ATM 241, Spring 2020
Lecture 5
The General Circulation

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Marshall & Plumb

Ch. 5, 8

In this section…

Definitions

- Geostrophic wind
- Polar cell
- Ferrel cell
- Hadley cell
- Intertropical Convergence Zone
- Jet streams
- Atmospheric rivers
- Thermal wind
- Veering winds
- Backing winds

Questions

- What are the dominant forms of balance in the atmosphere?
- What is the primary driver of the meridional structure of the atmosphere?
- What are the four mechanisms for meridional heat transport?
- Where are these mechanisms dominant?
- What are the key features of the Hadley cell?
- What are the key features of the Farrel cell?
- How are meridional temperatures and zonal wind speeds connected?

Review: Balanced Flow

Atmosphere in Balance

The atmosphere, to a large degree, is in a state of equilibrated balance. Processes in the atmosphere act to smooth out perturbations from that equilibrium through **geostrophic adjustment** (adjustment towards geostrophic balance).

The two dominant balances in the atmosphere are:

- **Hydrostatic balance**
    - Balance between vertical pressure gradient force and gravity
    - Holds because vertical velocities are small

- **Geostrophic balance**
    - Balance between horizontal pressure gradient force and Coriolis force
    - Holds in the midlatitudes where Coriolis is sufficiently large

Atmosphere in Balance

Dominant drivers of horizontal motion on large scales:
Pressure gradient force and **Coriolis force**

Change in velocity on constant pressure surfaces

$$\left(\frac{du}{dt}\right)_p = -\left(\frac{\partial \Phi}{\partial x}\right)_p + fv$$

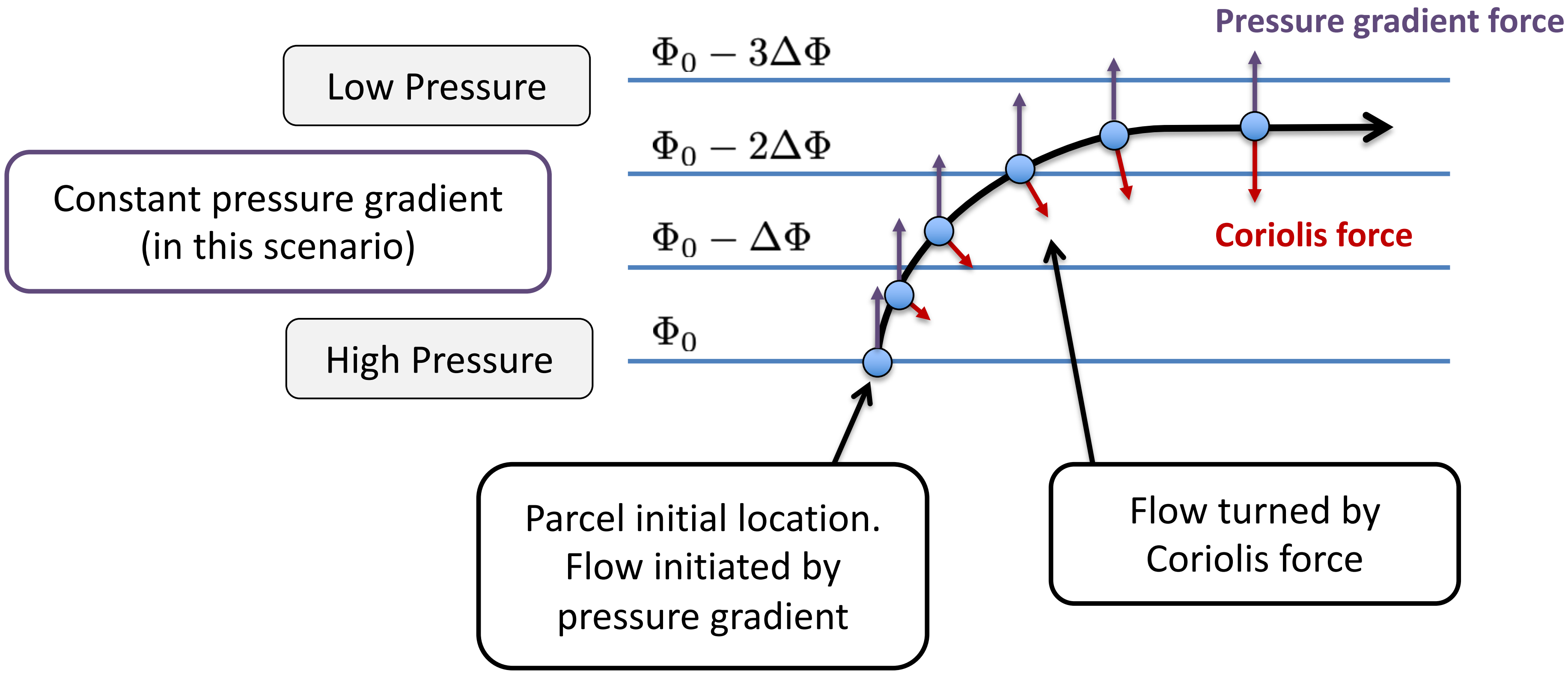
$$\left(\frac{dv}{dt}\right)_p = -\left(\frac{\partial \Phi}{\partial y}\right)_p - fu$$

Pressure gradient force
(gradient of geopotential)

Coriolis force
(acts to turn the flow to the right in the northern hemisphere and to the left in the southern hemisphere)

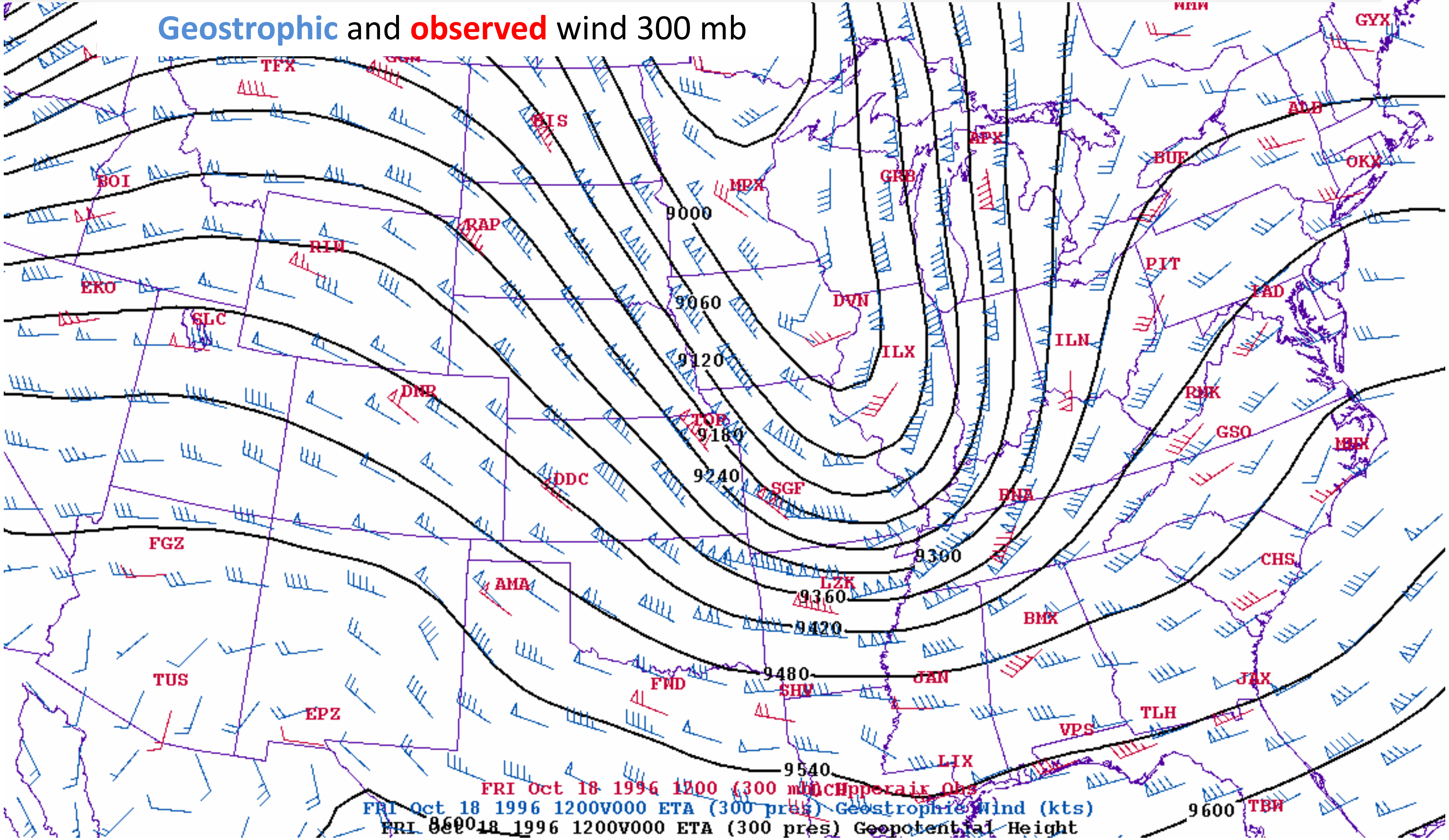
Geostrophic Balance

When pressure gradient force and Coriolis force simultaneously act on a fluid parcel, fluid parcels tend to **move along lines of constant pressure**.



Geostrophic Balance

Geostrophic and **observed** wind 300 mb



Geostrophic Balance

Three observations from the previous figure:

- At upper levels (where friction is negligible) the observed wind is parallel to geopotential height contours (on a constant pressure surface).
- Wind is faster when height contours are closer together.
- Wind is slower when height contours are farther apart.

Geostrophic Balance

Assume acceleration is small and solve for (u,v):

$$\left(\frac{du}{dt}\right)_p = -\left(\frac{\partial \Phi}{\partial x}\right)_p + fv$$

$$\left(\frac{dv}{dt}\right)_p = -\left(\frac{\partial \Phi}{\partial y}\right)_p - fu$$

Definition: The **geostrophic wind** is the theoretical wind that results from an exact balance of pressure gradient and Coriolis force:

$$u_g = -\frac{1}{f}\left(\frac{\partial \Phi}{\partial y}\right)_p \qquad v_g = \frac{1}{f}\left(\frac{\partial \Phi}{\partial x}\right)_p$$

The geostrophic wind explains approximately 90% of the total wind speed in the midlatitudes and away from the surface (in the free atmosphere).

Geostrophic Balance

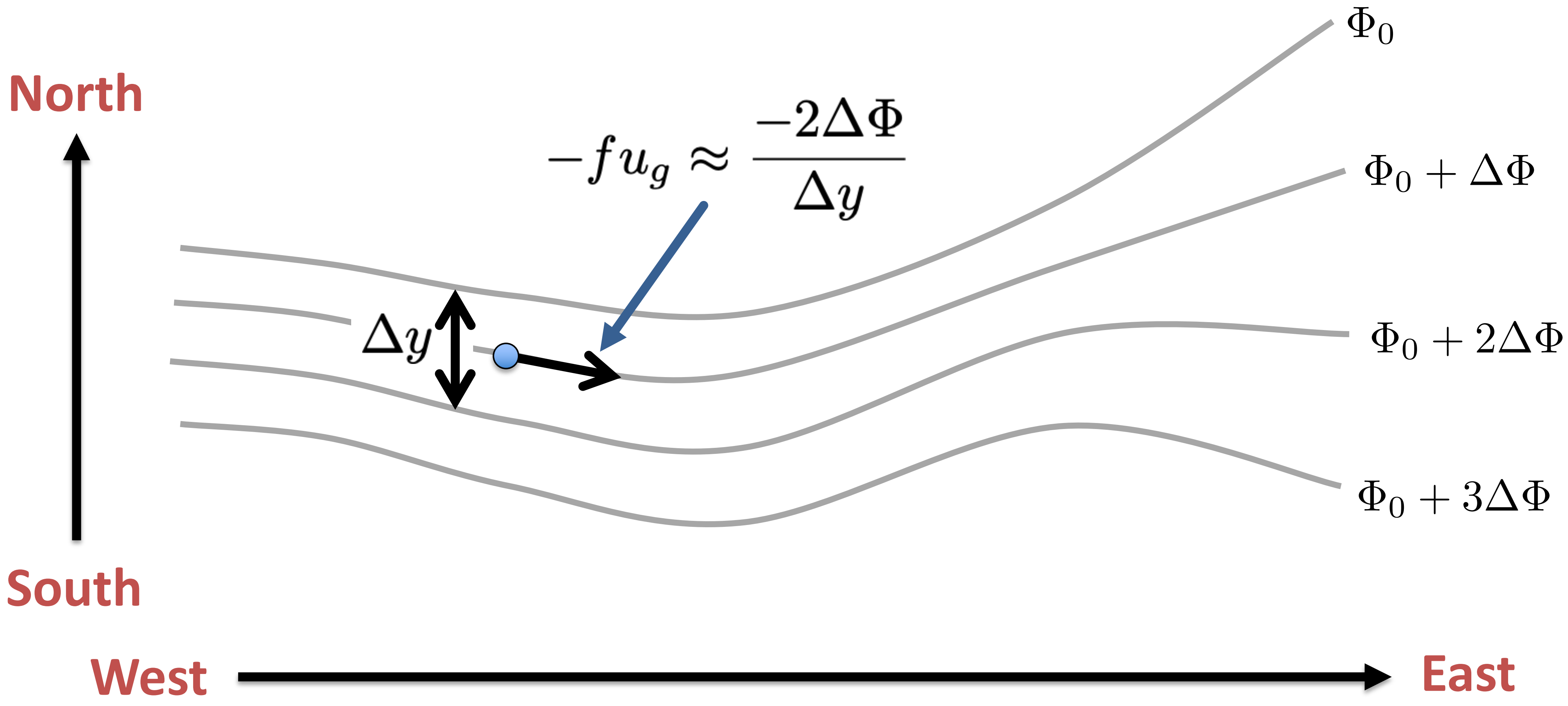
Geostrophic wind

$$u_g = -\frac{1}{f}\left(\frac{\partial \Phi}{\partial y}\right)_p \qquad v_g = \frac{1}{f}\left(\frac{\partial \Phi}{\partial x}\right)_p$$

Note that the geostrophic wind is perpendicular to geopotential gradients (and parallel to lines of constant geopotential):

$$\mathbf{u}_g \cdot \nabla \Phi = -\frac{1}{f}\left(\frac{\partial \Phi}{\partial y}\right)_p \left(\frac{\partial \Phi}{\partial x}\right)_p + \frac{1}{f}\left(\frac{\partial \Phi}{\partial x}\right)_p \left(\frac{\partial \Phi}{\partial y}\right)_p = 0$$

Geostrophic Balance



Geostrophic Balance

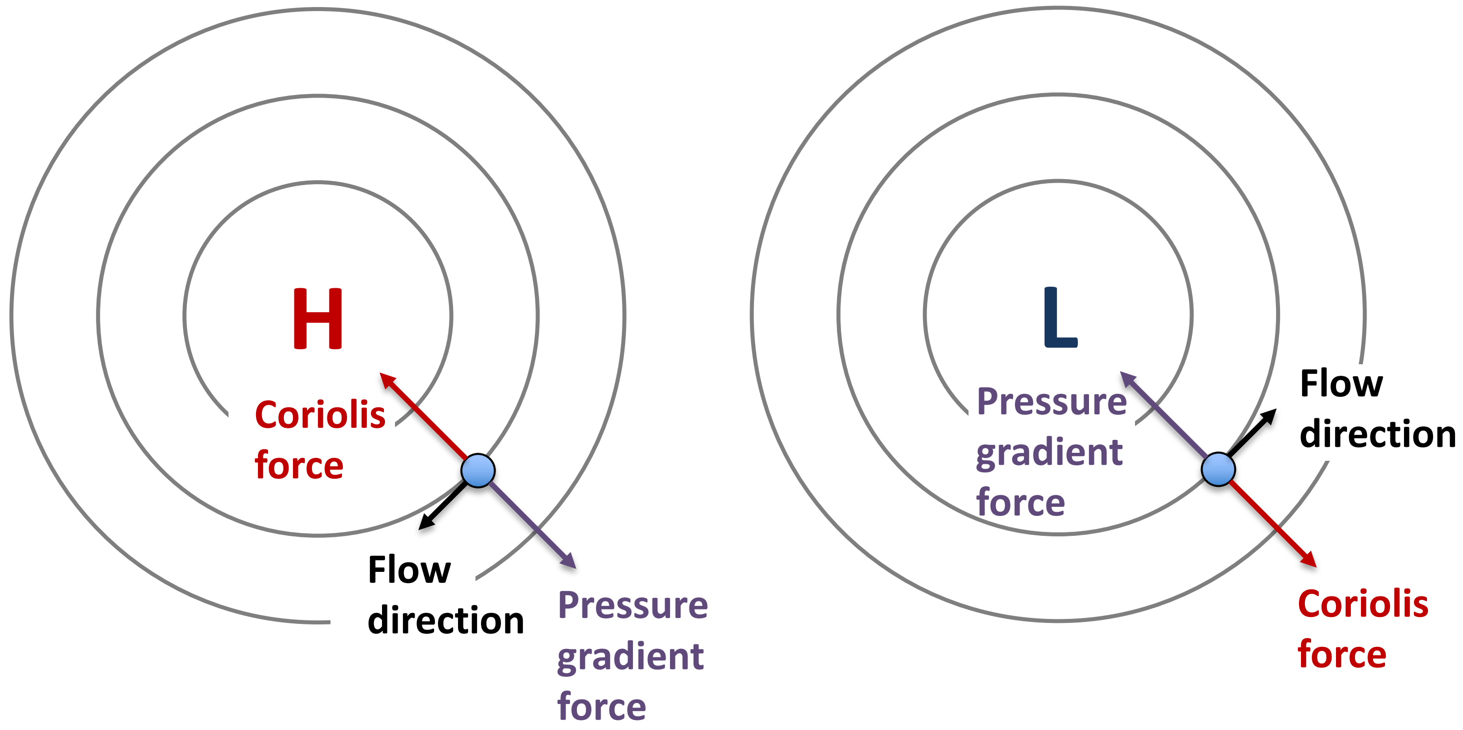


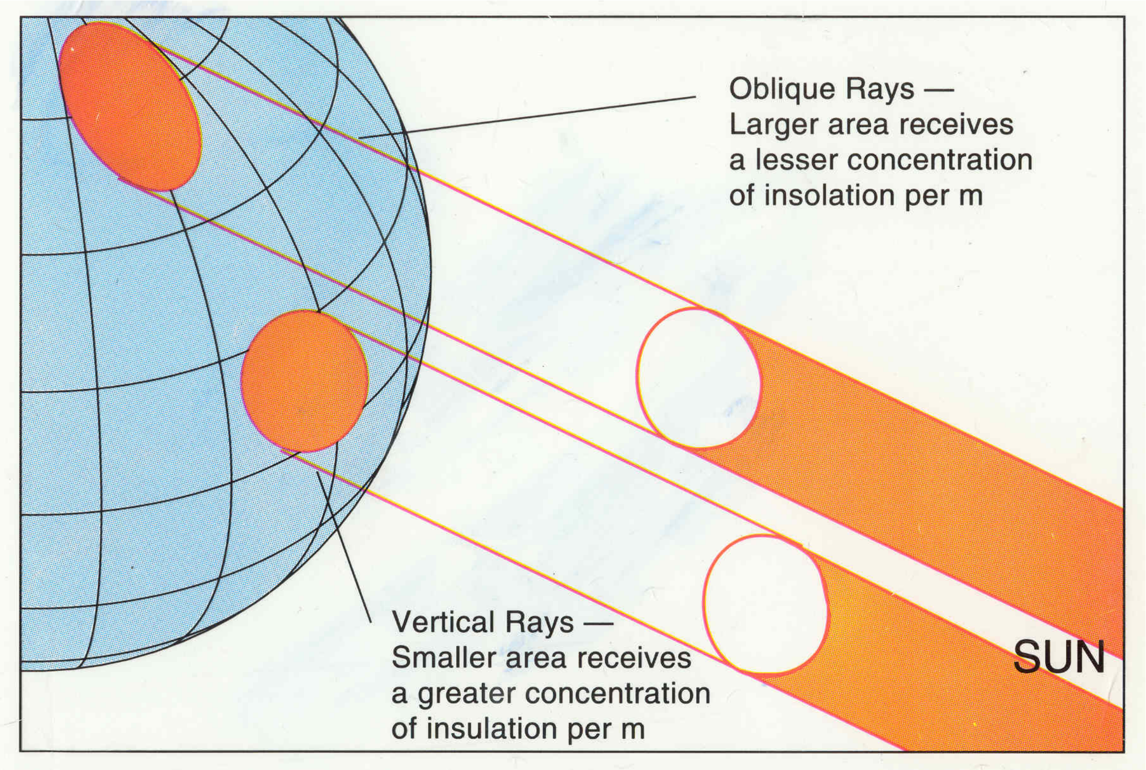
Figure: Geostrophic flow around (left) a high pressure center and (right) a low pressure center (right). The northern hemisphere case is depicted here. The southern hemisphere case maintains the same force vectors but with the flow direction flipped.

