

Project 2: Tracer transport

Data class- atmosphere

1. *Dust from the Sahara:*

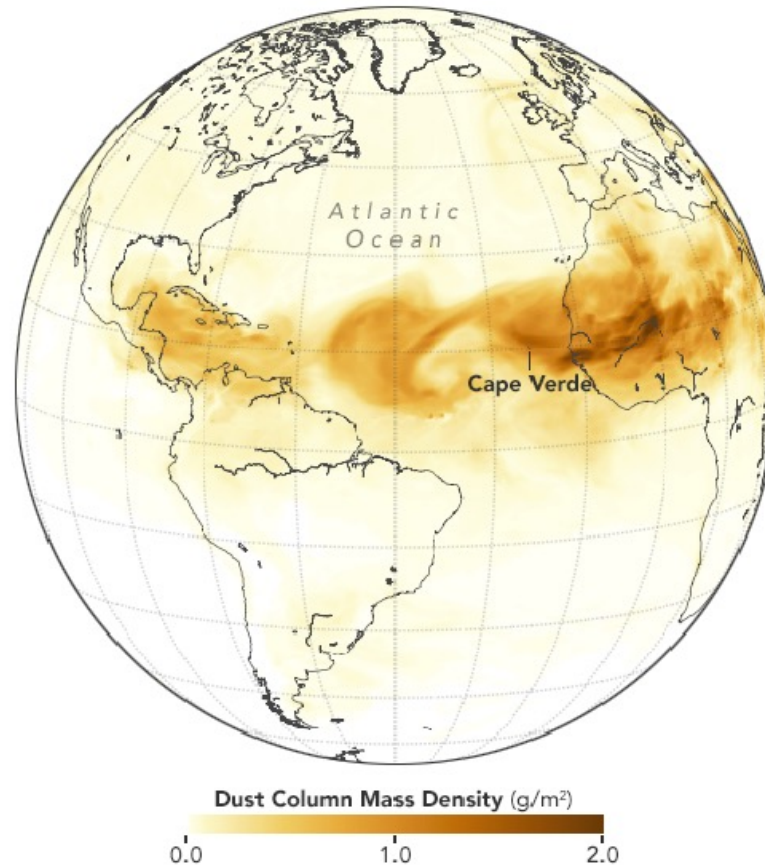
- Build by hand your own Lagrangian trajectories
- Compare to those obtained using the EsGlobe

How long does it take dust from the Sahara to cross the Atlantic and reach the United states?

2. *Temperature Advection:*

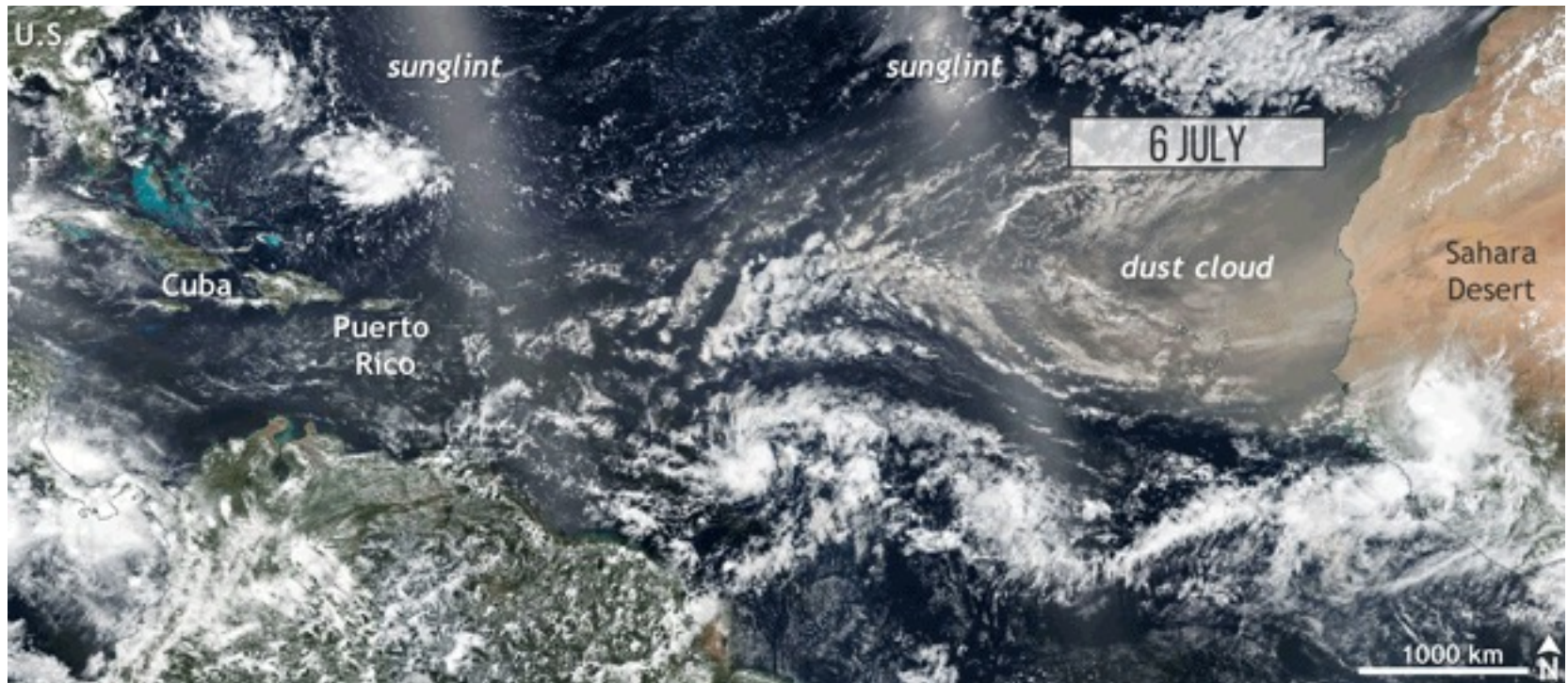
- Calculate temperature advection for an idealized front
- Temperature advection for a real front during winter

Saharan Dust - June/July 2018



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.

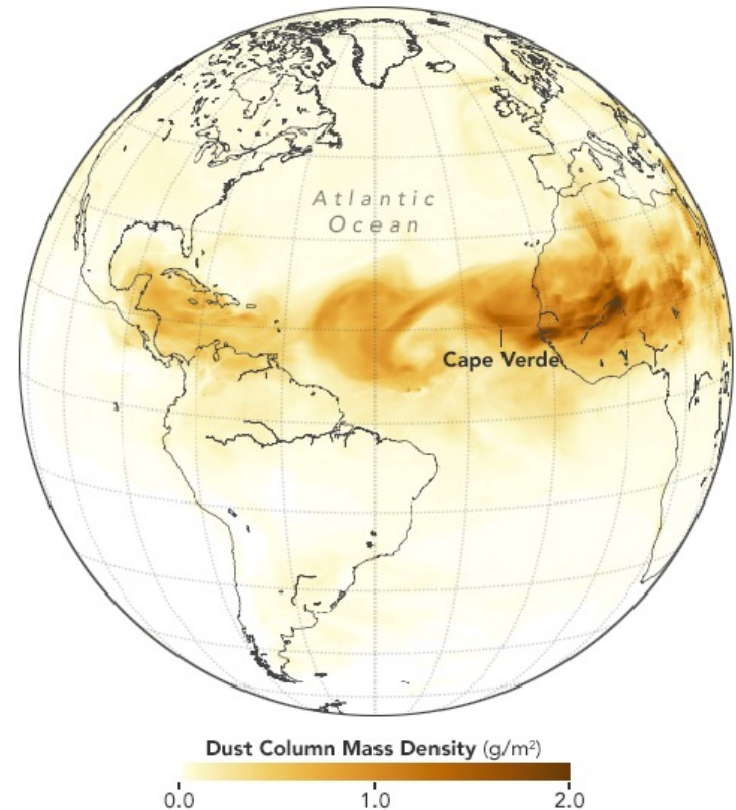
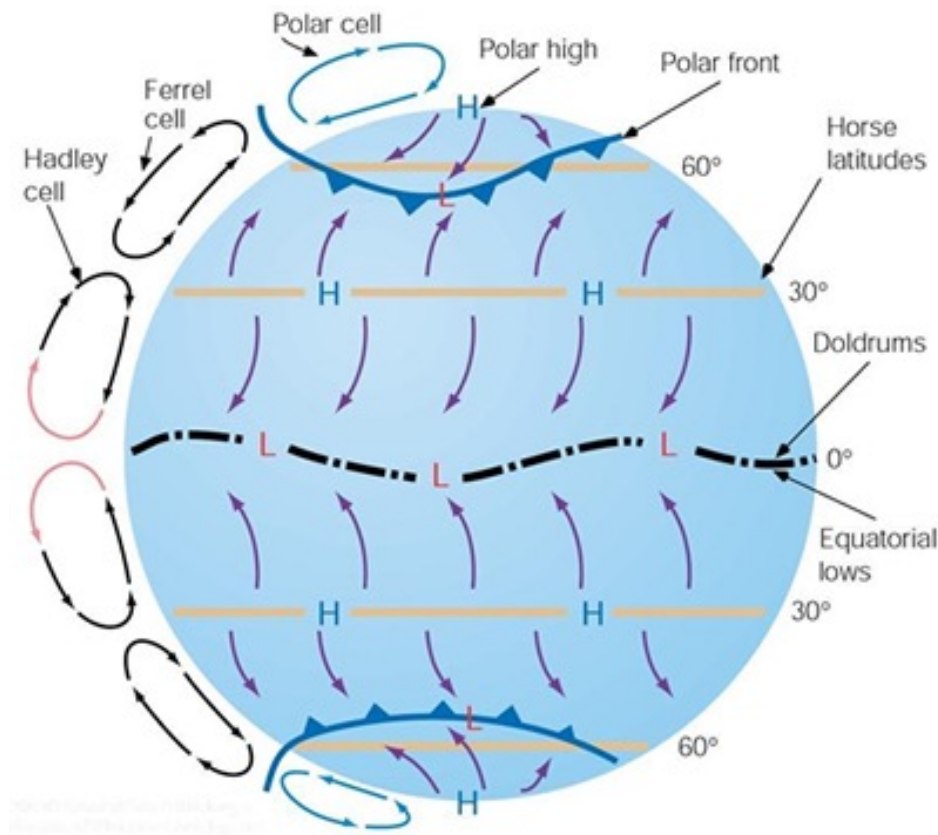
Saharan Dust - June/July 2018



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.

Watch also <https://youtu.be/ygulQJole2Y>

How can dust from the Sahara reach the US?



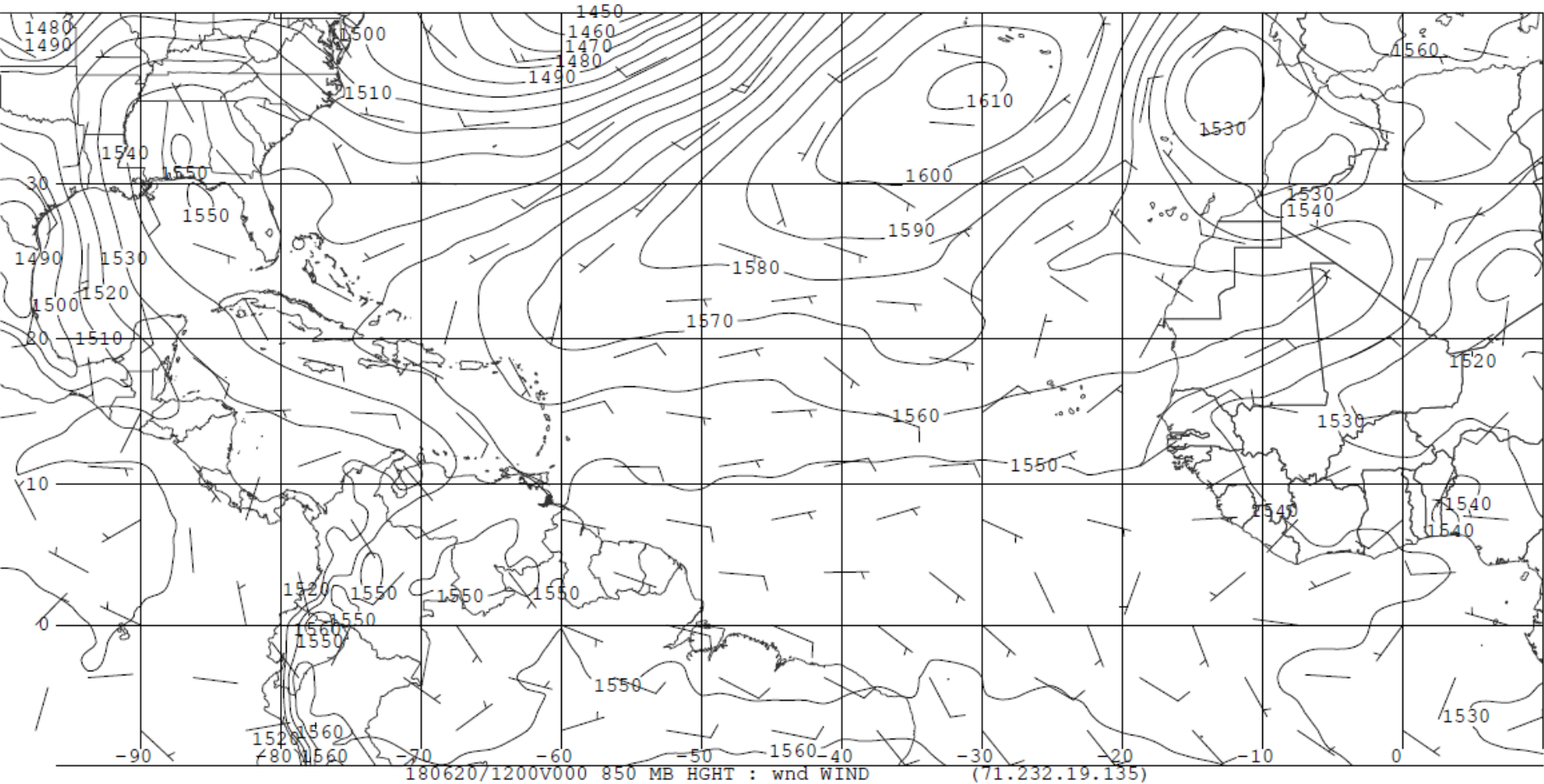
Coriolis force diverts the flow such that at the surface, we find **easterlies** (winds from the east) in the subtropics (also known as the **trade winds**)

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

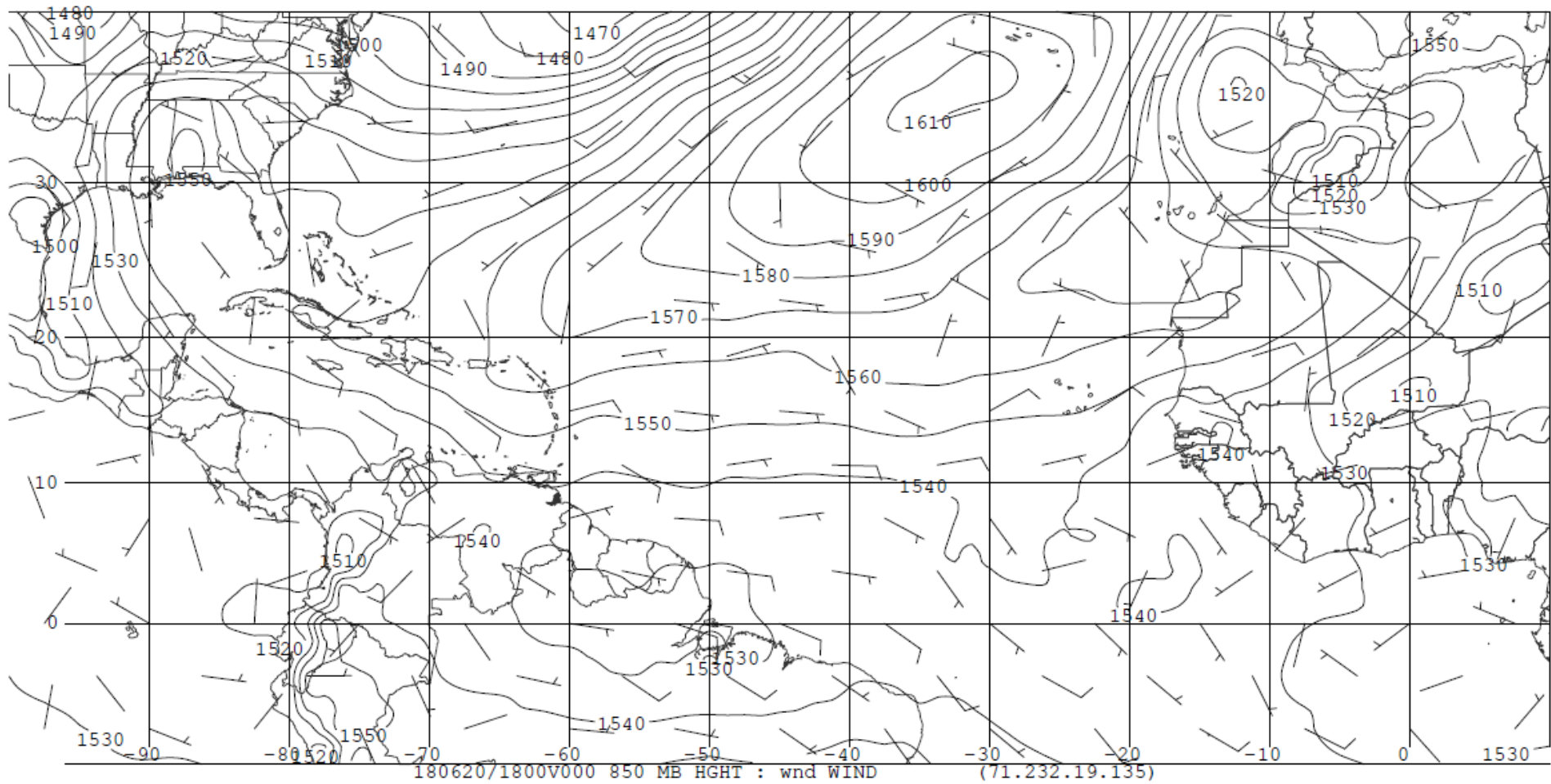
How long does it take Saharan dust to cross the Atlantic and reach Texas?

June 20 2018 12 GMT



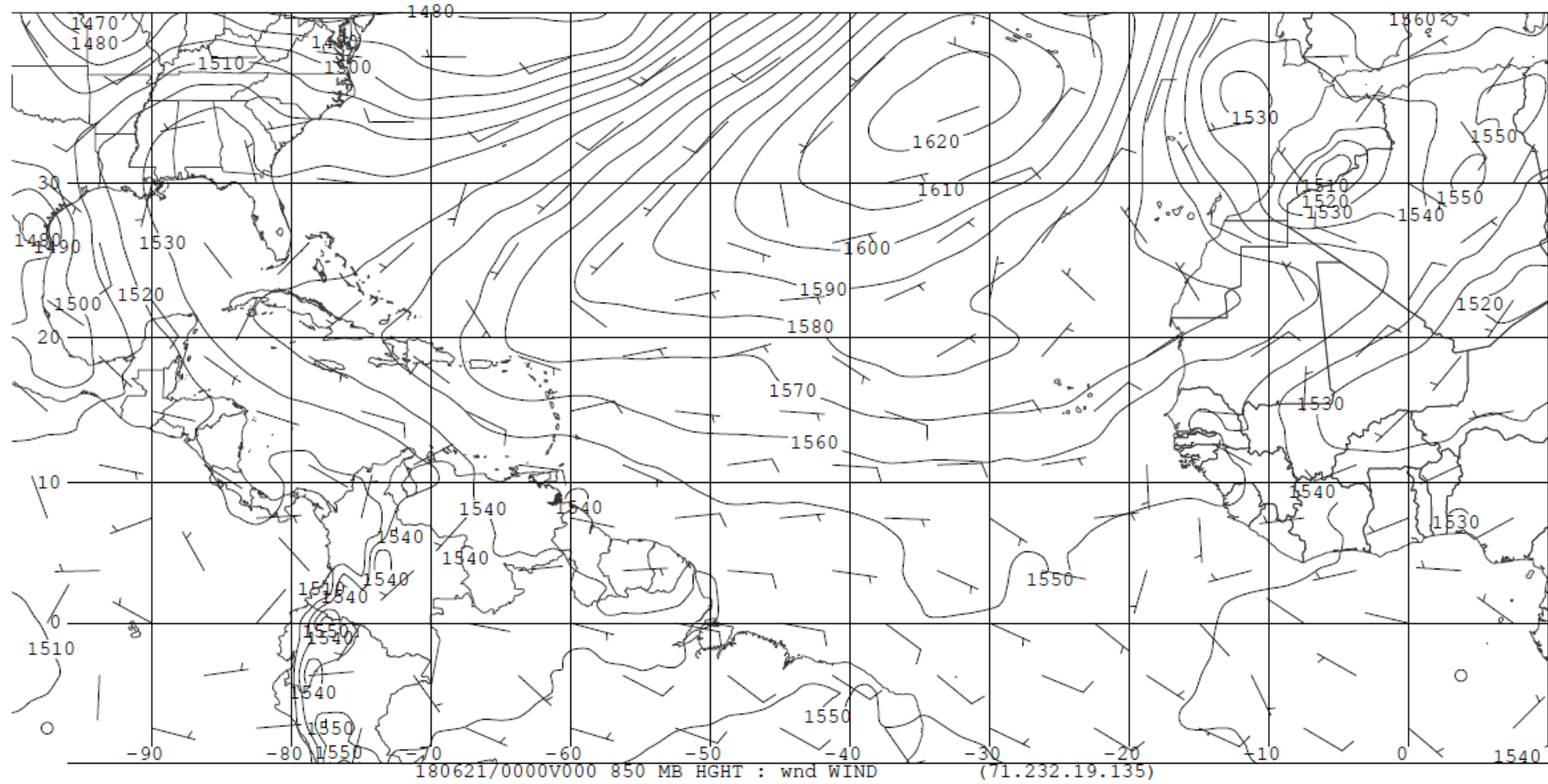
Note: barbs are in m/sec

June 20 2018 18 GMT



Note: barbs are in m/sec

June 21 2018 00 GMT



Note: barbs are in m/sec

Lagrangian vs Eulerian derivative

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

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

Lagrangian
derivative

Eulerian
derivative

Advection

Velocity and position:

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



$$\Delta x = u\Delta t$$
$$\Delta y = v\Delta t$$

- *How far did the dust reach after the 24 hours?*
- *Can you use this to estimate many days will it take it to cross the Atlantic?*
- *Now, use the EsGlobe to check this and compare your results!*

Temperature advection

- Extratropical weather systems
- Fronts
- Temperature advection

Midlatitude weather systems

How do midlatitude weather systems transfer heat poleward?

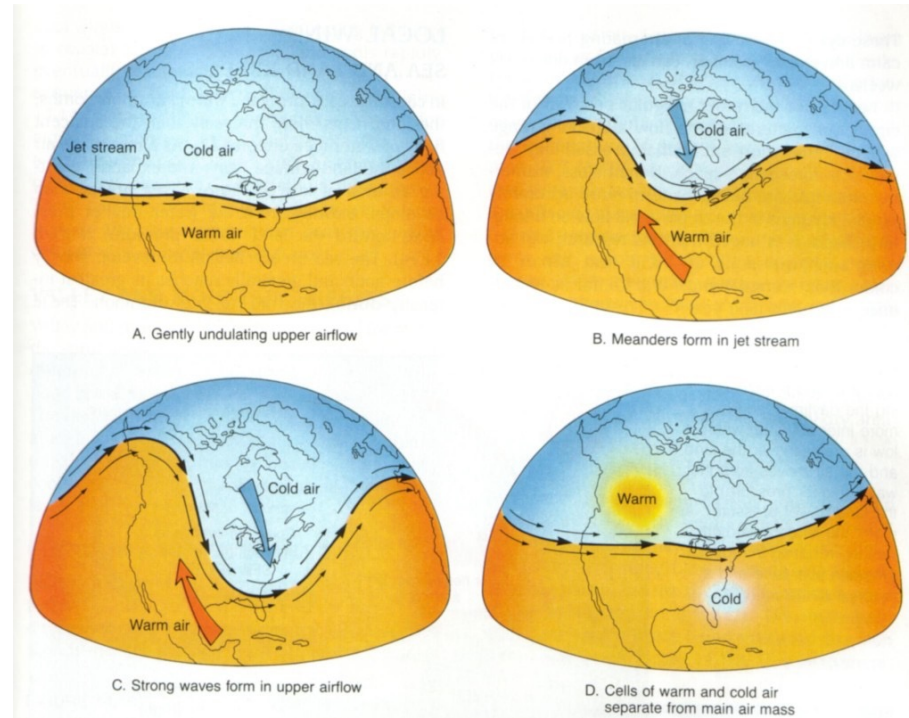


FIGURE 14.13

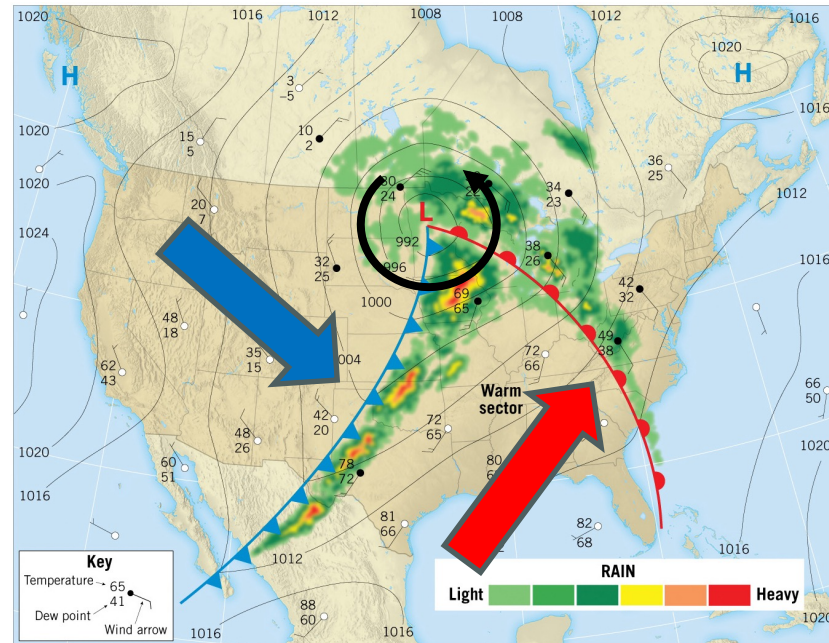
Cyclic changes that occur in the upper-level airflow of the westerlies. The flow, which has the jet stream as its axis, starts out nearly straight, then develops meanders, which are eventually cut off. (After J. Namias, NOAA)

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

Extratropical cyclones and fronts

Extratropical cyclones are associated with warm and cold fronts.

