QG Height Tendency Equation

$$\underbrace{\left(\nabla_p^2 + \frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p^2}\right)\chi}_{A} = \underbrace{-f_0 \boldsymbol{V_g} \cdot \boldsymbol{\nabla_p}\left(\frac{1}{f_0}\nabla_p^2\Phi + f\right)}_{B} \underbrace{- \frac{f_0^2}{\sigma}\frac{\partial}{\partial p}\left[-\boldsymbol{V_g} \cdot \boldsymbol{\nabla_p}\left(-\frac{\partial \Phi}{\partial p}\right)\right]}_{C} \underbrace{- \frac{\partial H}{\partial p}}_{D}$$

- **Height change (A) = B + C + D**
- **Term B: advection of geostrophic absolute vorticity by the geostrophic wind**
  - **Cyclonic vorticity advection (CVA) ≡ height falls**
  - **Propagation mechanism for troughs and ridges**
- **Term C: differential advection of thickness by the geostrophic wind**
  - **Referred to as thermal advection or temperature advection**
  - **Heights rise above and fall below level of maximum warm advection**
  - **Heights fall above and rise below level of maximum cold advection**
  - **Amplification mechanism for troughs and ridges**
- **Term D: differential diabatic heating**
  - **Heights rise above and fall below level of maximum latent heating**
  - **Heights fall above and rise below level of maximum radiational cooling**

QG Height Tendency Equation

$$\left(\nabla_p^2 + \frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p^2}\right)\chi = -f_0 \boldsymbol{V_g} \cdot \boldsymbol{\nabla_p}\left(\frac{1}{f_0}\nabla_p^2\Phi + f\right) - \frac{f_0^2}{\sigma}\frac{\partial}{\partial p}\left[\boldsymbol{V_g} \cdot \boldsymbol{\nabla_p}\left(-\frac{\partial \Phi}{\partial p}\right)\right] - \frac{\partial H}{\partial p} \qquad \chi \equiv \frac{\partial \Phi}{\partial t}$$

A B C D

- **Height change (A) = B + C + D**
- **Term B: advection of geostrophic absolute vorticity by the geostrophic wind**
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QG Height Tendency Equation

$$\left(\nabla_p^2 + \frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p^2}\right)\chi = -f_0 \boldsymbol{V_g} \cdot \boldsymbol{\nabla_p}(\zeta_g + f) - \frac{f_0^2}{\sigma}\frac{\partial}{\partial p}\left[-\frac{R}{p}\boldsymbol{V_g} \cdot \boldsymbol{\nabla_p} T\right] - \frac{\partial H}{\partial p} \qquad \chi \equiv \frac{\partial \Phi}{\partial t}$$

A B C D

- **Height change (A) = B + C + D**
- **Term B: advection of geostrophic absolute vorticity by the geostrophic wind**
  - **Cyclonic vorticity advection (CVA) ≡ height falls**
  - **Propagation mechanism for troughs and ridges**

$$-\chi \propto -f_0 \boldsymbol{V_g} \cdot \boldsymbol{\nabla_p}(\zeta_g + f)$$

QG Height Tendency Equation

$$\left(\nabla_p^2 + \frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p^2}\right)\chi = -f_0\boldsymbol{V_g}\cdot\boldsymbol{\nabla_p}(\zeta_g + f) - \frac{f_0^2}{\sigma}\frac{\partial}{\partial p}\left[-\frac{R}{p}\boldsymbol{V_g}\cdot\boldsymbol{\nabla_p}T\right] - \frac{\partial H}{\partial p} \qquad \chi \equiv \frac{\partial \Phi}{\partial t}$$

A B C D

- **Height change (A) = B + C + D**
- **Term C: differential advection of thickness/temperature by the geostrophic wind**
  - **Referred to as thermal advection or temperature advection**
  - **Heights rise above and fall below level of maximum warm advection**
  - **Heights fall above and rise below level of maximum cold advection**
  - **Amplification mechanism for troughs and ridges**

$$-\chi \propto -\frac{f_0^2}{\sigma}\frac{\partial}{\partial p}\left[-\frac{R}{p}\boldsymbol{V_g}\cdot\boldsymbol{\nabla_p}T\right] \rightarrow$$

$$\chi \propto \frac{f_0^2}{\sigma}\frac{\partial}{\partial p}\left[-\frac{R}{p}\boldsymbol{V_g}\cdot\boldsymbol{\nabla_p}T\right] \propto -\frac{f_0^2}{\sigma}\frac{\partial}{\partial z}\left[-\frac{R}{p}\boldsymbol{V_g}\cdot\boldsymbol{\nabla_p}T\right]$$

QG Height Tendency Equation

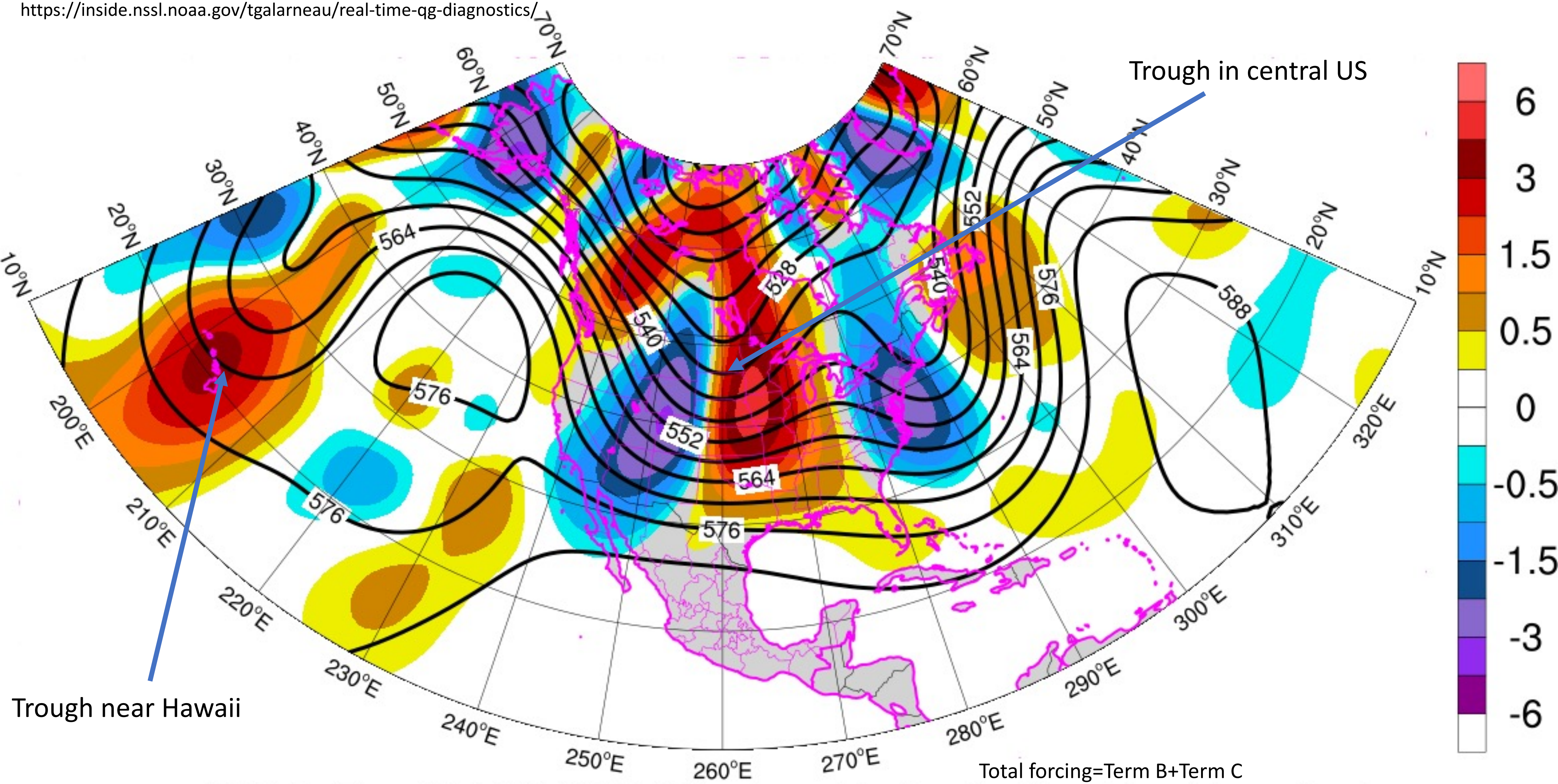
$$\left(\nabla_p^2 + \frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p^2}\right)\chi = -f_0 \boldsymbol{V_g} \cdot \boldsymbol{\nabla_p}(\zeta_g + f) - \frac{f_0^2}{\sigma}\frac{\partial}{\partial p}\left[-\frac{R}{p}\boldsymbol{V_g} \cdot \boldsymbol{\nabla_p} T\right] - \frac{\partial H}{\partial p} \qquad \chi \equiv \frac{\partial \Phi}{\partial t}$$

A B C D

- **Height change (A) = B + C + D**
- **Term D: differential diabatic heating**
  - **Heights rise above and fall below level of maximum latent heating**
  - **Heights fall above and rise below level of maximum radiational cooling**

$$-\chi \propto -\frac{\partial H}{\partial p} \rightarrow \chi \propto \frac{\partial H}{\partial p} \propto -\frac{\partial H}{\partial z}$$