Drivers of Meridional Structure

Recall: Insolation

The curvature of the Earth's surface means that the power due to incident solar radiation is not equal across the surface.

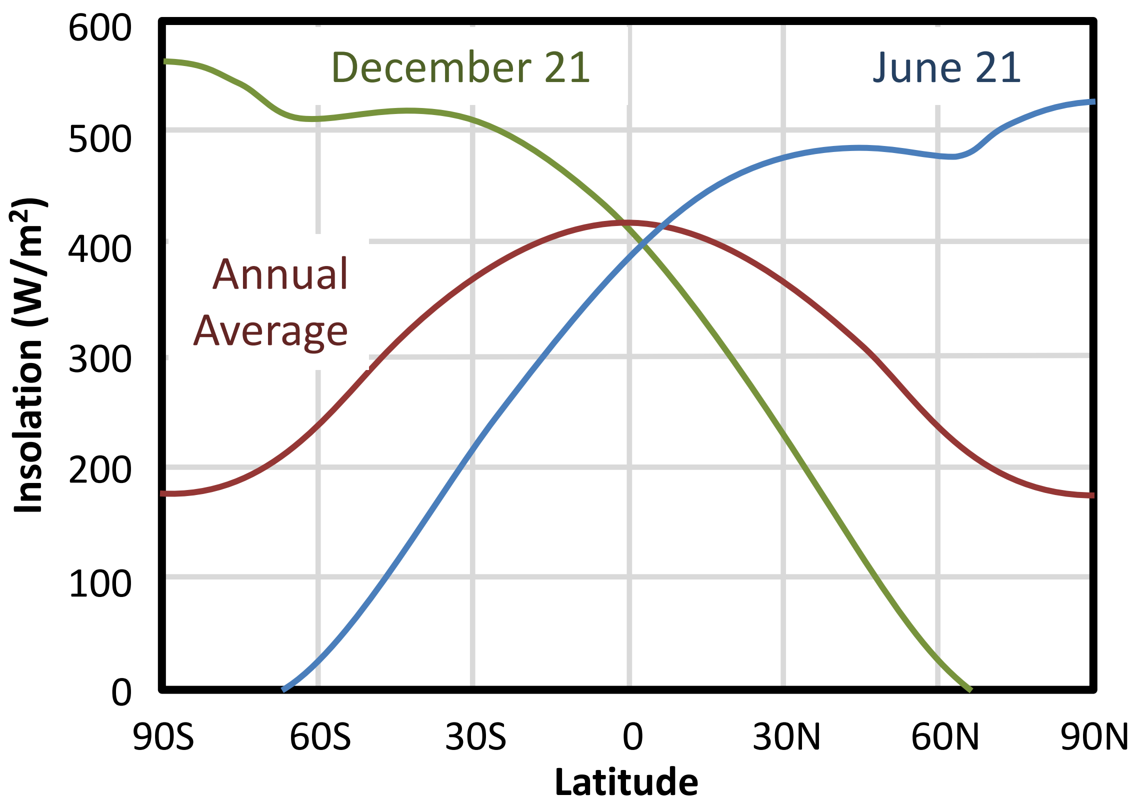
The amount of solar radiation received is proportional to great circle distance between location and sub-solar point (point directly under the sun).

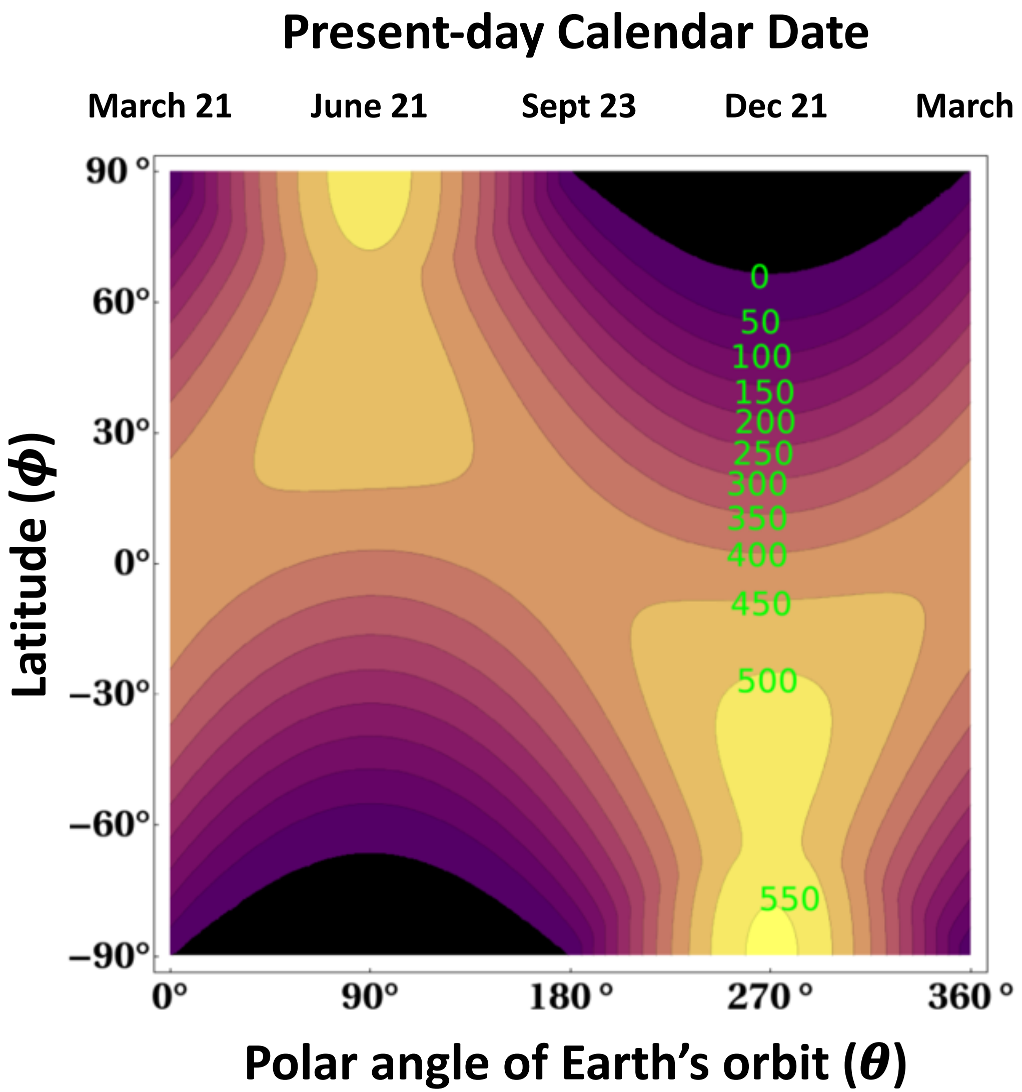


Definition: Insolation is a measure of solar radiation energy received on a given surface area and recorded during a given time.

Recall: Insolation

Figure: (Right) Theoretical daily-average insolation at the top of the atmosphere. (Bottom) Cross sections at Summer/Winter Solstice and annual mean.

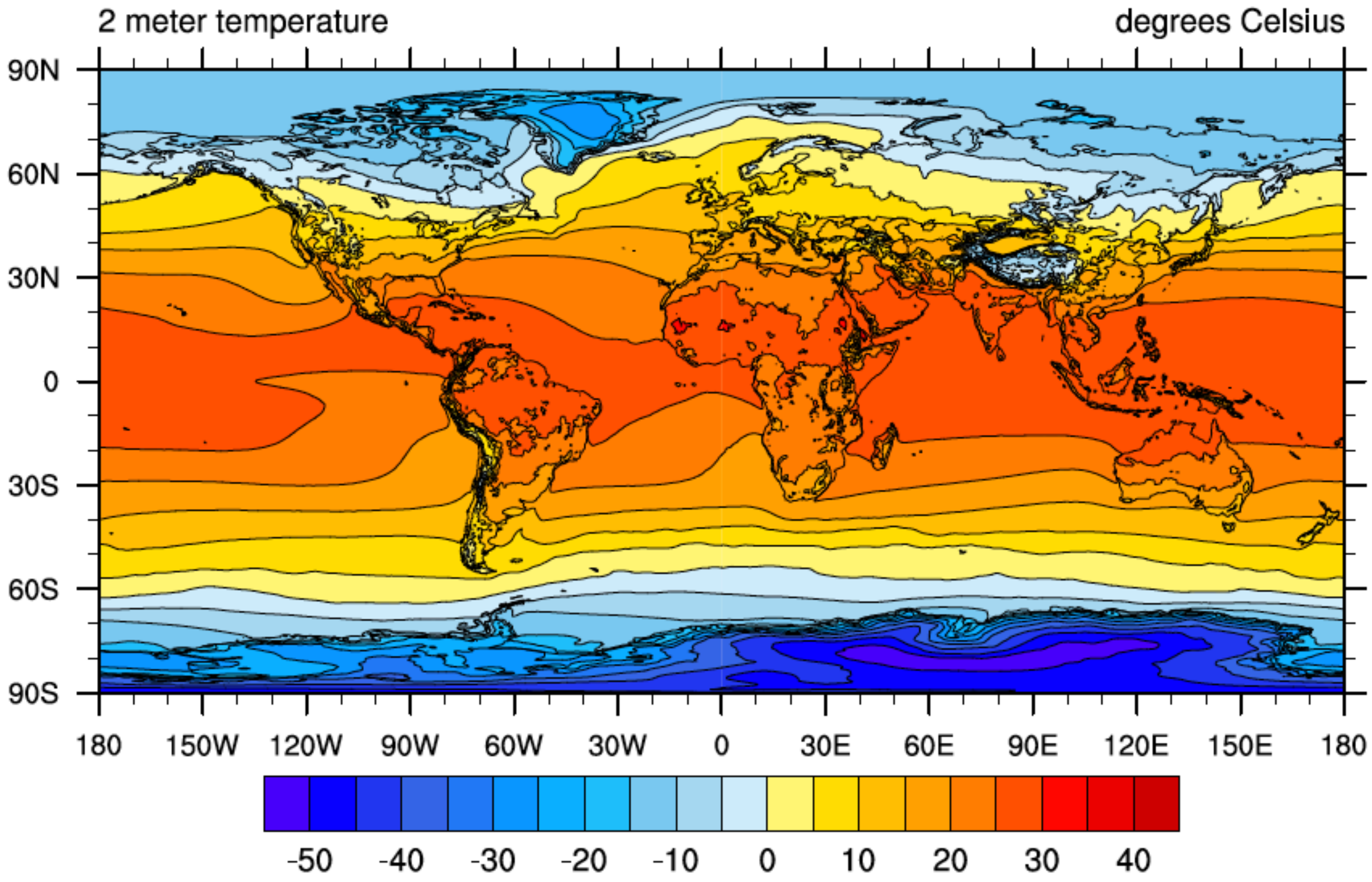




Global Near-Surface Temperature

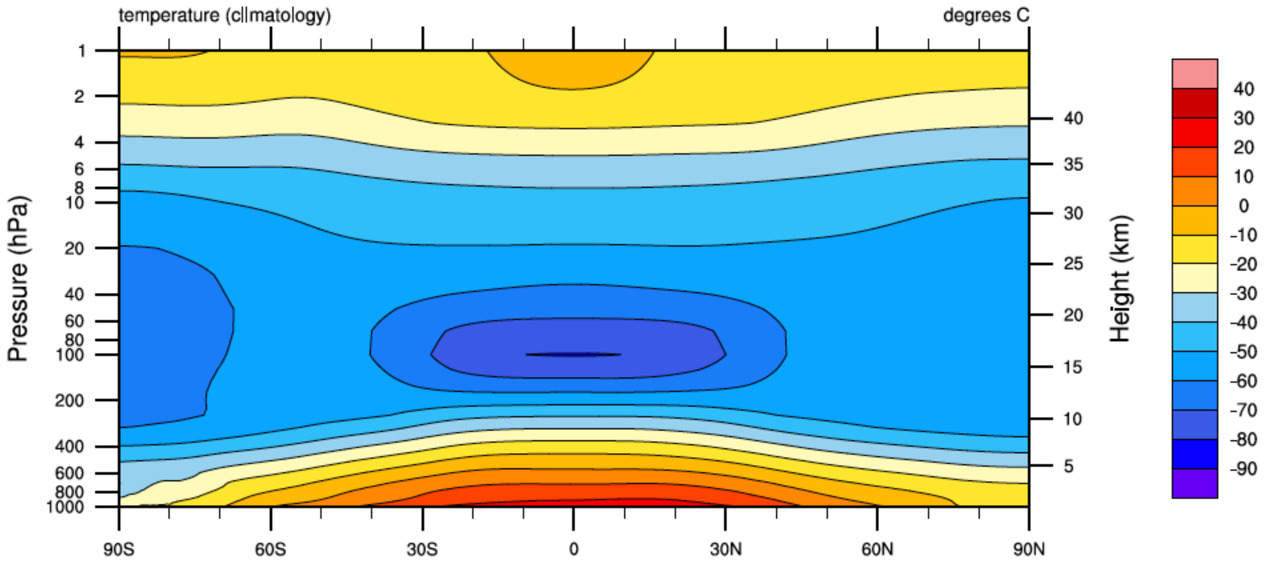
Figure: Annual mean 2-meter temperature of the Earth from ECMWF ERA5.

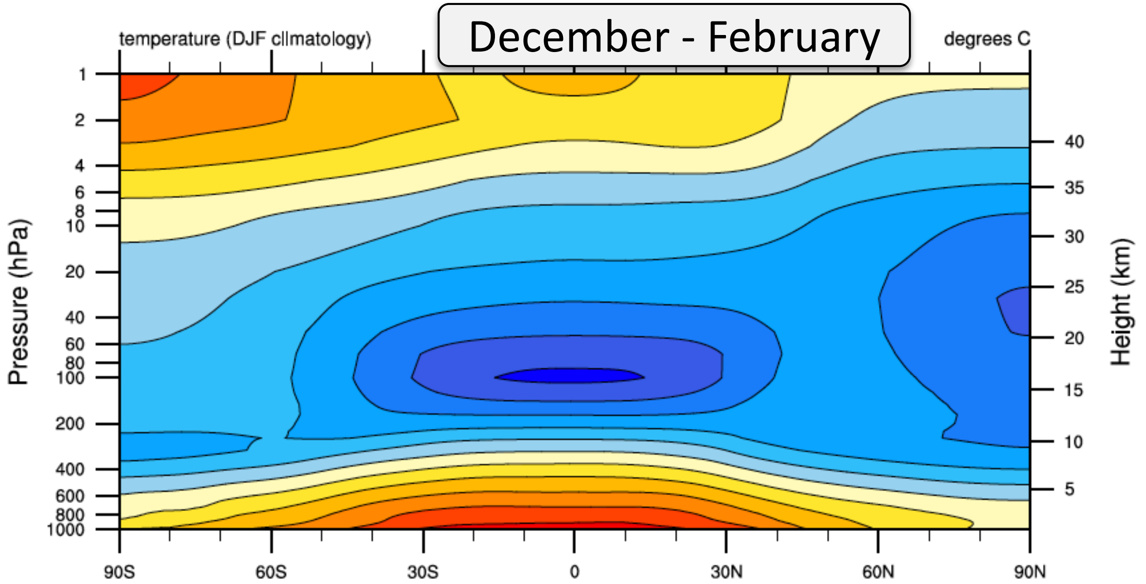
Key point: Spatial variation in insolation drives variations in temperature across the Earth's surface.

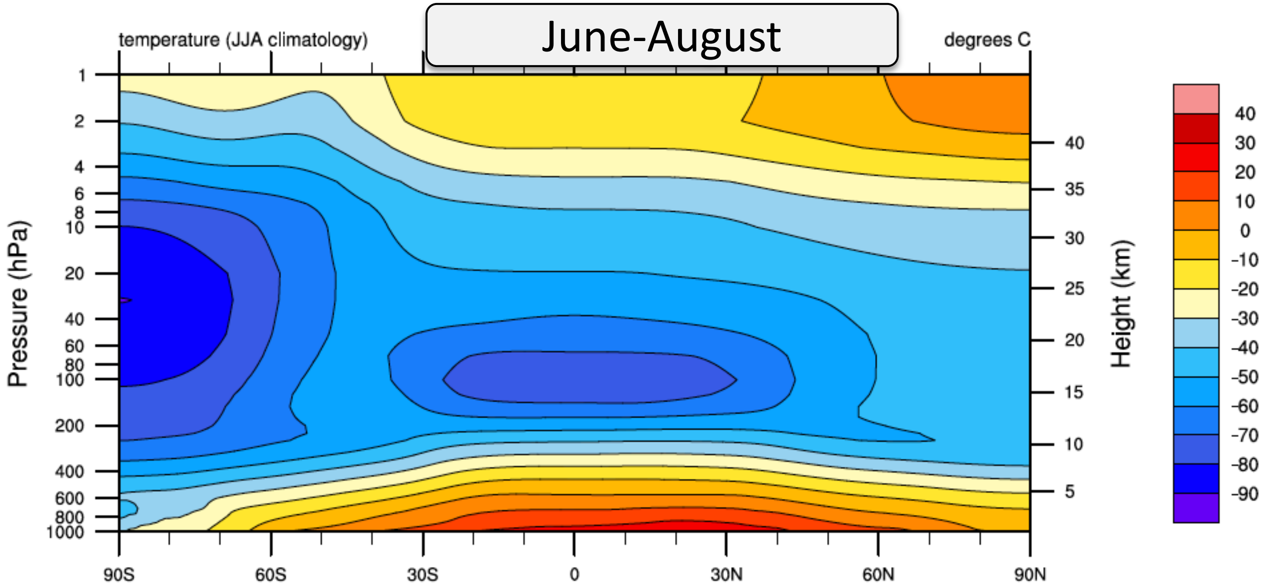


Zonally Averaged Temperature

Figure: Reanalysis climatology zonally averaged vertical temperature structure showing the troposphere and stratosphere from ECMWF ERA5.