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

Cold fronts

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

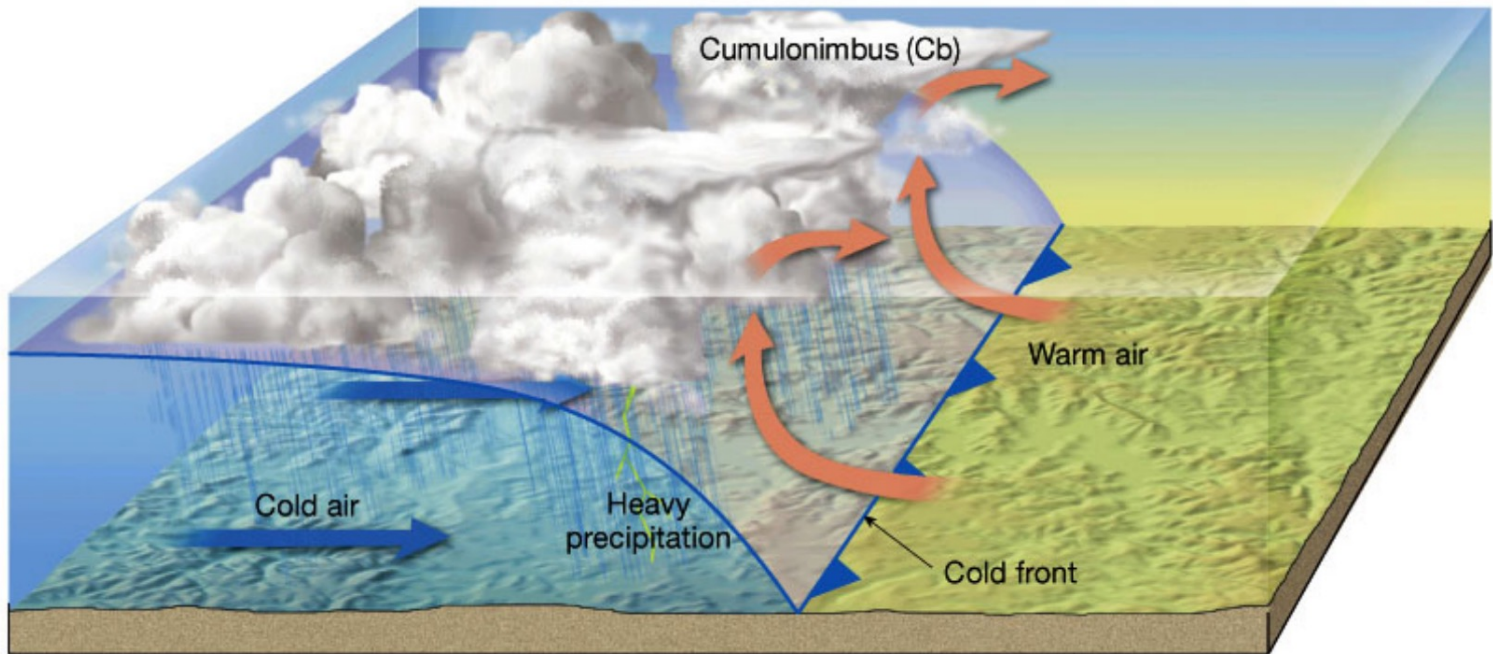


Figure 9.6 in *The Atmosphere, 8th edition*, Lutgens and Tarbuck, 8th edition, 2001.

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

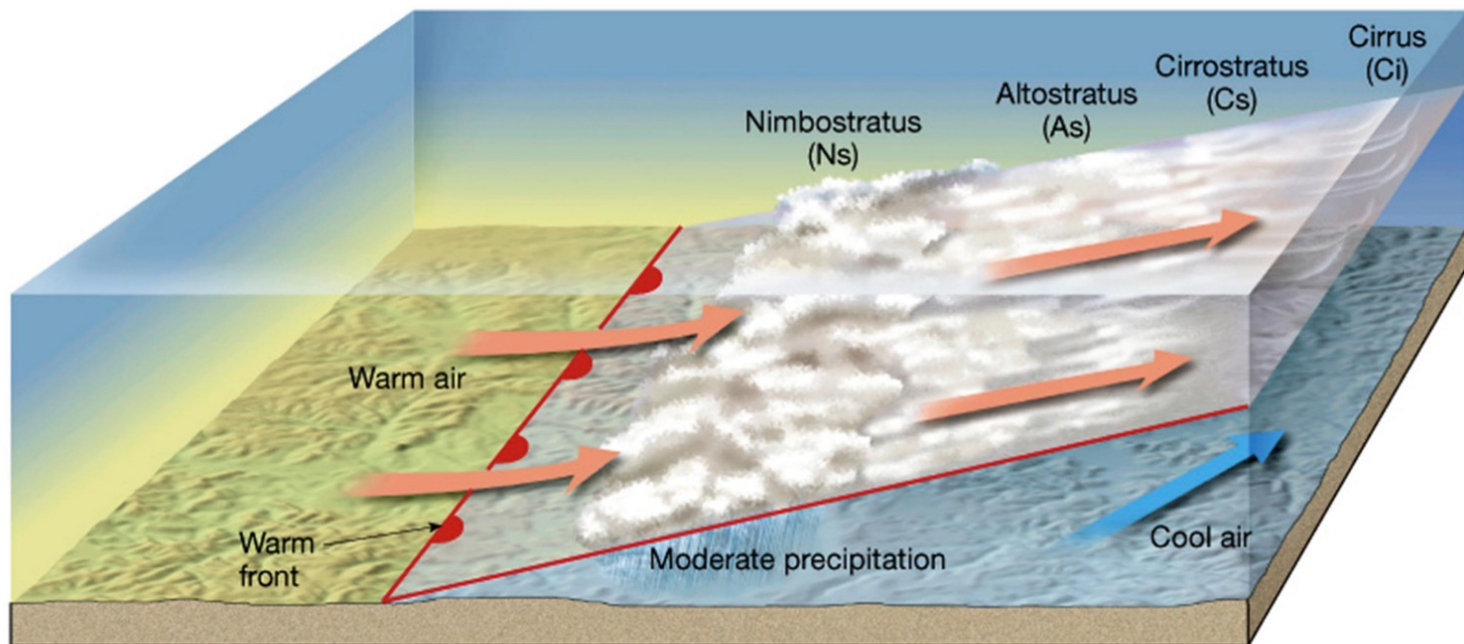
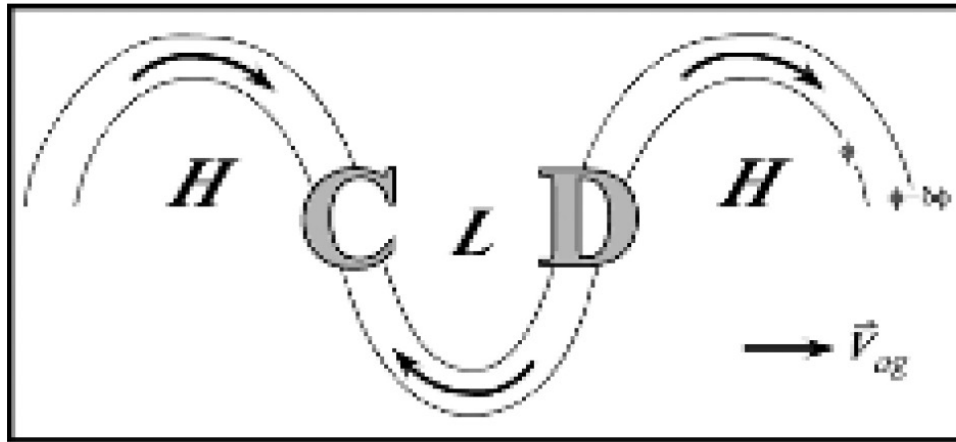


Figure 9.6 in *The Atmosphere, 8th edition*, Lutgens and Tarbuck, 8th edition, 2001.

How do midlatitude weather systems grow?

Reminder- From the gradient wind balance, we found that $v < v_g$ (or $v_a = v - v_g < 0$) for troughs (cyclonic circulations) and $|v| > |v_g|$ (or $v_a = v - v_g > 0$) for ridges (anticyclonic circulation)

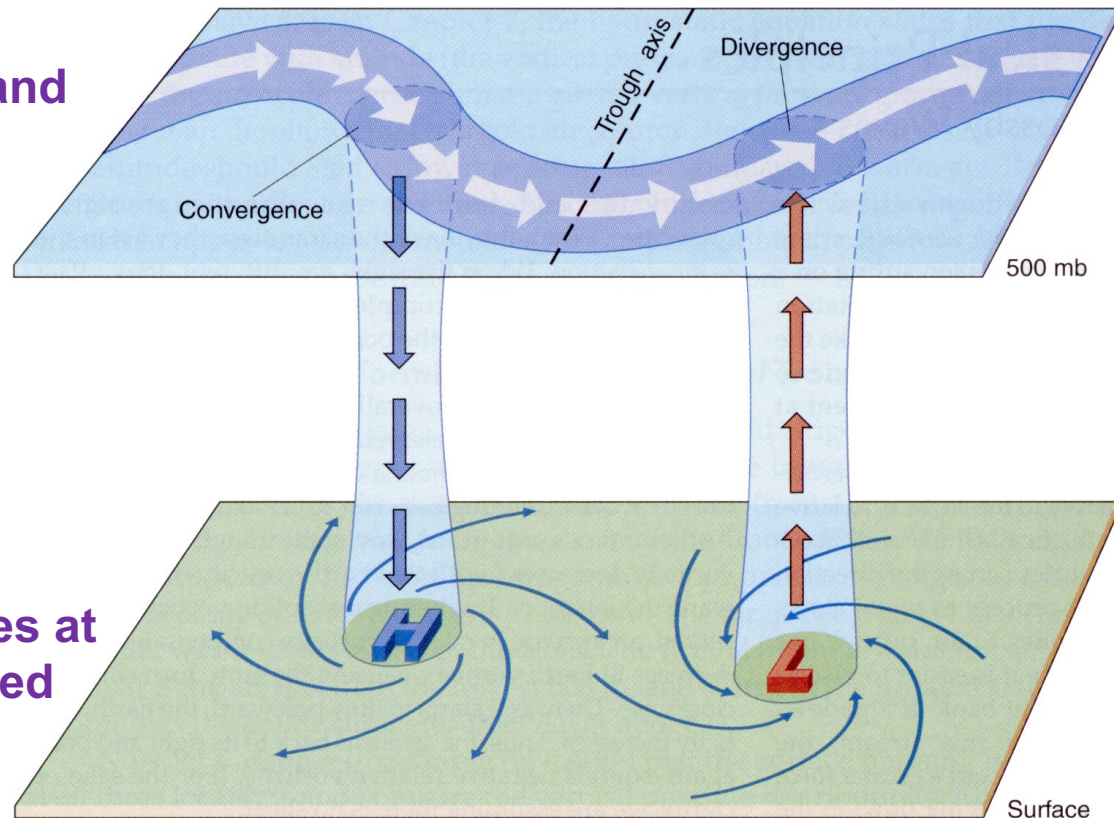


However, this implies Convergence (C) between the ridge and the trough, and Divergence (D) between the trough and the ridge!

How do midlatitude weather systems grow?

Interaction between upper level and lower level flows

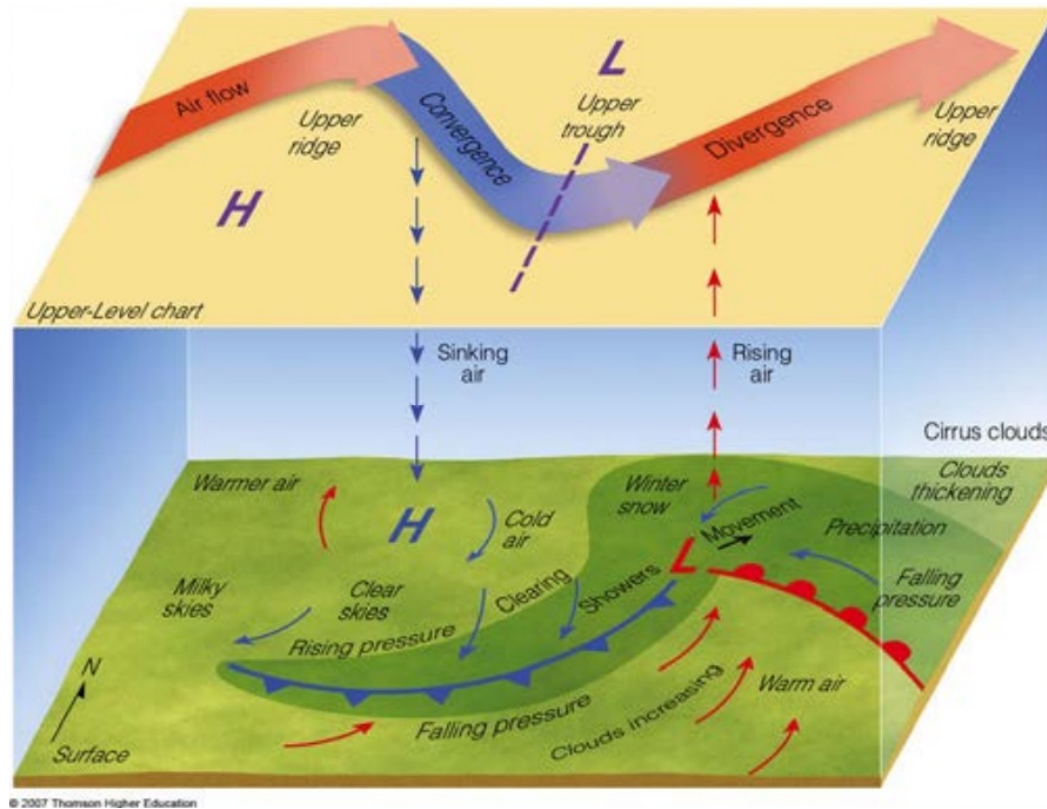
upper level Troughs and Ridges



Cyclone and anticyclones at low levels and associated surface temperatures

- Upper-level convergence (divergence) upstream (downstream) of the troughs
- Implies downward (upward) flow in the upstream (downstream)
- Divergence in the surface High (H), convergence in the surface Low (L) also due to friction

Role of temperature advection in cyclogenesis



- An upper level wavy disturbance in the jet passes. Upper level divergence and convergence are generated
- Upper level divergence and convergence lead to surface low/high, and thus to cold and warm advection
- Surface temperature advection enhances sinking and rising air, respectively, and intensifies upper level low/high
- More upper level divergence...

Temperature advection- reminder

3) Temperature advection-

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

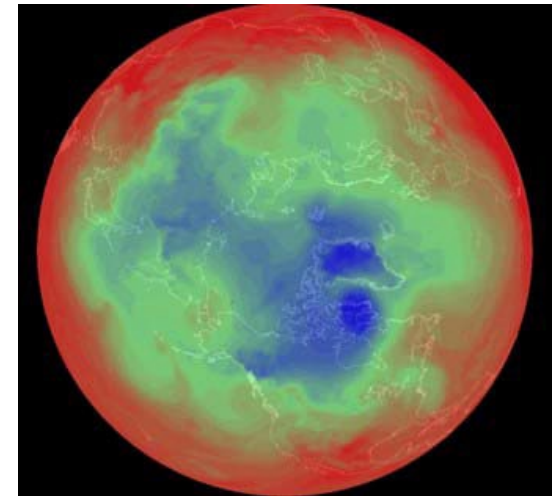
Assuming temperature is conserved (which is not generally correct), and that meridional (north-south) advection is dominant, we can write-

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

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

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

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

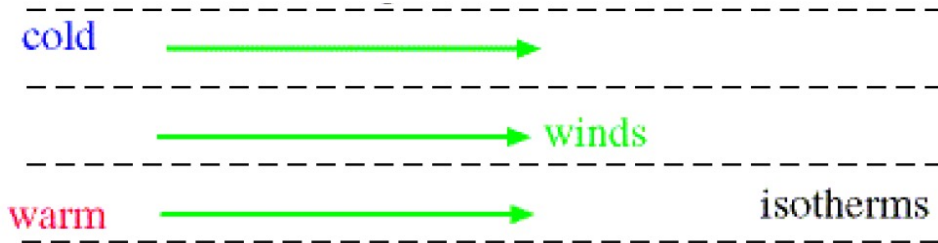


red = hot
blue = cold

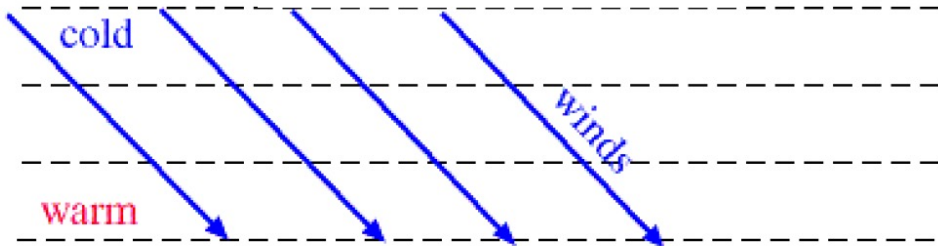
In regions where the cold air is moving south ($v < 0$) the local rate of change of temperature is negative (cooling). Similarly, local warming when $v > 0$

Temperature advection- reminder

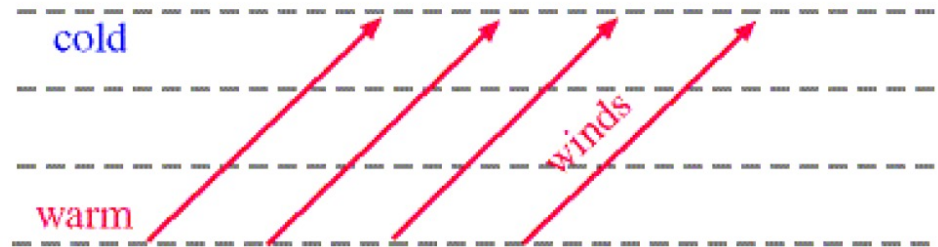
No advection



Cold temperature advection



Warm temperature advection

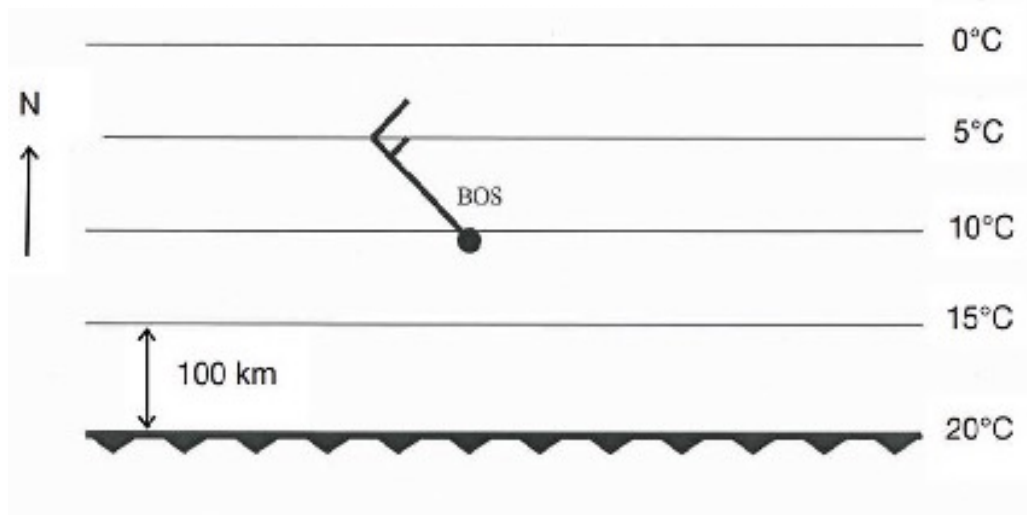


Temperature advection

Example: temperature changes in Boston due to a hypothetical front

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

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



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

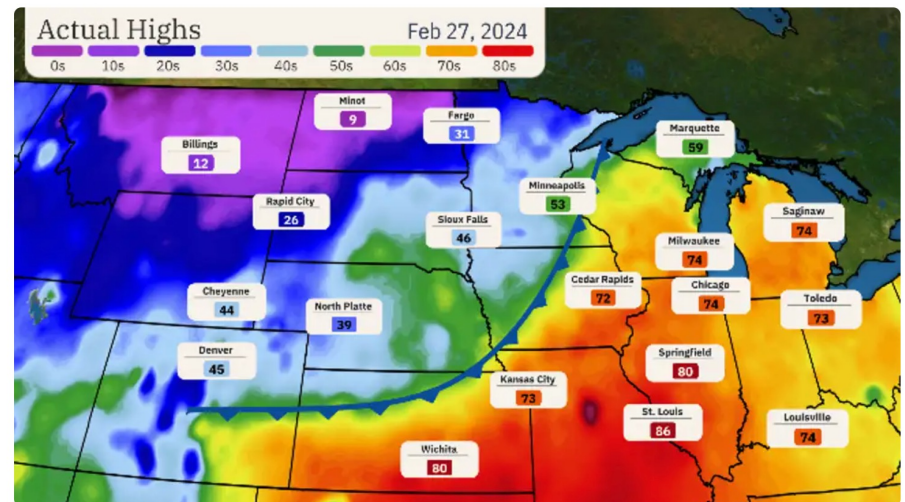
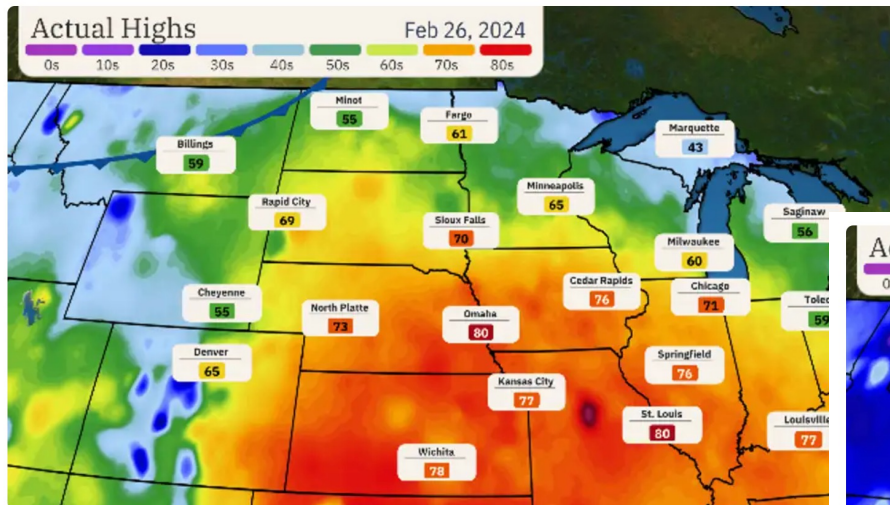
By how much did the temperature drop after 12 hours?

Temperature advection- real front

“Ahead of the front, over three dozen cities...set record highs, not just for the calendar day or month, but for the entire winter (December through February) period.

Much colder air behind the front sent temperatures crashing quickly from those record highs to temperatures these areas would expect in winter.

You can see the temperature contrast ahead of and behind the cold front in the two maps below, showing high temperatures on Monday, Feb. 26, followed by highs the following day.”

