Project 2: Fronts and temperature

Data class- atmosphere

1.   *Thermal wind and atmospheric fronts*

-   Margules equation for a real atmospheric fronts

2. Transport (advection) in the atmosphere:

-   Example: transport of Saharan dust over the ocean

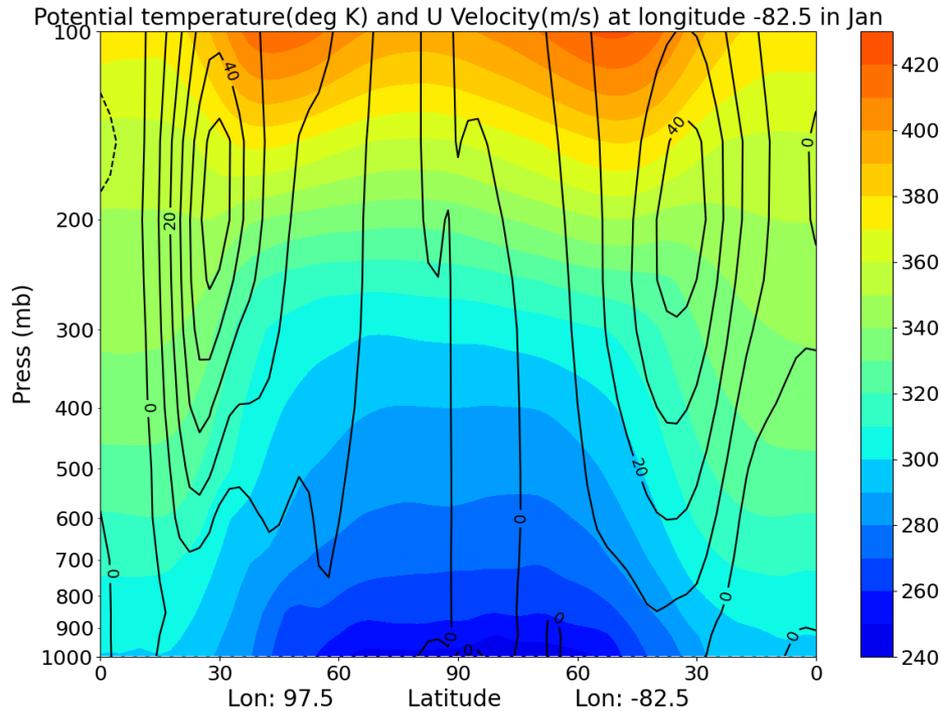**Next class:**

2. Temperature Advection:

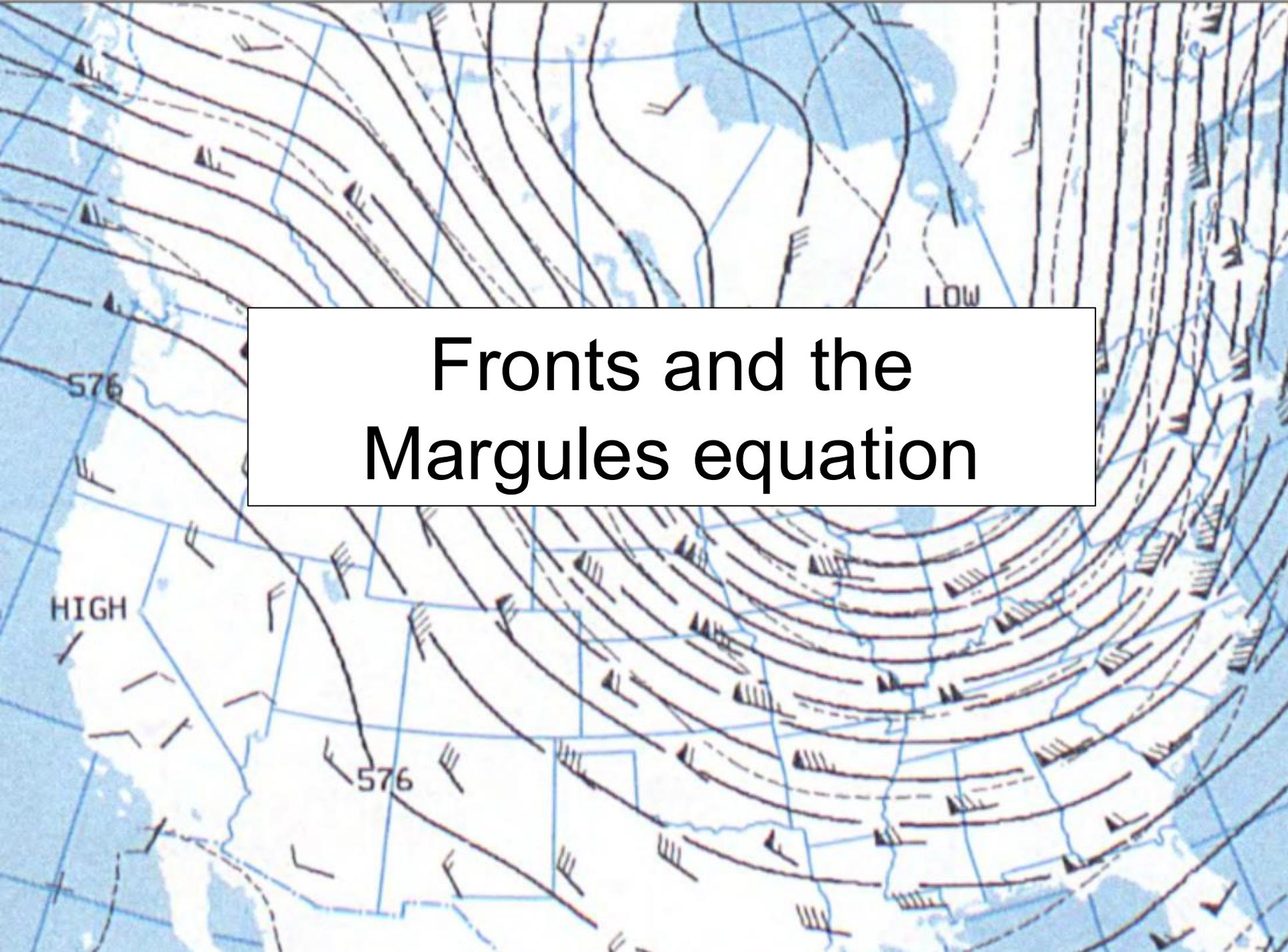-   Temperature change in a real front during winter

3. Temperature variability in current and future climate

-   Temperature variations in the atmosphere
-   Temperature variability in current and future climate (analyze state-of-the-art climate model data!)

Thermal wind

In terms of potential temperature- $f\left(\dfrac{\partial u_g}{\partial p},\ \dfrac{\partial v_g}{\partial p}\right) = \dfrac{1}{\rho\theta}\left(\left(\dfrac{\partial\theta}{\partial y}\right)_p,\ -\left(\dfrac{\partial\theta}{\partial x}\right)_p\right)$

Potential temperature(deg K) and U Velocity(m/s) at longitude -82.5 in Jan
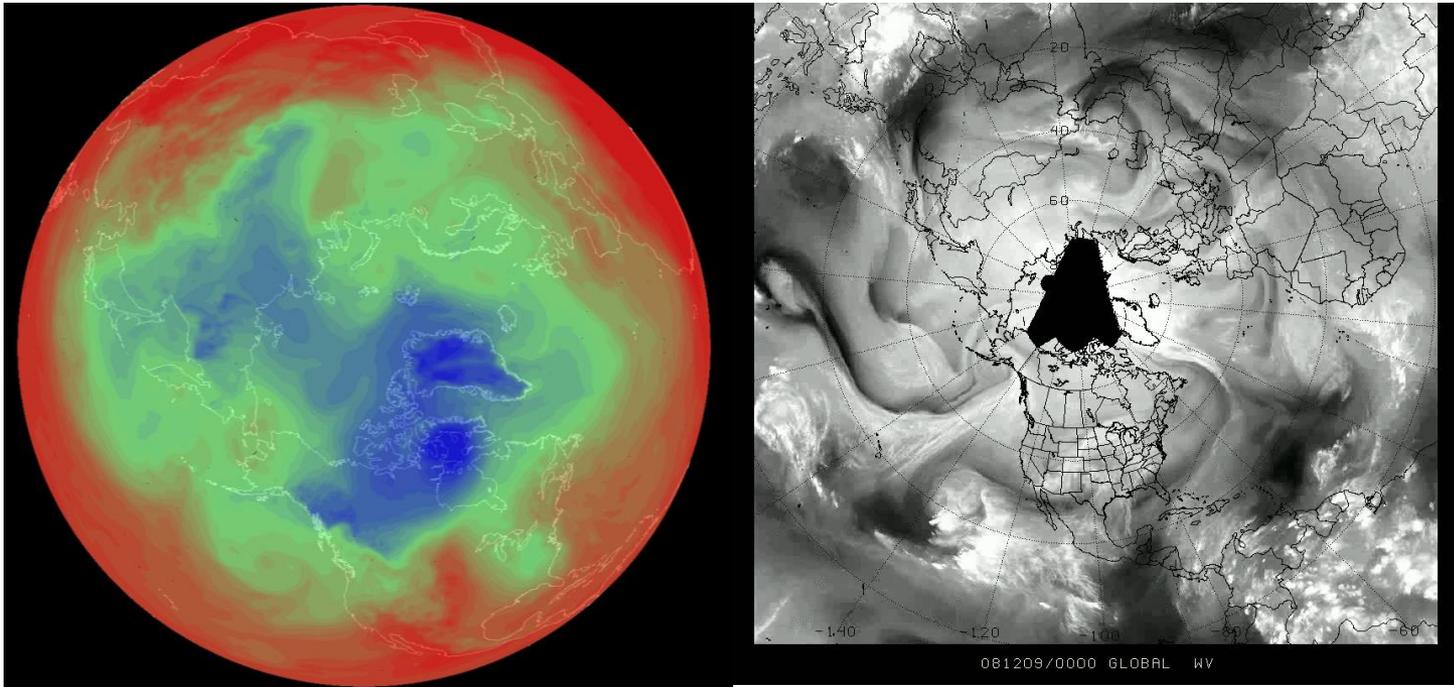
Fronts and the Margules equation

The Polar Front

The air mass over the pole is considerably colder (and dryer) than that over the equator


- The most active weather occurs in middle latitudes where the two air masses meet.
- The transition from cold to warm is not smooth, but occurs quite abruptly in a region of high gradients, known as the *polar front*.
- Much of our day-to-day weather is associated with the evolution of this frontal region
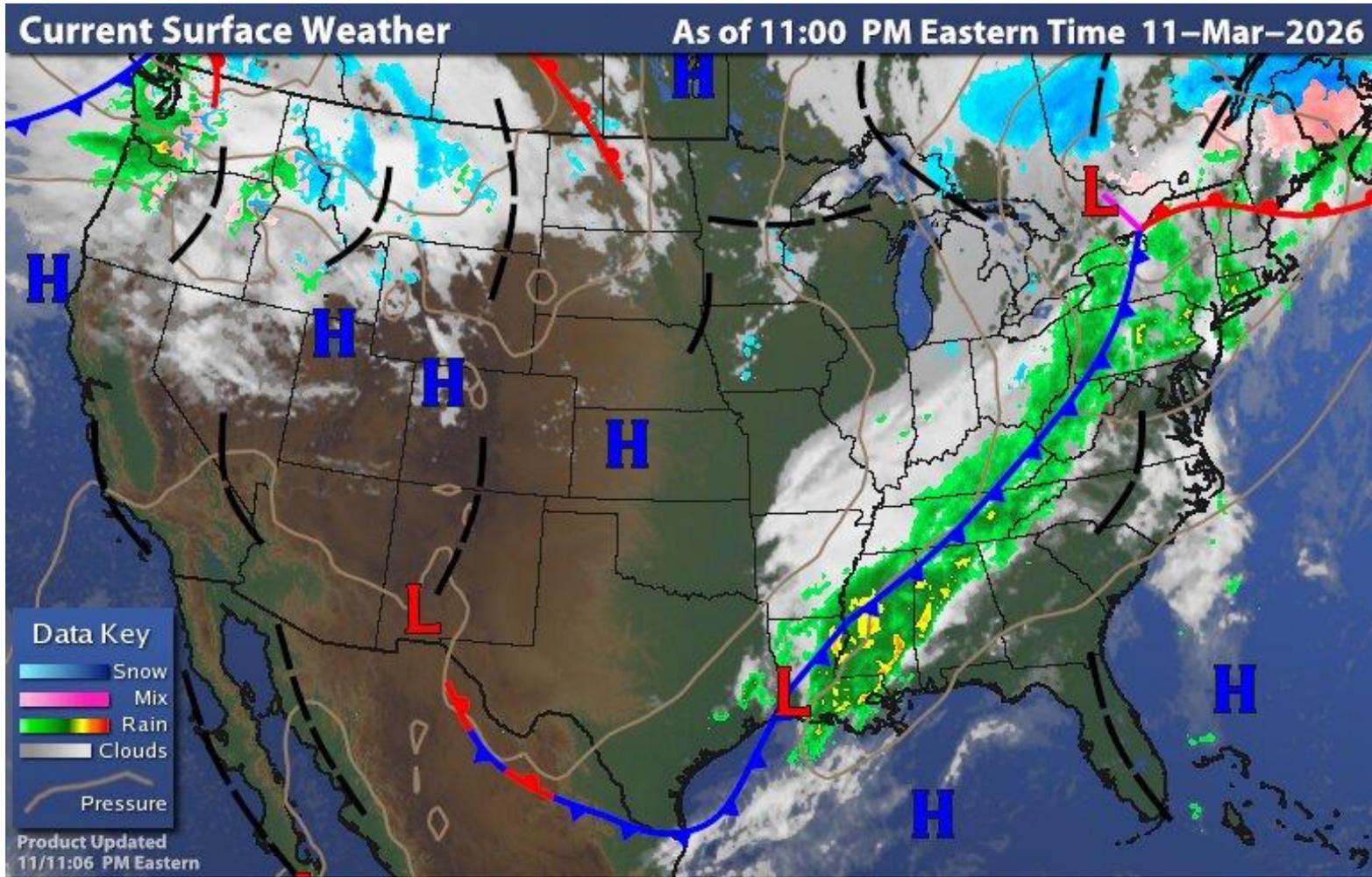
Synoptic fronts and weather systems

