MET 3502/5561 Synoptic Meteorology

Lecture 19:

Cyclongenesis

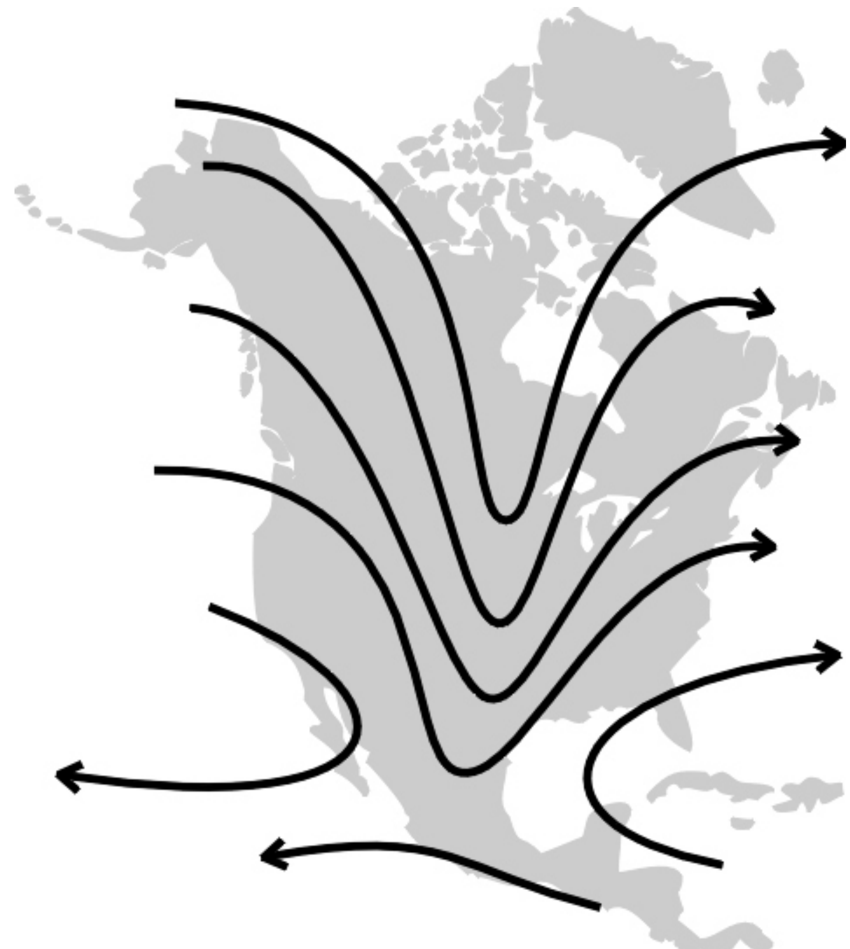
Meridional & Zonal Flows

Zonal Flow Pattern

- Flow is predominantly east-west
- Small temperature contrasts
- Import little moisture
- Relatively weak, short-wave cyclones
- Fast moving
- Rapid alternation of showery and clear weather