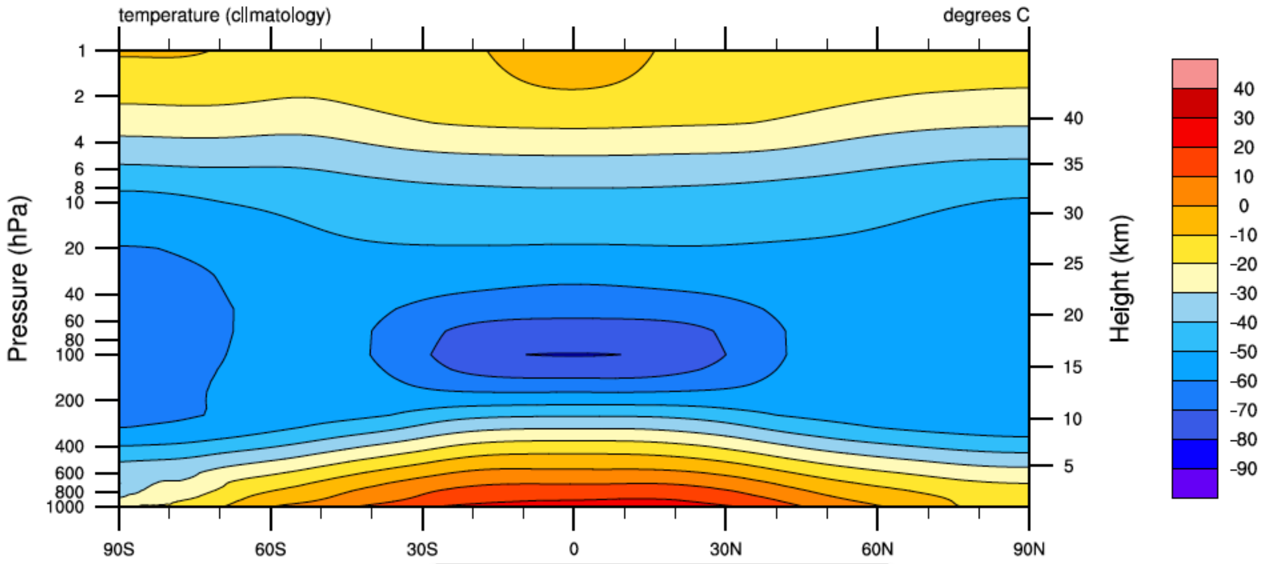


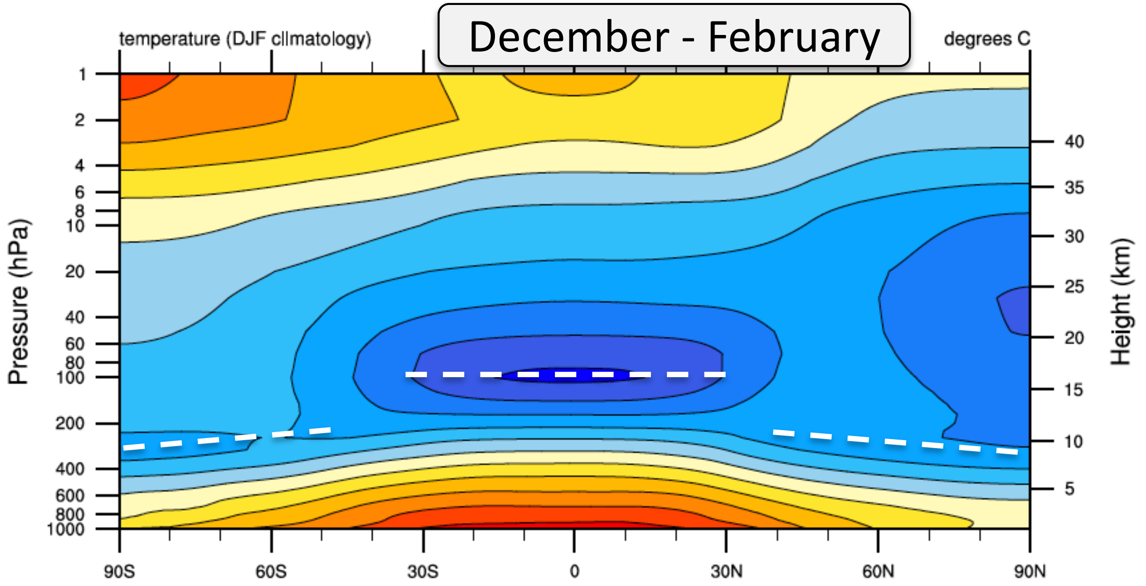


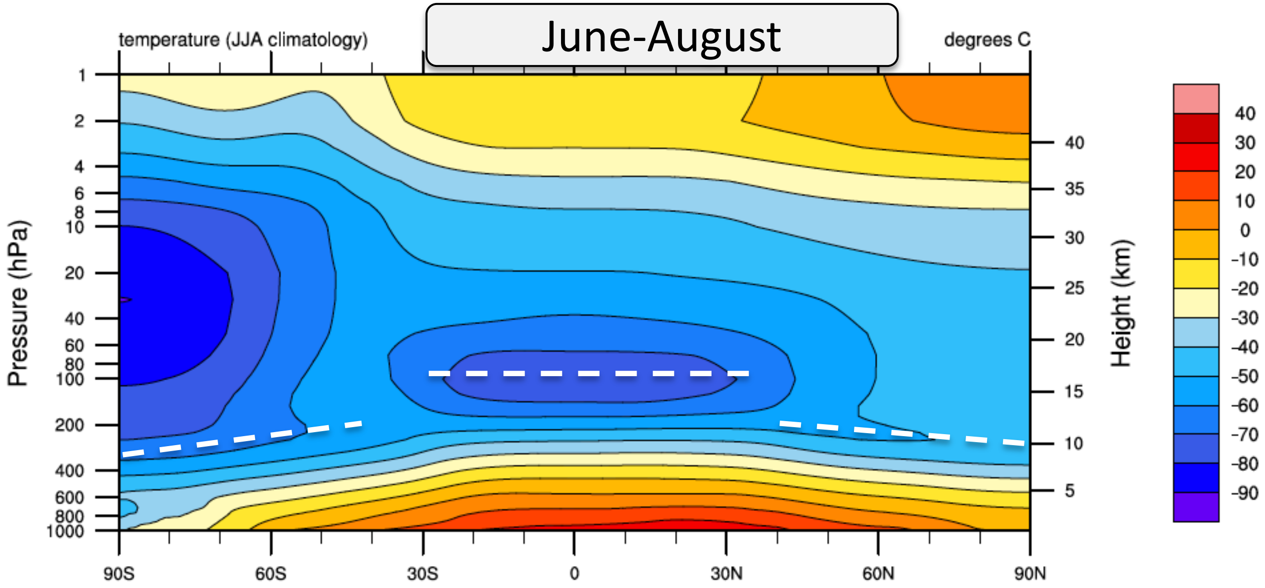


Zonally Averaged Temperature

Figure: Reanalysis climatology zonally averaged temperature. Approximate tropopause location shown with dashed lines. The deeper troposphere in the tropics leads to cooler temperatures at altitude.







Zonally Averaged Temperature

Temperature gradients in the stratosphere agree with the latitudinal structure of incoming solar radiation.

Temperature gradients in the troposphere exhibit maximum temperature near the equator.

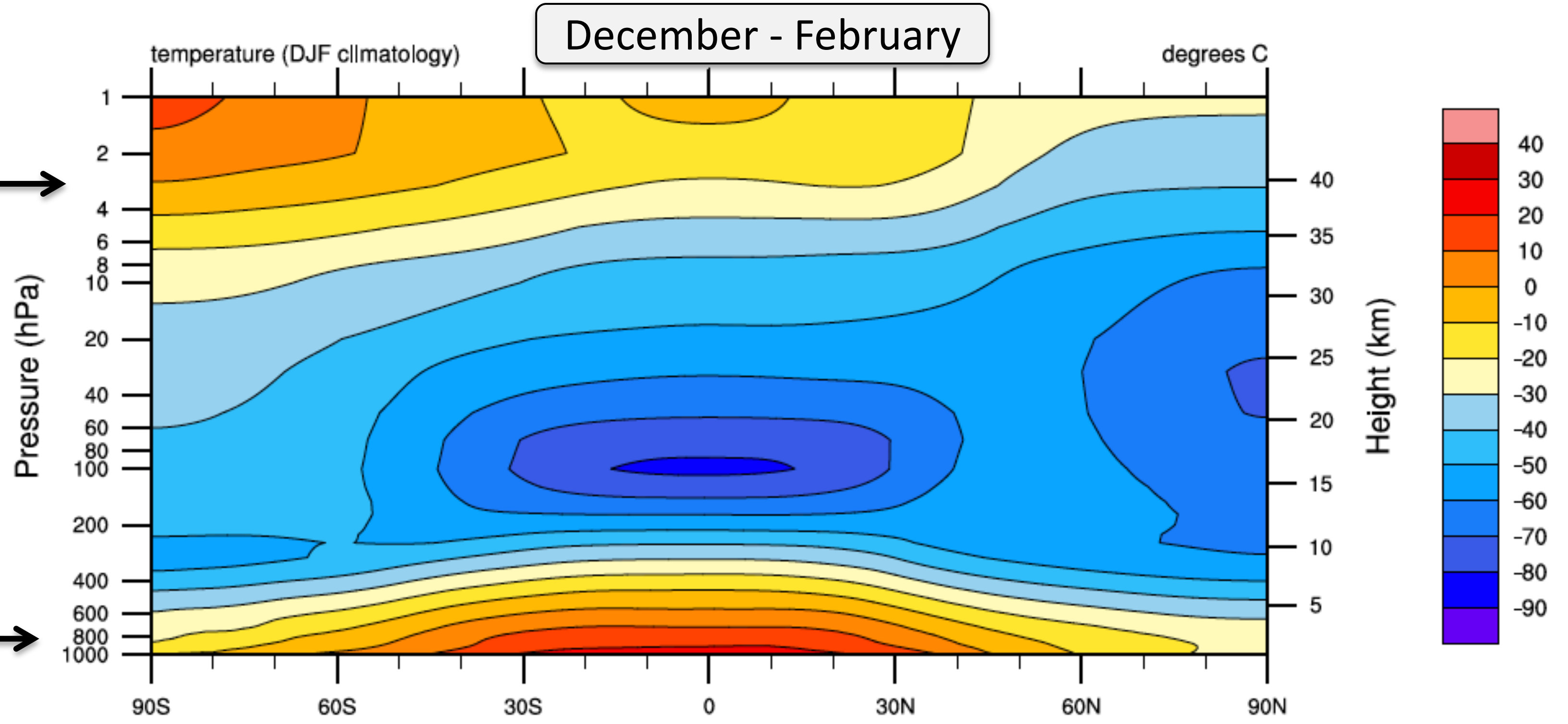
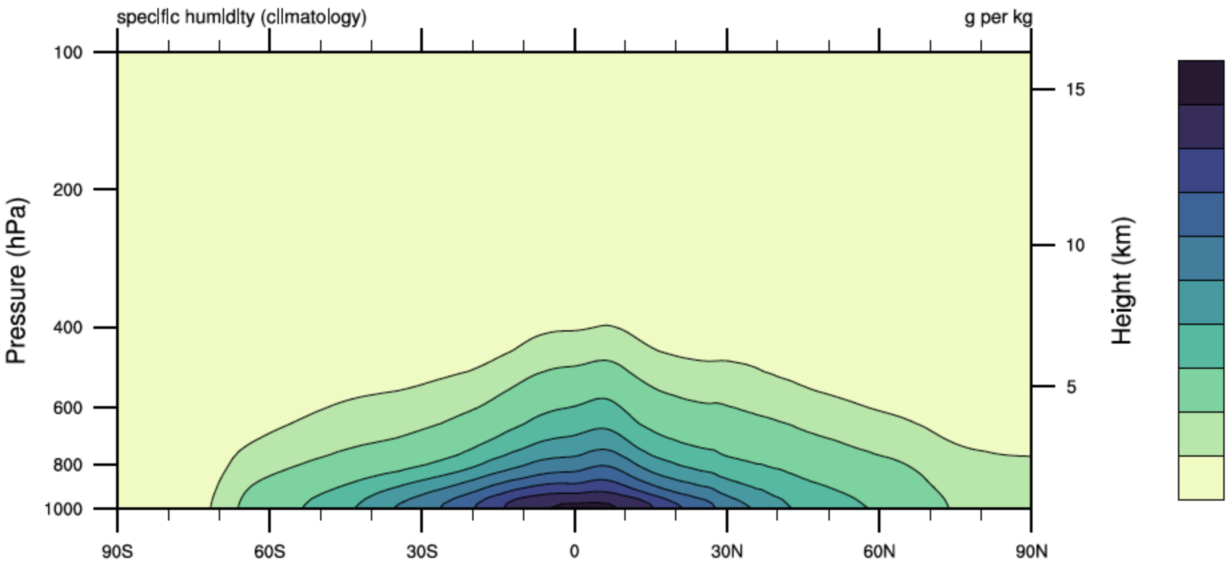
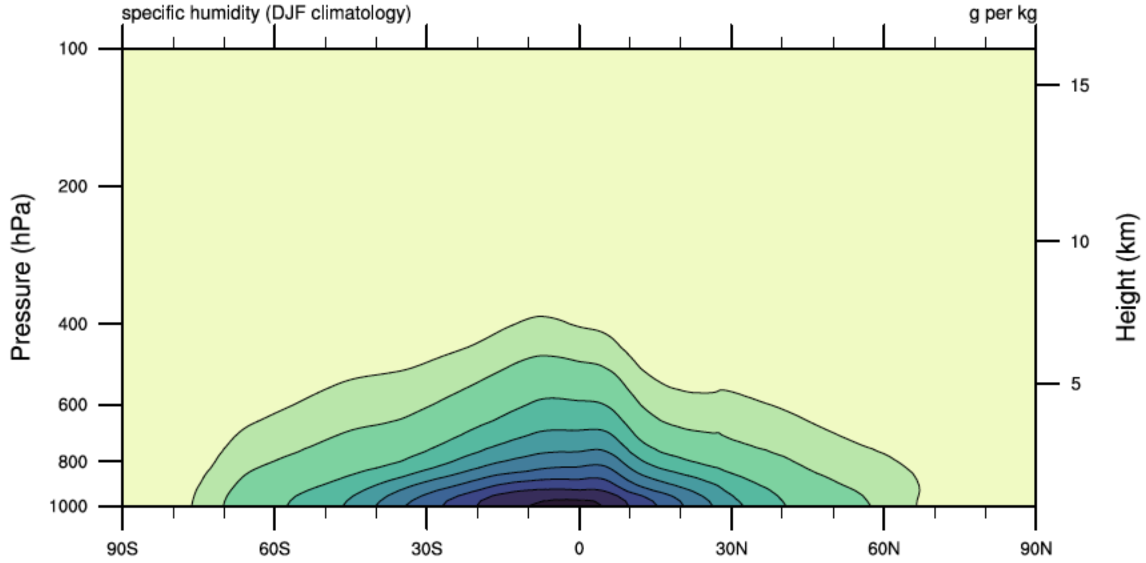


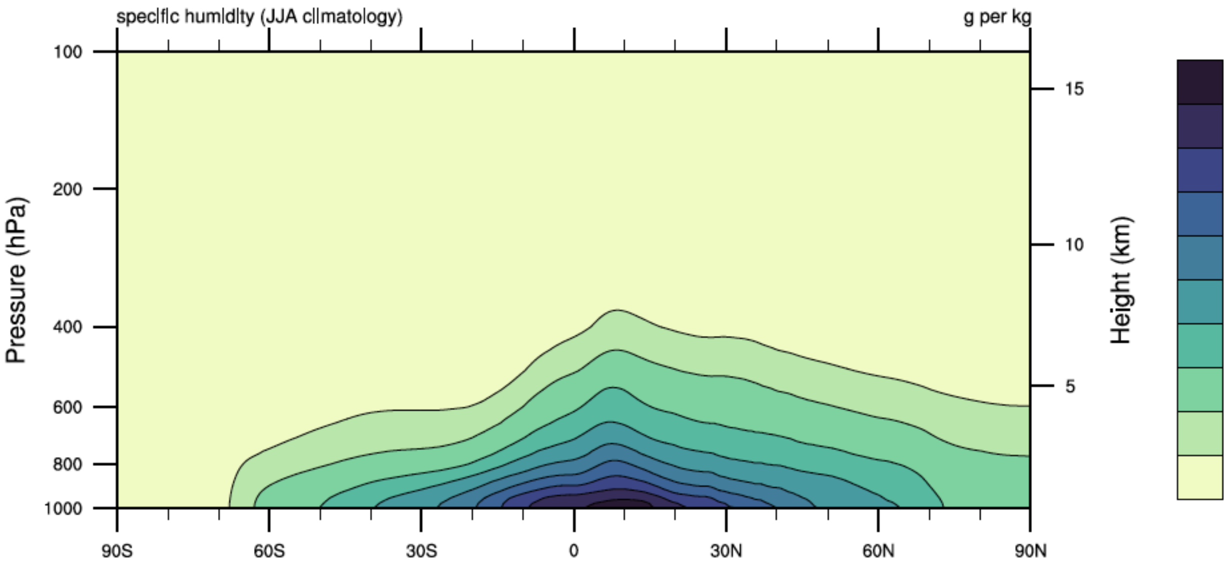
Figure: Zonal mean temperature for the northern hemisphere winter season (December – February).

Zonally Averaged Specific Humidity

Figure: Zonally-averaged specific humidity (g/kg), obtained from ECMWF ERA5. Moisture variations in the troposphere largely follow atmospheric temperature patterns.

