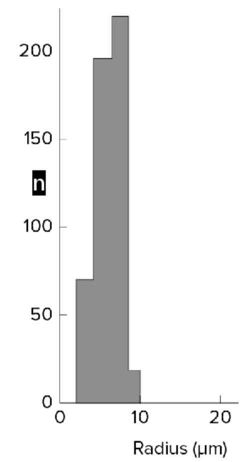
EAS270, "The Atmosphere" <u>Final Exam</u> 17 Dec. 2015

<u>Professor</u>: J.D. Wilson <u>Time available</u>: 120 mins <u>Value</u>: 50%

No formula sheets; no use of tablet computers etc. or cell phones. It is recommended you look at the provided **formulae/data** before starting the exam. Numbered figures are at the back of the exam; smaller figures, un-numbered are scattered through the exam.

Multi-choice (50 x 1 → 50 %)

1. The adjacent figure represents the size distribution **n** of cloud condensation nuclei (CCN) in continental air, also known as the "size spectrum." The unit for **n** is [$\#\,\mathrm{cm}^{-3}\,\mu\mathrm{m}^{-1}$], where "#" denotes "number" and is dimensionless. Which best approximates the total number of CCN per unit volume in $\#\,\mathrm{cm}^{-3}$ (Hint: area under the "curve.")



   (a) 10
   (b) 50
   (c) 100
   (d) 200
   (e) 1200

2. Consider an air parcel at a middle latitude latitude where the Coriolis parameter is $f_c = 10^{-4}\,\mathrm{s}^{-1}$. Let the horizontal speed of the parcel be $10\,\mathrm{m\,s}^{-1}$. If the parcel is $\Delta T = 3\,\mathrm{K}$ degrees warmer than the environment, whose temperature is $T_0 = 300\,\mathrm{K}$, then what is the ratio of the Coriolis to the buoyancy force on the parcel? (Force formulae p13.)

   (a) 10^{-3}
   (b) 10^{-2}
   (c) 10^{-1}
   (d) 1
   (e) 10

3. Regarding the slope winds represented in the diagram, which statement is **false**?

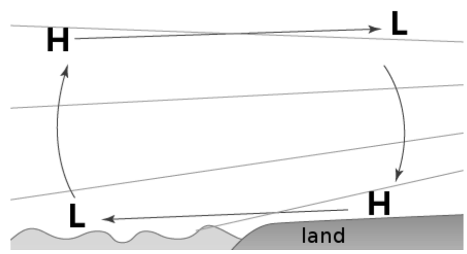
   (a) these are known as valley winds
   (b) this circulation is a response to solar heating
   (c) at the same elevation, air adjacent to the slope is warmer than air at valley centre
   (d) afternoon clouds are more likely to form above the valley floor than along the ridges

4. This is an example of which cloud type?

   (a) altostratus
   (b) altocumulus
   (c) stratocumulus
   (d) cirrus
   (e) cirrostratus

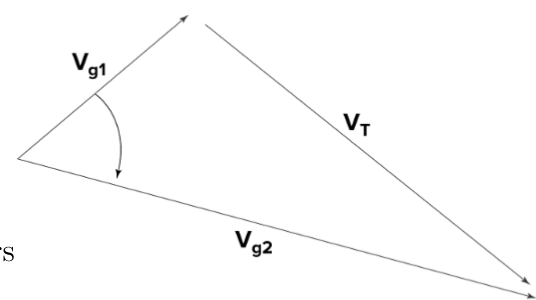
5. Which is the most reasonable value for the updraft velocity in a stratiform cloud?
   (a) $0.001\,\mathrm{m\,s^{-1}}$
   (b) $0.1\,\mathrm{m\,s^{-1}}$
   (c) $1\,\mathrm{m\,s^{-1}}$
   (d) $10\,\mathrm{m\,s^{-1}}$
   (e) $100\,\mathrm{m\,s^{-1}}$

6. The adjacent figure represents a type of thermally-driven mesoscale circulation occurring at a coastline. Which interpretive statement is **implausible**?



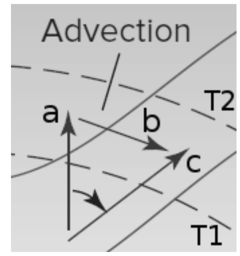
   (a) arrows represent the wind
   (b) straight, sloping lines are isobaric surfaces
   (c) the return onshore flow occurs at the top of the troposphere
   (d) the Coriolis force induces a wind component perpendicular to the plane of the diagram
   (e) the ocean is warmer than the land (i.e. night time case)

7. Assume geostrophic flow in the free atmosphere of the N. hemisphere. Which is the **valid inference**, if the geostrophic wind vector $\vec{V}_g$ "veers" (as shown) with increasing height?



   (a) thickness contours are parallel to height contours
   (b) no thermal advection is occurring
   (c) cold advection is occurring
   (d) warm advection is occurring

8. In the figure solid lines are 500 hPa height contours and dashed lines are thickness contours for the 700-500 hPa layer. Assuming thickness contour T1 is "warmer" than contour T2, which option is correct?



   (a) thermal wind is the vector labelled **a**
   (b) thermal wind is the vector labelled **b**
   (c) thermal wind is the vector labelled **c**
   (d) cold advection is occurring

9. The geostrophic wind law may be written

$$V_g = \frac{g}{f_c} \left| \frac{\Delta Z}{\Delta x} \right| .$$

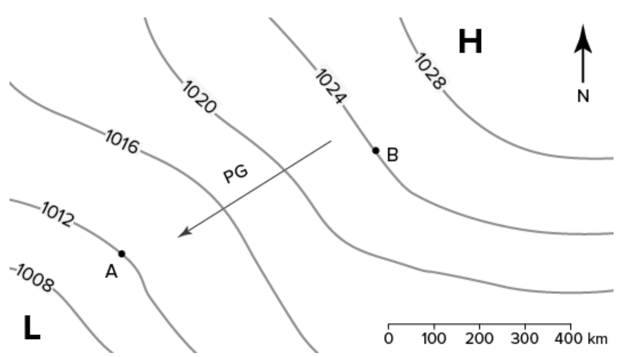
Taking $g/f_c = 10^5\,\mathrm{m\,s^{-1}}$, what isobaric slope ($\Delta Z/\Delta x$ in [m m^{-1}]) corresponds to $V_g = 10\,\mathrm{m\,s^{-1}}$?

   (a) 10^{-4}
   (b) 10^{4}
   (c) 10^{-6}
   (d) 10^{6}

10. Suppose the wind above the friction layer is blowing at speed $V_{\mathrm{gr}} = 10\,\mathrm{m\,s^{-1}}$ parallel to a circular isobar around a low, the radius of the isobar being $R = 1000$ km and the latitude being such that the Coriolis parameter $f_c = 10^{-4}\,\mathrm{s^{-1}}$. Assuming the gradient wind equation applies (i.e. $V_{\mathrm{gr}} = 10\,\mathrm{m\,s^{-1}}$), which option best estimates the values (V_{g}, $|\Delta Z/\Delta x|$) of the geostrophic wind and the implied isobaric slope? (The relationship between V_{gr} and V_{g} is given as data).