Meridional Flow Pattern

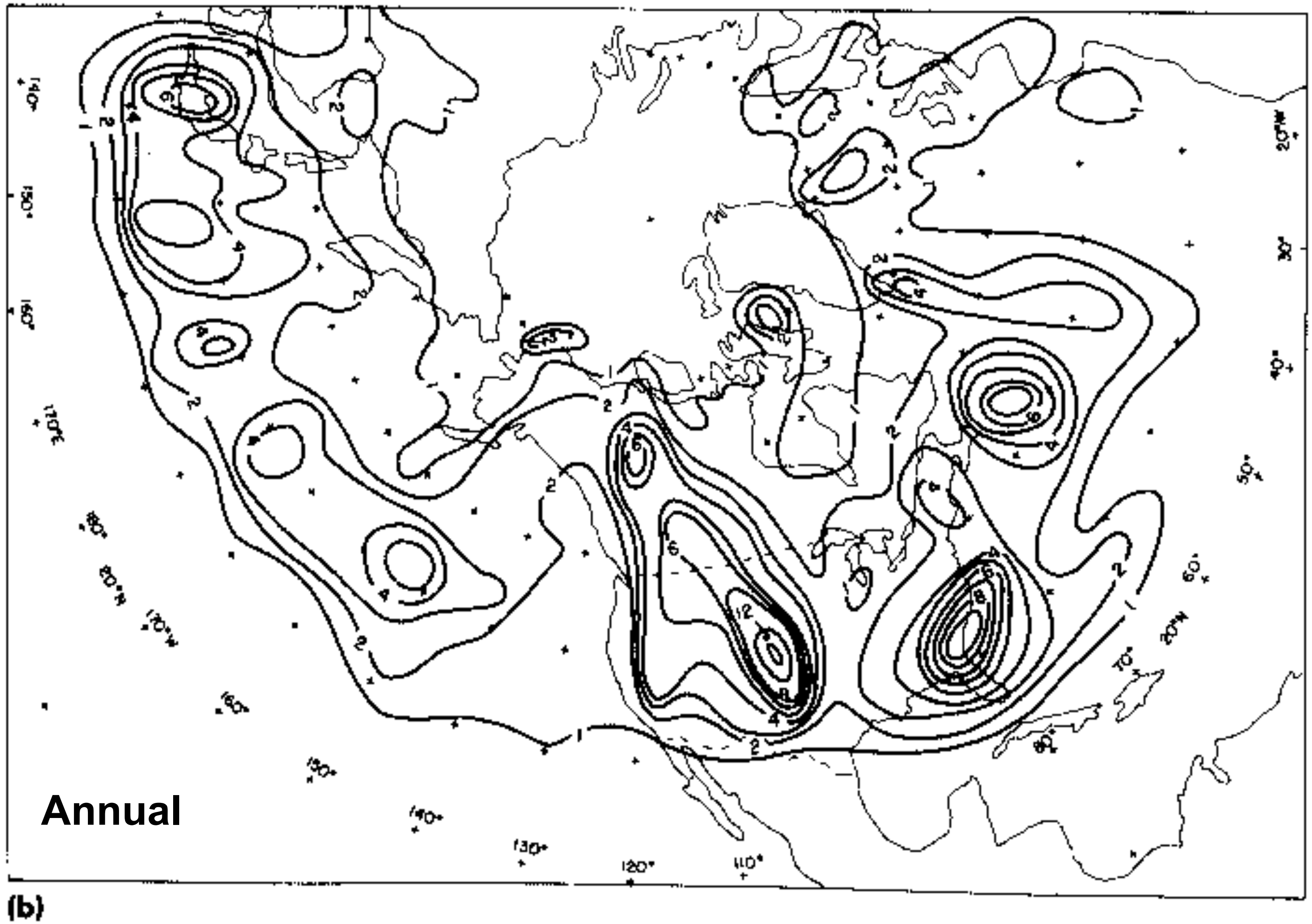
- Deep trough over continent
- Flow is predominantly north-south
- Large temperature contrasts
- Import lots of moisture
- Strong, long-wave cyclones
- Slow moving
- Rainy and cold clear episodes linger