Northern Hemisphere 500 mb temperature on January 23, 2005 0z

Note the north-south undulations of the polar front, marked by the transition from orange to green color
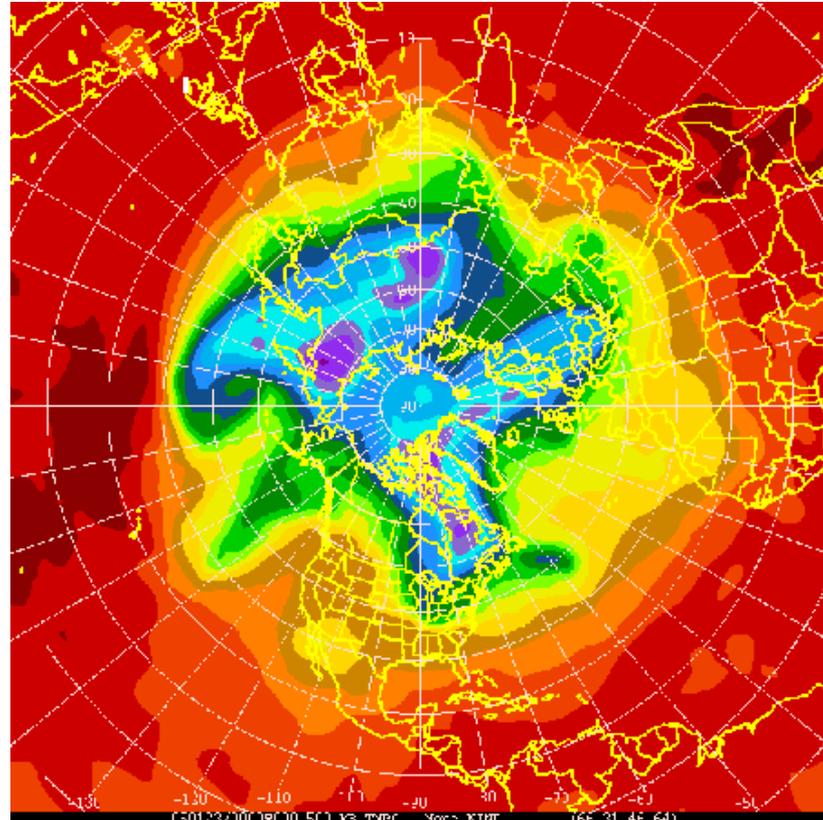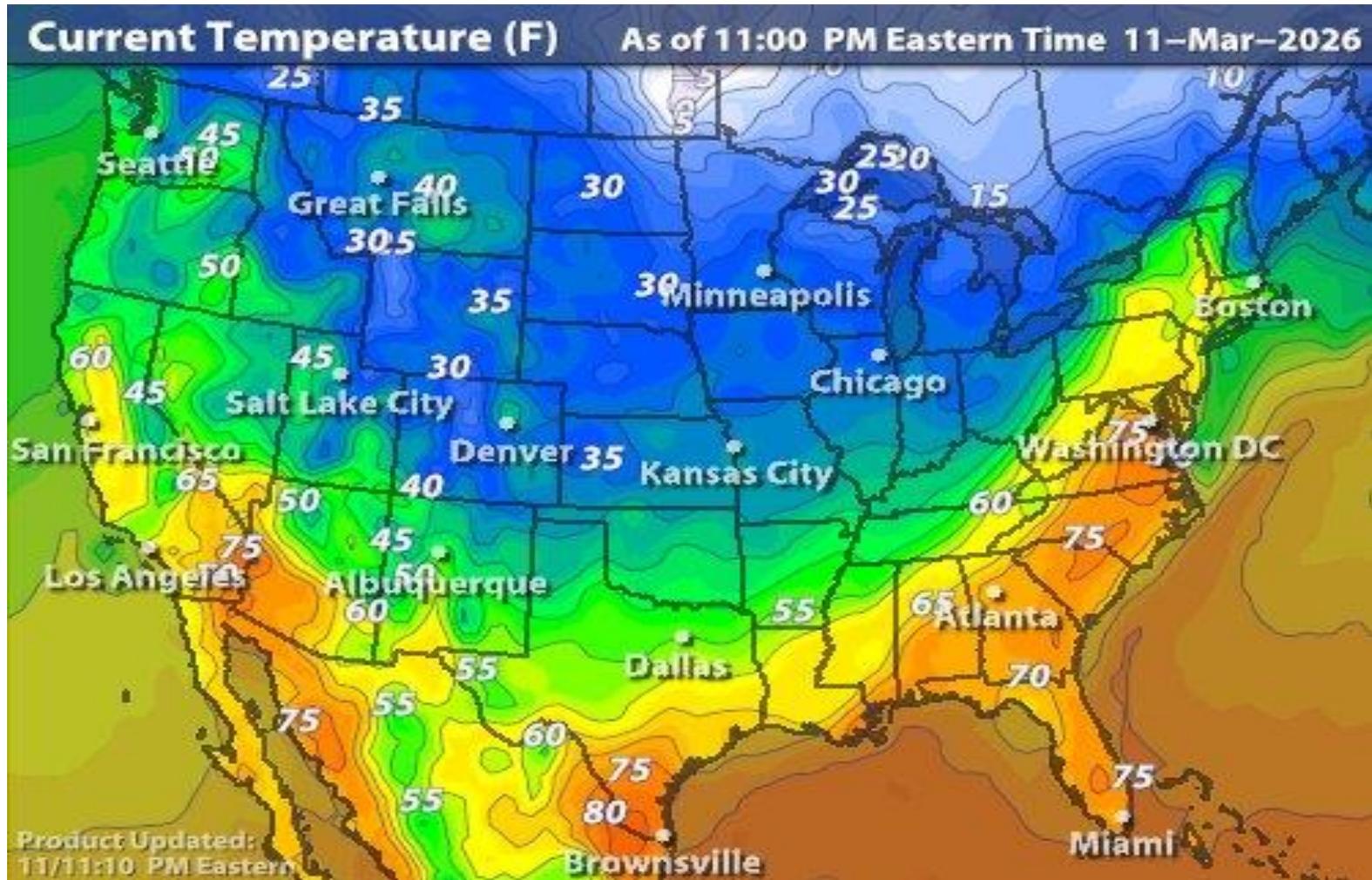
- Everyday weather is often associated with undulations of this frontal surface
- Meanders of the frontal region are associated with high and low pressure synoptic systems which develop on the polar front

Front= sharp transition between cold & warm air masses

Front= sharp transition between cold & warm air masses

Current Temperature (F)   As of 11:00 PM Eastern Time 11–Mar–2026

Synoptic fronts and weather systems

Jet stream Cold air

Warm air

A. Gently undulating upper airflow

Cold air

Warm air

B. Meanders form in jet stream

Cold air

Warm air

C. Strong waves form in upper airflow

Warm

Cold

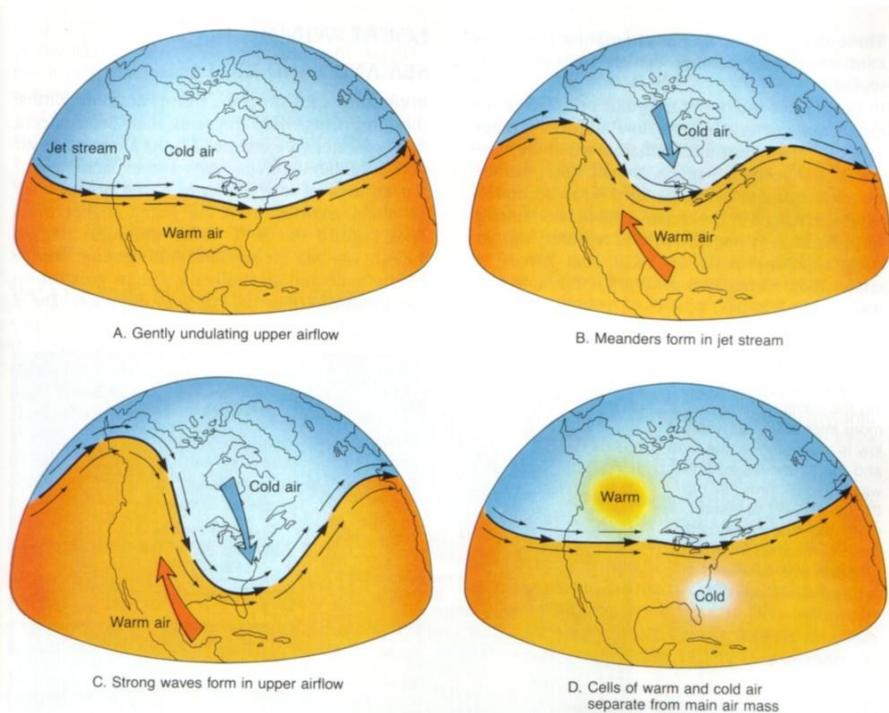D. Cells of warm and cold air
separate from main air mass

FIGURE 14.13
Cyclic changes that occur in the upper-level airflow of the westerlies. The flow,
which has the jet stream as its axis, starts out nearly straight, then develops
meanders, which are eventually cut off. (After J. Namias, NOAA)

As storms grow, they bring warm air poleward (and upward), and cold air
equatorward (and downward)

Synoptic fronts and weather systems

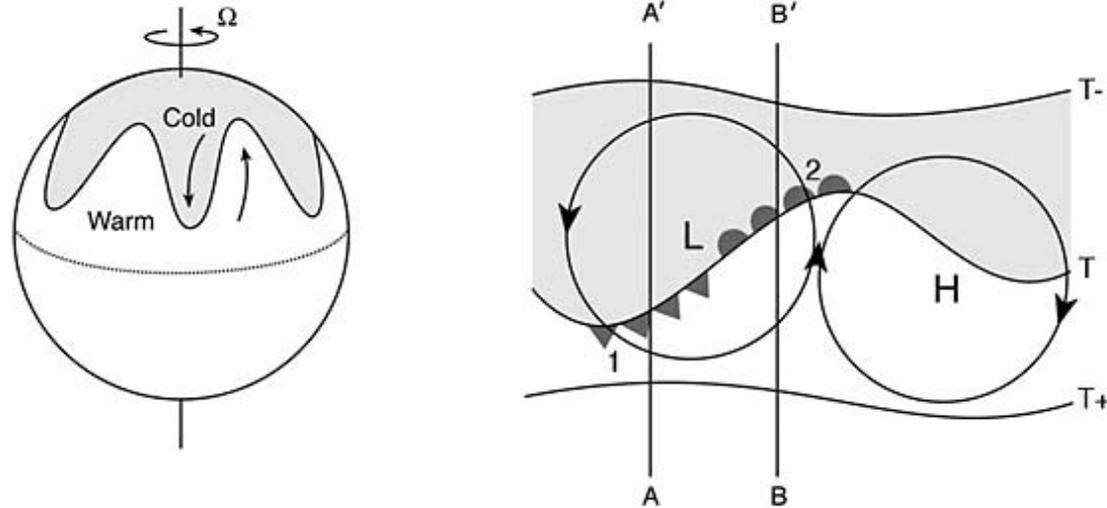The surface manifestations of these systems are warm and cold fronts

Figure 2: (left) In mid-latitudes, eddies form along the polar front and transport warm air poleward and cold air equatorward. (right) To the west of the 'L', or low pressure, cold air is carried to the tropics. To the east, warm air is carried toward the pole. The resulting cold front (triangles) and warm front (semicircles) are marked. The sections A–A' and B–B' through the fronts are sketched in Fig.6 below.

- In mid-latitudes, eddies form along the polar front (left) and transport warm air poleward and cold air equatorward. (right)
- To the west of the 'L' (low pressure), cold air is carried to the tropics. To the east, warm air is carried toward the pole. The resulting cold front (triangles) and warm front (semicircles) are marked.

Synoptic fronts and weather systems

Synoptic scale fronts are associated with cyclones development

A *front* is a boundary separating two air masses with different temperatures
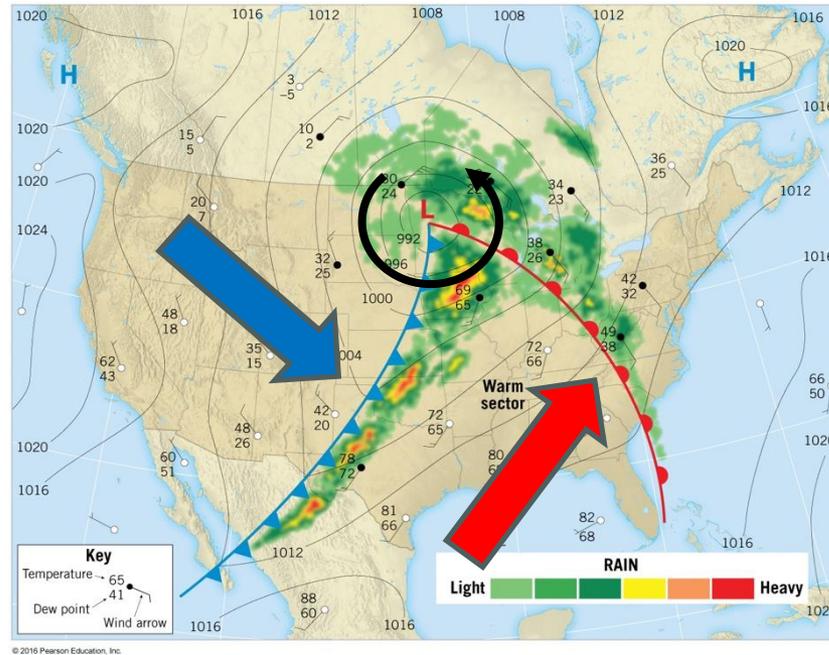
- As the **cold** air moves southward, where the air is warmer, the **cold front** develops. The cold air is lifting the warm and moist air and hence precipitation is formed

- As the **warm** air moves poleward, where the air is colder, the **warm front** develops. The warm and moist air travels above the cold air, and again precipitation is formed

Synoptic fronts and weather systems
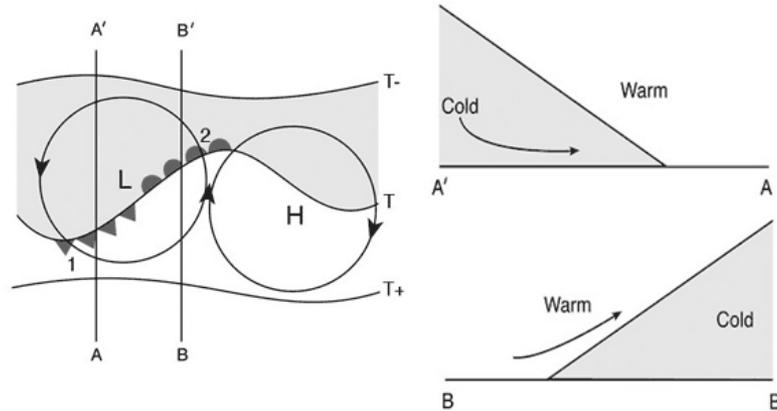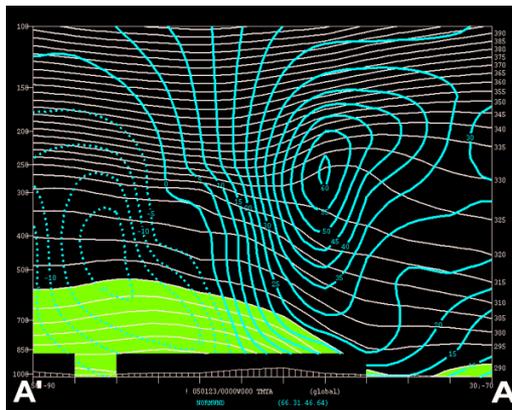

potential temperature and wind

The region of cold air is shaded in green

Thermal wind!
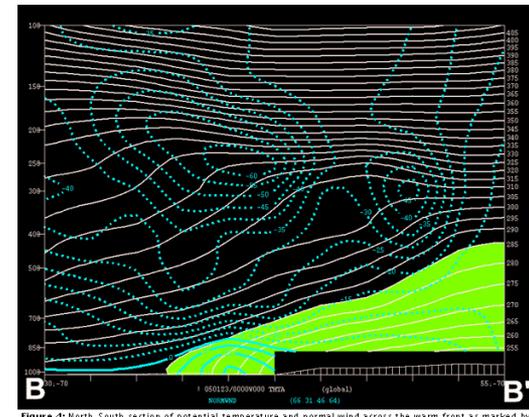
A section across the cold front as marked by the A'A line in the schematic diagram

A section across the warm front as marked by the B'B line in the schematic diagram

- Cold air wedges underneath warm air in the cold front, while warm air overrides cold air in the warm front
- In both cases, warm, moist air rises, cools and condenses, forming clouds & precipitation along the fronts
- Because the cold fronts are usually stronger than the warm fronts, the precipitation associated with the passage of a cold front is usually heavier than in a warm front

Cold fronts

- Produce strong convection and heavy precipitation at the boundary
- Are vertically steep
- Often produces cumulonimbus towers
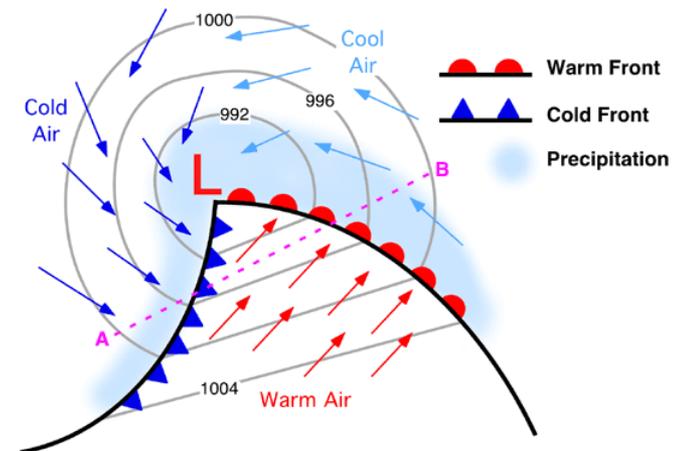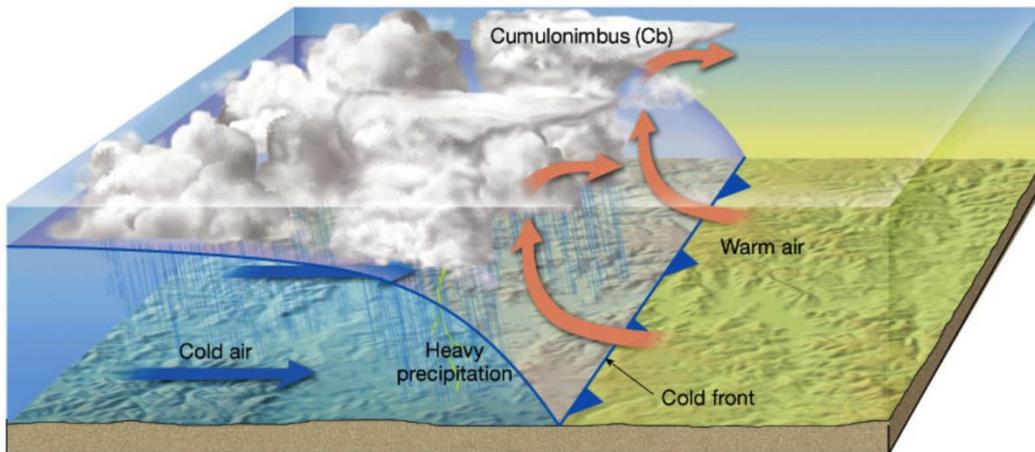- Move relatively fast

Figure 9.6 in *The Atmosphere, 8th edition*, Lutgens and Tarbuck, 8th edition, 2001.

