EAS270 "The Atmosphere" Final Exam 14 Dec. 2011

Professor: J.D. Wilson Time available: 120 mins Value: 40%

Formula sheets not permitted. Cell phones must not be used. Record your multichoice answers on the scantron sheet. Respond to short answer questions **in the space provided**.

**You must hand in this exam booklet PLUS your scantron sheet**

## Equations and Data.

$$Q^* = Q_H + Q_E + Q_G$$

Surface energy balance on a reference plane at the base of the atmosphere, all fluxes in [W m$^{-2}$]. $Q^*$ the net radiation, positive if directed towards the surface; $Q_H, Q_E$ the sensible and the latent heat fluxes, positive if directed from the surface towards the atmosphere; $Q_G$ the heat flux to the substrate below the reference plane, positive if directed from the surface into ground/lake/ocean. The latent heat flux is related to the vertical flux of water vapour $E$ by the relationship $Q_E = L_v E$, where $L_v$ [J kg$^{-1}$] is the latent heat of vapourization.

$$V = \frac{g}{f}\frac{\Delta h}{\Delta n}$$

The Geostrophic wind equation. $\Delta h$ [m], the change in height of a constant pressure surface over distance $\Delta n$ [m] normal to the height contours; $f = 2\Omega\ \sin\phi$ [s$^{-1}$] the Coriolis parameter (where $\Omega \approx 2\pi/(24\times 60\times 60) = 7.27\times 10^{-5}$ s$^{-1}$ is the angular velocity of the earth, and $\phi$ is latitude); $g = 9.81$ [m s$^{-2}$] acceleration due to gravity. The Geostophic wind is oriented *parallel* to the height contours.

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**Short answer questions (12 x 1.5 → 18 %)**

**Enter your name** on each of the next three pages. Enter your responses tidily, using **only** the space provided. Blank pages for rough working are provided at the back of this exam booklet.

1. Using the formula for a geostrophic wind (given as data), compute the geostrophic wind speed corresponding to the height gradient $\Delta h/\Delta n$ implied by the smaller arrow on Figure (1). Assume the latitude is $\phi = 58^o$. The long arrow corresponds to a true distance of $11 \times 111$ km. Show your steps in the space below.

$$\begin{aligned}
f &= 2\,\Omega\,\sin 58 = \; 1.454 \times 10^{-4} \times \; 0.848 = 1.23 \times 10^{-4}\,\mathrm{s} \\
\Delta h &= 60\ [\mathrm{m}]\ \text{(as usual; or could be deduced from numeric data on Fig. 1)} \\
\Delta n &= (17/54)\; \times\; 11\; \times 111,000 = (17/54)\; \times\; 1.22 \times 10^6\,\mathrm{m} = \; 3.84 \times 10^5\ [\mathrm{m}] \\
V &= 12.4\ [\mathrm{m\,s^{-1}}]
\end{aligned}$$

2. Define the significance and mode of action of a "greenhouse gas."

Mode of action: *A greenhouse gas (GHG) is an atmospheric gas, such as water vapour or carbon dioxide or methane, that is capable of* ***absorbing*** *and* ***re-radiating*** *photons/radiation in the* ***long-wave*** *(or IR or terrestrial) band.* A GHG is therefore a selective absorber/radiator of radiative energy.

Significance: *Plays an active role in redistribution of heat within the atmosphere, such that earth's mean surface temperature is warmer than it would otherwise be.*

3. Write down an approximate radial force balance (a single force giving rise to the needed radial acceleration) applicable to an axially-symmetric (i.e. circular), vertical dust devil, defining all terms used.

The rotation period (i.e. time scale) of a dust devil (order seconds or less) is so short that the Coriolis force is irrelevant to the motion. Thus

$$\begin{aligned}
F_{pg} &= \frac{1}{\rho}\,\frac{\Delta P}{R}\ \text{(pressure-gradient force per unit mass)} \\
a_{cntr} &= \frac{V^2}{R}\ \text{(centripetal acceleration)} \\
a_{cntr} &= F_{pg}\ \text{(acceleration=force per unit mass)}
\end{aligned}$$

so $\boxed{\rho\, V^2 = \Delta P}$ or $\boxed{V = \sqrt{\Delta P/\rho}}$, where $R$ is the radius of the dust devil (distance its axis to its exterior); $\Delta P$ is the pressure deficit on the axis of the dust devil (difference between pressure on the axis and pressure outside the dust devil); $\rho$ is air density; $V$ is the tangential wind speed. Checking the units is useful: taking the box on the left,

$$[\mathrm{kg\,m^{-3}\,m^2\,s^{-2} = kg\,m^{-1}\,s^{-2}}] = [\mathrm{N\,m^{-2} = kg\,m\,s^{-2}\,m^{-2} = kg\,m^{-1}\,s^{-2}}]$$

4. Explain why the diurnal range in temperature is typically smaller over ocean than over land.

   Consider the surface energy balance (equation is given in the data section). Over ocean, *water is freely available for evaporation*, making it likely that over the ocean the latent heat flux $Q_E$ will consume a larger proportion of the energy $Q_H + Q_E$ (equalling $Q^* - Q_G$) that is partitioned to the atmosphere, than over land. Sunlight is able to penetrate into water, so that absorption is spread over some depth. Furthermore the ocean surface layer is *mixed*, so that its thermal response to the energy added or subtracted daily is more modest than that of a land surface (participating ocean layer has *higher effective heat capacity* than participating land layer).

5. Give a verbal definition of "potential evapotranspiration."

   Potential evapo-transpiration (also known as "atmospheric demand", and serving in some sense as a *benchmark*) is the water loss that *would* occur under specified (or imposed) climatic conditions (of radiation, temperature, humidity, windspeed) *if* water were freely available to be evaporated. In other words it is the rate of evaporation that *would* occur from a small area of freely wetted surface, under the imposed climate. (The reason for the stipulation of a "small area" is that freely watering a regional surface would alter the regional climate, for the altered surface energy balance would lead to increased humidity and a lowered temperature). In a "dry" climate, potential evapotranspiration will exceed the actual avapotranspiration.

6. Explain why a deep (ie. order 500 - 1000 m) ground-based temperature inversion sometimes persists in winter over central Alberta.

   Long nights and a low daytime sun whose energy is largely reflected by snowpack mean that daily-averaged net radiation can be negative. This in turn means that the atmosphere is being cooled from below day after day, leading to the formation of a deep inversion. Sometimes the flow in the middle troposphere advects mild air over the cold surface air, accentuating the inversion. [c.f. multichoice question on Quiz 3, 2009]

7. The Koeppen climate classification "Dfb" embraces much of central Alberta. Explain the *qualitative* meaning of the three characters.