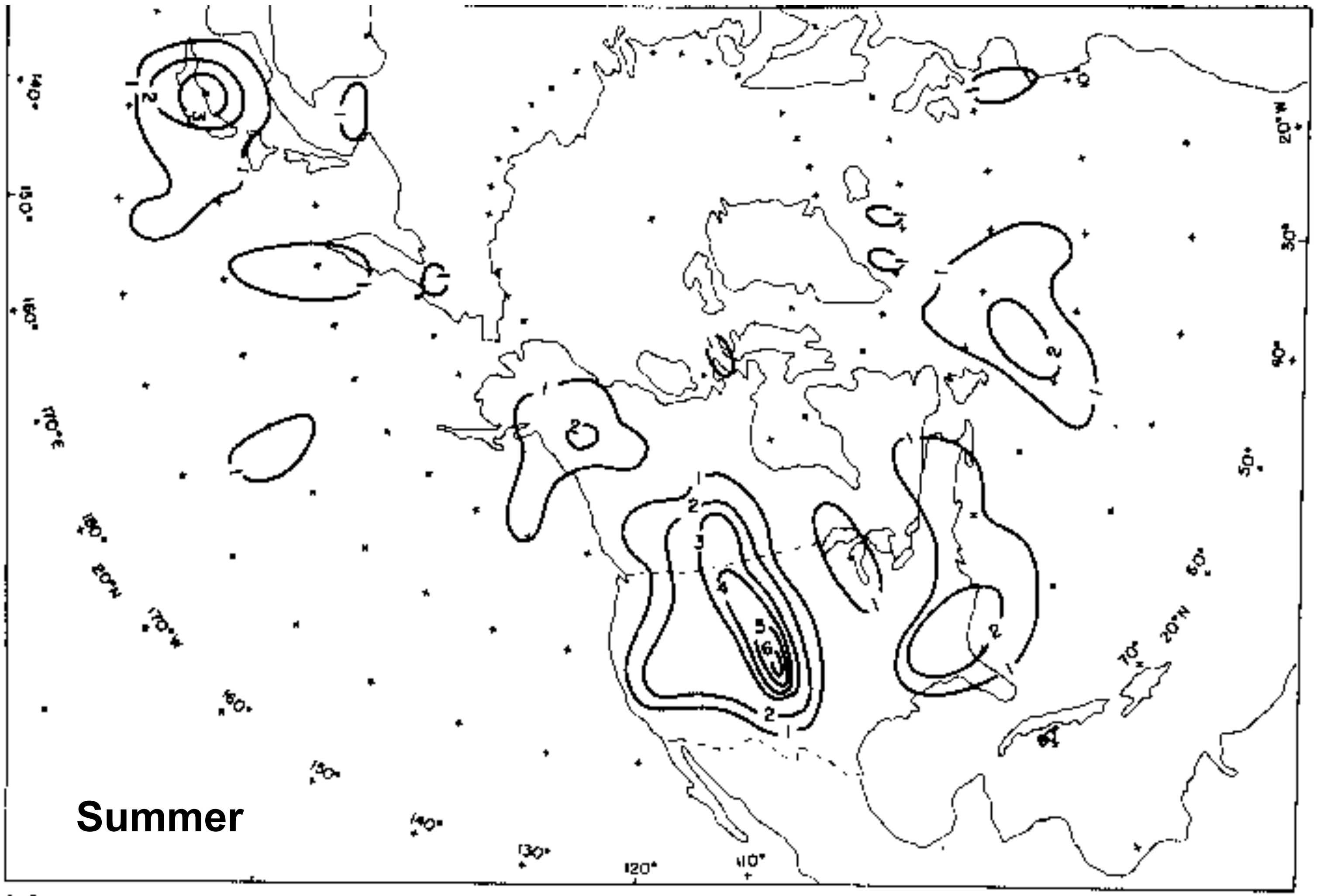
Favorable conditions for cyclogenesis

- Cyclogenesis tends to occur where Topography is favorable for producing low-level convergence
- where there is already a local absolute vorticity maximum at the surface
- Low static stability
- Significant lower-tropospheric gradients of temperature
- Mid-level gradients of vorticity
- Favorable locations: the lee of moutains, coastal regions, and areas with strong horizontal temperature gradients in the lower troposphere.

Where do Frontal Cyclones Form?



Where do Frontal Cyclones Form?



