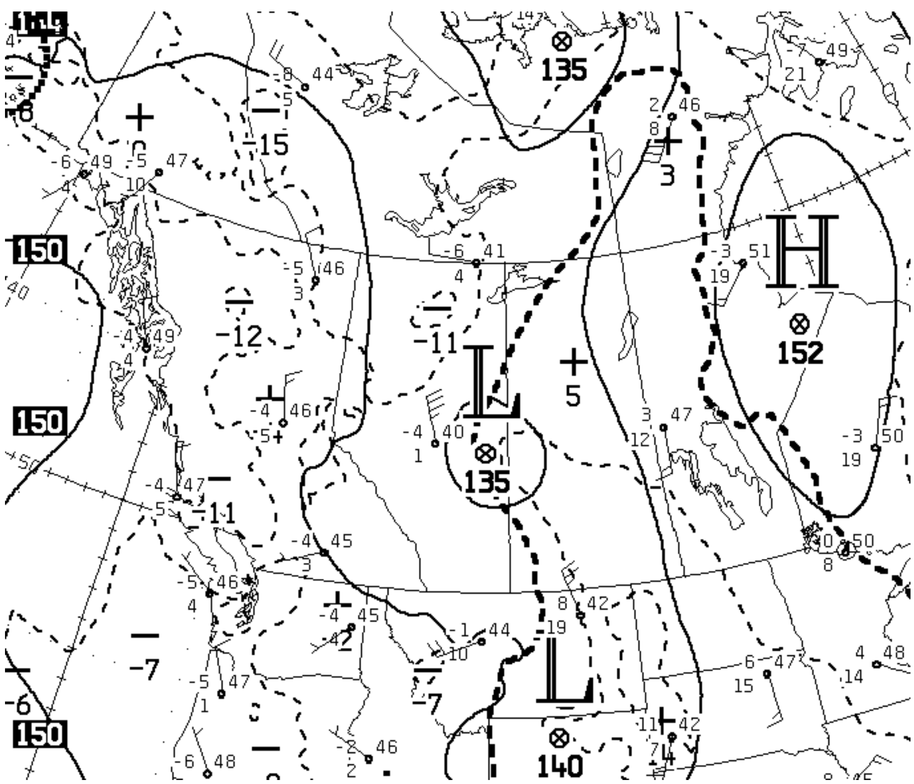

Figure 6: MSC 850 hPa analysis, 12Z Thurs 5 April 2012.