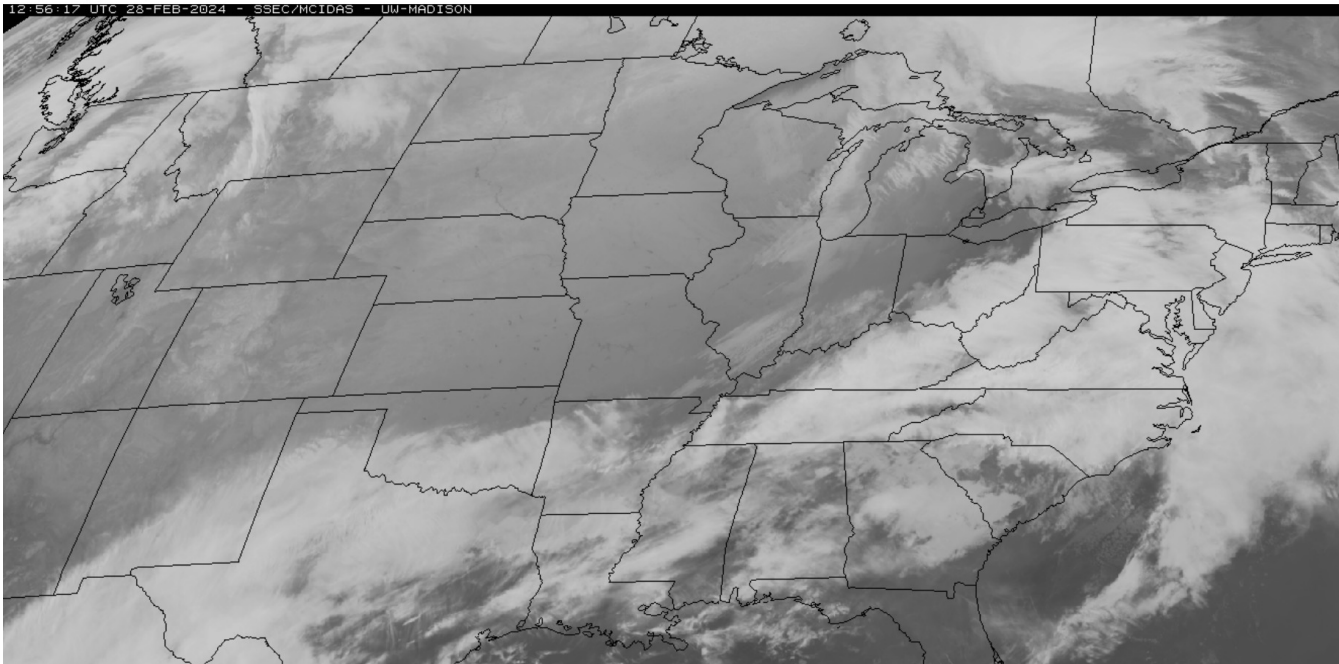


Temperature advection- real front

Example from last week!

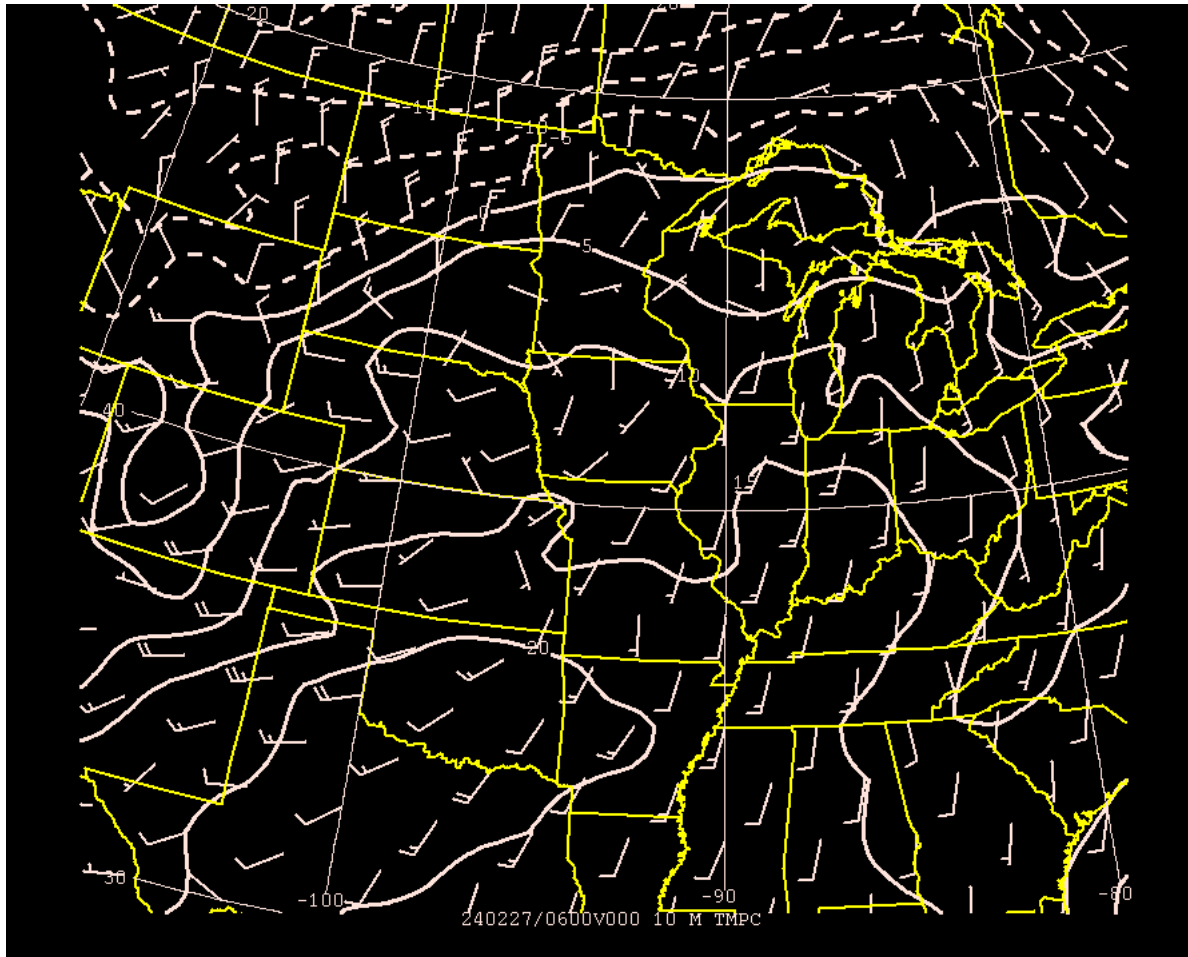
Let's try to estimate manually the temperature change in Chicago using real weather maps from last week

Infrared satellite image for February 28 2024 06Z



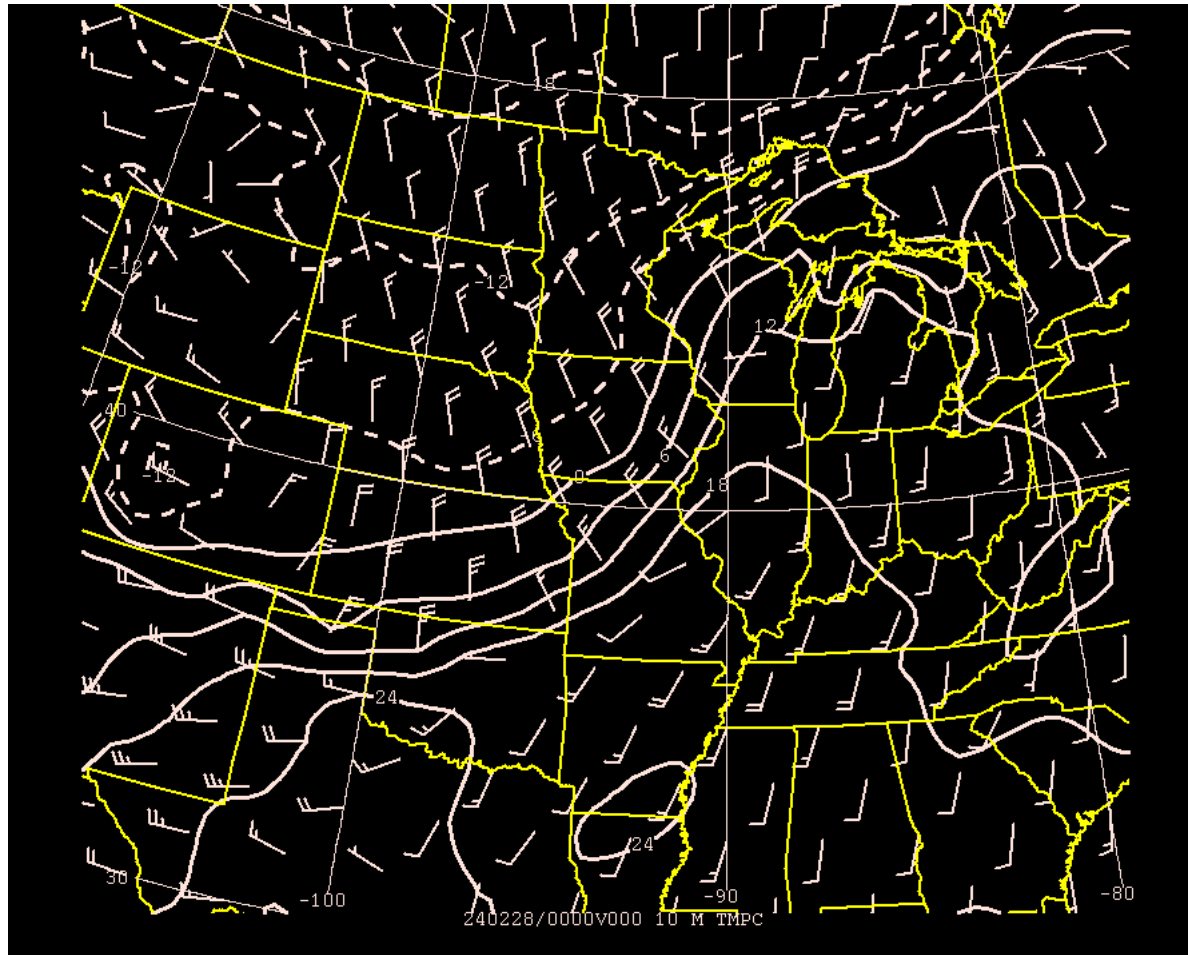
Temperature advection- real front

February 27 2024 06Z



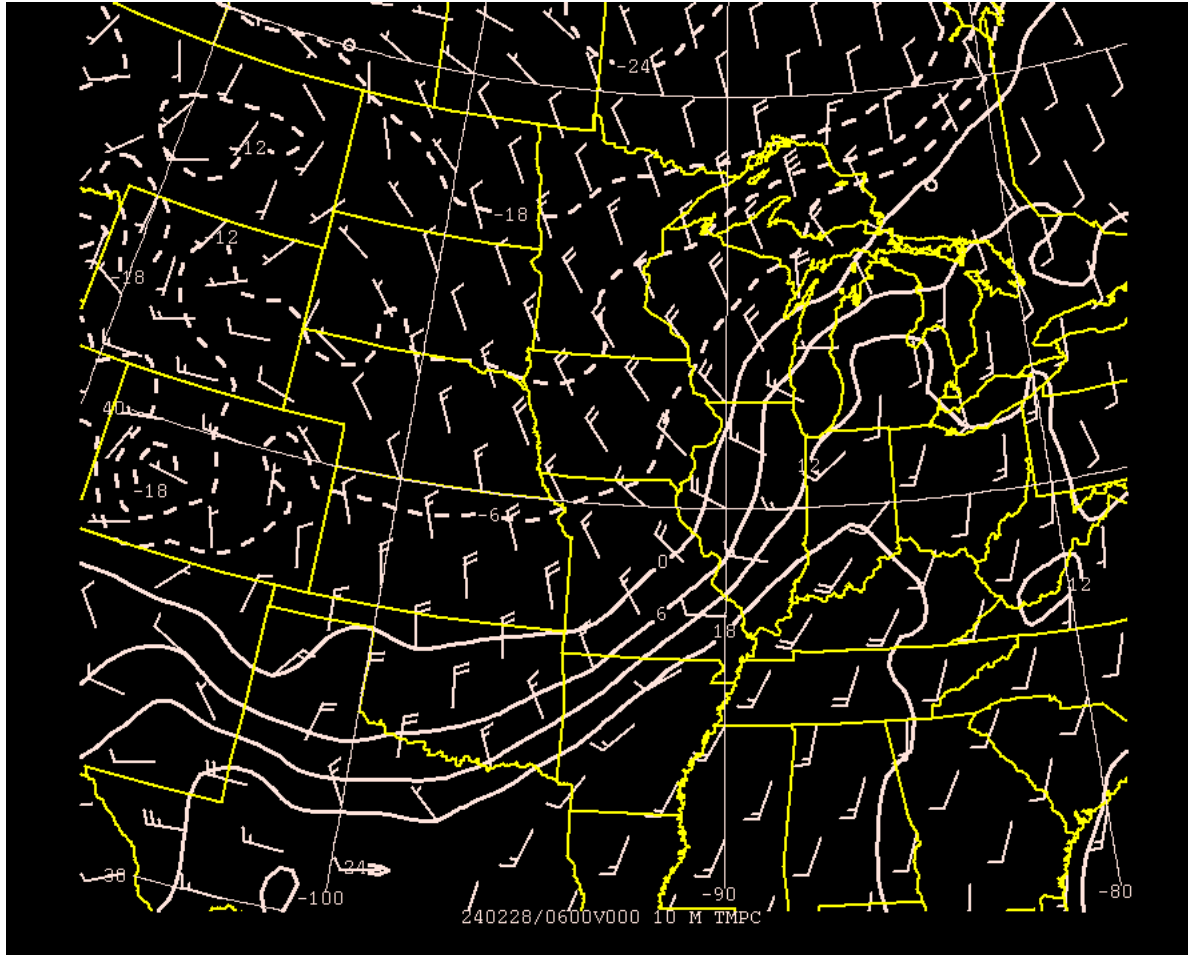
Temperature advection- real front

February 28 2024 00Z



Temperature advection- real front

February 28 2024 06Z



$$\frac{\partial T}{\partial t} \approx -|\vec{u}| \frac{\Delta T}{\Delta |\vec{r}|}$$



$$\frac{\Delta T}{\Delta t} (12Z) \approx -|\vec{u}| \frac{\Delta T}{\Delta |\vec{r}|} (6Z)$$

$\Delta t = 6 h$
 $|\vec{u}| \approx 15 \text{ kt}$
 $\Delta T \approx 12^\circ\text{C}$
 $\Delta r \approx 200 \text{ km}$



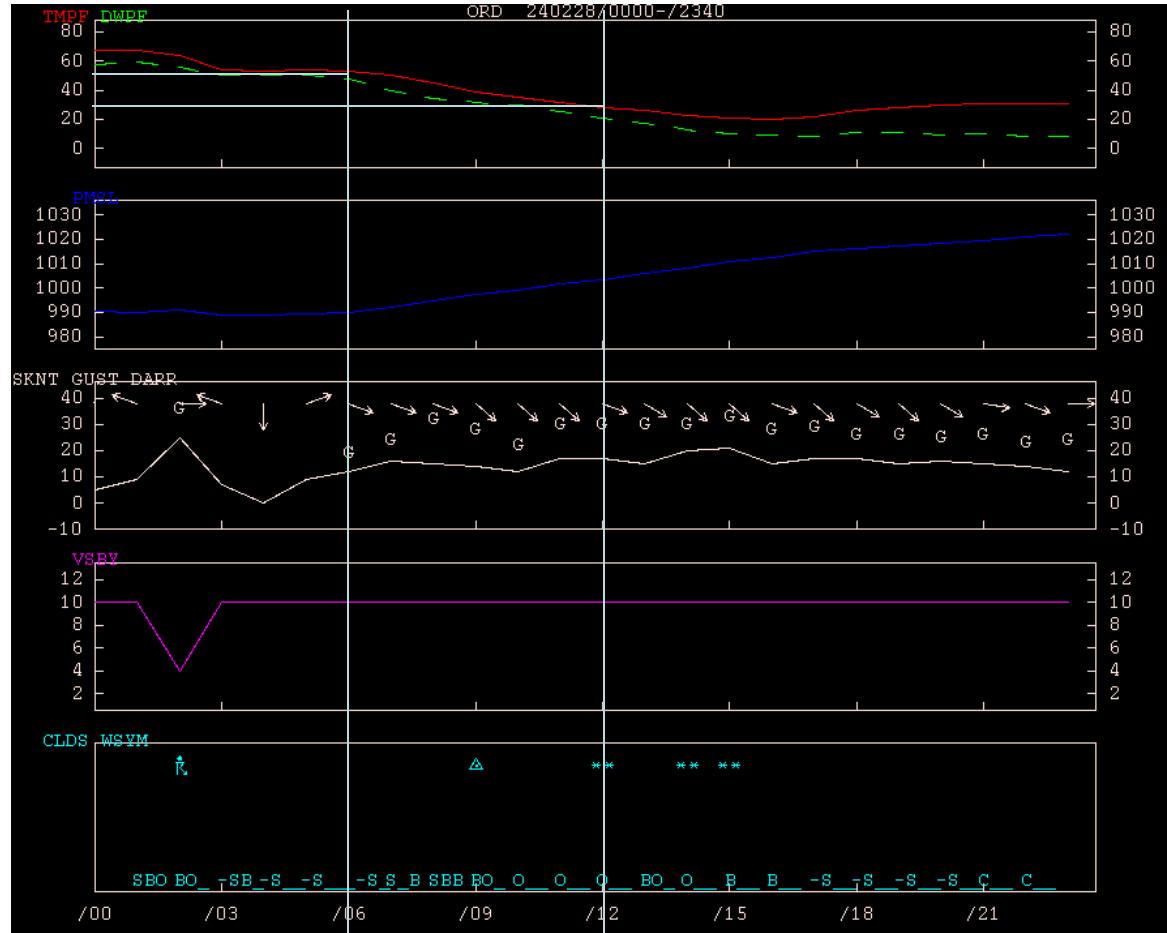
$$\Delta T(12Z) \approx \frac{6[h] \cdot 15[\text{kt}] \cdot 12^\circ\text{C}}{200 [\text{km}]} \approx 10^\circ\text{C}$$

Temperature advection- real front

$T(06Z) \approx 50^{\circ}\text{F} \approx 10^{\circ}\text{C}$

$T(12Z) \approx 30^{\circ}\text{F} \approx -1^{\circ}\text{C}$

$\Delta T(12Z) \approx 11^{\circ}\text{C}$



Our simple and rough manual estimation is actually very useful!

Temperature advection- real front

Case Study of January 22, 2013

Compute:

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

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

Temperature advection- real front

January 22 2013 06Z

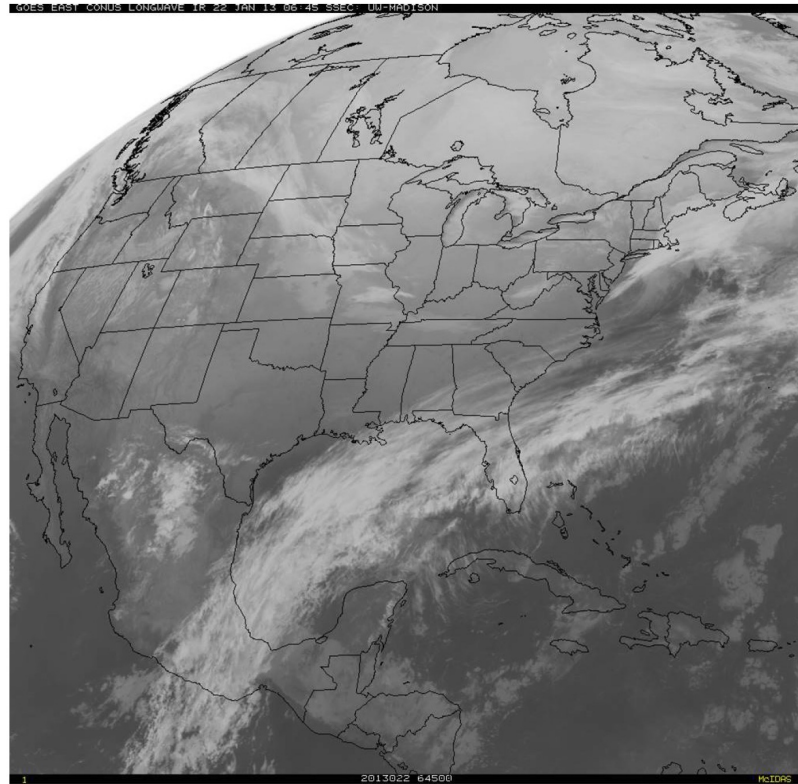


Figure 12: IR satellite image for January 22, 2013 at 06z

Temperature advection- real front

January 22 2013 06Z

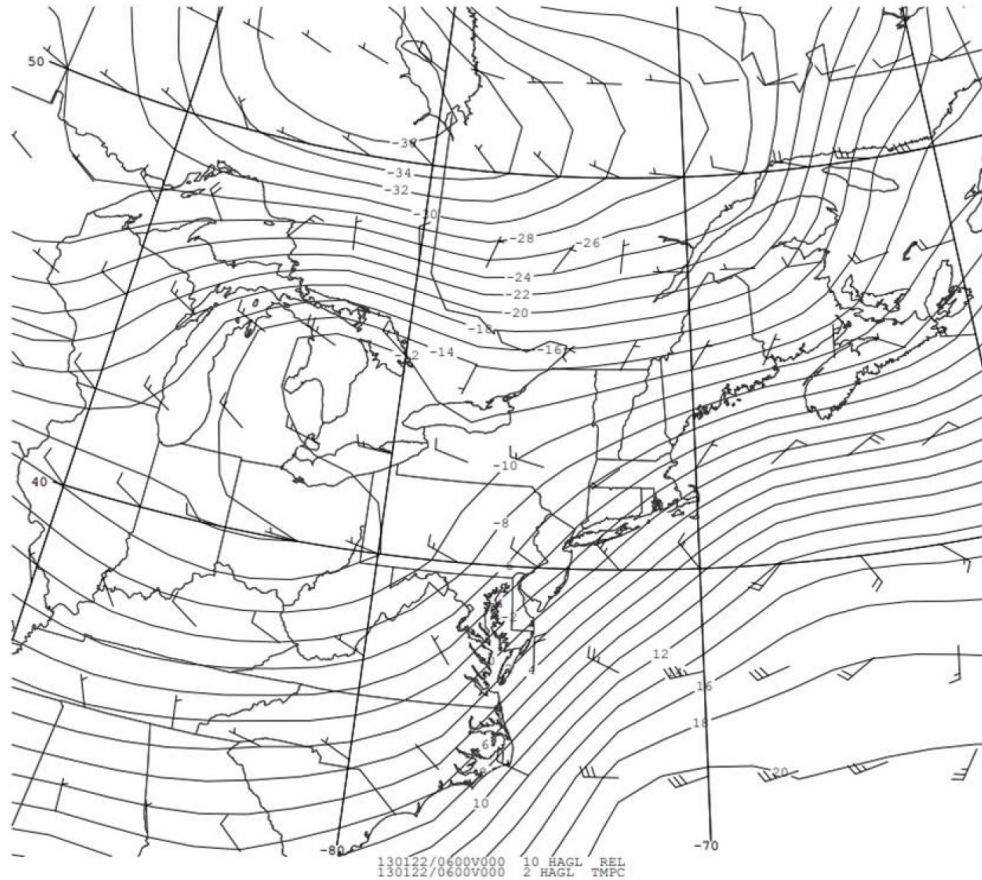
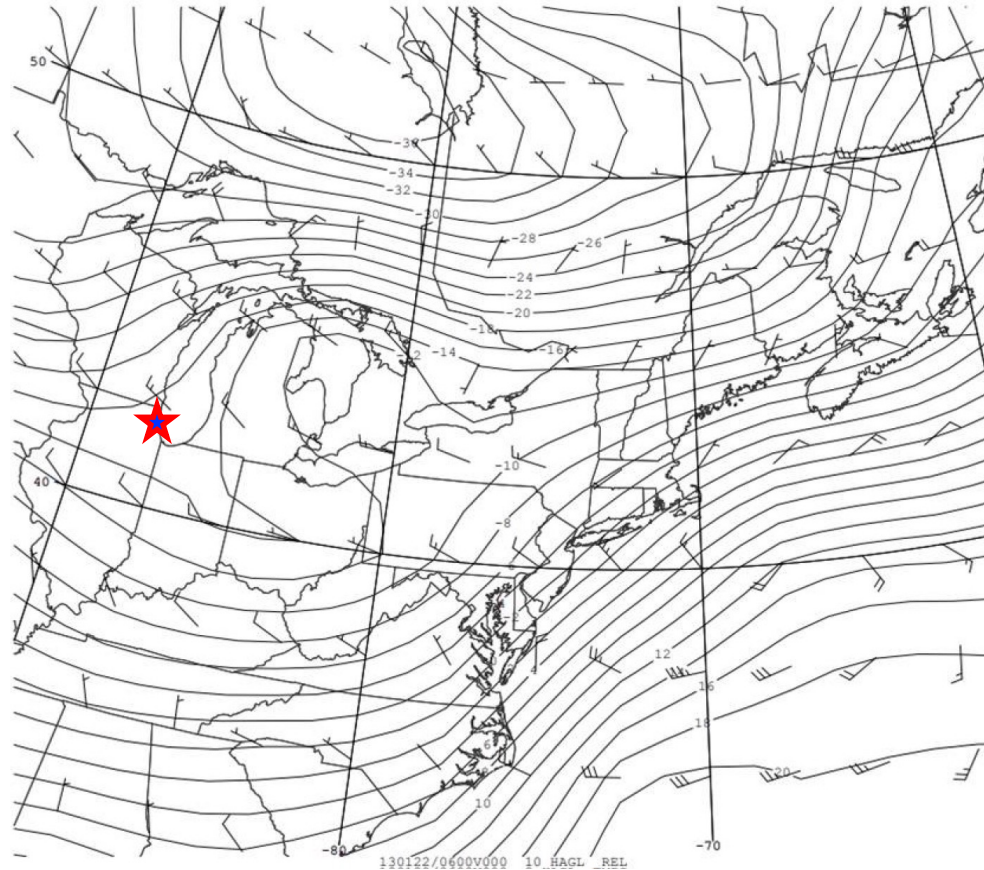


Figure 13: Analyzed surface temperature (contored in $^{\circ}C$) and surface wind (vectors in *kts*) for the same time, as in January 22, 2013 at 06z.