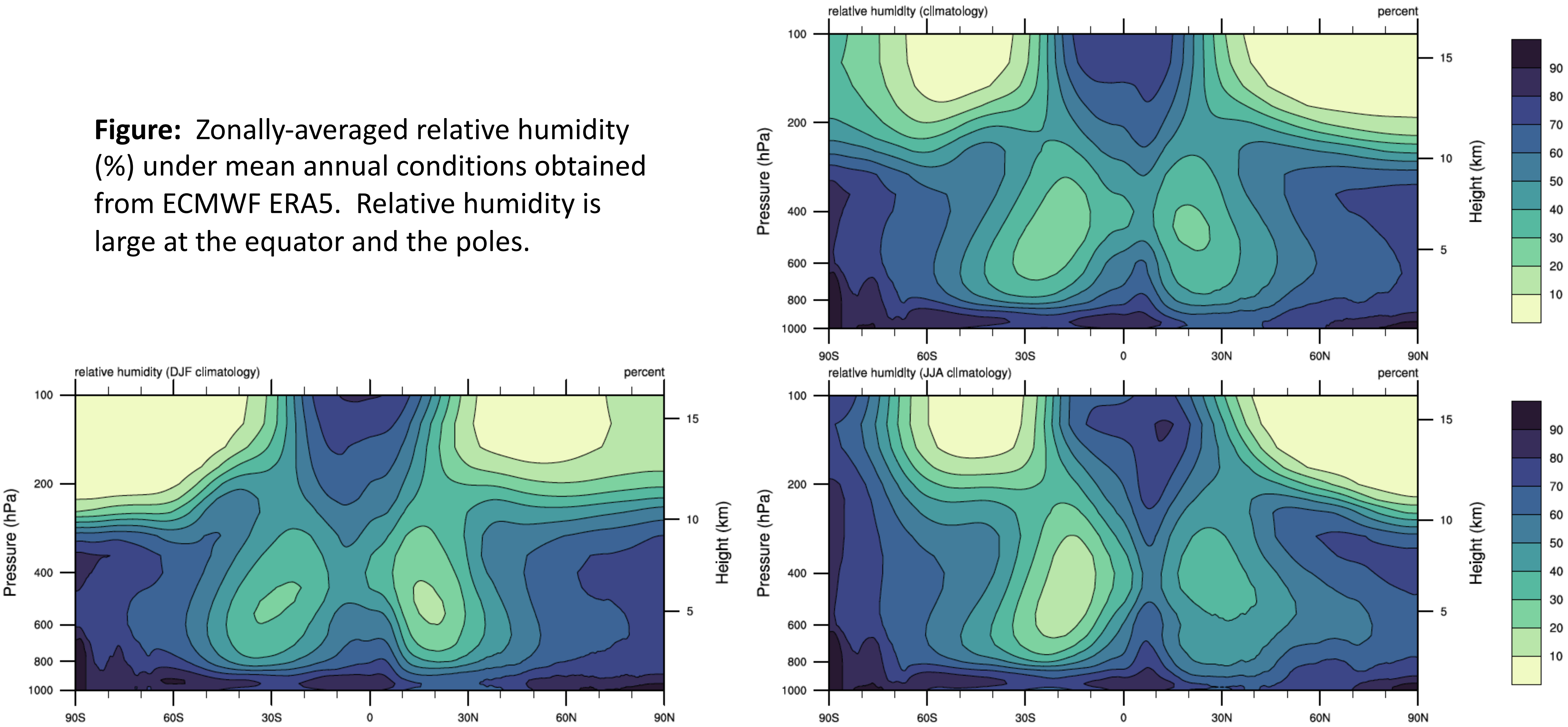




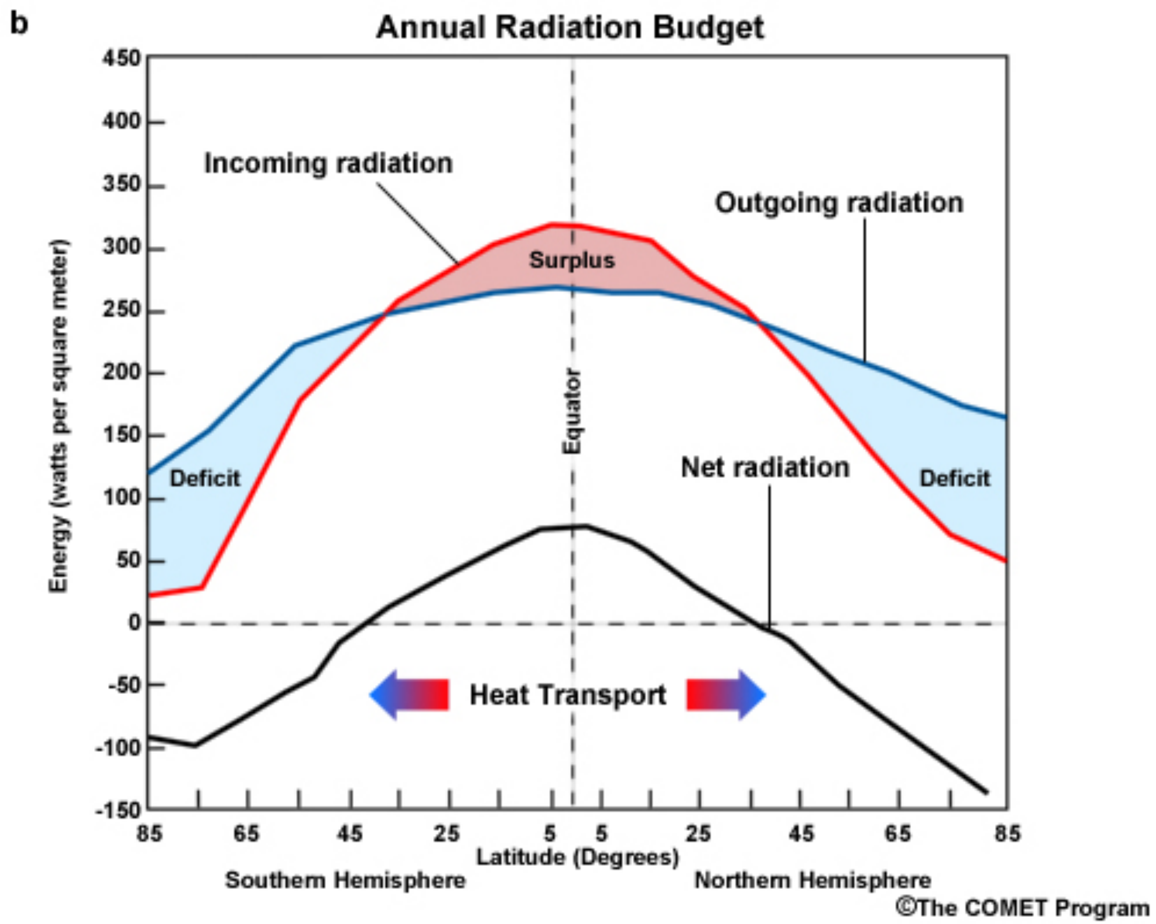


Zonally Averaged Relative Humidity

Figure: Zonally-averaged relative humidity (%) under mean annual conditions obtained from ECMWF ERA5. Relative humidity is large at the equator and the poles.



Temperature Gradients



Temperature variations lead to differences in radiative emissivity.

However, outgoing terrestrial radiation is smoothed compared with incoming radiation because of **meridional heat transport**.

Meridional heat transport induced by temperature differences then give rise to **large-scale circulation patterns** and **regional weather features**.

Global Heat Transport

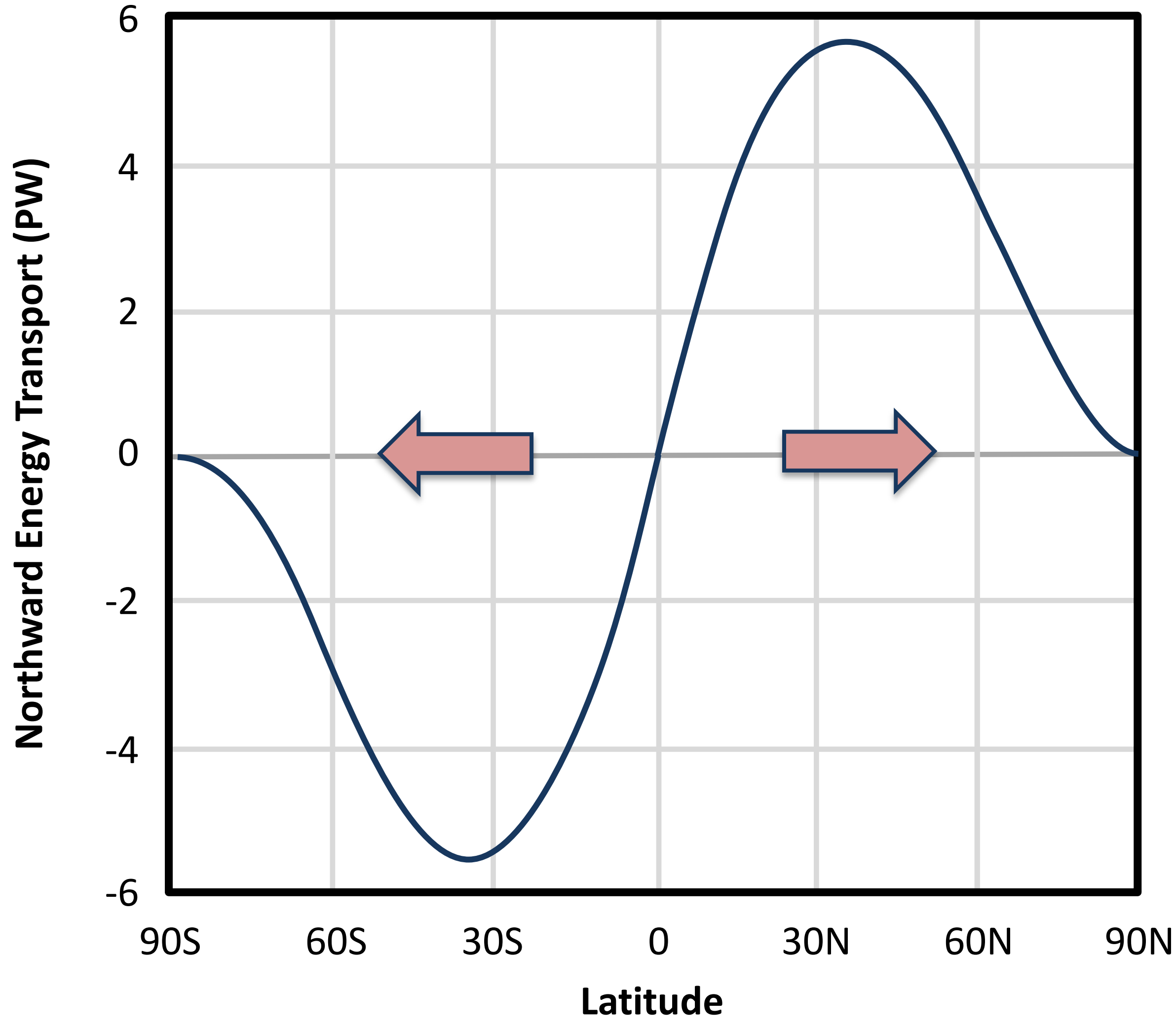
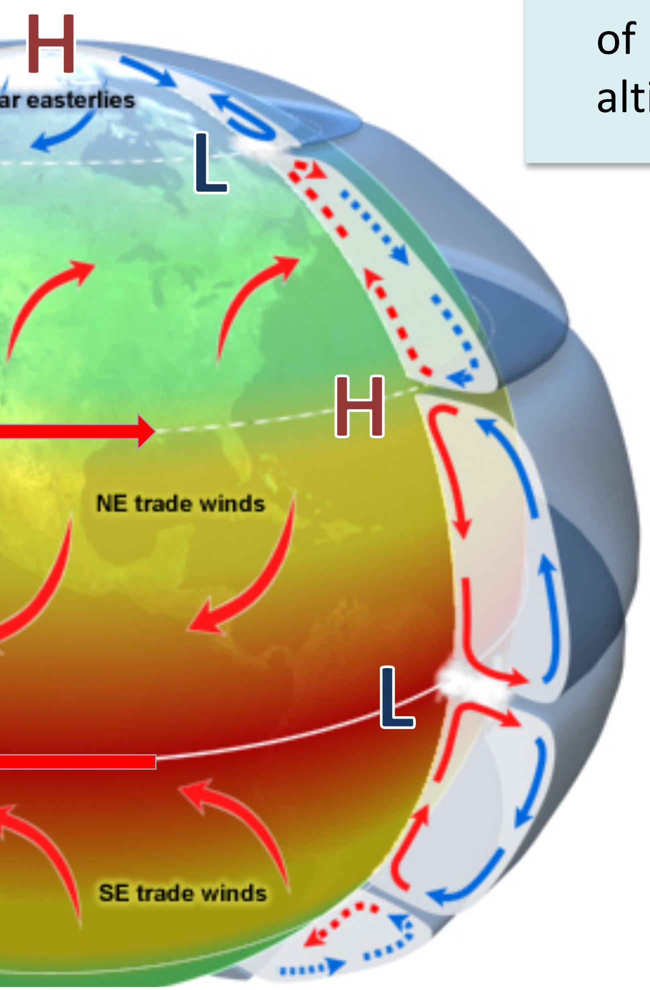


Figure: The northward energy transport deduced by top of the atmosphere energy measurements of incoming and outgoing solar and terrestrial radiation. Units are PetaWatts (= 10^{15} W).

Global Heat Transport (Four Mechanisms)

- **Large-scale circulation.** Bulk transport via the Hadley circulation. This is the primary mechanism for atmospheric heat transport near the equator.
- **Eddy flux of temperature.** Turbulent transport due to large-scale eddies (extratropical cyclones). This mechanism arises due to the rotation of the Earth.
- **Meridional latent heat transport.** Moisture transport from the subtropics to the midlatitudes (and farther north), largely due to atmospheric rivers.
- **Ocean currents.** Transport and release of heat via, for example, the Gulf stream.

Meridional Circulation



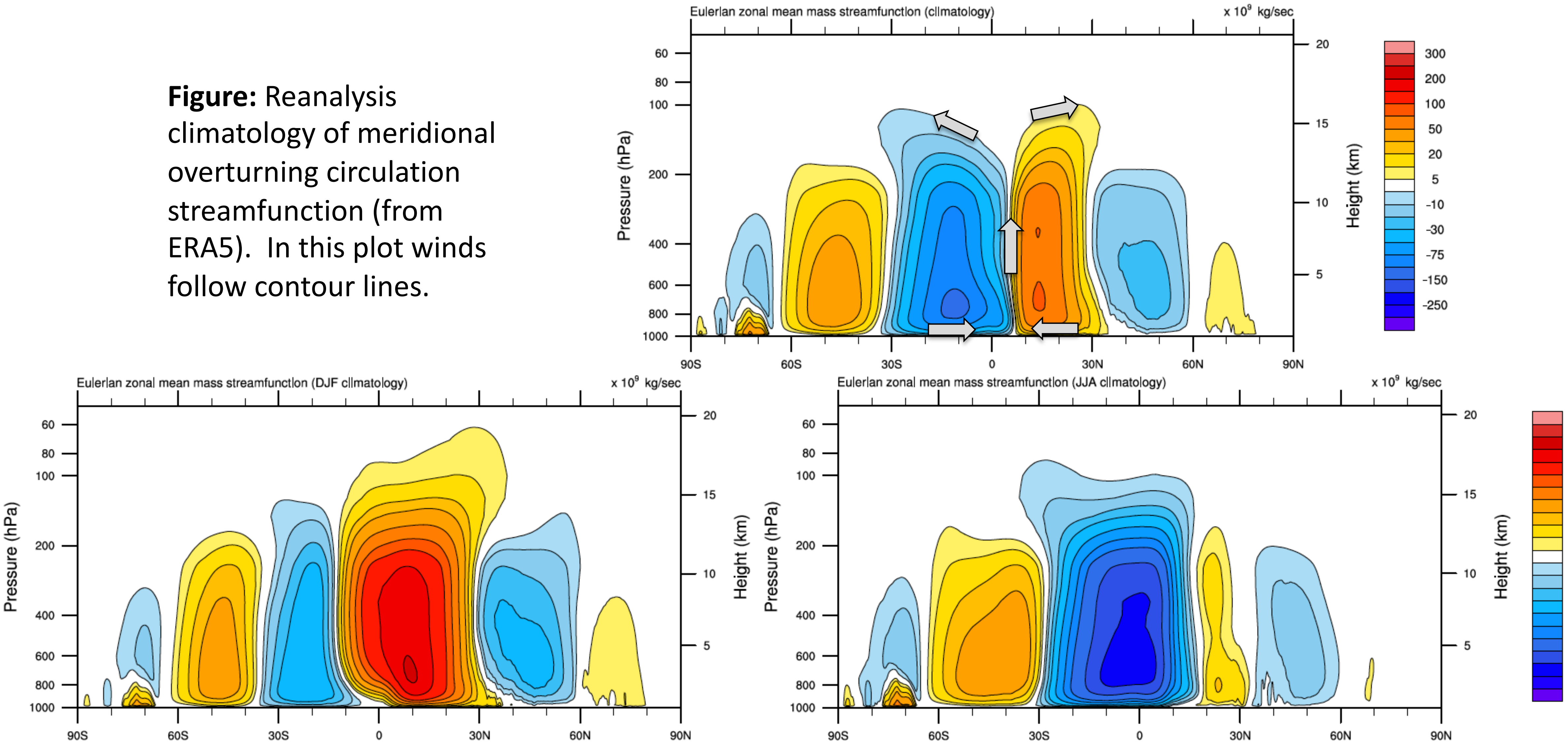
Definition: The **polar cell** is a large-scale circulation consisting of rising air around 60N and 60S, poleward transport at altitude, and subsidence at the poles.

Definition: The **Farrel cell** is a secondary circulation feature with variable airflow and temperature. Air within this region is heavily mixed by large-scale eddies. It is bounded by the sinking branch of the Hadley cell to the south and the polar front to the north.

Definition: The **Hadley cell** is a large-scale atmospheric convection cell in which air rises at the equator and sinks in the subtropics, about 30N or 30S.

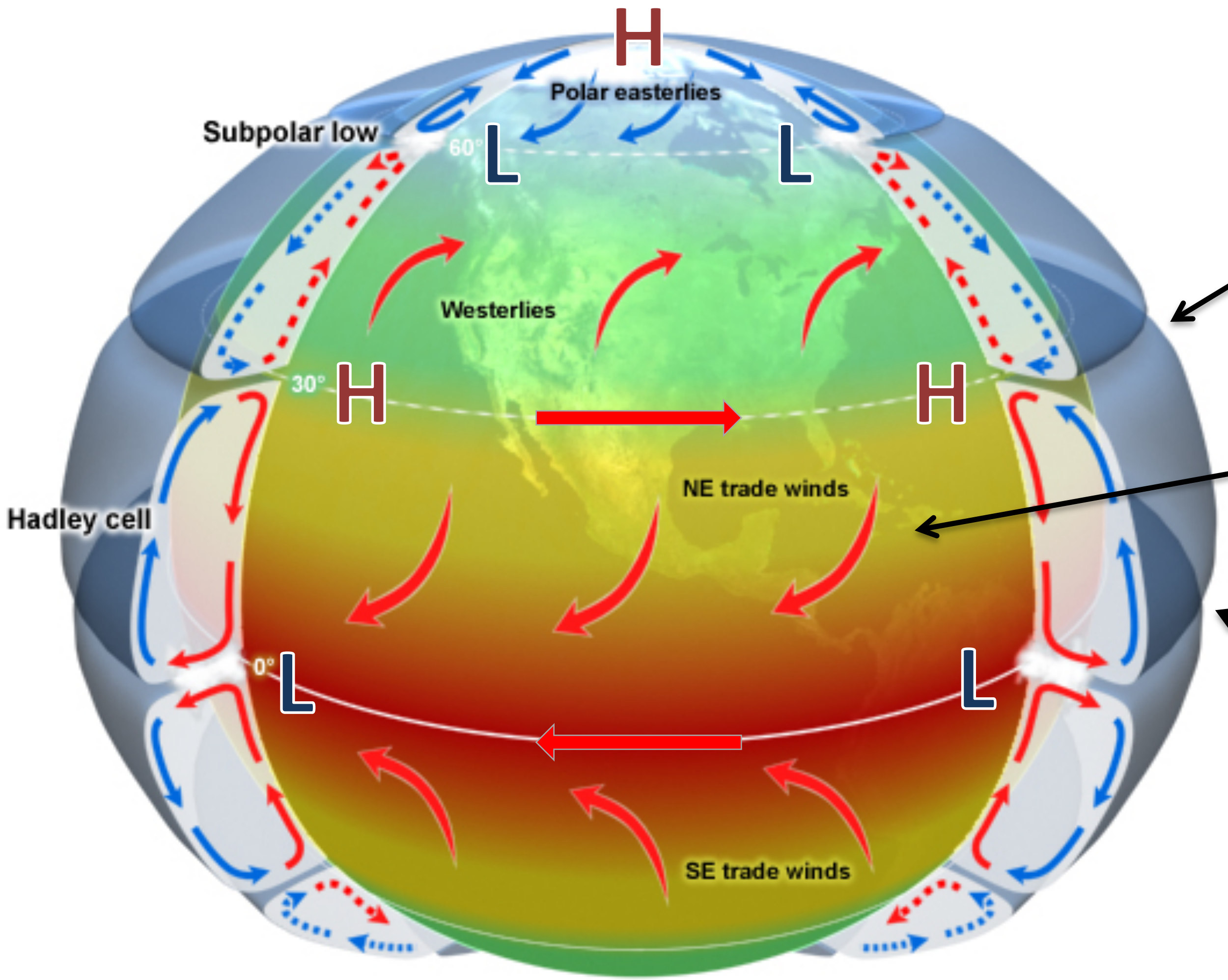
Meridional Circulation

Figure: Reanalysis climatology of meridional overturning circulation streamfunction (from ERA5). In this plot winds follow contour lines.