   The "D" corresponds to a "severe midlatitude" climate; the "f" corresponds to "no dry season," and the "b" corresponds to "warm summer."

8. If $I$ labels a set of equally-spaced gridpoints with separations $\Delta x$ at which the values of temperature are $T(I)$, give a formula valid at gridpoint $I$ for the gradient (in the $x$-direction) of temperature.

$$\frac{\Delta T}{\Delta x}(I) = \frac{T(I+1) - T(I-1)}{2\,\Delta x}$$

9. List characteristics (of storm structure or storm mechanism or storm energetics) that distinguish a hurricane from a midlatitude storm.

   Hurricane — midlatitude storm:

   - warm downdraft at core — cold core updraft
   - axial symmetry — irregular shape
   - typical horizontal scale of order 500-1000 km — typically larger horizontal scale
   - strongest horiz. winds near surface — aloft
   - forms at low latitude ($5 - 20^o$) — mid- and high- latitudes
   - energy drawn from heat of ocean surface layer — energy drawn from gravitational potential energy of frontal structure

10. Summarize the key differences between climate prediction and weather prediction.

    This question does not ask for a summary of the differences between "climate" and "weather." The focus is prediction — and (implicitly) *causal prediction* of climate and weather. And since the relevant processes are so complex, this (practically) implies *numerical prediction*. Thus, how does numerical climate prediction differ from numerical weather prediction? Or how does a GCM differ from an NWP model?

    - aim of NWP is to predict specific weather, *locally in time and space*; whereas the aim of climate prediction is to predict statistics of weather for a prescribed set of "forcings" (solar constant, etc.), the statistics (averages and other measures) being defined over some interval of space and time (e.g. global annual mean; or $50 - 60^o$N January mean)
    - weather prediction an initial value problem, whereas climate prediction an equilibrium problem (find statistics of weather for fixed, given "boundary conditions")
    - initial state crucial for weather prediction, irrelevant for climate prediction
    - weather model may ignore some slow processes or heat reservoirs that are crucial for climate models (e.g. evolution of ocean temperature)
    - depending on the averaging time scale, a climate model must embrace more (perhaps many more) facets of the climate system and more climate feedback processes; on the other hand it may be feasible for a GCM to simplify or ignore some very "rapid" component of the climate system

11. Explain why numerical weather forecasts at 48-hour range (lead time) are imperfect.

    - imperfect initial state
    - extremely sensitive to growth of initial errors
    - impossible to represent all processes and all scales of motion with available computational resources
    - some processes neglected; some parameterized, albeit imperfectly

12. Referring to Figure (2), state the most significant differences between the two meteorological regimes.

    Here it was preferable to convey the big picture, rather than point out details (e.g. 1 degree colder at 850 hPa over Edmonton, on Dec. 2).

| | 26 Nov. | 2 Dec. |
|---|---|---|
| 1 | SW flow aloft over BC and into Alberta<br>due to trough off BC coast | northerly flow aloft over Alberta<br>induced by storm in Saskatchewan |
| 2 | lee trough in Alberta due to the SW upper flow | no obvious topographic influences on Alberta weathe |
| 3 | trowal in SW Alberta due to adiabatic compression | |
| 4 | | midlatitude storm in Saskatchewan |
| 5 | localized warm advection in SE. Alberta | cold advection over N. Central Alberta<br>warm advection over N. Central Manitoba |
| 6 | low heights on west coast | ridge on west coast |
| 7 | large $T - T_d$ spread in Alberta<br>due to flow over Rockies | smaller $T - T_d$ spread |
| 8 | moderate height gradient over Alberta | stronger height gradient over Alberta |
| 9 | light 850 hPa wind over Edmonton | strong 850 hPa wind over Edmonton |
| 10 | axis of a broad ridge centred over Alberta<br>(lee trough a smaller scale feature within it)<br>& axis of a trough over NWT/Manitoba | trough through central prairies |
| 11 | ridge in E. BC upwind of Rockies (orographic)<br>(counterpart of Ab. lee trough) | |

## Multi-choice (44 x 1/2 → 22 %)

1. According to the IPCC, simulations using Global Climate Models (GCMs) match the observed evolution of global mean near surface temperature in the industrial era provided they account for which forcings?
   (a) evolving orbital (Milankovich) parameters
   (b) volcanism, evolving orbital (Milankovich) parameters
   (c) greenhouse gas concentration, Southern Oscillation
   (d) solar output, cloud, latitude
   (e) volcanism, solar output, greenhouse gas concentration ✓✓

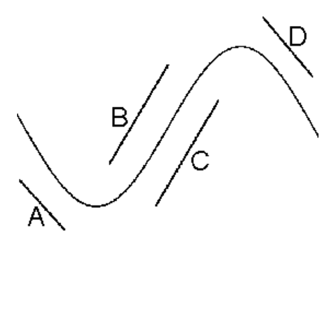
2. Suppose the rotation rate of a certain hypothetical planet is four rotations per earth day. Gravitational acceleration on this planet is the same as on earth. Assuming characteristic values of the atmospheric pressure (and height) gradients are also the same as on earth, how would the free atmosphere wind speeds on that planet compare with those on earth?
   (a) the same
   (b) faster by a factor of four
   (c) slower by a factor of four ✓✓
   (d) faster by a factor of two
   (e) slower by a factor of two

3. Which is the most commonly occurring summertime airmass over central and northern Alberta?
   (a) mT
   (b) mP
   (c) cA
   (d) cP ✓✓
   (e) cT

4. Which option describes the expected trend in the central (sea-level corrected) pressure of a midlatitude storm, if divergence aloft exceeds convergence in the boundary layer?
   (a) decreasing ✓✓
   (b) increasing
   (c) steady
   (d) oscillating
   (e) hydrostatic

5. Which (A, B, C or D) is the most probable location for a surface cold front relative to the wave in the upper height contour?