Temperature advection- real front

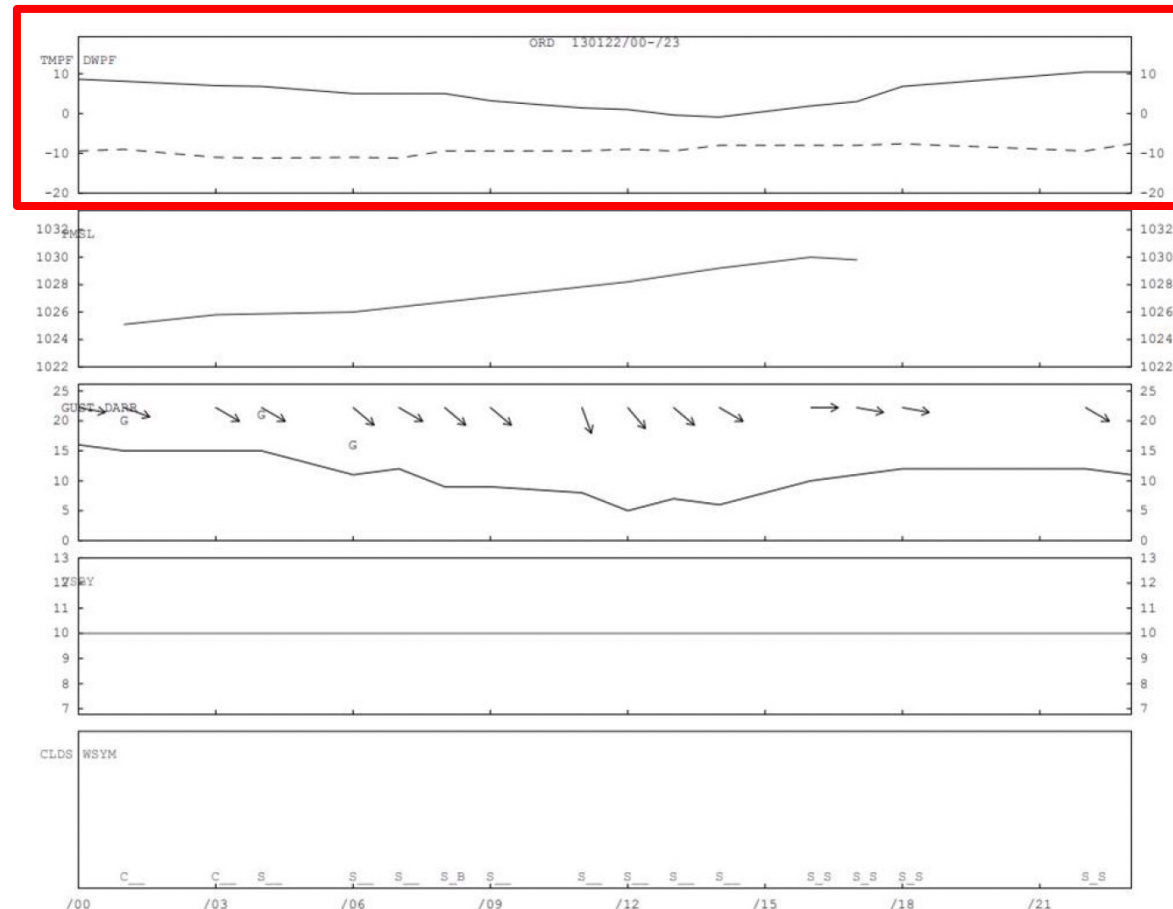
January 22 2013 06Z



- ***Estimated the horizontal temperature advection in Chicago***
- ***What is the expected 6-hour temperature change due to this horizontal temperature advection?***
- ***Compare with the observed change from the surface meteogram in Chicago***

Temperature advection- real front

Surface Meteogram data for Chicago on January 22 2013



Note:

- **The temperature units here are Fahrenheit, so you need to convert to Celsius**
- **Dashed line is the dew point (you can ignore)**

Figure 14: Surface meteogram for Chicago O'Hare (ORD) on January 22, 2013 showing temperature (continuous line) and dewpoint temperature (dashed line), surface pressure, wind speed and direction, visibility and cloud cover.

NWP Model

Numerical Weather Prediction Model

Dynamics

(model grid)

Numerical
Advection

Physics

(sub-grid)

Radiation

Convection

Clouds

Condensation and Precipitation

Planetary Boundary Layer

Surface Fluxes

Project 2: Tracer transport

2nd data class- atmosphere

Temperature Advection:

- Thermal wind balance and jet streams
- Temperature variance
- Climate change

- Exercises:
 - Verify thermal wind balance
 - Temperature variance and projected changes from CMIP6 models

Thermal wind balance

The most fundamental and significant dynamical balance controlling the large-scale circulation of the atmosphere and ocean. A consequence of hydrostatic and geostrophic balance!

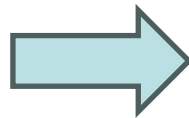
Assuming a small Rossby number-

$$u_g = -\frac{1}{\rho f} \frac{\partial p}{\partial y};$$
$$v_g = \frac{1}{\rho f} \frac{\partial p}{\partial x}.$$

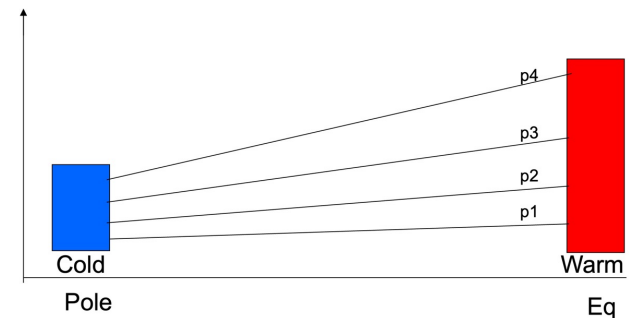
And a hydrostatic balance (at rest in the vertical)

$$\frac{\partial p}{\partial z} + g\rho = 0$$

$$1/\rho = RT/p$$



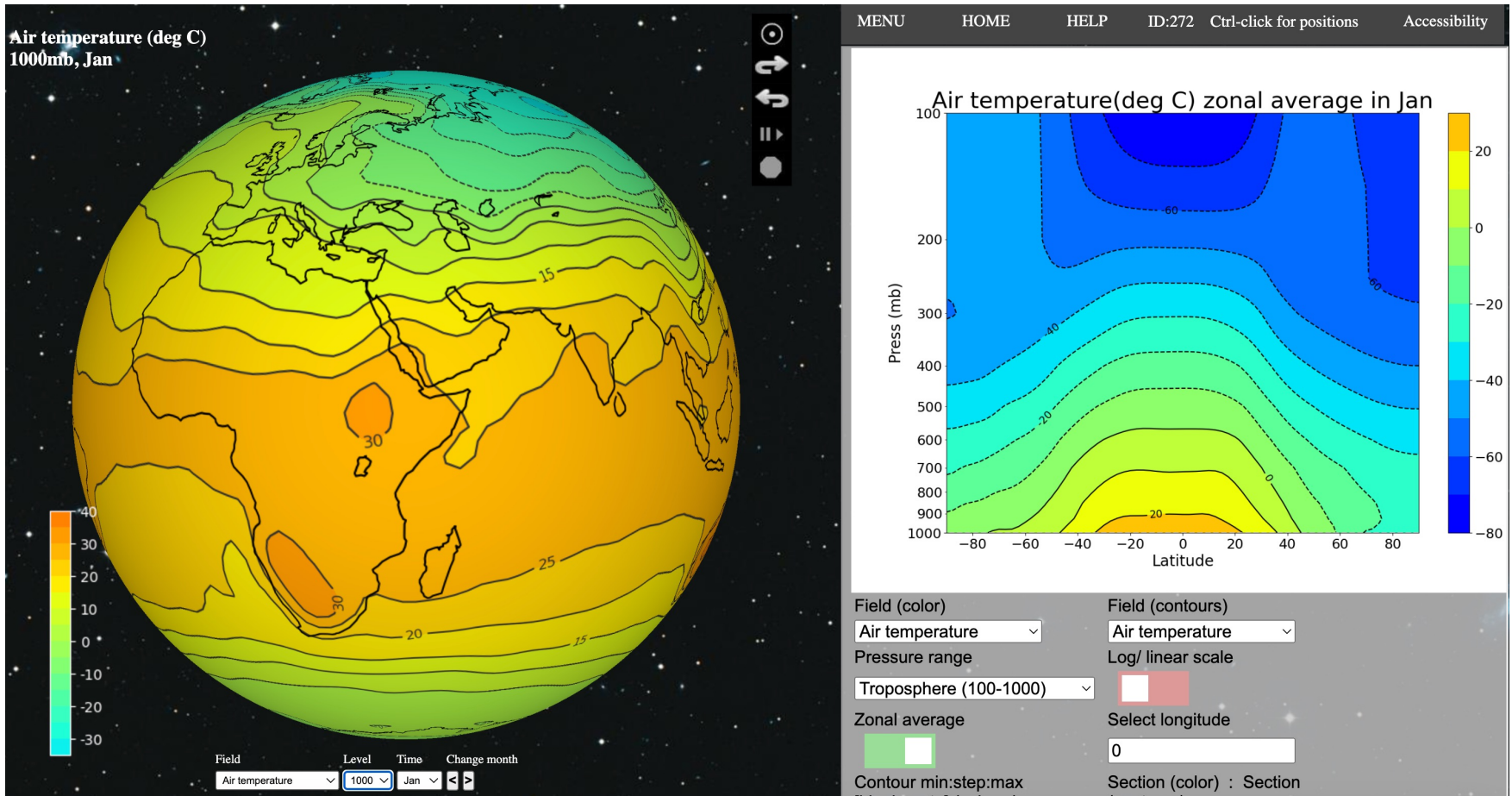
$$\frac{\partial u}{\partial p} = \frac{R}{fp} \left(\frac{\partial T}{\partial y} \right)_p$$
$$\frac{\partial v}{\partial p} = -\frac{R}{fp} \left(\frac{\partial T}{\partial x} \right)_p$$



Relates horizontal temperature gradients to changes in the horizontal wind with pressure/height

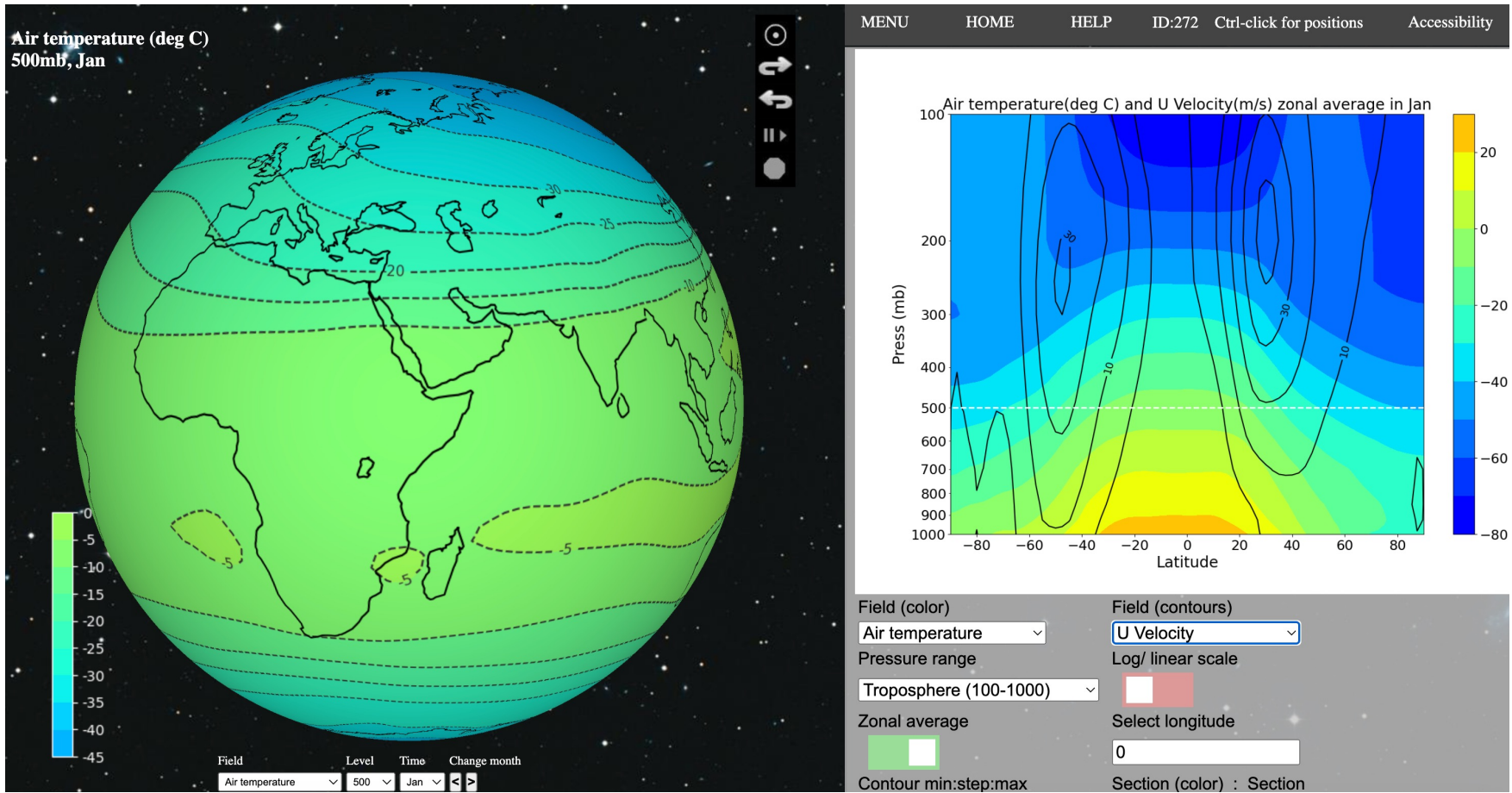
Mean temperature

1000 mb T mean + Vertical structure of zonal mean T

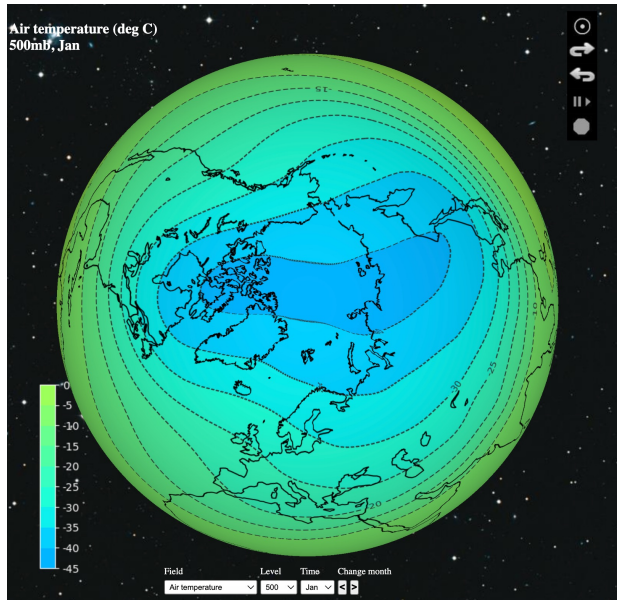


Mean temperature

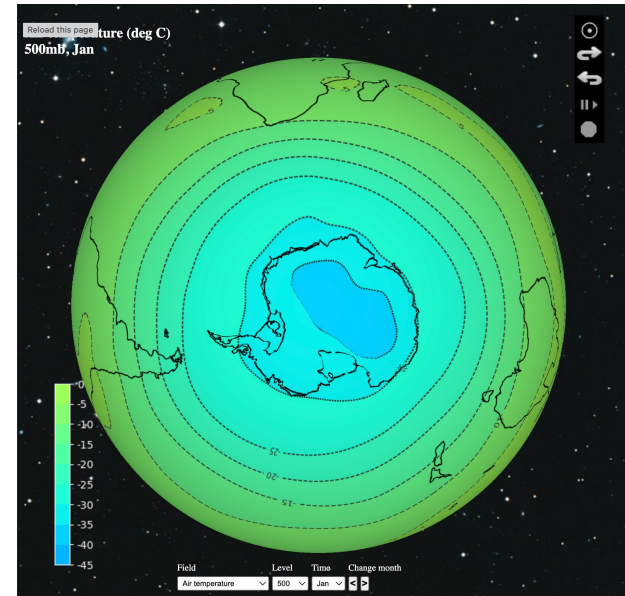
850 mb T mean + Vertical structure of zonal mean T + Zonal mean U



Mean temperature



SH pole view
mean T 500 mb



NH pole view
mean T 500 mb

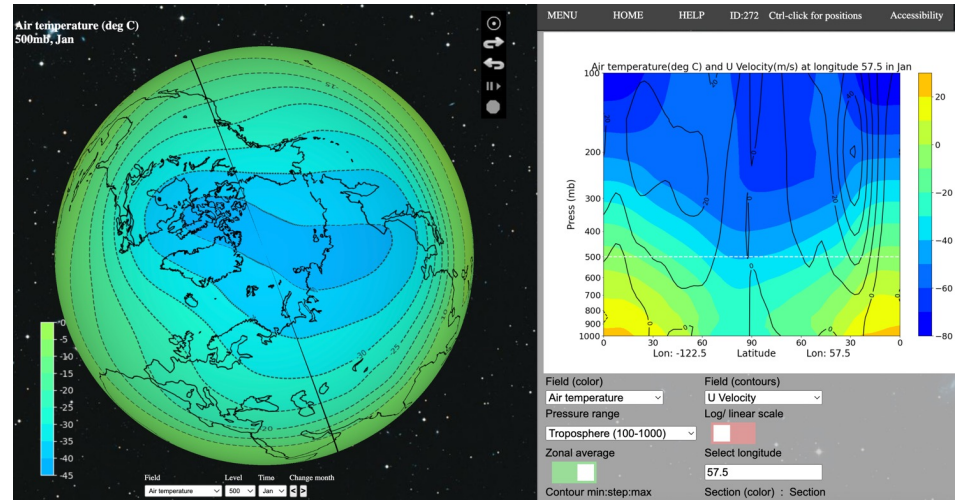
The SH is much more zonally symmetric → less land that break the zonal and meridional symmetries

Mean temperature

Example-

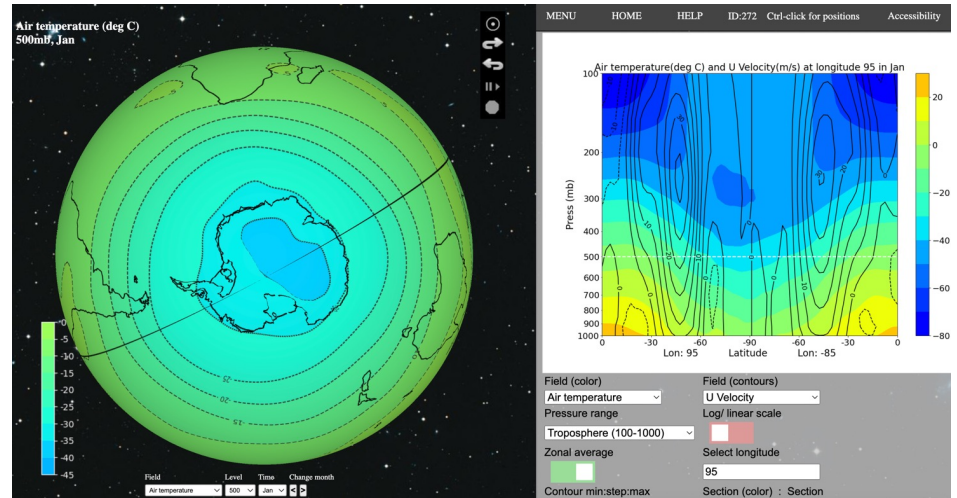
Cross section at some random longitude passing the pole

NH



The SH is much more zonally symmetric

SH



Thermal wind balance- Exercise

The Using EsGlobe, verify the thermal wind balance

$$\frac{\Delta u}{\Delta p} = \frac{R}{fP} \frac{\Delta T}{\Delta y}$$

$$R_d = 287 \text{ m}^2\text{K}^{-1}\text{sec}^{-2}$$

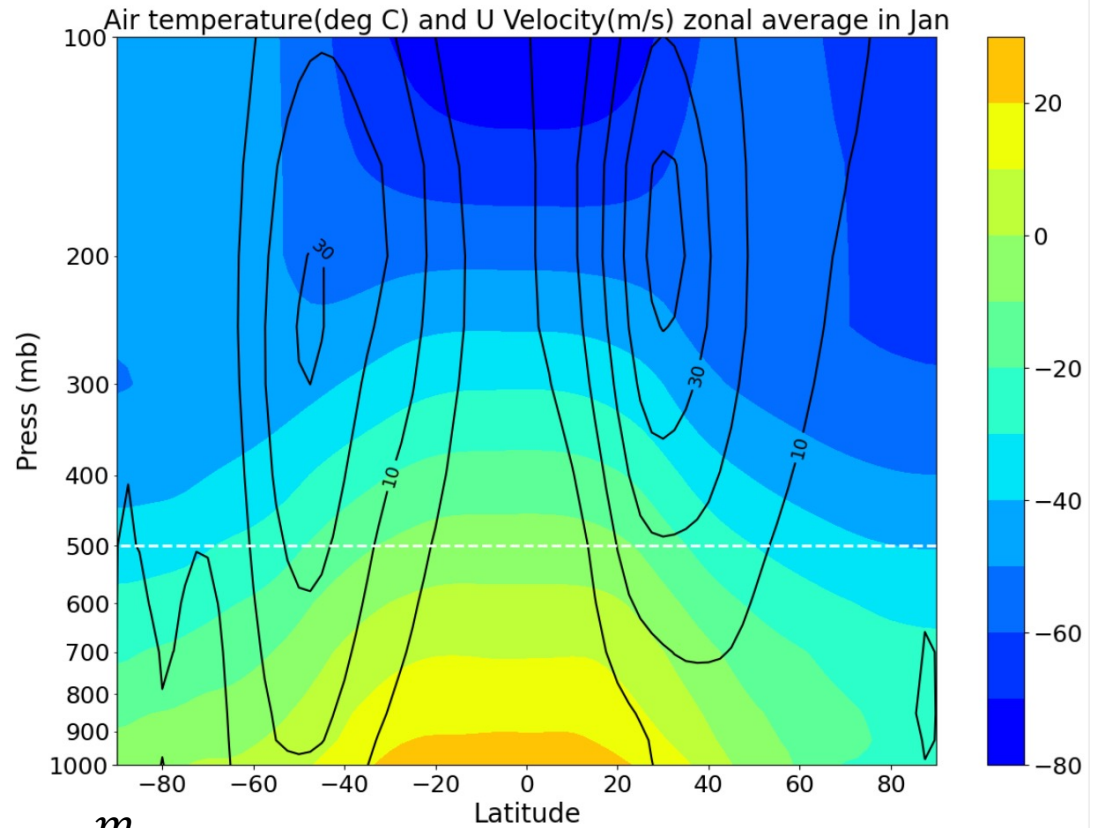
$$f \approx 10^{-4} \frac{\text{rad}}{\text{sec}}$$

$$\Delta u \approx 19 \frac{\text{m}}{\text{sec}}$$

$$\Delta P = 500 \text{ hPa}$$

$$\Delta T \approx 20 \frac{\text{m}}{\text{sec}}$$

$$\Delta y \approx 30^\circ \approx 30 \cdot 110 \text{ km}$$



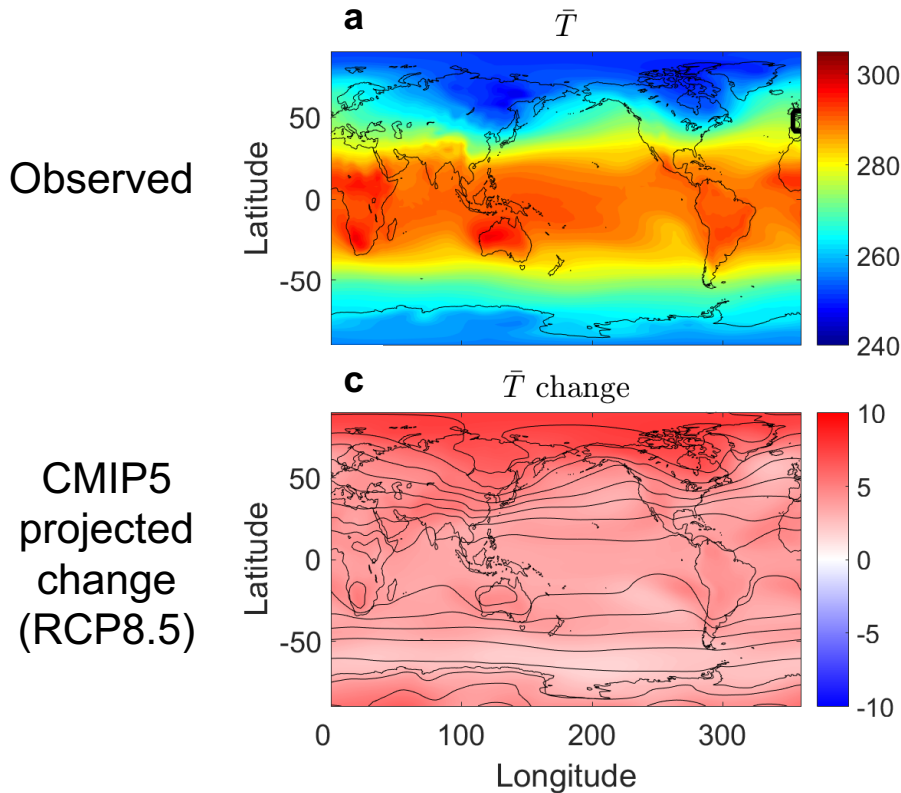
$$\frac{\Delta u}{\Delta p} = \frac{R}{fP} \frac{\Delta T}{\Delta y}$$



$$\frac{19 \frac{\text{m}}{\text{sec}}}{500 \text{ hPa}} \approx \frac{287 \text{ m}^2\text{K}^{-1}\text{sec}^{-2}}{10^{-4} \frac{\text{rad}}{\text{sec}} 500 \text{ hPa}} \frac{20^\circ\text{K}}{(30 \cdot 110 \cdot 10^3 \text{ m})}$$