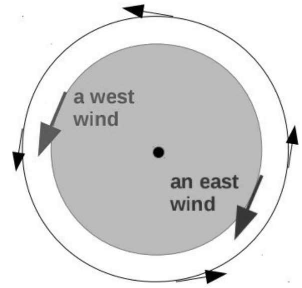
   (a) $11\,\mathrm{m\,s^{-1}},\ 11 \times 10^{-5}\,\mathrm{m\,m^{-1}}$
   (b) $11\,\mathrm{m\,s^{-1}},\ 11 \times 10^{5}\,\mathrm{m\,m^{-1}}$
   (c) $10\,\mathrm{m\,s^{-1}},\ 10^{-4}\,\mathrm{m\,m^{-1}}$
   (d) $9\,\mathrm{m\,s^{-1}},\ 9 \times 10^{-5}\,\mathrm{m\,m^{-1}}$
   (e) $9\,\mathrm{m\,s^{-1}},\ 9 \times 10^{5}\,\mathrm{m\,m^{-1}}$

11. What is the pressure gradient $\Delta P/\Delta x$ if estimated from the pressure difference between A and B?



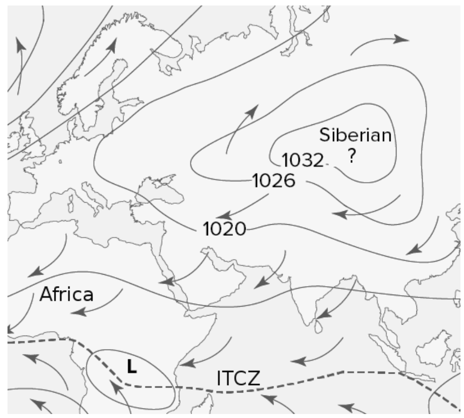
   (a) $2\,\mathrm{Pa\,m^{-1}}$
   (b) $2 \times 10^{-2}\,\mathrm{Pa\,m^{-1}}$
   (c) $2 \times 10^{-3}\,\mathrm{Pa\,m^{-1}}$
   (d) $2\,\mathrm{hPa\,km^{-1}}$

12. The figure is a view looking downwards at the north geographic pole (i.e. down earth's spin axis), such that earth rotates anticlockwise. Taking the convention that earth has positive angular momentum L and that wind drag on the surface exerts a positive torque Γ about earth's spin axis if it tends to increase L (increase earth's rotation rate, reduce daylength), which statement is **false**?



(a) a surface westerly in the S. hemisph. exerts a negative torque on earth
(b) a surface easterly in the N. hemisp. exerts a negative torque on earth
(c) imperfectly cancelling contributions from W. and E. surface winds can cause (small) variations in daylength
(d) drag of a meridional wind on earth's surface exerts no torque about earth's spin axis

13. The figure gives climatological surface isobars and winds representing one month of the year. Which statement regarding the Siberian system is true?

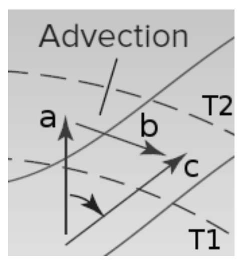


(a) it is a summer-time thermal high
(b) it is a summer-time thermal low
(c) it is a winter-time thermal high
(d) it is a winter-time thermal low

14. Which option correctly fills in the blanks of the following statement? "Turbulence is maximised when ____ wind speeds and an ____ atmosphere occur over a ____ surface."

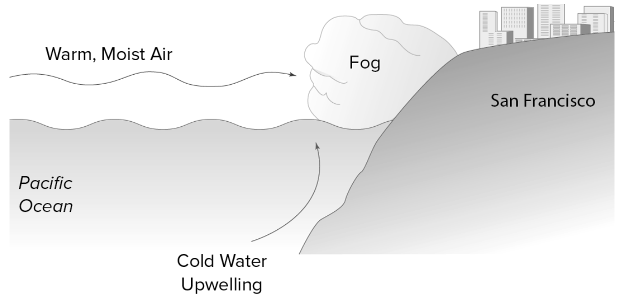
(a) fast; unstable; smooth
(b) fast; unstable; rough
(c) fast; stable; smooth
(d) slow; stable; smooth
(e) slow; stable; rough

15. In the figure solid lines are 500 hPa height contours and dashed lines are thickness contours for the 700-500 hPa layer. Assuming thickness contour T1 is "warmer" than contour T2, which option is correct?



(a) the vector labelled **a** is the wind vector at the 700 hPa level
(b) the vector labelled **a** is the wind vector at the 500 hPa level
(c) this has to be a S. hemisphere scenario
(d) the configuration corresponds to "barotropic" flow

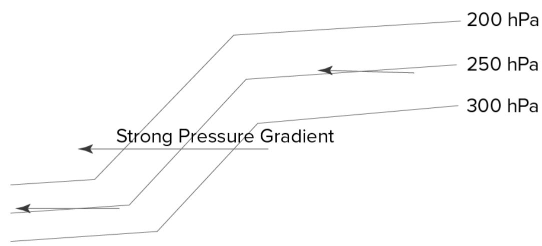
16. Which meteorological process seems *least relevant* for the type of fog shown?



   (a) advection (of warm surface air over a colder surface)
   (b) upslope motion
   (c) the Bergeron (cold cloud) process
   (d) heat exchange (Q_H) between air and surface
   (e) sea breeze circulation (onshore wind)

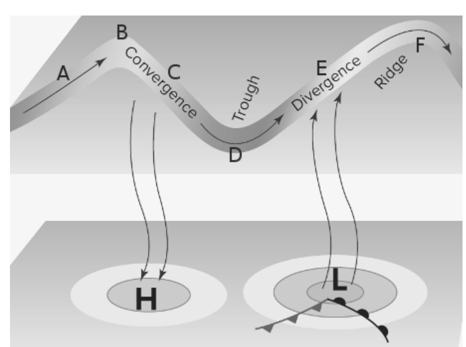
17. Regarding Numerical Weather Prediction models, which association is **incorrect**?
   (a) forecast range ↔ difference between forecast "valid time" (t) and initialisation time (t_0)
   (b) gridlengths ↔ distances between adjacent nodes ($\Delta x, \Delta y, \Delta z$)
   (c) parameterization ↔ submodel to compensate for the effects of (otherwise) unresolved (or "subgrid") processes
   (d) skillful NWP model ↔ on average, performs better than climatology
   (e) domain ↔ set of equations constituting the model

18. The figure represents the height of isobaric surfaces in the upper troposphere of the N. hemisphere in the vicinity of the polar jetstream. Which statement is true?