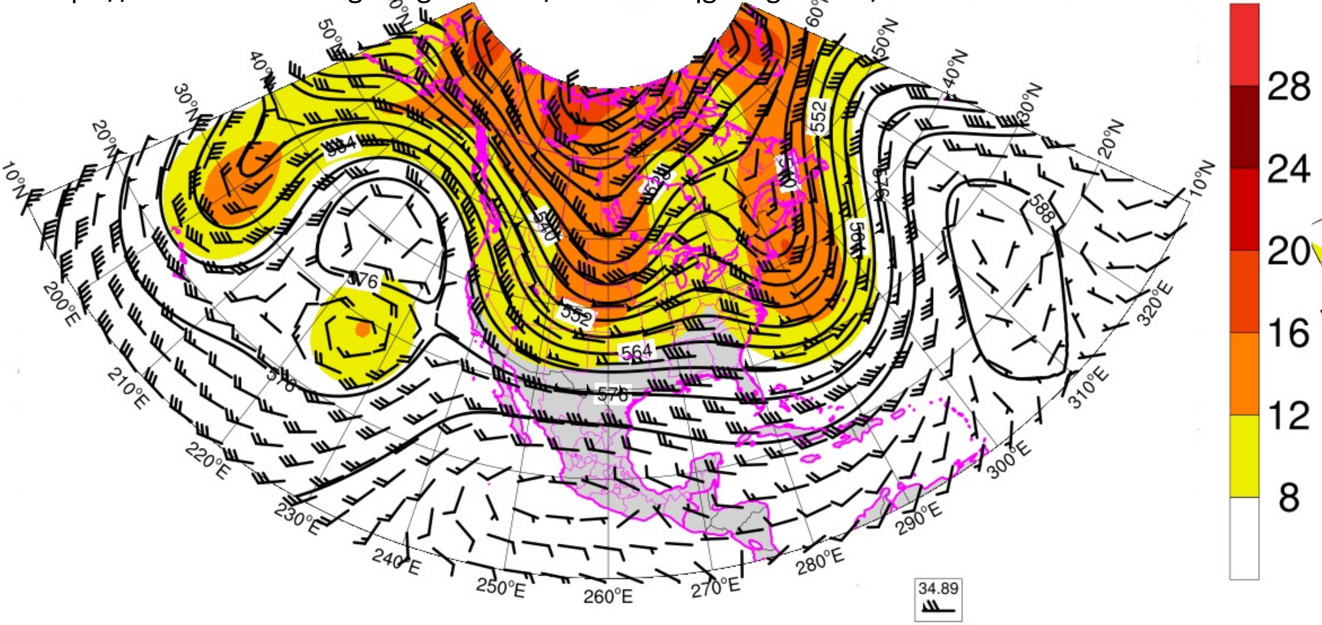
https://inside.nssl.noaa.gov/tgalarneau/real-time-qg-diagnostics/



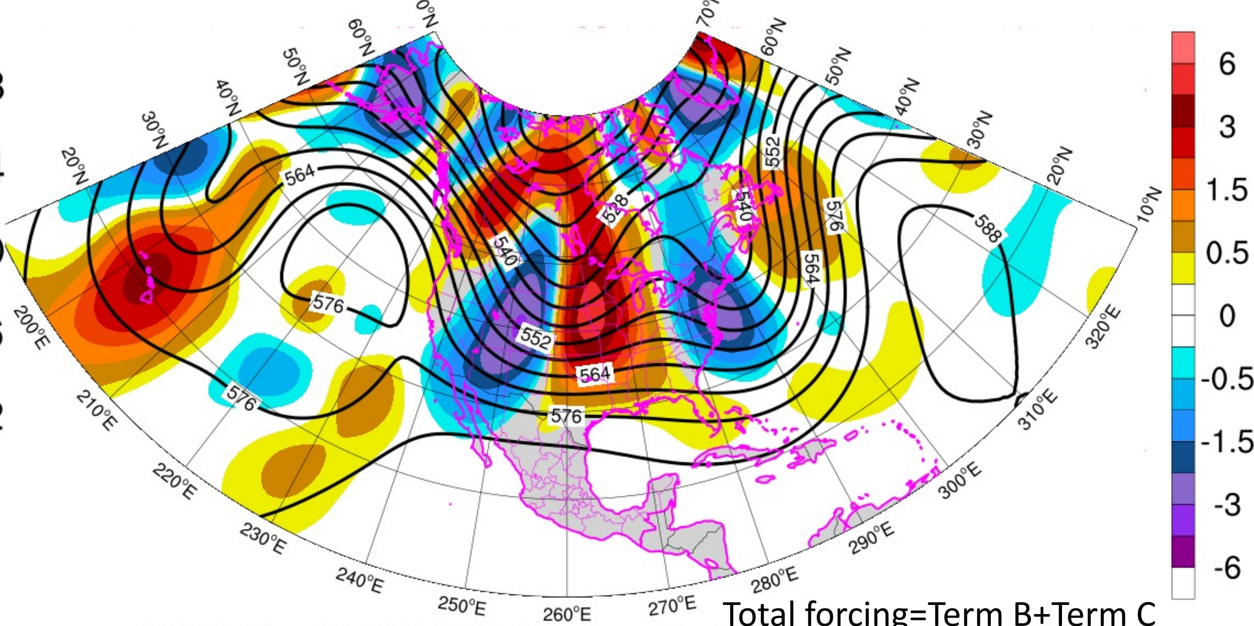
Total forcing=Term B+Term C

500 hPa Z and Total RHS QG Z Tendency Forcing (traditional form) (smoothed)
0-h CMC Global forecast at 2021020412

https://inside.nssl.noaa.gov/tgalarneau/real-time-qg-diagnostics/

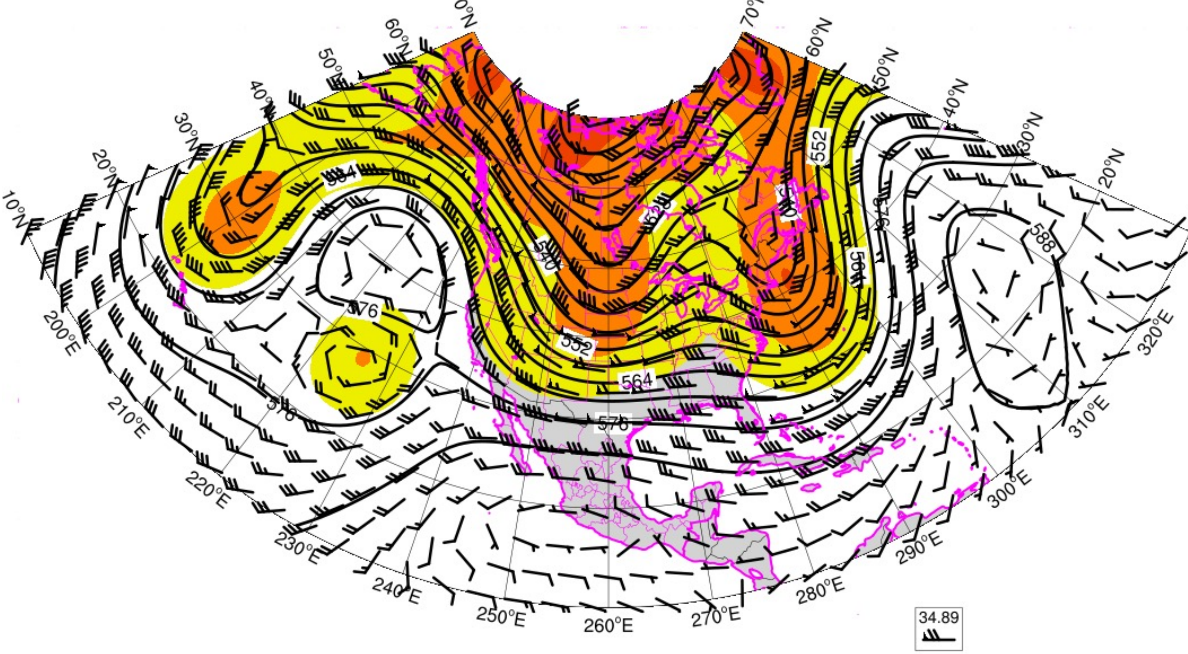


500 hPa Height, Geostrophic Wind, and Geostrophic Absolute Vorticity (smoothed)
0-h CMC Global forecast at 2021020412

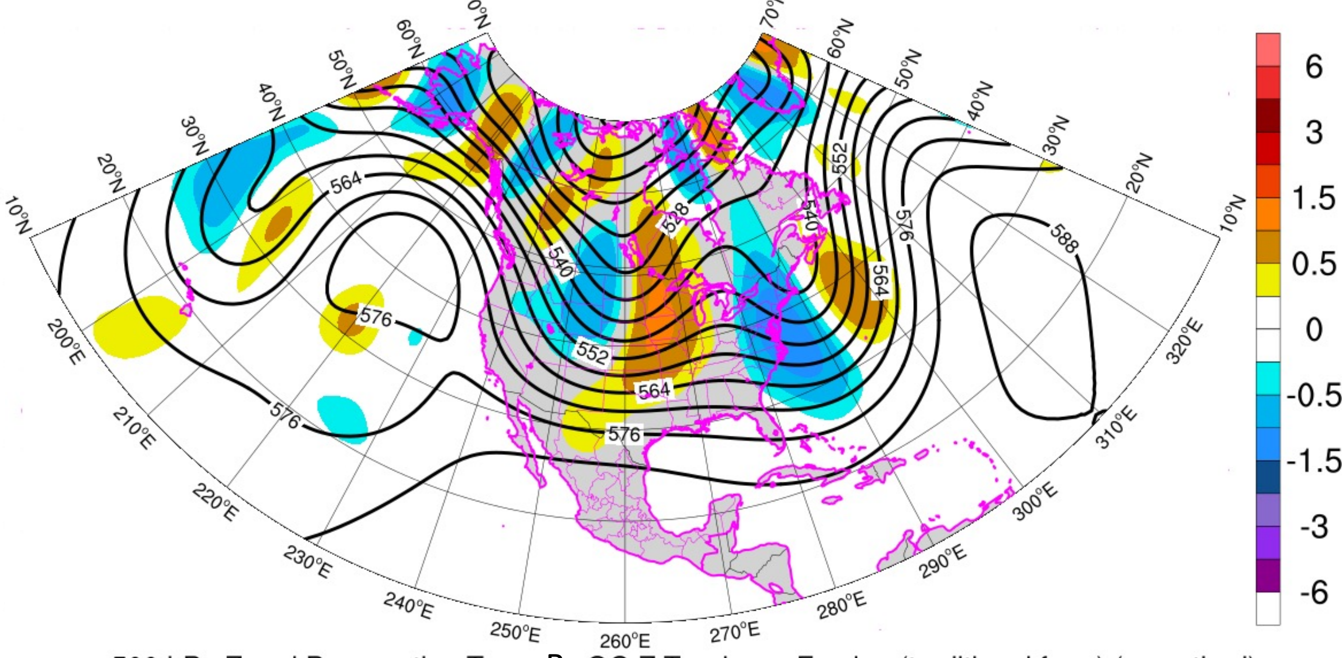


Total forcing=Term B+Term C

500 hPa Z and Total RHS QG Z Tendency Forcing (traditional form) (smoothed)
0-h CMC Global forecast at 2021020412