   (a) A    (b) B    (c) C ✓✓    (d) D



6. Suppose one were using prognostic charts at the mandatory levels to assess the likelihood of precipitation at a point P. Which of the listed factors noted from the charts would be **least** significant?
   (a) ascending vertical motion in the region of P at one or more levels
   (b) small temperature-dewpoint spreads in the region of P at one or more levels
   (c) upslope surface winds in the region of P
   (d) a midlatitude cyclone in close proximity to P
   (e) surface temperature in the region of P near normal ✓✓

7. Which statement regarding lightning is **false**?
   (a) lightning occurs in both warm and cold clouds ✓✓
   (b) the stepped leader is an irregular conductive (ionized) channel that progresses downward from cloud towards ground
   (c) if the delay between a lightning flash and thunder is $t$ [s], then the distance to the lightning stroke is about $300\,t$ [m]
   (d) the uppermost layer of a thunderstorm is positively charged
   (e) just prior to the occurrence of lightning, the base of the thunderstorm is negatively charged

8. Which statement regarding the role of a shallow inversion aloft is **false**?
   (a) an elevated inversion may restrict convection early in the day
   (b) deep convection may occur wherever exceptional thermals penetrate a shallow inversion aloft
   (c) severe convective storms cannot occur where an elevated inversion exists ✓✓
   (d) a subsidence inversion aloft is not uncommon downwind of a mountain range
   (e) plumes of rising air may become negatively buoyant upon penetrating into an elevated inversion

9. Which association is **false**?
   (a) Rossby wave – conditionally unstable atmosphere ✓✓
   (b) atmospheric window – satellite cloud imagery
   (c) overrunning – airmass boundary
   (d) cyclogenesis – polar front theory
   (e) lee trough – Chinook wind

10. What is the significance of an “Omega-block” (or “Omega high”) in the mid-tropospheric flow?
   (a) rapid changes in weather can be expected
   (b) stable (unchanging) weather can be expected ✓✓
   (c) warm weather can be expected
   (d) cold weather can be expected
   (e) zonal flow is occurring

11. Which of the following air properties would normally increase as you travelled upward through the summer, daytime atmospheric boundary layer?
   (a) air density
   (b) air pressure
   (c) air temperature
   (d) wind speed ✓✓
   (e) humidity

12. On a fine autumn afternoon during a period of airmass weather (i.e. weak horizontal temperature gradients) a weather forecaster predicts an overnight minimum temperature $T^{\min} = 0^{\circ}$C, expecting the night should be clear and *calm*. If (counter to his or her expectation) a firm wind (e.g. $1-2\,\mathrm{m\,s^{-1}}$) continued overnight, what outcome would you anticipate, and why?
    (a) $T^{\min}$ about the same as predicted, as the unexpected wind would not influence nocturnal cooling rate
    (b) $T^{\min}$ warmer than predicted due to the unexpected vertical mixing ✓✓
    (c) $T^{\min}$ warmer than predicted, due to release of advected of latent heat
    (d) $T^{\min}$ colder than predicted due to longwave radiation
    (e) $T^{\min}$ colder than predicted due to unexpected adiabatic expansion

13. Which two families of curves on a skew T–log p diagram are parallel to each other *high in the atmosphere*?
    (a) isotherms & isobars
    (b) isobars & dry adiabats
    (c) isobars & moist adiabats
    (d) isotherms & dry adiabats
    (e) dry adiabats & moist adiabats ✓✓

14. Which statement best describes the idealized "cold conveyor belt" (CCB) that may be an identifiable feature of a midlatitude storm?
    (a) the CCB is a surface wind (typically W or NW) advancing behind the cold front and displacing the air in the warm sector
    (b) the CCB is a dry W or NW upper wind that overruns the warm front
    (c) the CCB is a cold surface S or SE wind in the warm sector that overruns the warm front
    (d) the CCB is a cold surface E or SE wind located on the cold side of the warm front, that ascends and emerges as a westerly ✓✓

15. Consider a parcel of air in the mid-troposphere moving alternately north then south along height contours that mark a Rossby wave. Which statement is most reasonable?
    (a) parcel's absolute vorticity is constant ✓✓
    (b) parcel's longtitude is constant
    (c) parcel's relative vorticity is constant
    (d) parcel's latitude is constant
    (e) parcel's earth vorticity is constant

16. For several reasons, significant spatial patterns of lower atmospheric wind and temperature can be better sought or assessed by referring to 850 hPa analysis than to the surface analysis. Which of the listed reasons is **spurious** (false)?
    (a) except in mountainous regions, this is away from the complicating influences of local terrain
    (b) patterns at 850 hPa evolve less rapidly than at ground
    (c) provided the 850 hPa level is above (or high in) the friction layer, observed winds reflect the synoptic scale pressure gradient
    (d) this is a good level for identifying the jetstream ✓✓
    (e) regions of warm or cold advection are readily identified

17. How may one identify a region of the atmosphere that is baroclinically unstable?
    (a) by identifying regions of warm or cold advection aloft (e.g. 850 hPa level) ✓✓
    (b) by comparing the environmental lapse rate with the dry & moist adiabatic lapse rates
    (c) from the pattern of the thickness contours on the 500 hPa analysis
    (d) from the pattern of the isotherms on the 700 hPa anaysis
    (e) by identifying regions of low temperature-dewpoint spread at the 700 hPa level

18. Which statement best describes the pattern of surface winds associated with a mid-latitude cyclonic storm in the northern hemisphere?
    (a) winds spiral clockwise around the Low, with an inward-directed cross-isobar component that results in sink
    (b) winds spiral anti-clockwise around the Low, with an inward-directed cross-isobar component that results in ascent ✓✓
    (c) winds spiral clockwise around the Low, with an outward-directed cross-isobar component that results in sink
    (d) winds spiral anti-clockwise around the Low, with an outward-directed cross-isobar component that results in ascent

19. Which statement has a *weak* or *false* scientific basis or justification?
    (a) global annual mean surface temperature has increased by roughly 1°C since the middle of the twentieth century
    (b) according to the IPCC, GCMs track the record of global annual mean surface temperature since 1900 only if they include anthropogenic GHG forcing (in addition to natural forcing)
    (c) the ice core record over some 800KyrBP shows correlated fluctuations in $CO_2$ concentration and inferred climate whose respective magnitudes are roughly 100 ppm and 10°C
    (d) the Little Ice Age (and associated Maunder sunspot Minimum) was an unforced (i.e. internal) oscillation of the climate system, and therefore the post-1900 trend in global annual mean surface temperature is likely to be an unforced oscillation ✓✓
    (e) the trend in global annual mean surface temperature since 1900 could plausibly be due to anthropogenic GHG forcing

20. Which is believed to be the cause of the glacial/interglacial phases of the Quaternary ice age?
    (a) an internal (i.e. unforced) oscillation of the earth's climate system
    (b) changing parameters of earth's orbit ✓✓
    (c) changing solar output
    (d) plate tectonics
    (e) unstable interactions of animal and plant life altering planetary albedo