   (a) pole lies to the left; geostrophic wind blows parallel to the arrows
   (b) pole lies to the right; geostrophic wind blows parallel to the arrows
   (c) pole lies to the left; geostrophic wind blows into the page (⊗, towards east)
   (d) pole lies to the left; geostrophic wind blows out of the page (⊙, towards west)
   (e) pole lies to the right; geostrophic wind blows out of the page (⊙, towards east)

19. At which location(s) on the wave aloft is the Geostrophic wind model expected to best apply?



   (a) B,F
   (b) A,C,E
   (c) D
   (d) B,D,F

20. Referring to Figure (1), suppose the relative humidity of the air were sustained at 100.5%. Which droplets will be activated?
    (a) A,B,C,D
    (b) C,D
    (c) D
    (d) B,C
    (e) A,B

21. Again referring to Figure (1), which option correctly gives the fate of droplets of type A assuming the relative humidity of the air were sustained at 100.05%?
    (a) complete evaporation
    (b) continuous growth
    (c) survival with equilibrium 0.2 μm
    (d) survival with equilibrium 0.3 μm
    (e) survival with equilibrium 0.4 μm

22. Again referring to Figure (1), droplets A, B are both solutions of sodium chloride (NaCl). Which contains the greater *mass* of salt?
    (a) droplet A
    (b) droplet B
    (c) both contain the *same* mass of salt
    (d) answer cannot be determined unless the droplet radius is specified
    (e) answer cannot be determined unless the relative humidity is specified

23. Referring to Figure (2), what is the height Z_{LCL} of the LCL (above ground level)?
    (a) 200 m
    (b) 400 m
    (c) 600 m
    (d) 700 m
    (e) 1000 m

24. Again referring to Figure (2), what is the surface dewpoint?
    (a) 21.6°C
    (b) 23.0°C
    (c) 24.4°C
    (d) 30.0°C
    (e) 35.6°C

25. Again referring to Figure (2), what is the static stability of the surface layer?
    (a) neutral with respect to unsaturated adiabatic motion
    (b) neutral with respect to saturated adiabatic motion
    (c) absolutely stable
    (d) conditionally unstable
    (e) absolutely unstable

26. Referring to Figure (3), which option correctly identifies respectively the (warm, cold, dry) conveyor belts?
    (a) A,B,C
    (b) B,C,A
    (c) C,A,B
    (d) C,B,A
    (e) B,A,C

The next three questions refer to Fig. (4). Assume you are situated at ground at the point marked **X** under the cloud shield, *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.*

27. When your position at **X** relative to the storm is as shown by Fig. (4), the two lowest layers of the air column above **X** would represent ____
    (a) the warm conveyor belt overridden by the cold conveyor belt
    (b) the cold conveyor belt overridden by the warm conveyor belt
    (c) the cold conveyor belt overridden by the dry conveyor belt
    (d) the dry conveyor belt overridden by the warm conveyor belt

28. As the storm approached, passed over, and moved away from **X**, a thermometer at **X** would show these phases ____
    (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

29. Which statement correctly describes events at **X** as the cold front passes?
    (a) pressure will reach a minimum then begin to rise, winds will become south-easterlies
    (b) pressure will reach a maximum then begin to fall, winds will become south-easterlies
    (c) pressure will reach a minimum then begin to rise, winds will become north-westerlies
    (d) pressure will reach a maximum then begin to fall, winds will become north-westerlies

30. Referring to Figure (5), which statement is **false**?

    (a) the diagram depicts turbulent convective momentum and heat transport along the vertical axis (and more generally, the mechanism for "turbulent mixing")
    (b) on an average over time, for every volume δV of air descending across level $z = z_1$ elsewhere an equal volume ascends across z_1
    (c) during a hot and dry summer afternoon, on average $T_d > T_u$
    (d) the product $\rho\, U\, [(\mathrm{kg\,m\,s^{-1}})\,\mathrm{m^{-3}}]$ of each parcel's density and speed gives its horizontal momentum per unit volume
    (e) the product $\rho\, c_p\, T\, [\mathrm{J\,m^{-3}}]$ gives a parcel's sensible heat content per unit volume (c_p, $\mathrm{J\,kg^{-1}\,K^{-1}}$ is the specific heat capacity at constant pressure)

31. During cloudless, summertime "airmass weather," wind speed near ground tends to be highest in mid-afternoon and calm overnight, picking up again in the morning. Which aspect of the following explanation is **false**?

    (a) under such conditions the atmospheric surface layer is absolutely unstable at mid-afternoon and absolutely stable overnight
    (b) turbulent mixing is most "active" (largest magnitudes $|w|$ of the fluctuating vertical velocity) during strong winds in an unstably stratified boundary layer over rough ground
    (c) descending parcels bring down a "momentum excess" (or velocity surplus) relative to average conditions at the surface, pushing the surface air along
    (d) the rate of exchange of air volumes across any given level in the friction layer should be inversely proportional to the standard deviation σ_w of the vertical velocity

32. What is the error in Figure (6).

    (a) the Coriolis force vector CF should point to the *left* of the wind vector
    (b) the Coriolis force vector CF should be perpendicular to the wind vector
    (c) the friction vector F should be perpendicular to the pressure gradient force vector PGF
    (d) the wind should cross the isobars towards *higher* pressure
    (e) isobars ought to be curved

33. Regarding the angle A of the wind relative to isobars in Figure (6) and its implication, which statement is true?

    (a) over a smooth surface like the ocean, $A \sim 45^\circ$
    (b) over a rough surface like a forest, $A \sim 5^\circ$
    (c) the cross-isobar wind results in surface convergence into a low
    (d) with increasing height above ground, normally the angle A increases in magnitude

34. Referring to Figure (7), which option best estimates the measured mean wind speed U at $x/H = -3$ if the measured value at $x/H = +5$ was $U = 3\,\mathrm{m\,s^{-1}}$? (Ignore the "model" curve, basing your answer on the stars).

(a) $30\,\mathrm{m\,s^{-1}}$
(b) $10\,\mathrm{m\,s^{-1}}$
(c) $6\,\mathrm{m\,s^{-1}}$
(d) $3\,\mathrm{m\,s^{-1}}$
(e) $1\,\mathrm{m\,s^{-1}}$

35. In relation to Figure (7), the curve depicts the *relative* wind speed U/U_0, where "U_0" is a normalizing "scale" (or reference value) for speed. Based on the diagram, and again ignoring the "model" curve, which suggestion seems **most plausible** to explain how the scale (U_0) was chosen in order to "normalize" the measured wind speed?

(a) U_0 was chosen to be equal to the wind speed ("U") measured at $x/H = -3$
(b) U_0 was chosen to be equal to the wind speed ("U") measured at $x/H = +5$
(c) U_0 was set equal to a computed geostrophic wind speed
(d) U_0 was set equal to the climatological August wind speed for that location

36. Referring to Figure (8), which statement is **false**?

(a) the indicated horizontal winds apply at the surface
(b) highs at the polar ends of the Hadley cells are known as "subtropical highs"
(c) according to this model, winds aloft in the Ferrel cell are westerlies
(d) surface winds in the Hadley cells are known as the "trade winds"
(e) the polar front lies at the boundary of the Ferrel and Polar cells

37. Referring to Figure (9), which statement is **false**?

(a) In Case 1, the atmosphere at **A** is barotropic
(b) In Case 2, the atmosphere at **A** is baroclinic
(c) In Case 1, the thermal wind at **A** lies parallel to height contours
(d) In Case 2, strong warm advection is occurring at **A**
(e) In Case 1, negligible thermal advection is occurring at **A**

38. Which statement about modern NWP models (horizontal grid lengths $\sim$ 10 km) is **false**?

(a) equations are included to model heat and moisture exchange (Q_H, Q_E) with the surface
(b) some terms in the governing equations are neglected or simplified
(c) long range forecasts from almost-identical initial states may be very different
(d) a sparse observation network reduces accuracy of the initial state
(e) the grid resolves atmospheric motion on all scales of importance

39. The feasibility of NWP is contingent on provision of sufficient computing power (i.e. adequate memory and speed), while model skill depends on many factors. In this context, which statement is **false**?