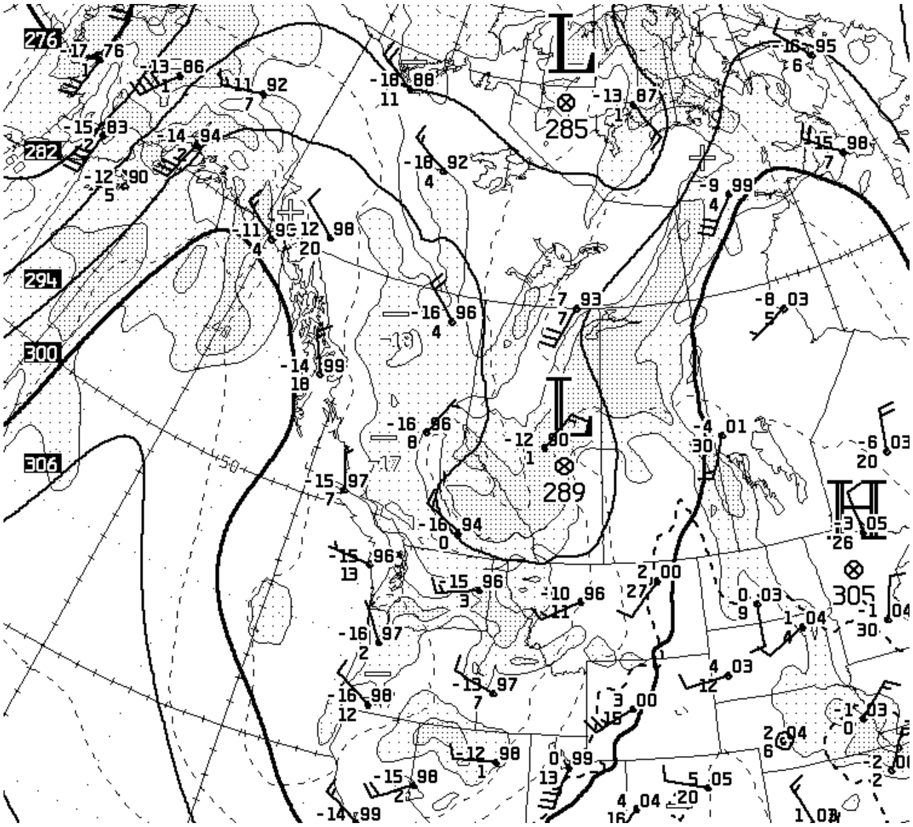

Figure 7: MSC 700 hPa analysis, 12Z Thurs 5 April 2012.

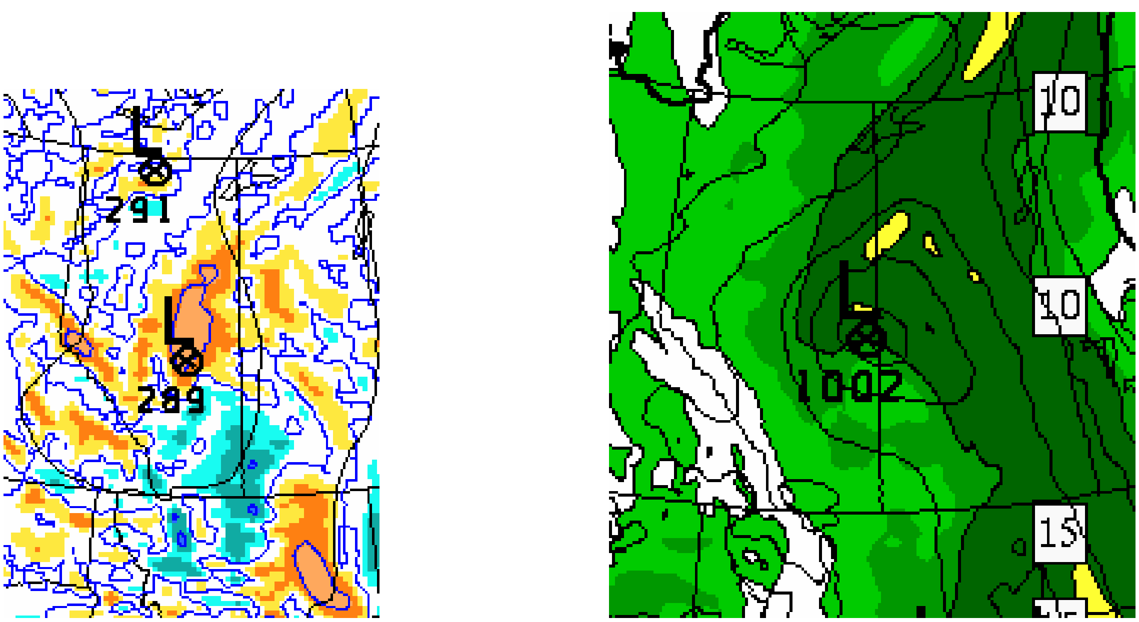

Figure 8: Left panel: Omega at 700 hPa (light orange, $-1 \rightarrow -2\,\mathrm{Pa\,s^{-1}}$). Right panel: precipitable water (yellow/green boundary, 15 mm). From GEM 0h prog valid 12Z, Thurs 5 April 2012