21. Which group of factors determines daily potential evapotranspiration (also known as "atmospheric demand" for water vapour)?
    (a) latitude, longitude, elevation
    (b) latitude, daily mean temperature
    (c) daily mean temperature and daily total precipitation
    (d) solar constant, Coriolis parameter, Geostrophic windspeed
    (e) daily mean net radiation, vapour pressure deficit and windspeed ✓✓

22. Which of the following aspects of GCMs contributes most to differences in their equilibrium climate sensitivities?
    (a) assumed change in atmospheric $CO_2$ concentration
    (b) parameterizations affecting cloud feedback(s) ✓✓
    (c) solar constant
    (d) orbital parameters
    (e) spatial domain of the model atmosphere

23. Which atmospheric process is predominantly responsible for "coupling" the values of humidity at neighbouring gridpoints of a numerical weather or climate model?
    (a) radiation
    (b) diffusion
    (c) adiabatic expansion
    (d) subsidence
    (e) wind (i.e. convective) transport ✓✓

24. The equation

$$\begin{aligned}\Delta x\,\Delta y\,\Delta z\,\Delta\,\rho(I,J,K) &= \Delta t\,\Delta z\,\Delta y\;[F_x(x_1) - F_x(x_2)]\\ &+ \Delta t\,\Delta z\,\Delta x\;[F_y(y_1) - F_y(y_2)]\\ &+ \Delta t\,\Delta x\,\Delta y\;[F_z(z_1) - F_z(z_2)]\end{aligned}$$

gives the change $\Delta\rho(I,J,K)$ [$\mathrm{kg\,m^{-3}}$] in the air density at gridpoint $I, J, K$ during a single model time step $\Delta t$, where $(\Delta x, \Delta y, \Delta z)$ are the dimensions of the "cell" labelled $(I, J, K)$, whose faces are (parts of) the six planes defined by $x = x_1$, $x = x_2$, $y = y_1$, $y = y_2$, $z = z_1$, $z = z_2$. Which statement concerning the quantity $F_x(x_1)$ is **incorrect**?
    (a) it is the flux of mass carried across the face $x = x_1$ during the time step
    (b) it has units [$\mathrm{kg\,m^{-2}\,s^{-1}}$]
    (c) it can have either sign
    (d) it (and all the other $F$s) must vanish, otherwise mass cannot be conserved ✓✓
    (e) it can be specified $F_x(x_1) = U(x_1)\,\rho(x_1)$ in terms of the wind velocity $U(x_1)$ and density $\rho(x_1)$ on the $x_1$ face of the cell

25. Each year Environment Canada provides a regional Dec-Jan-Feb (DJF) temperature forecast: "above normal" (red) or "near normal" (white) or "below normal" (blue), where normal refers to a reference interval (e.g. 1971-2000 normals). For a given region, how are the boundaries ($T_{\min}$, $T_{\max}$) for each category determined?
    (a) to ensure 33% of the observed regional DJF temperatures during the reference interval fall into each category ✓✓
    (b) to ensure 33% of the numerical forecasts for regional DJF temperature fall into each category
    (c) to ensure 33% of the forecast domain is red, 33% white and 33% blue
    (d) so as to coincide with positive, normal and negative values of the Southern Oscillation Index
    (e) so as to coincide with negative, normal and positive values of the Southern Oscillation Index

26. Which specialized numerical weather or climate prediction model might most plausibly be initialized with an artificial axisymmetric vortex defining its initial state over some region?
   (a) a hurricane model ✓✓
   (b) a seasonal outlook model
   (c) an operational tornado forecast model
   (d) a regional model making very short term (say, 6-hr) predictions for locations of thunderstorms
   (e) a regular short range (say, 72-hr) weather prediction model

27. Why are the tops of thunderstorms often located just above the tropopause?
   (a) intense solar radiation at that level provides energy to evaporate cloud droplets
   (b) wind shear across the tropopause blows off the top of the cloud
   (c) the updraft becomes negatively buoyant in the unconditionally stable stratosphere ✓✓
   (d) a downdraft from the stratosphere falls into the updraft
   (e) the updraft is sucked into the polar jetstream

28. Which statement regarding the "equilibrium climate sensitivity" of a GCM is most reasonable?
   (a) it depends on the assumed rise in atmospheric $CO_2$ concentration, i.e. $2\times$ or $4\times$ etc.
   (b) it is determined by the atmospheric component of the GCM, i.e. indifferent to the model ocean
   (c) it is determined by the oceanic component of the GCM, i.e. indifferent to the model atmosphere
   (d) it is sensitive to the initialization of the GCM
   (e) it is not independent of parameterizations in the GCM that determine its cloud processes ✓✓

29. Many numerical weather and climate models assume layer clouds will form in grid cells whose temperature-dewpoint spread $T - T_d$ is smaller than some threhold value, and various processes ensue (including an interaction with the model's treatment of solar radiation). This is (one example of) a "cloud parameterization." Which statement is **incorrect**?
   (a) microphysics of droplet formation/interaction (etc.) is entirely ignored
   (b) small scale vertical motions that may have much to do with the development of cloud cannot be resolved by existing global weather/climate models
   (c) the treatment entails arbitrarily setting certain parameters, e.g. theshhold value of $T - T_d$ for cloud formation
   (d) explicit treatment of cloud processes is not (computationally) feasible
   (e) the details of such parameterizations do not affect the equilibrium climate sensitivity of a GCM ✓✓

30. Recent global warming, whether or not it is driven by increasing atmospheric $CO_2$ concentration, is (or may be) resulting in decreased global coverage of ice and snow. Which of the following *posited* climate feedbacks of retreating snow/ice cover is **least speculative**, i.e. most certain?
   (a) increased evaporation and increased cloud cover (decreased insolation, cloud feedback *negative*)
   (b) increased evaporation and increased cloud cover (upwelling longwave radiation absorbed, cloud feedback *positive*)
   (c) decreased planetary albedo (shortwave reflectivity) – *positive* feedback ✓✓
   (d) poleward migration of climate zones favourable to plants and trees (*negative* feedback, by way of increased $CO_2$ sequestration in form of plant biomass)

(e) slowing of global thermohaline currents as melt water decreases salinity of polar ocean surface waters, decreasing $CO_2$ transfer to storage in the deep ocean (*positive* feedback)

31. Considering a particular season (e.g. Dec-Jan-Feb) and hemisphere, what climatological factor should best correlate with the seasonal average strength of the midlatitude westerlies at the 500 hPa level?

    (a) seasonal mean vertical lapse rate averaged over the hemisphere
    (b) seasonal mean position of the Rossby wave troughs and ridges
    (c) seasonal mean latitudinal gradient in precipitation rate
    (d) seasonal mean latitudinal gradient in 1000-500 hPa thickness ✓✓
    (e) seasonal anomaly in mean temperature for the hemisphere

32. Which of the listed activities is **not** a function of the analysis phase in Numerical Weather Prediction in defining the initial state (time "$t_0$") for a forecast?