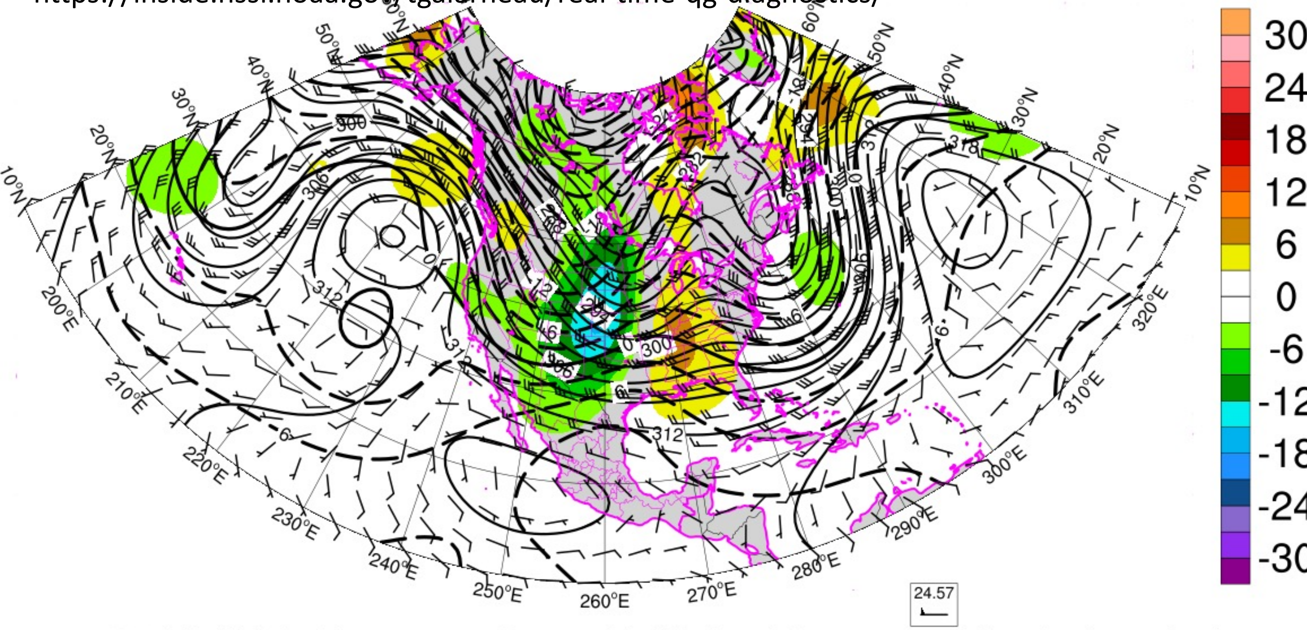


500 hPa Height, Geostrophic Wind, and Geostrophic Absolute Vorticity (smoothed)
0-h CMC Global forecast at 2021020412

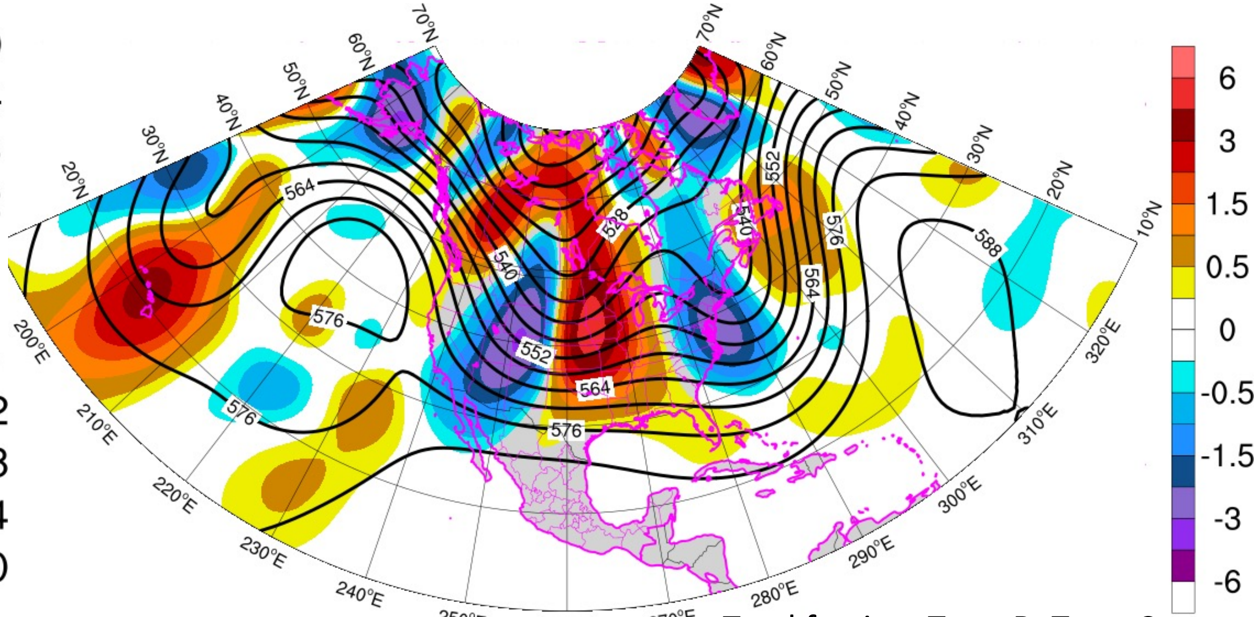


500 hPa Z and Propagation Term B QG Z Tendency Forcing (traditional form) (smoothed)
0-h CMC Global forecast at 2021020412

https://inside.nssl.noaa.gov/tgalarneau/real-time-qg-diagnostics/

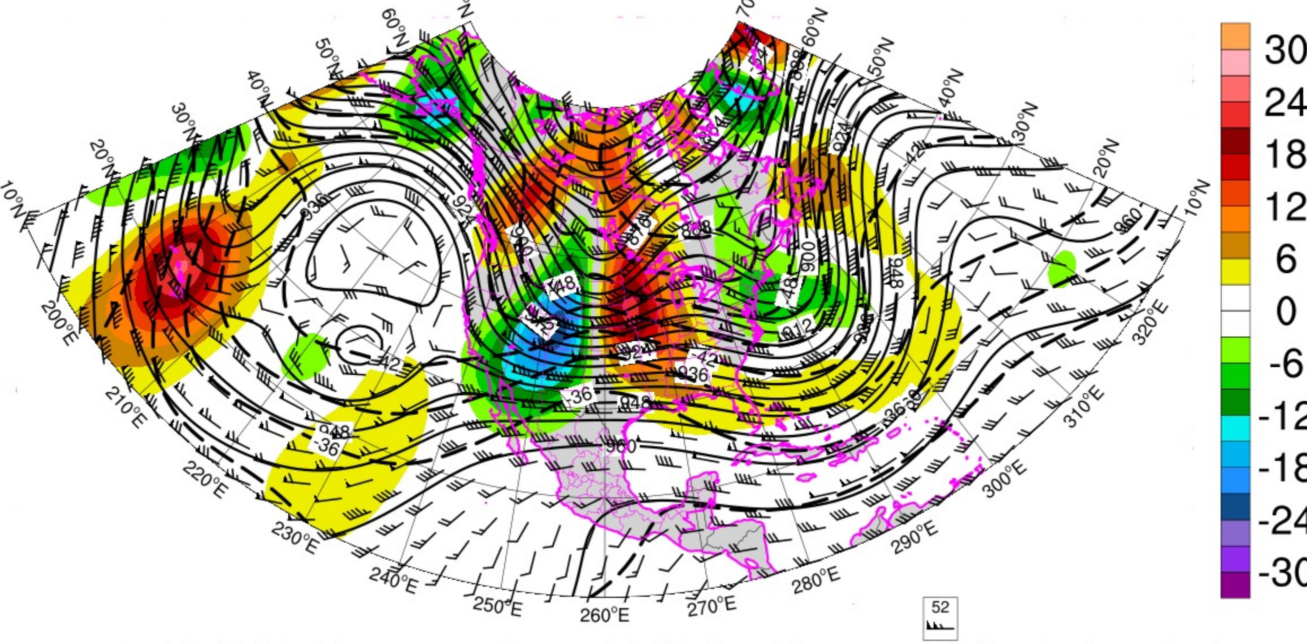


700 hPa Height, Temperature, Geostrophic Wind, and Temperature Advection (smoothed)
0-h CMC Global forecast at 2021020412

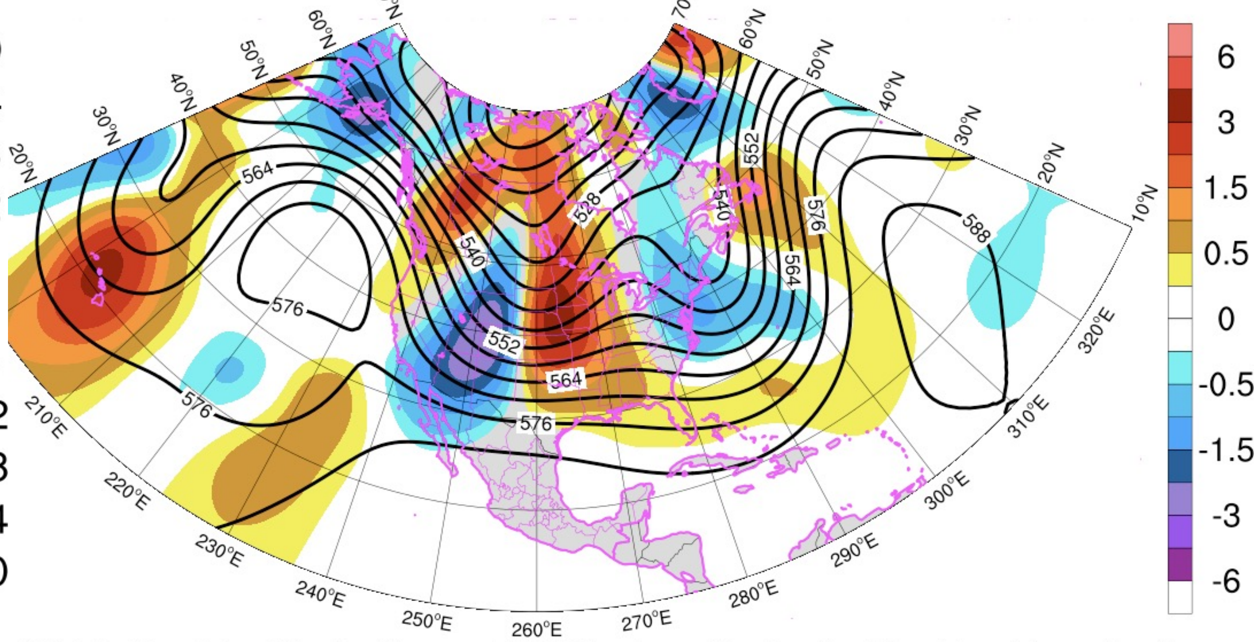


Total forcing=Term B+Term C

500 hPa Z and Total RHS QG Z Tendency Forcing (traditional form) (smoothed)
0-h CMC Global forecast at 2021020412