Mean temperature and projected changes

DJF (850 hPa)

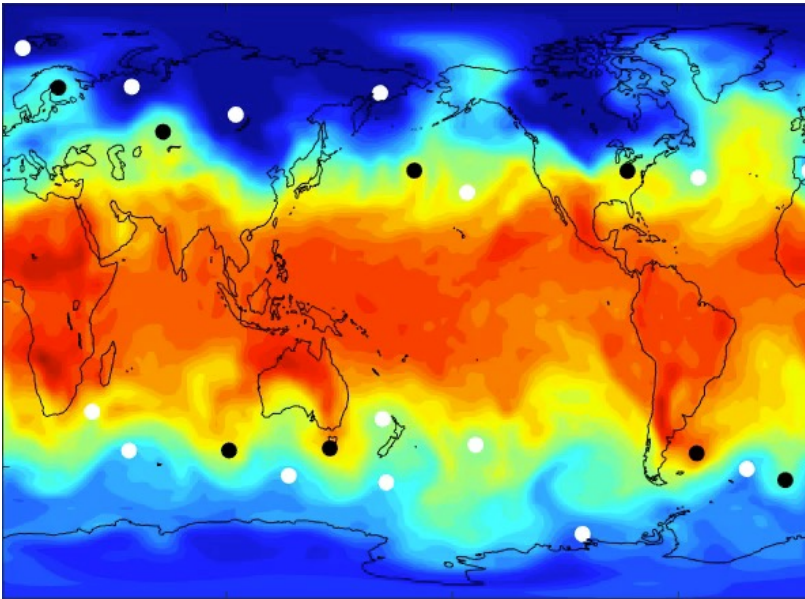
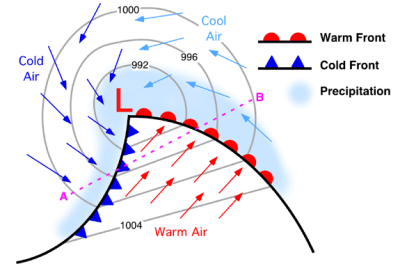


- Warm in the equator/tropics, cold in the poles
- Climatological mean temperature increases everywhere, but more in the NH pole (Arctic Amplification)

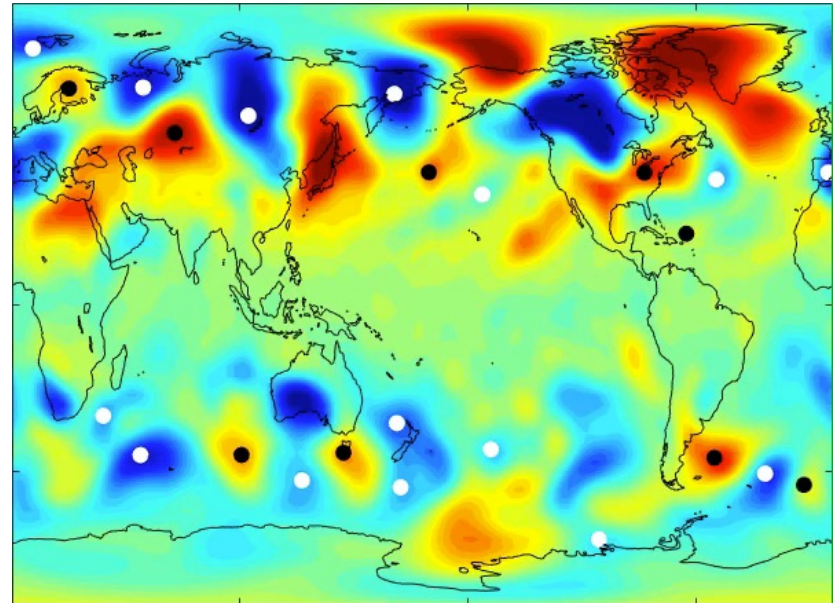
Temperature anomalies

Deviations from the climatological mean-

$$T' = T - T_{clim}$$



Full temperature (850hPa)



Temperature anomaly (850hPa)

Anomalies are defined as deviations from the climatology

The life-time these anomalies is roughly 7 days- also called synoptic eddies!

A link to last week's T850 movie-

<http://synoptic.mit.edu:3001/animated-forecast/last-week/850>

Weather vs. Climate

Weather



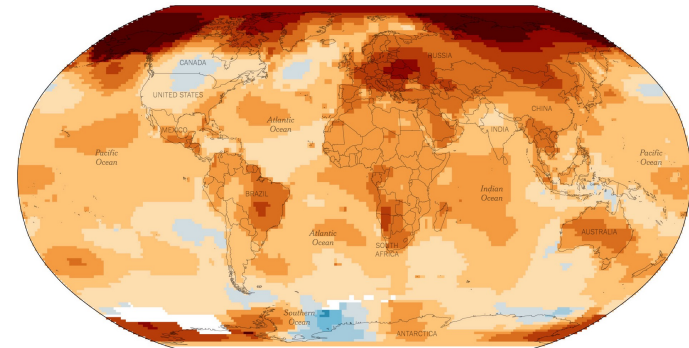
NOAA GOES

Winter storm 2018: almost the entire East Coast is covered in snow

Boston's streets were flooded with icy stormwaters.

By Brian Resnick | @B_resnick | brian@vox.com | Updated Jan 5, 2018, 1:47pm EST

Climate



NASA Goddard Institute for Space Studies

Degrees cooler or warmer in 2019
compared to the middle of the 20th century



2019 Was the Second-Hottest Year Ever, Closing Out the Warmest Decade

By Henry Fountain and Nadja Popovich Jan. 15, 2020

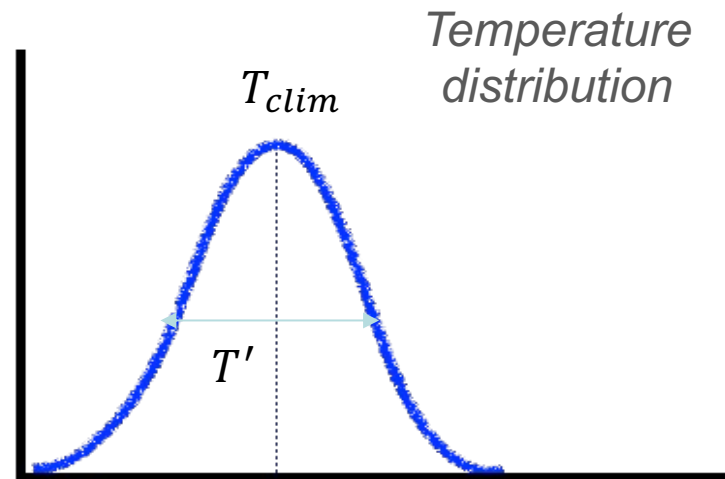
How can we think about temperature anomalies from a “climate” perspective?

Temperature variance

Anomalies: deviations from the climatological mean-

$$T' = T - T_{clim}$$

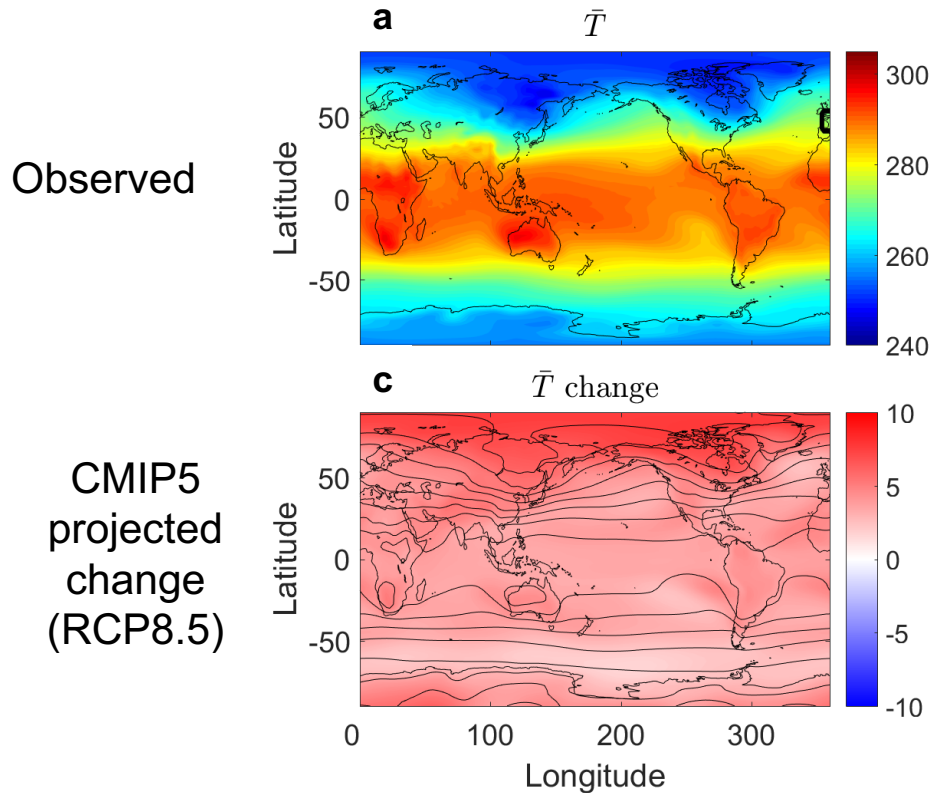
$$\text{Var} = \overline{T'^2}$$



- Temperature variability can be described by the underlying temperature Probability Density Function (PDF)
- Temperature **variance** measures the width of the PDF
- Measures how variable are temperature fluctuations around the mean temperature

Temperature variability and projected changes

DJF (850 hPa)



- Temperature variance is larger in the mid-latitudes and over the continents
- Temperature variance decreases over most of the NH (Screen 2014, Schneider et. al 2015)

Meridional temperature advection dominates temperature changes in the atmosphere

Assuming temperature is conserved and dominated by horizontal advection-

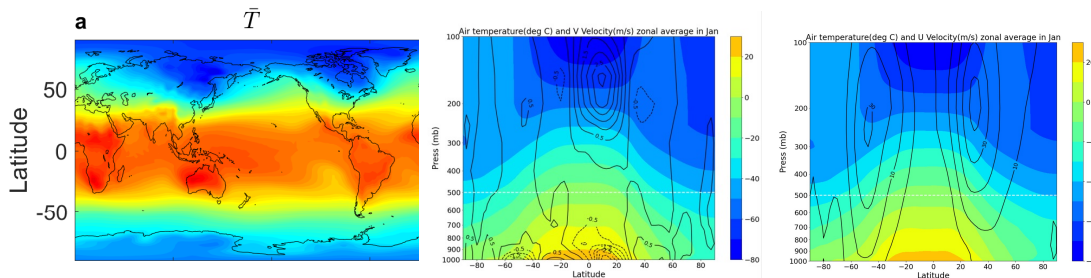
$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = 0$$

Assuming further:

$$T = T' + \bar{T} \quad \text{where} \quad T' \ll \bar{T}$$

And also- $\frac{\partial \bar{T}}{\partial x} \ll \frac{\partial \bar{T}}{\partial y}$ & $\bar{v} \ll \bar{u}$

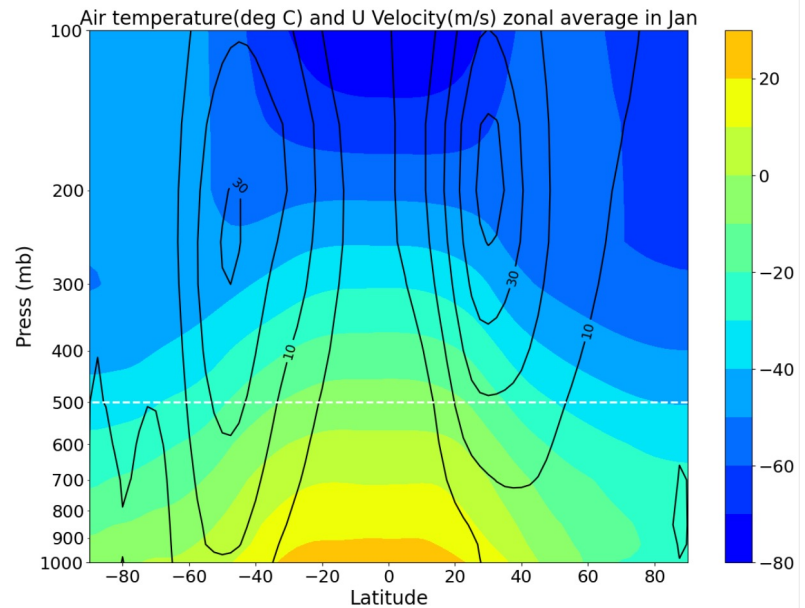
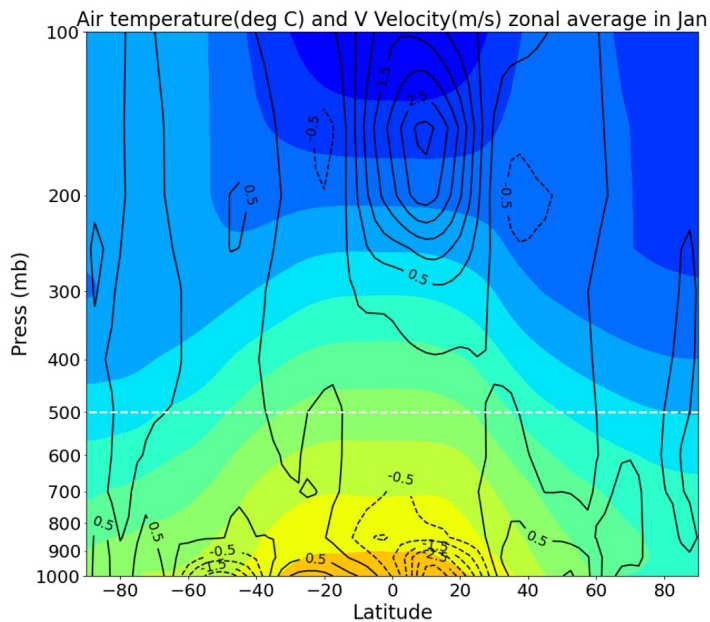
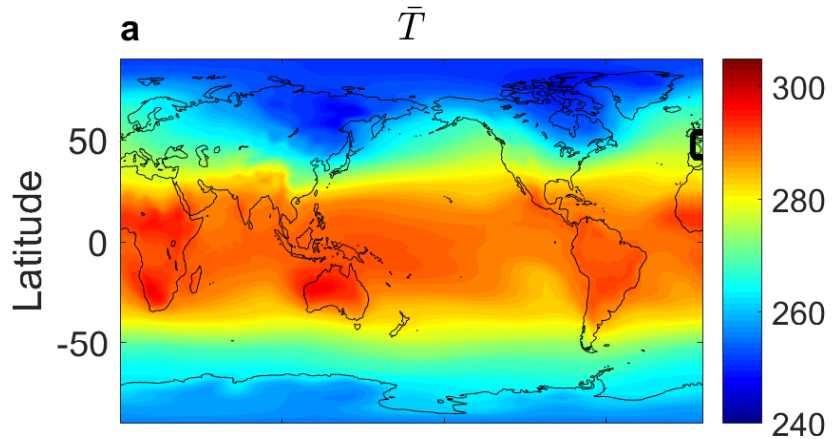
(how justified are these assumption?? Check!)



$$\frac{\partial T'}{\partial t} = -v' \frac{\partial \bar{T}}{\partial y}$$

How justified are these assumption?

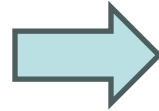
$$\frac{\partial \bar{T}}{\partial x} \ll \frac{\partial \bar{T}}{\partial y}$$



$$\bar{v} \ll \bar{u}$$

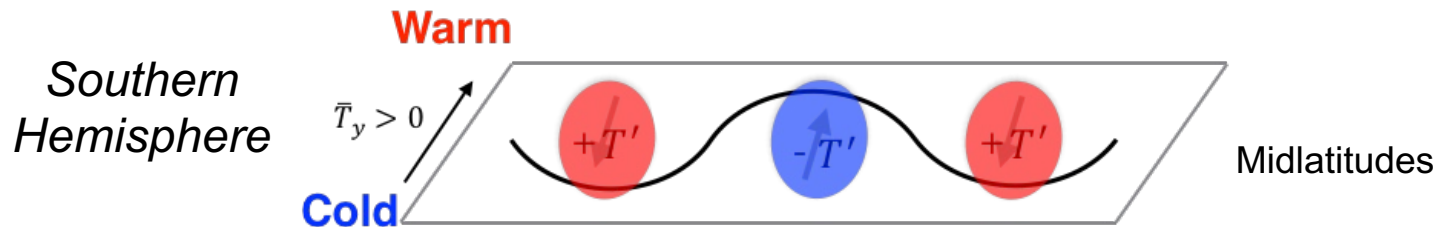
Temperature anomalies form due to meridional temperature advection

$$\frac{\partial T'}{\partial t} = -v' \frac{\partial \bar{T}}{\partial y}$$



$$T' = -\eta' \frac{\partial \bar{T}}{\partial y}$$

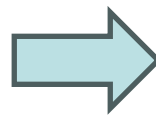
$$v' = \frac{D\eta'}{Dt}$$



Temperature variance

~

**Meridional
temperature gradient**

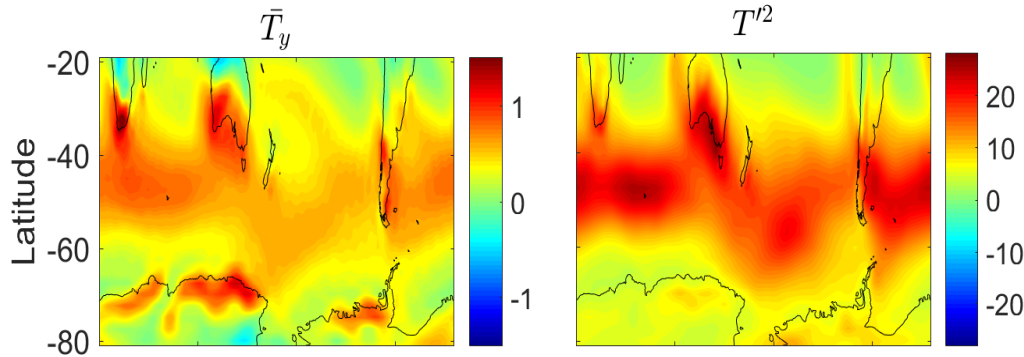


$$\overline{T'^2} = \overline{\eta'^2} \left(\frac{\partial \bar{T}}{\partial y} \right)^2$$

Temperature variance in the Southern Hemisphere

$$\overline{T'^2} = \overline{\eta'^2} \left(\frac{\partial \bar{T}}{\partial y} \right)^2$$

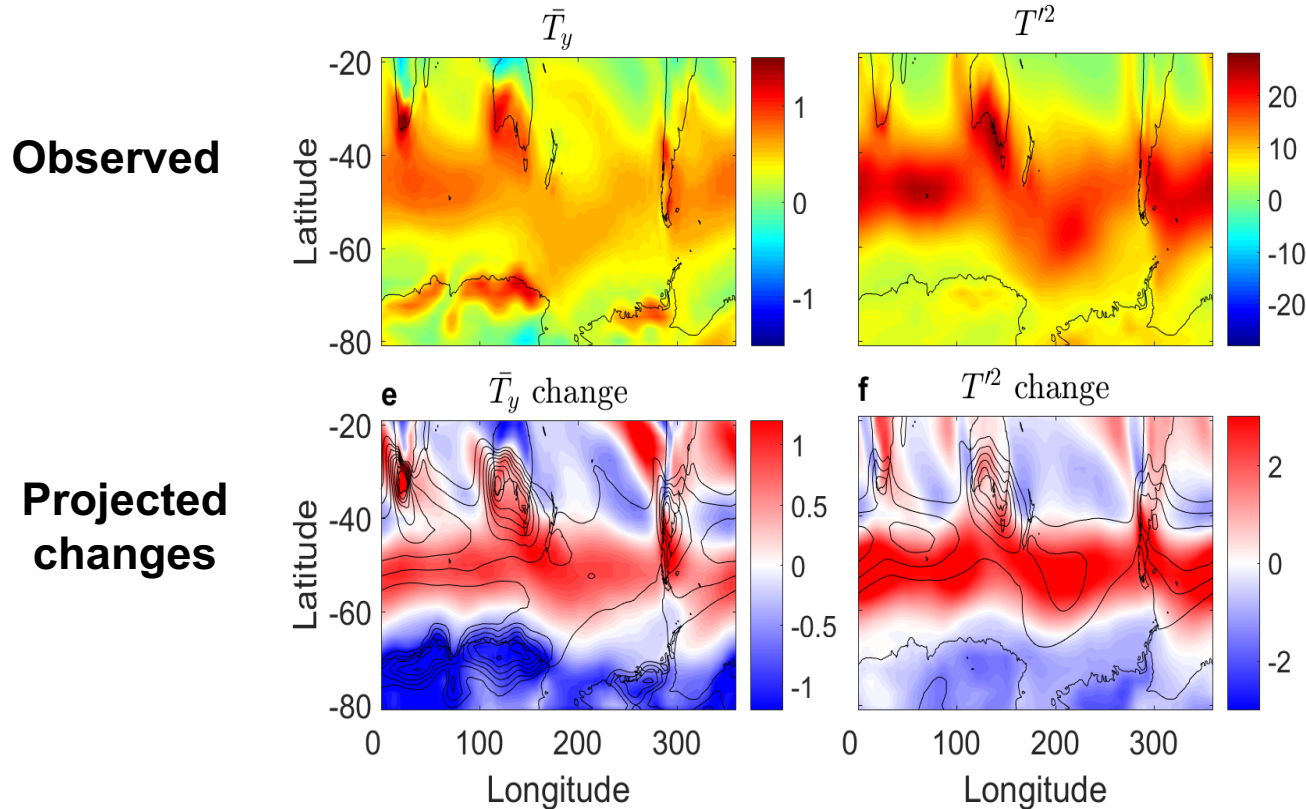
Observed



- The Southern Hemisphere (SH) meridional temperature gradient is maximized in the midlatitudes
- Consistent with that, temperature variance is also maximized in the SH midlatitudes

Temperature variance in the Southern Hemisphere

$$\overline{T'^2} = \overline{\eta'^2} \left(\frac{\partial \bar{T}}{\partial y} \right)^2$$