    (a) eliminate features that cannot be represented by the model
    (b) ensure the gridded wind field satisfies mass conservation
    (c) run those algorithms collectively known as Model Output Statistics to estimate secondary variables such as airport visibilities ✓✓
    (d) blend the observations (which have been interpolated onto the grid) with a forecast initialized at $t_0 - 6$ hr
    (e) eliminate observations that (from the perspective of the relevant climatology) are unrealistic

33. Which statement concerning hurricanes is **false**?

    (a) the strongest pressure gradient occurs in the eye of the hurricane ✓✓
    (b) hurricanes rarely (if ever) form at latitudes lower than about 5°
    (c) hurricanes form over surface ocean waters whose temperature must exceed about 27°C
    (d) highest rainfall rate coincides with the thunderstorms comprising the eyewall
    (e) the pattern of the surface winds about a hurricane is cyclonic

34. Where are the strongest tornadoes associated with supercell thunderstorms most often formed?

    (a) in the roll cloud
    (b) in the shelf cloud
    (c) in the vault
    (d) in the anvil
    (e) in the wall cloud ✓✓

35. What is the energy source for the kinetic energy of katabatic surface winds?

    (a) gravitational potential energy of warm, moist surface air released by convection
    (b) gravitational potential energy of cold, dense air pooled on elevated topography ✓✓
    (c) gravitational potential energy of abutting warm and cold air masses
    (d) latent heat released when rain freezes at high elevation
    (e) kinetic energy of the dry conveyor belt descending to the surface

36. The "Alberta clipper" and "Colorado low" are storms that form (or re-form) in the lee of the Rockies and track across the continent. Another common winter storm path runs northeastward along the east coast of North America. Why are the latter storms more likely to produce heavy snowfalls?

(a) because they are usually initiated by arrival of an upper trough over a stationary front
(b) because of the lower topography along the east coast
(c) because their "warm conveyor belt" supplies moist maritime air ✓✓
(d) because they are moving from lower to higher latitude
(e) because heavier industrialization along the east coast implies more anthropgenic particulates, which function as CCN

**For the remaining questions, please refer to the attached charts.**

*For the next three questions, please refer to Fig. (3). Assume you are situated at the point marked A and observe a sequence of events in time (first → last) as the storm moves from the WSW towards the ENE parallel to the indicated straight line.*

37. When your position at **A** relative to the storm is as shown by Fig. (3), what would the two lowest layers of the air column above **A** represent?

(a) the cold conveyor belt riding over the warm conveyor belt
(b) the warm conveyor belt riding over the cold conveyor belt ✓✓
(c) the dry conveyor belt riding over the cold conveyor belt
(d) the warm conveyor belt riding over the dry conveyor belt

38. In order first-to-last, what temperature transitions would a thermometer at **A** demonstrate?

(a) cold-to-warm transition followed by warm-to-cold transition ✓✓
(b) cold-to-warm transition followed by warm-to-warmer transition
(c) warm-to-cold transition followed by cold-to-warm transition
(d) warm-to-cold transition followed by cold-to-colder transition

39. In order first-to-last, what sequence of wind directions is probable?

(a) E; calm; E
(b) E; SSW; SE
(c) E; SSW; NW ✓✓
(d) W; NNE; SE
(e) calm; NNE; NW

40. Heavy short-dashed lines on the skew T-log p diagram (Figure 4) identify several families of reference curves. Which line represents the family of dry adiabats?

(a) A
(b) B ✓✓
(c) C
(d) D
(e) E

41. Referring to Figure (5), consider the stratification of the layer beneath 850 hPa. This layer is almost "well-mixed" relative to the dry adiabats, but not quite. How should it be classified?

    (a) unconditionally unstable ✓✓
    (b) unconditionally stable
    (c) conditionally unstable
    (d) conditionally stable
    (e) an inversion

42. Which statement concerning Figure (6) seems most reasonable?

    (a) The dry conveyor belt is represented by the wind vector at Edmonton, i.e. a NW wind with $T - T_d = 3^oC$
    (b) This weather map does not evidence the classic frontal structure of a midlatitude storm
    (c) The cold conveyor belt is represented by the wind vector in the Northwest Territories ($T = -11^oC$) ✓✓
    (d) There is no evidence on this map of a warm conveyor belt
    (e) The dry conveyor belt is represented by the mild, dry current seen on the map at the three stations in the SE corner

43. Referring to Figure (7), the Polar Front Theory suggests one might analyze surface fronts associated with the mid-latitude storm north of the Great Lakes. Which of the listed points is **least relevant** to the question of whether the dashed line on Figure (7) legitimately represents a cold front?

    (a) wind direction differs across the dashed line
    (b) temperature and dewpoint both contrast across the dashed line
    (c) temperatures east of the low are compatible with there being a warm front there ✓✓
    (d) pressure is falling east of the line, and rising west of the dashed line
    (e) the dashed line lies along a "kink" in the isobars

44. Referring to Figure (8), which statement is **incorrect**?

    (a) cold advection is occurring at **C** and **D**
    (b) warm advection is occurring at **B**
    (c) **A** is in the warm sector of the storm
    (d) observed conditions at **A** are inconsistent with the Conveyor Belts model ✓✓
    (e) bunched isotherms curving through **C** and **D** designate a cold front