(a)

Quasi-Geostrophic (QG) Approximation

- Assume that the flow is geostrophic, and use Vg to substitute the actual wind V to get a simplified version of equations
- For momentum equations, the QG momentum equations neglect the vertical derivative term (vertical divergence) and friction (Carlson textbook *Mid-latitude weather systems* Page16-18).
- For vorticity equation, the QG version is (Please see Holton's book for derivations of QG vorticity and height tendency equations): :

$$\frac{\partial \xi_g}{\partial t} = -V_g \cdot \nabla \left(\xi_g + \mathrm{f} \right) + f_0 \frac{\partial \omega}{\partial p}$$

Physical interpretation: geostrophic relative vorticity is determined by 1) Absolute vorticity advection; 2) Convergence/divergence (streching & compression).

QG Geopotential Height Tendency Equation

- Motivation: need to a tool to diagnose height tendency in order to understand movement, development, & decay of upper-level troughs & ridges, as well as surface cyclones and anticyclones
- Derivation: following Holton, the QG vorticity equation & the thermodynamic energy equation can be used to derive the QG height tendency equation:

$$[\nabla^2 + \frac{\partial}{\partial p}(\frac{f_0^2}{\sigma}\frac{\partial}{\partial p})]\chi =$$

$$-f_0\vec{V_g}\cdot\nabla(\frac{1}{f_0}\nabla^2\Phi + f) - \frac{\partial}{\partial p}[\frac{-f_0^2}{\sigma}\vec{V_g}\cdot\nabla(-\frac{\partial\Phi}{\partial p})]$$

Terms in QG Height Tendency Equation

$\chi = \frac{\partial \Phi}{\partial t}$ is the geopotential height tendency or height tendency

- Lefthand side term: is proportional to LapLacian of χ, which is proportional to – χ.
- Two terms in the righthand side of the QG height tendency equation

Right hand-side terms

- Term A: $A = f_0\left(-V_g \cdot \nabla\left(\xi_g + f\right)\right)$, geostrophic vorticity advection

  -X is proportional to (geostrophic vorticity advection) =>

  - Cyclonic vorticity advection (CVA; or positive vorticity advection PVA) will cause **Height falls**
  - Anticyclonic Vorticity Advection (AVA; or negative vorticity advection NVA) will cause **Height rises**
  - In the QG system, vorticity advection is usually zero along the trough axis when the trough is symmetric ➔ vorticity advection act to move a wave, but not amplify it.

Right hand-side terms

- Term B: is proportional to: $-\frac{\partial}{\partial z}(-V_g \cdot \nabla T)$, Differential temperature advection with respect to height

-X is proportional to (differential temperature advection with respect to height) =>

  - Positive differential temperature advection (increasing with height) -> X<0 → **Height falls**
  - Negative differential temperature advection (decreasing with height) -> X>0 → **height rises;**

QG Height Tendency Equation

- Examples:
  - 1) Cold advection @ 700 mb, no temperature advection @ 300 mb

    ➔ Positive differential temperature advection (increasing with height) -> X<0 → height falls @ 500mb
  - 2) Warm advection @ 700mb, no temperature advection @ 300 mb

    ➔ Negative differential temperature advection (decreasing with height) -> X<0 → height rises @ 500mb;
  - 3) No advection @ 700mb, cold advection @ 300 mb

    ➔ Negative differential temperature advection (decreasing with height) -> X<0 → height rises @ 500mb;