The Hadley Circulation

The Hadley Cell



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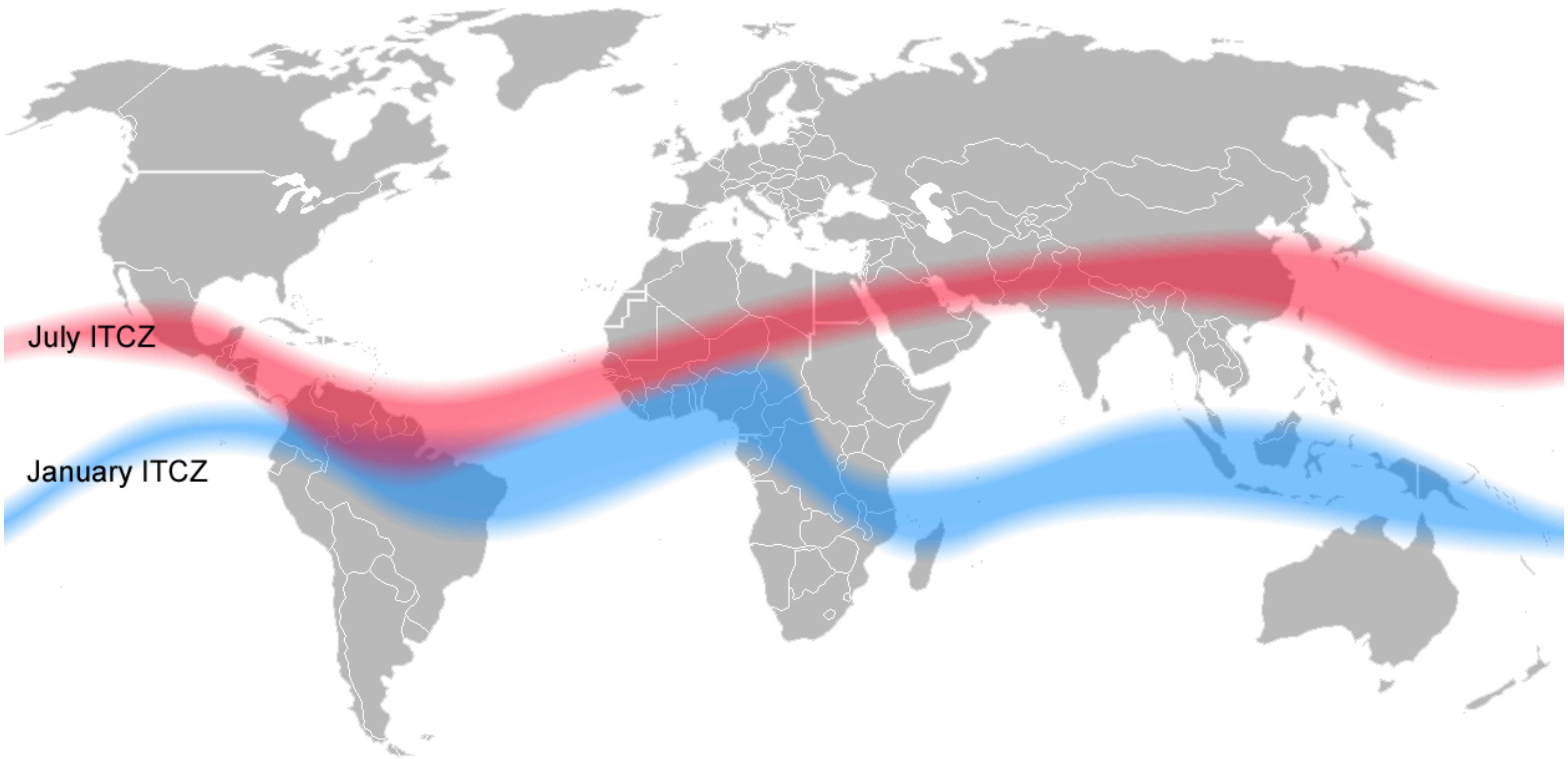
Sinking air here leads to dry conditions and high pressure. Air diverges at low levels and converges at high levels.

Trade winds are winds that blow steadily towards the equator from the NE in the northern hemisphere and SE in the southern hemisphere.

Rising air here leads to wet conditions and low pressure. Air converges at low levels and diverges at high levels.

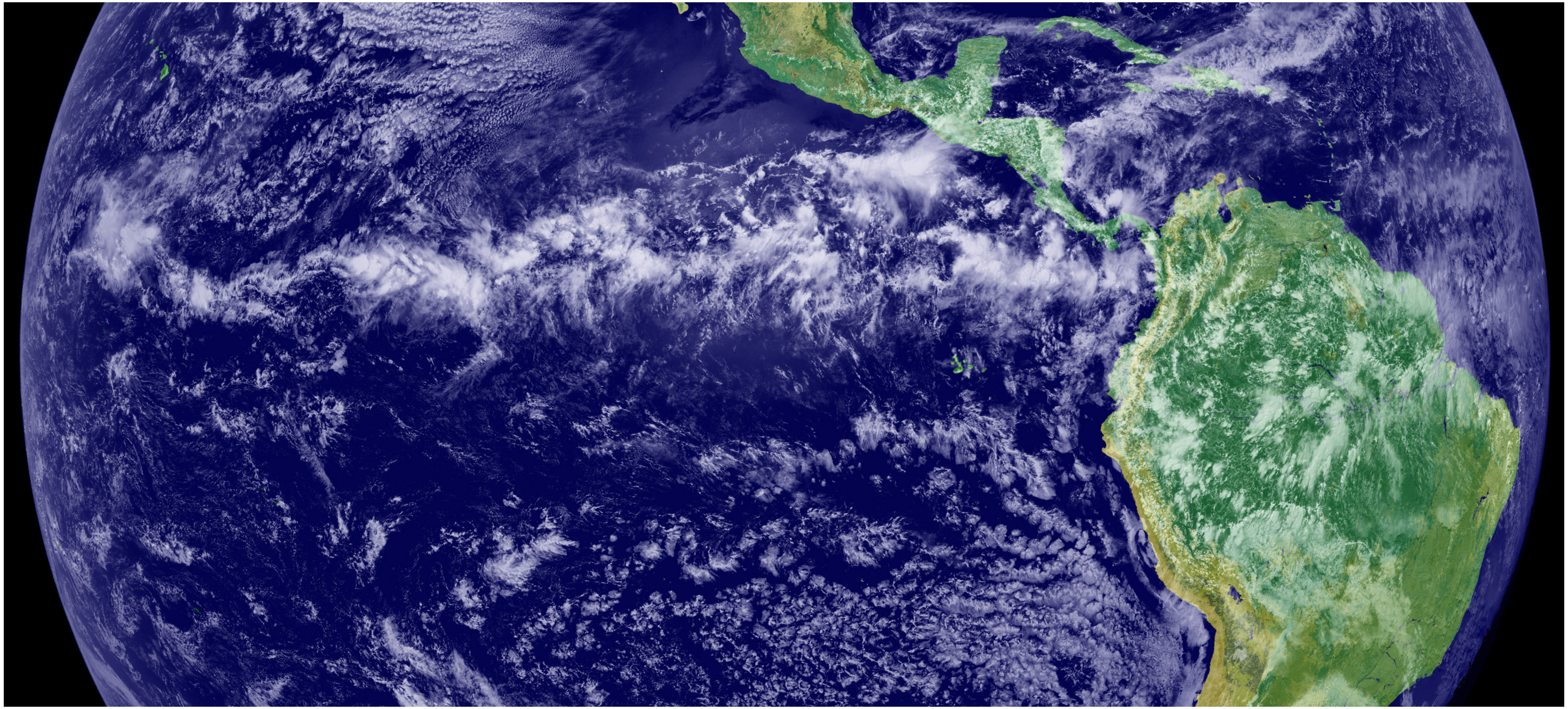
Intertropical Convergence Zone

Definition: The **Intertropical Convergence Zone (ITCZ)** is a region in the equatorial zone where the trade winds converge. This region varies seasonally as the sun shifts between hemispheres.

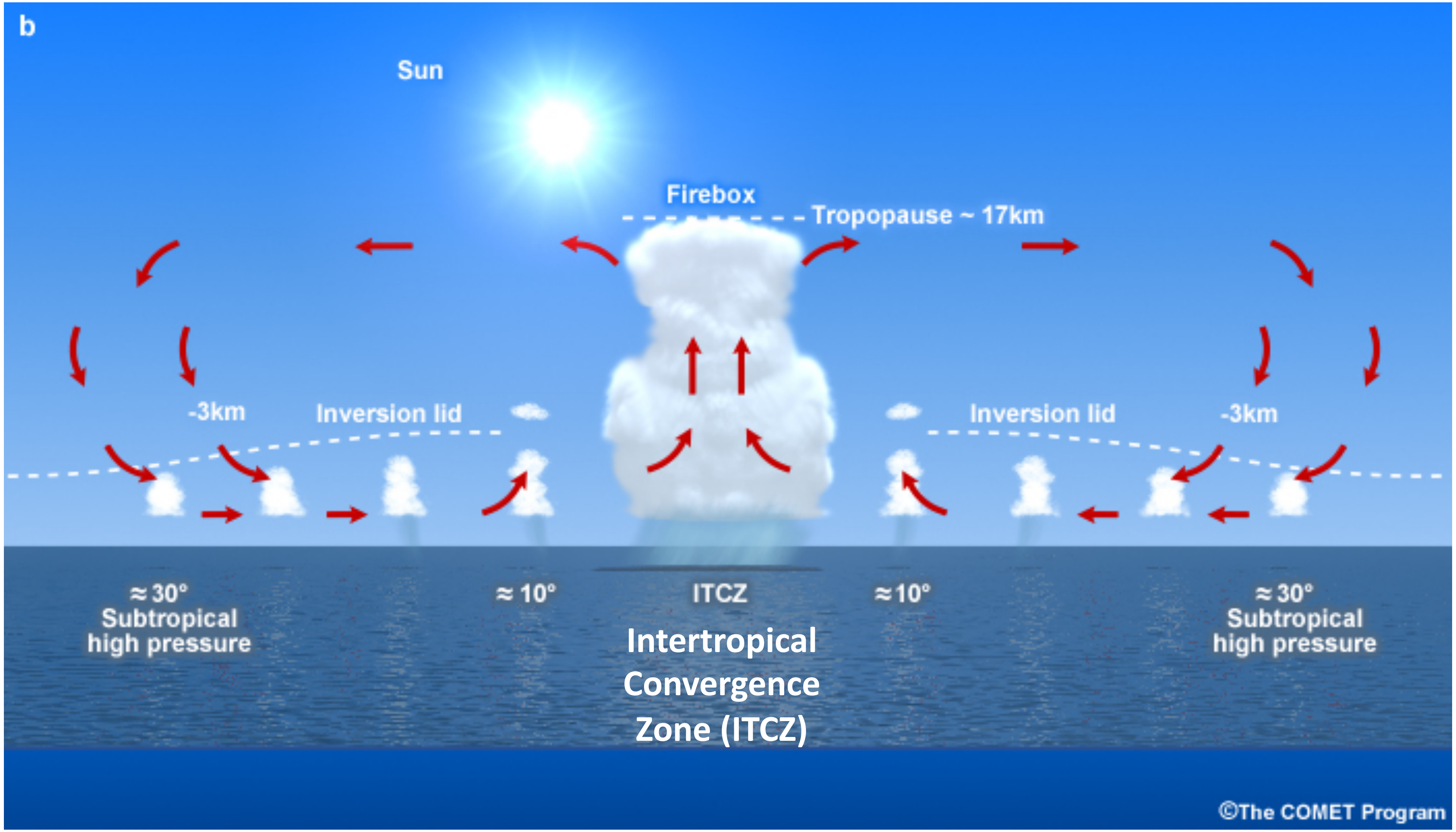


Intertropical Convergence Zone

The **Intertropical Convergence Zone** is visible as a band of clouds encircling Earth near the Equator.

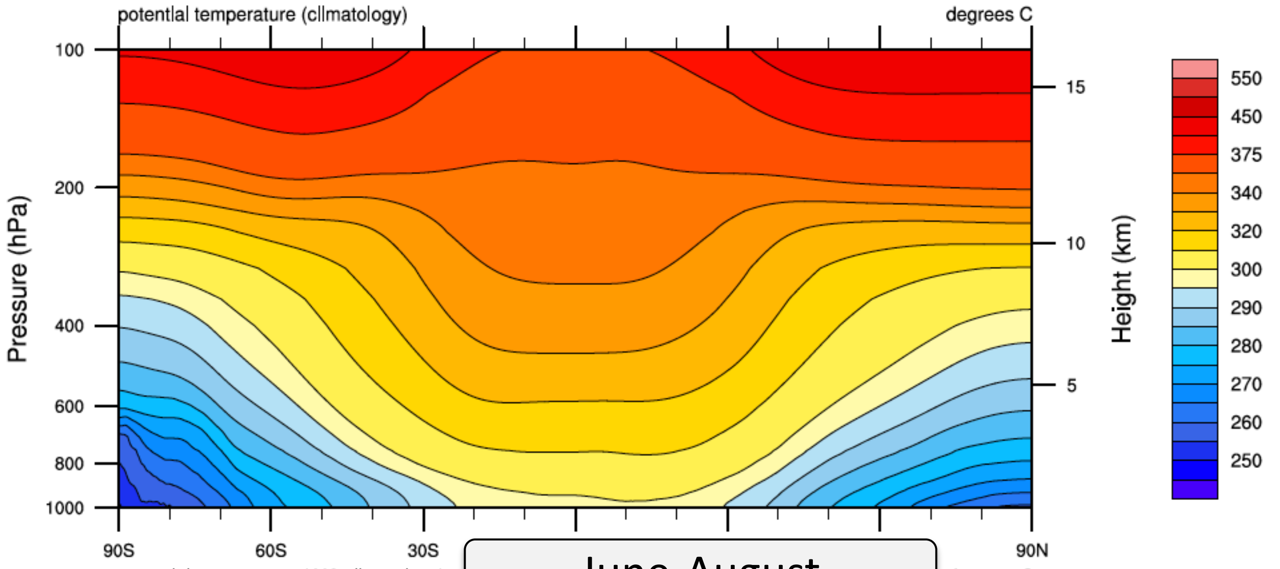


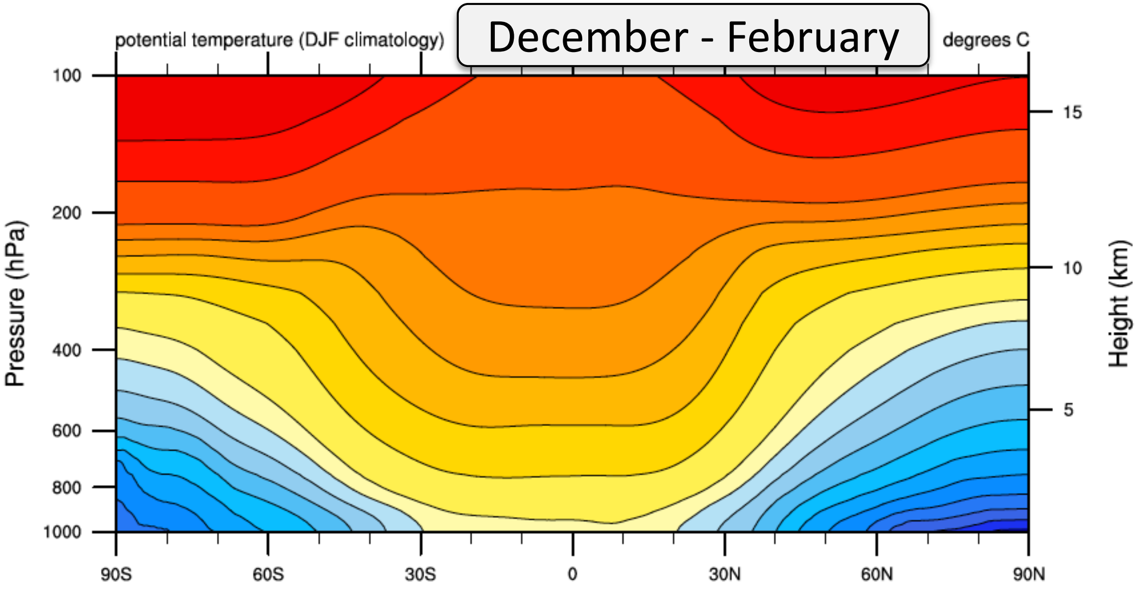
The Hadley Cell

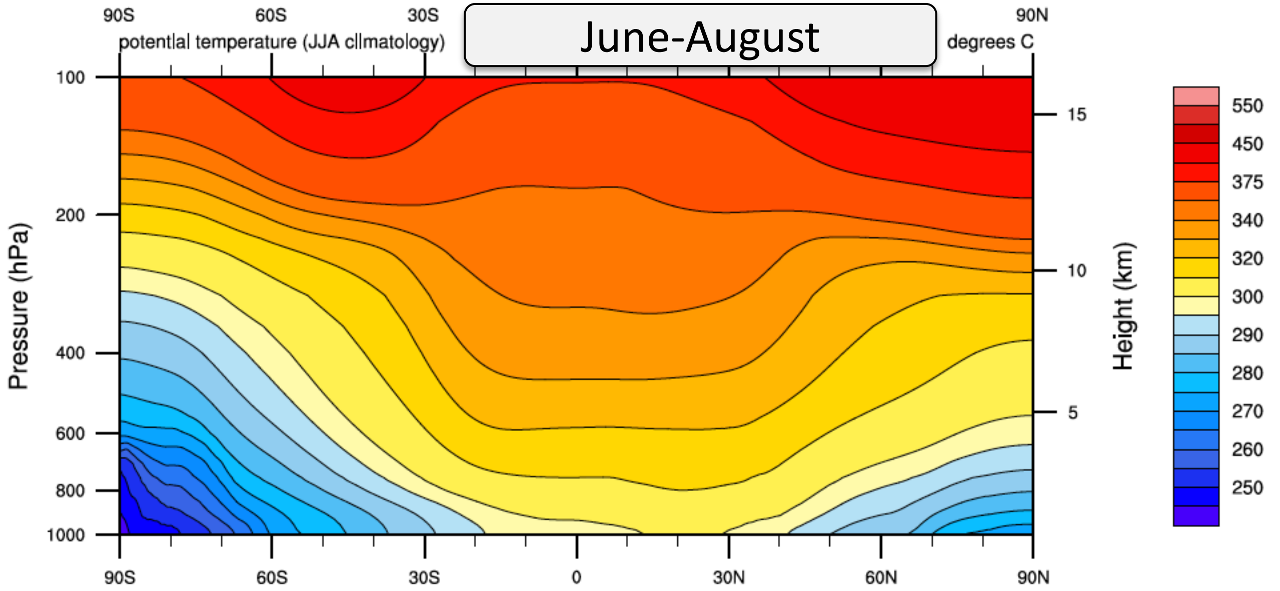


Zonally Averaged Potential Temperature

Figure: Reanalysis climatology zonally averaged potential temperature (tropospheric perspective).

