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

This class:

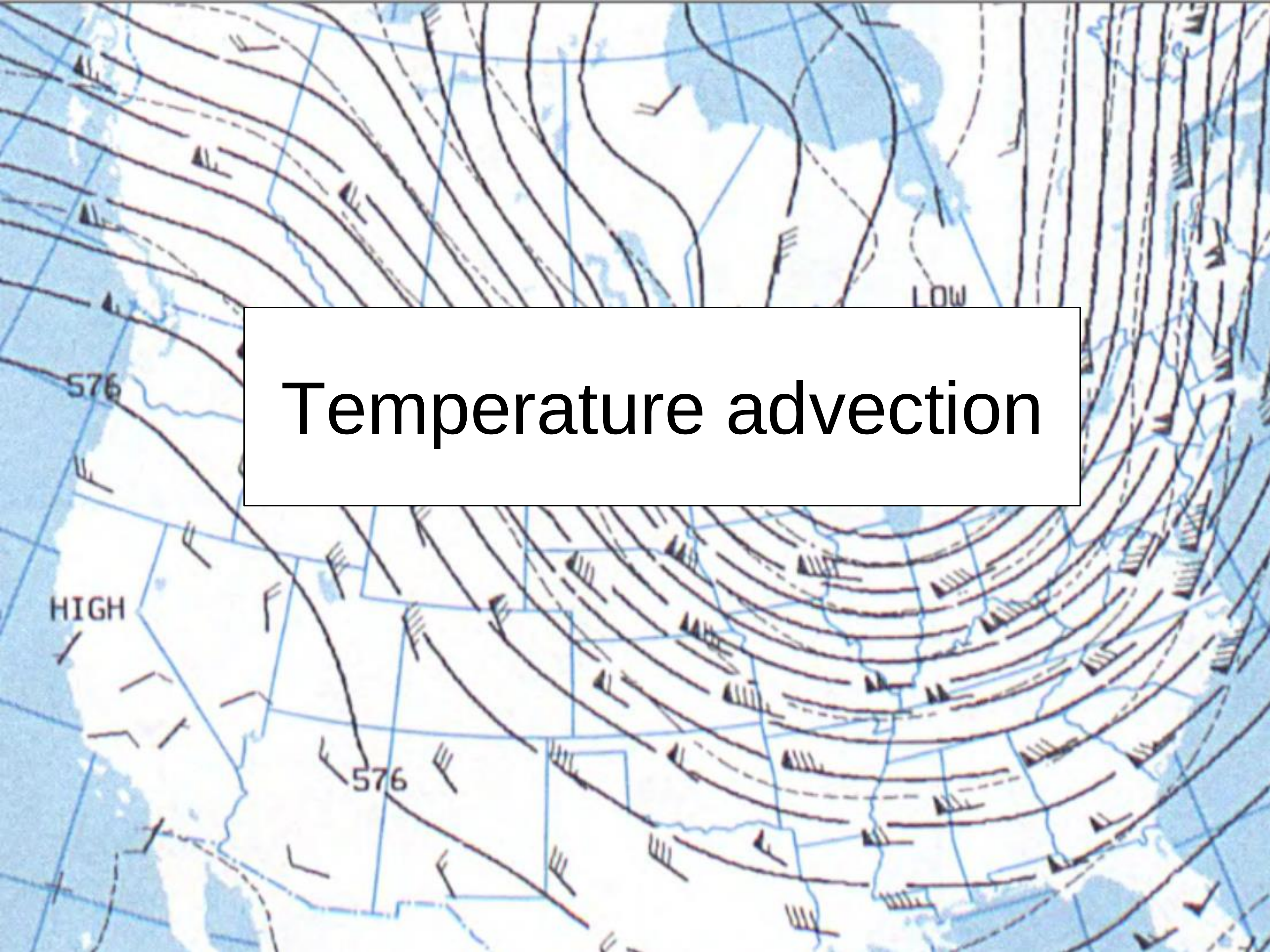
2. *Temperature Advection*:

- 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!)

Temperature advection



Lagrangian vs. Eulerian derivative

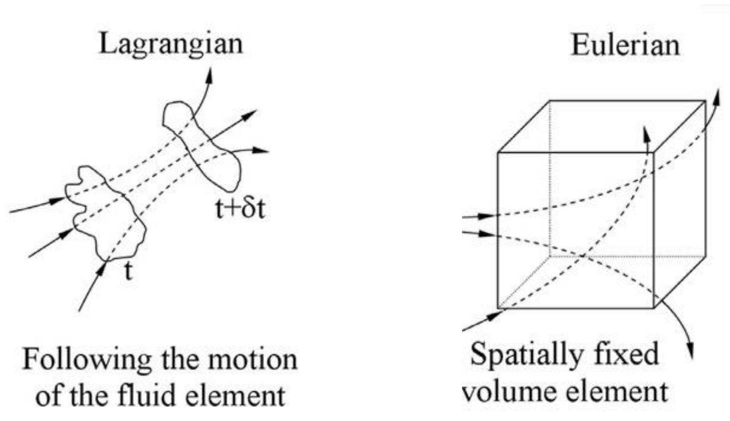
$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{u}.\nabla$$

Lagrangian Eulerian Advection

Where

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

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



Examples:

1) Velocity and position of a fluid parcel-

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

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

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

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

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

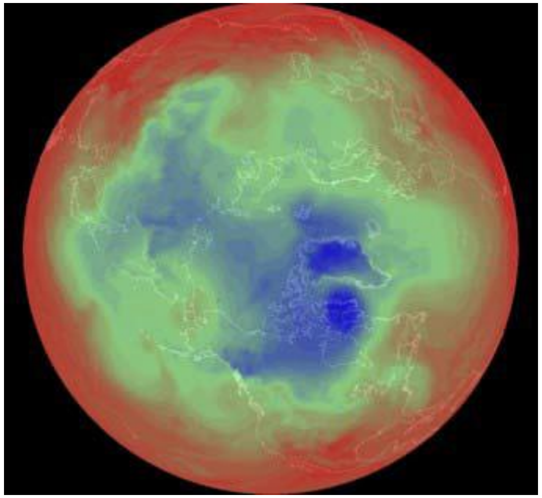
Examples:

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-

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



red =hot
blue=cold

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

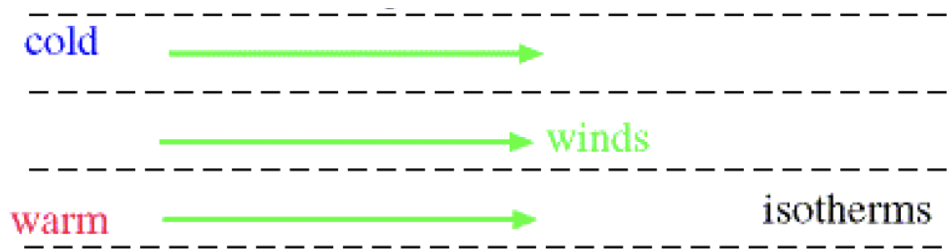
Hence, $v < 0 \Rightarrow \frac{\partial T}{\partial t} \simeq -v\frac{\partial T}{\partial y} < 0$

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

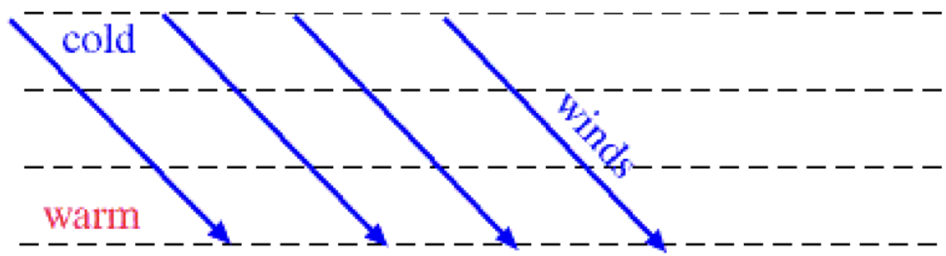
In regions where the cold air is moving south (v<0) the local rate of change of temperature is negative (cooling). Similarly, local warming when v>0

Temperature advection

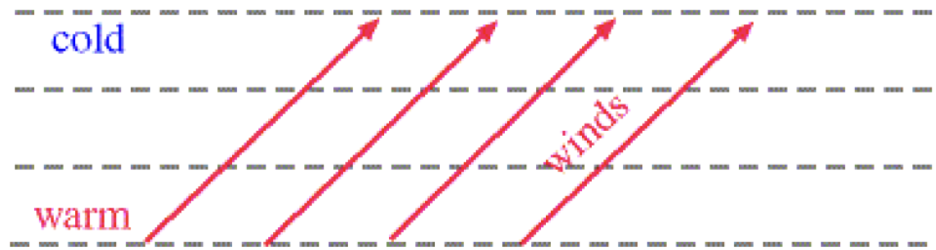
No advection



Cold temperature advection



Warm temperature advection

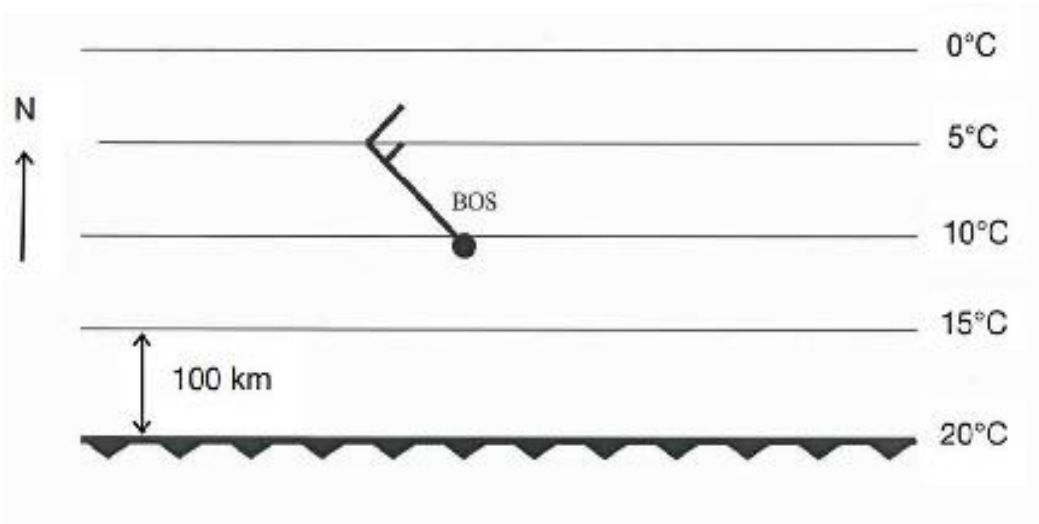


Temperature advection

Example: temperature changes in Boston due to a hypothetical front

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

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 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?