Warm fronts

- Are braider in shape, more "wedge" shaped
- Precipitation is more moderate but can spread out more
- Various clouds at varying altitudes
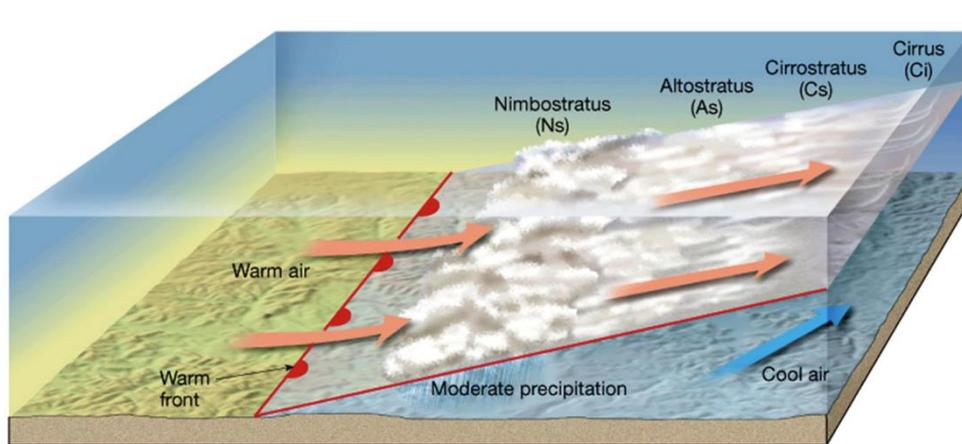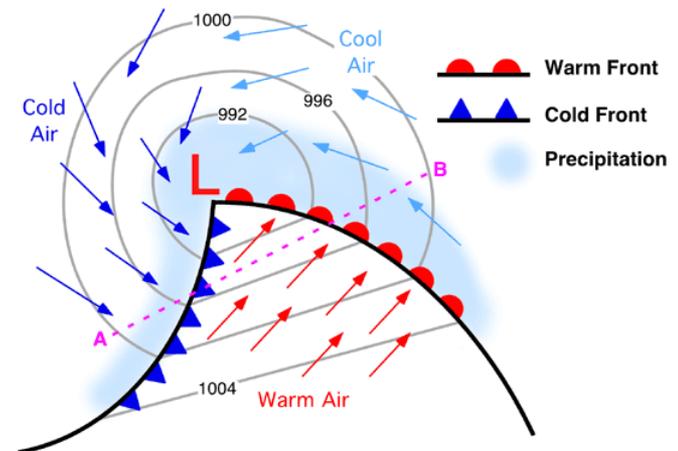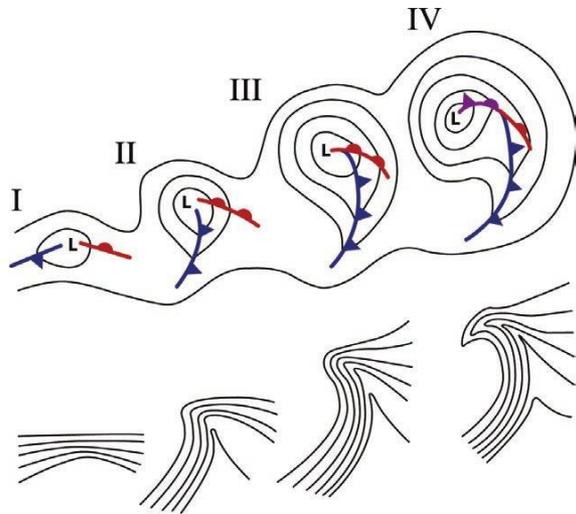- Moves relatively slower compared to the cold front

Figure 9.6 in *The Atmosphere, 8th edition*, Lutgens and Tarbuck, 8th edition, 2001.

Conceptual cyclone life cycle models
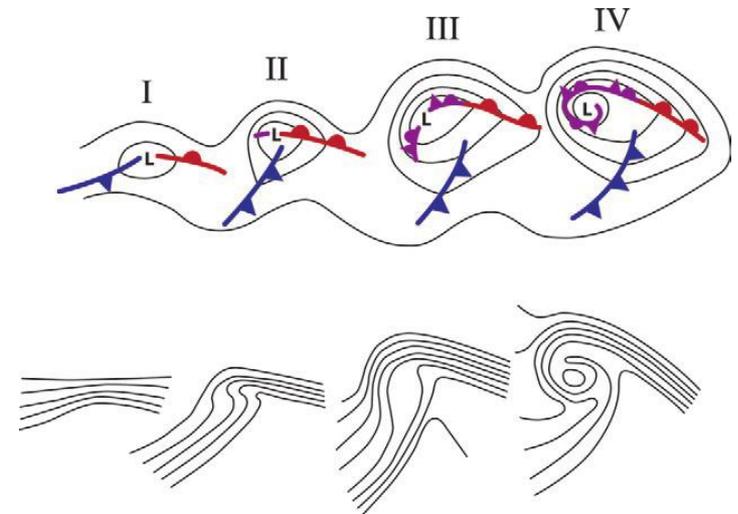
Norwegian cyclone model

beginning of the last century

Shapiro-Keyser cyclone model

developed in the late 1980s,

adapted from Schultz et al. (1998)

adapted from Shapiro and Keyser (1990)

(top) Lower-tropospheric geopotential height and fronts, and (bottom) lower tropospheric temperature. The stages in the respective cyclone evolutions are separated by approximately 6–24 h and the frontal symbols are conventional.

- By the end of the cyclone life, the cold front, moving faster than the warm front, "catches up" with the warm front, and an occluded front forms.
- In the Norwegian model, the cyclone remains "cold core" during the final occlusion
- In Shapiro-Keyser case, there is no occlusion during the mature stage, but instead warm seclusion and a typical T-bone pattern

Atmosphere vs lab: Fronts and Thermal wind

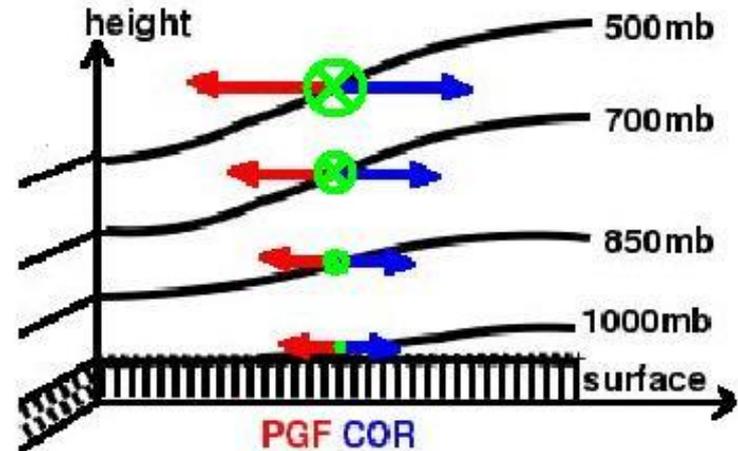A tank experiment to illustrate the Polar Front and the Jet Stream
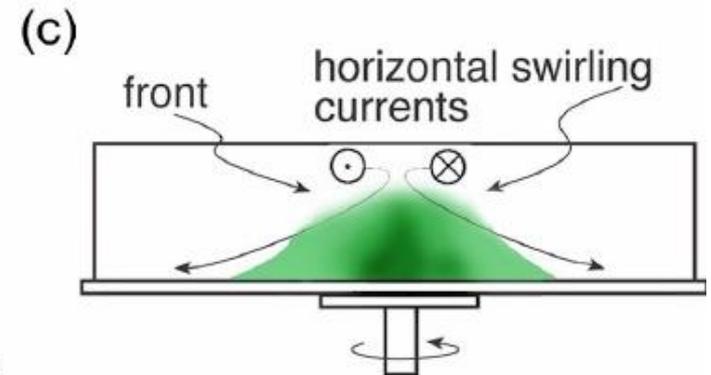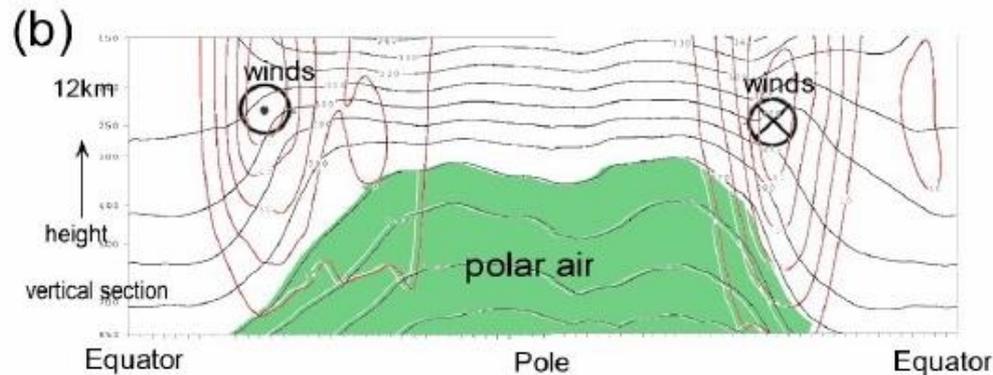
Atmosphere: *fronts due to temperature difference*
Lab: *front due to a density difference*

Thermal wind balance can be written in terms of density gradient as well
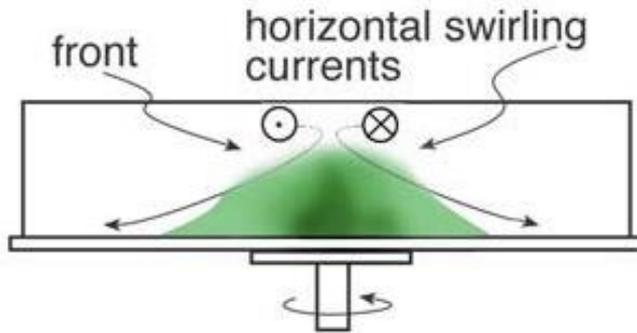
Fronts and Thermal wind

Cold   Warm
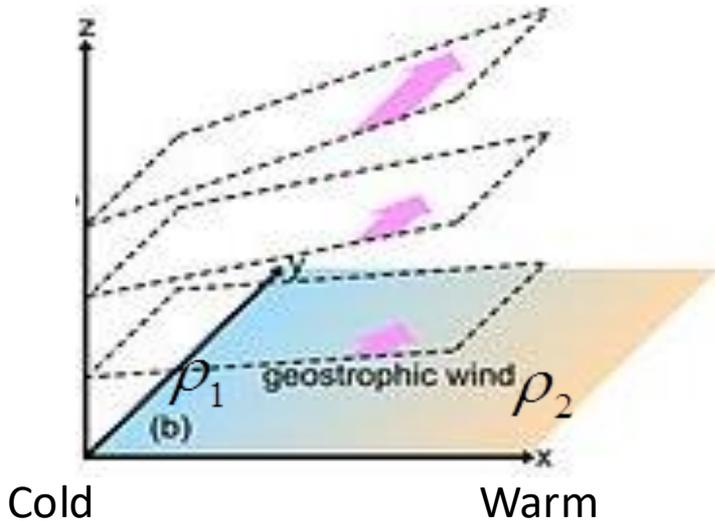
$$\frac{du}{dz} = \frac{g}{\rho_o f}\frac{d\rho}{dy}$$

$$\frac{\partial u}{\partial p} = \frac{R}{fp}\left(\frac{\partial T}{\partial y}\right)_p$$

Vertical wind shear is proportional to the
horizontal density (or temperature) gradient

The Margules relation- lab

front

horizontal swirling currents

The Margules equation:

$$\tan \gamma = \frac{f(u_2 - u_1)}{g\left(\dfrac{\rho_1 - \rho_2}{\rho_1}\right)}$$

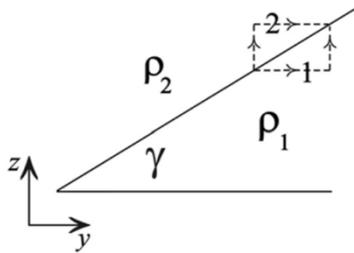Where ρ_1 is the denser fluid ($\rho_1 > \rho_2$) and $u_2 > u_1$

Figure 7.17: Geometry of the front separating fluid of differing densities used in the derivation of Margules relation, Eq.(7.21).

For rotation rates of ~ 10 rpm, a relative density of $\sim 2\%$, and a swirl speed of about $6\frac{cm}{sec}$, the Margules equation predicts $\gamma \sim 30°$

The Margules relation- polar front

Polar front

Figure 5: Schematic vertical north–south cross section in the Northern Hemisphere through the polar front, denoted by the heavy lines. Note that north is to the left in this schematic, whereas it is to the right in previous figures. Dotted isotachs marked every 10 ms−1 (from 10 to 80 ms−1) show the jet in thermal wind balance with the temperature field. Dashed lines are isotherms marked every 10°C (from 10 to −70°C). (from E. Palmén and C. W. Newton, Atmospheric Circulation Systems, Academic Press, New York, 1969)

The Margules equation:

$$\tan \gamma = \frac{f(u_2 - u_1)}{g\left(\dfrac{\theta_2 - \theta_1}{\bar{\theta}}\right)}$$

A similar slope can be calculated for the atmospheric front!

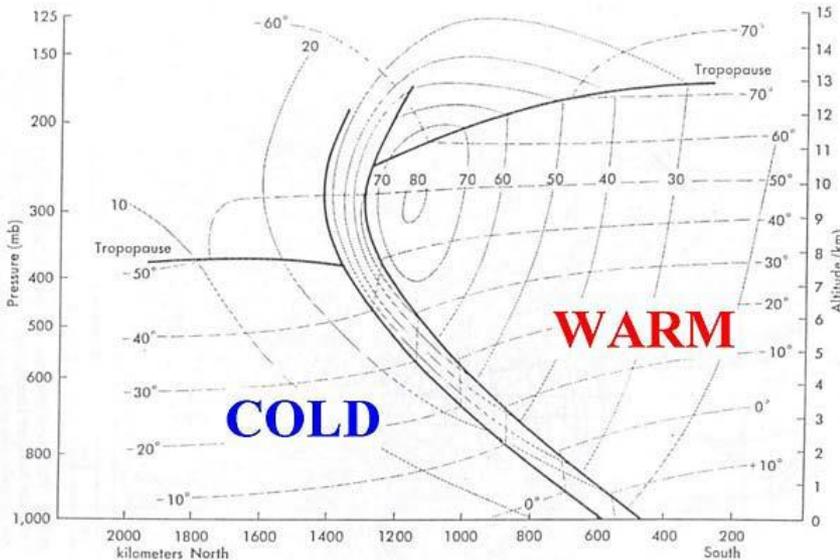# The Margules relation- polar front
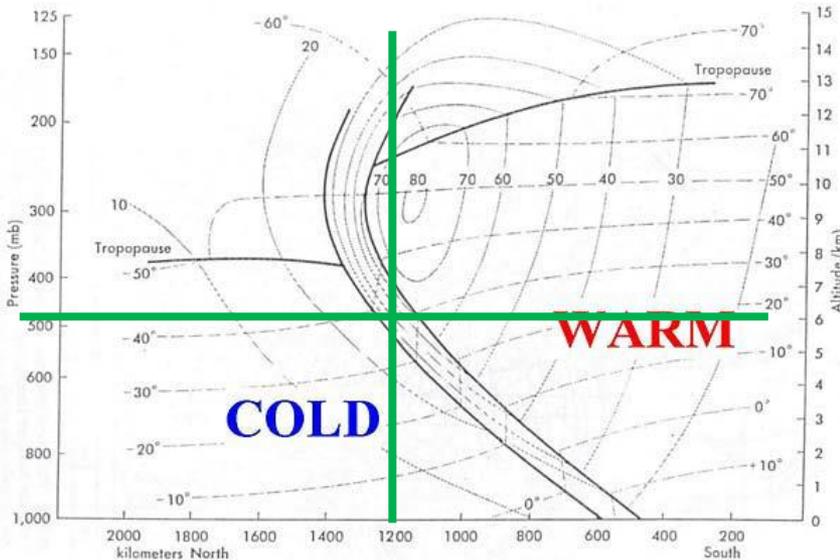
Polar front

Figure 5: Schematic vertical north–south cross section in the Northern Hemisphere through the polar front, denoted by the heavy lines. Note that north is to the left in this schematic, whereas it is to the right in previous figures. Dotted isotachs marked every 10 ms−1 (from 10 to 80 ms−1) show the jet in thermal wind balance with the temperature field. Dashed lines are isotherms marked every 10°C (from 10 to −70°C). (from E. Palmén and C. W. Newton, Atmospheric Circulation Systems, Academic Press, New York, 1969)

The Margules equation:

$$\tan \gamma = \frac{f(u_2 - u_1)}{g\left(\dfrac{\theta_2 - \theta_1}{\bar{\theta}}\right)}$$

What are typical values of this angle?