   (a) reducing model gridlengths yields a model with higher (or "finer") "resolution" that should be more accurate
   (b) however all else being equal, reducing model gridlengths increases computing load
   (c) weather predictions using a limited (regional) domain fail to account for changes that (should) occur on (and advect across) their domain boundaries
   (d) yet all else being equal, choosing a larger (or global) domain increases computing load
   (e) the compromise reached in "regional" NWP modeling is to use coarse spatial resolution over a non-global domain

40. In reference to Figure (10) and dynamical (as opposed to statistical) climate forecasting, which of the following statements is **false**?

   (a) though the skill of dynamical *weather* forecasts (i.e. NWP) is negligible for forecast ranges exceeding a couple of weeks, the same model's forecast of *climate* may be skillful
   (b) a 3-month seasonal forecast by NWP (e.g. Figure 10) is not a weather forecast, but is rather a forecast of *weather statistics* (i.e. of *climate* or climate anomaly)
   (c) correctness of NWP climate must hinge on correctness of those external factors that govern climate, e.g. solar constant, atmospheric CO_2 concentration and so on
   (d) by virtue of the forecast categories being (historically) equiprobable, the forecast methodology here is skillful *only* if forecasts are correct on more than **50%** of occasions
   (e) on 30 Nov. 2015 (i.e. at forecast initialization) an El Nino was present (anomalous sea surface temperature in the equatorial Pacific): the above normal seasonal temperature forecast for most of Canada probably reflects the model's response to that anomaly

41. Which association, referring to conditions on an isobaric chart in the free troposphere, is **incorrect**?

   (a) barotropic atmosphere $\leftrightarrow$ no thermal advection
   (b) baroclinic atmosphere $\leftrightarrow$ isotherms intersect height contours
   (c) trough exit region $\leftrightarrow$ divergence
   (d) warm advection $\leftrightarrow$ ascent
   (e) cyclonic vorticity maximum $\leftrightarrow$ shortwave ridge

42. Which statement is **false**?

(a) ice nuclei are generally less abundant in the atmosphere than cloud condensation nuclei

(b) the likelihood of growing large raindrops increases with increasing cloud depth

(c) the likelihood of growing large raindrops decreases with increasing cloud updraft velocity

(d) the "curvature effect" on equilibrium vapour pressure is negligible for droplets whose radius is 5μm or larger

(e) the upper size limit for activated cloud droplets grown by diffusion of water vapour is about 10μm

43. What is the result of the ice-crystal (Bergeron) process, operating above the freezing level in a cloud?

(a) transfers water from few ice crystals to many supercooled droplets

(b) transfers water from few supercooled droplets to many ice crystals

(c) transfers water from many ice crystals to few supercooled droplets

(d) transfers water from many supercooled droplets to few ice crystals

(e) "activates" hygroscopic cloud condensation nuclei

44. Referring to Figure (11), which airmass identification is **incorrect**?

(a) **A**= mP

(b) **E,G,H**= mT

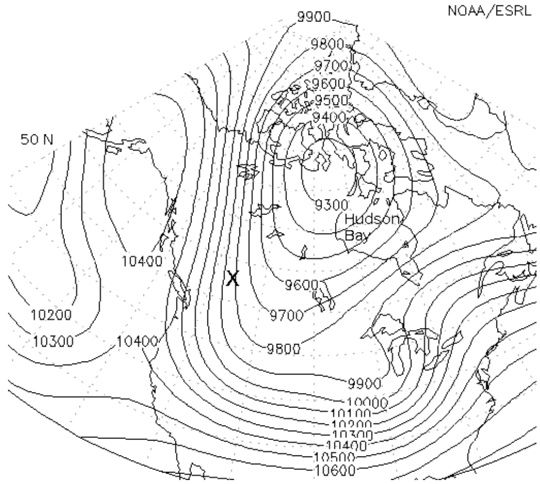
(c) **D**= cP

(d) **C**= cP or cA

(e) **F**= cT

The remaining questions document a period of extreme cold in Canada in Dec. 2009. Edmonton International Airport (YEG) reported lows of $-44.7°, -46.1°, -41.7°$ **on 12, 13, 14 Dec. respectively.**

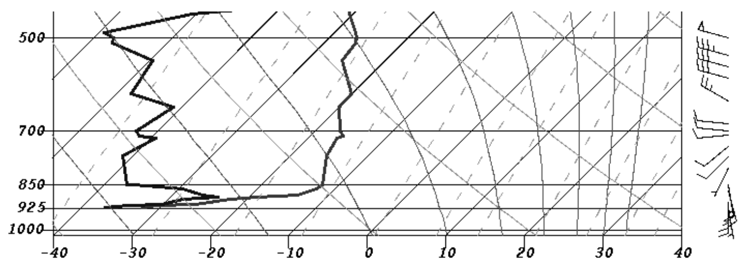
45. The adjacent image is a "reanalysis" of the 250 hPa surface, valid 12Z on 9 Dec. 2009, and showing the circulation that later resulted in extreme cold (**X** denotes C. Alberta). Which statement is **false**?



   (a) contour labels give height in [m]
   (b) a deep low was centred NW of Hudson Bay
   (c) a strong wind linked W. Canada to the N. Pole
   (d) a high-amplitude ridge lay along the W. coast
   (e) this was generally a zonal flow configuration

46. Which statement with respect to Figs. (12– 15), valid 12Z Dec. 13, is **wrong**?
   (a) the Canadian prairies have been invaded by a maritime polar (mP) airmass
   (b) a ridge of high surface pressure extends from the Yukon through Alberta to S. Saskatchewan
   (c) as expected, the 0h forecast (Figure 12) closely matches the analysis (Figure 13)
   (d) cold thickness advection (advective cooling) is occurring in E. Canada, e.g. near **X**
   (e) a station near Edmonton reported a surface temperature of -46°C

47. The adjacent sounding is from Stony Plain at 12Z on December 13, 2009. Which statement is **false**?



   (a) the 925 hPa surface pressure is sea-level corrected ("MSLP")
   (b) potential temperature $\theta \approx 0$°C at the top of the inversion (i.e. 850 hPa level)
   (c) the sounding exhibits characteristics of a cA airmass, e.g. deep surface inversion
   (d) below 850 hPa the wind is southerly, with a milder and veering wind aloft
   (e) air at the surface was near or at saturation, possibly resulting in fog