Temperature advection- real front

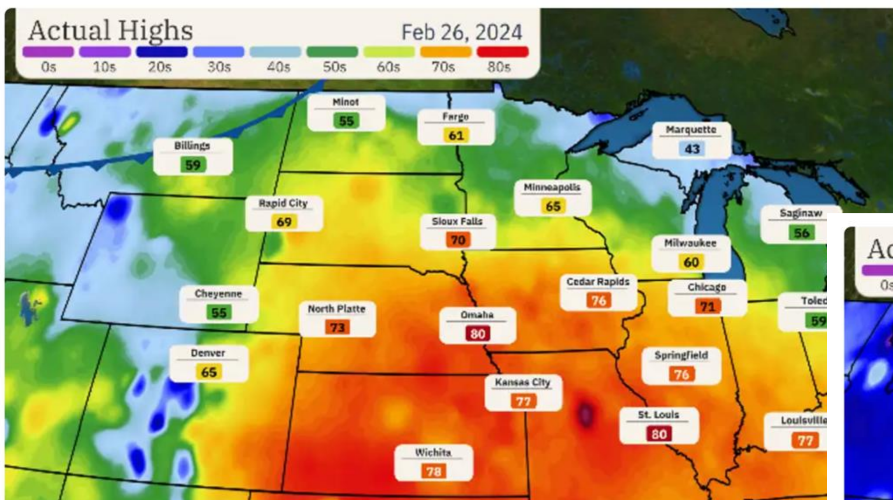
Example

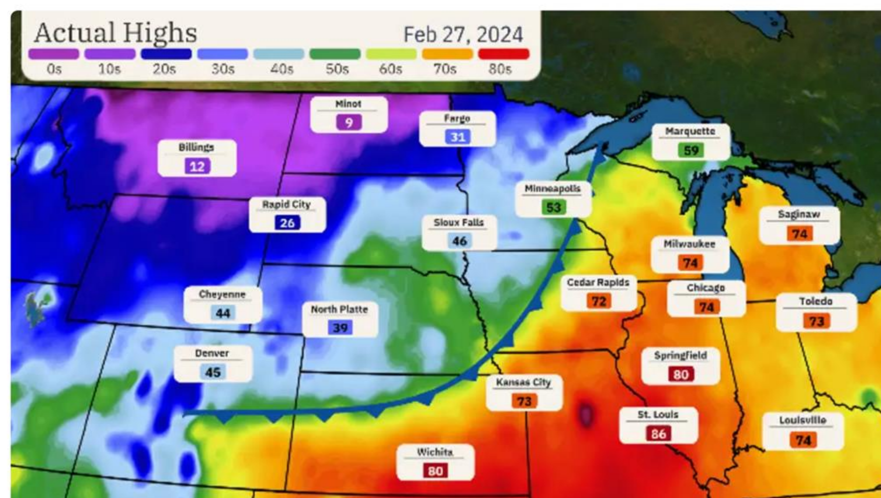
NEWS

The Weather Channel

Weather Whiplash: From Record February And Winter Warmth To Cold And Snow In Plains, Midwest

By Jonathan Erdman · February 29, 2024



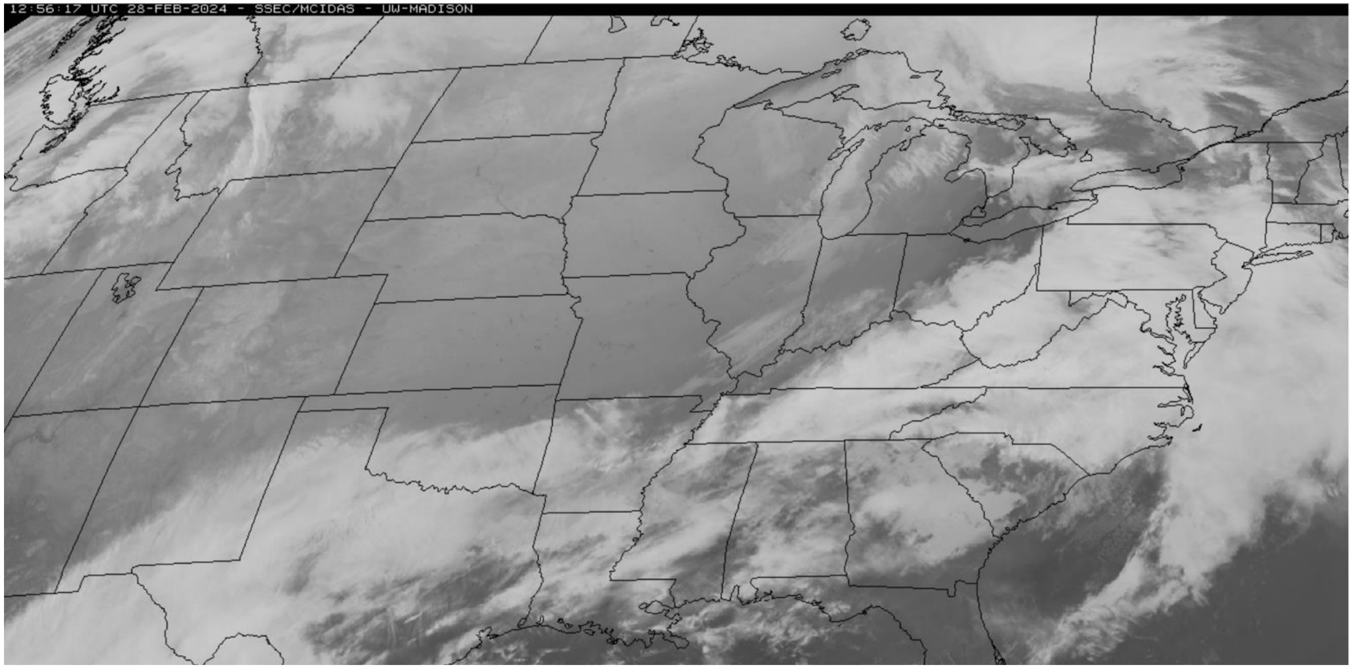


Temperature advection- real front

Example

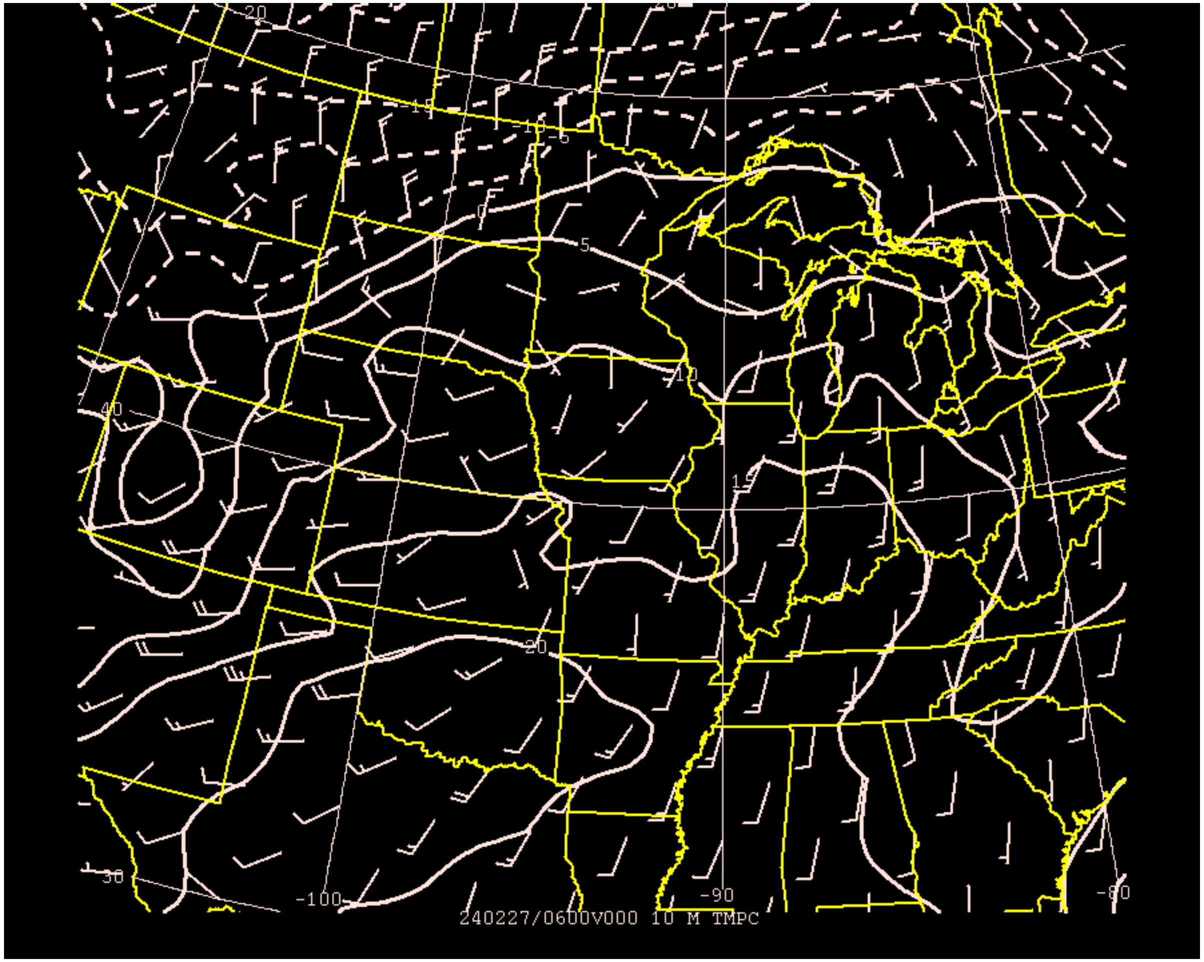
Let’s try to estimate manually the temperature change in Chicago using real weather maps