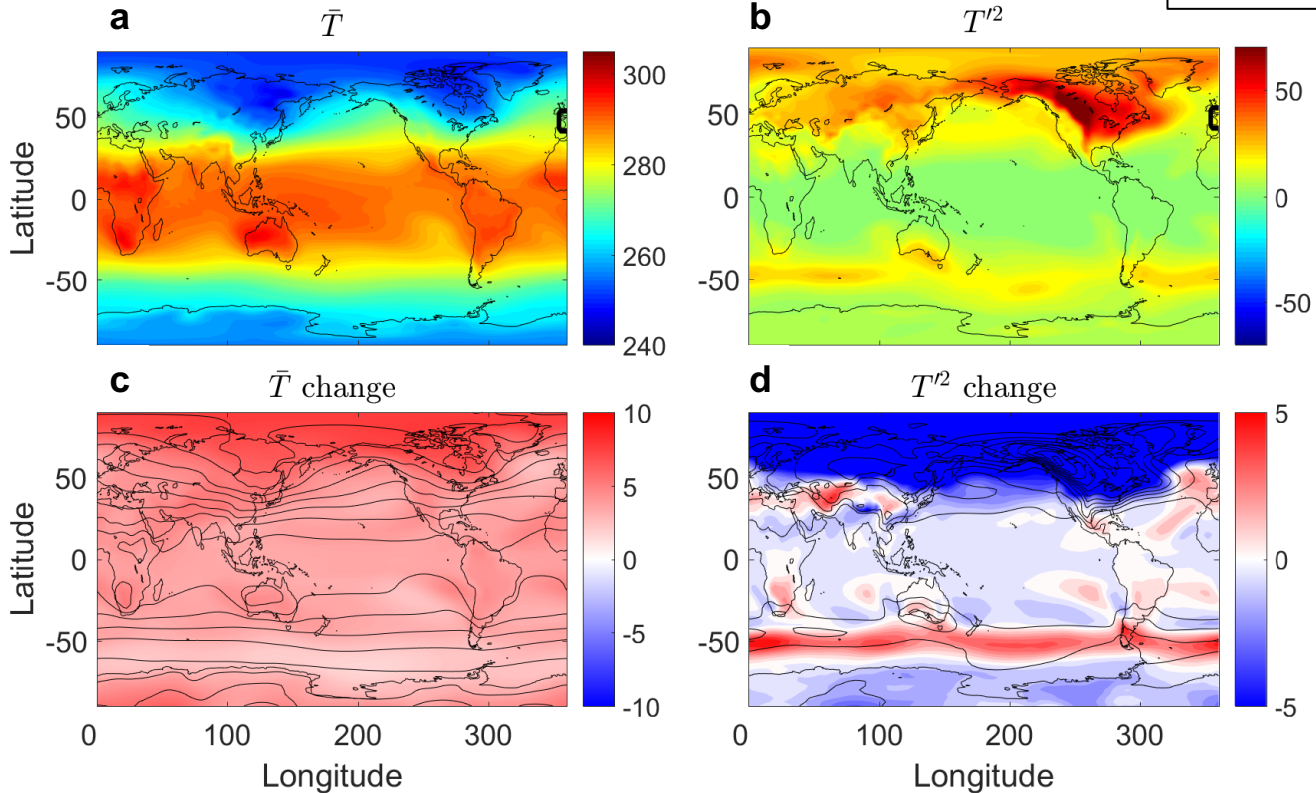


- The SH meridional temperature gradient increases in the future
- Consistent with that, temperature variance increases

Temperature variance in the Northern Hemisphere

$$\overline{T'^2} = \overline{\eta'^2} \left(\frac{\partial \bar{T}}{\partial y} \right)^2$$

Observed



- Temperature variance is larger in the mid-latitudes and over the continents
- Temperature variance decreases over most of the NH (Screen 2014, Schneider et. al 2015)

Exercise-

- Go to the course website (2nd project, Observation Data) and download the zip folder “temperature_variability”.
- Unzip the files and put them in the same folder
- Run the file plot_temp_models_for_class.m (in MATLAB) or the script “course_plot_t2m.py” (in python).
- This should produce a figure showing the historical mean T2m data for one model in the first data year
- Now, modify the script so that it plots the mean over all models and all years, and plot the historical mean T2m, historical T2m variance, and their projected changes. There are some instructions on the script.

Questions:

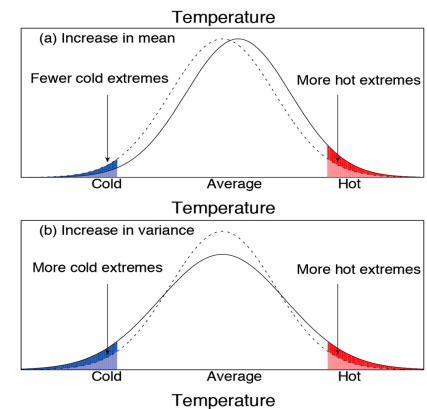
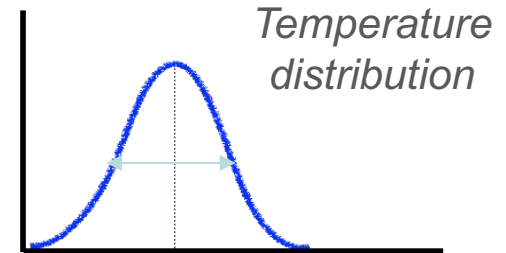
- What do you find for the T2m mean temperature and variance in the historical simulations? Is it similar to what we found for the 850mb level?
- What do the projected mean temperature and variance show? Can you explain this response using temperature advection arguments?
- **Optional:** Examine the model-to-model spread and the year-to-year variability of global mean temperature. Do all models agree on the changes? Can you observe a trend in the historical/projected data? Is the trend larger than the year-to-year variability?

Extra slides-

**The role of temperature advection for
temperature skewness**

Temperature variability

- Temperature variability can be described by the underlying PDF. However, very often mistakenly measured as the **variance** of the PDF ($\overline{T'^2}$)
- Similarly, when studying temperature extremes and their response to climate change, often only the mean and variance changes are discussed



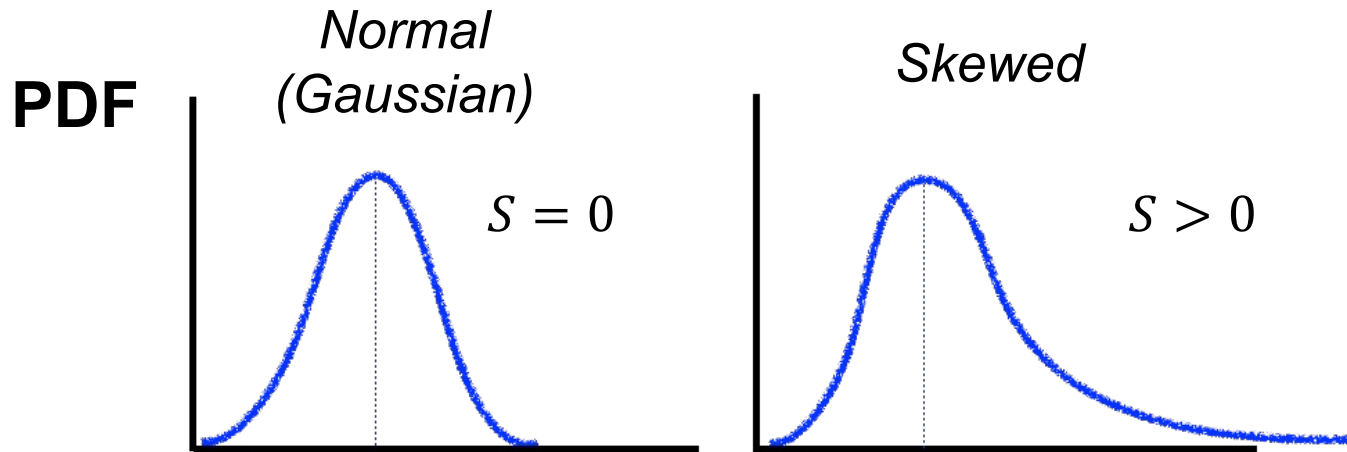
For example, response of temperature extremes to climate change (IPCC AR5 report)

However, several previous studies highlighted the importance of the higher order terms and the non-Gaussianity of the underlying PDFs

(e.g., Garfinkel & Harnik 2016; Loikith and Neelin 2015; Sardeshmukh et al. 2015...)

Skewness

Skewness measures the *asymmetry* of the PDF. It usually involves the tails and thus strongly related to extremes events



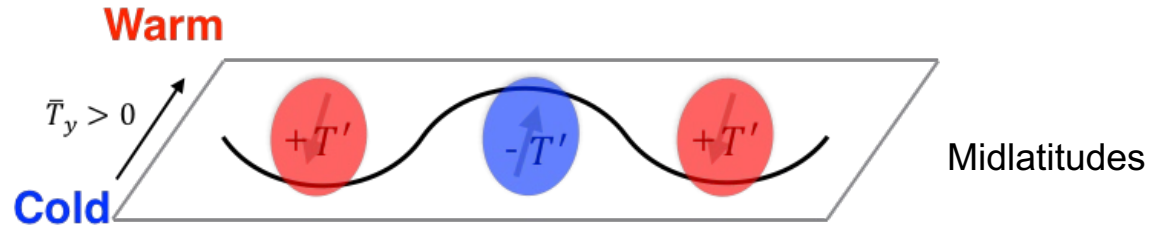
Skewness $S = \frac{\overline{T'^3}}{(\overline{T'^2})^{3/2}}$

For example: for a right-skewed PDF, the positive tail is longer than the negative tail (extreme warm anomalies occur more frequently)

How is skewness generated?

Linear Vs. Nonlinear advection

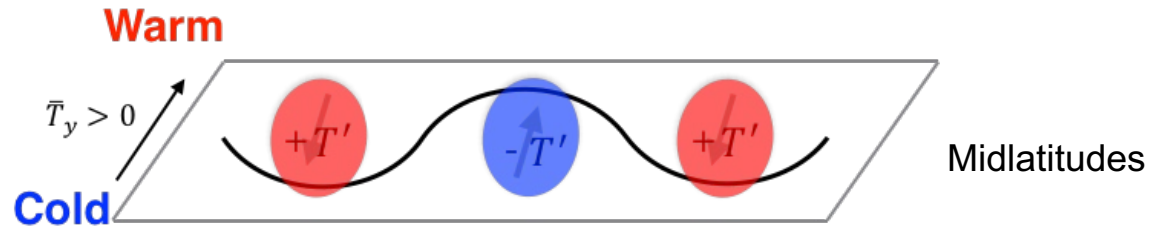
$$T' = -\eta' \frac{\partial \bar{T}}{\partial y}$$



How is skewness generated?

Linear Vs. Nonlinear advection

$$T' = -\eta' \frac{\partial \bar{T}}{\partial y}$$

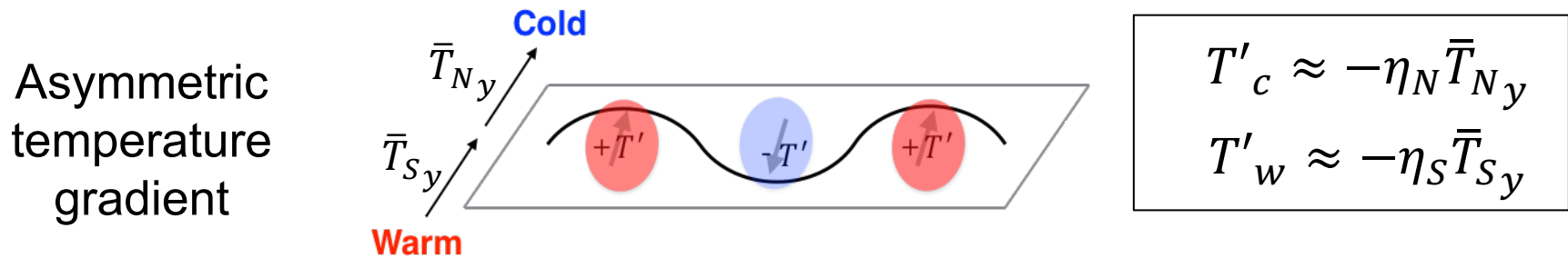


If the background temperature gradient is symmetric for poleward and equatorward motions → warm and cold anomalies will have alternating signs but equal magnitudes

→ *skewness is zero!*

$$S = 0$$

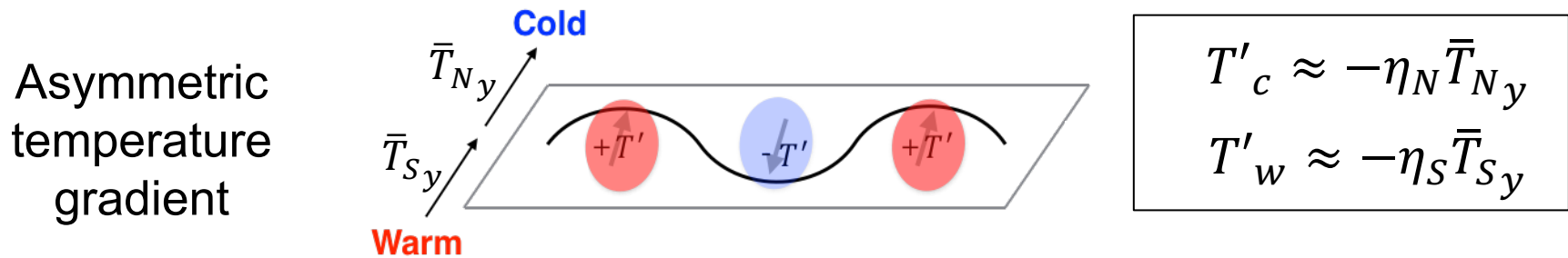
Skewness due to asymmetric linear advection



If the gradients to the north & south are different:

$$S = \frac{T_w - T_c}{\sigma}$$

Skewness due to asymmetric linear advection



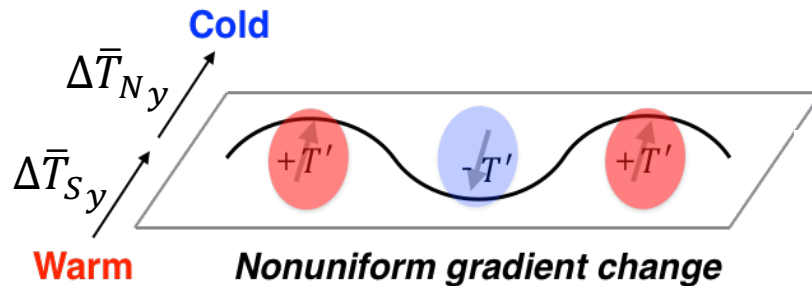
If the gradients to the north & south are different:

$$S = \frac{T_w - T_c}{\sigma} \sim \frac{\eta_S = \eta_N}{\frac{1}{2} (|\bar{T}_{Ny}| + |\bar{T}_{Sy}|)} \left(|\bar{T}_{Sy}| - |\bar{T}_{Ny}| \right)$$

For example, if the background temperature gradient to the north is smaller, then the cold anomalies are weaker and the skewness is therefore positive

Skewness changes due to asymmetric background temperature gradient changes

Assume nonuniform gradient changes to the north and south-



Change in cold anomalies-

$$\Delta T'_c \sim -\eta_N \Delta\bar{T}_{Ny}$$

Change in warm anomalies-

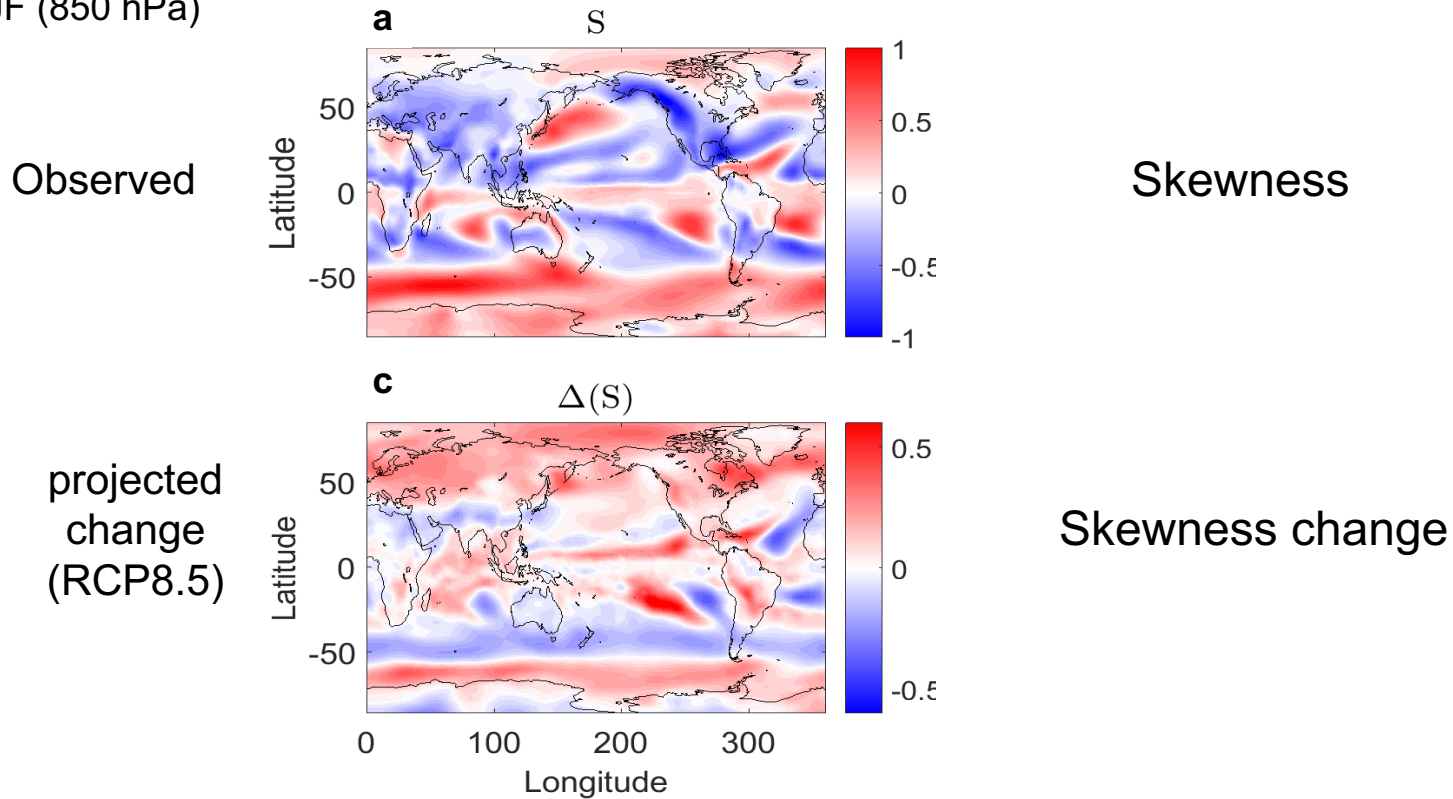
$$\Delta T'_w \sim -\eta_S \Delta\bar{T}_{Sy}$$

For example, if the background temperature gradient to the north weakens more, then the cold anomalies weaken more compared to warm anomalies and there is therefore a positive skewness change!

This is what happens over most of the NH during winter → since Arctic Amplification is largest near the NH pole → cold anomalies weaken more

Temperature variability and its response to climate change

DJF (850 hPa)



Mostly a positive skewness changes is found in the NH

Temperature gradient weakens mostly near the NH pole → it is mostly the cold anomalies that weaken in the future!

Thermal wind balance

The most fundamental and significant dynamical balance controlling the large-scale circulation of the atmosphere and ocean. A consequence of hydrostatic and geostrophic balance!

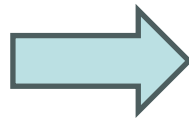
Assuming a small Rossby number-

$$u_g = -\frac{1}{\rho f} \frac{\partial p}{\partial y};$$
$$v_g = \frac{1}{\rho f} \frac{\partial p}{\partial x}.$$

And a hydrostatic balance (at rest in the vertical)

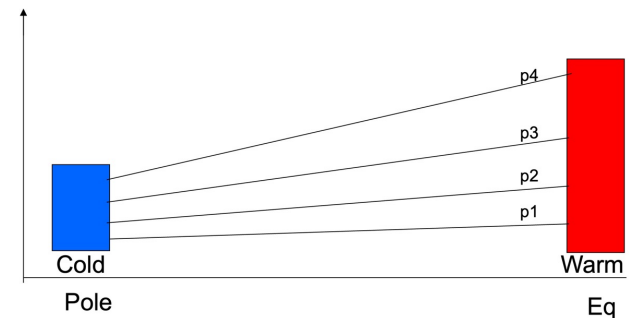
$$\frac{\partial p}{\partial z} + g\rho = 0$$

$$1/\rho = RT/p$$



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

$$\frac{\partial v}{\partial p} = -\frac{R}{fp} \left(\frac{\partial T}{\partial x} \right)_p$$



Relates horizontal temperature gradients to changes in the horizontal wind with pressure/height. See class [notes](#) on thermal wind for full derivation

See class [notes](#) on thermal wind for full derivation

hydrostatic relation thus:

$$\frac{\partial z}{\partial p} = -\frac{1}{g\rho}.$$

and take, for example, the p -derivative of the x -component of the geostrophic wind in pressure coordinates — $(u_g, v_g) = \left(-\frac{g}{f}\frac{\partial z}{\partial y}, \frac{g}{f}\frac{\partial z}{\partial x}\right)$ — yielding:

$$\frac{\partial u}{\partial p} = -\frac{g}{f}\frac{\partial^2 z}{\partial p \partial y} = -\frac{g}{f}\left(\frac{\partial}{\partial y}\left[\frac{\partial z}{\partial p}\right]\right)_p = \frac{1}{f}\frac{\partial}{\partial y}\left(\frac{1}{\rho}\right)_p.$$

Since $1/\rho = RT/p$, its derivative *at constant pressure* is

$$\frac{\partial}{\partial y}\left(\frac{1}{\rho}\right)_p = \frac{R}{p}\left(\frac{\partial T}{\partial y}\right)_p,$$

whence

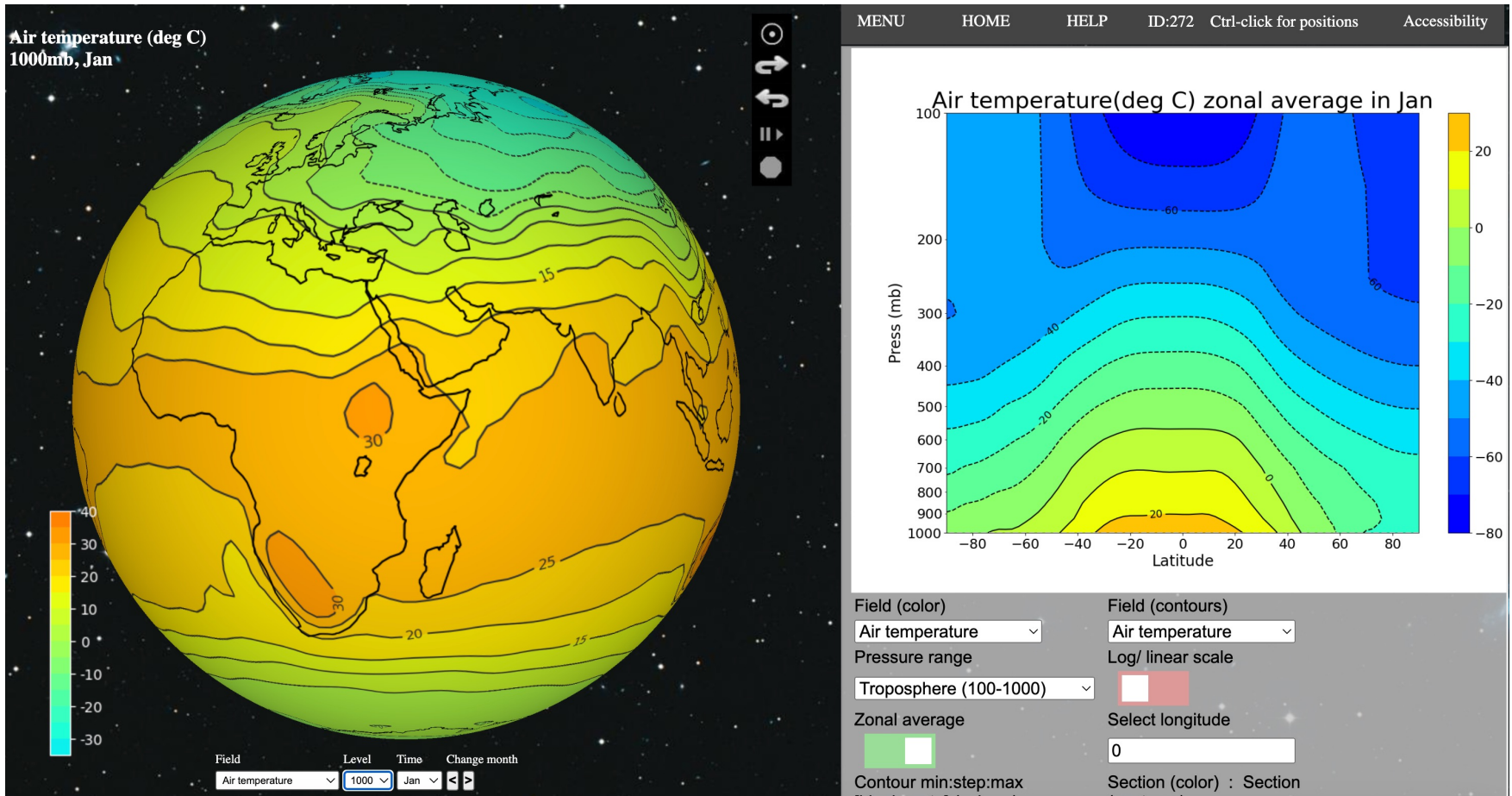
$$\frac{\partial u}{\partial p} = \frac{R}{fp}\left(\frac{\partial T}{\partial y}\right)_p.$$