48. The 498 dam thickness contour on Figure (12) loops around four *closed* thickness contours west of the E. Canada low, the innermost thickness contour designating $\Delta Z = 474$ dam. *This feature may also be seen, and is perhaps better defined visually, on Figure (15) — on which, however, the label* 474^- *designates* height*, not thickness.* Which statement regarding this feature (i.e. roughly circular column of air) is **false**?
   (a) it is a core of very cold air, moving towards the south or southeast
   (b) in this column $Z_{500} = Z_{500} - Z_{1000} = 474$ dam, implying $Z_{1000} = 0$
   (c) Figure (12) *contradicts* the above deduction that in this feature the 1000 hPa isobaric surface lies at sea level
   (d) the coldest air aloft lies somewhat west of the surface low

49. Based on Figures (14, 15), which suggestion is **false**?
   (a) the low over Hudson Bay is "vertically stacked"
   (b) spatial variation of T_{850} over Sask. is much weaker than around **X**
   (c) strong warm advection is occurring at **X**
   (d) 850 hPa winds around **Y** are weaker than at **X**
   (e) the main 500 hPa current loops down the W. coast and south around the Canadian prairies, with cold air on its left

50. Which statement is **false**?
   (a) any precipitation associated with the Hudson Bay low would be rain
   (b) height contours at 850 hPa suggest a N. wind from the N. pole into C. Canada
   (c) at the 850 hPa level, subzero temperatures extend to and beyond the W. coast
   (d) at Edmonton the sky was 3/4 clear, and the wind light
   (e) nocturnal radiative cooling may explain the frigid 12Z surface temperature at Edmonton

Equations and Data.

Notation for vectors: $\vec{A}$ or **A**. One full barb on the wind vector means 5 m s^{-1}, while a solid triangle means 25 m s^{-1}. The dewpoint lapse rate is $\Gamma_{T_d} \approx -0.002\,\mathrm{K\,m^{-1}}$ (i.e. -0.2 K per 100 m).

A. Height of the LCL in metres AGL $z_{\mathrm{LCL}} = 125\,(T_{\mathrm{sfc}} - T_{\mathrm{d,sfc}})$ is proportional to the difference between surface temperature and surface dewpoint.

B. The potential temperature θ of a sample of air whose pressure and temperature are (P, T) is $\theta = T\ \ (P_0/P)^{R/c_p}$, and gives the temperature the temperature the sample *would* have if its pressure were changed adiabatically to the reference pressure P_0 (where $R/c_p = 2/7 = 0.286$).

C. The Geostrophic wind speed is given by

$$V_g = \frac{g}{f_c}\left|\frac{\Delta Z}{\Delta x}\right| = \frac{1}{\rho\, f_c}\left|\frac{\Delta P}{\Delta x}\right|$$

where ΔZ [m] is the change in height of a constant pressure surface over distance Δx [m] normal to the height contours; $f_c = 2\Omega\ \sin\phi$ [s^{-1}] is the Coriolis parameter (where $\Omega \approx 2\pi/(24\text{x}60\text{x}60) = 7.27\text{x}10^{-5}$ s^{-1} is the angular velocity of the earth, and ϕ is latitude); $g = 9.81$ [m s^{-2}] acceleration due to gravity; ρ is the air density. The Geostrophic wind is oriented *parallel* to the height contours.

D. Forces (per unit mass) on an air parcel:

$$F_P = \frac{1}{\rho}\left|\frac{\Delta P}{\Delta x}\right|\ ,\ F_C = f_c\,V\ ,\ F_B = g\,\frac{T_p - T}{T} = g\,\frac{\theta_p - \theta}{\theta}\ .$$

F_P is the magnitude of the pressure gradient force per unit mass, ρ being air density and x a horizontal coordinate oriented perpendicular to isobars. F_c is the Coriolis force (per unit mass) on a parcel whose horizontal speed is V, with f_c being the Coriolis parameter. F_B is the buoyancy force (per unit mass) on a parcel whose temperature is T_p (and potential temperature is θ_p) at a level where the environmental temperature and potential temperature are T, θ (the denominator must be in Kelvin unit, and F_B is positive for an upward force).

E. Gradient wind equation

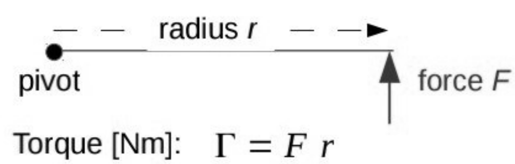
$$V_{\mathrm{gr}} = V_{\mathrm{g}} \pm \frac{1}{f_c} \frac{V_{\mathrm{gr}}^2}{R} ,$$

relates the gradient wind speed V_{gr} to the geostrophic wind speed V_{g} for motion parallel to contours (or isobaric height or pressure) that curve about a pressure centre with radius of curvature R (terms on the right are added for winds about a high, subtracted for winds about a low).

F. The thermal wind is the vector difference $\vec{V}_{T21} = \vec{V}_2 - \vec{V}_1$ between the wind vectors at two levels (Z_1 the lower level and Z_2 the upper level). Its magnitude is related to the gradient in the thickness $h = Z_2 - Z_1$ of the layer, viz.

$$|V_{T21}| = \frac{g}{f_c} \left| \frac{\Delta h}{\Delta x} \right|$$

where the thickness gradient is evaluated with x pointing perpendicular to thickness contours ($f_c = 2\Omega \sin\phi$ is the Coriolis parameter, Ω being the angular velocity of the earth and ϕ the latitude). The thermal wind is oriented parallel to thickness contours, with cold air on its left (in the N. hemisphere).



G. Suppose a body is free to rotate (or pivot) about an axis, and that $\vec{r}$ (with magnitude r) is the radius vector from that axis to the point where a force F is acting perpendicular both to the spin axis and to the radius vector. Then the torque exerted by the force about the axis is $\Gamma = F\,r$, and results in an angular acceleration such that $\frac{\Delta L}{\Delta t} \propto \Gamma$, where L is the angular momentum of the body and $\Delta L/\Delta t$ the time rate of change of L.

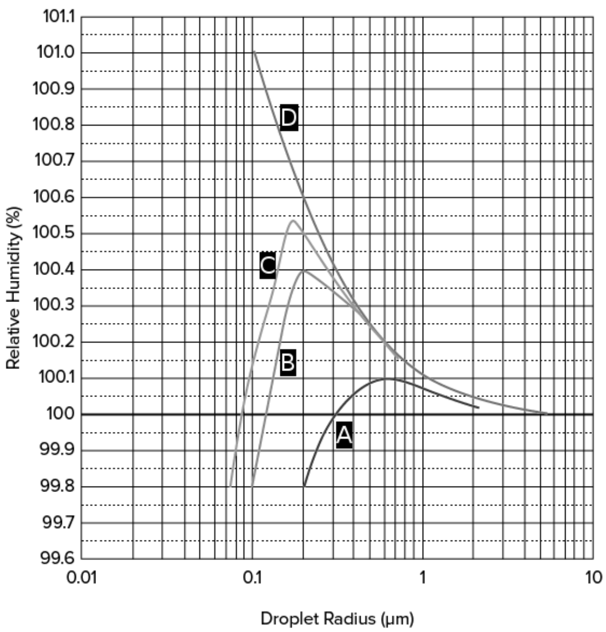


Figure 1: Relative humidity required to assure the equilibrium of a droplet of pure water (D, "Kelvin curve") or containing various types and masses of solute ("Kohler curves" for droplets A,B,C).