Infrared satellite image for February 28 2024 06Z



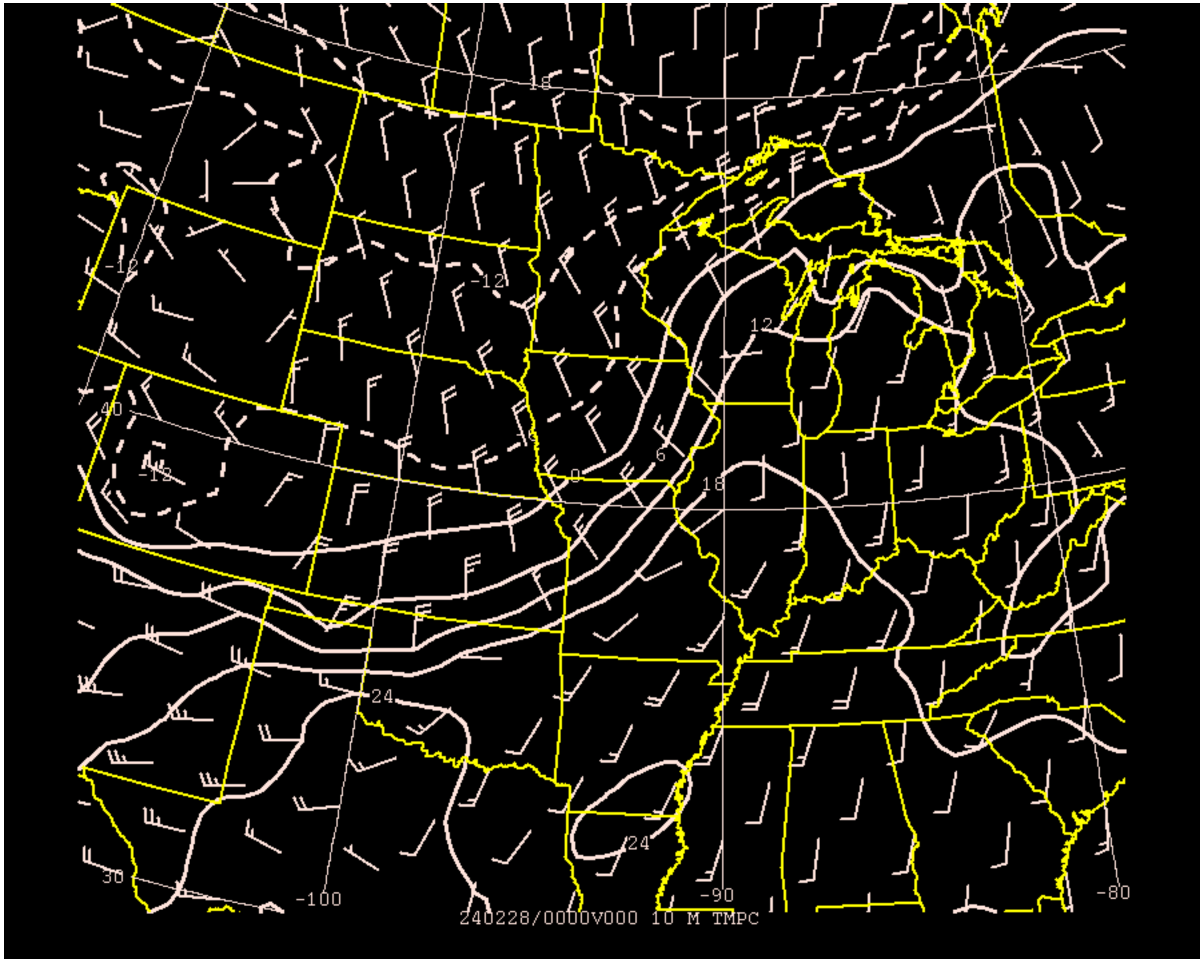
Temperature advection- real front

February 27 2024 06Z



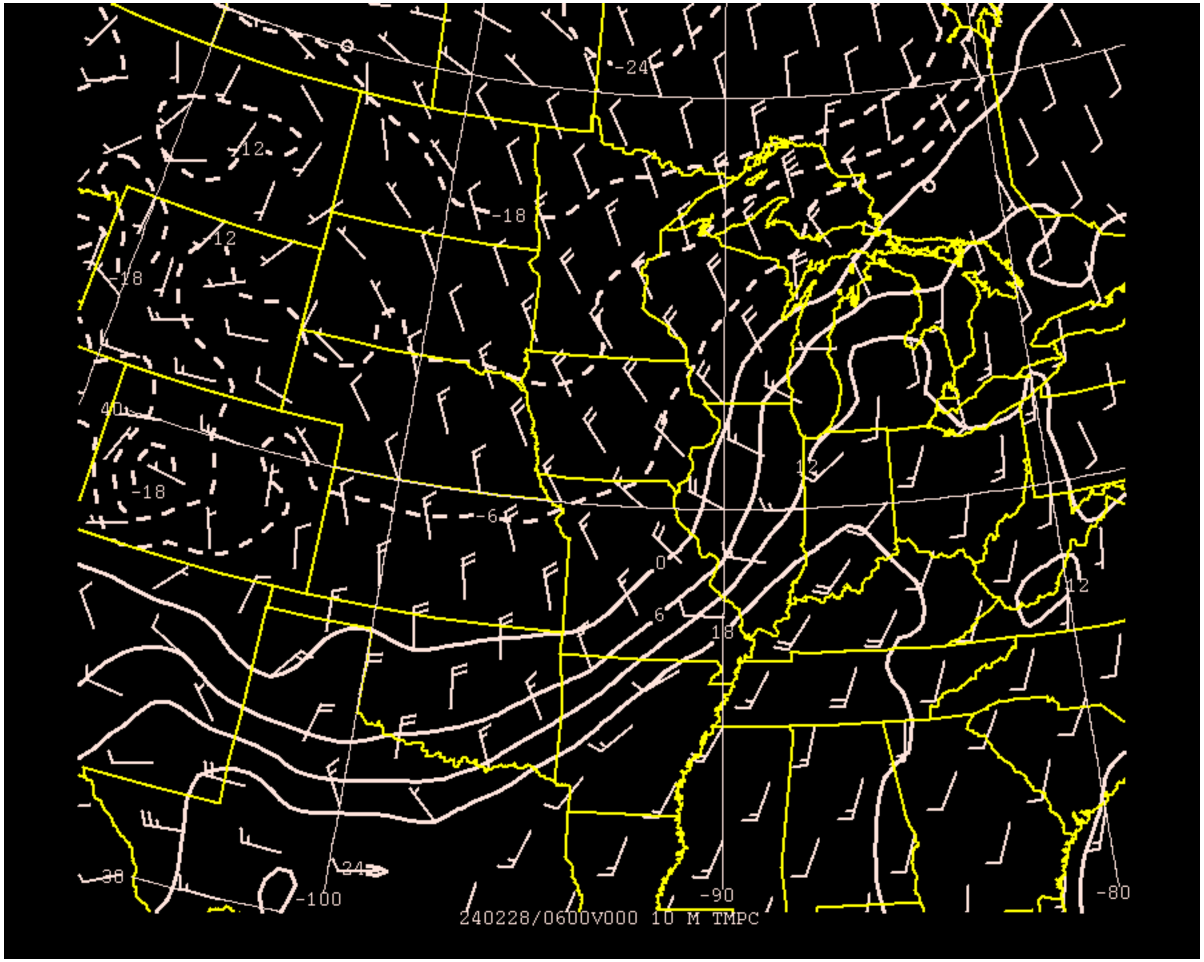
Temperature advection- real front

February 28 2024 00Z



Temperature advection- real front

February 28 2024 06Z



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

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

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

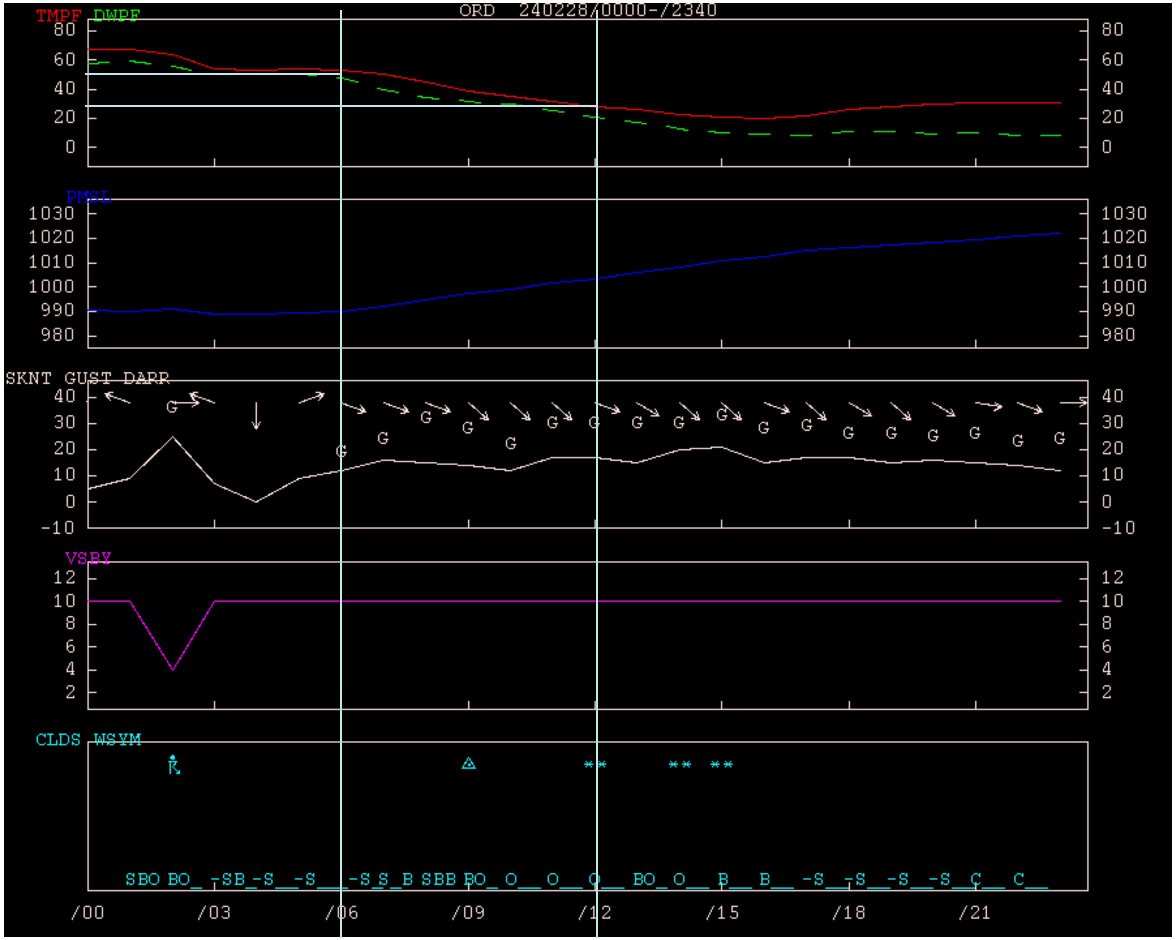
$$\Delta T(12Z) \approx \frac{6[h] \cdot 15[kt] \cdot 12℃}{200\ [km]} \approx 10℃$$

Temperature advection- real front

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

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

$\Delta T(12Z) \approx 11°\text{C}$



Our simple and rough manual estimation is actually useful!

Temperature advection- real front

Case Study of January 22, 2013

Compute:

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

Temperature advection- real front

January 22 2013 06Z

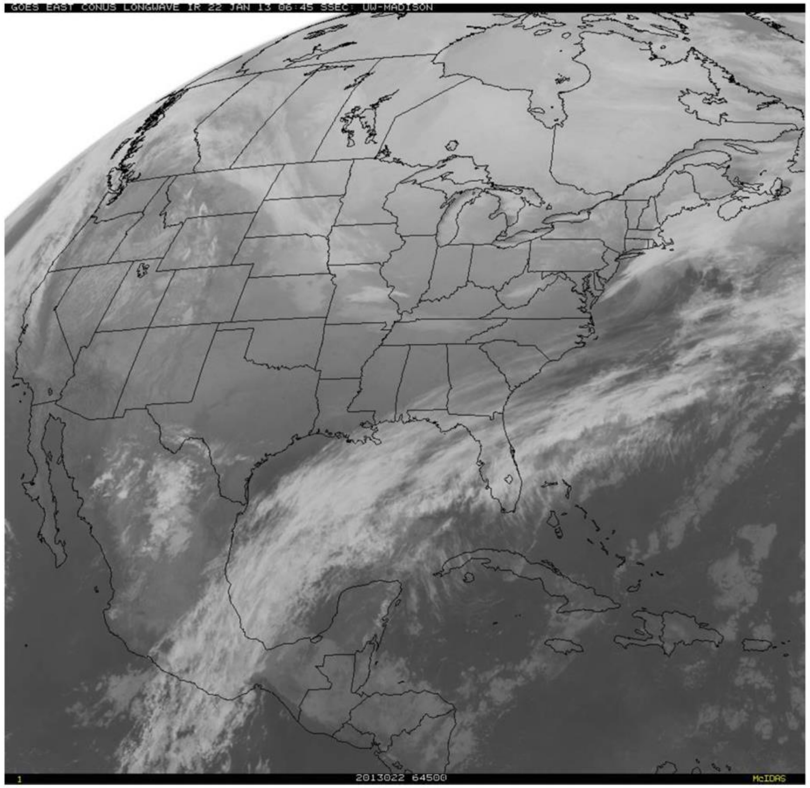


Figure 12: IR satellite image for January 22, 2013 at 06z

Temperature advection- real front

January 22 2013 06Z

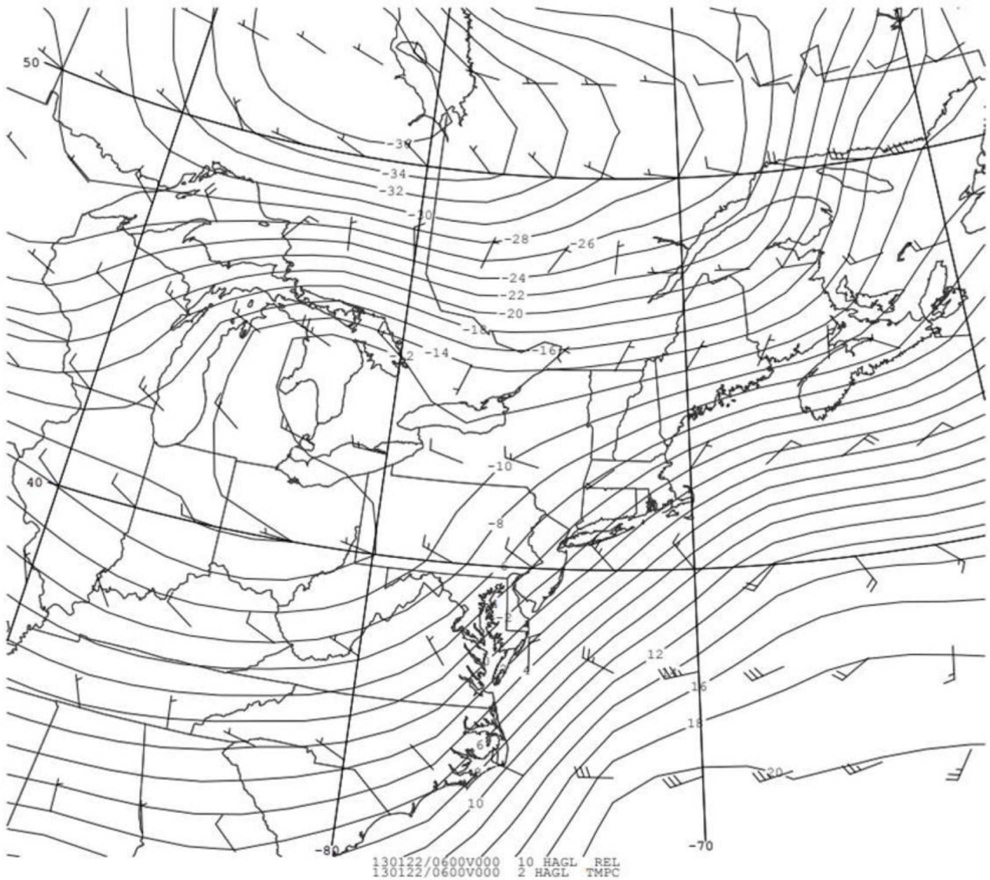
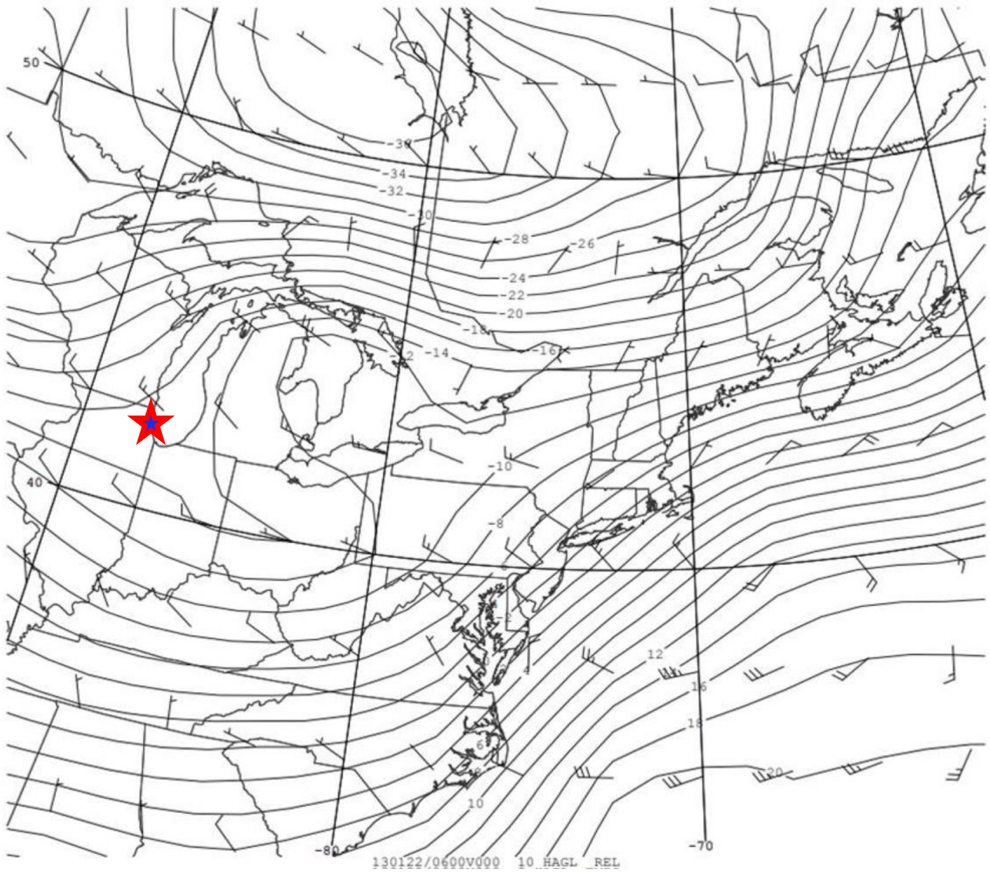


Figure 13: Analyzed surface temperature (contored in ^oC) and surface wind (vectors in kts) for the same time, as in January 22, 2013 at 06z.

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

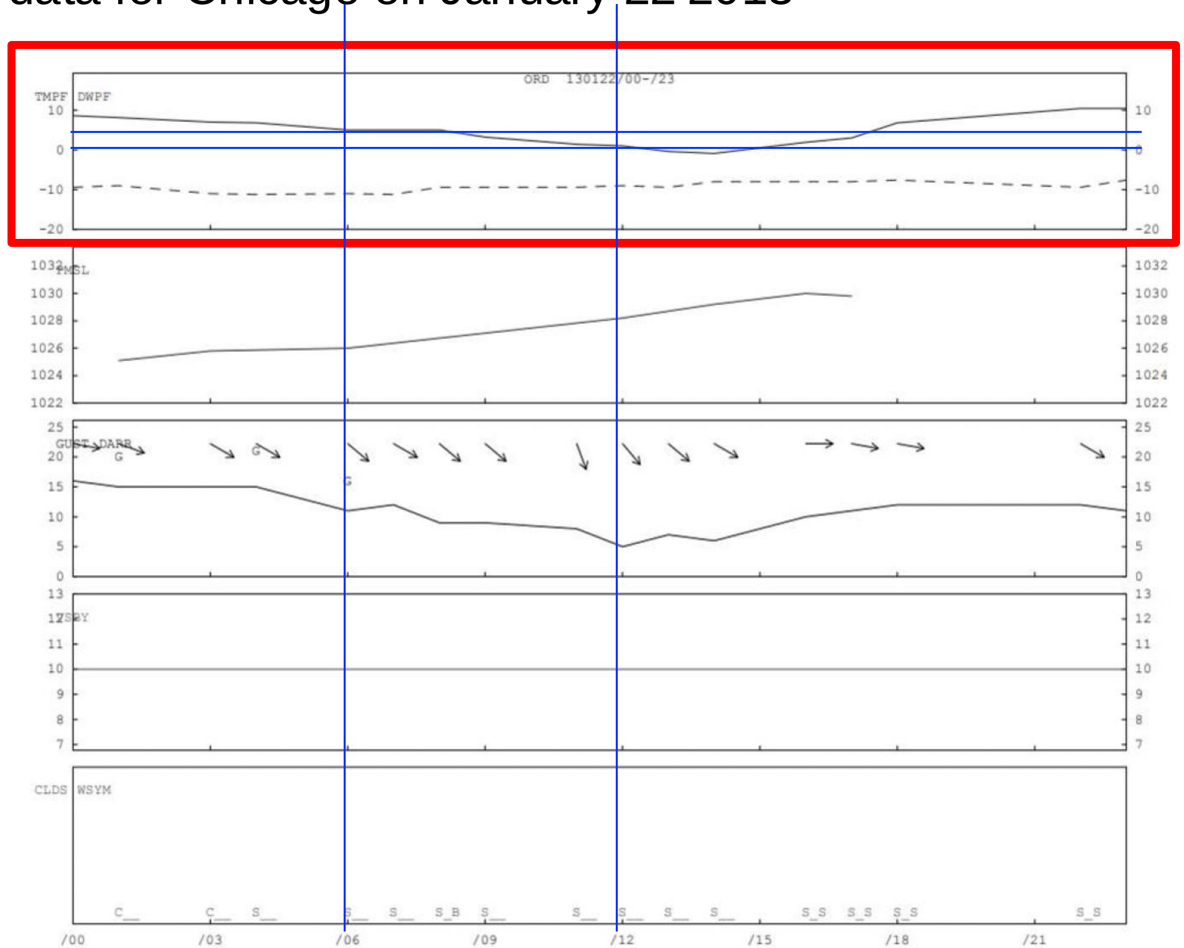


Figure 14: Surface meteogram for Chicago O'Hare (ORD) on January 22, 2013 showing temperature (continuous line) and dewpoint temperature (dashed line), surface pressure, wind speed and direction, visibility and cloud cover.

Note:

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

NWP Model

Numerical Weather Prediction Model

Dynamics
(model grid)

Numerical
Advection

Physics
(sub-grid)

Radiation

Convection

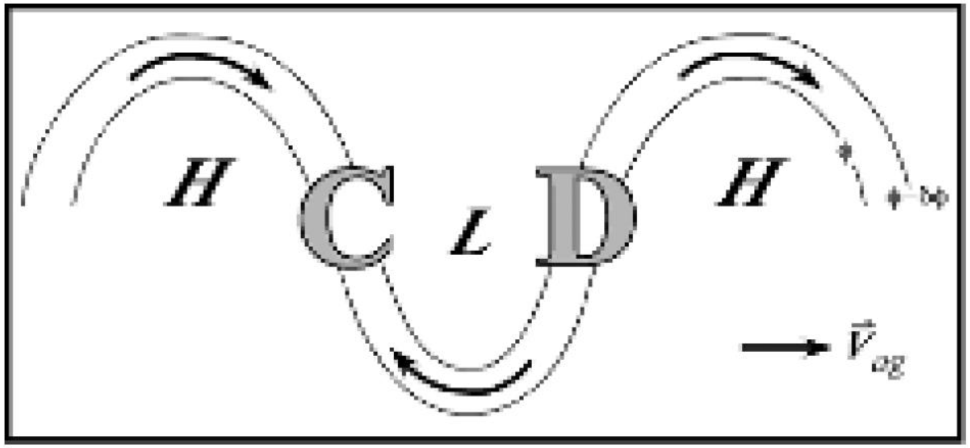
Clouds

Condensation and Precipitation

Planetary Boundary Layer
Surface Fluxes

Role of temperature advection in cyclogenesis

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)



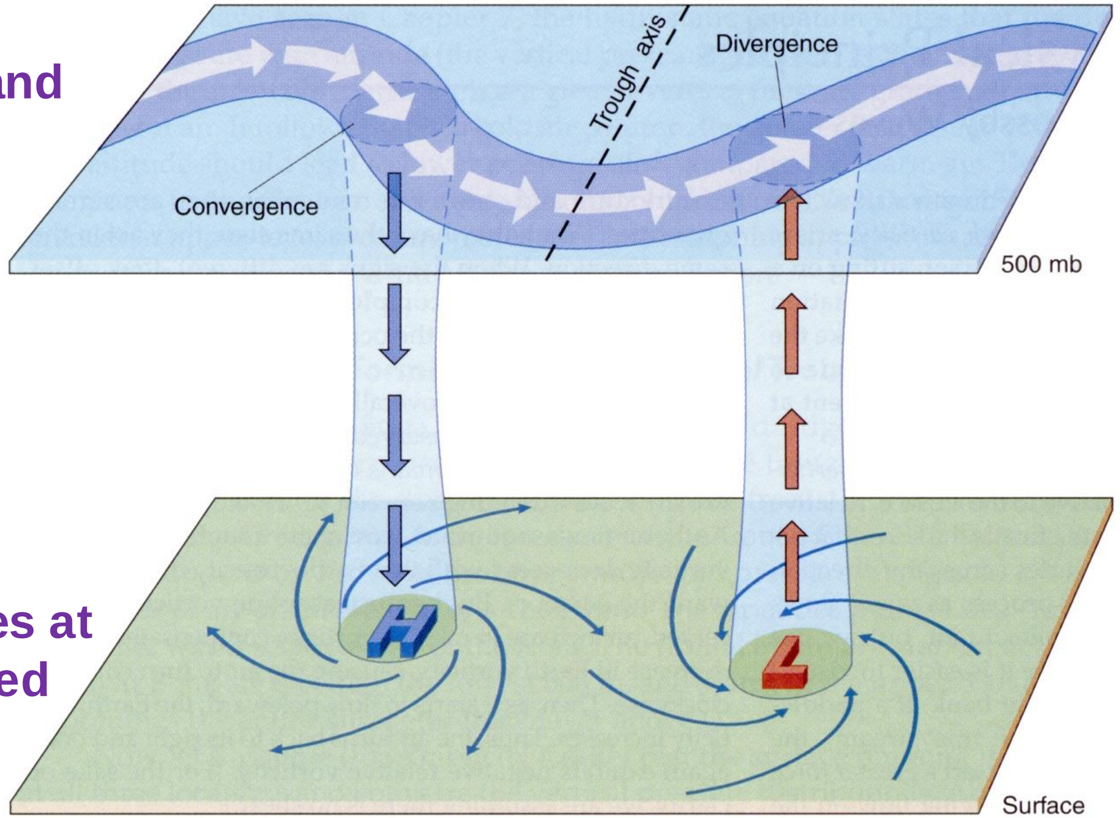
However, this implies Convergence (C) between the ridge and the trough, and Divergence (D) between the trough and the ridge!