Similarly, for v we find

$$\frac{\partial v}{\partial p} = -\frac{R}{fp}\left(\frac{\partial T}{\partial x}\right)_p.$$

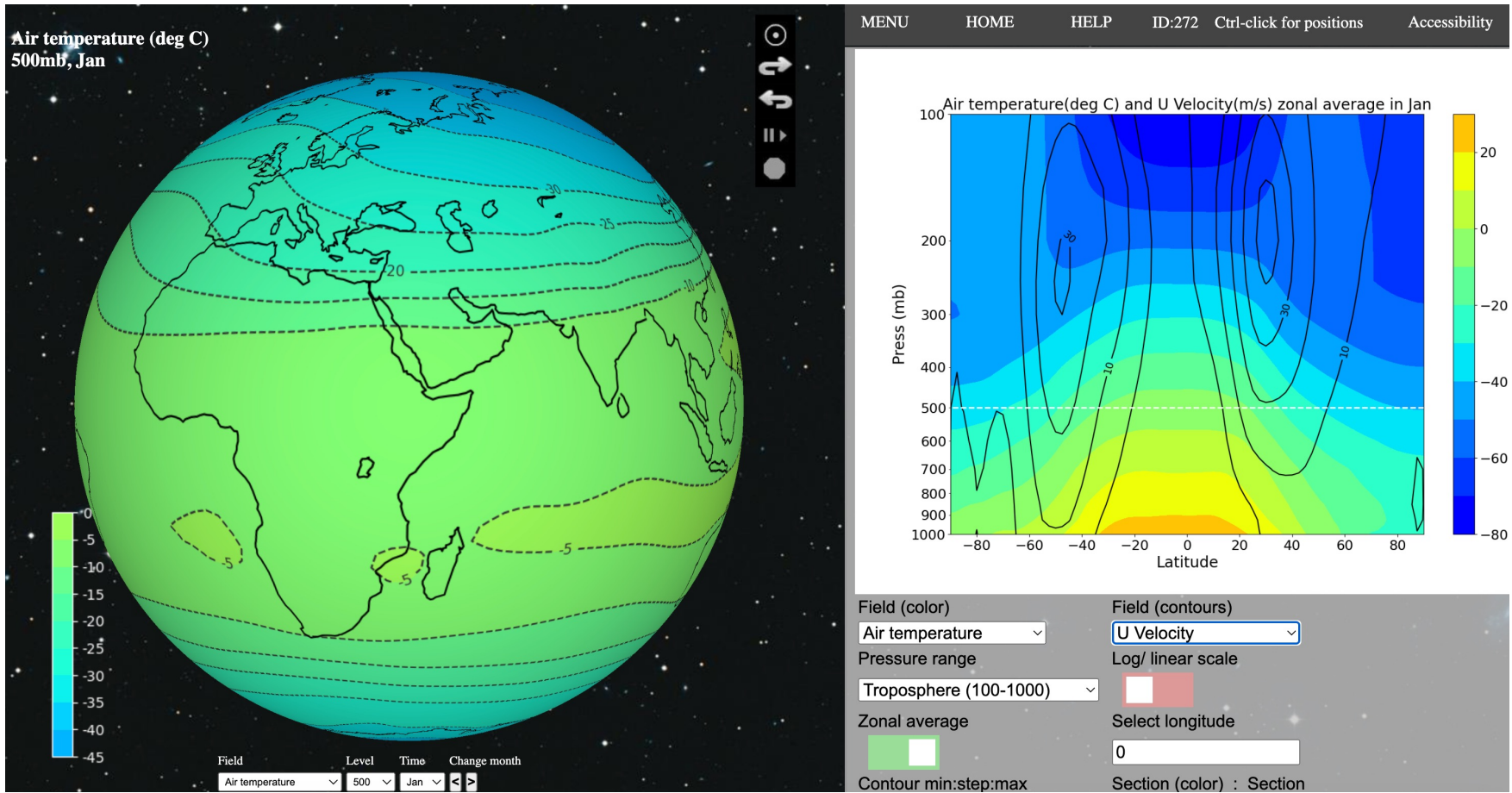
Mean temperature

1000 mb T mean + Vertical structure of zonal mean T

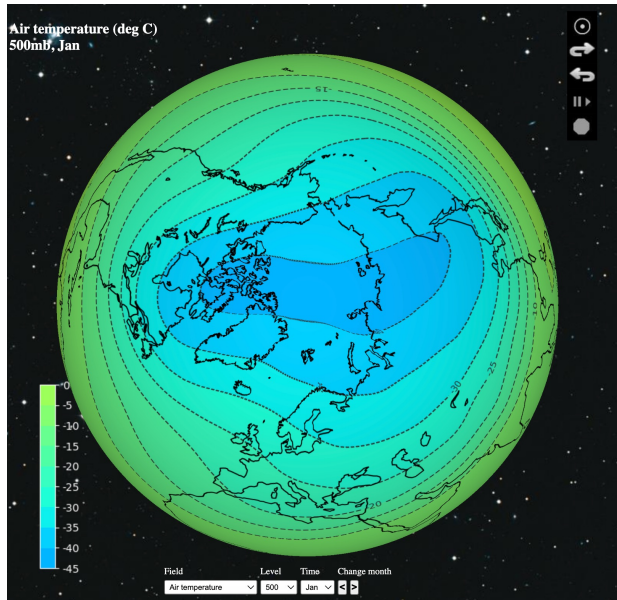


Mean temperature

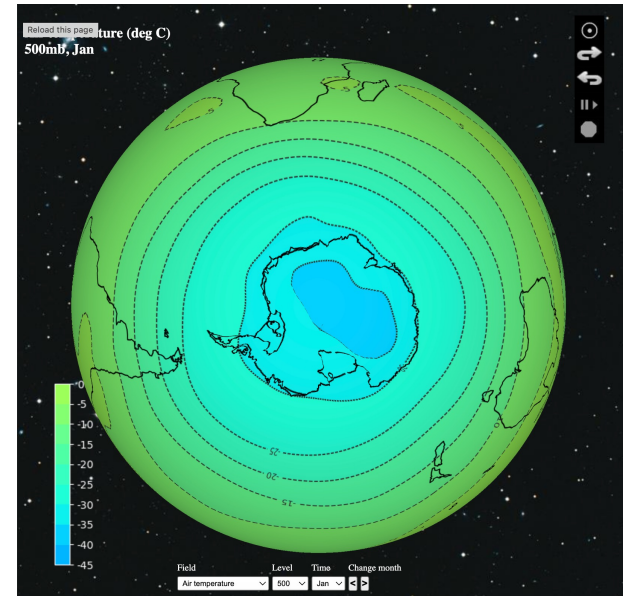
500 mb T mean + Vertical structure of zonal mean T + Zonal mean U



Mean temperature



NH pole view
mean T 500 mb



SH pole view
mean T 500 mb

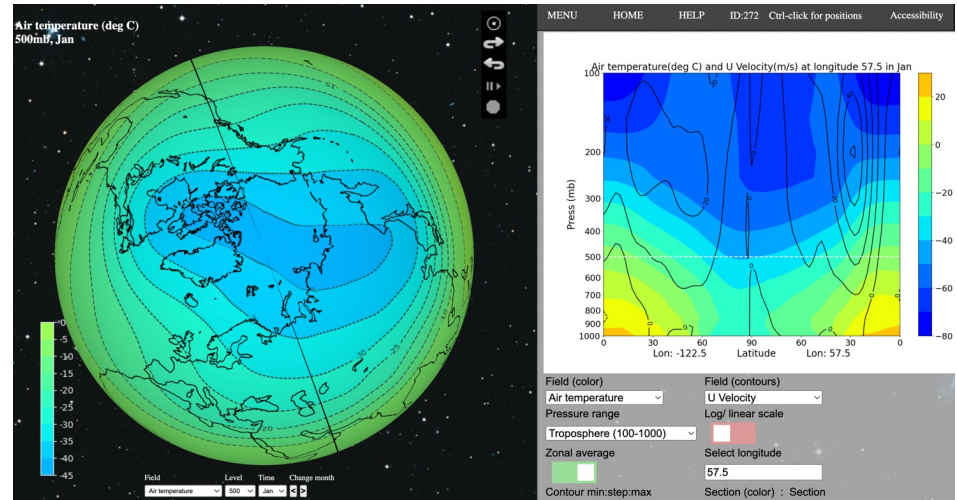
The SH is much more zonally symmetric → less land that break the zonal and meridional symmetries

Mean temperature

Example-

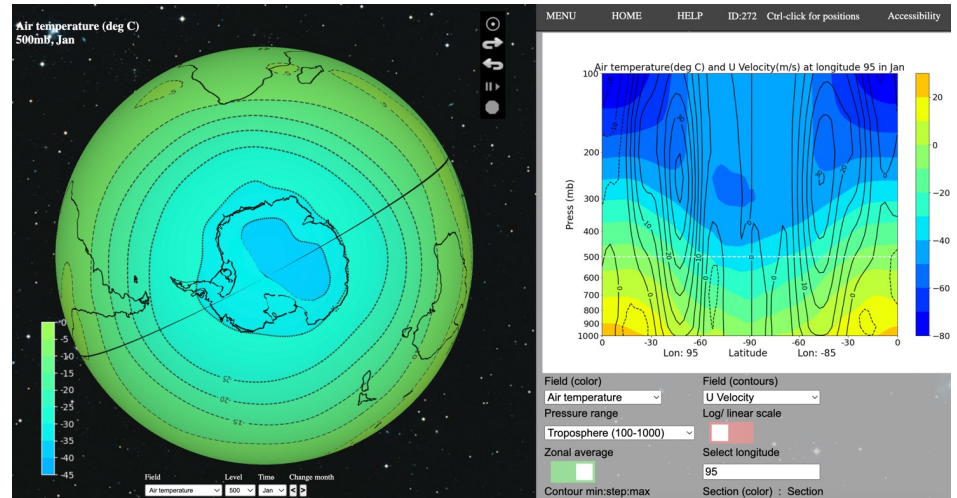
Cross section at some random longitude passing the pole

NH



The SH is much more zonally symmetric

SH



Thermal wind balance- Exercise

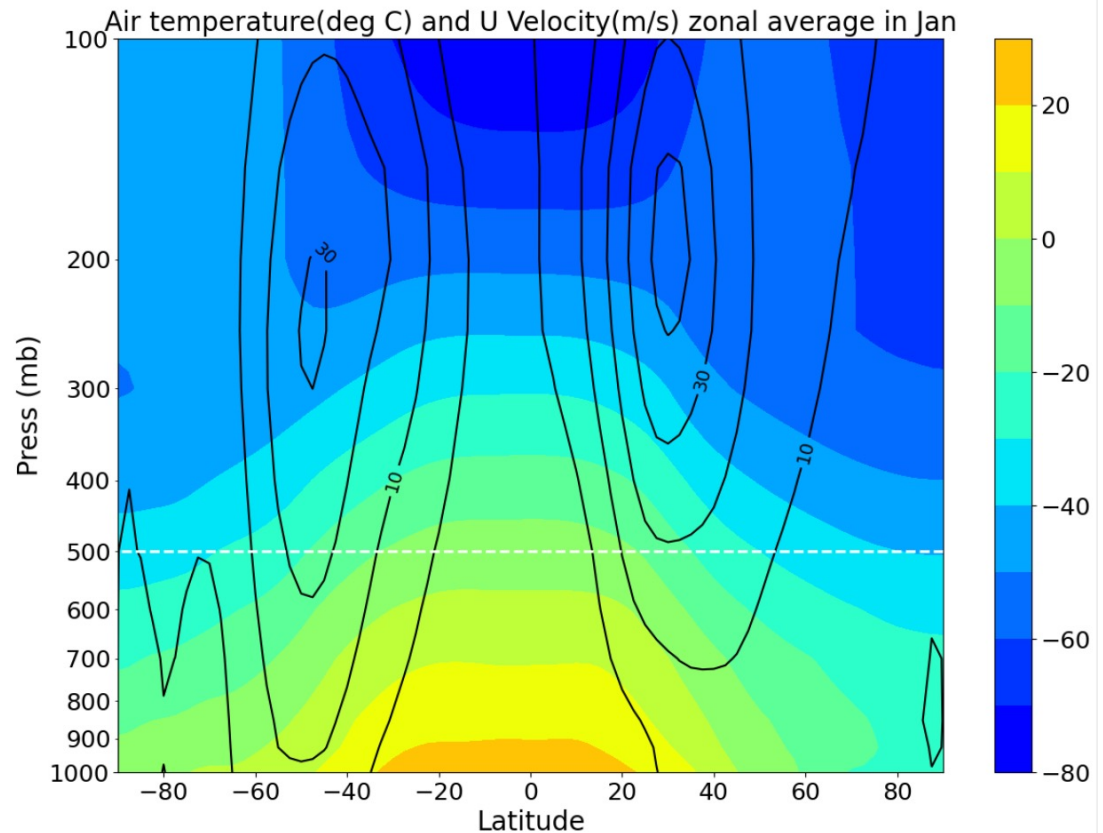
The Using EsGlobe, verify the thermal wind balance

$$\frac{\Delta u}{\Delta p} = \frac{R}{fP} \frac{\Delta T}{\Delta y}$$

$$R_d = 287 \text{ m}^2 \text{K}^{-1} \text{s}^{-2}$$

$$f \approx 10^{-4} \text{ s}^{-1}$$

$$\Delta u \approx \frac{R}{fP} \frac{\Delta T}{\Delta y} \Delta p$$



Thermal wind balance- Exercise

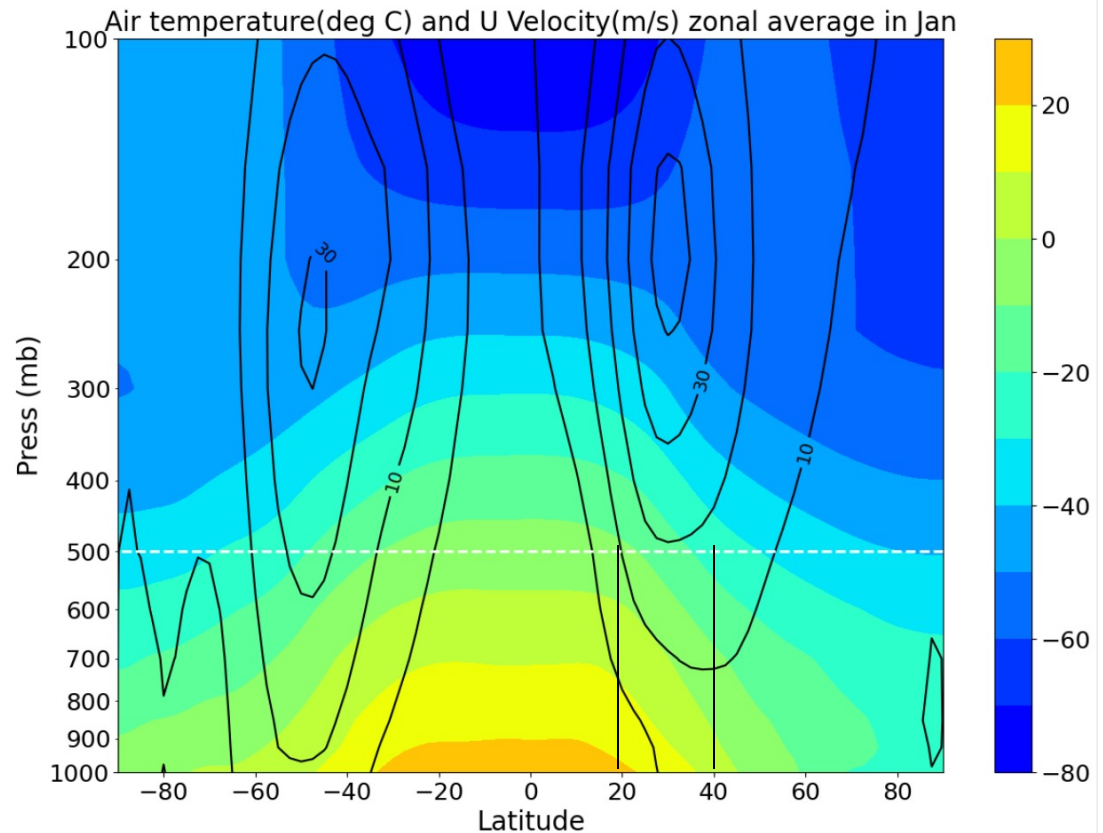
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Thermal wind balance- Exercise

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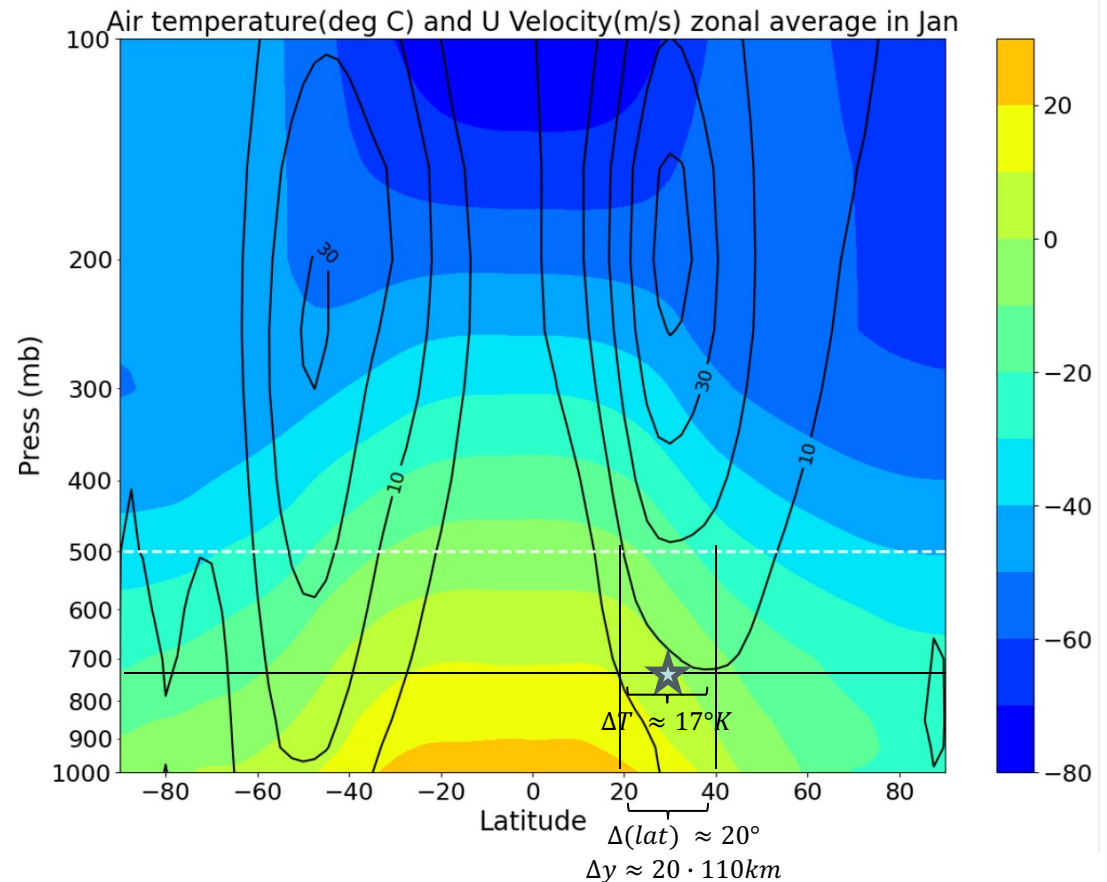
$$\Delta u \approx 19 \frac{\text{m}}{\text{sec}}$$

$$\Delta P = 500 \text{ hPa}$$

$$P \approx 720 \text{ hPa}$$

$$\Delta T \approx 18^\circ \text{K}$$

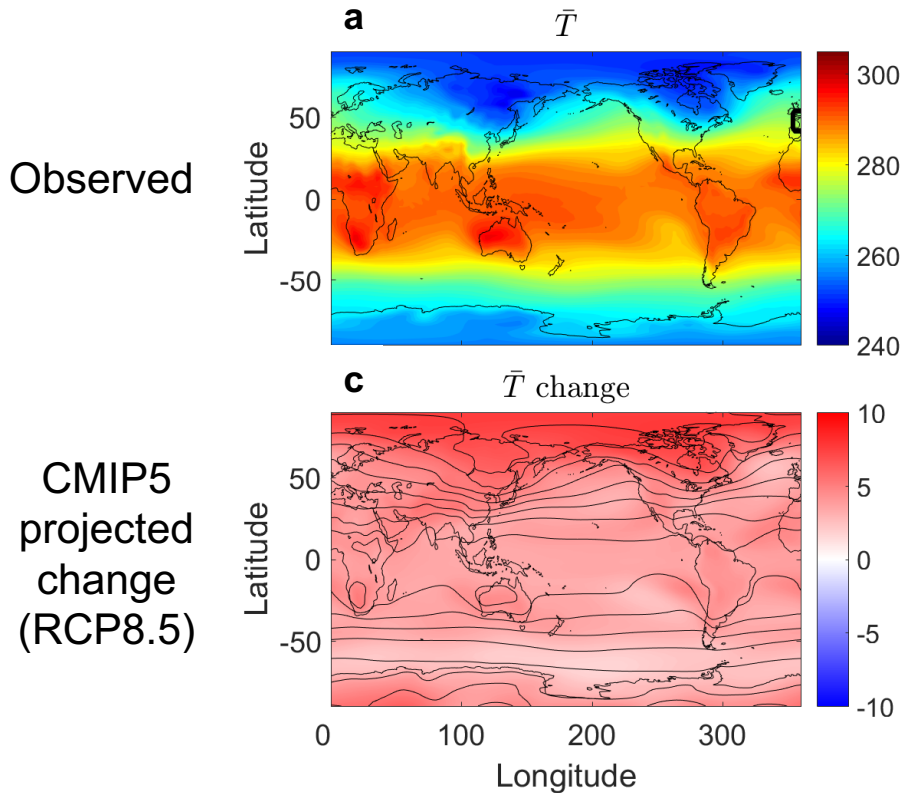
$$\Delta y \approx 20^\circ \approx 20 \cdot 110 \text{ km}$$



$$\Delta u \approx \frac{287 \text{ m}^2 \text{K}^{-1} \text{s}^{-2}}{10^{-4} \text{ s}^{-1} 720 \text{ hPa}} \frac{18^\circ \text{K}}{(20 \cdot 110 \cdot 10^3 \text{ m})} 500 \text{ hPa} \approx 16.3 \frac{\text{m}}{\text{sec}}$$

Mean temperature and projected changes

DJF (850 hPa)



*Arctic Amplification occurs mainly due to the **Ice-albedo effect**:*

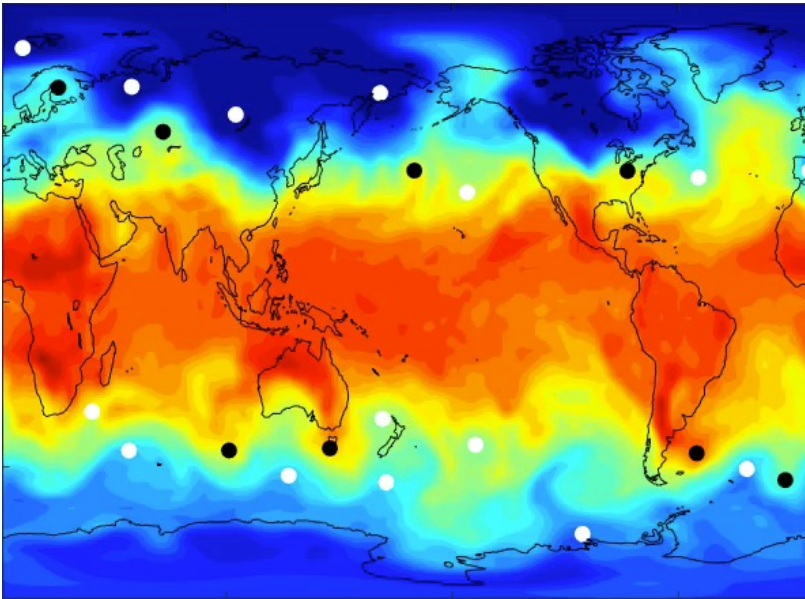
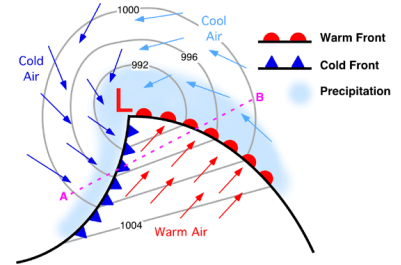
Warming → snow and ice melt → reflective ice-covered area decreases → albedo decreases → more solar energy absorbed → more warming!