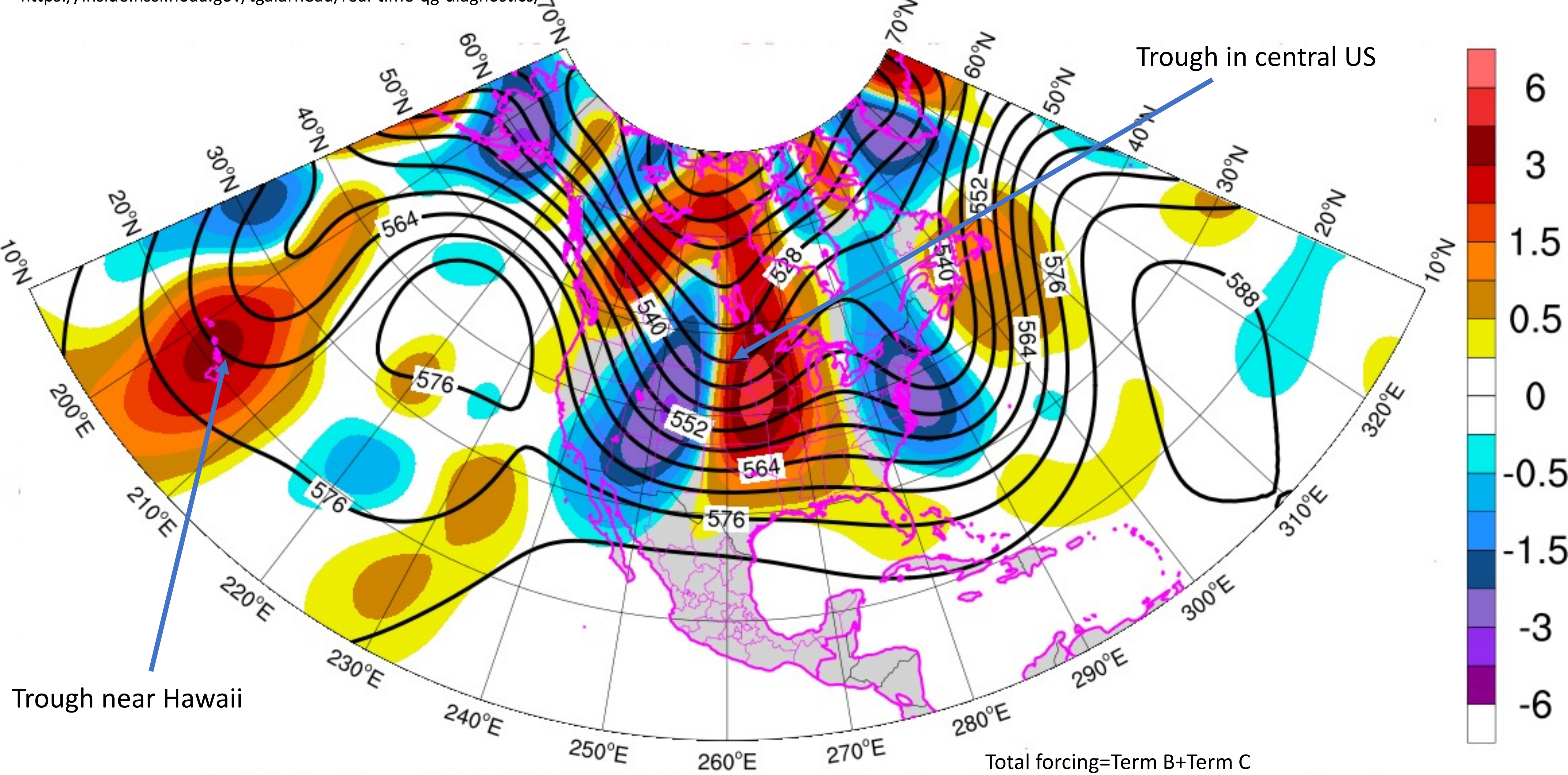


300 hPa Height, Temperature, Geostrophic Wind, and Temperature Advection (smoothed)
0-h CMC Global forecast at 2021020412



500 hPa Z and Amplification Term C QG Z Tendency Forcing (traditional form) (smoothed)
0-h CMC Global forecast at 2021020412

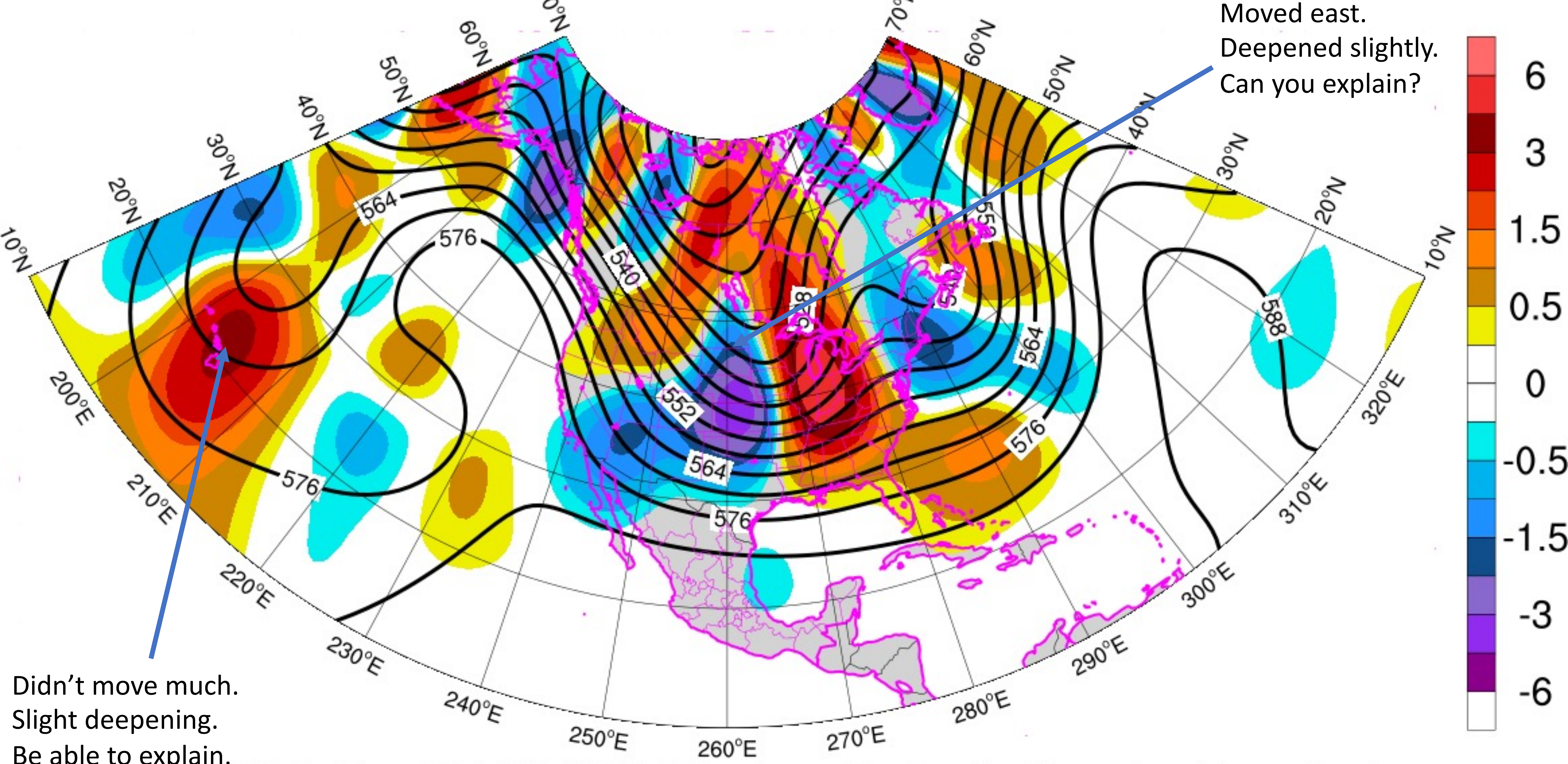
https://inside.nssl.noaa.gov/tgalarneau/real-time-qg-diagnostics/



500 hPa Z and Total RHS QG Z Tendency Forcing (traditional form) (smoothed)
0-h CMC Global forecast at 2021020412

https://inside.nssl.noaa.gov/tgalarneau/real-time-qg-diagnostics/

Moved east.
Deepened slightly.
Can you explain?



Didn't move much.
Slight deepening.
Be able to explain.