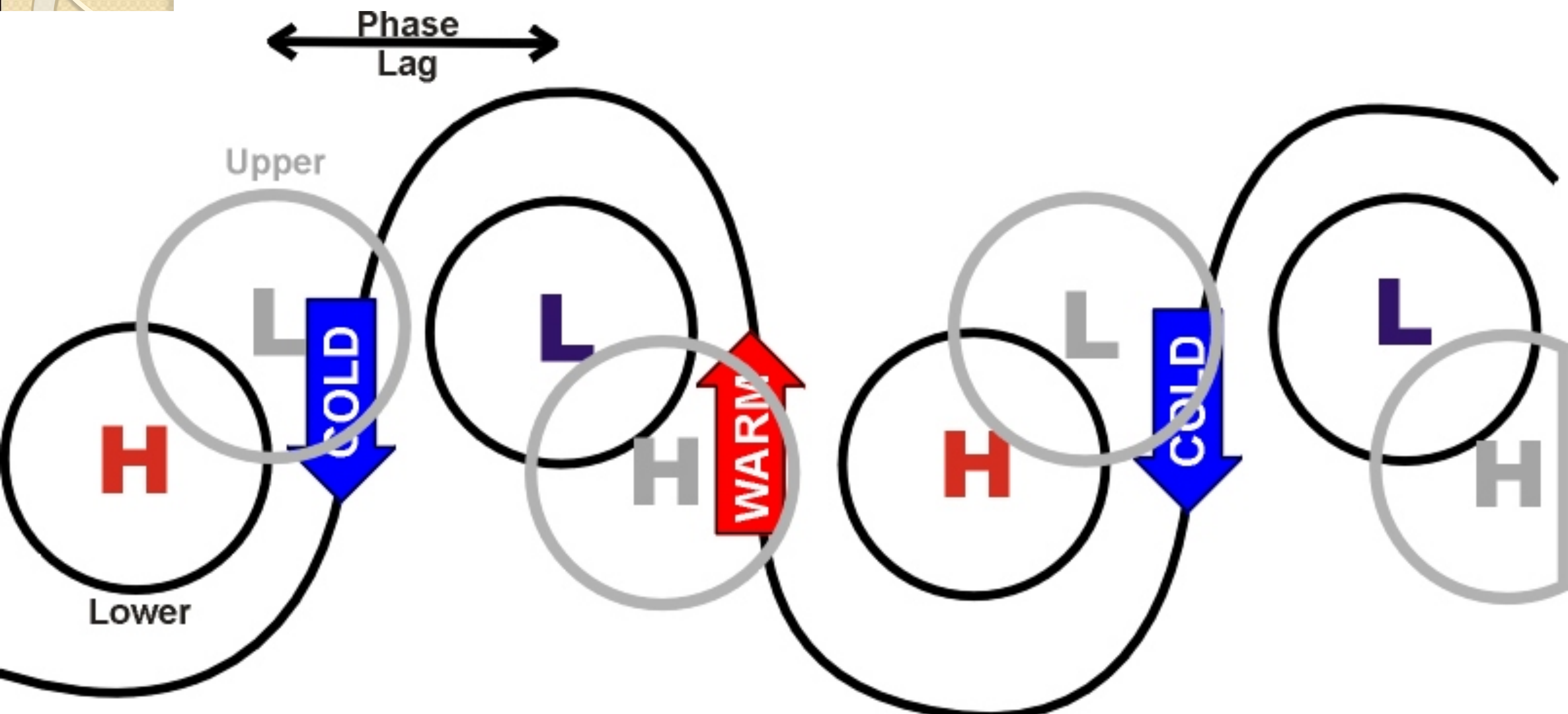
QG Height Tendency Equation

- Synoptic Applications:
  - 1) Warm advection above an upper level trough will tend to deepen the trough
  - 2) Cold advection above an upper level ridge will tend to build the ridge
  - 3) Cold advection beneath an upper level trough will tend to deepen the trough
  - 4) Warm advection beneath an upper level ridge will tend to build the ridge
  - 5) Best situation for building an upper-level ridge is lower level warm advection & upper level cold advection
  - 6) Best situation for deepening an upper-level trough is lower level cold advection & upper level warm advection
  - 7) Always remember it is how the advection changes with height matters!