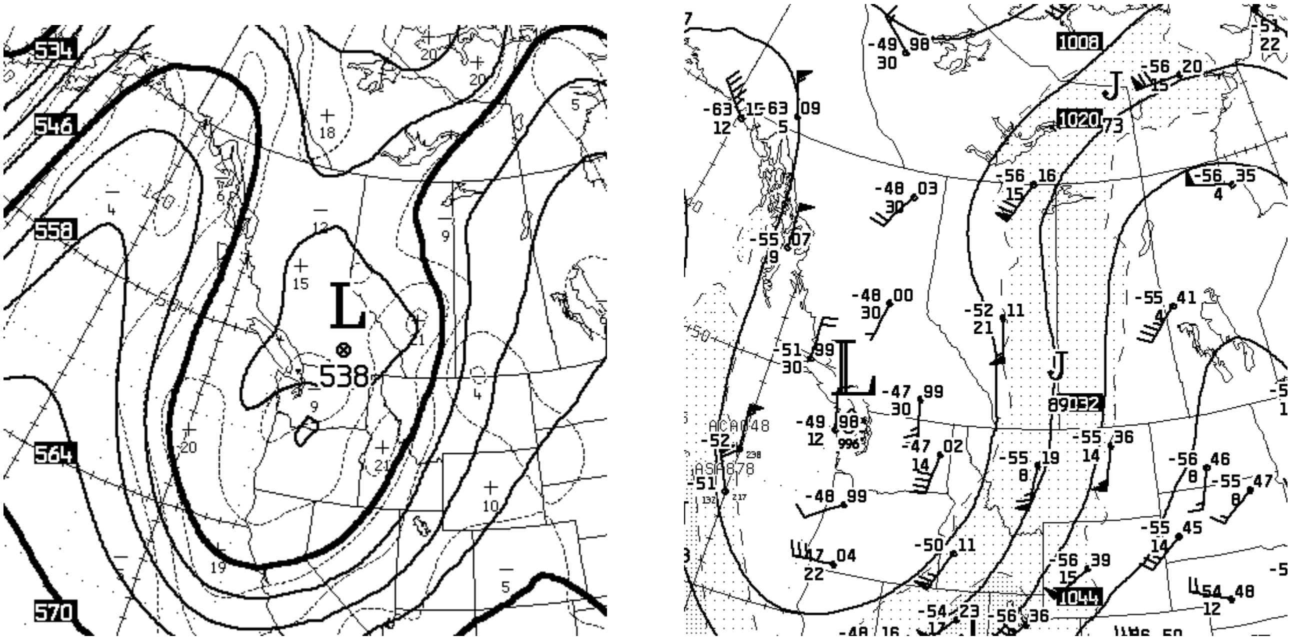

Figure 9: Left panel: 500 hPa height and absolute vorticity(GEM reg 0h prog). Right panel: MSC 250 hPa analysis. Valid 12Z Thurs 5 April 2012.

Figure 10: Left panel: Horizontal divergence at 900 hPa (deep purple, $< -1 \times 10^{-4}\,\mathrm{s}^{-1}$). Right panel: temperature advection at 850 hPa (orange, $> 3\,\mathrm{K\,hr}^{-1}$). From NAM 0h prog valid 12Z, Thurs 5 April 2012

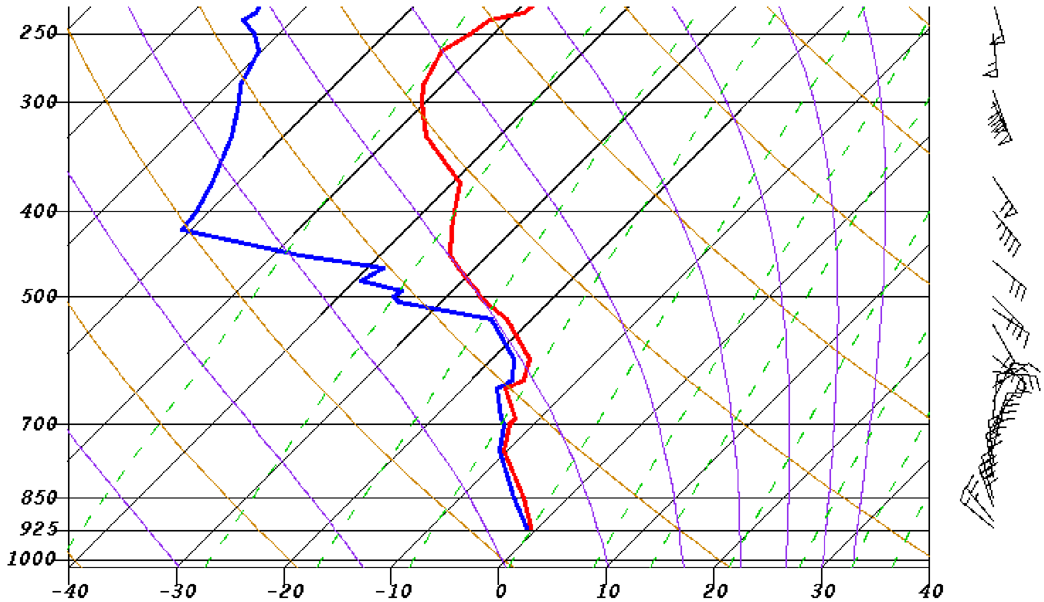

Figure 11: Stony Plain sounding, 12Z Thurs 5 April 2012 (data below).