500 hPa Z and Total RHS QG Z Tendency Forcing (traditional form) (smoothed)
0-h CMC Global forecast at 2021020500

Frontogenesis

- **Frontogenesis (frontolysis) is the strengthening (weakening) of a temperature gradient**

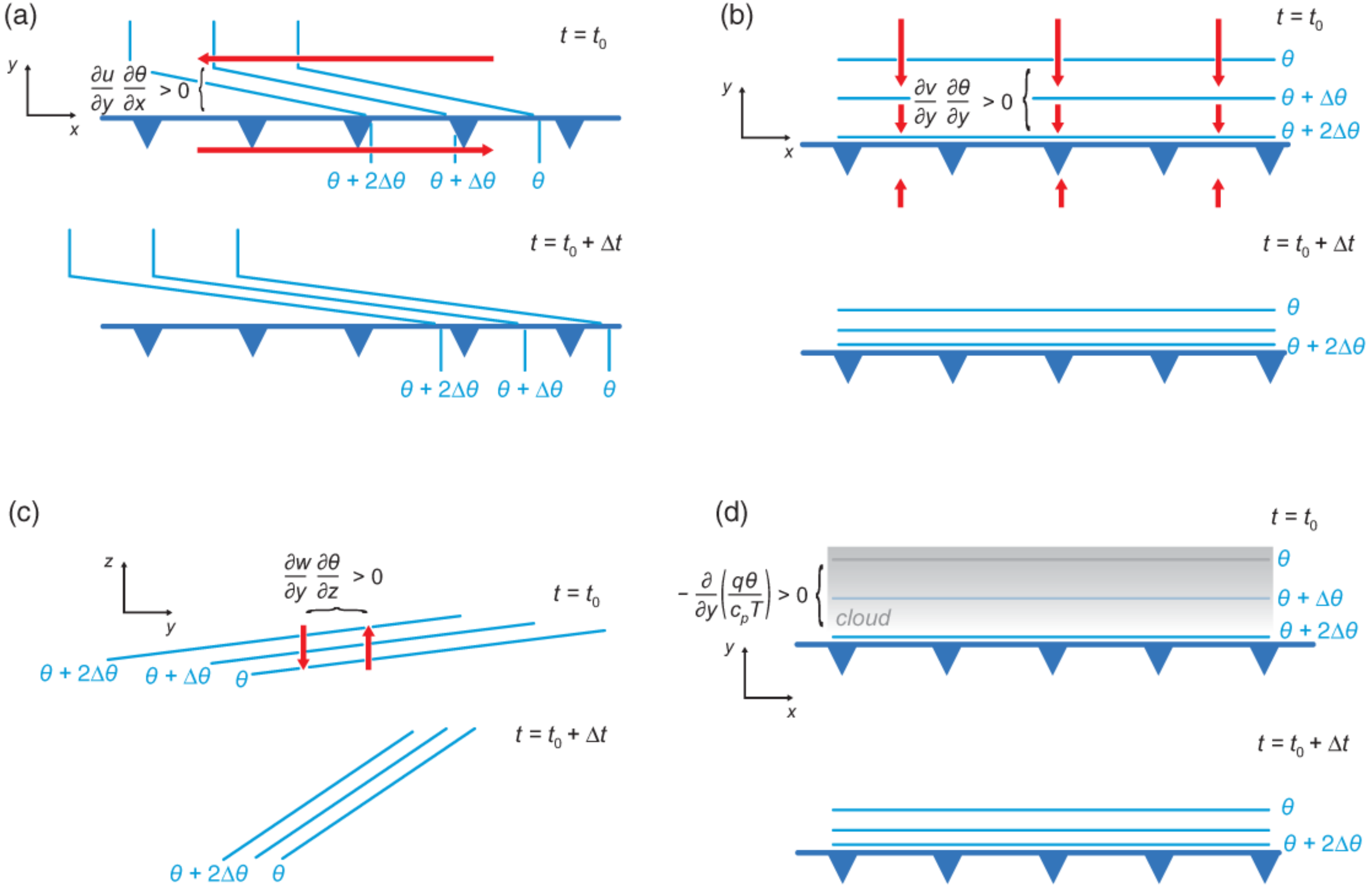
- **In case of frontogenesis, thermal wind balance (TWB) is violated because temperature gradient is too strong for the given wind shear**
  - **To restore TWB, atmosphere weakens temperature gradient via ascent (adiabatic cooling) on warm side and descent (adiabatic warming) on cold side of gradient**

- **Fronts are zones where thermal advection and frontogenesis are easily enhanced and are also preferred corridors for cyclones/cyclogenesis**

Frontogenesis Mechanisms

horizontal shear

confluence



tilting

Differential diabatic heating

Fig. 5.4 MR 2010

Frontogenesis and Frontolysis by Confluence

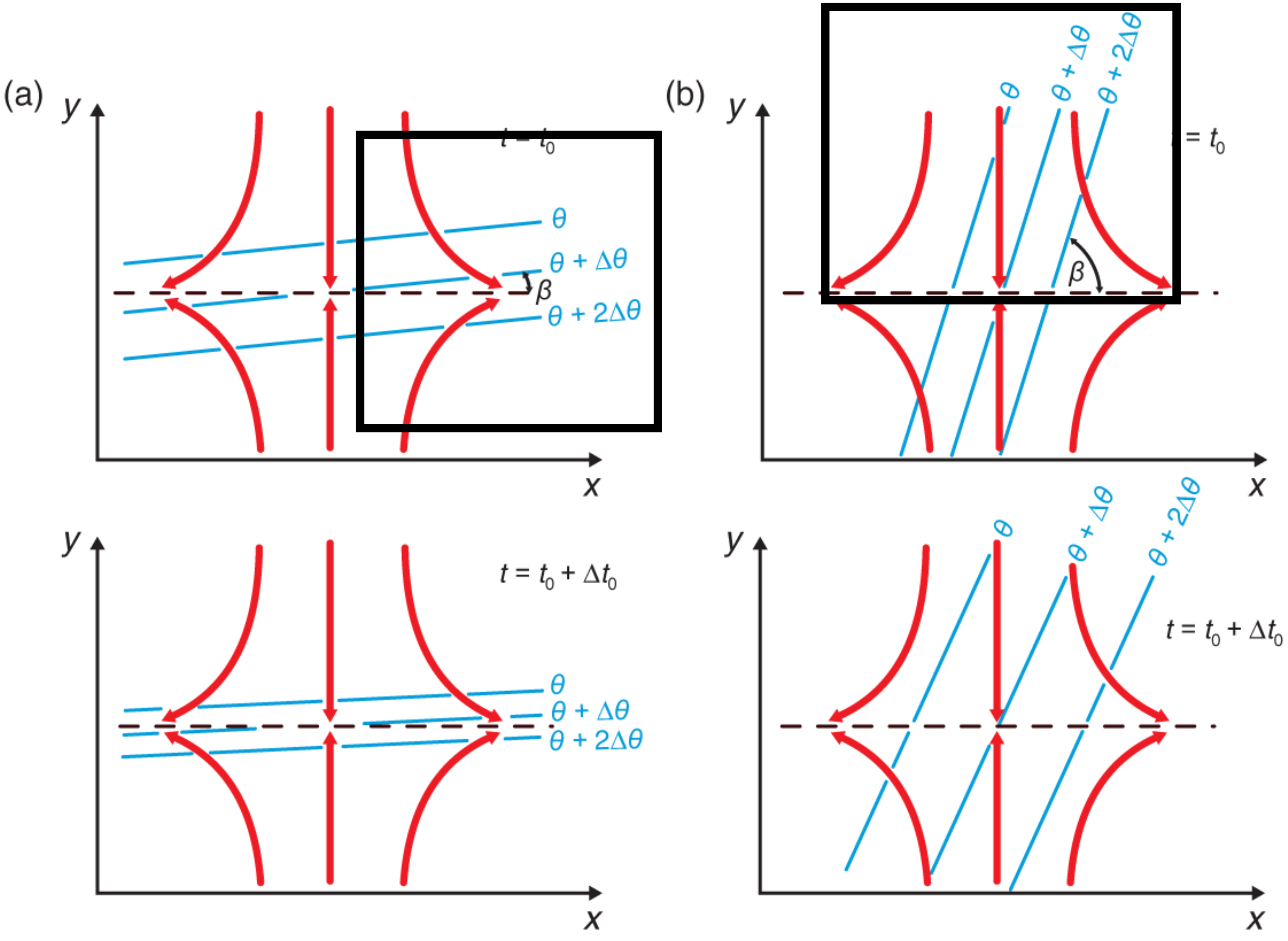
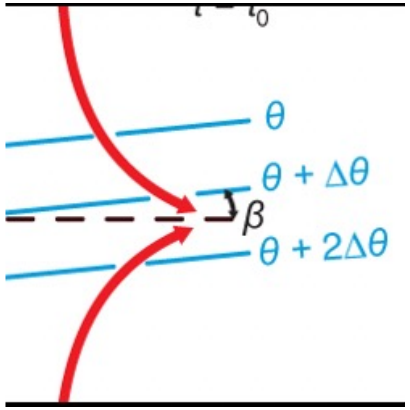
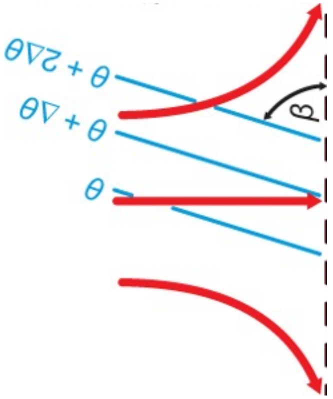


Fig. 5.5 MR 2010

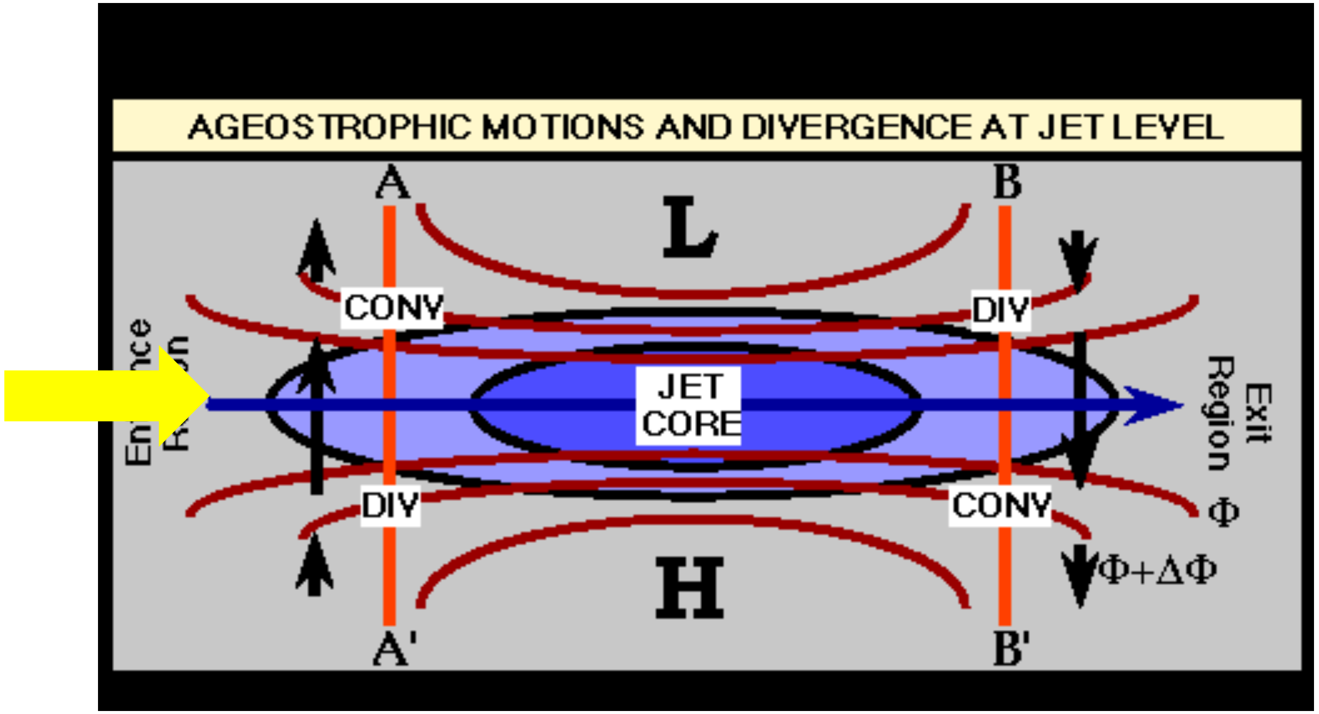
Like a jet entrance region: Frontogenesis!