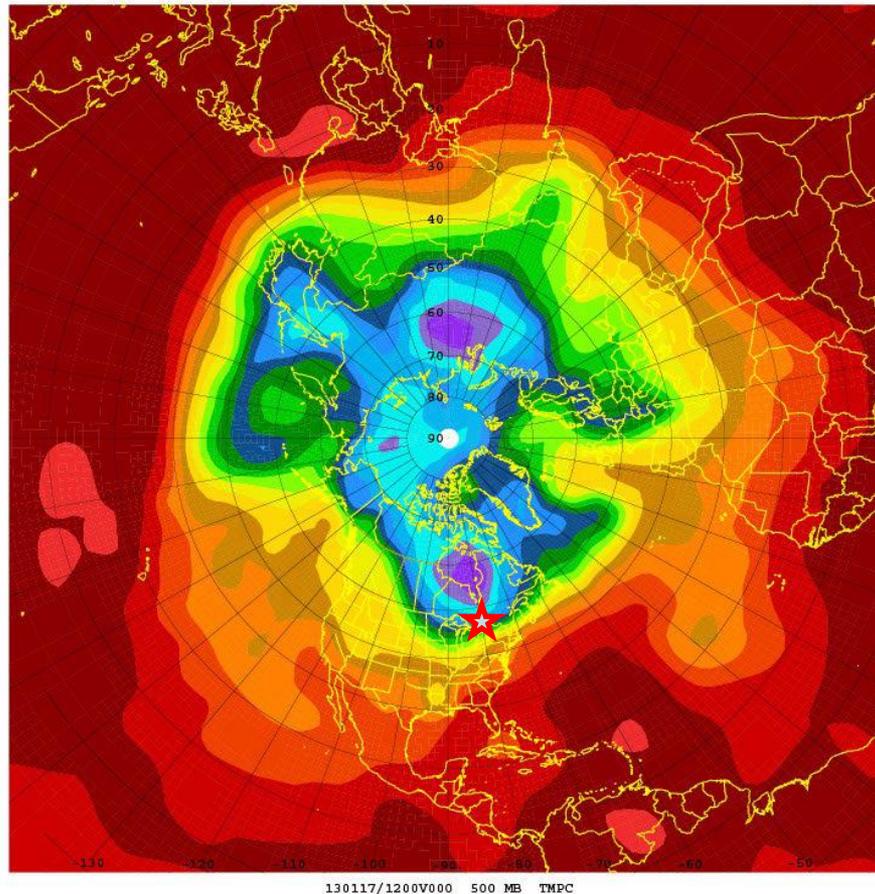*Horizontal length scales in the atmosphere are much larger than the vertical!*

$$Z_{500} \approx 5.5 \text{ km}$$

$$\Delta y \approx 700 \text{ km}$$

$$\tan \gamma \approx \frac{5.5}{700} \rightarrow \gamma \approx 0.45°$$

The Margules relation- polar front

Let's examine a case study of a front that occurred on Jan 17th 2013, and make an analogy to the Front experiment we performed in class:

130117/1200V000 500 MB TMPC

Jan 17th 2013
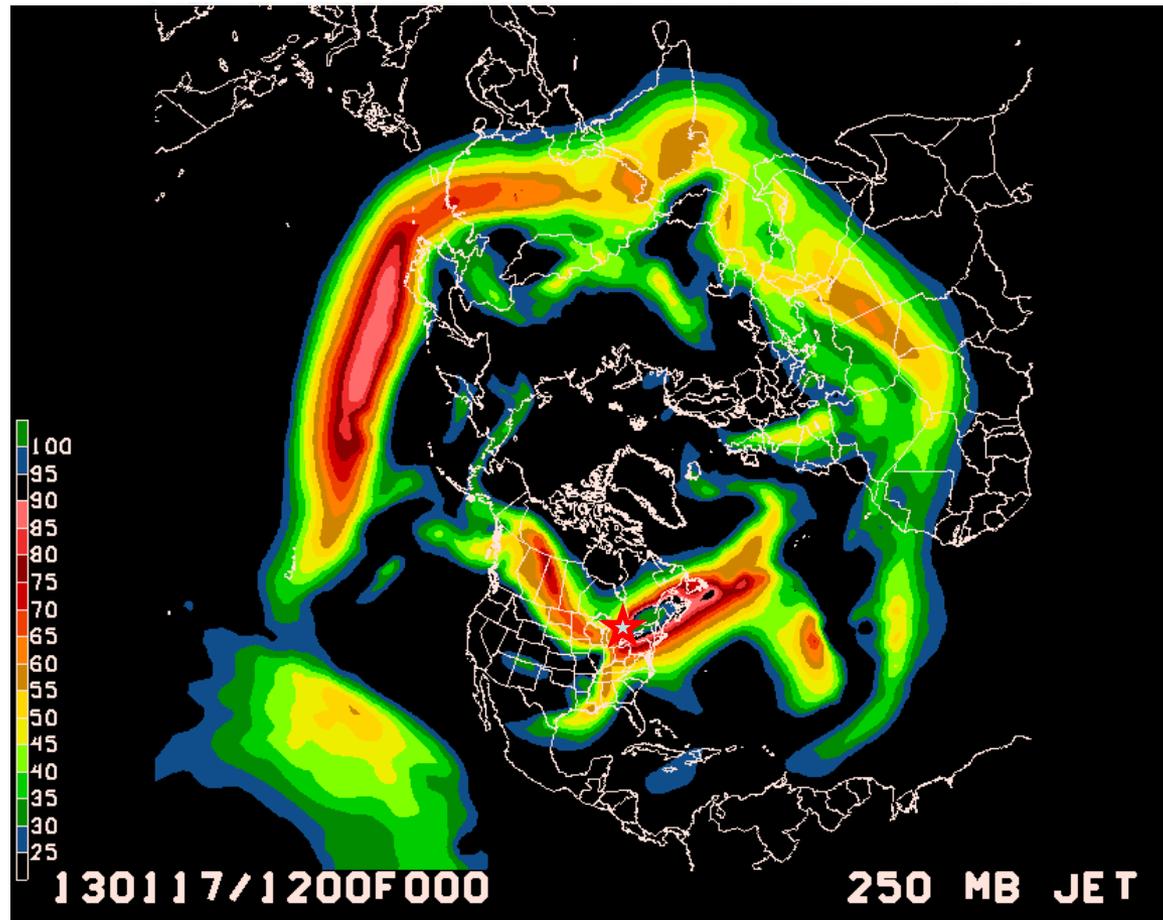
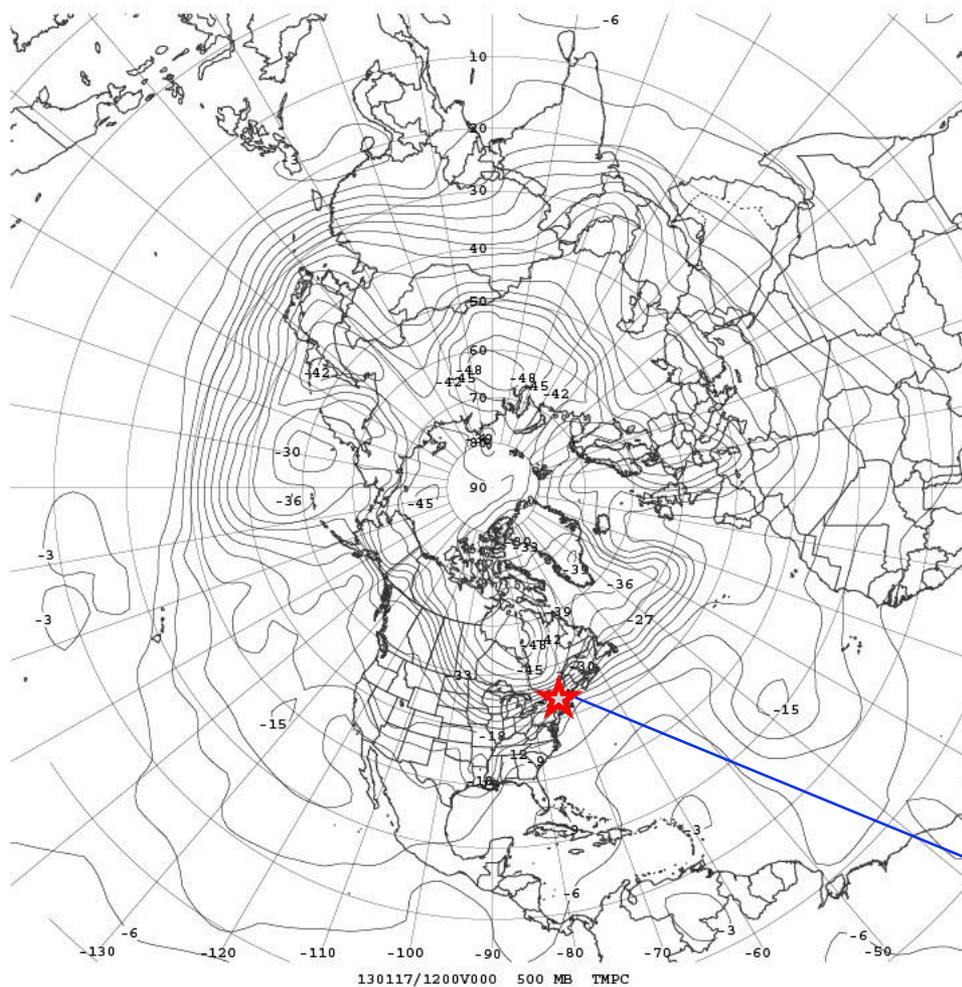# The Margules relation- polar front

Let's examine a case study of a front that occurred on Jan $17th$ 2013, and make an analogy to the Front experiment we performed in class:

Jan 17th 2013

Temperature contours

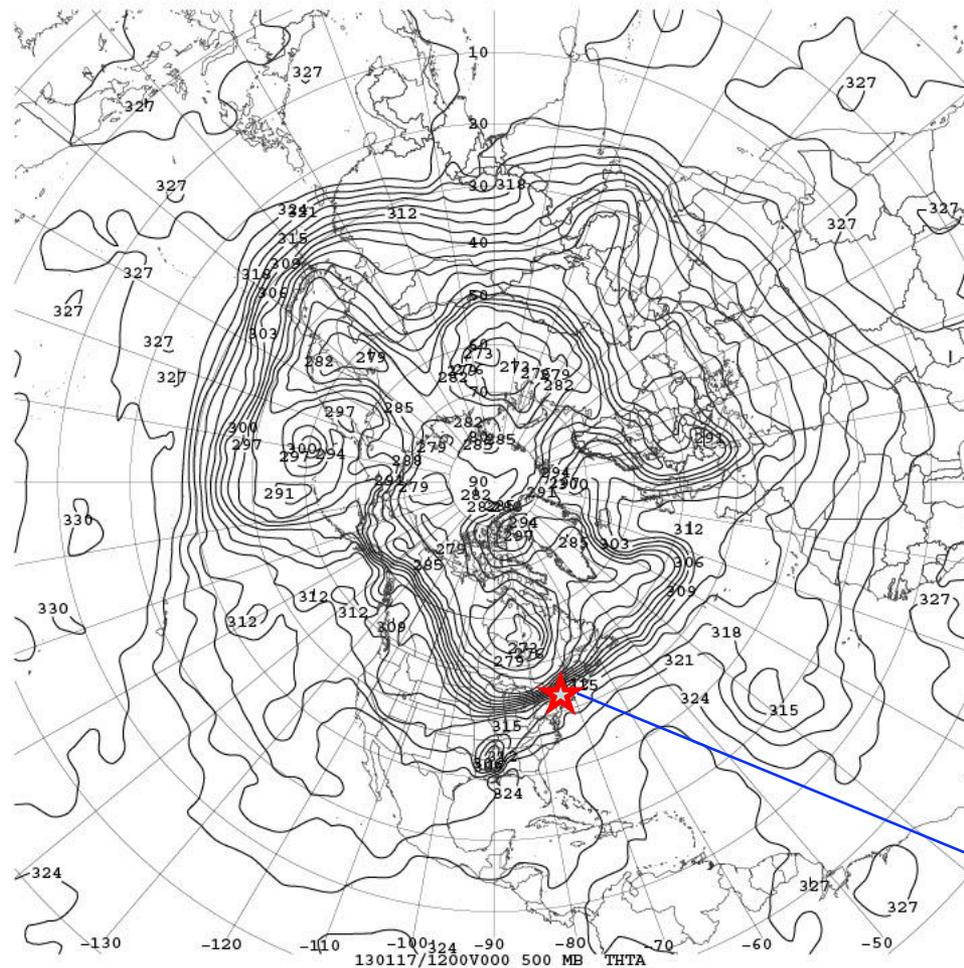*Temperature (C) at 500 mb over the northern hemisphere on the 17th of January, 2013 12Z*

Jan 17th 2013

A front!

Sharp temperature change

Potential temperature contours

Potential temperature (C) at 500 mb over the northern hemisphere on the 17th of January, 2013 12Z
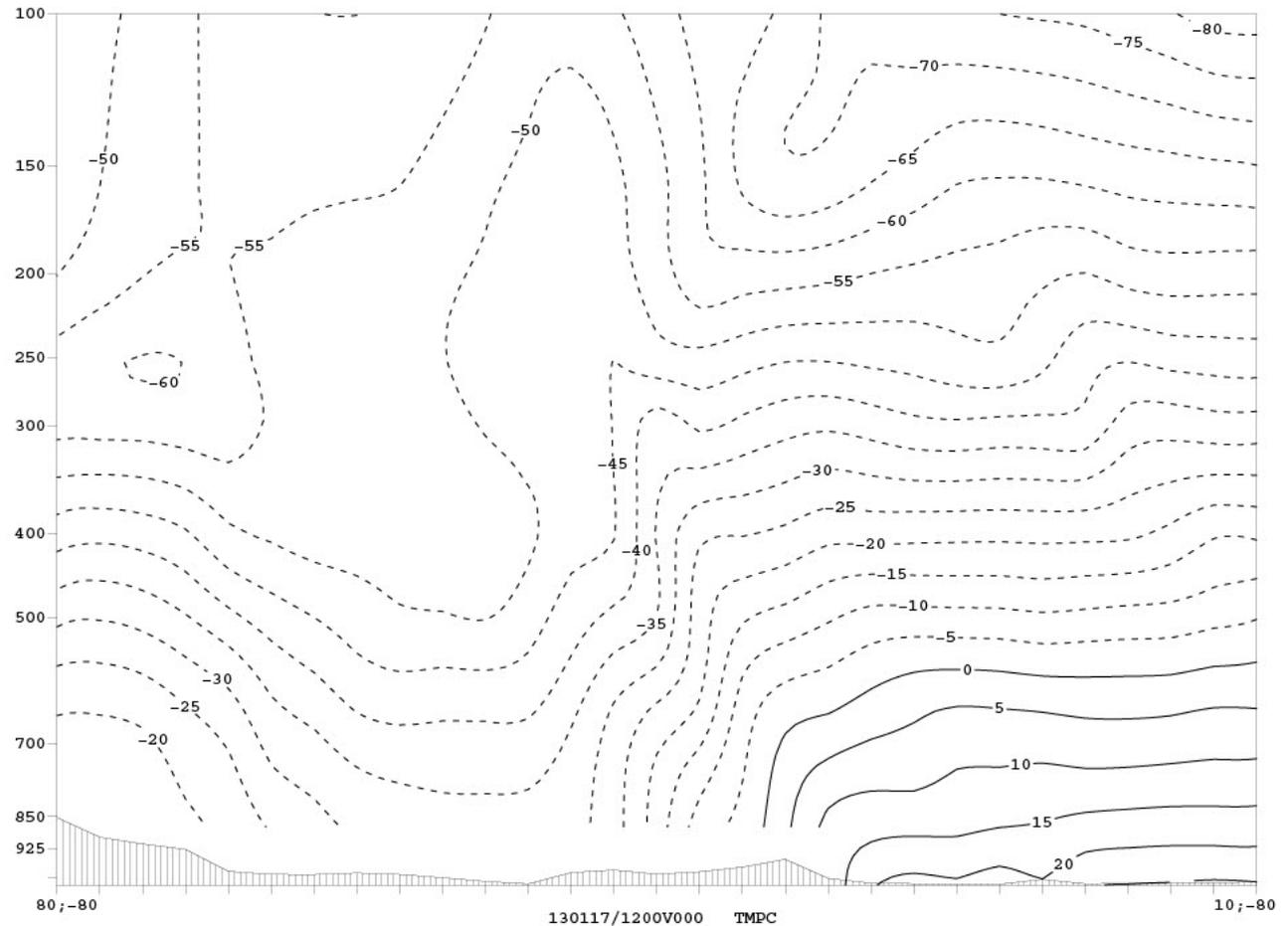

Jan 17th 2013

A front!