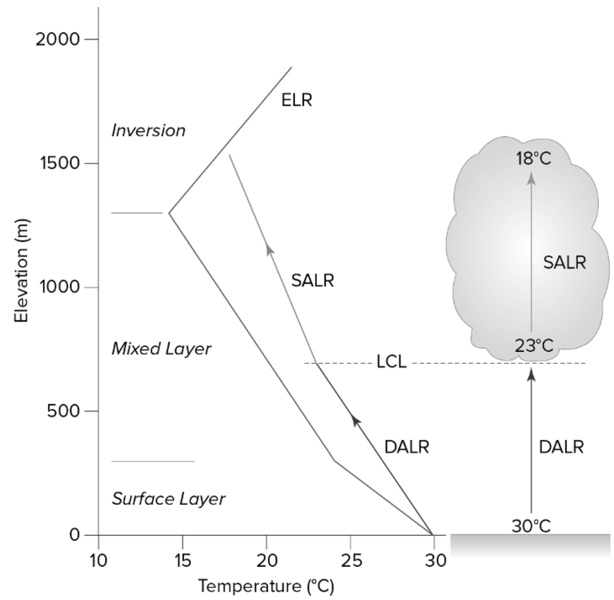


Figure 2: Simplified three-layer scenario for the temperature profile in the ABL (ELR constant within each layer). (Ross's Figure 9.13).

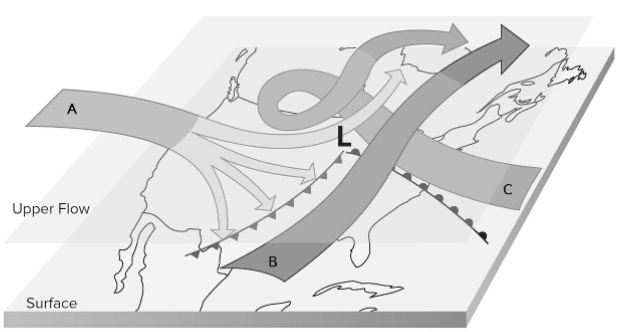


Figure 3: Conveyor belt paradigm for the midlatitude storm.

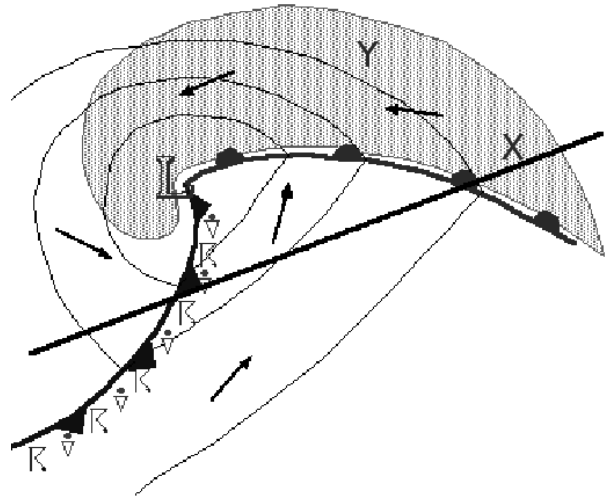


Figure 4: N. hemisphere midlatitude cyclone (north to the top of the diagram). Lighter lines, isobars; arrows, surface wind direction; single heavy arrow, direction of motion of the storm; "R" designates thunderstorms; "dot over triangle", rain showers; shading, precipitating stratiform cloud.

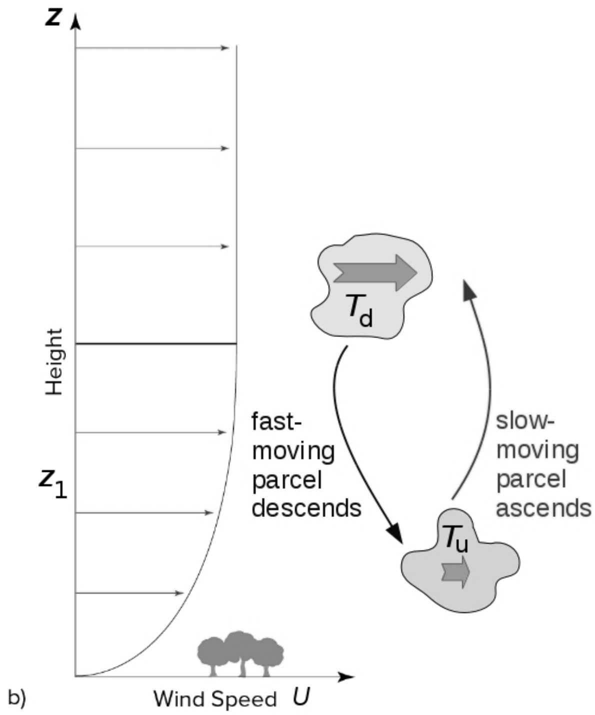


Figure 5: Height profile of mean horizontal wind speed $U = U(z)$ in the atmospheric boundary layer, in relation to the mechanism of friction (Ross's Figure 11.7b, modified). Temperatures of the upward- and downward-moving parcels are (T_u, T_d).

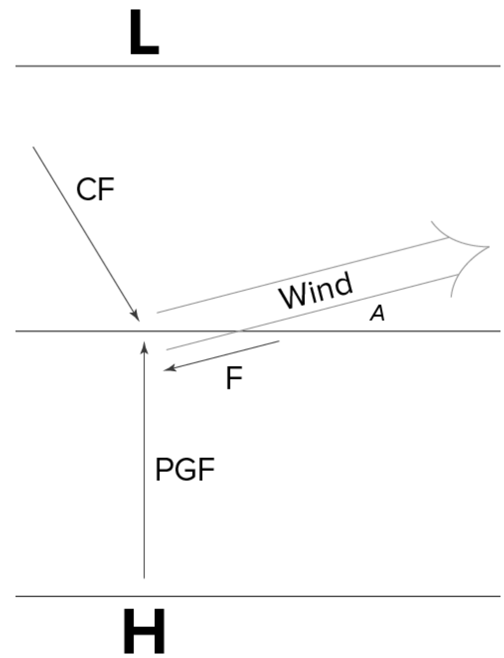


Figure 6: Force budget controlling the horizontal wind in the friction layer of the N. hemisphere (Ross's Fig 11.14c). Straight lines are isobars, and A is the angle of the wind relative to those isobars.