PRES hPa	HGHT m	TEMP C	DWPT C	RELH %	MIXR g/kg	DRCT deg	SKNT knot	THTA K	THTE K	THTV K
1000.0	92									
925.0	725									
920.0	766	-0.7	-1.0	98	3.88	310	16	279.0	289.9	279.7
903.1	914	-1.5	-1.9	97	3.69	320	25	279.7	290.1	280.3
869.2	1219	-3.1	-3.9	95	3.32	340	42	281.0	290.5	281.6
850.0	1397	-4.1	-5.0	93	3.12	345	34	281.8	290.8	282.4
804.2	1829	-6.9	-7.6	95	2.70	350	30	283.4	291.2	283.8
773.4	2134	-8.9	-9.4	96	2.44	355	25	284.4	291.6	284.8
752.0	2353	-10.3	-10.7	97	2.26	9	32	285.1	291.9	285.5
743.7	2438	-10.6	-11.0	97	2.23	15	35	285.7	292.4	286.1
714.7	2743	-11.7	-12.2	96	2.11	20	15	287.8	294.1	288.1
700.0	2903	-12.3	-12.8	96	2.05	35	15	288.8	295.1	289.2
690.0	3013	-12.3	-13.5	91	1.97	12	13	290.0	296.1	290.4
686.8	3048	-12.5	-13.7	91	1.94	5	13	290.2	296.1	290.5
659.8	3353	-14.4	-15.3	93	1.77	25	16	291.4	296.9	291.7
636.0	3632	-16.1	-16.8	94	1.62	52	17	292.5	297.6	292.8
633.8	3658	-15.9	-16.7	94	1.64	55	17	293.0	298.2	293.3
623.0	3788	-15.1	-16.1	92	1.76	72	22	295.4	300.9	295.7
608.8	3962	-15.7	-16.9	91	1.69	95	28	296.7	302.0	297.0
590.0	4198	-16.5	-17.9	89	1.59	122	27	298.4	303.5	298.7
584.6	4267	-17.0	-18.4	89	1.54	130	27	298.6	303.6	298.9
538.5	4877	-21.5	-22.9	88	1.13	150	19	300.3	304.0	300.5
531.0	4982	-22.3	-23.7	88	1.07	142	18	300.6	304.1	300.8
516.6	5182	-24.4	-29.7	61	0.63	125	17	300.4	302.5	300.5
507.0	5320	-25.9	-33.9	47	0.43	131	24	300.2	301.7	300.3
500.0	5420	-26.9	-34.9	47	0.40	135	30	300.2	301.6	300.2
492.0	5536	-27.7	-34.7	51	0.41	134	30	300.6	302.0	300.7
479.0	5728	-29.5	-39.5	37	0.26	133	31	300.7	301.6	300.7
464.0	5954	-31.5	-38.5	50	0.30	131	32	300.9	302.0	301.0
454.7	6096	-32.6	-43.7	32	0.18	130	32	301.2	301.9	301.3
448.0	6201	-33.5	-47.5	23	0.12	131	34	301.4	301.9	301.5
420.0	6652	-35.7	-60.7	6	0.03	136	41	304.2	304.3	304.2
400.0	6990	-37.1	-61.1	6	0.03	140	46	306.7	306.8	306.7
371.0	7509	-39.3	-62.3	7	0.02	144	56	310.4	310.5	310.4
365.0	7620	-40.3	-62.6	7	0.02	145	58	310.6	310.7	310.6
327.0	8362	-46.9	-64.9	11	0.02	151	69	311.4	311.5	311.4
300.0	8930	-50.3	-67.3	12	0.01	155	78	314.3	314.4	314.4
290.3	9144	-51.4	-68.4	11	0.01	160	77	315.8	315.8	315.8
286.0	9241	-51.9	-68.9	11	0.01	162	75	316.4	316.4	316.4
262.0	9807	-53.3	-70.3	11	0.01	175	64	322.4	322.4	322.4
250.0	10110	-52.3	-72.3	7	0.01	175	54	328.2	328.2	328.2