Even clearer in potential temperature field

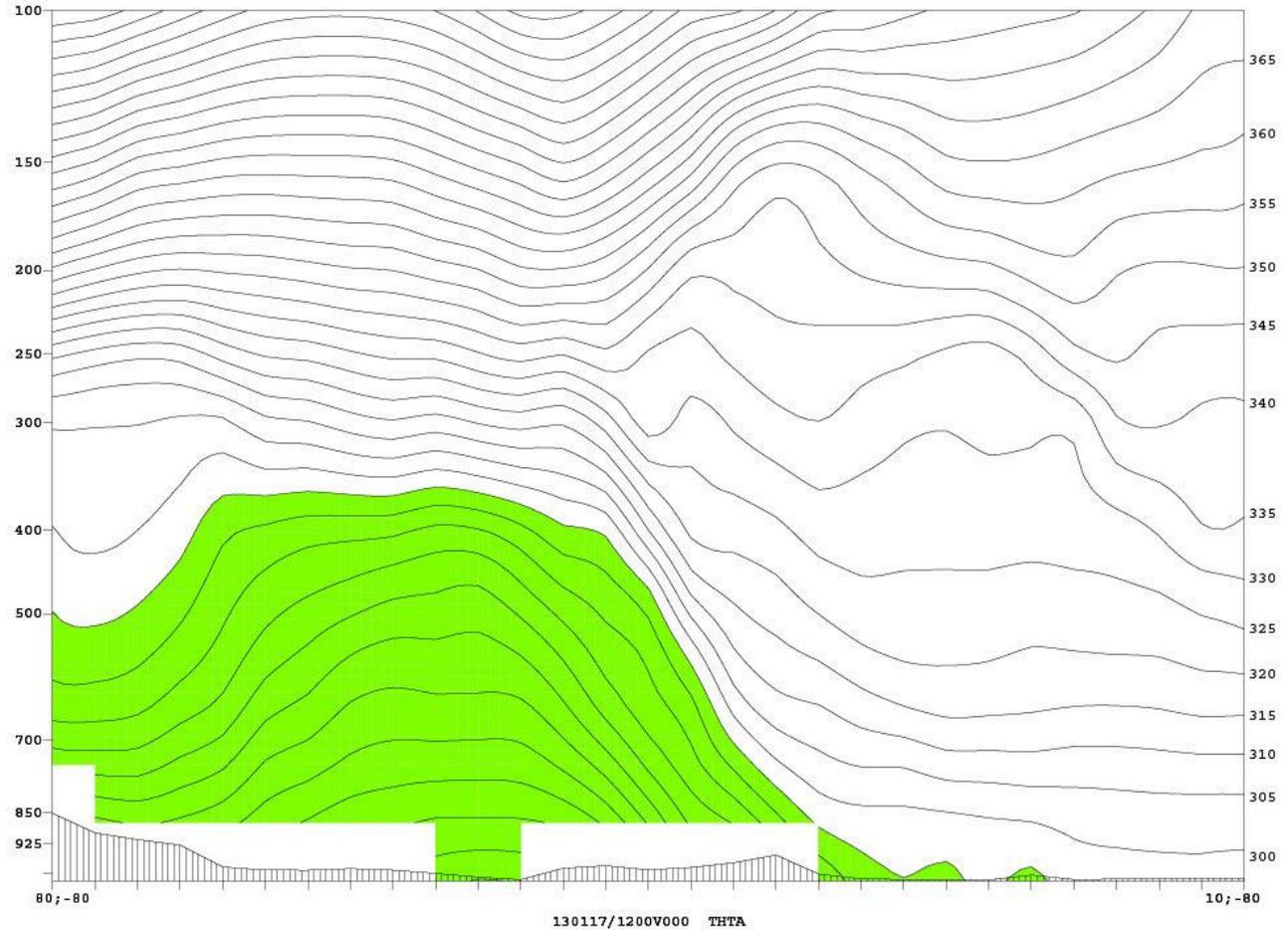# Temperature- vertical cross section

A north-south vertical section of temperature along the 80W longitude

Jan 17th 2013

Potential temperature- vertical cross section

A north-south vertical section of *potential temperature* along the 80W longitude

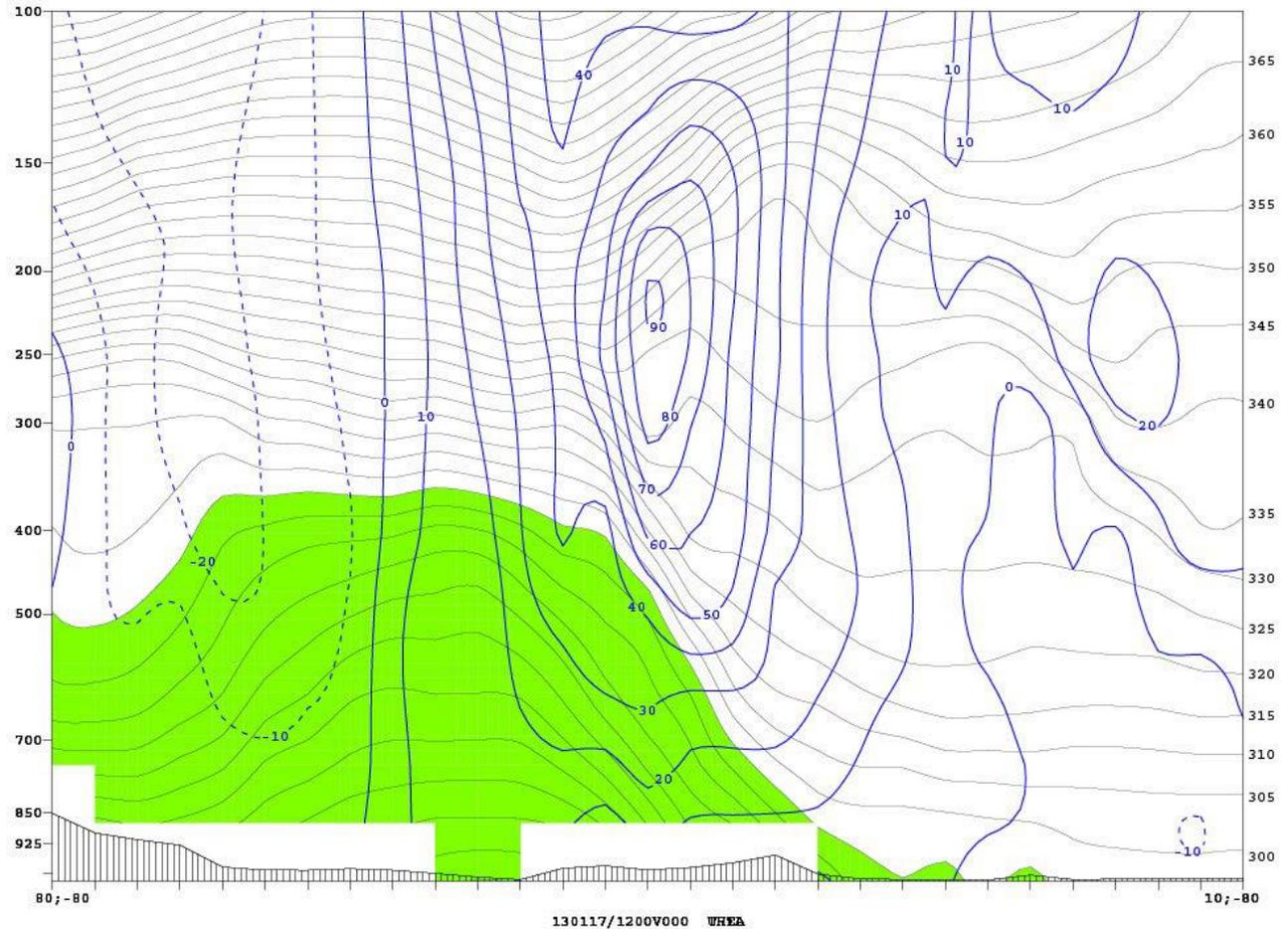*The frontal zone between the cold and warm air has been marked by shading in green air with temperature below 295 K*

Jan 17th 2013

Potential temperature & U- vertical cross section

A north-south vertical section of potential temperature along the 80W longitude

Jan 17th 2013

The frontal zone between the cold and warm air has been marked by shading in green air with temperature below 295 K

Margules relation for a real front-

What is the sloping of the front on Jan 17*th* 2013?

The Margules equation:

$$\tan \gamma = \frac{f(u_2 - u_1)}{g\left(\frac{\theta_2 - \theta_1}{\bar{\theta}}\right)}$$

Often easier to identify the front and the cold dome in terms of *potential temperature*

What is the angle of the front? Calculate using Margules equation and verify from the figure using the estimated distances!
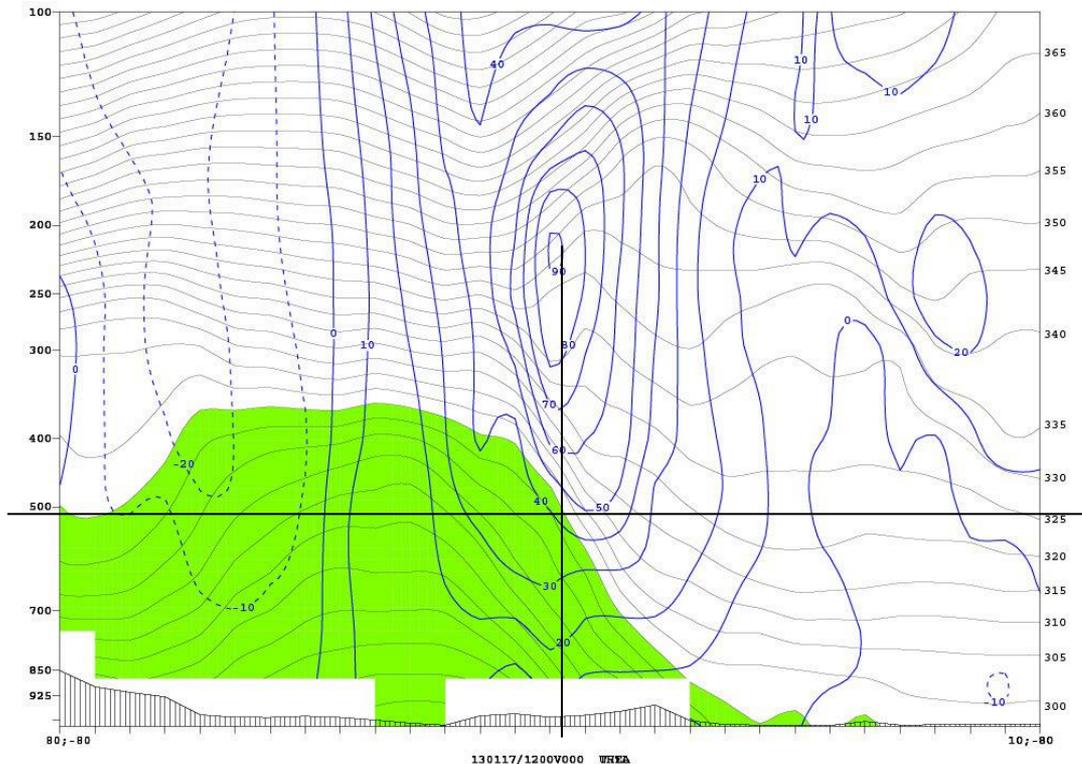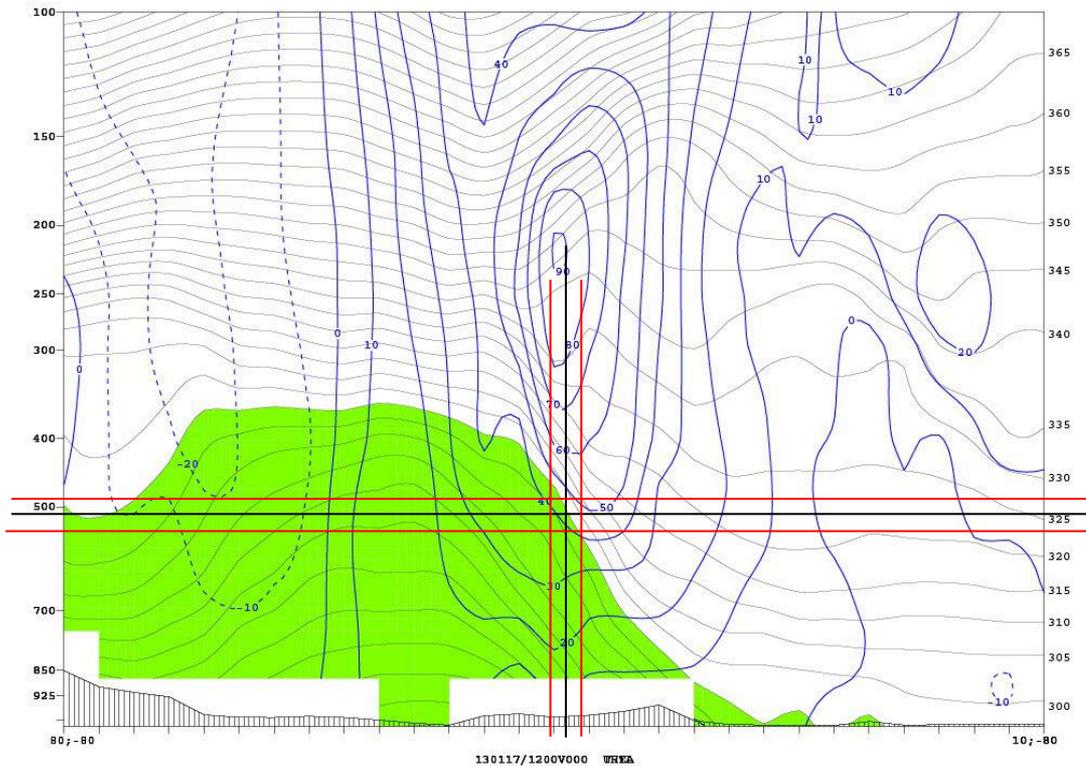
Margules relation for a real front-

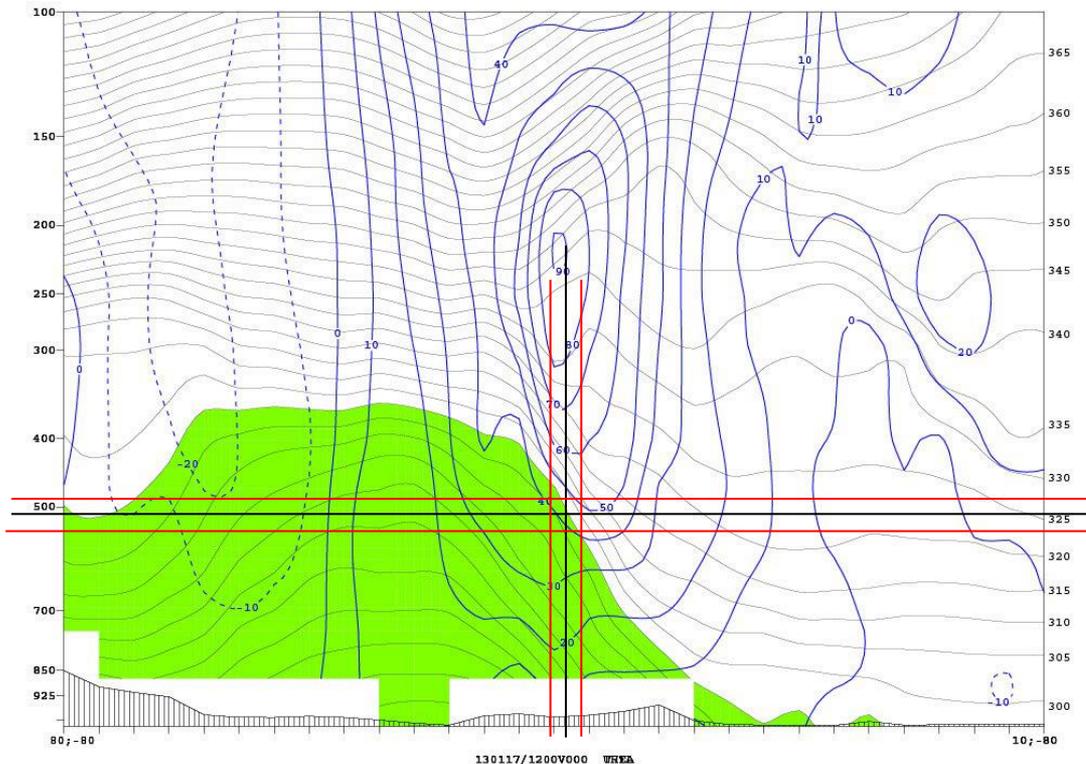What is the sloping of the front on Jan 17*th* 2013?

The Margules equation:

$$\tan \gamma = \frac{f(u_2 - u_1)}{g\left(\dfrac{\theta_2 - \theta_1}{\bar{\theta}}\right)}$$

Margules relation for a real front-

What is the sloping of the front on Jan 17*th* 2013?