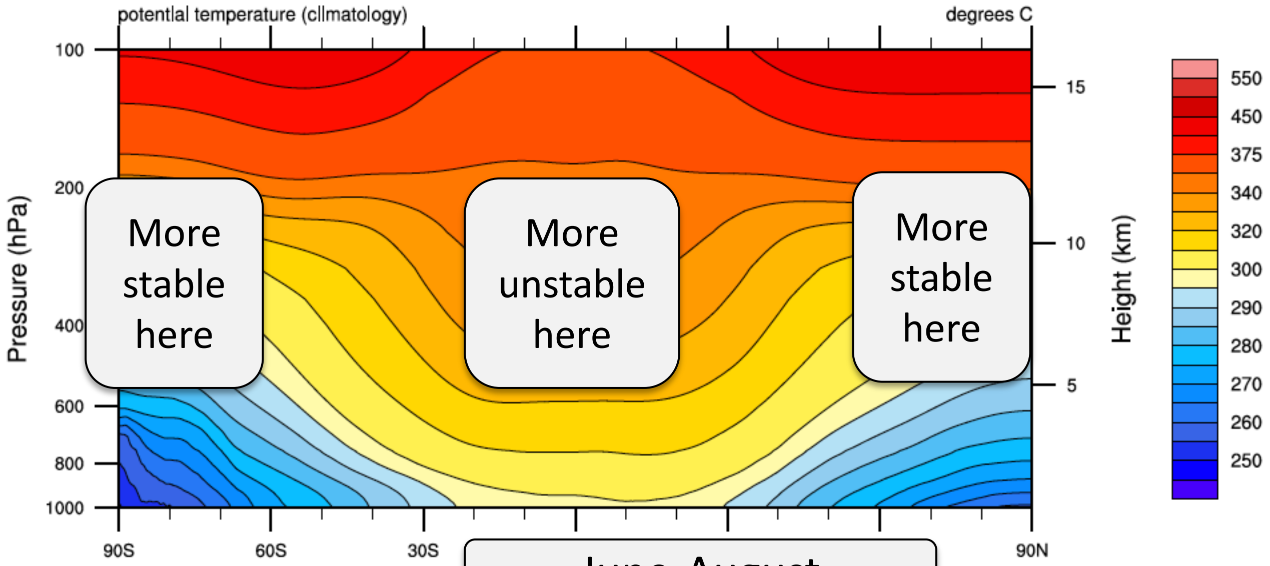


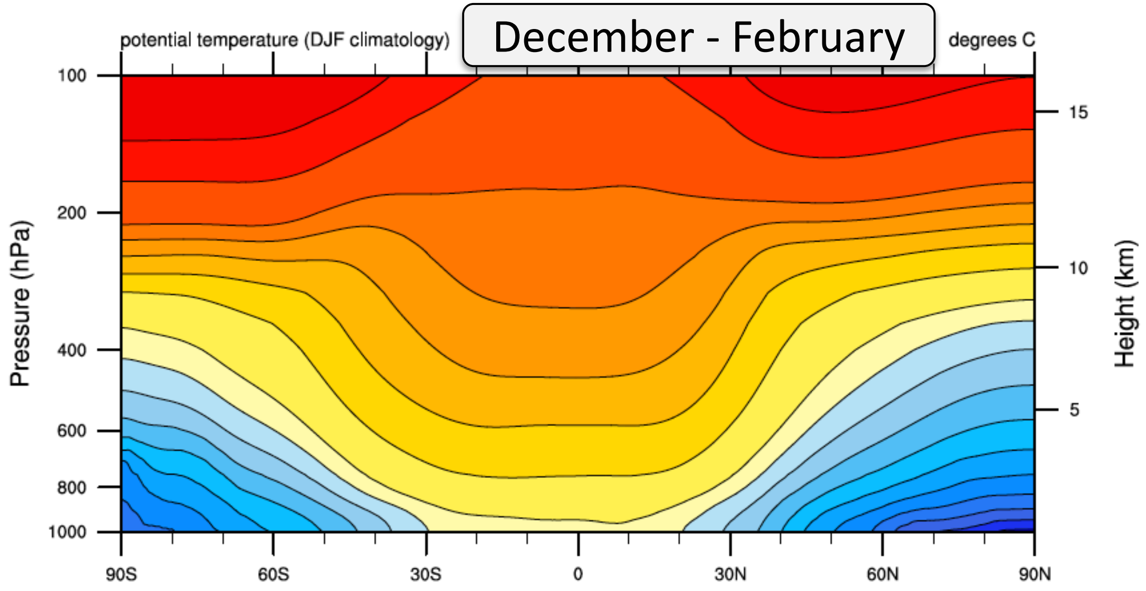


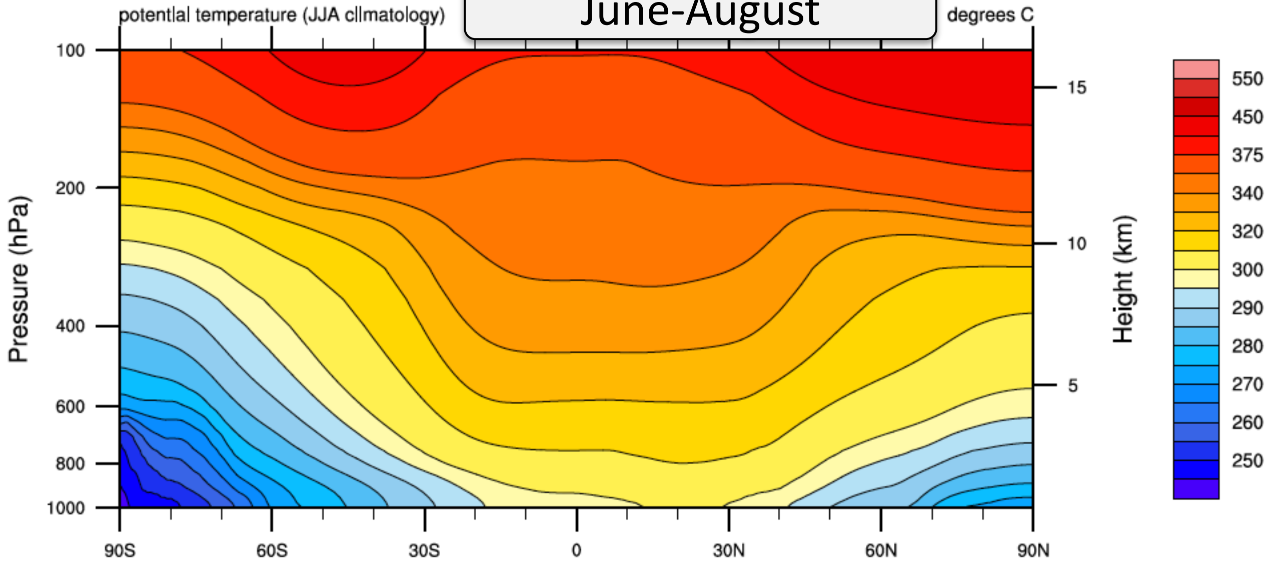


Zonally Averaged Potential Temperature

Recall that stability of the atmosphere is determined by the slope of the potential temperature with respect to height. A flatter slope corresponds to greater instability.

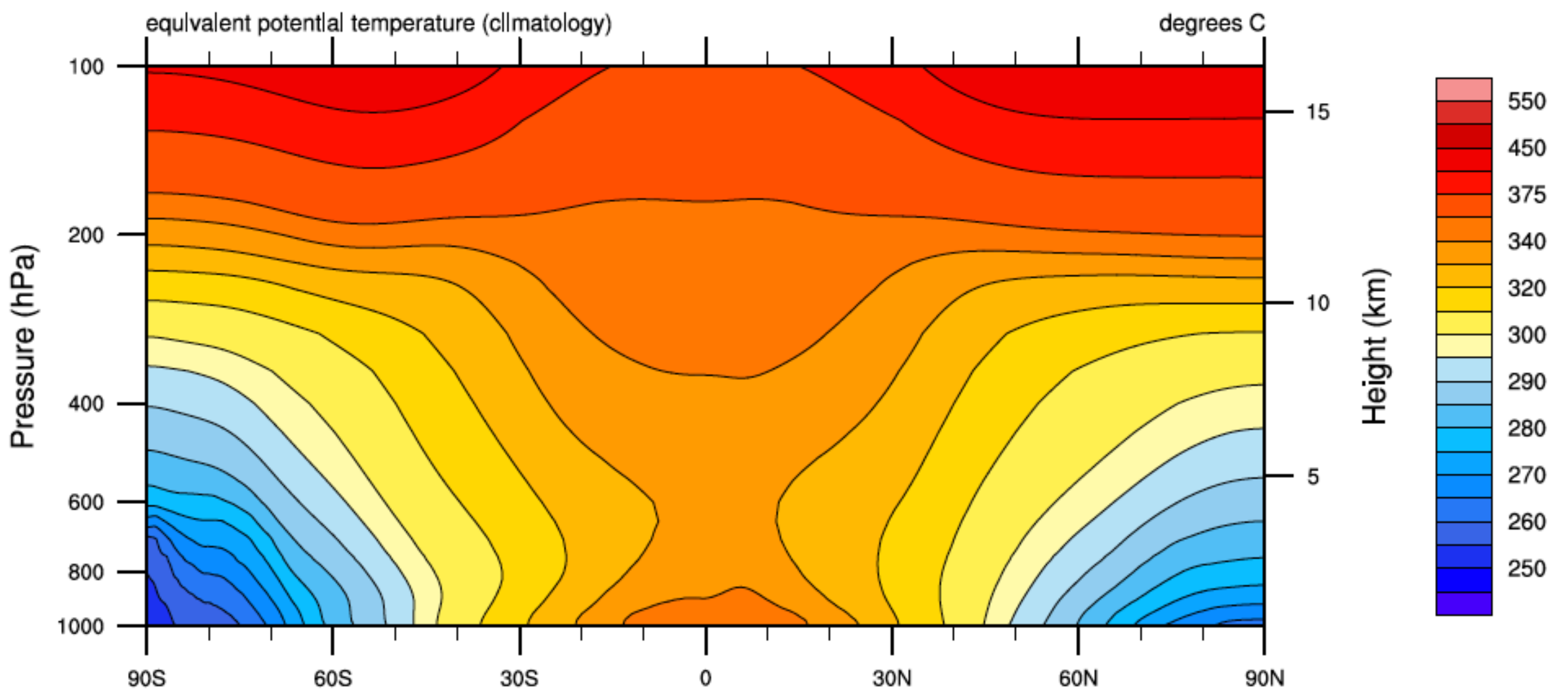






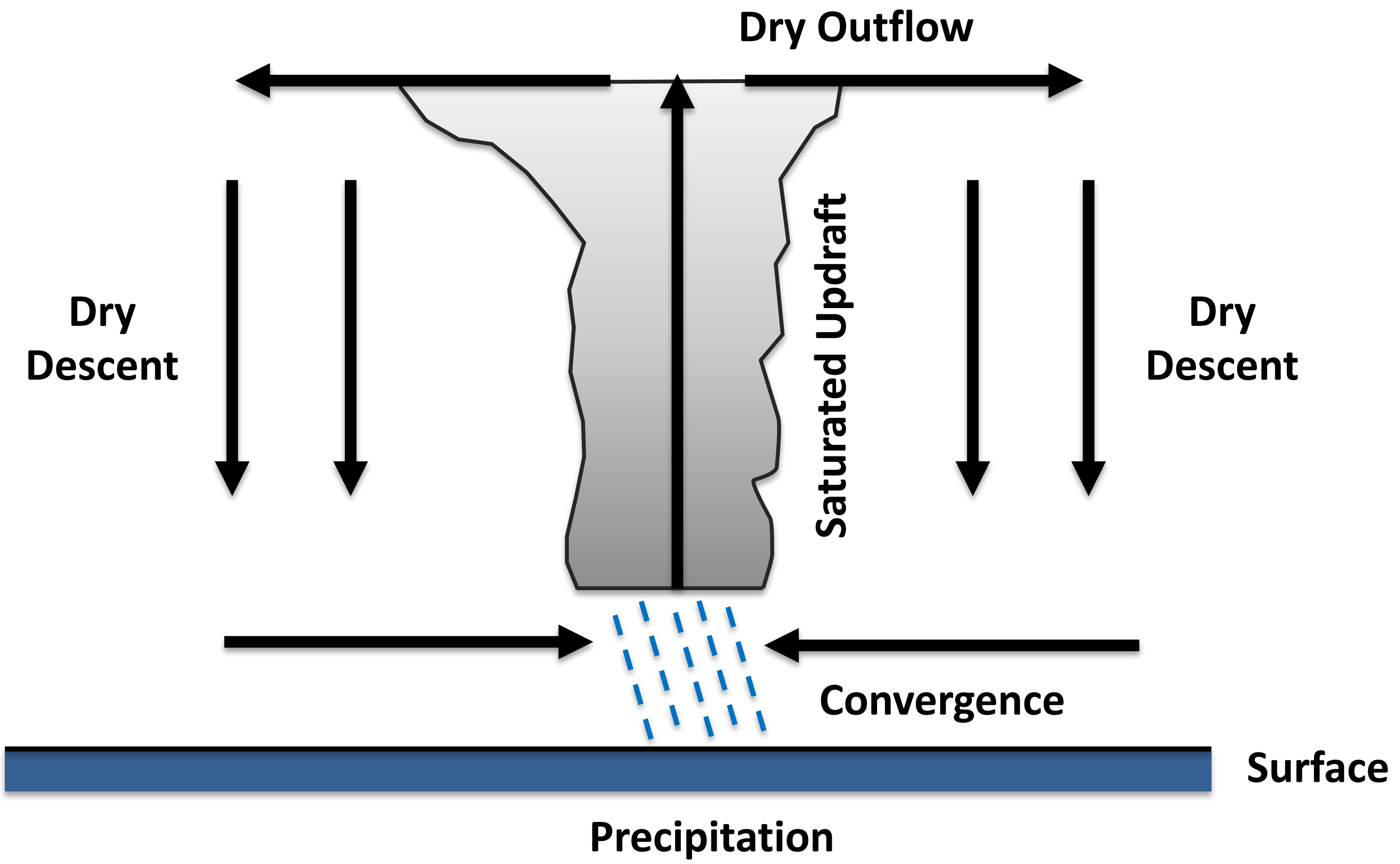
Zonally Averaged Equiv. Potential Temperature

Figure: Zonally-averaged moist potential temperature θ_e. Observe that vigorous convection in the tropics effectively removes vertical gradients in equivalent potential temperature.



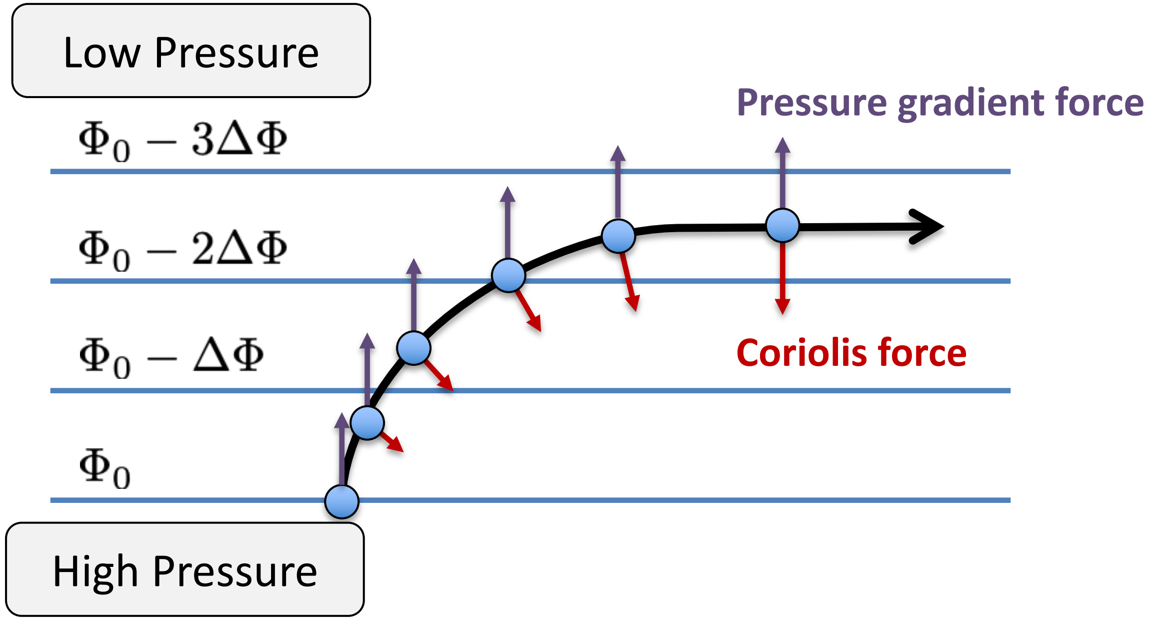
Convection

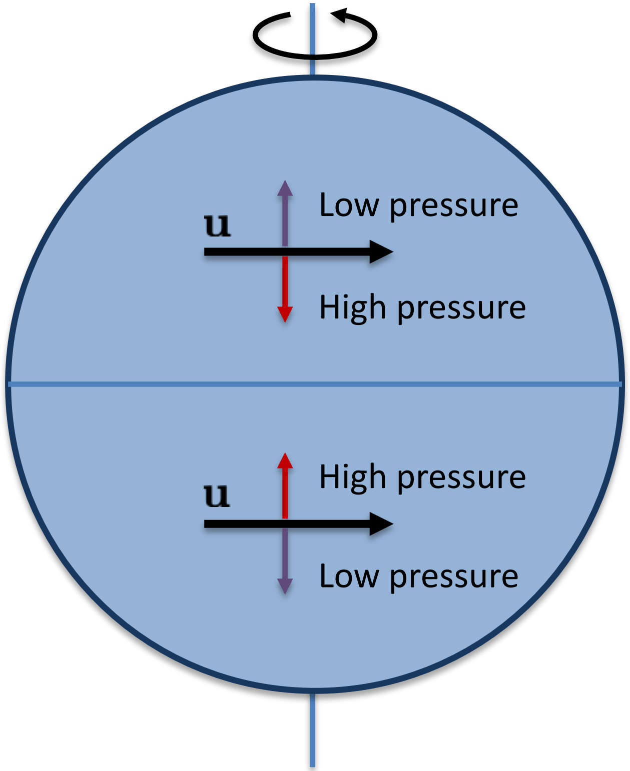
Figure: Drying due to convection. Within the updraft, air becomes saturated and excess water is rained out. The descending air is very dry. Because the region of ascent is rather narrow and the descent broad, convection acts as a drying agent for the whole atmosphere.