- Warm in the equator/tropics, cold in the poles
- Climatological mean temperature increases everywhere, but more in the NH pole (Arctic Amplification)

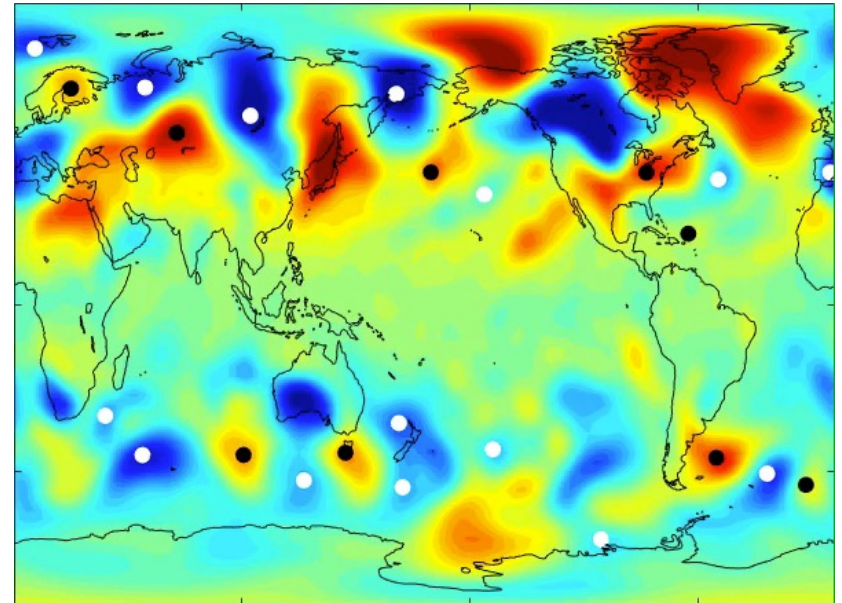
Temperature anomalies

Deviations from the climatological mean-

$$T' = T - T_{clim}$$



Full temperature (850hPa)



Temperature anomaly (850hPa)

Anomalies are defined as deviations from the climatology

The life-time these anomalies is roughly 7 days- also called synoptic eddies!

A link to last week's T850 movie-

<http://synoptic.mit.edu:3001/animated-forecast/last-week/850>

Weather vs. Climate

Weather



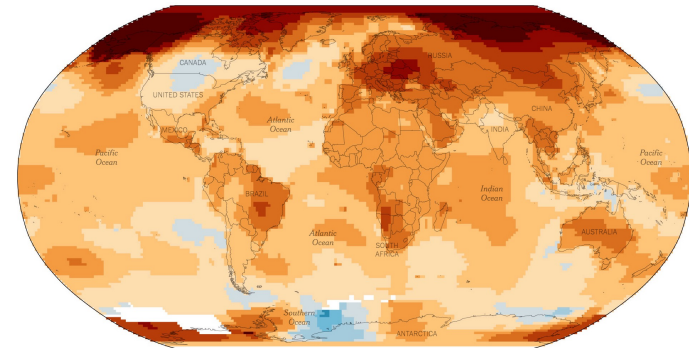
NOAA GOES

Winter storm 2018: almost the entire East Coast is covered in snow

Boston's streets were flooded with icy stormwaters.

By Brian Resnick | @B_resnick | brian@vox.com | Updated Jan 5, 2018, 1:47pm EST

Climate



NASA Goddard Institute for Space Studies

Degrees cooler or warmer in 2019
compared to the middle of the 20th century



2019 Was the Second-Hottest Year Ever, Closing Out the Warmest Decade

By Henry Fountain and Nadja Popovich Jan. 15, 2020

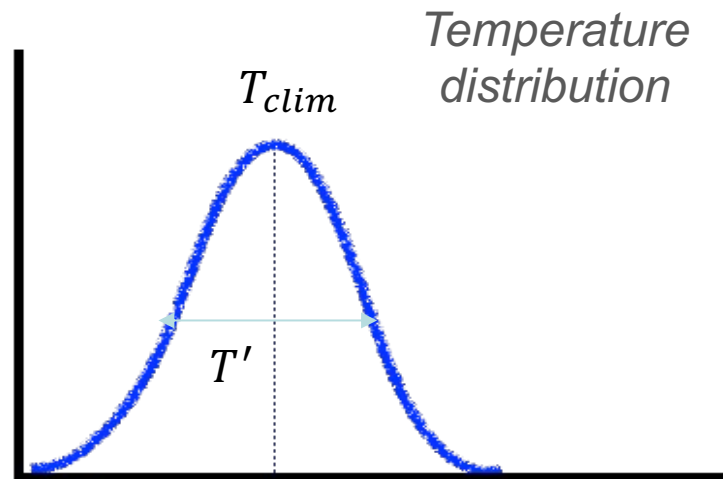
How can we think about temperature anomalies from a “climate” perspective?

Temperature variance

Anomalies: deviations from the climatological mean-

$$T' = T - T_{clim}$$

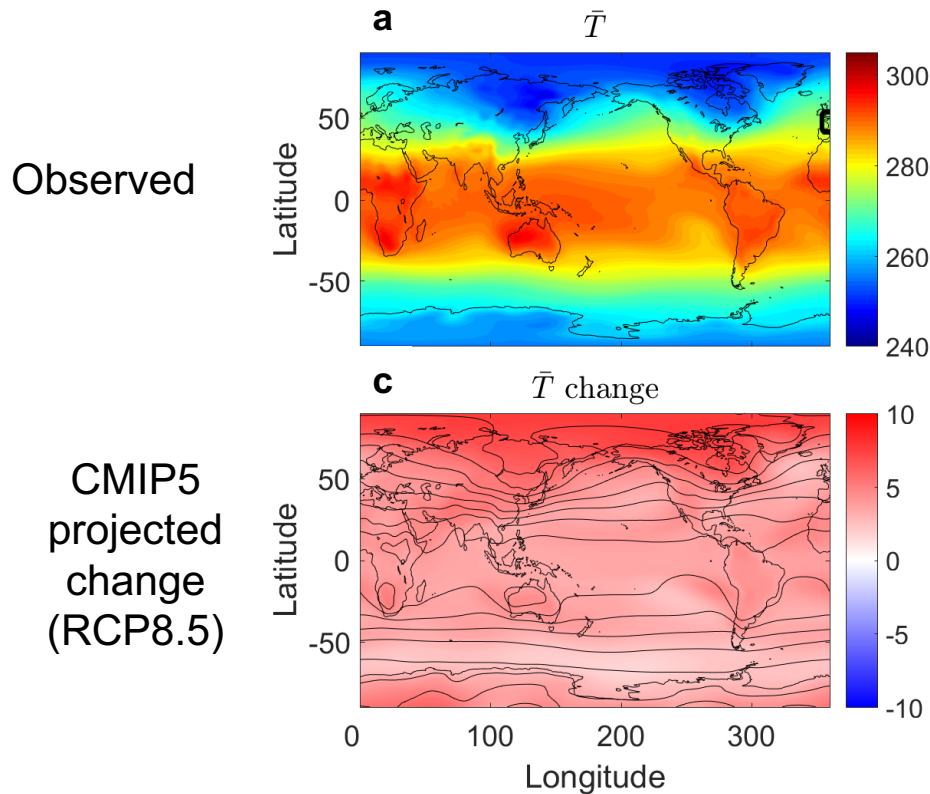
$$\text{Var} = \overline{T'^2}$$



- Temperature variability can be described by the underlying temperature Probability Density Function (PDF)
- Temperature **variance** measures the width of the PDF
- Measures how variable are temperature fluctuations around the mean temperature

Temperature variability and projected changes

DJF (850 hPa)



- Temperature variance is larger in the mid-latitudes and over the continents
- Temperature variance decreases over most of the NH (Screen 2014, Schneider et. al 2015)

Meridional temperature advection dominates temperature changes in the atmosphere

Assuming temperature is conserved and dominated by horizontal advection-

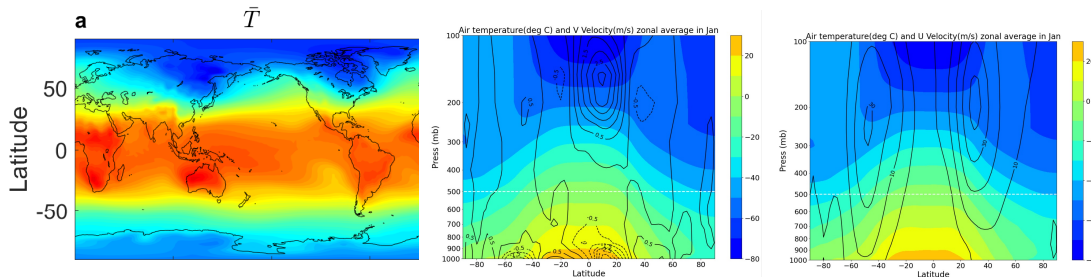
$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = 0$$

Assuming further:

$$T = T' + \bar{T} \quad \text{where} \quad T' \ll \bar{T}$$

And also- $\frac{\partial \bar{T}}{\partial x} \ll \frac{\partial \bar{T}}{\partial y}$ & $\bar{v} \ll \bar{u}$

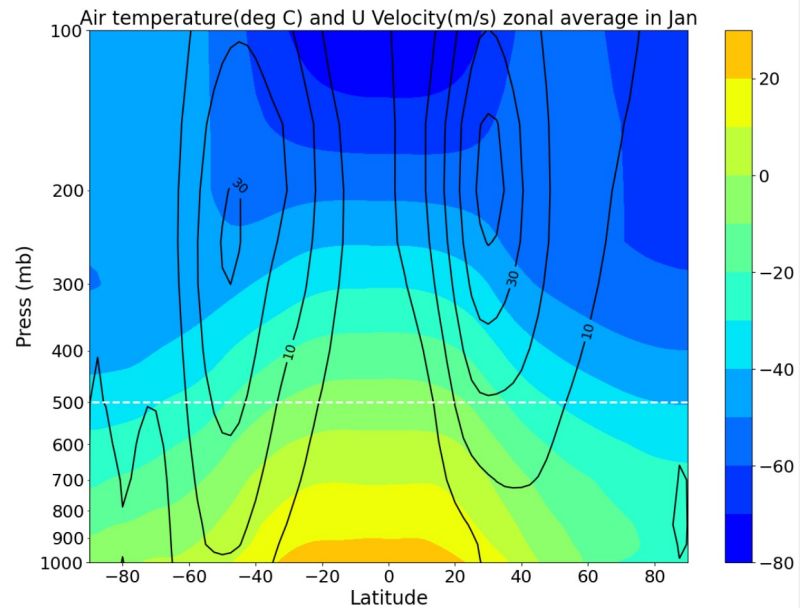
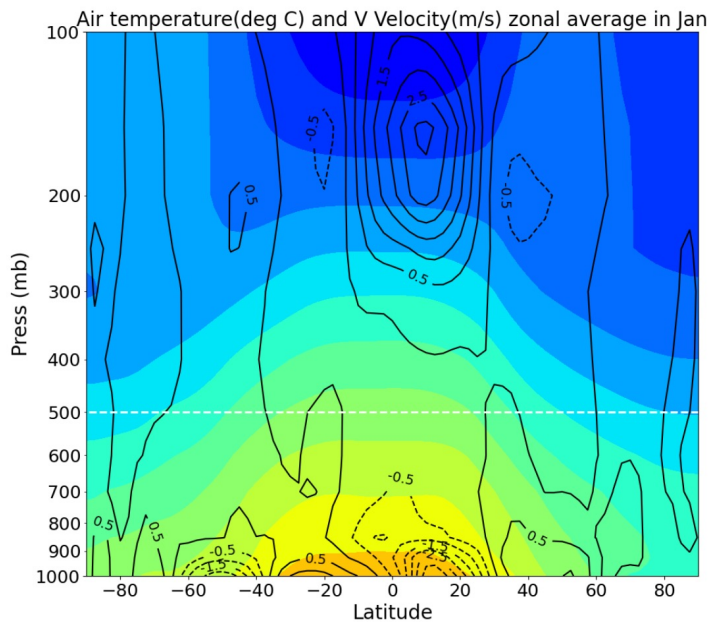
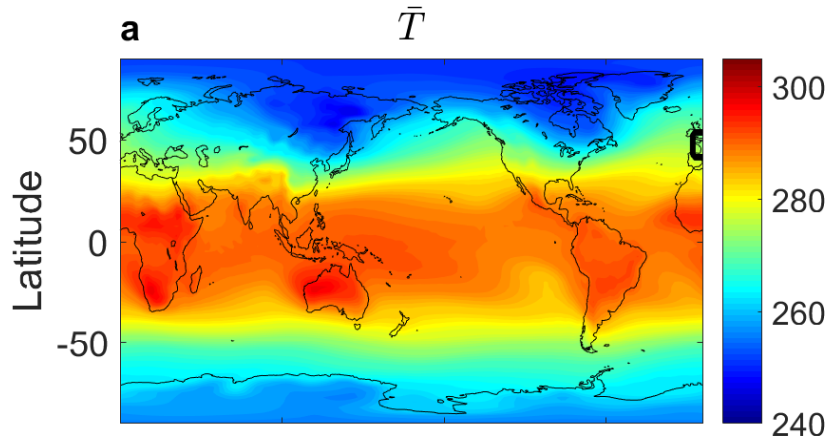
(how justified are these assumption?? Check!)



➔
$$\frac{\partial T'}{\partial t} = -v' \frac{\partial \bar{T}}{\partial y}$$

How justified are these assumptions?

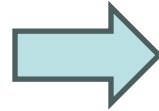
$$\frac{\partial \bar{T}}{\partial x} \ll \frac{\partial \bar{T}}{\partial y}$$



$$\bar{v} \ll \bar{u}$$

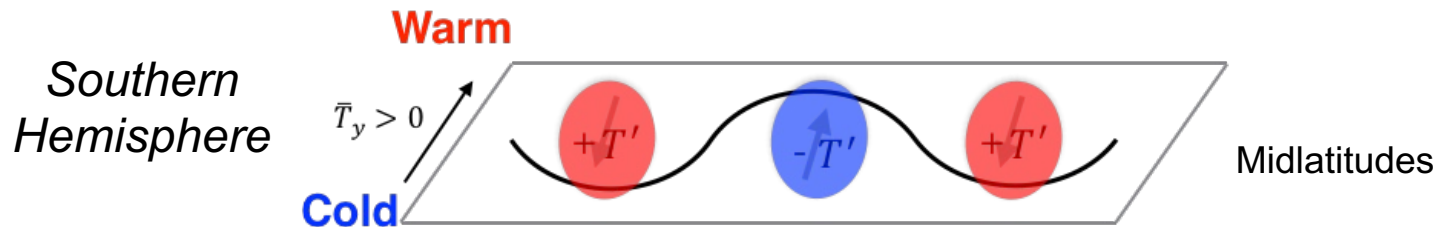
Temperature anomalies form due to meridional temperature advection

$$\frac{\partial T'}{\partial t} = -v' \frac{\partial \bar{T}}{\partial y}$$



$$T' = -\eta' \frac{\partial \bar{T}}{\partial y}$$

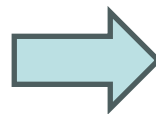
$$v' = \frac{D\eta'}{Dt}$$



Temperature variance

~

**Meridional
temperature gradient**

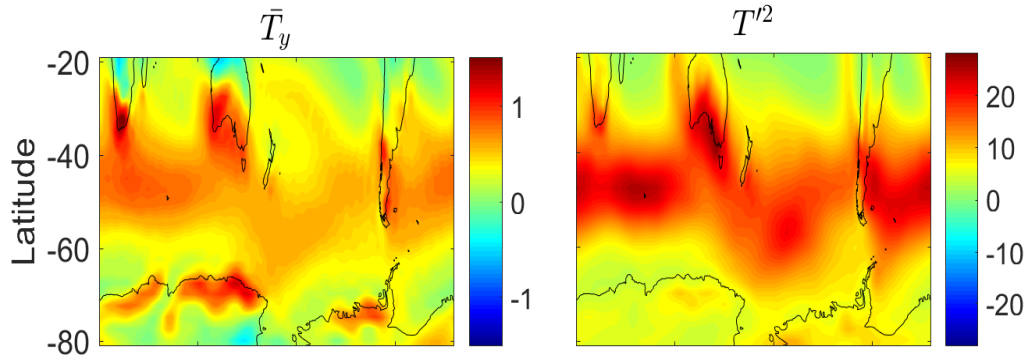


$$\overline{T'^2} = \overline{\eta'^2} \left(\frac{\partial \bar{T}}{\partial y} \right)^2$$

Temperature variance in the Southern Hemisphere

$$\overline{T'^2} = \overline{\eta'^2} \left(\frac{\partial \bar{T}}{\partial y} \right)^2$$

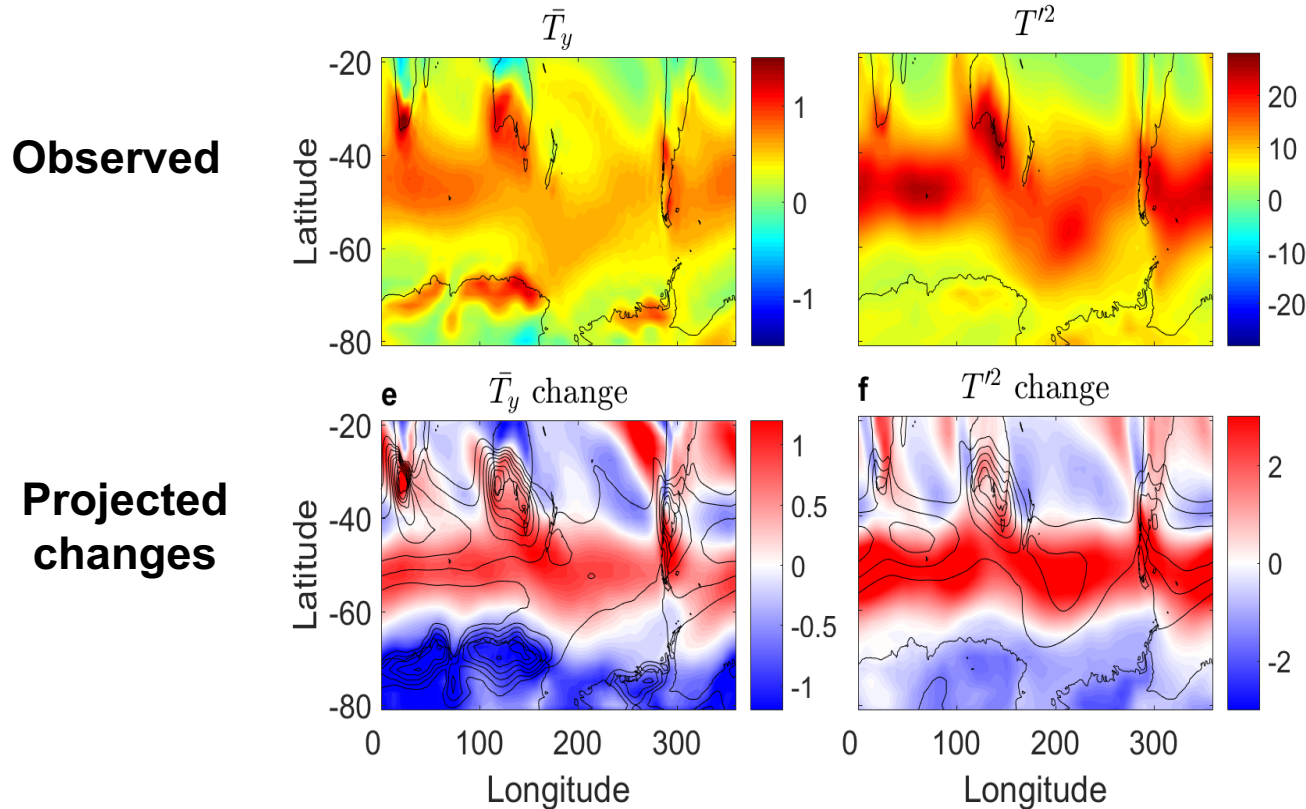
Observed



- The Southern Hemisphere (SH) meridional temperature gradient is maximized in the midlatitudes
- Consistent with that, temperature variance is also maximized in the SH midlatitudes

Temperature variance in the Southern Hemisphere

$$\overline{T'^2} = \overline{\eta'^2} \left(\frac{\partial \bar{T}}{\partial y} \right)^2$$

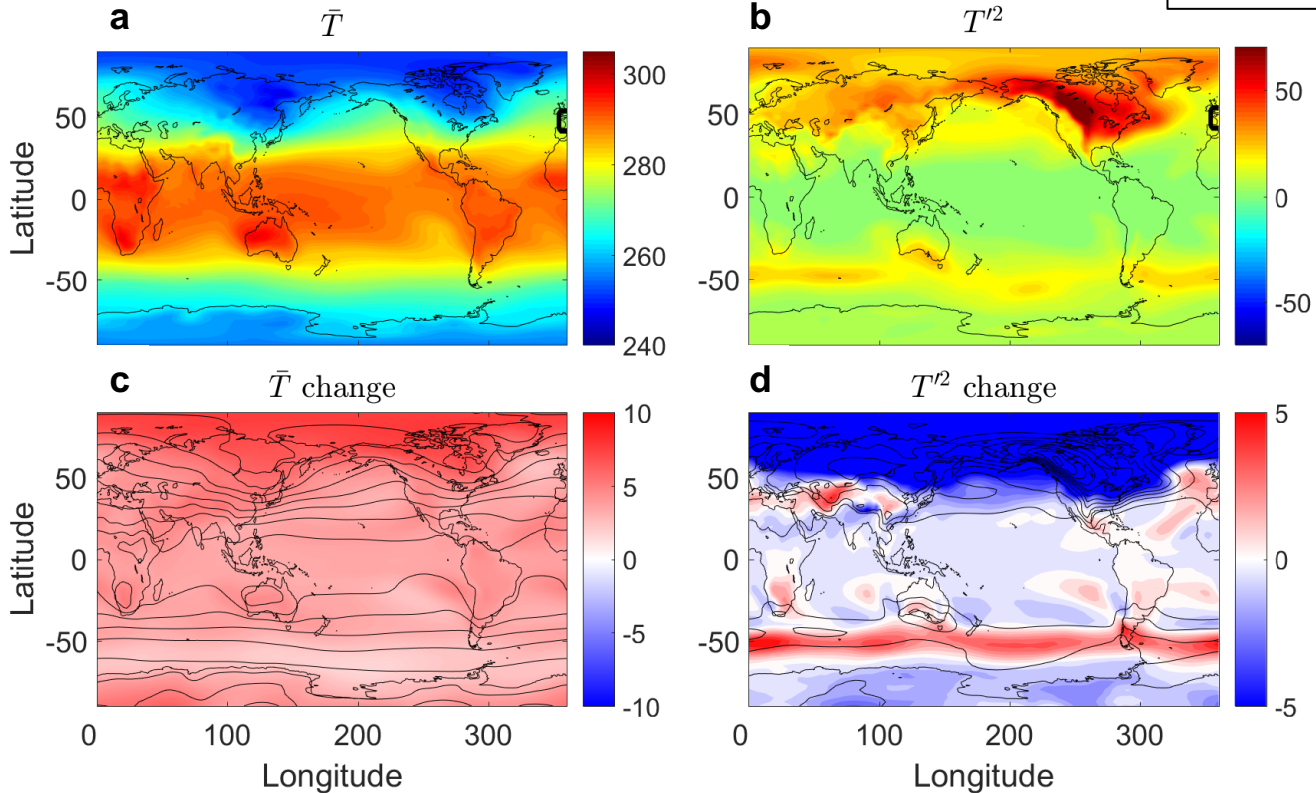


- The SH meridional temperature gradient increases in the future
- Consistent with that, temperature variance increases

Temperature variance in the Northern Hemisphere

$$\overline{T'^2} = \overline{\eta'^2} \left(\frac{\partial \bar{T}}{\partial y} \right)^2$$

Observed



projected change

- Temperature variance is larger in the mid-latitudes and over the continents
- Temperature variance decreases over most of the NH (Screen 2014, Schneider et. al 2015)

Exercise-

- Go to the course website (2nd project, Observation Data) and download the zip folder “temperature_variance”.
- Unzip the files and put them in the same folder
- Run the file plot_T2m.m (in MATLAB) or the script “plot_T2m_python.py” (in python).
- This should produce a figure showing the historical mean T2m data for one model in the first data year
- Now, modify the script so that it calculates the mean over all models and all years, and plot the historical mean T2m, historical T2m variance, and their projected changes. There are some instructions on the script.

Questions:

- What do you find for the T2m mean temperature and variance in the historical simulations? Is it similar to what we saw for the 850mb level?
- What do the projected mean temperature and variance show? Can you explain this response using temperature advection arguments?
- **Optional:** Examine the model-to-model spread and the year-to-year variability of global mean temperature. Do all models agree on the changes? Can you observe a trend in the historical/projected data? Is the trend larger than the year-to-year variability?