The Margules equation:

$$\tan \gamma = \frac{f(u_2 - u_1)}{g\left(\dfrac{\theta_2 - \theta_1}{\bar{\bar{\theta}}}\right)}$$

$$\Delta u = u_2 - u_1 \approx 8 \, ms^{-1}$$

$$\theta_2 - \theta_1 \approx 300K - 290K = 10K$$
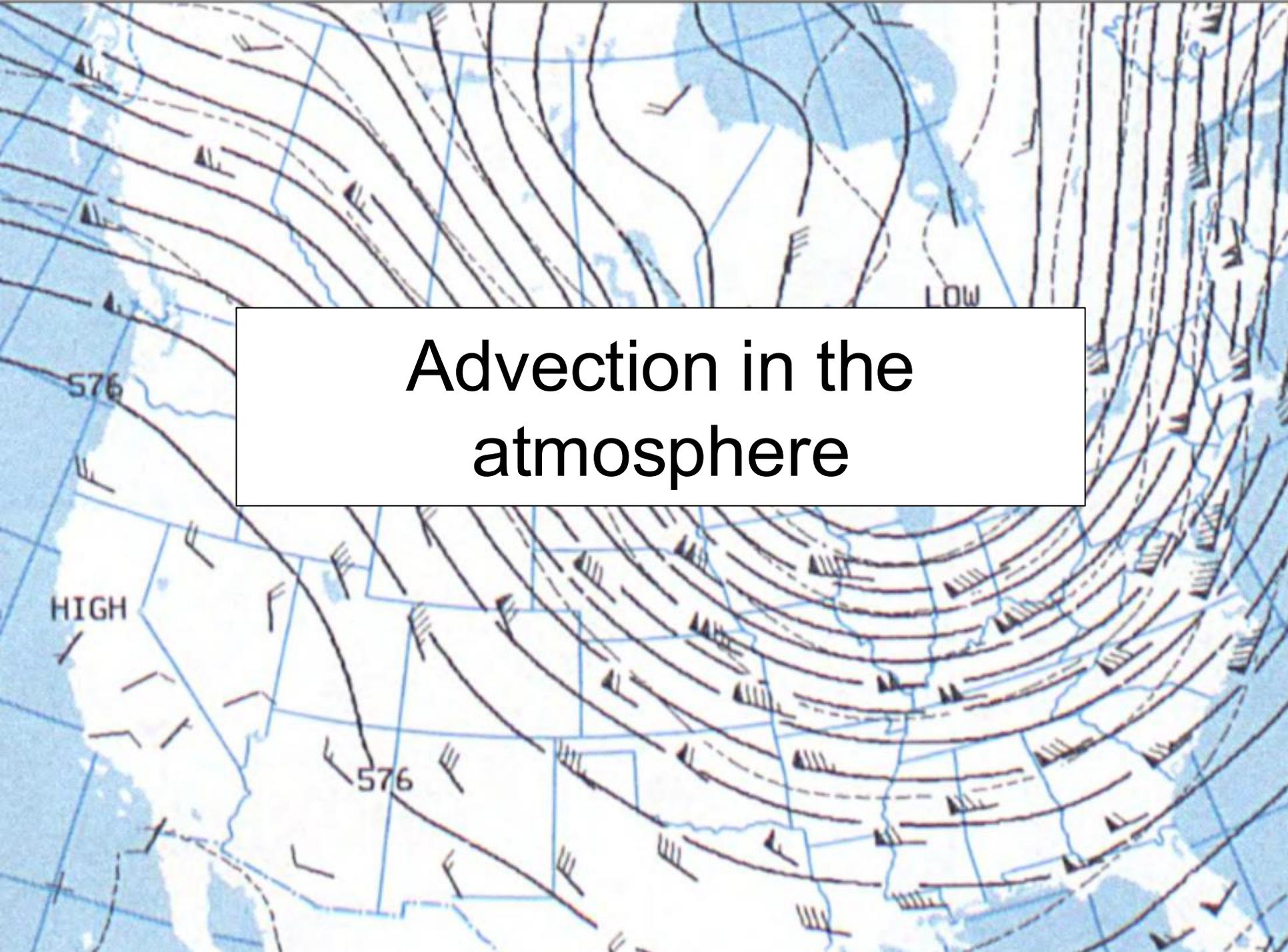
$$\theta \approx 295K$$

$$\tan \gamma \approx \frac{10^{-4} \cdot 8}{9.8 \left(\dfrac{10}{295}\right)} \rightarrow \gamma \approx 0.14°$$

$$Z_{500} \approx 5.5 \text{ km}$$

$$\Delta y \approx 15° \approx 15 * 110 \text{ km}$$

$$\tan \gamma \approx \frac{5.5}{1650} \rightarrow \gamma \approx 0.19°$$

Advection in the atmosphere

Tracer transport in the atmosphere

In the atmosphere:

- Aerosols
- Water vapor
- Temperature
- Dust, volcanic eruptions (ash)
- Checmical tracers: carbon (wildfires), ozone…
- Radioactive plumes (e.g., Fukushima)
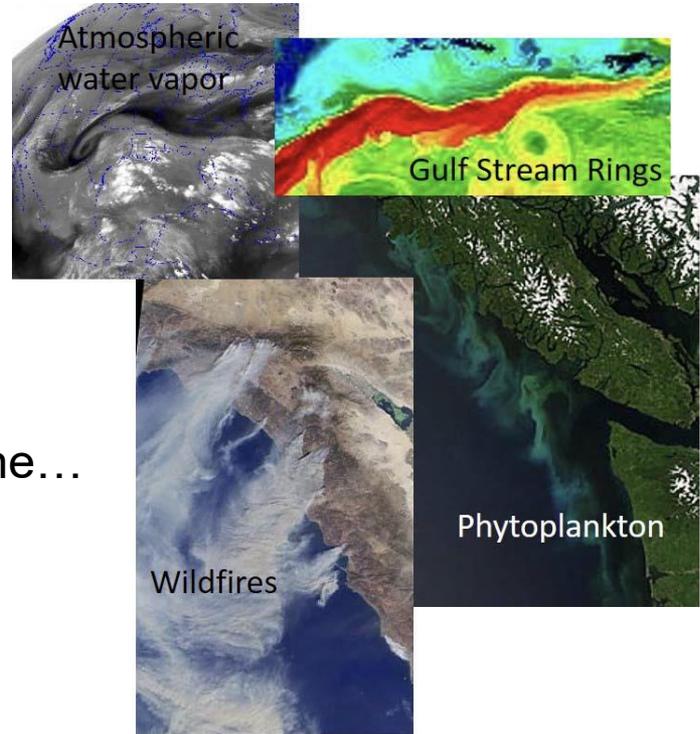
In the ocean:

- Biological substances (e.g., Phytoplankton)
- Marine pollution- plastics in the ocean
- Oil Spill
- …

- Tracers are transported by winds and currents in the atmosphere & Ocean
- Their dispersal depends on the motion and Earth's rotation

Temperature advection

Temperature
at 850 mb, ~1.5 km

Color scale:
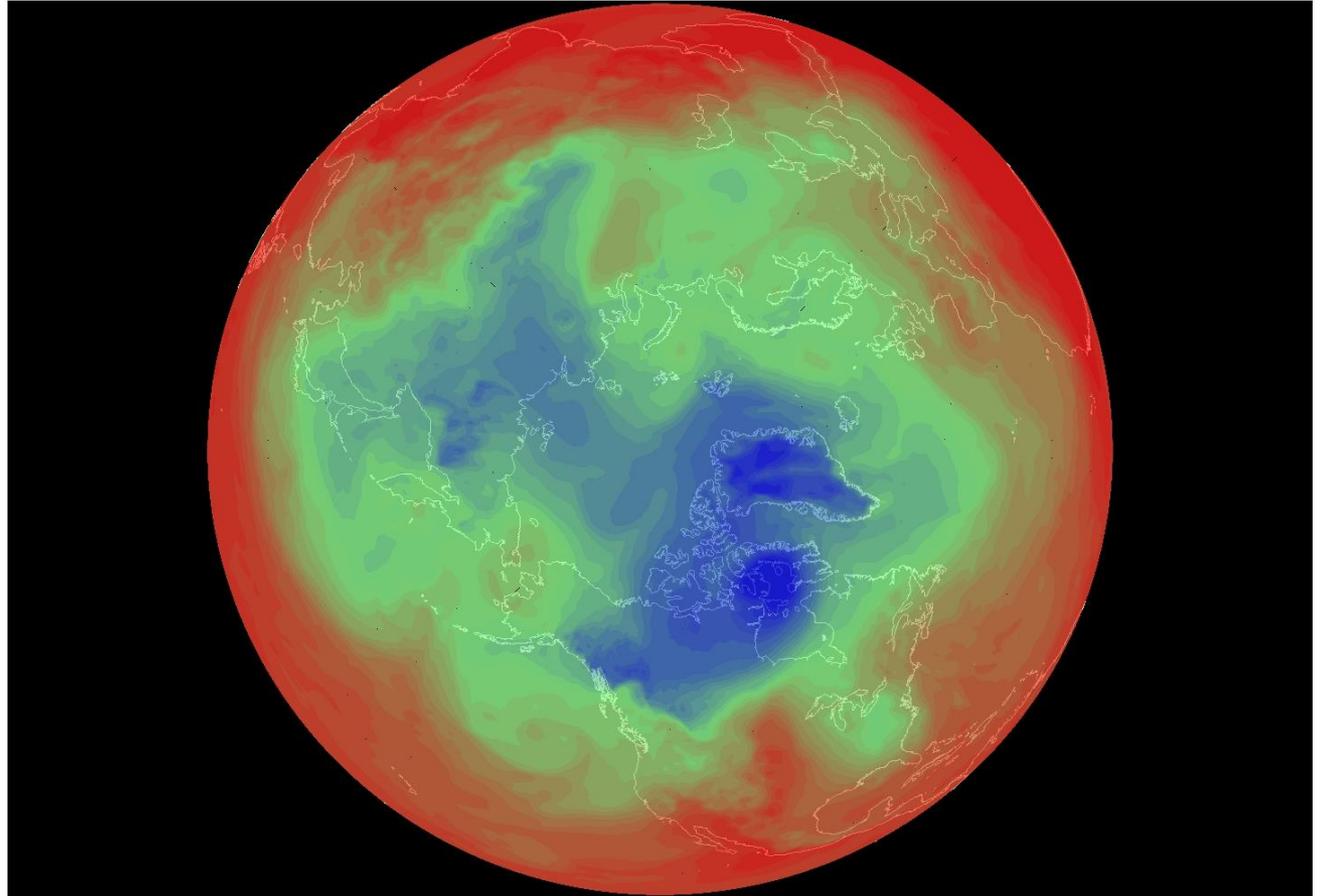red =hot
blue=cold

Water vapor

Total precipitable water (white)
and
rainfall (colors 0-15 mm/hr;
red=highest).

NASA Goddard Earth Observing System
Model (GEOS-5) – 10 km global simulation
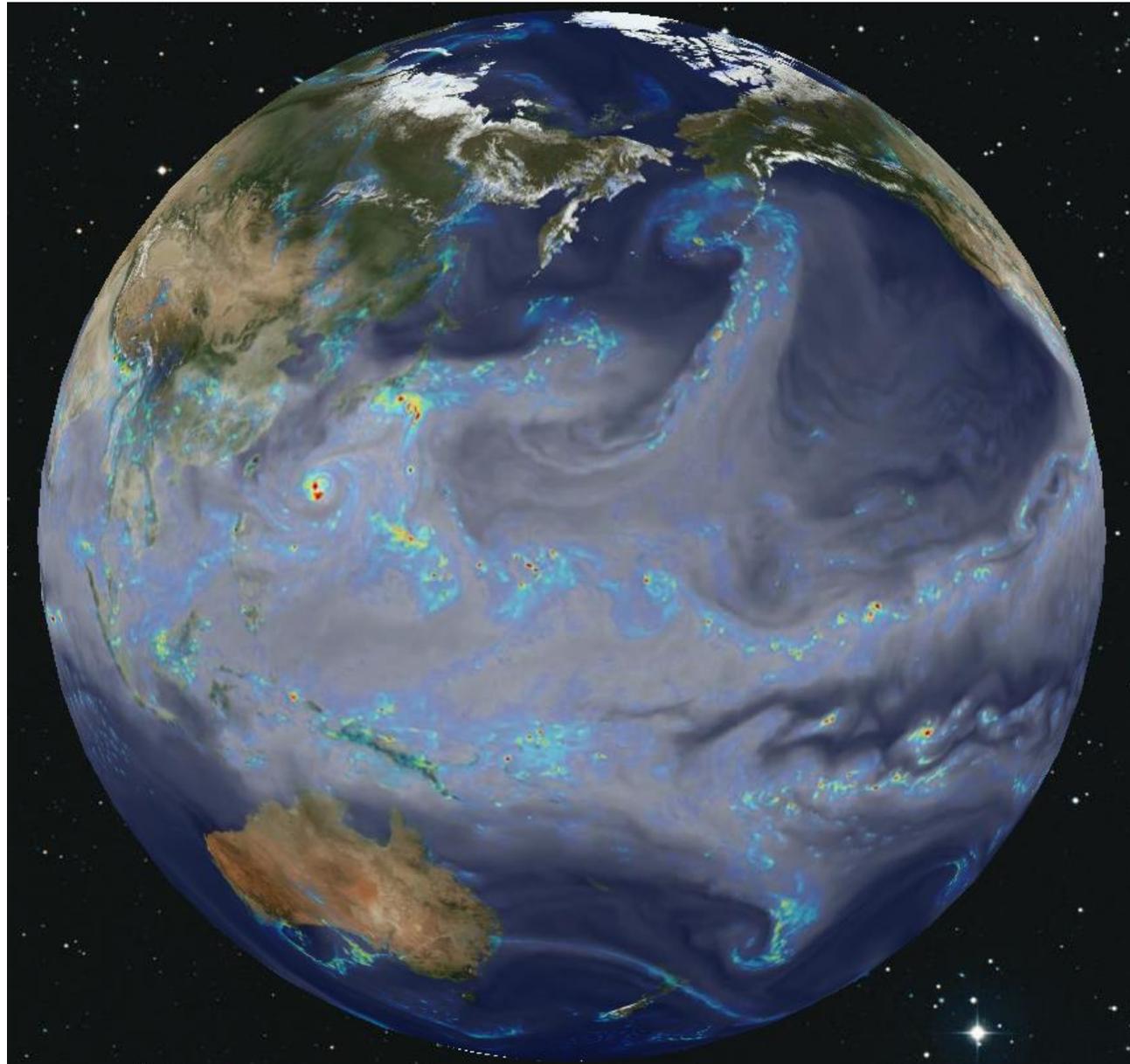
Movie is available on the EsGlobe under
"GEOS-5 Water Vapor"

Aerosols

The colors show four different aerosols:
- grey=sulfate
- green=organic and black carbon
- blue=sea-salt
- red=dust

The simulation uses GEOS-5 and the Goddard Chemistry Aerosol Radiation and Transport (GOCART) Model.
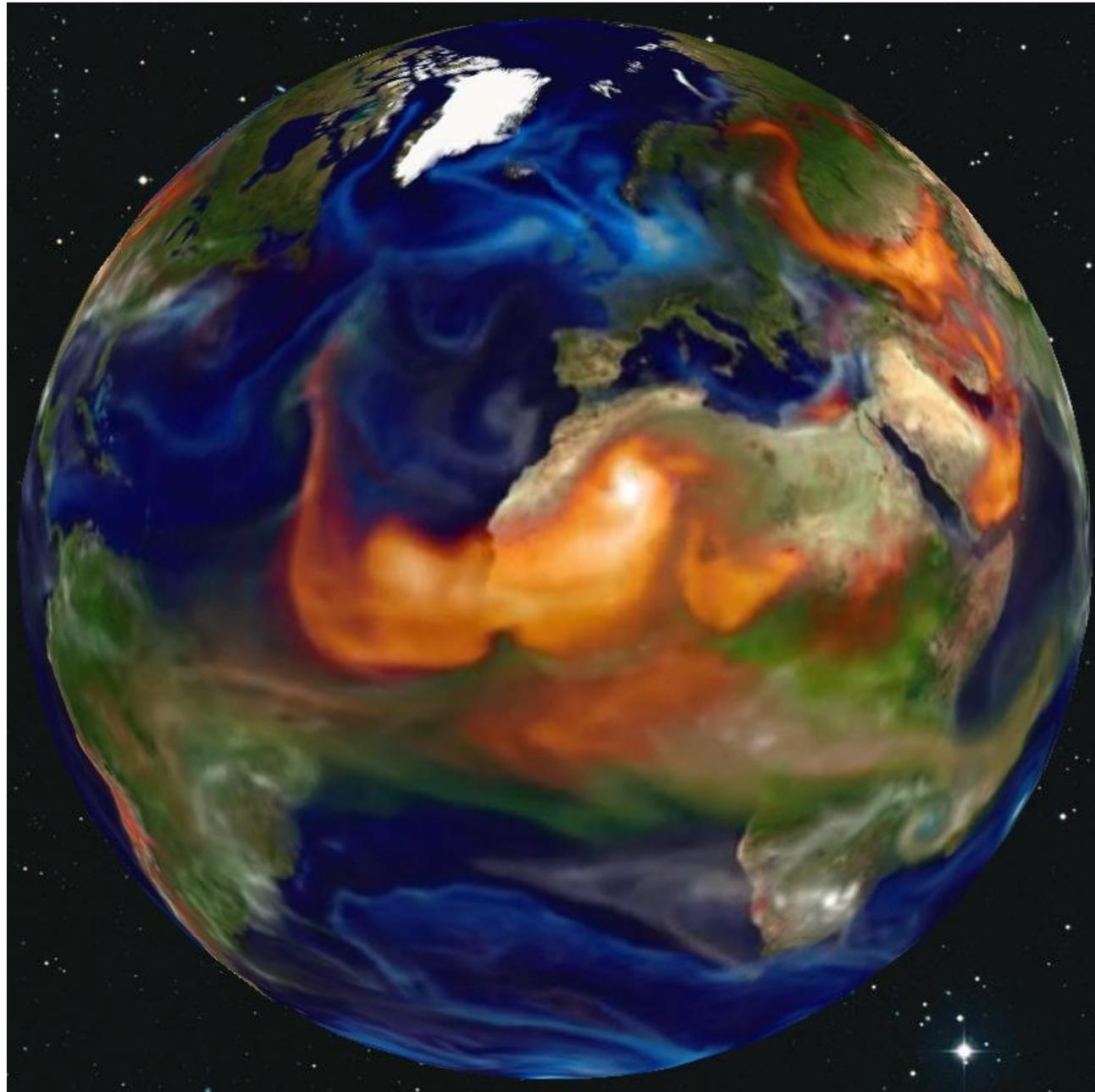
Movie is available on the EsGlobe under "Atmospheric aerosols"

Fukushima radioactive aerosols

March 11, 2011

Cesium-137 emitted from Fukushima

Each change in particle color
represents a decrease in radioactivity
by a factor of 10.