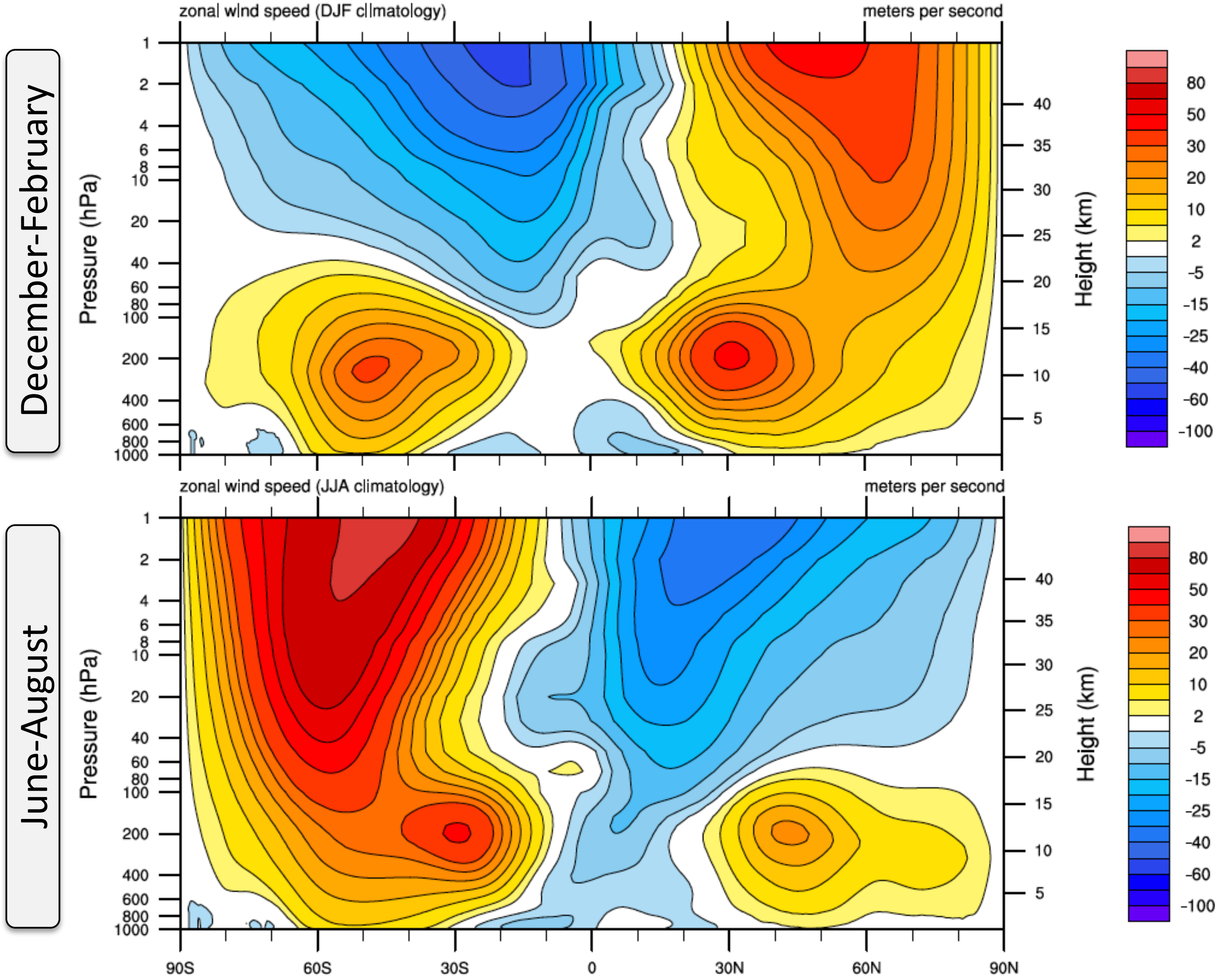
Zonal Mean Winds

Upper-level winds that diverge from the equator are subject to **geostrophic balance**. As fluid parcels move poleward they are diverted to the east because of Coriolis force.





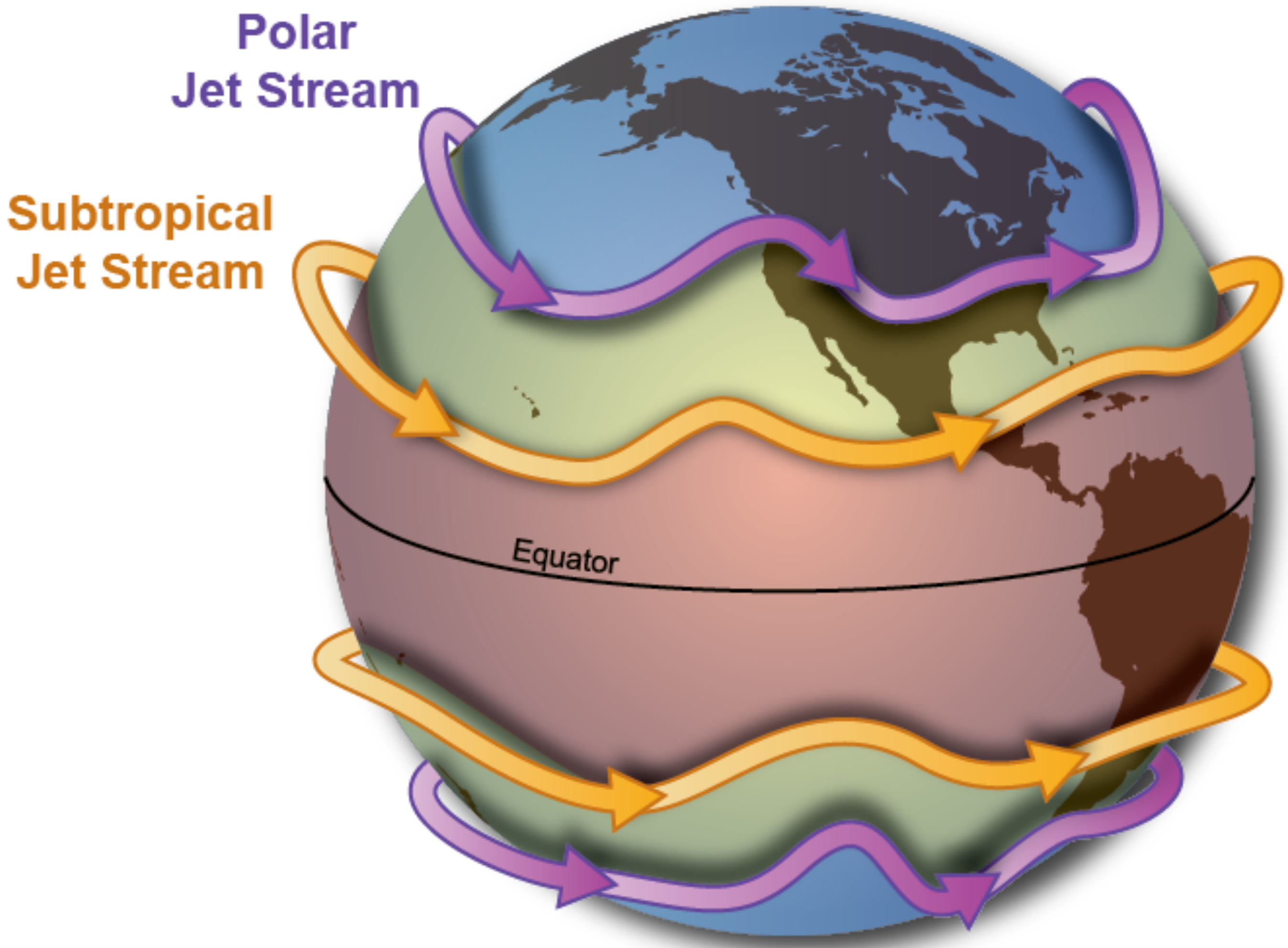
Jet Streams



Definition: Jet streams are fast flowing, narrow, meandering air currents in the atmosphere.

In the troposphere, **subtropical jets** appear around 200-300hPa (~10km) around the northernmost extent of the Hadley circulation. They also tend to be stronger in the wintertime because of increased poleward transport of heat.

Jet Streams



https://www.weather.gov/jetstream/jet

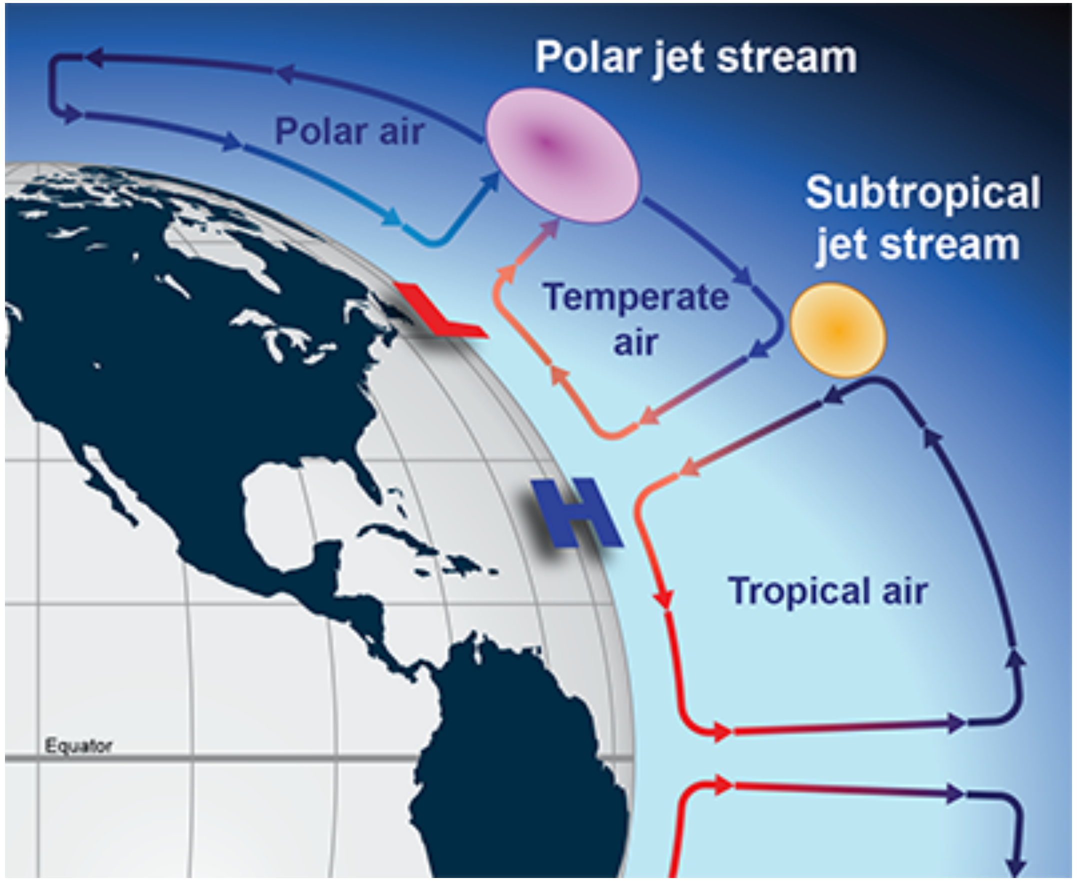
The **subtropical jets** appear at the confluence of the Hadley and Farrel cells.

The **polar jets** appear at the confluence of the polar and Farrel cells.

The position of both jets shifts seasonally, moving north in June-August and south in Dcecember-February.

Air speed within the jets can be more than 400 km/h (250 mph).

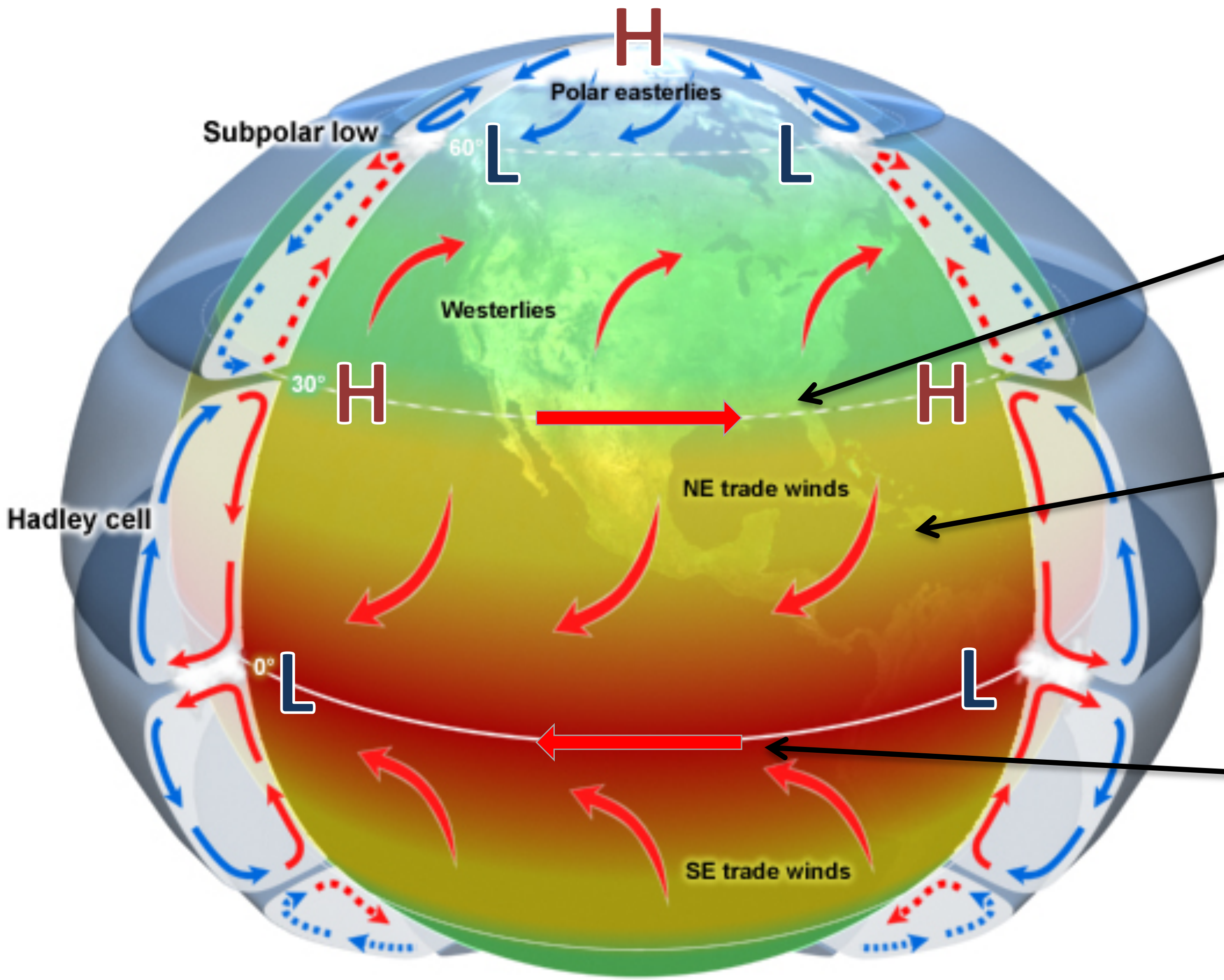
Jet Streams



https://www.weather.gov/jetstream/jet

Figure: Idealized position of the subtropical and polar jet streams relative to the large-scale circulation cells.

The Hadley Cell



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Westerly flow induced by air diverging from the equator and geostrophic balance.

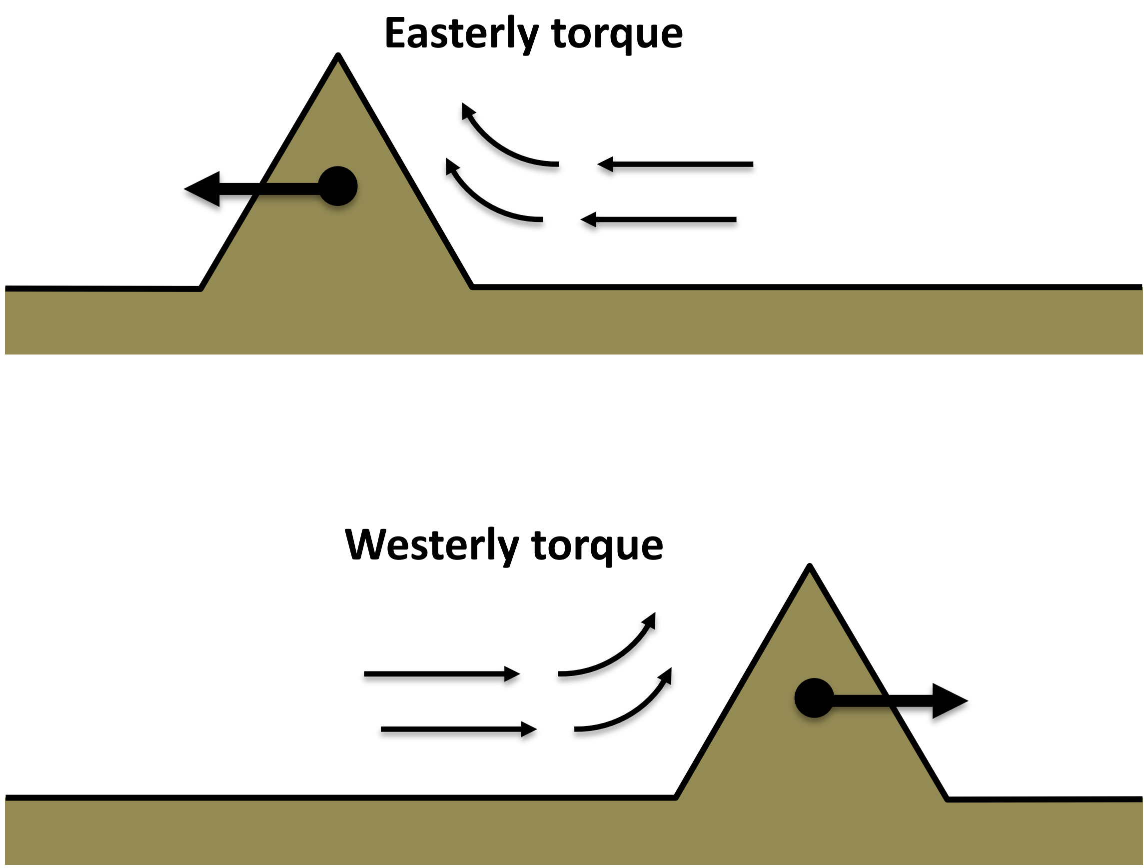
Trade winds are winds that blow steadily towards the equator from the NE in the northern hemisphere and SE in the southern hemisphere.