Role of temperature advection in cyclogenesis

Interaction between upper level and lower level flows

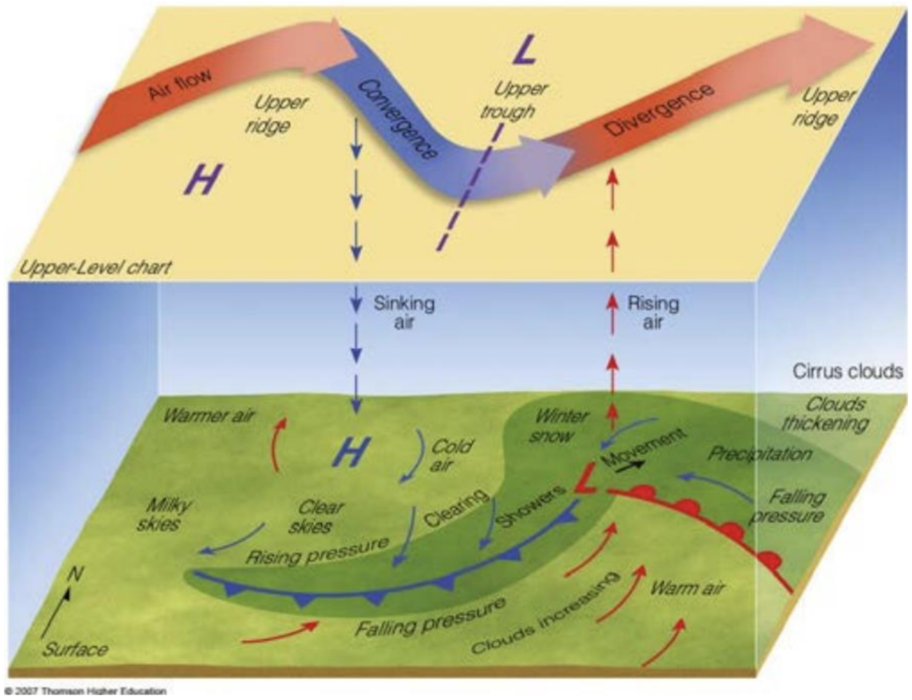
upper level Troughts and Ridges

Cyclone and anticyclines at low levels and associated surface temperatures



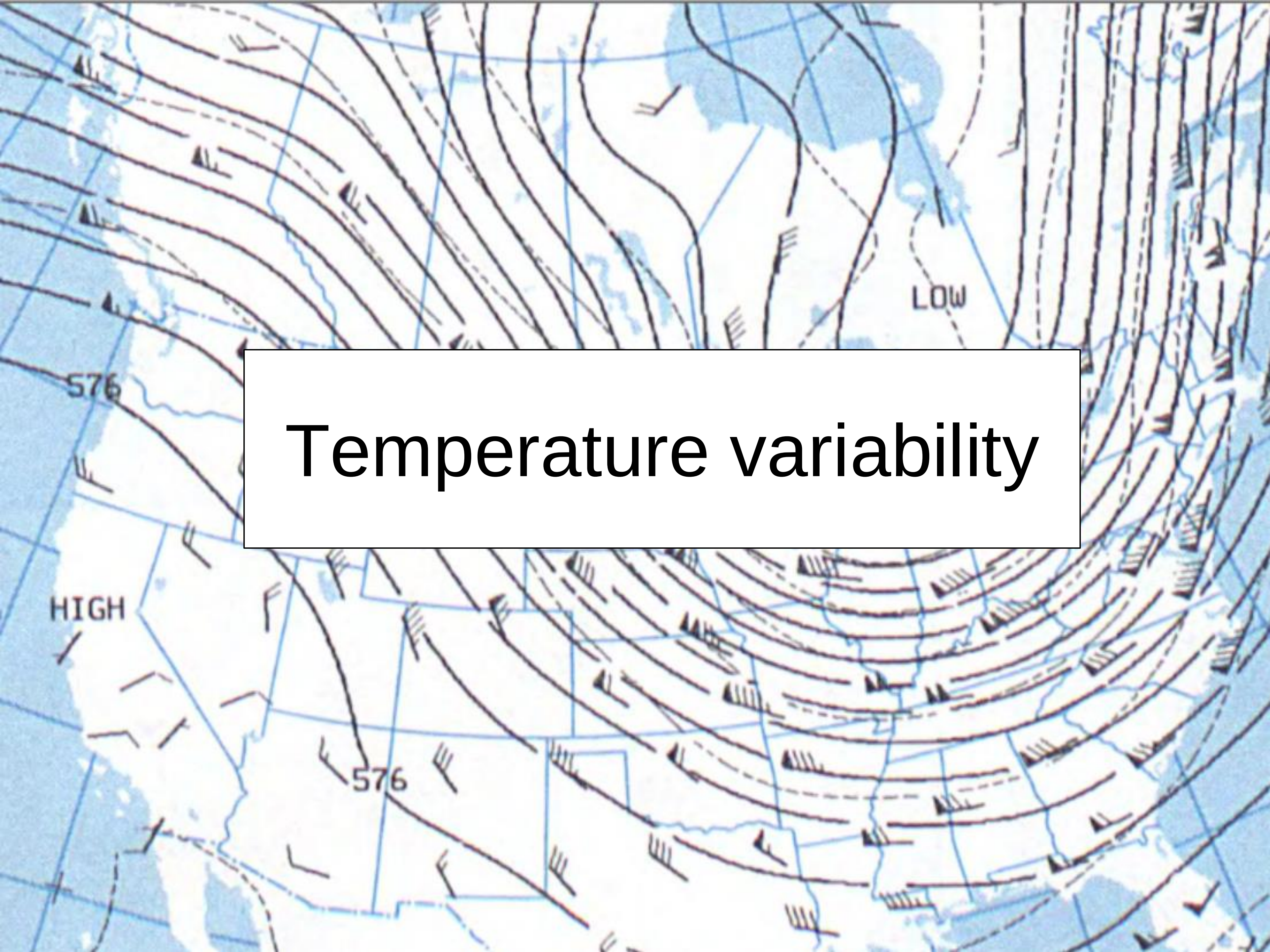
- Upper-level convergence (divergence) upstream (downstream) of the troughs
- Implies downward (upward) flow in the upstream (downstream)
- Divergence in the surface High (H), convergence in the surface Low (L) also due to friction

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 variability



Weather vs. Climate

Weather

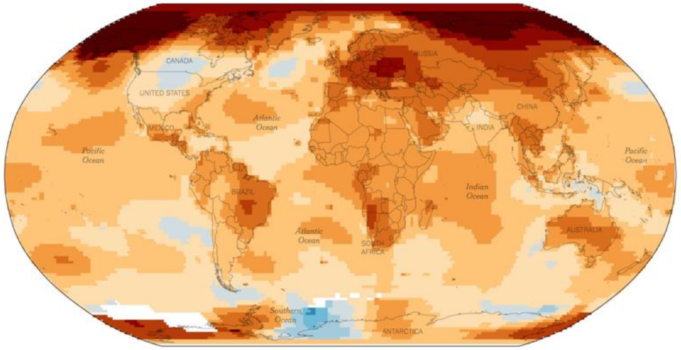
NOAA GOES

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

−2°C −1° **0°** +1° +2° +3°

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

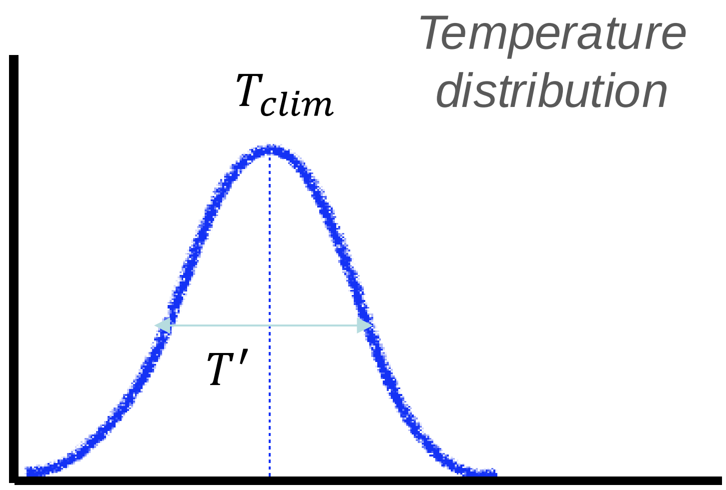
By Henry Fountain and Nadja Popovich Jan. 15, 2020