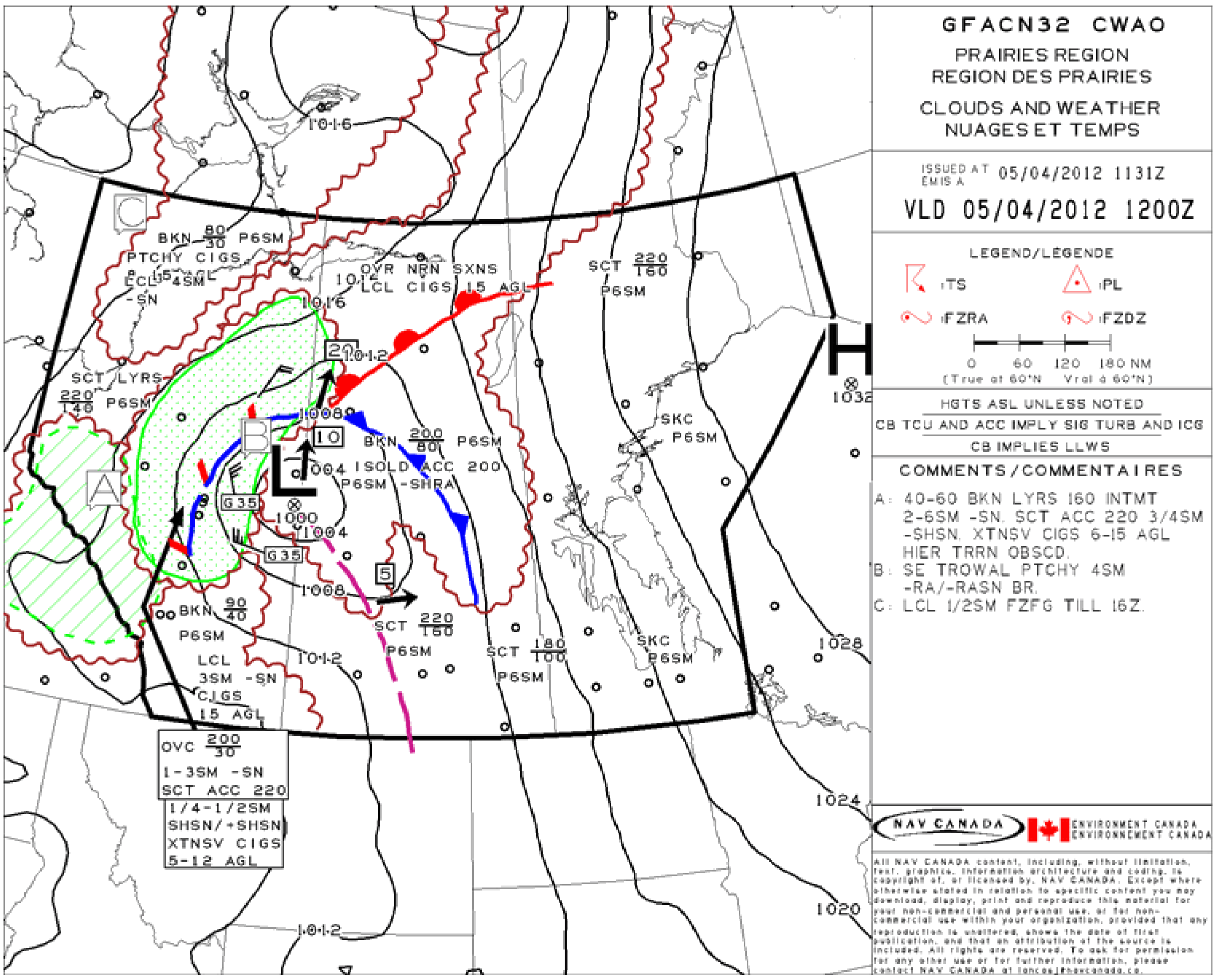

Figure 12: GFA valid 12Z Thurs 5 April 2012.