QG Height Tendency Equation

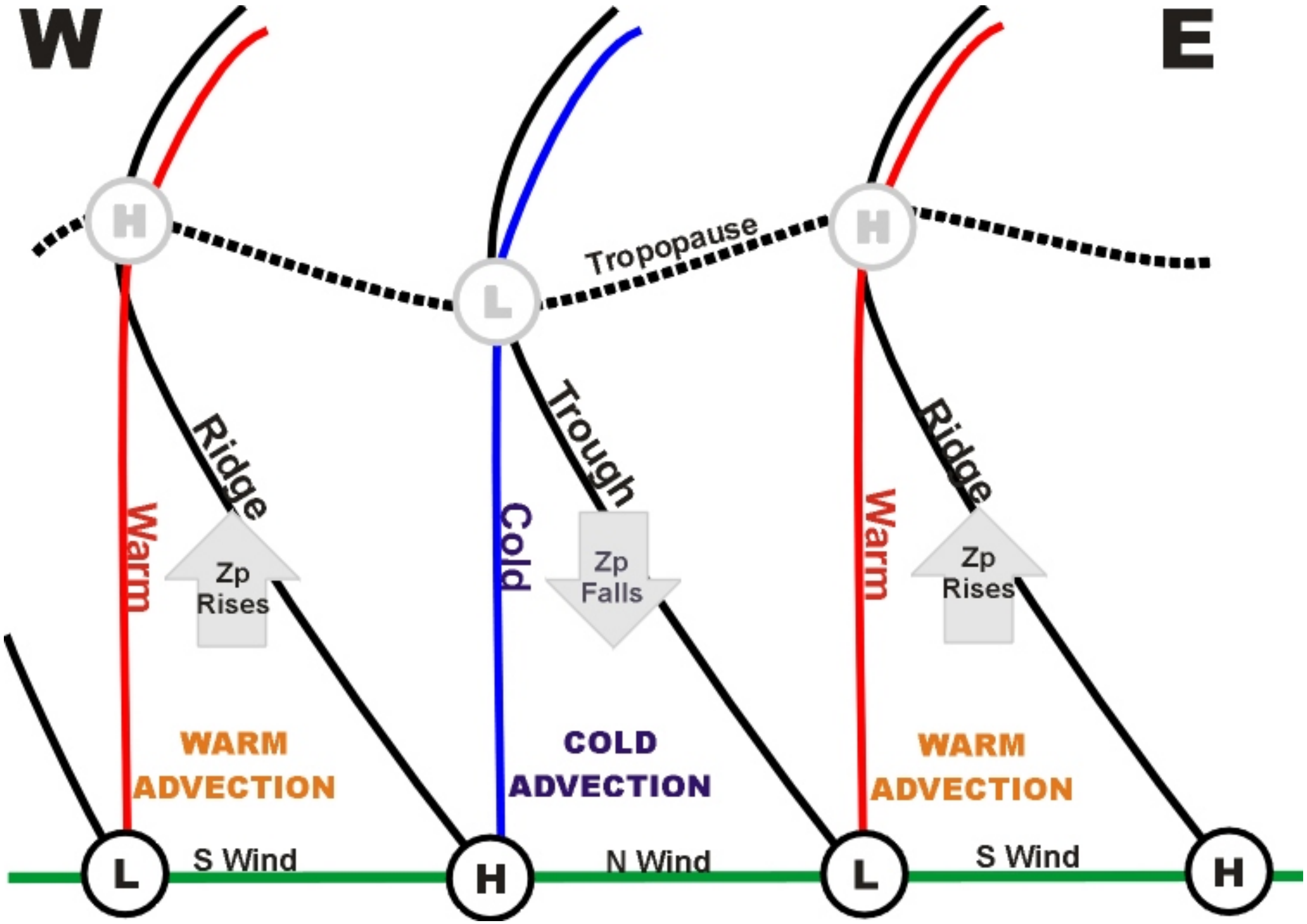
- Additional Applications:
  - 1) Warm advection above a surface cyclone will tend to deepen the cyclone
  - 2) Cold advection above a surface anticyclone will tend to build the anticyclone
- Additional term in height tendency equation: diabatic effects
  - 1) X is proportional to (vertical gradient in diabatic heeting/cooling): => Positive gradient in diabatic heating (heating increase with height) **->**) X <0, **Height falls; Negative** gradient in diabatic heating (heating decreases with height) **->**) X >0, will cause **Height rises;**
  - 2) Synoptic application: A maximum in condensational heating in the lower to middle troposphere produce low-level height falls and upper level height rises → important in cyclone genesis

Effect of meridional temperature advection at surface on upper-level trough/ridge intensification



On the east (right) side of surface low is warm advection, which is below the upper level high. So based on QG height tendency equation, warm advection below the upper level high will build up the high (height rises). On the west (left) side of surface low is cold advection, which is below the upper level low. So based on QG height tendency equation, cold advection below the upper level low will deepen the low (height falls).