Lagrangian vs. Eulerian derivative

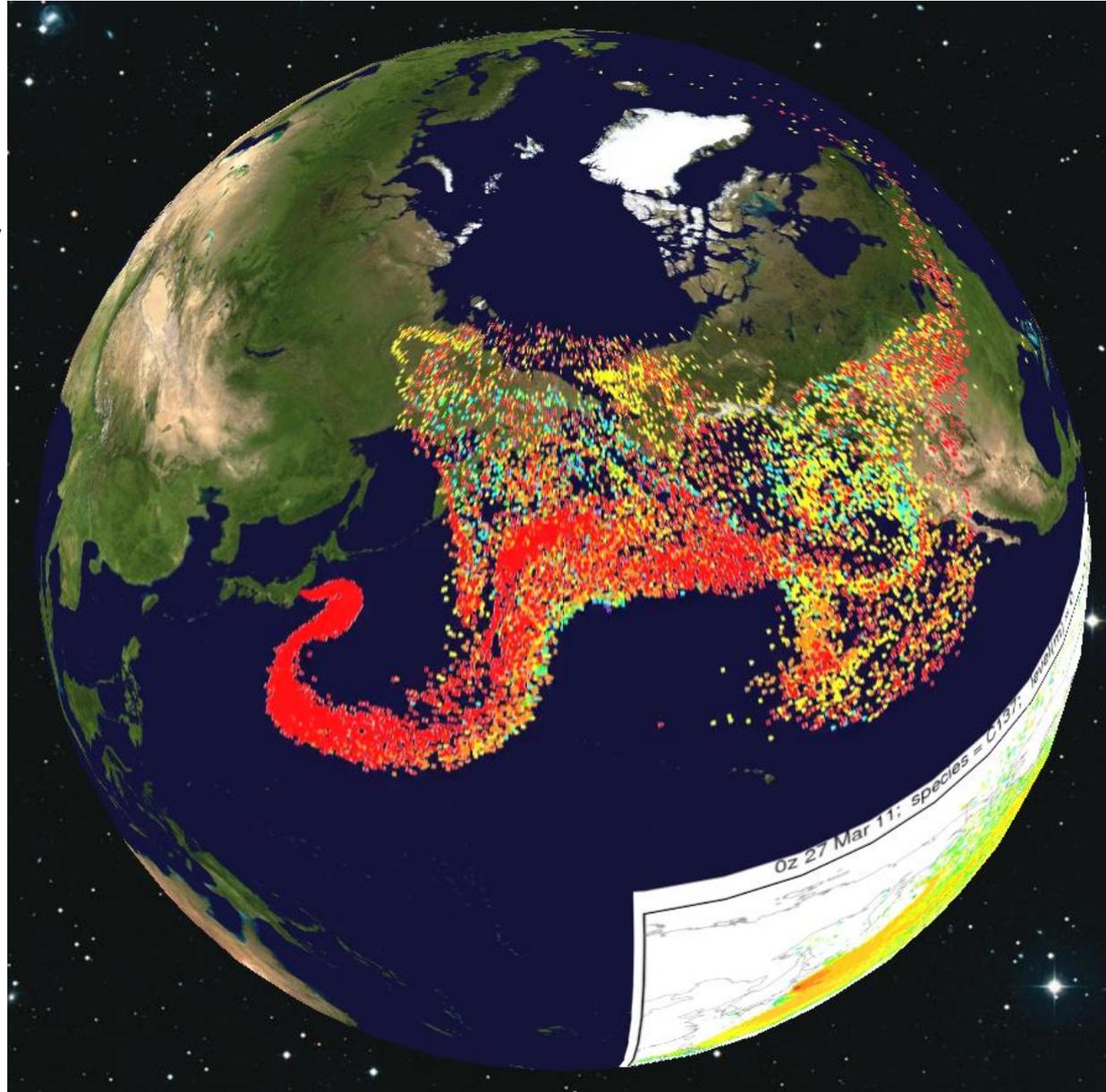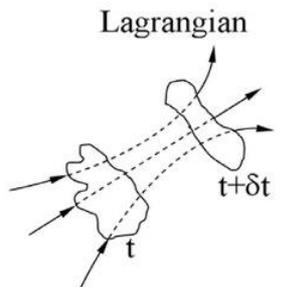$$\left(\frac{\partial C}{\partial t}\right)_{\substack{\text{fixed} \\ \text{particle}}} = \underbrace{\frac{\partial C}{\partial t}}_{\text{fixed point}} + \underbrace{u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z}}_{\text{advection}} = \frac{DC}{Dt}$$

Where
$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z} \equiv \frac{\partial}{\partial t} + \mathbf{u}.\nabla$$

$$\nabla \equiv \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$$

Lagrangian

t+δt

t

Following the motion
of the fluid element
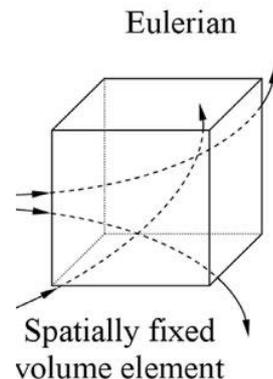
Eulerian

Spatially fixed
volume element

$$\boxed{\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{u}.\nabla}$$

Lagrangian   Eulerian   Advection

Eulerian derivative

- Mountains produce Lee waves
- Steady state: pattern of clouds
- Cloud amount=C does not change with time

$$C = C(x, y, z, t)$$

$$\left(\frac{\partial C}{\partial t}\right)_{\substack{\text{fixed point} \\ \text{in space}}} = 0$$

Lenticular clouds looking downwind of the continental divide
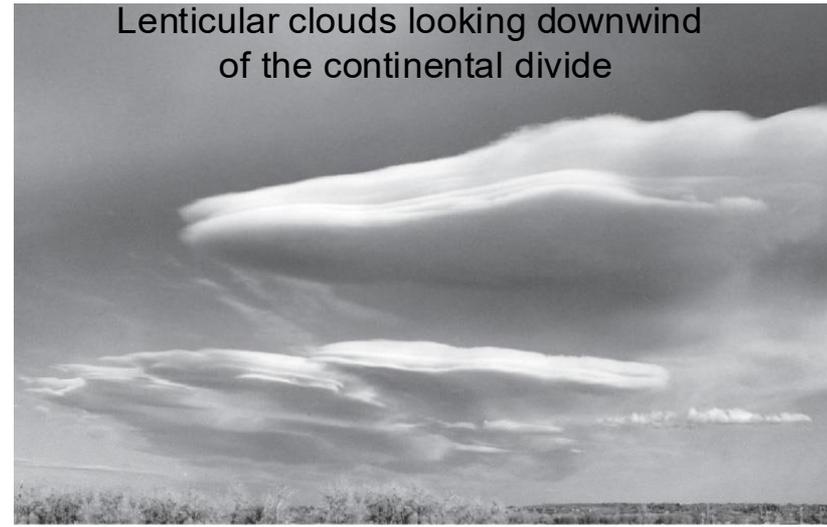
(Photo courtesy of Dale Durran, University of Washington.)

Eulerian

Spatially fixed volume element
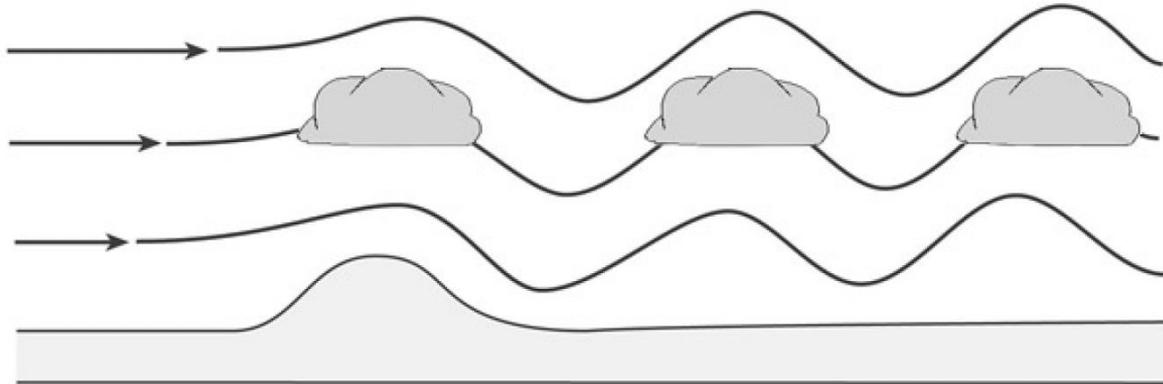
At any fixed location, cloud fraction does not change, even though the air is flowing through!
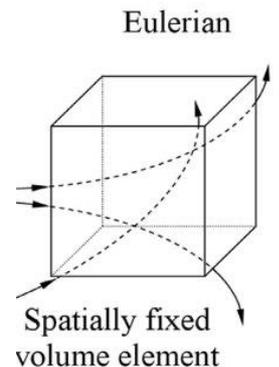
Lagrangian derivative

- However, C is not constant following a particular parcel $C = C(x, y, z, t)$

- As the parcel moves upward, it cools, water condenses out, cloud forms → C increases

- As the parcel moves downward, the water goes back into the gaseous phase, the cloud disappears → C decreases.

$$\left(\frac{\partial C}{\partial t}\right)_{\substack{\text{fixed} \\ \text{particle}}} \neq 0$$
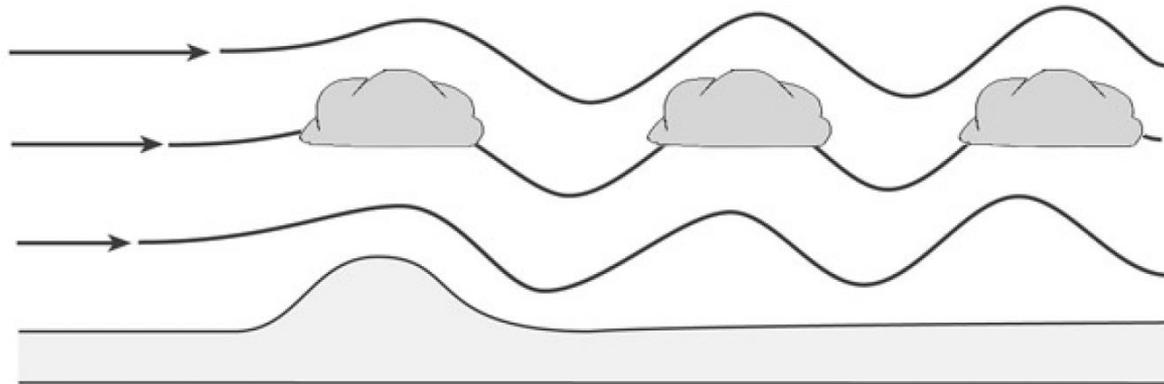
Lagrangian derivative

- For small deviations of $C = C(x, y, z, t)$, which is a function of position and time:

$$\delta C = \frac{\partial C}{\partial t}\delta t + \frac{\partial C}{\partial x}\delta x + \frac{\partial C}{\partial y}\delta y + \frac{\partial C}{\partial z}\delta z$$

$$(\delta C)_{\substack{\text{fixed} \\ \text{particle}}} = \left(\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z}\right)\delta t$$

Where we used: $\delta x = u\delta t, \ \delta y = v\delta t, \ \delta z = w\delta t.$

The variation of a property C following an element of fluid!

Lagrangian

t+δt

t
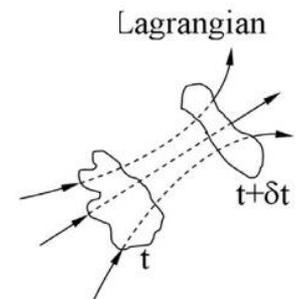
Following the motion of the fluid element

Lagrangian vs. Eulerian derivative

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{u}.\nabla$$

Lagrangian   Eulerian   Advection

Where

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z} \equiv \frac{\partial}{\partial t} + \mathbf{u}.\nabla$$
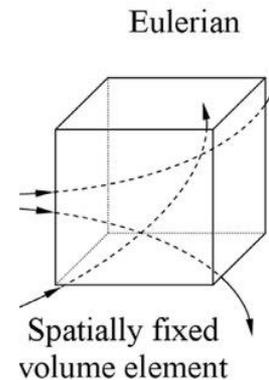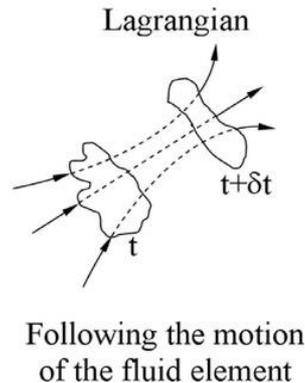
$$\nabla \equiv \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right)$$

Lagrangian

t+δt

t

Following the motion
of the fluid element

Eulerian

Spatially fixed
volume element

Examples:

1) Velocity and position of a fluid parcel-

$$u = \frac{D}{Dt}x; \quad v = \frac{D}{Dt}y$$

$$x = \int u\,dt; \quad y = \int v\,dt$$

Where u is the speed in the x direction and v is the speed in the y direction

The positions of a fluid particle can be determined Lagrangianly from the winds!

Saharan Dust - June/July 2018

Dust Column Mass Density (g/m²)

0.0   1.0   2.0
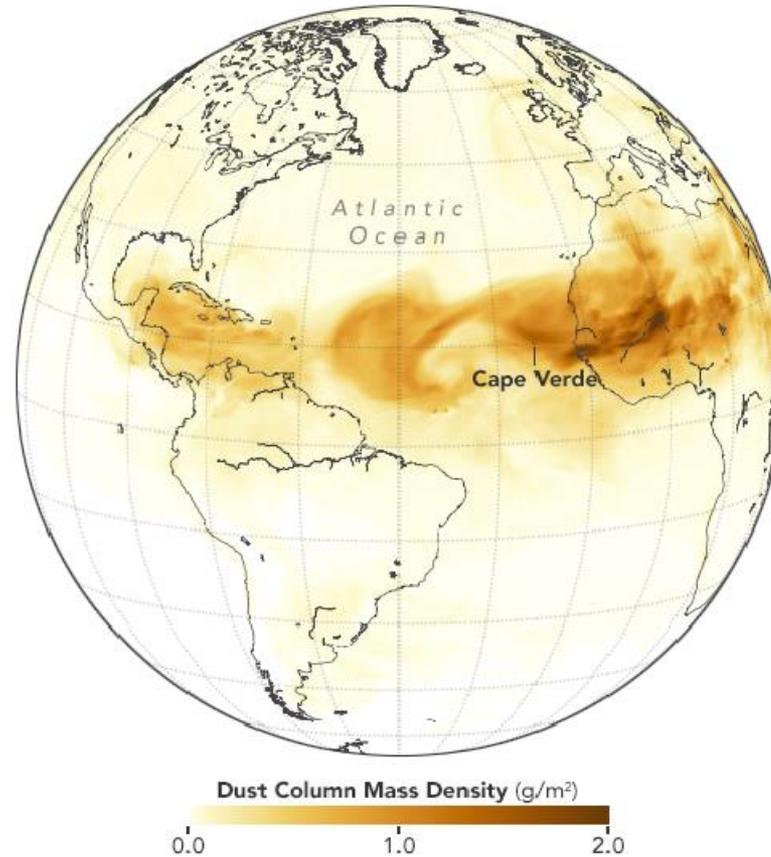
On June 18, satellites began to detect thick plumes of Saharan dust passing towards the Atlantic Ocean. This brought the tropical Atlantic one of its dustiest weeks in 15 years.