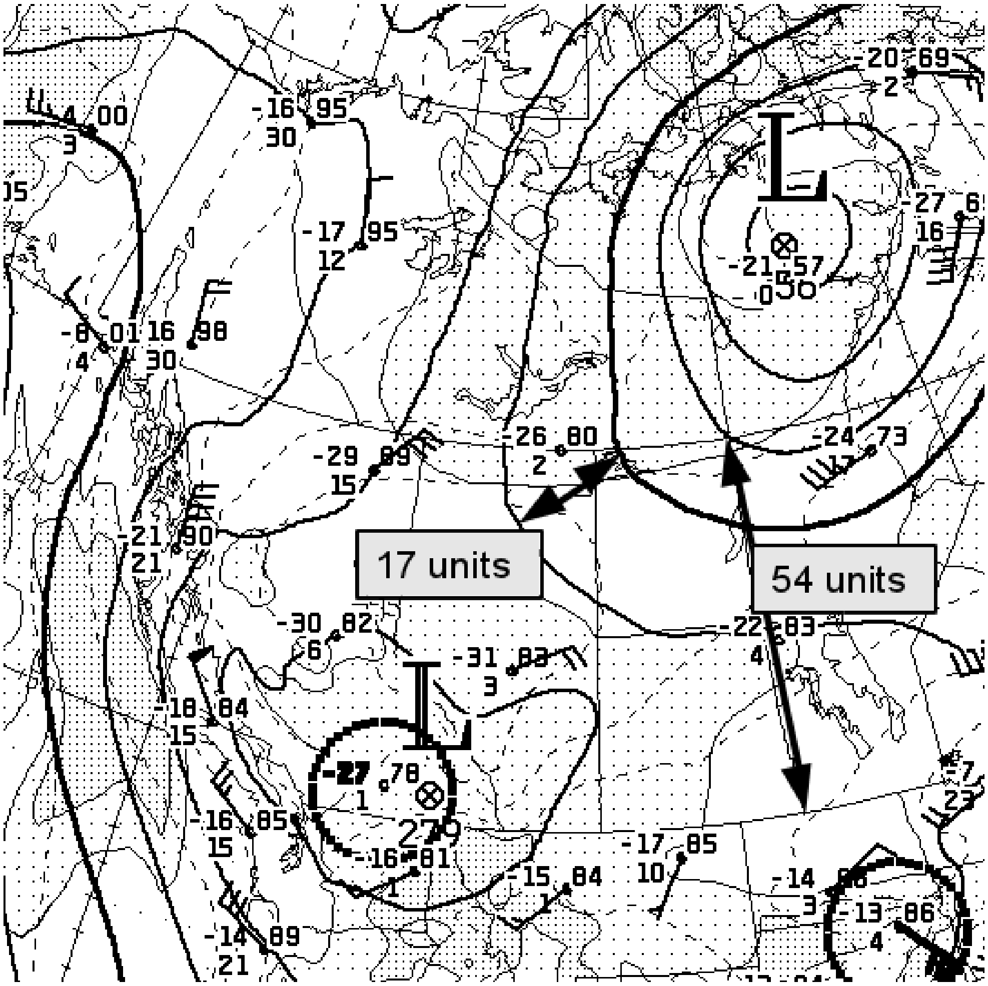



Figure 1: MSC 700 hPa analysis, 12Z 22 Nov., 2010. The numbers in boxes refer to the lengths of the two heavy arrows, in arbitrary units.

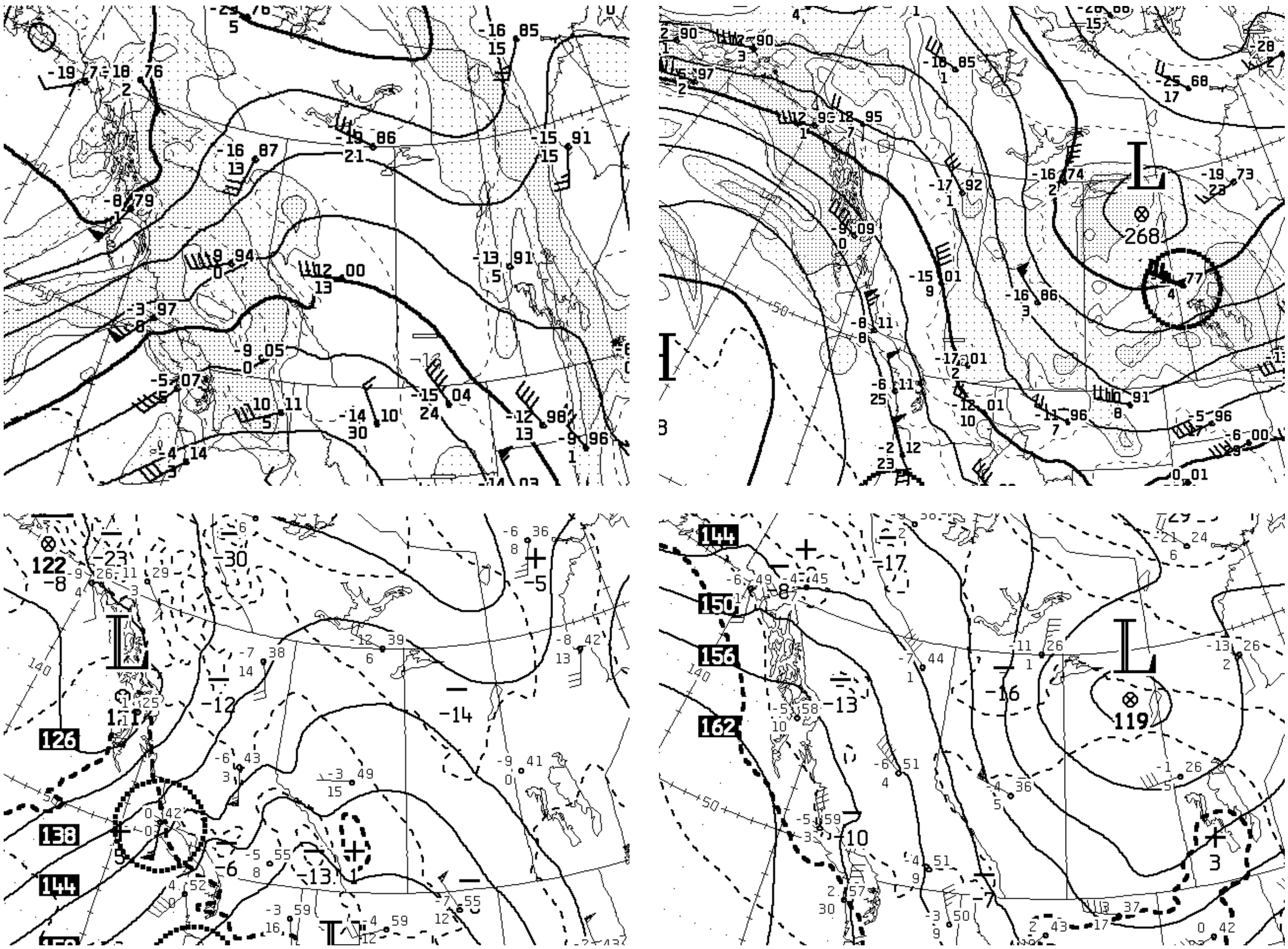



Figure 2: MSC 850 hPa and 700 hPa analyses for 12Z 26 Nov. (left side) and 12Z 2 Dec. (right side), 2011.