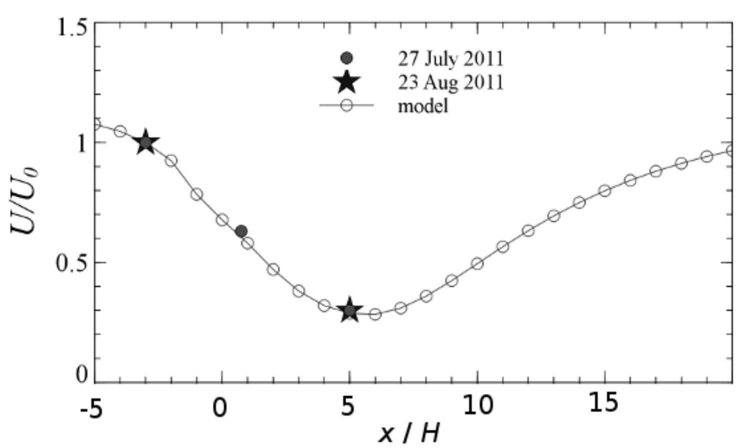


Figure 7: Relative mean wind speed curve at height $z = 2$ m for normally-incident winds about a long windbreak of height $H = 10$ m situated at $x/H = 0$. U_0 is the mean wind speed at $z = 2$ m far upwind of the shelterbelt.

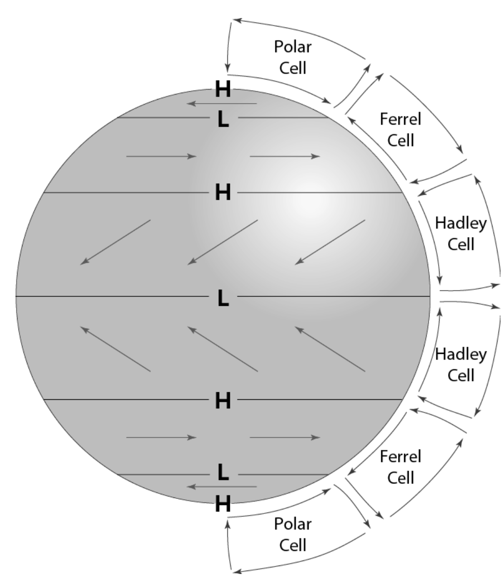


Figure 8: Three cell model of the Global Circulation.

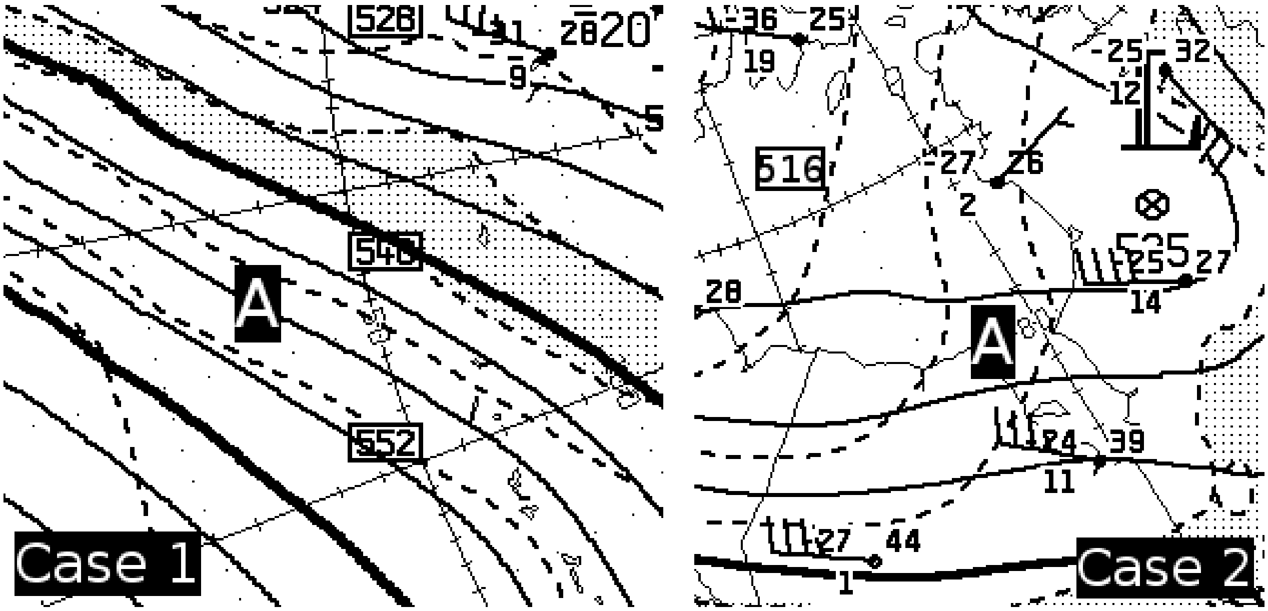


Figure 9: Height contours (solid lines) and thickness contours (dashed lines) on the 500 hPa isobaric surface, the stippled region highlighting thickness in the interval $534 \leq \Delta Z \leq 540$ dam. (Cropped from CMC 500 hPa analyses. The two diagrams have been reproduced at somewhat differing scales. Note that curved grid lines are lines of constant *latitude*.)

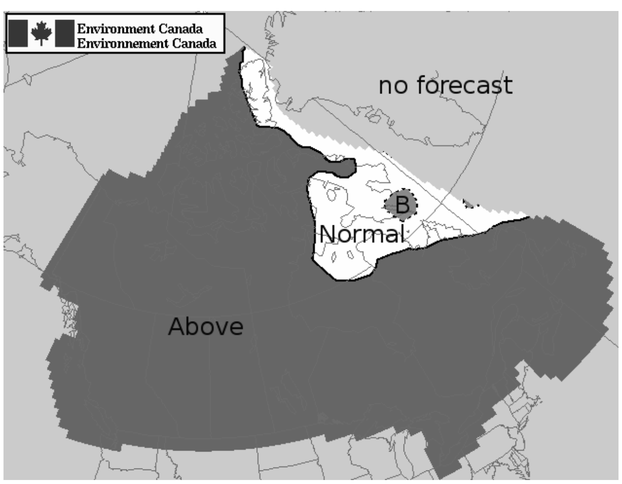


Figure 10: Environment Canada categorical temperature anomaly forecast, for the season 1 Dec. 2015 through 28 Feb. 2016 (forecast basis: ensemble NWP, initialized 30 Nov. 2015). Historically, the categories (**Above** normal, **Normal**, **B**elow normal) have occurred with equal frequency.