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

Temperature variability

Anomalies: deviations from the climatological mean- $T' = T - T_{clim}$

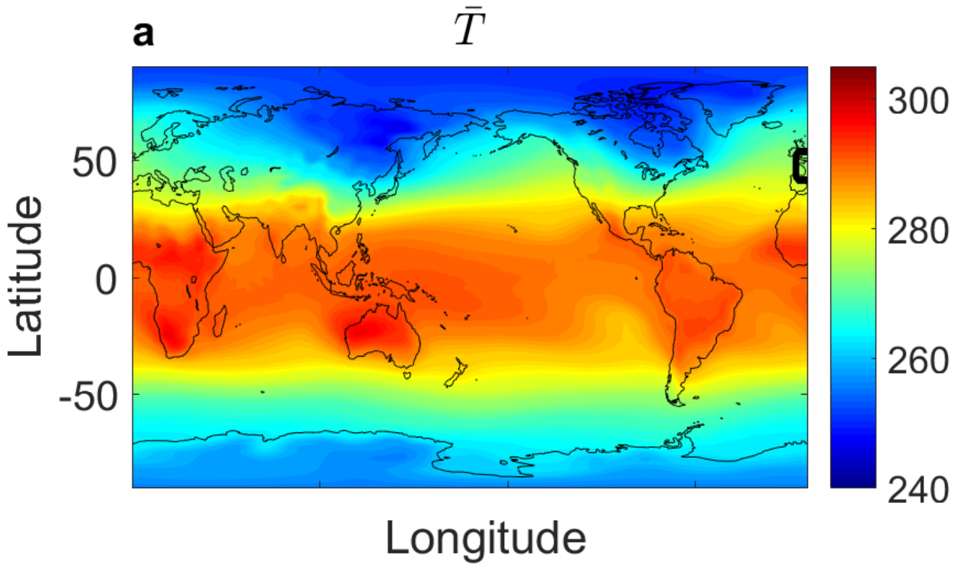
Var= $\overline{T'^2}$

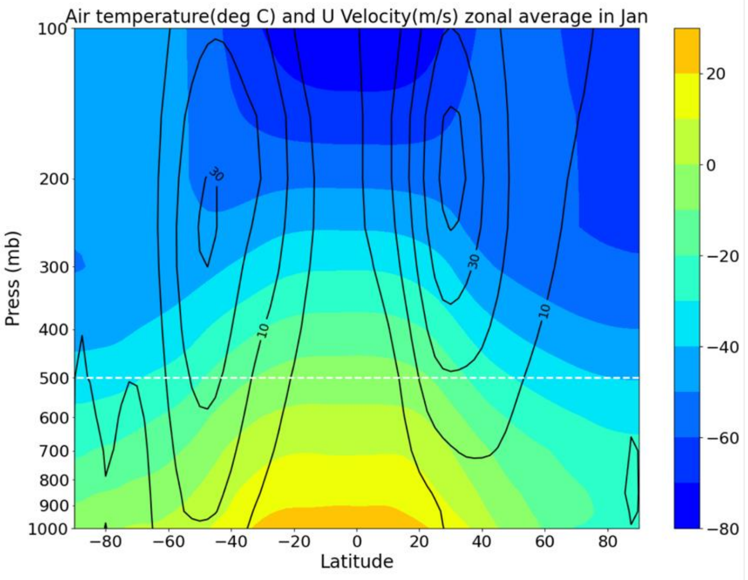


- Temperature variability can be described by the underlying temperature Probability Density Function (PDF)
- Temperature ***variance*** measures the width of the PDF
- Measures how variable are temperature fluctuations around the mean temperature

Climatological mean temperature

1000 mb T mean + Vertical structure of zonal mean T

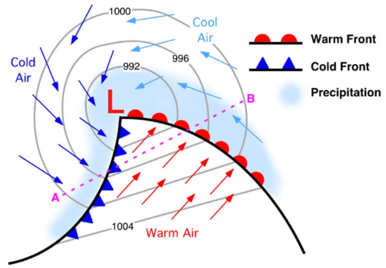


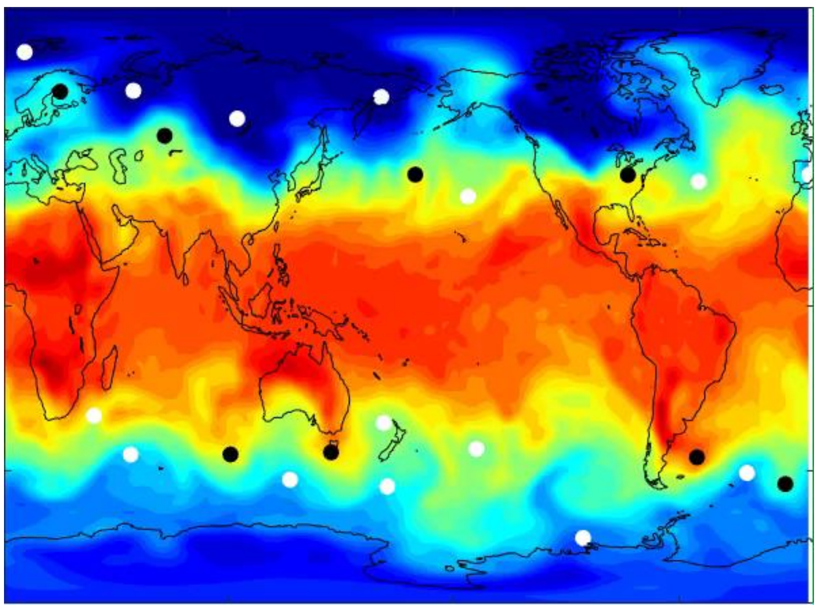


Temperature anomalies

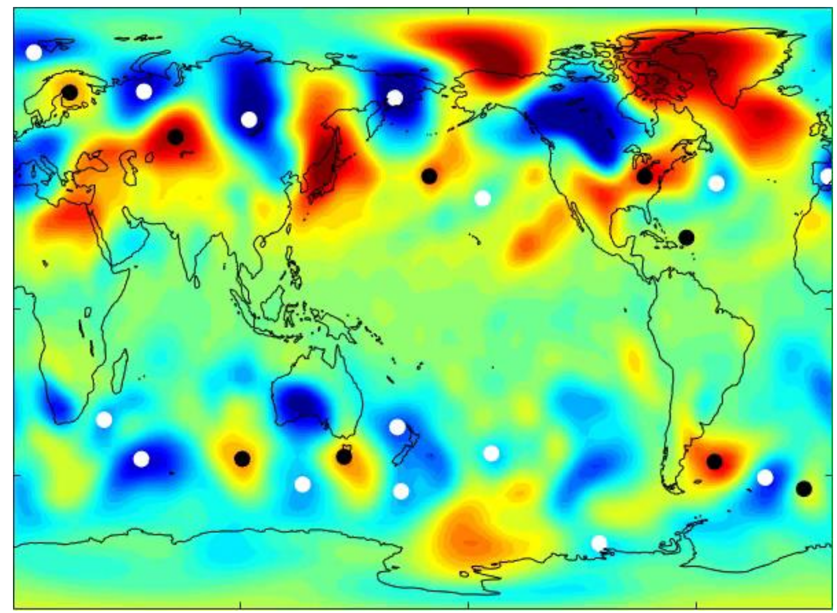
Deviations from the climatological mean-

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





Full temperature (850hPa)



Temperature anomaly (850hPa)

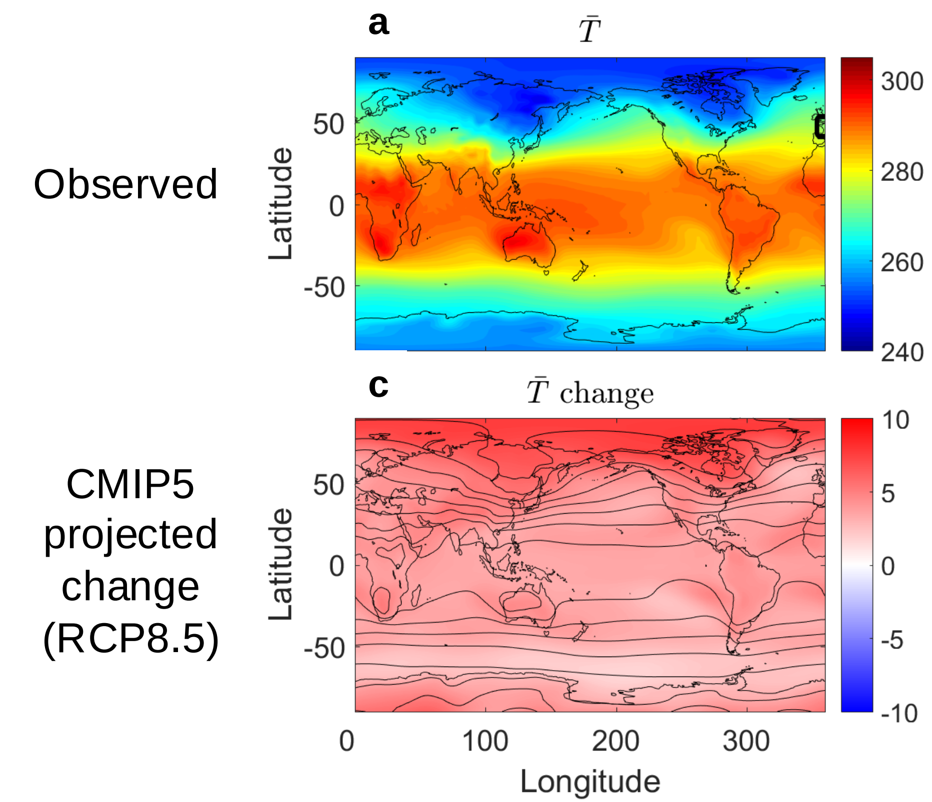
Anomalies are defined as deviations from the climatology

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

Code ‘TRACK’ of Kevin Hodges

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!

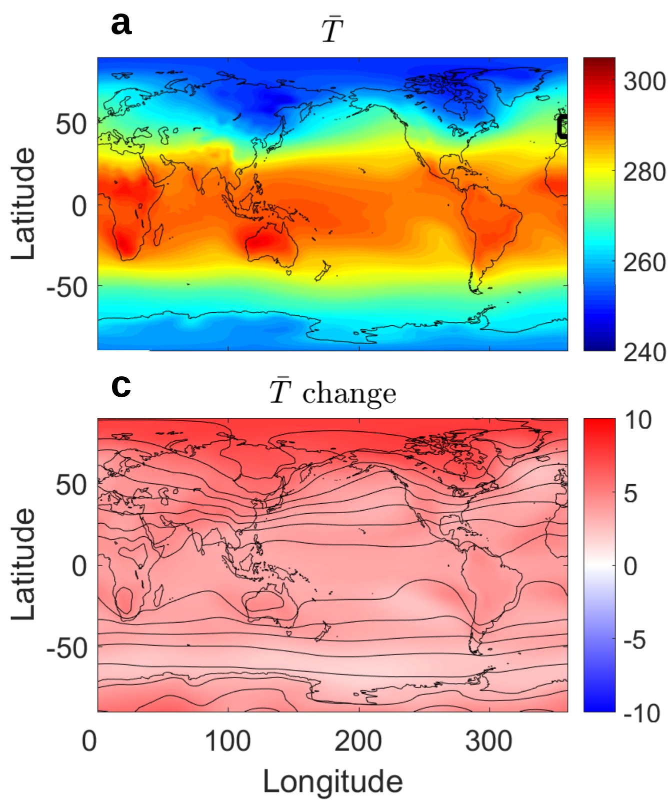
- Warm in the equator/tropics, cold in the poles
- Climatological mean temperature increases everywhere, but more in the NH pole (Arctic Amplification)

Temperature variability and projected changes

DJF (850 hPa)

Observed

CMIP5 projected change (RCP8.5)



- 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:

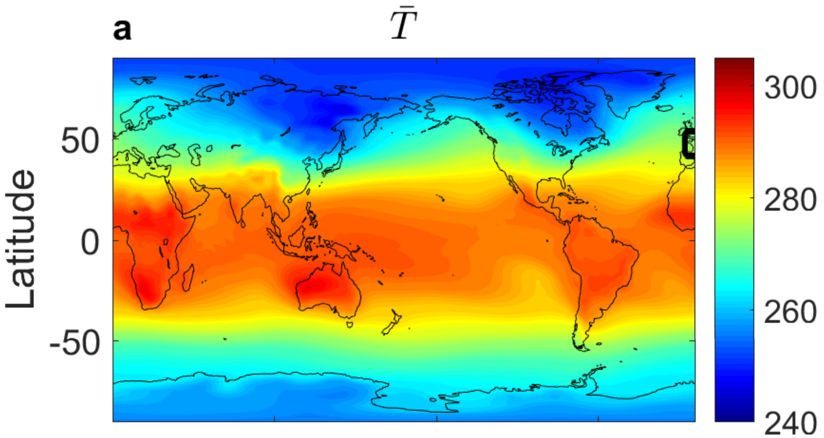
$T = T' + \bar{T}$ where $T' \ll \bar{T}$

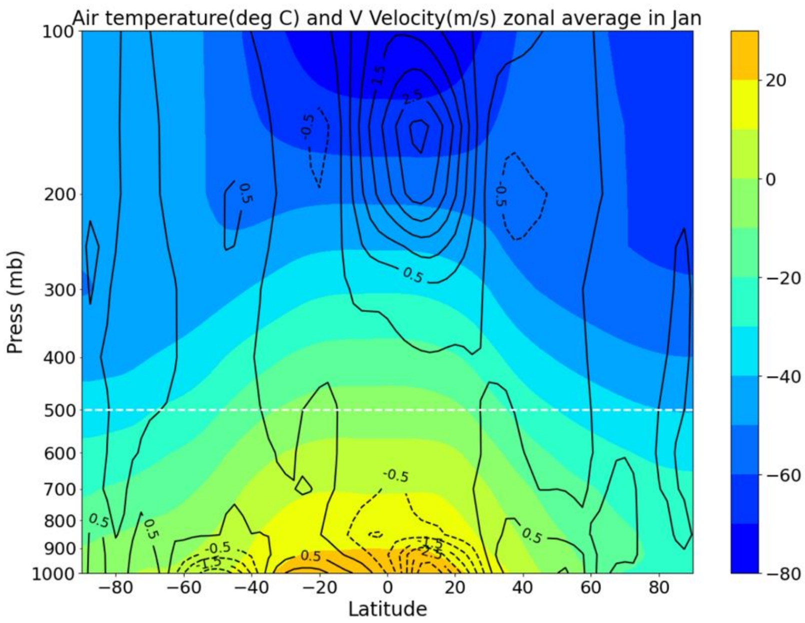
And also- $\frac{\partial \bar{T}}{\partial x} \ll \frac{\partial \bar{T}}{\partial y}$ & $\bar{v} \ll \bar{u}$ (how justified are these assumption?? Check!)