Another look at height tencencies



“Omega” is the vertical velocity in *p* coordinates

$$\omega = \frac{dp}{dt} \approx \frac{\partial p}{\partial z}\frac{dz}{dt} = -g\rho w$$

QG Omega Equation

- Motivation: need to a tool to diagnose synoptic vertical motion
- QG Omega equation provided a relationship between vertical velocity, differential vorticity advection & temperature advection
- Two terms:

QG Omega Equation

- **Term A: differential vorticity advection term**
  - ω is proportional to (differential vorticity advection with respect to height) => vorticity advection increasing with height → ω <0; W >0 → **rising motion**; Vorticity advection decreasing with height → ω >0; W <0 → **subsidence**;
  - Synoptic meteorologists typically examine 700mb vertical motion. To evaluate W at 700mb, one need to evaluate vorticity advection above & below at: ideally 500mb & 1000mb
  - In practice, meteorologists assume the magnitude of the vorticity advection at low level is smaller than that at 500mb, therefore:

CVA (cyclonic vorticity advection)@500mb → w>0 → rising

AVA(anticyclonic vorticity advection)@500mb → w<0->subsidence

  - Synoptic Application: 1) CVA @ 500mb is associated with synoptic scale ascent in the lower to middle troposphere; 2) AVA @ 500mb is associated with synoptic scale descent in the lower to middle troposphere; 3) Caveats: really need to consider how advection changes with height!; 4) much like previous JET max discussion

QG Omega Equation

- **Two B: LaPlacian of temperature advection term**
  - W is proportional to (temperature advection; although technically we should consider the LaPlacian) =>
    1) warm advection → W >0 → rising motion;
    2) cold advection → W <0 → subsidence;
  - Synoptic applucation
    1) Areas of lower to middle troposphere warm advection are associated with rising motion
    2) Areas of lower to middle troposphere cold advection are associated with sinking motion