Like a jet exit region: Frontolysis!



Frontogenesis and Jet Streaks



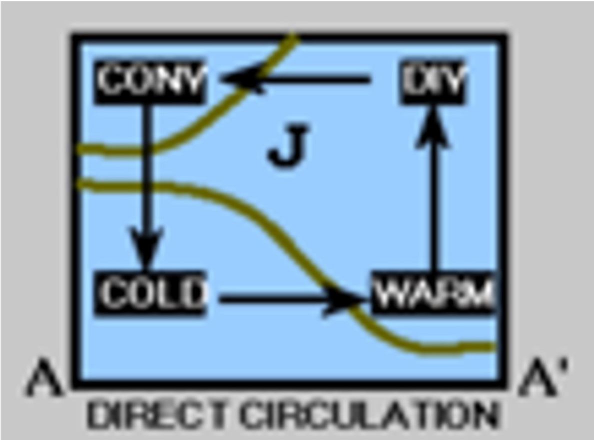
Air entering jet streak – sinking on cold side, rising on warm side.

Air leaving jet streak – rising on cold side, sinking on warm side.

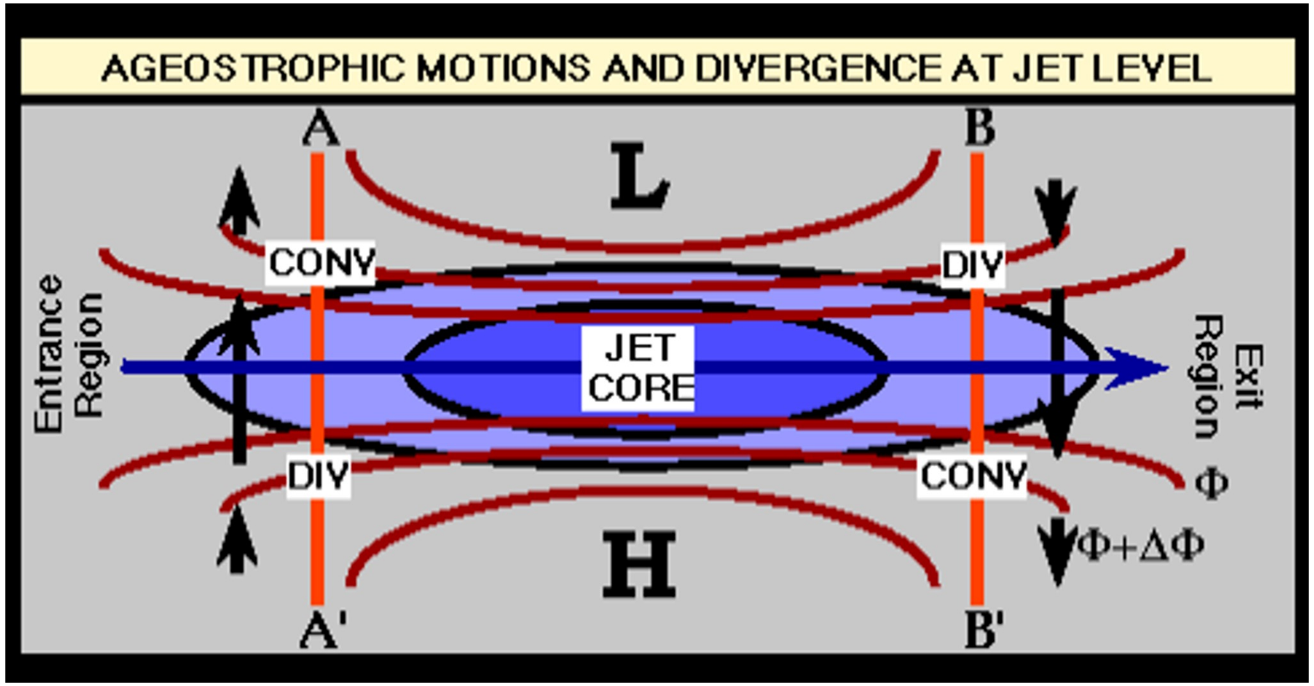
Vertical Wind Shear

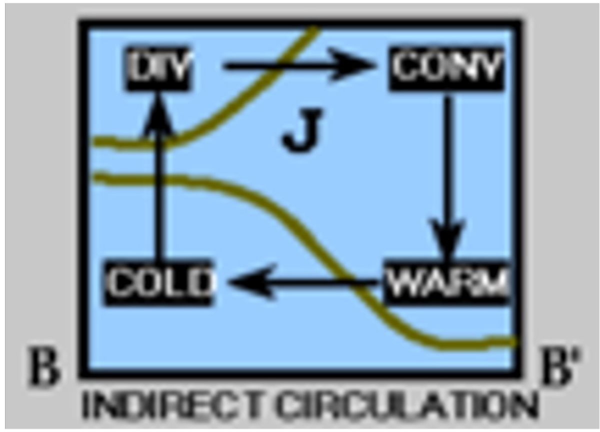
Where does it come from?

Secondary contributions:
Large accelerations of the horizontal wind due to large ageostropic winds
(think near jet streaks, areas of frontogenesis, and/or rapidly intensifying cyclones).



Erodes horizontal temperature gradient (weaker thermal wind)





Enhances horizontal temperature gradient (stronger thermal wind!)

For additional reading: M.R. 2010 and Doswell

Frontogenesis and Jet Streaks

- **Jet streaks are coincident with strong temperature gradients (thermal wind balance!)**

- **Air flows through a jet streak**
  - **Encounters strengthening temperature gradient (frontogenesis) in entrance region**
  - **Encounters weakening temperature gradient (frontogenesis) in exit region**

- **Response to frontogenesis in entrance region is ascent on warm side (right entrance) and descent on cold side (left entrance)**

- **Response to frontolysis in exit region is?**

Baroclinic systems

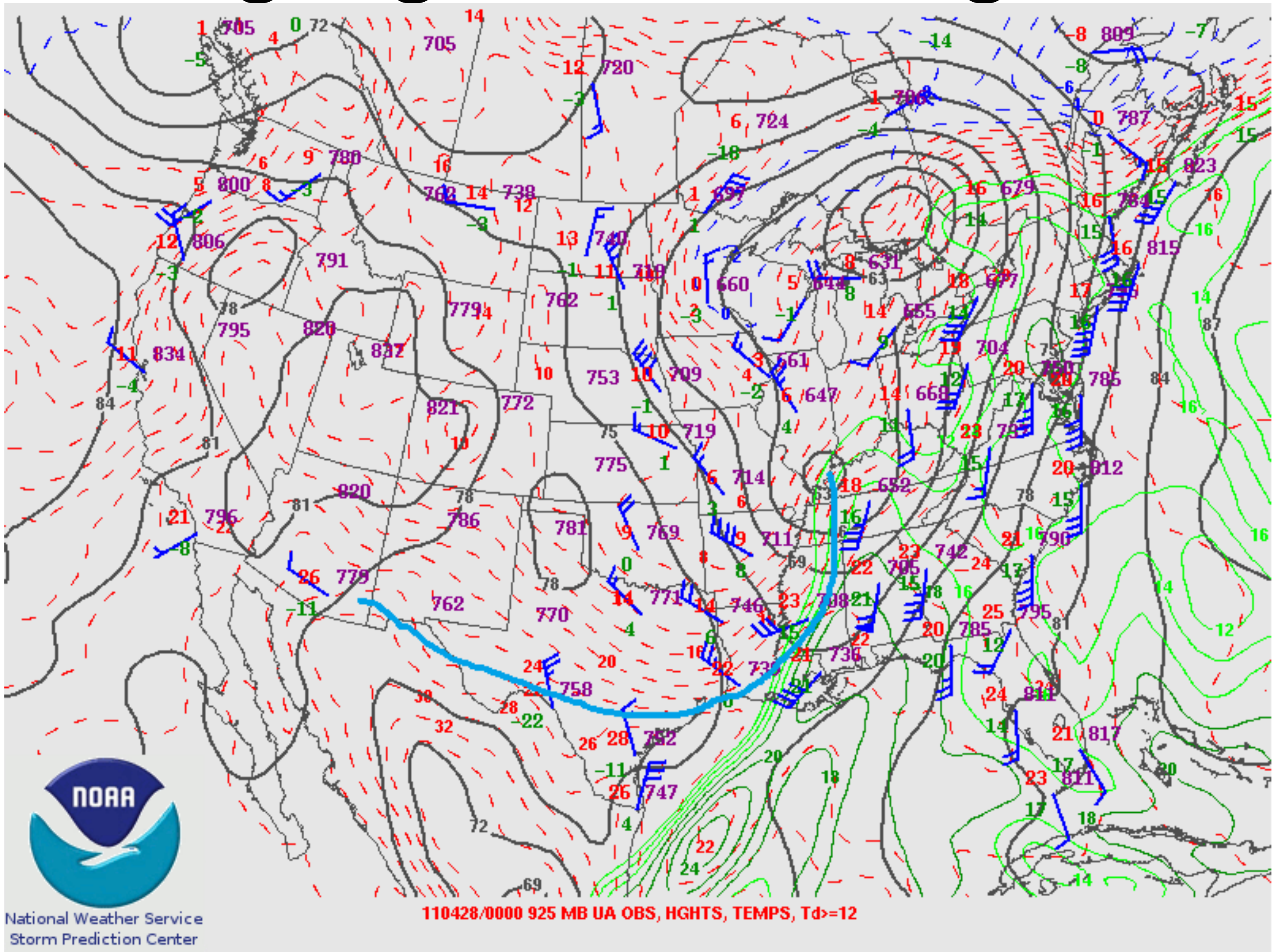
- **Vorticity and thermal structure tilts westward (upstream) with height**
  - **Deepening/strengthening systems**
  - **Differential thermal advection leads to destabilization**