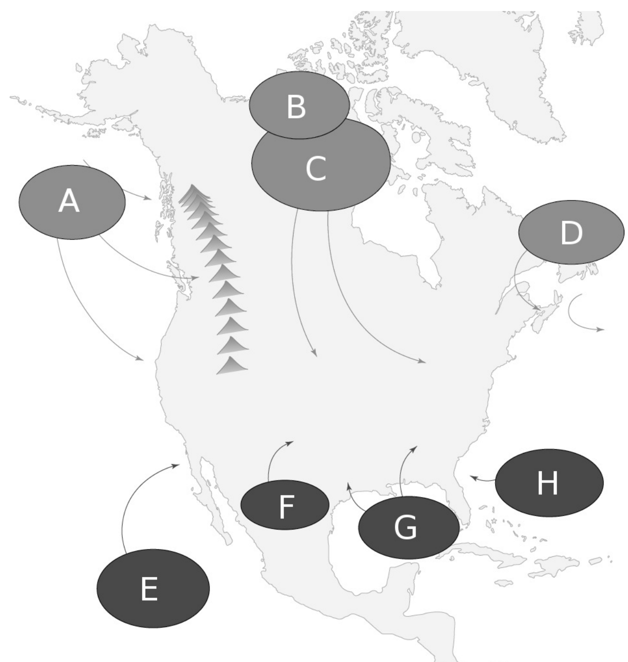


Figure 11: Air masses that affect North America (Ross's Figure 13.3).

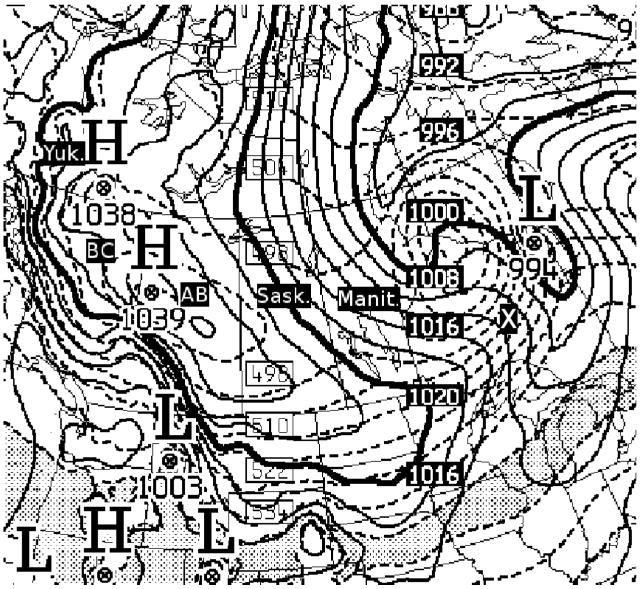


Figure 12: CMC 0h prog valid 12Z 2009/12/13: sea level corrected surface pressure and 1000-500 hPa thickness ΔZ (stippled, $534 \leq \Delta Z \leq 540$ dam).

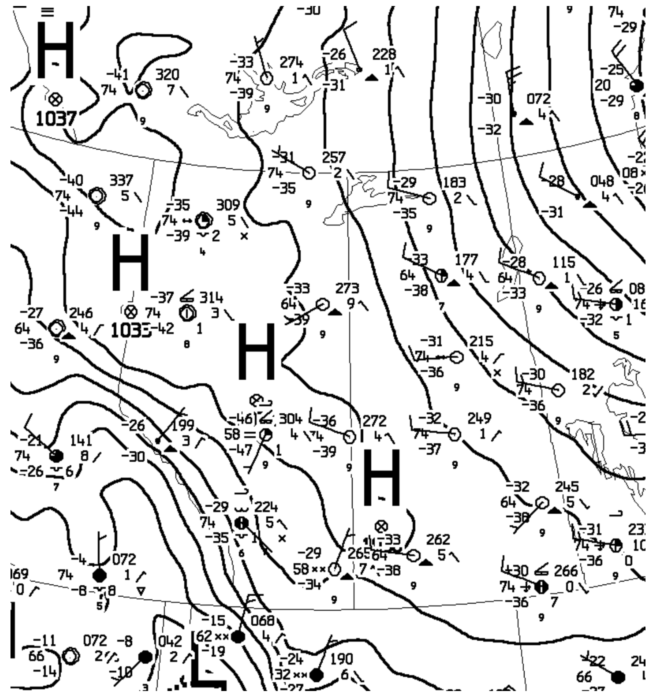


Figure 13: CMC ‘preliminary’ surface analysis 12Z 2009/12/13.

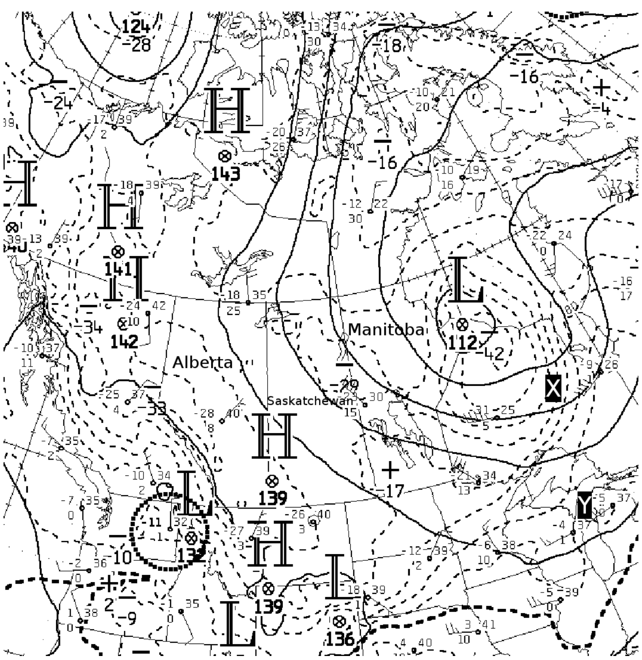


Figure 14: CMC 850 hPa analysis 12Z 2009/12/13. Dashed lines are isotherms (bold dashed line 0°C).

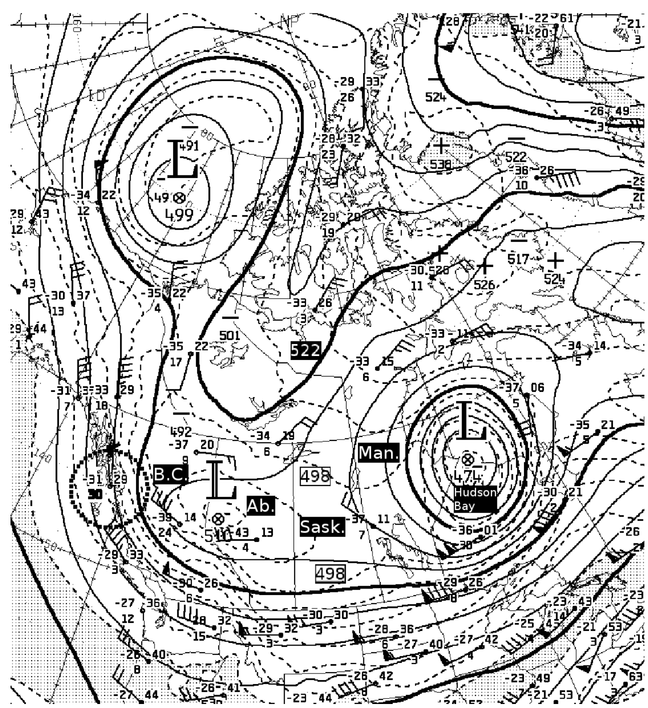


Figure 15: CMC 500 hPa analysis 12Z 2009/12/13. White-on-black label is height Z_{500} of the isobaric surface; black-on-white labels give thickness ΔZ.