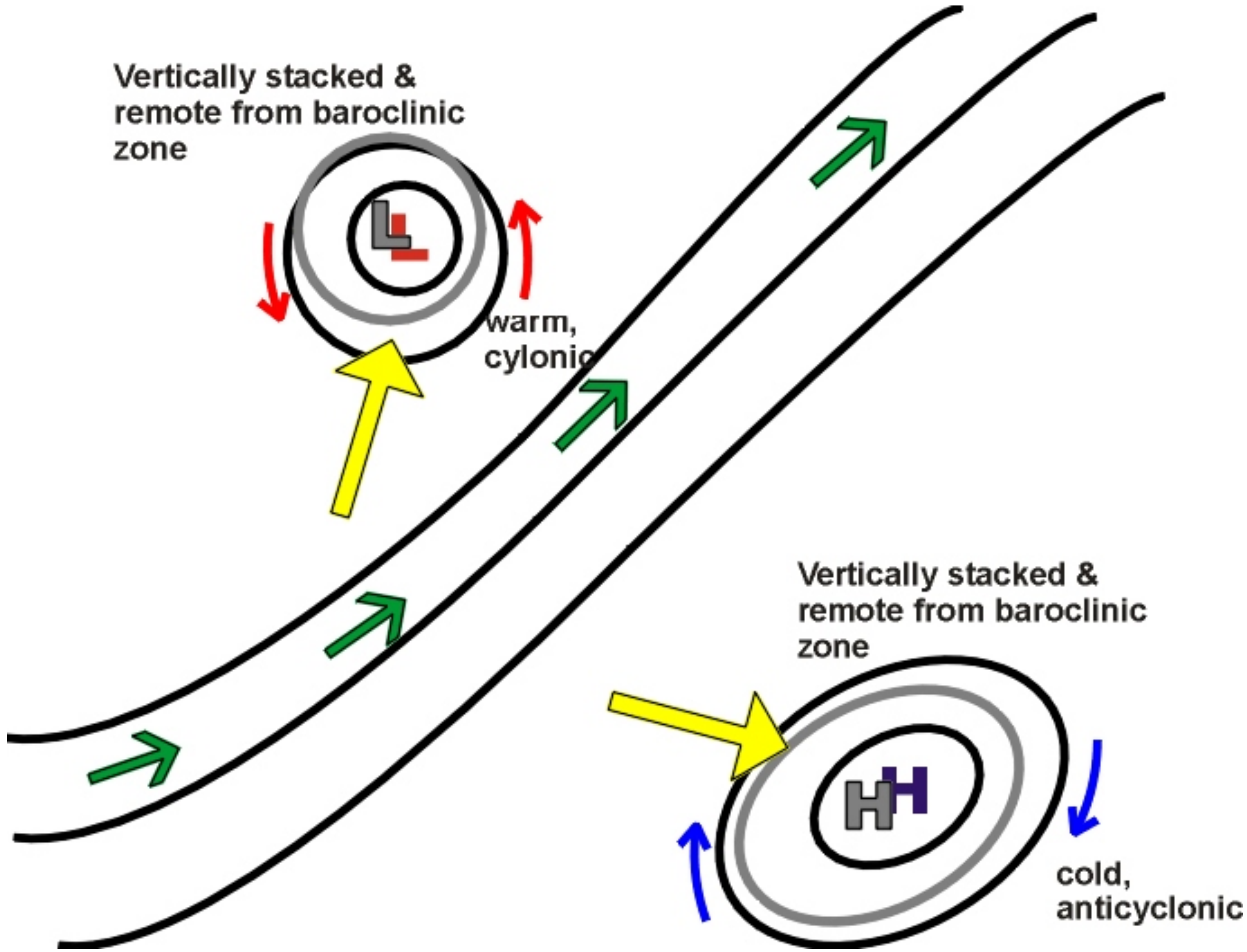
Summary of QG Omega Equation

- **Differential vorticity advection & LaPlacian of temperature advection can be used to diagnose synoptic-scle vertical motion**
- **500mb CVA & lower to middle troposphere warm advection contribute to rising motion**
- **500mb AVA & lower to middle troposphere cold advection contribute to subsidence**
- **Advantage:**
  - Allow for diagnosis of vertical velocity from available synoptic observations, analyses, & model forecasts
- **Disadvantage:**
  - Based on simplified QG equations
  - Complex math relationships in Omega equation must be simplified
  - Terms often cancel
  - Should evaluate Differential vorticity advection on multiple levels

Baroclinic Instability

- Phase lag is essential
  - Upper low over surface high, and conversely
  - Meridional cold advection below upper low deepens it
  - Meridional warm advection below upper high accentuates it
- Ascent-descent couplet forced by zonal vorticity equation
- Rising motion originating in surface low and terminating in upper high spins up both
- Sinking motion originating in upper low and terminating in surface high spins up both

The Results



Vertically stacked &
remote from baroclinic
zone
warm,
cylonic
Vertically stacked &
remote from baroclinic
zone
cold,
anticyclonic

Summary

- Zonal (E-W) flow-weak fast moving cyclones
- Meridional Flow-strong, slowly moving cyclones
- Frontal cyclone formation: E of Rockies and Gulf Coast
- Vorticity and thermodynamic equations become height tendency & omega equations
- Phase lagged unstable wave
  - Meridional thermal advection accentuates highs and lows
  - Zonal vorticity advection causes vertical motion
  - That spins up cyclones and anticyclones
- In the end: Vertically stacked cyclone and anticyclone, isolated from baroclinic zone
- Spin up planetary low-latitude anticyclonic and high latitude cyclonic flow while moving heat poleward.