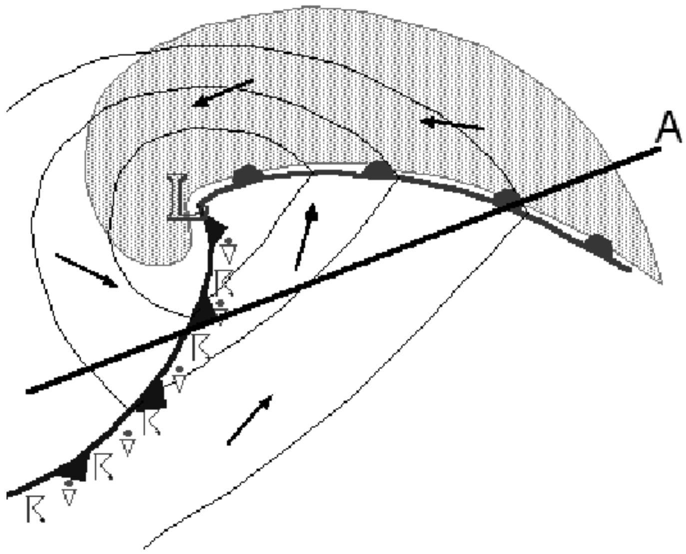



Figure 3: Midlatitude storm (from Doswell & Maddox, 1986). Arrows show direction of wind in the friction layer (the diagram is oriented such that the north-south axis is parallel to the right edge of the page). The “R-like” symbols designate thunderstorms; the “dot over triangle” symbols designate rain showers. Questions concern the sequence of events or conditions at **A** as the storm moves to the ENE parallel to the indicated line through **A**.

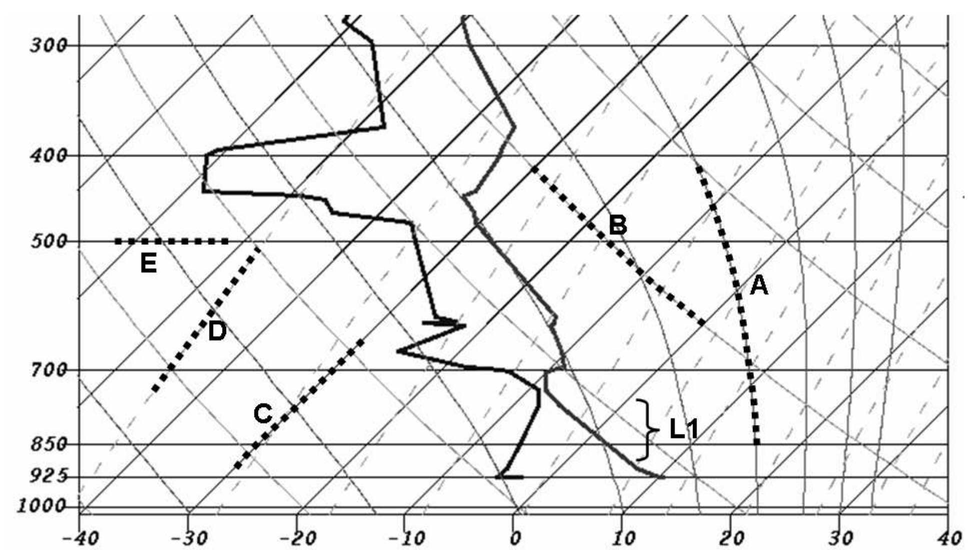



Figure 4: Thermodynamic chart.

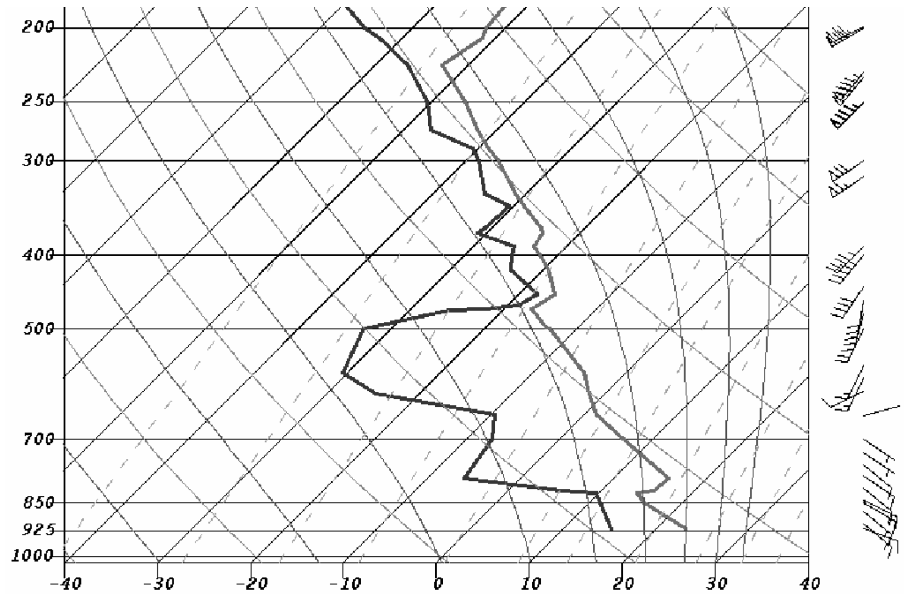



Figure 5: Thermodynamic chart, Stony Plain, 00Z on 23 July 2005.