- **Warm advection corresponds to veering winds with height**
  - **Large clockwise turning hodographs in warm sector**

- **Strong jet streaks and fronts are present**

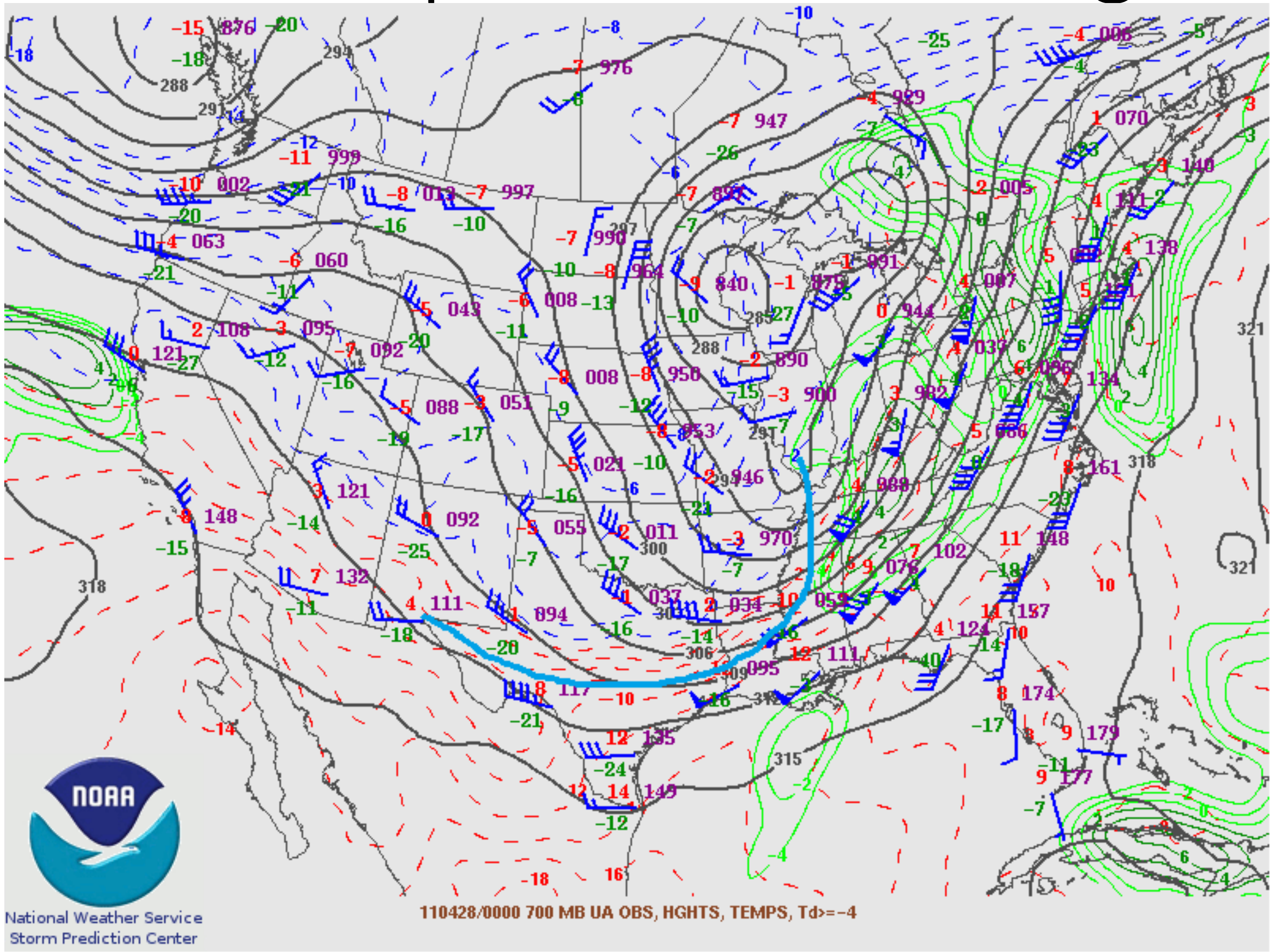
Edge of stronger gradient near ground

925mb

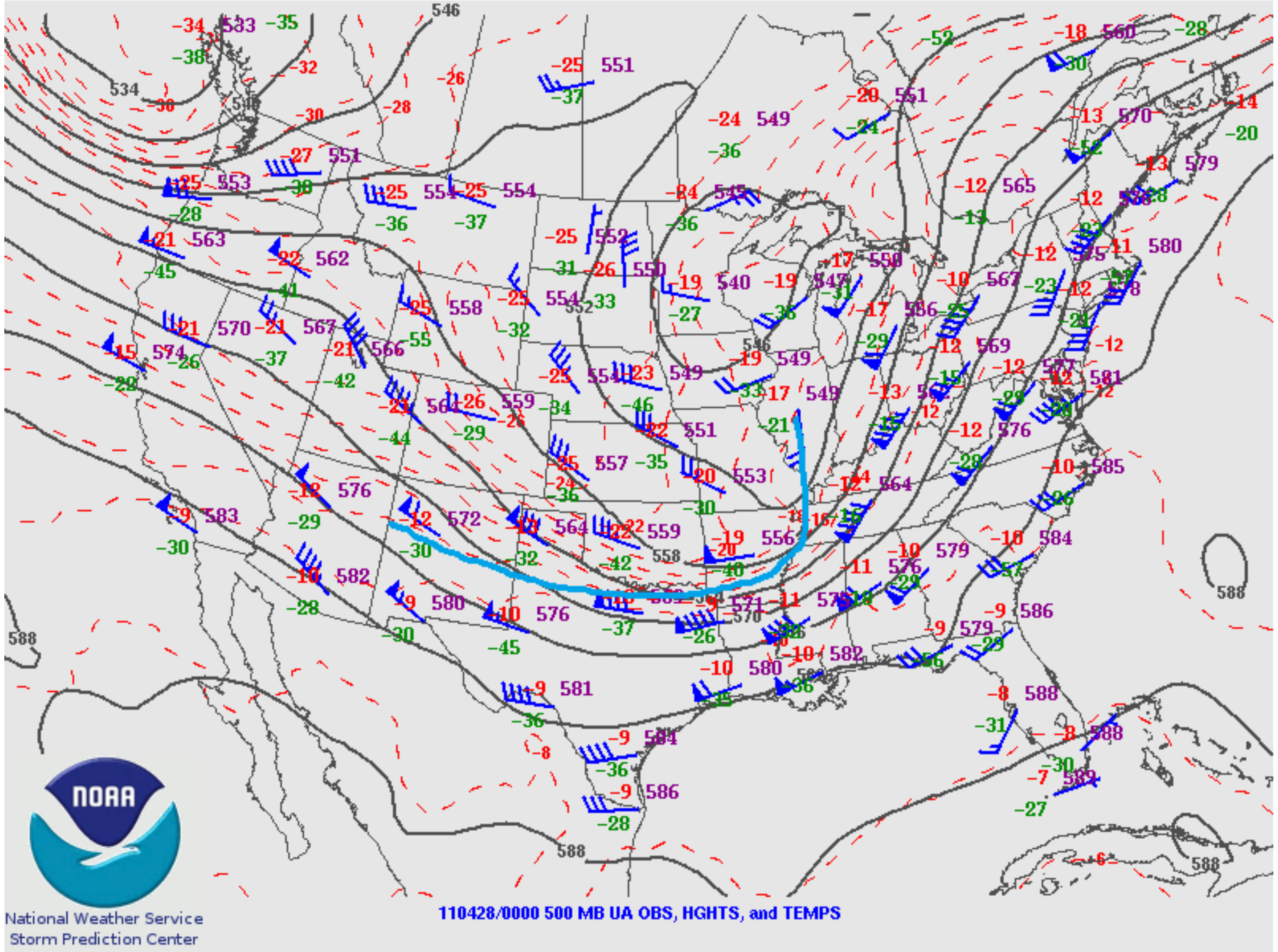


Temp gradient slopes NW with height

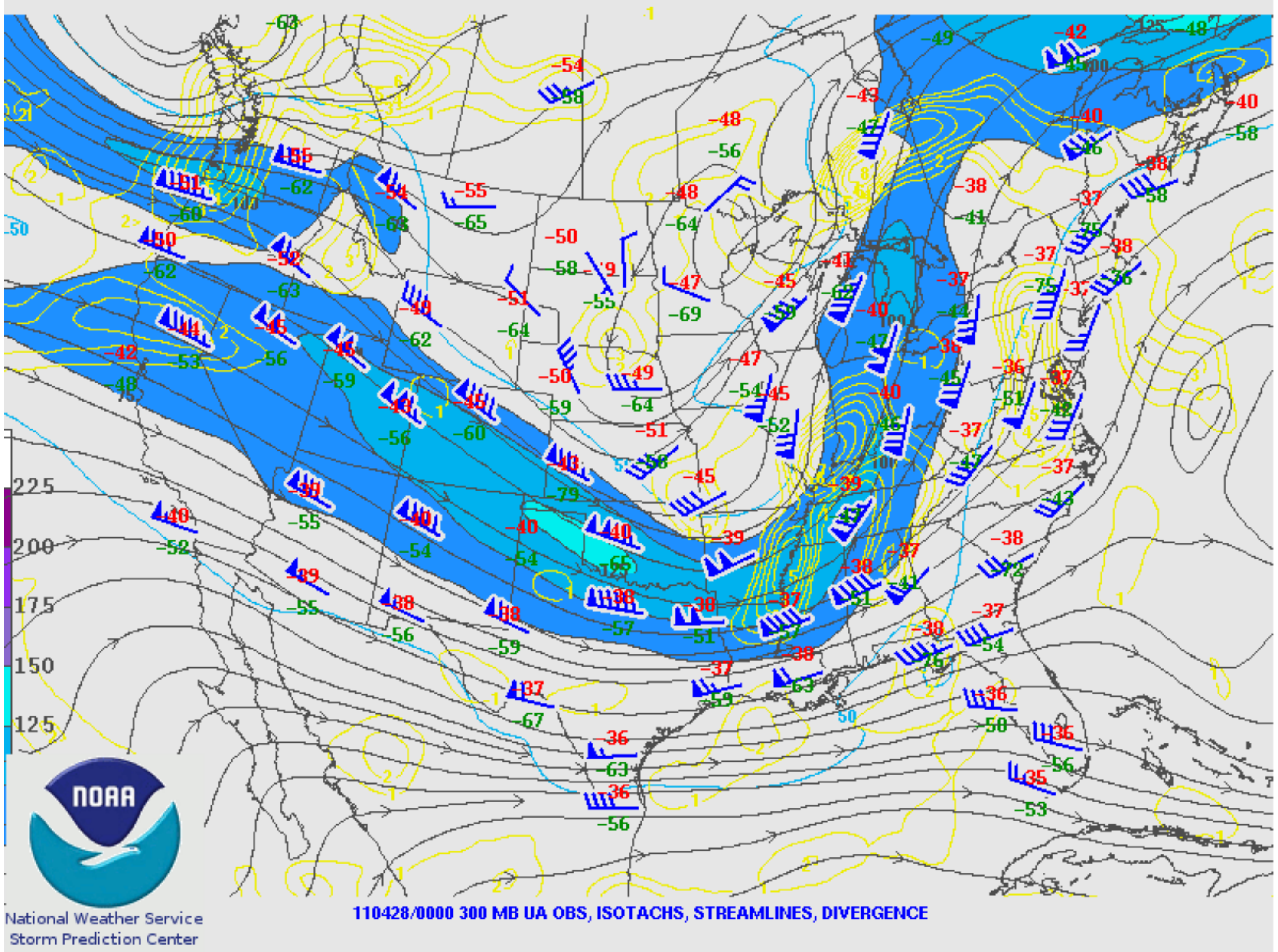
700mb



500mb

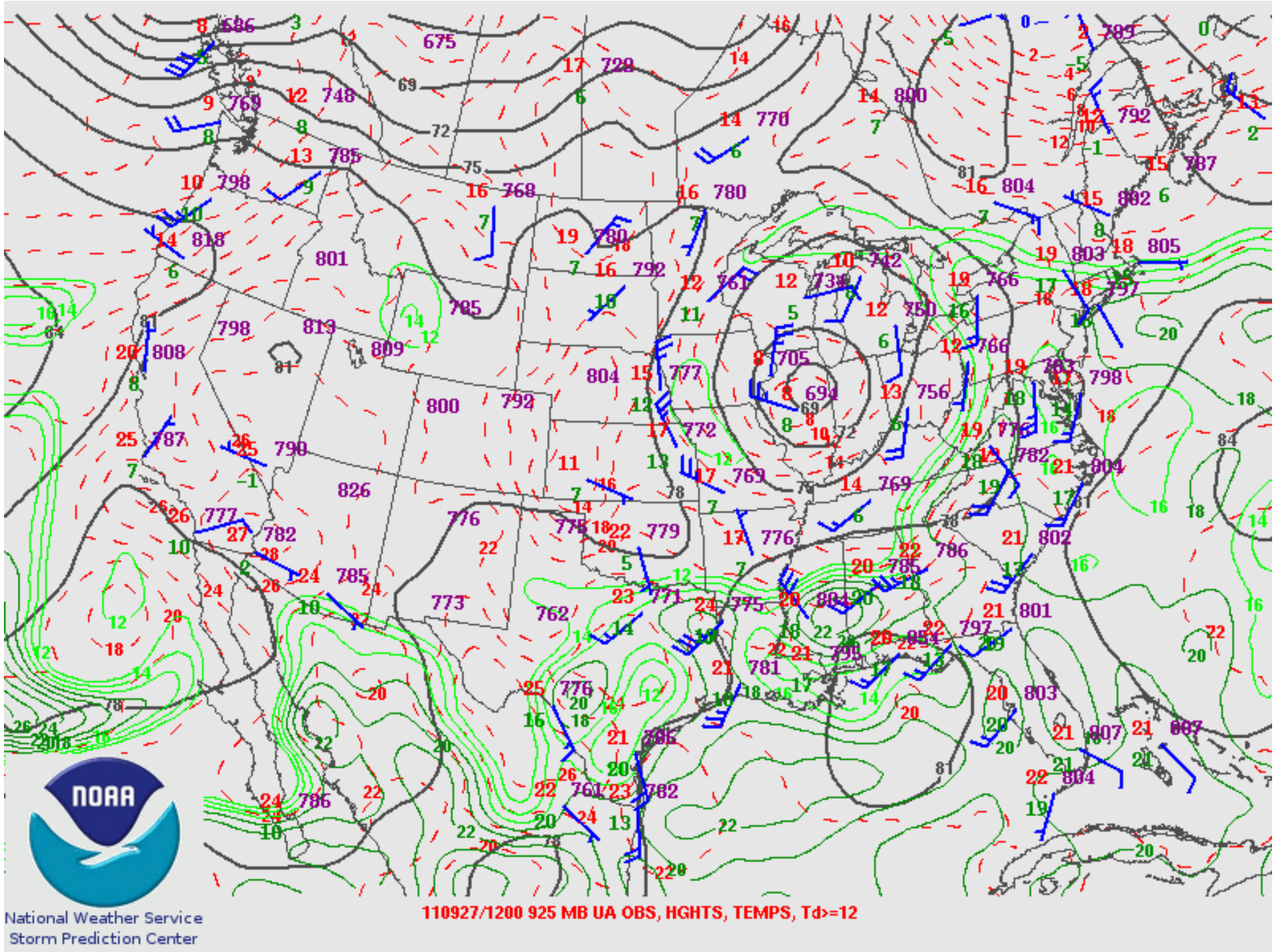

110428/0000 500 MB UA OBS, HGHTS, and TEMPS
NOAA
National Weather Service
Storm Prediction Center

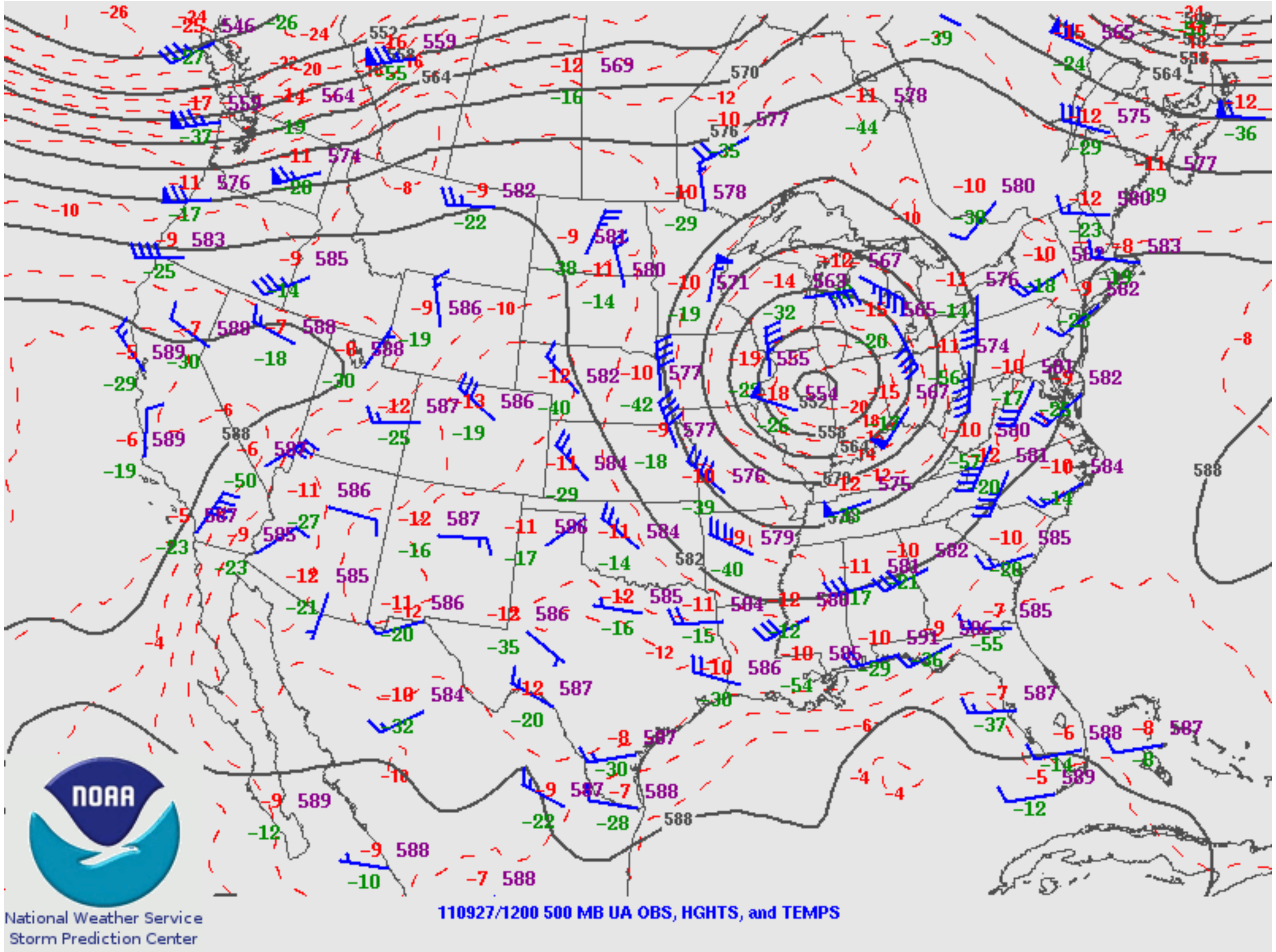
300mb


225
200
175
150
125
NOAA
National Weather Service
Storm Prediction Center
110428/0000 300 MB UA OBS, ISOTACHS, STREAMLINES, DIVERGENCE

Equivalent Barotropic Systems

- **Vorticity and thermal structure vertically stacked with height**
  - **Steady state or weakening systems**
- **Minimal temperature advection corresponds to weak vertical shear**
- **Weak gradients – weak flow – slow moving**


National Weather Service
Storm Prediction Center
110927/1200 925 MB UA OBS, HGHTS, TEMPS, Td>=12


NOAA
National Weather Service
Storm Prediction Center
110927/1200 500 MB UA OBS, HGHTS, and TEMPS

Final Comments

- **Can explain development of weather systems (QG height tendency and QG cyclogenesis)**

- **Can explain why ascent occurs where it does near troughs, jets, and fronts**

- **Look for gradients!**

- **Synoptic-scale processes set the stage for severe thunderstorm development**