NASA-EO

Saharan Dust - June/July 2018

Animated Suomi NPP satellite image taken of the tropical Atlantic Ocean from July 6 through July 12, 2018 using the VIIRS instrument. During the period, Saharan dust (yellow-orange in color in the images) is blown thousands of miles from West Africa all the way across the Atlantic Ocean. The dust reduced visibility and air quality, and has helped suppress tropical cyclone activity. NOAA Climate.gov image using data provided by the NOAA Visualization Laboratory.

Wacth also https://youtu.be/ygulQJoIe2Y

How can dust from the Sahara reach the US?
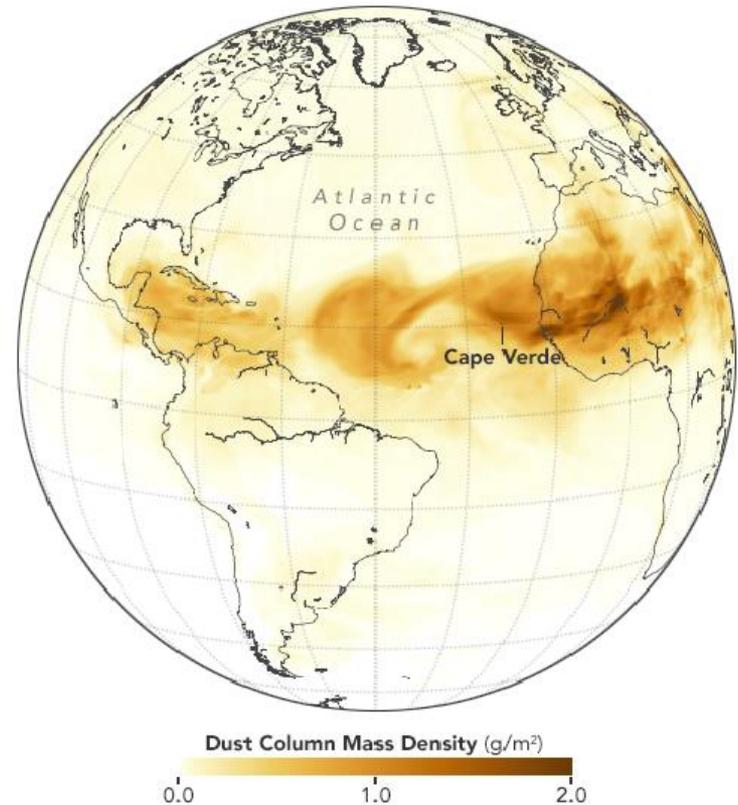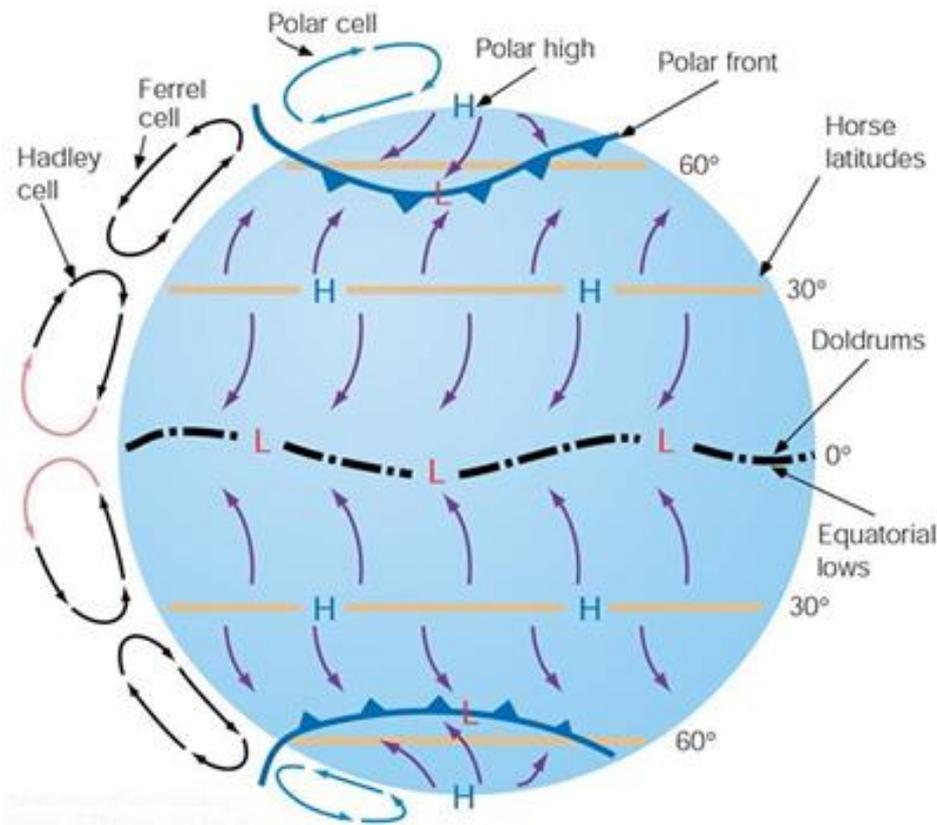
Coriolis force diverts the flow such that at the surface, we find **easterlies** (winds from the east) in the subtropics (also known as the **trade winds**)
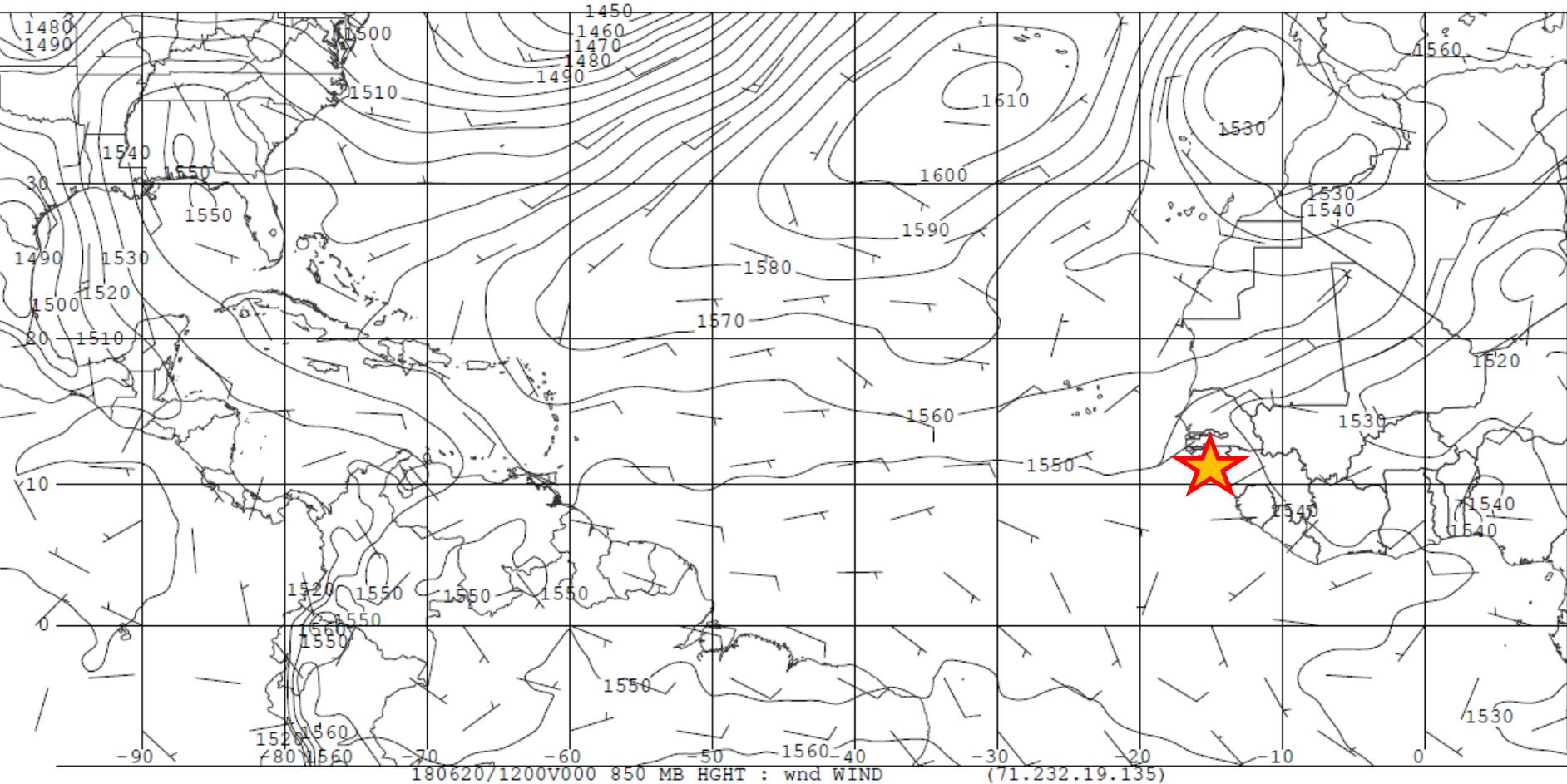
Case study: June 20 - 21, 2018

- Build by hand trajectories using 850 mb wind (GFS analyses)

- Verify your calculation by using EsGlobe – atmospheric patch of particles

How long does it take Saharan dust to cross the Atlantic and reach Texas?

June 20 2018 12 GMT

1480
1490
1500
1510
1540
1550
1490
1530
1520
1500
1510

1450
1460
1470
1480
1490
1500

1610
1600
1590
1580
1570

1560

1530
1530
1540
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1520
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1560
1560
1550
1560

1530

30
20
10
0

-90 -80 -70 -60 -50 -40 -30 -20 -10 0

180620/1200V000 850 MB HGHT : wnd WIND   (71.232.19.135)

Note: barbs are in m/sec

June 20 2018 18 GMT

180620/1800V000 850 MB HGHT : wnd WIND   (71.232.19.135)

Note: barbs are in m/sec

June 21 2018 00 GMT

180621/0000V000 850 MB HGHT : wnd WIND   (71.232.19.135)

Note: barbs are in m/sec

June 21 2018 06 GMT

180621/0600V000 850 MB HGHT : wnd WIND   (71.232.19.135)

Note: barbs are in m/sec

Case study: June 20 - 21, 2018

How long does it take Saharan dust to cross the Atlantic and reach Texas?

Verify your calculation by using EsGlobe – atmospheric patch of particles!

Examples:

1) Velocity and position of a fluid parcel-
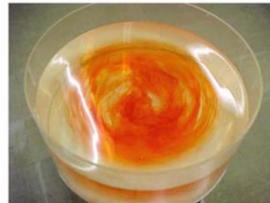
$$u = \frac{D}{Dt}x; \quad v = \frac{D}{Dt}y$$

$$x = \int u\,dt; \quad y = \int v\,dt$$

Where u is the speed in the x direction and v is the speed in the y direction

2) Tracer Transport- assume T is some conserved tracer $\quad \frac{D}{Dt}T = 0$

Fluid parcels conserve (except for small diffusive processes) the concentration of dye

Examples:

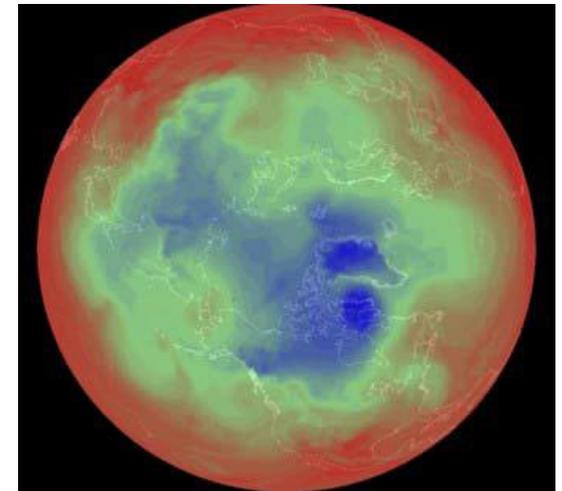3) Temperature advection-

$$\frac{D}{Dt}T = 0$$

Assuming temperature is conserved (which is not entirely correct), and that meridional (north-south) advection is dominant, we can write-

$$\frac{\partial T}{\partial t} \simeq -v\frac{\partial T}{\partial y}$$

Where $\frac{\partial T}{\partial y} < 0$

red =hot
blue=cold

Hence, $\quad v < 0 \implies \frac{\partial T}{\partial t} \simeq -v\frac{\partial T}{\partial y} < 0$

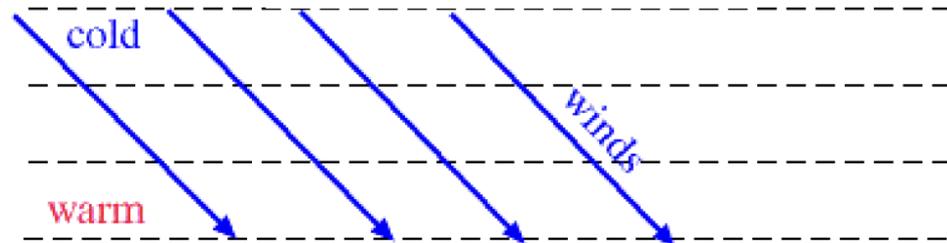$$v > 0 \implies \frac{\partial T}{\partial t} \simeq -v\frac{\partial T}{\partial y} > 0$$

In regions where the cold air is moving south (v<0) the local rate of change of temperature is negative (cooling). Similarly, local warming when v>0
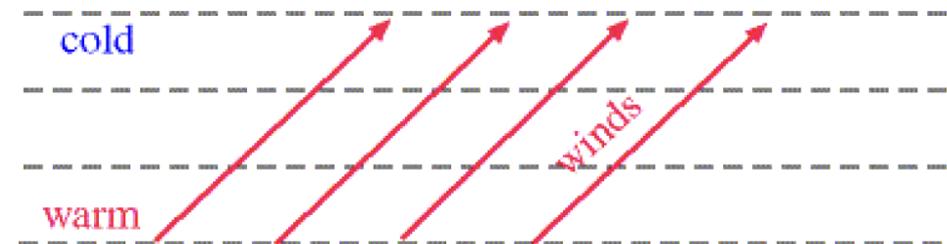
Temperature advection

No advection
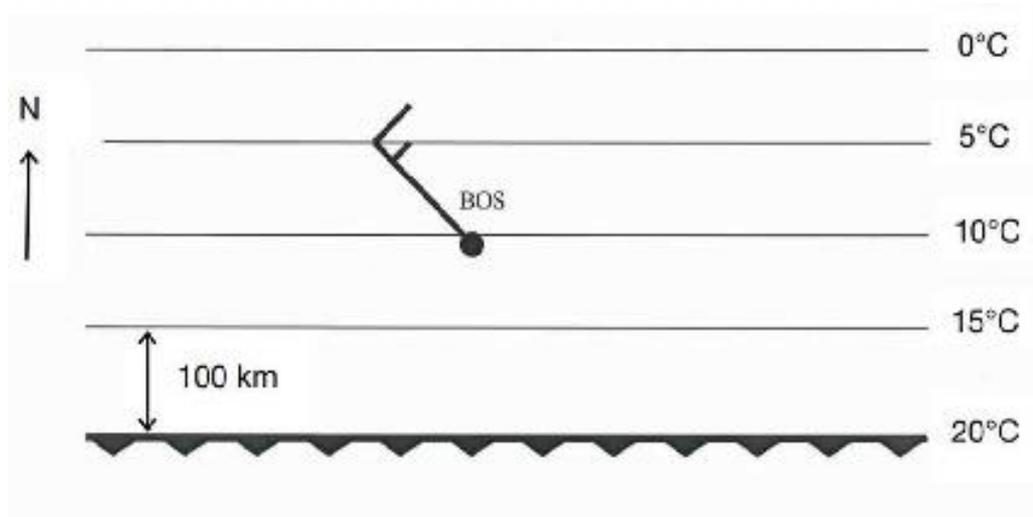
Cold temperature advection

Warm temperature advection

Temperature advection

Example: temperature changes in Boston due to a hypothetical front

If we assume that temperature T is conserved: $\dfrac{D}{Dt}T = 0$

then: $(\partial T/\partial t)_{\text{at Boston}} = -u\partial T/\partial x - v\partial T/\partial y$

A Schematic front. Suppose a cold front has just passed over Boston. The front is oriented west to east and the temperature drops 5^oC every $100\,\text{km}$ (as sketched in Fig.11). As the wind blows from the NW at $15kts$, where $1kts = 0.5m/s$, infer how much the temperature will be expected to drop in 12 hours due to cold air advection?

By how much did the temperature drop after 12 hours?