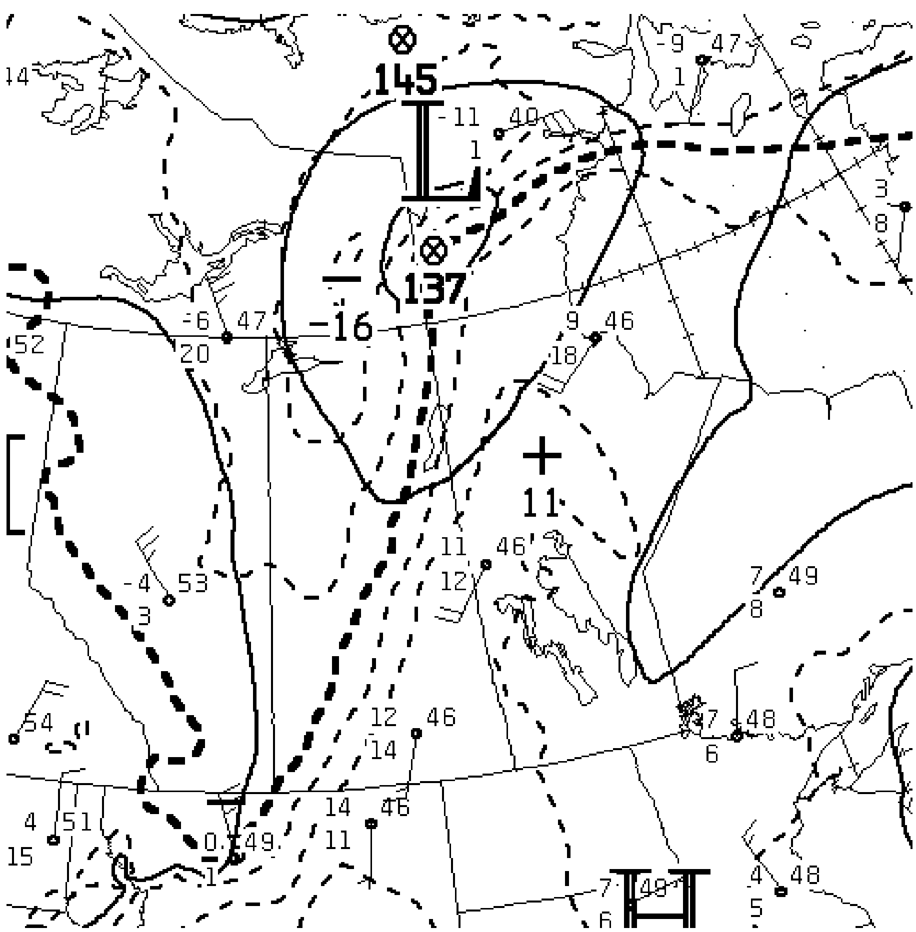



Figure 6: MSC 850 hPa analysis for 00Z on 23 April 2006.

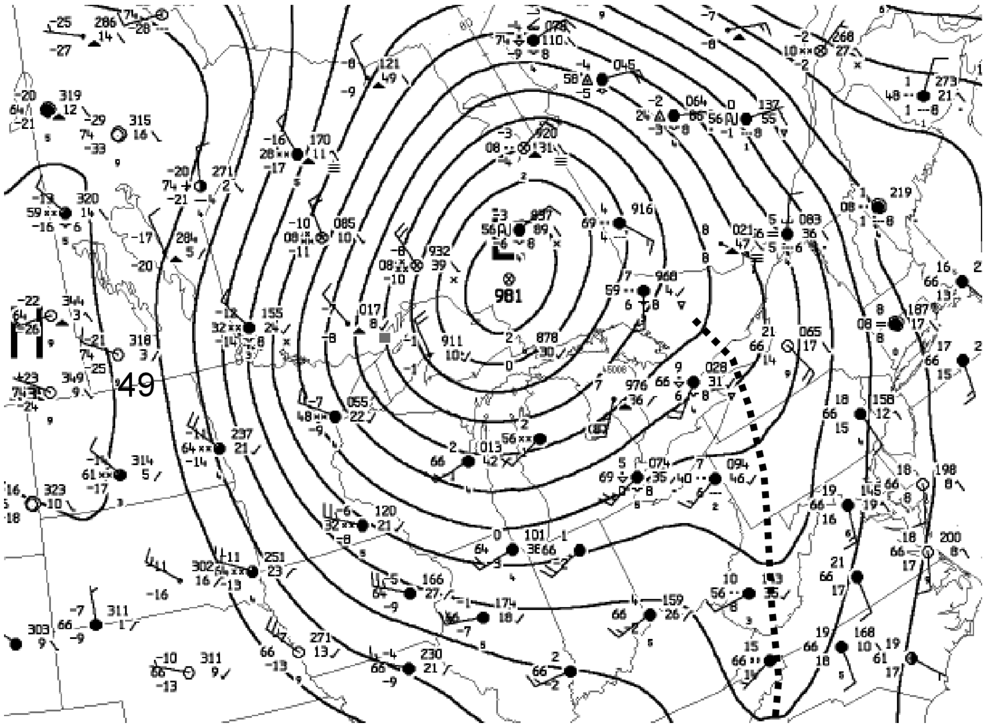



Figure 7: MSC surface analysis, 12Z Nov 16, 2005. Orientation of longitude lines defines the local north-south axis. The stamped "**49**" on the southern border of Manitoba indicates 49° latitude, and that latitude line marks the direction of the east-west axis.

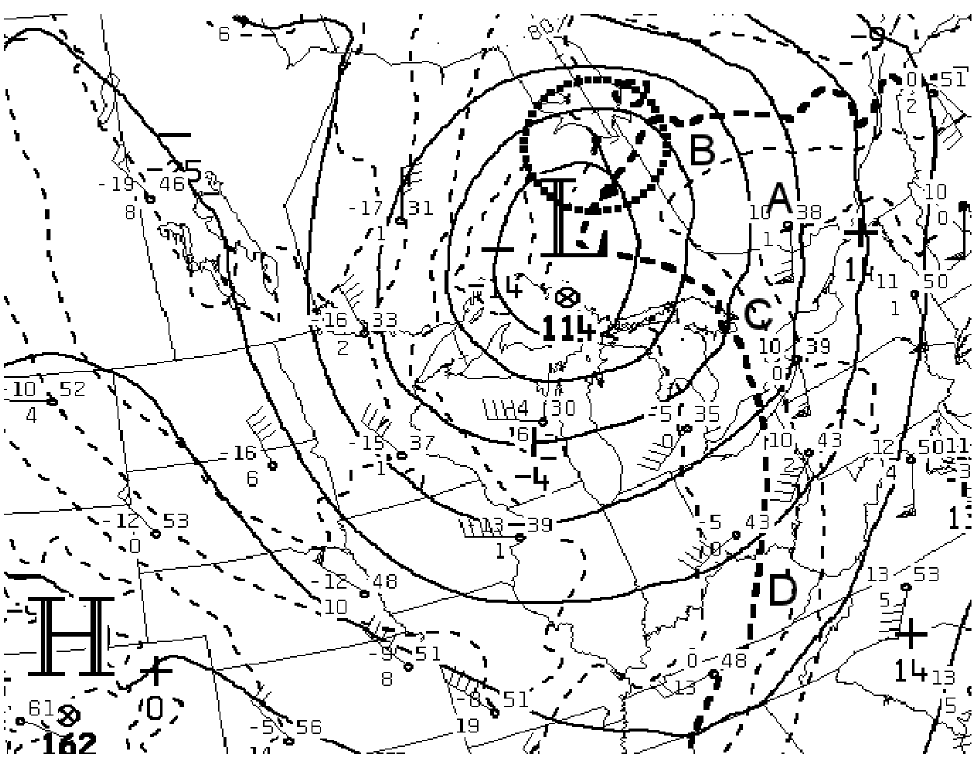



Figure 8: MSC 850 mb analysis, 12Z Nov 16, 2005.