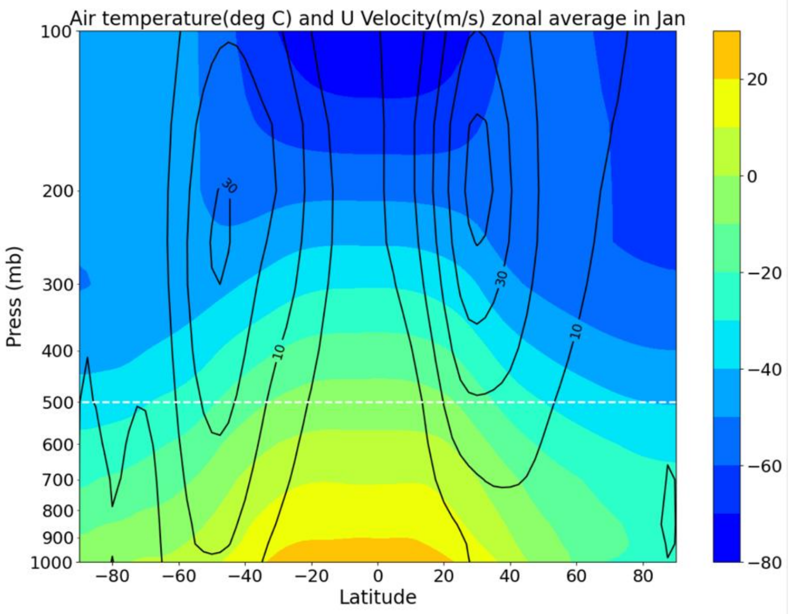
$$\Rightarrow \quad \frac{\partial T'}{\partial t} = -v'\frac{\partial \bar{T}}{\partial y}$$

How justified are these assumption?

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







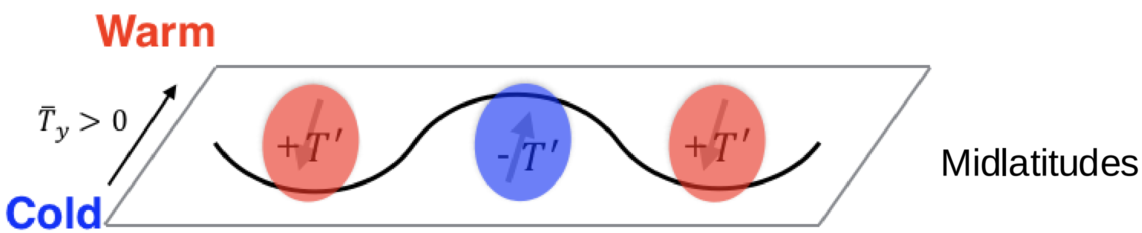
$$\bar{v} \ll \bar{u}$$

Temperature anomalies form due to meridional temperature advection

$$\frac{\partial T'}{\partial t} = -v'\frac{\partial \bar{T}}{\partial y} \quad \Rightarrow \quad \boxed{T' = -\eta'\frac{\partial \bar{T}}{\partial y}}$$

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

Southern Hemisphere



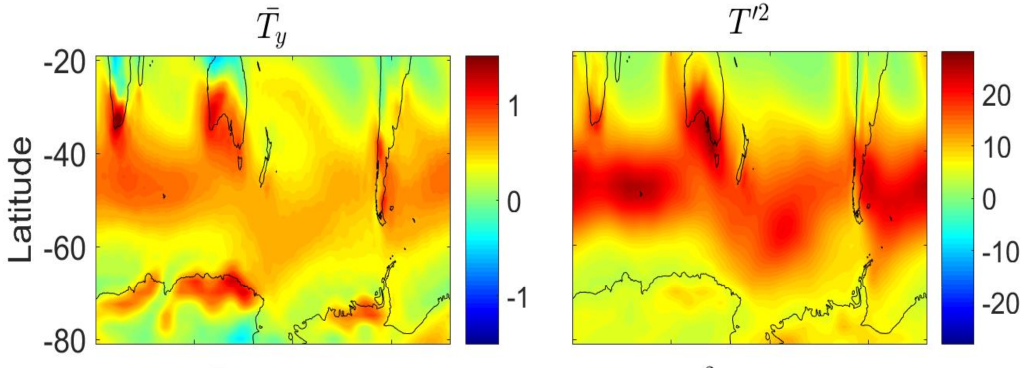
Temperature variance
~
Meridional temperature gradient

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

Temperature variance in the Southern Hemisphere

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

Observed



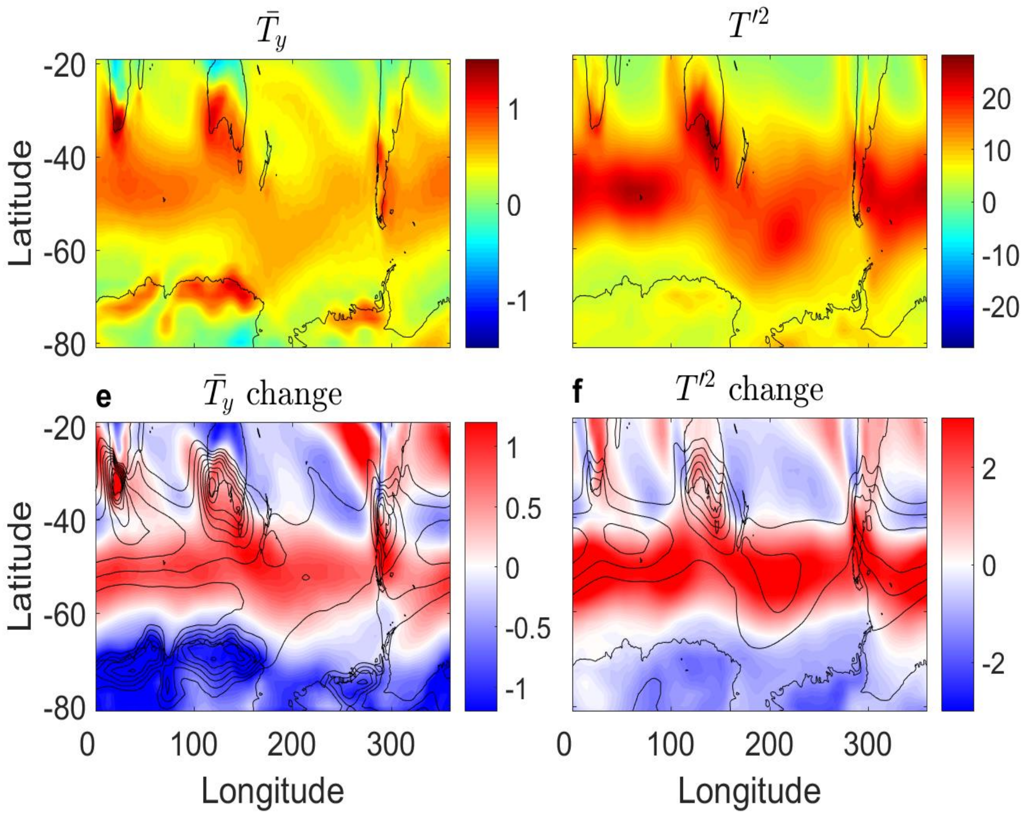
- The Southern Hemisphere (SH) meridional temperature gradient is maximized in the midlatitudes
- Consistent with that, temperature variance is also maximized in the SH midlatitudes

Temperature variance in the Southern Hemisphere

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

Observed

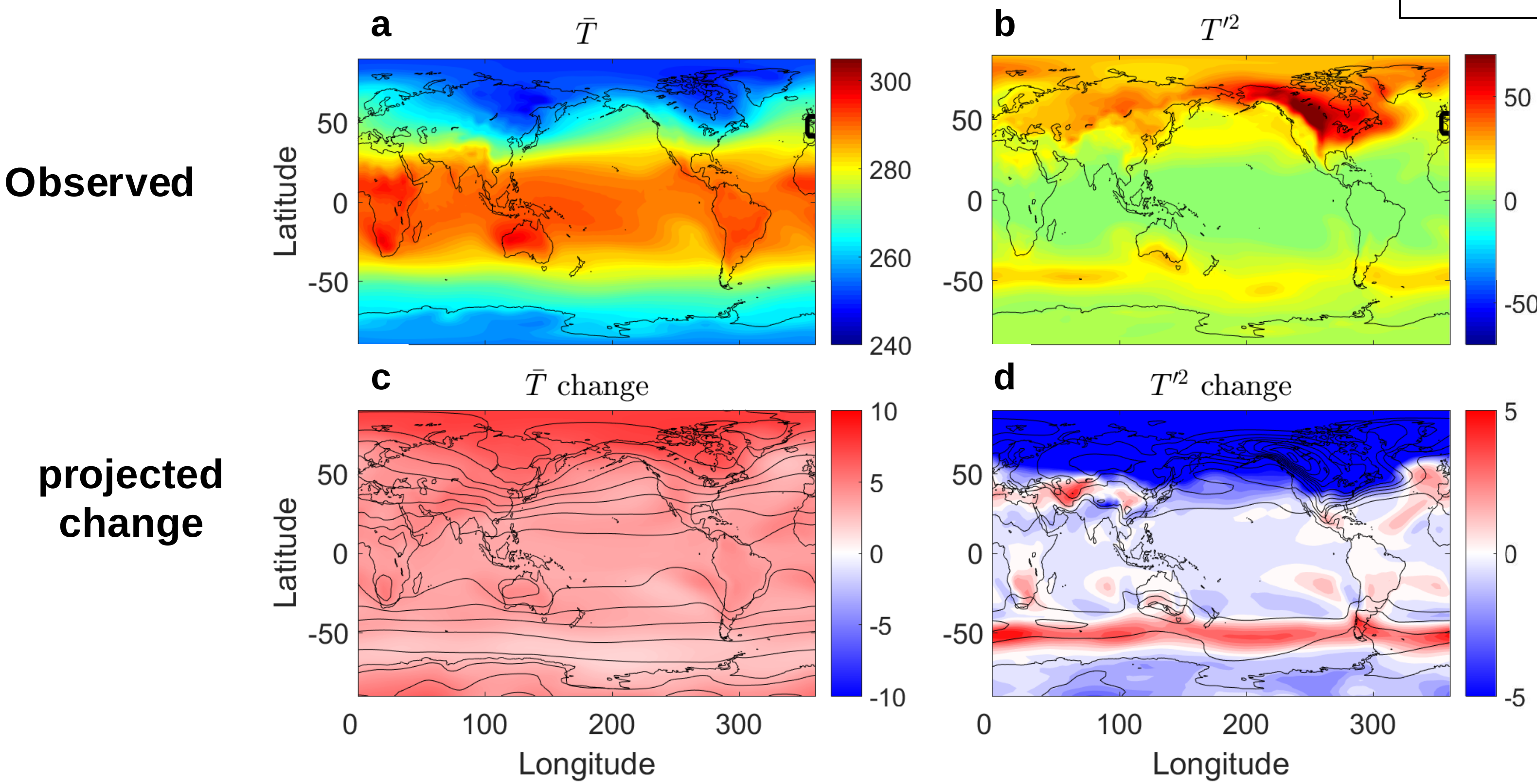
Projected changes



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

Temperature variance in the Northern Hemisphere

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



- 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_T2m.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:

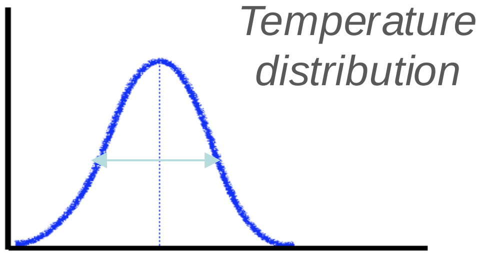
- What do you find for the T2m mean temperature and variance in the historical simulations? Is it similar to what we found for the 850mb level?
- What do the projected mean temperature and variance show? Can you explain this response using temperature advection arguments?
- ***Optional:*** Examine the 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

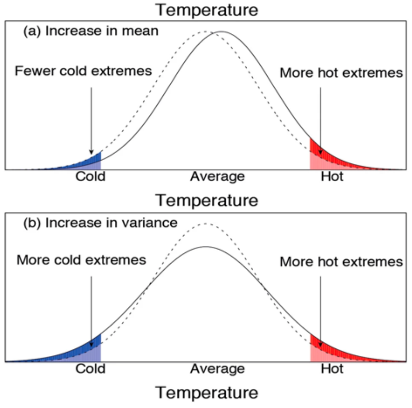
Temperature variability

- 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

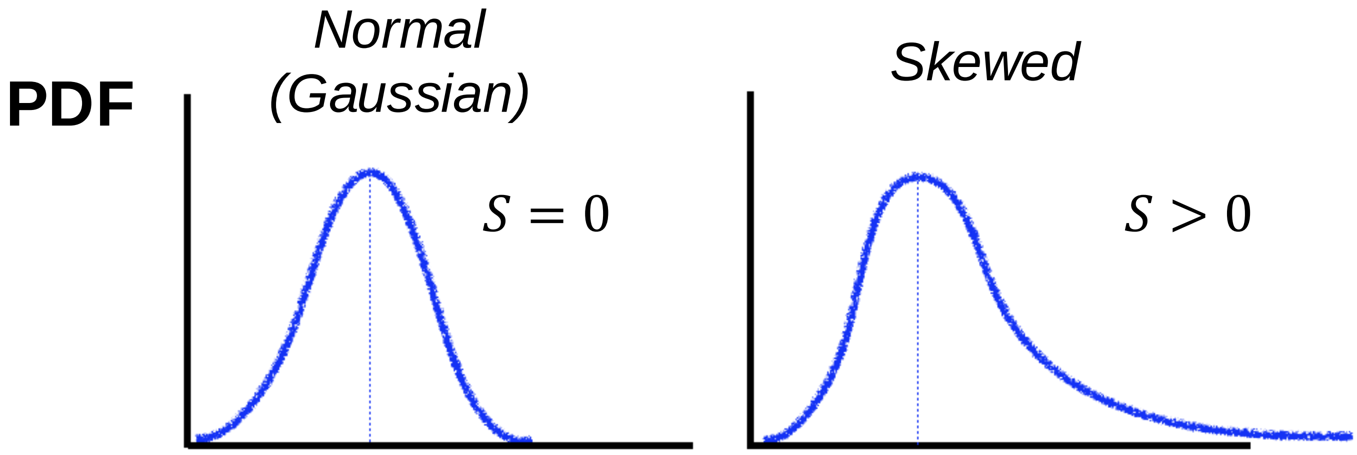
For example, response of temperature extremes to climate change (IPCC AR5 report)



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



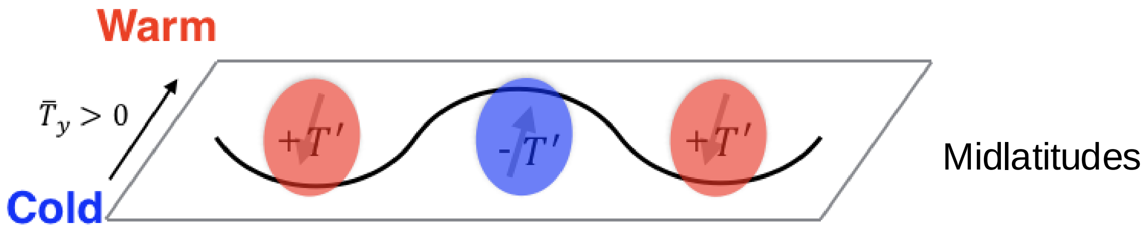
Skewness $S = \frac{\overline{T'^3}}{\left(\overline{T'^2}\right)^{3/2}}$

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

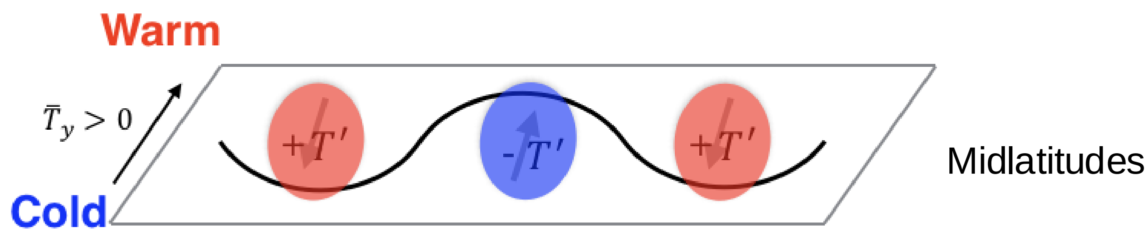
$$T' = -\eta' \frac{\partial \bar{T}}{\partial y}$$



How is skewness generated?

Linear Vs. Nonlinear advection

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



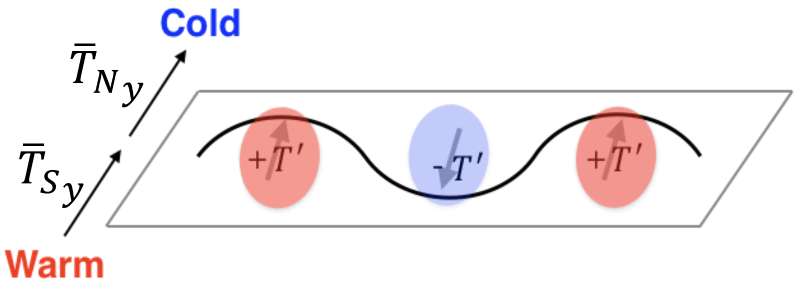
If the background temperature gradient is symmetric for poleward and equatorward motions → warm and cold anomalies will have alternating signs but equal magnitudes

→ *skewness is zero!*

$$S = 0$$

Skewness due to asymmetric linear advection

Asymmetric temperature gradient



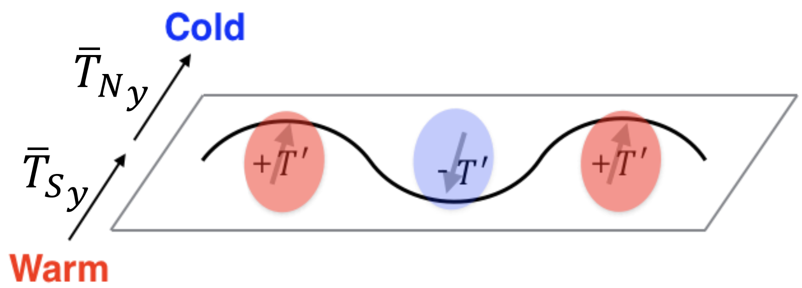
$$T'_c \approx -\eta_N \bar{T}_{N_y}$$
$$T'_w \approx -\eta_S \bar{T}_{S_y}$$

If the gradients to the north & south are different:

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

Skewness due to asymmetric linear advection

Asymmetric temperature gradient



$$T'_c \approx -\eta_N \bar{T}_{N_y}$$
$$T'_w \approx -\eta_S \bar{T}_{S_y}$$

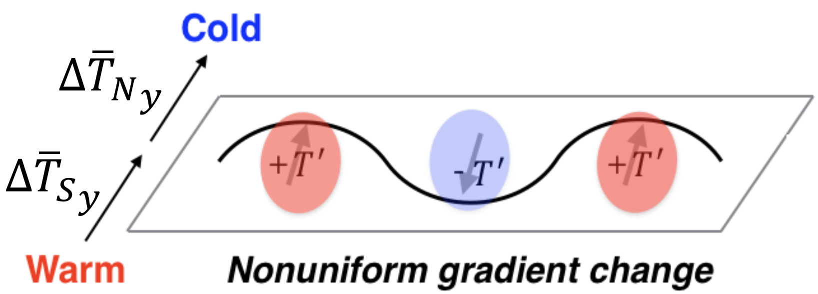
If the gradients to the north & south are different:

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

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

Change in warm anomalies- $\Delta T'_w \sim -\eta_S \Delta\bar{T}_{S_y}$

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!

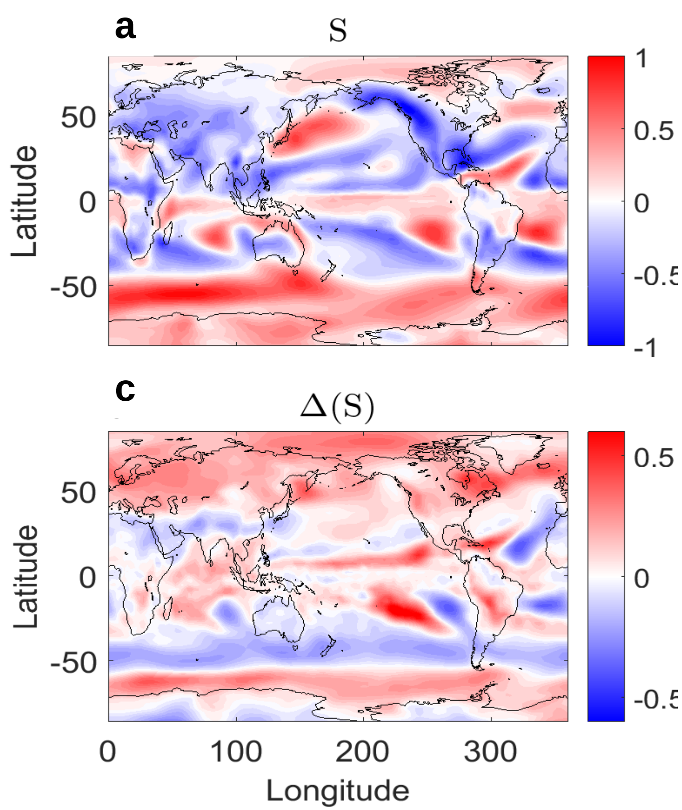
This is what happens over most of the NH during winter → since Arctic Amplification is largest near the NH pole → cold anomalies weaken more

Temperature variability and its response to climate change

DJF (850 hPa)

Observed

projected change (RCP8.5)



Skewness

Skewness change

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!