Easterly flow produced by the returning circulation to the equator.

Net Torque

Note that there must be an adequate balance between easterly and westerly wind regimes: If winds only blew in one direction then the net torque on the planet would accelerate or decelerate its rotation.

Thus westerly winds in the midlatitudes must be balanced by easterly winds in the tropics.



Midlatitudinal Structure

Midlatitudinal Eddies

Extratropical Cyclones (ETCs) are large-scale rotating meteorological systems that appear in the midlatitudes and arise due to instabilities in the mean flow.

They are important for driving weather in the mid-latitudes.

Particularly strong extratropical systems are responsible for large-scale storm systems.

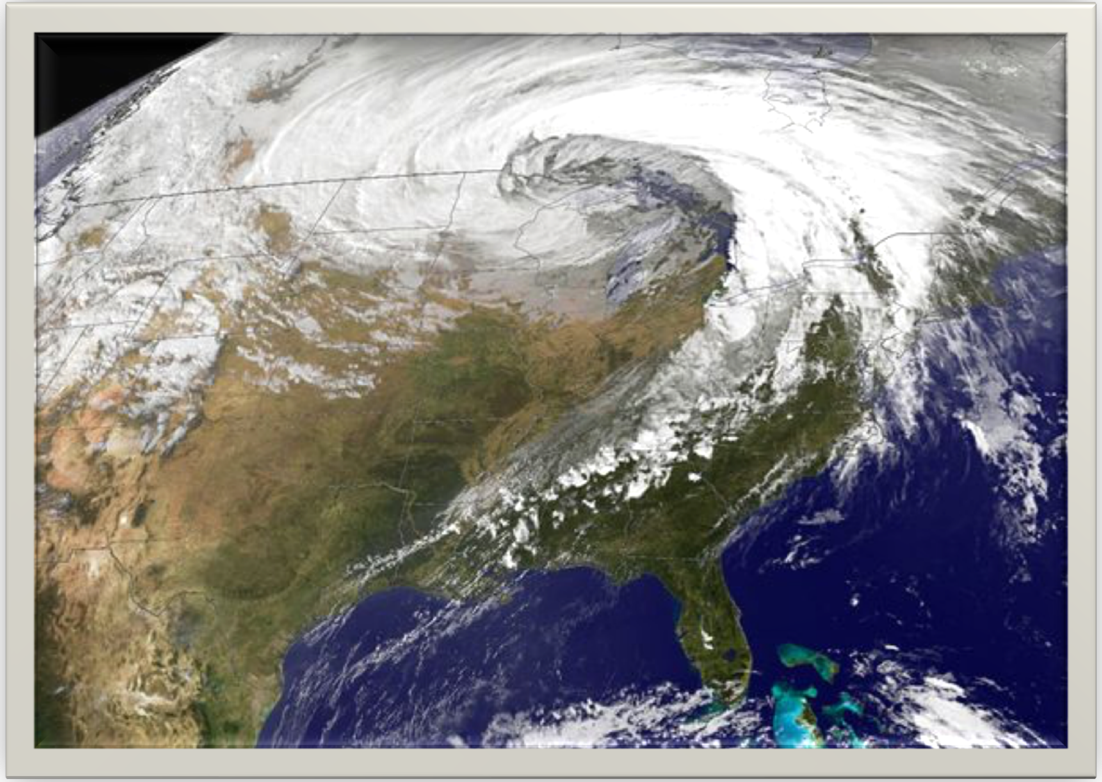
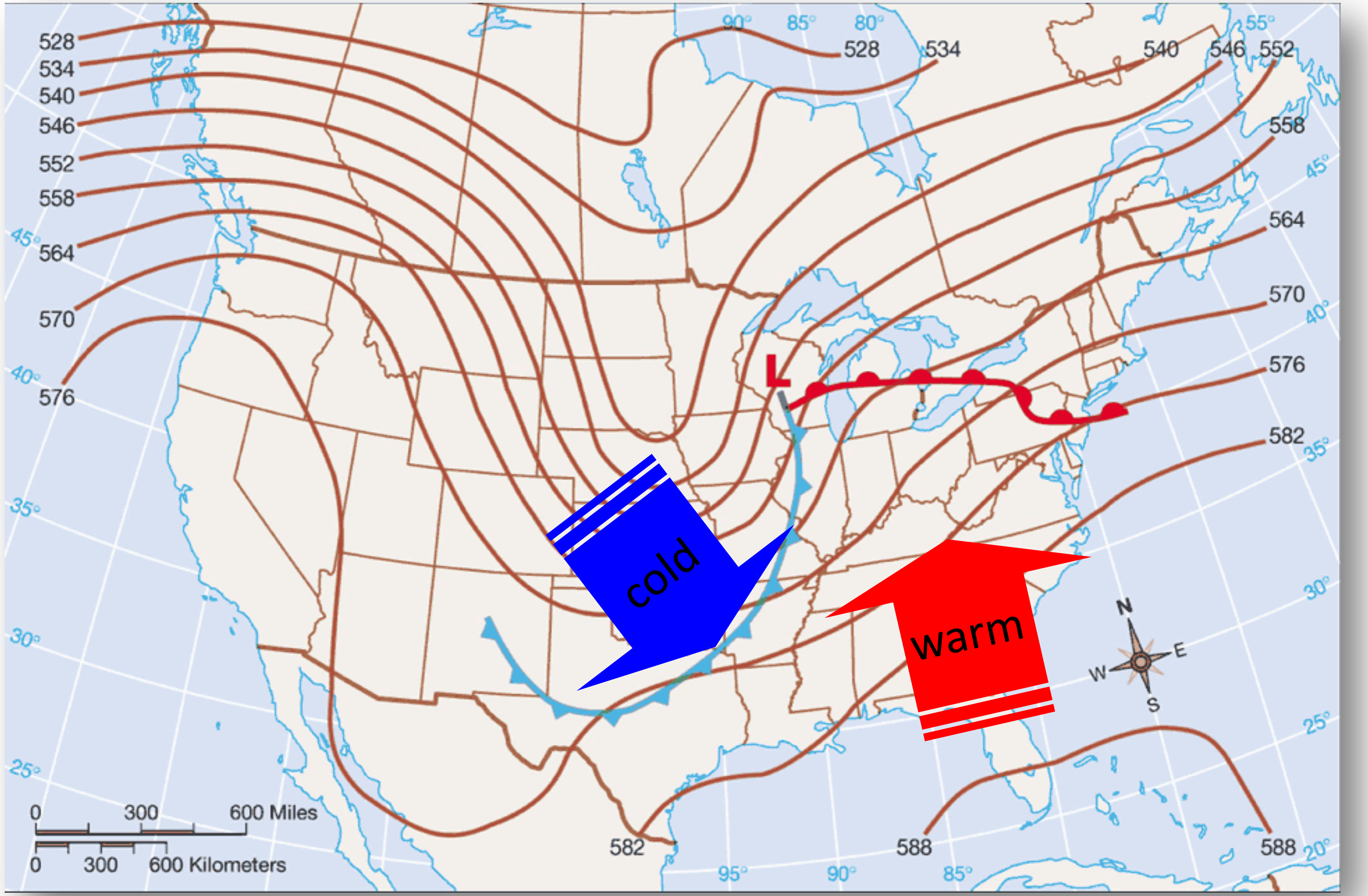


Figure: Extratropical Cyclones are associated with severe winter storm systems, and are particularly relevant for the US Northwest and Northern Europe.

Extratropical Cyclones

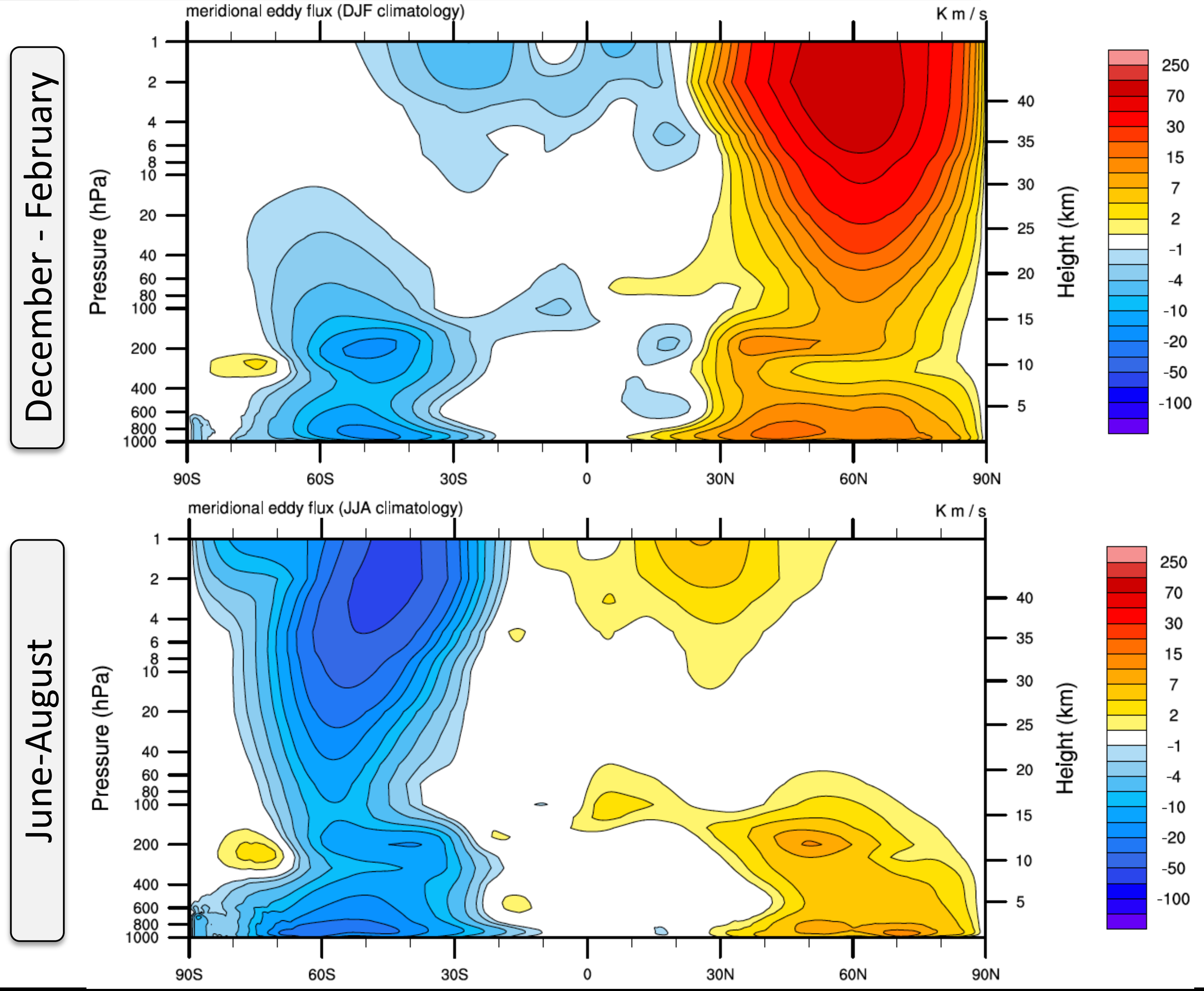


Extratropical Cyclones and Sensible Heat Flux

Figure: Reanalysis climatology northward eddy flux of temperature in the troposphere and stratosphere.

Note that sensible heat flux by eddies is strongly dependent on season, with the strongest poleward transport occurring in each hemisphere's winter season.

This transport is associated with winter storms.

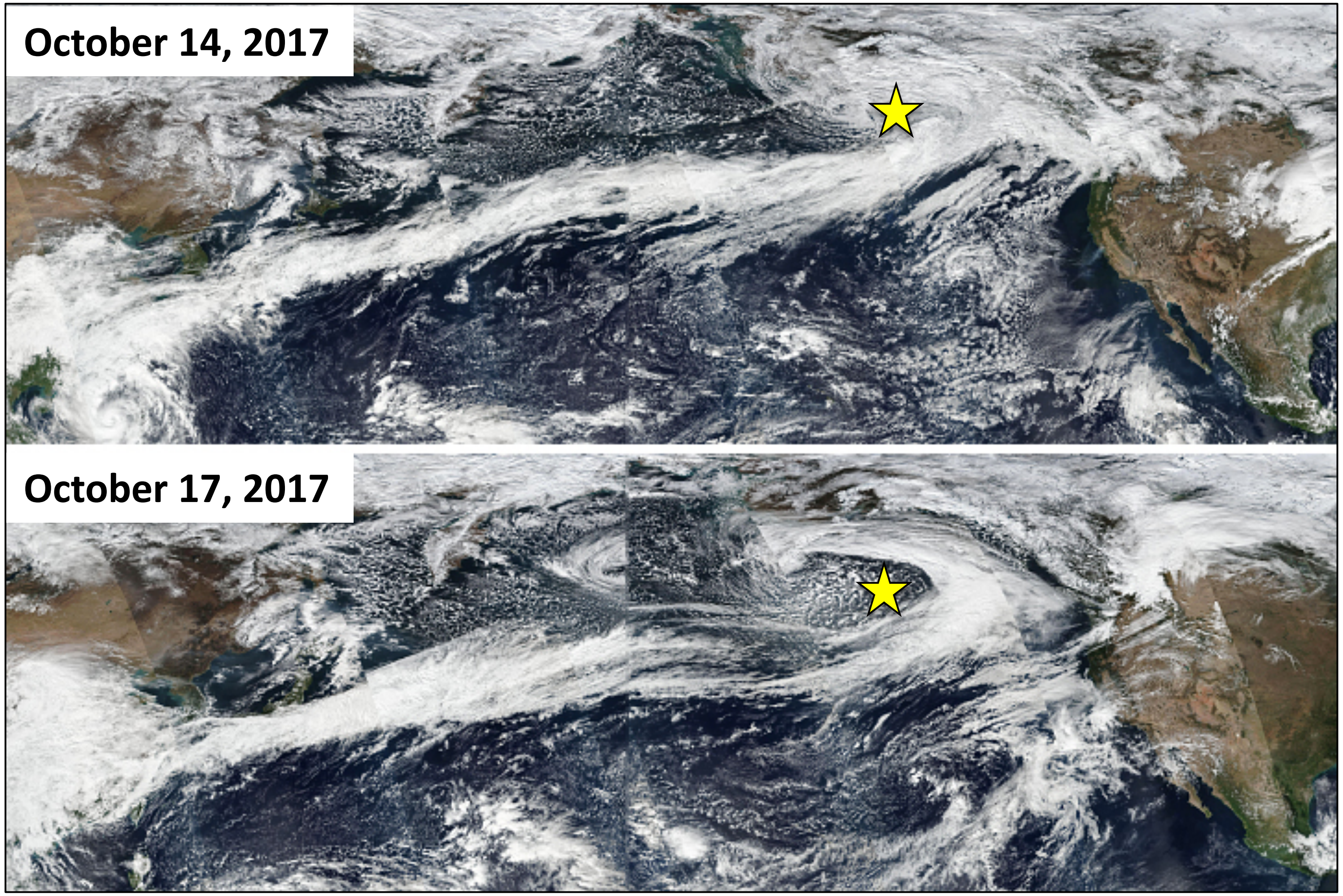


Extratropical Cyclones and Latent Heat Flux

Extratropical cyclones are also responsible for significant latent heat flux (moisture transport) through induced **atmospheric rivers**.

Definition: Atmospheric rivers are long, narrow, transient corridors of enhanced water vapor transport.

Figure: Satellite image of an atmospheric river event connecting Asia and North America across the Pacific. The extratropical storm center is highlighted by the yellow star.



Extratropical Cyclones and Latent Heat Flux

Atmospheric rivers are key to the global water cycle, responsible for **90% of global meridional water vapor** transport, yet only covering 10% of the Earth's circumference.

They are also a primary driver for precipitation along the west coasts of continents, and account for **30-40% of precipitation and snowpack in these regions**.

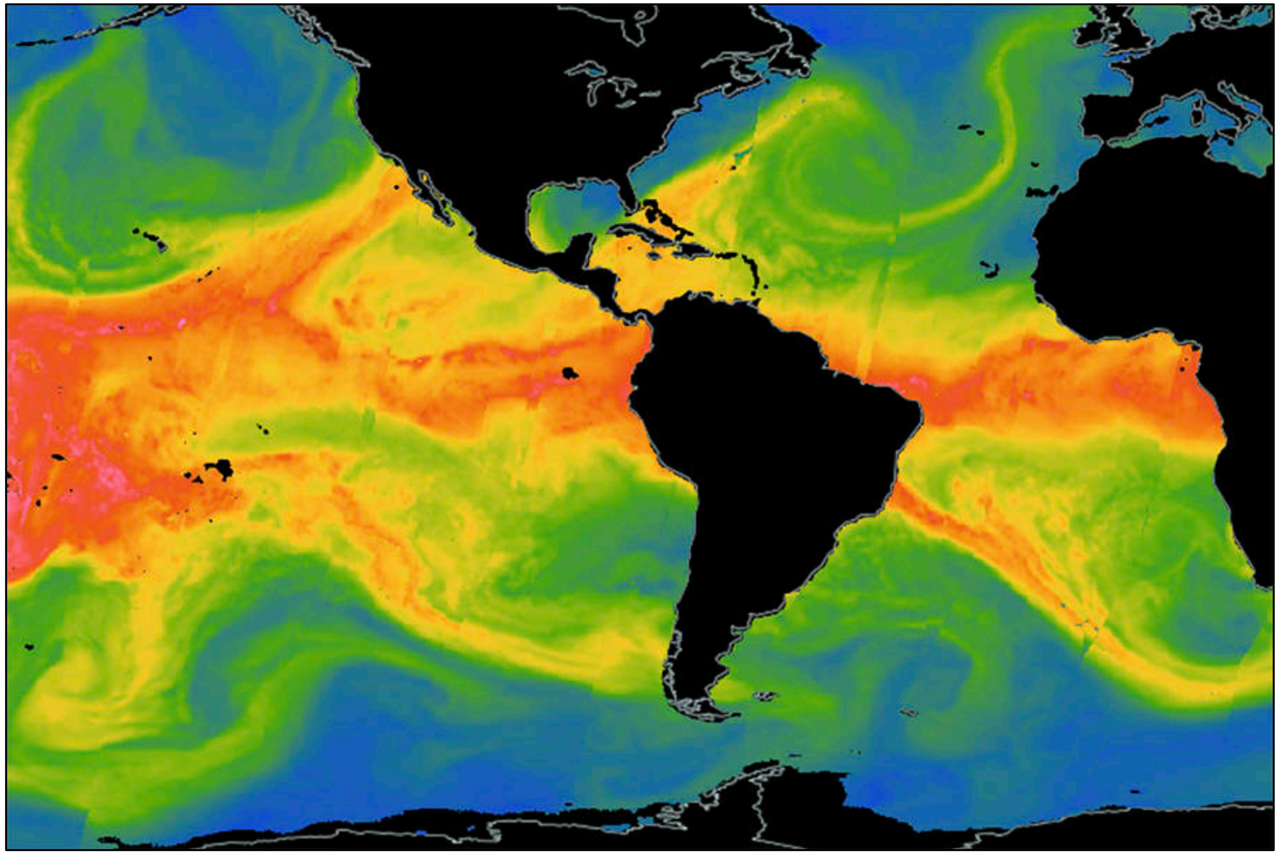
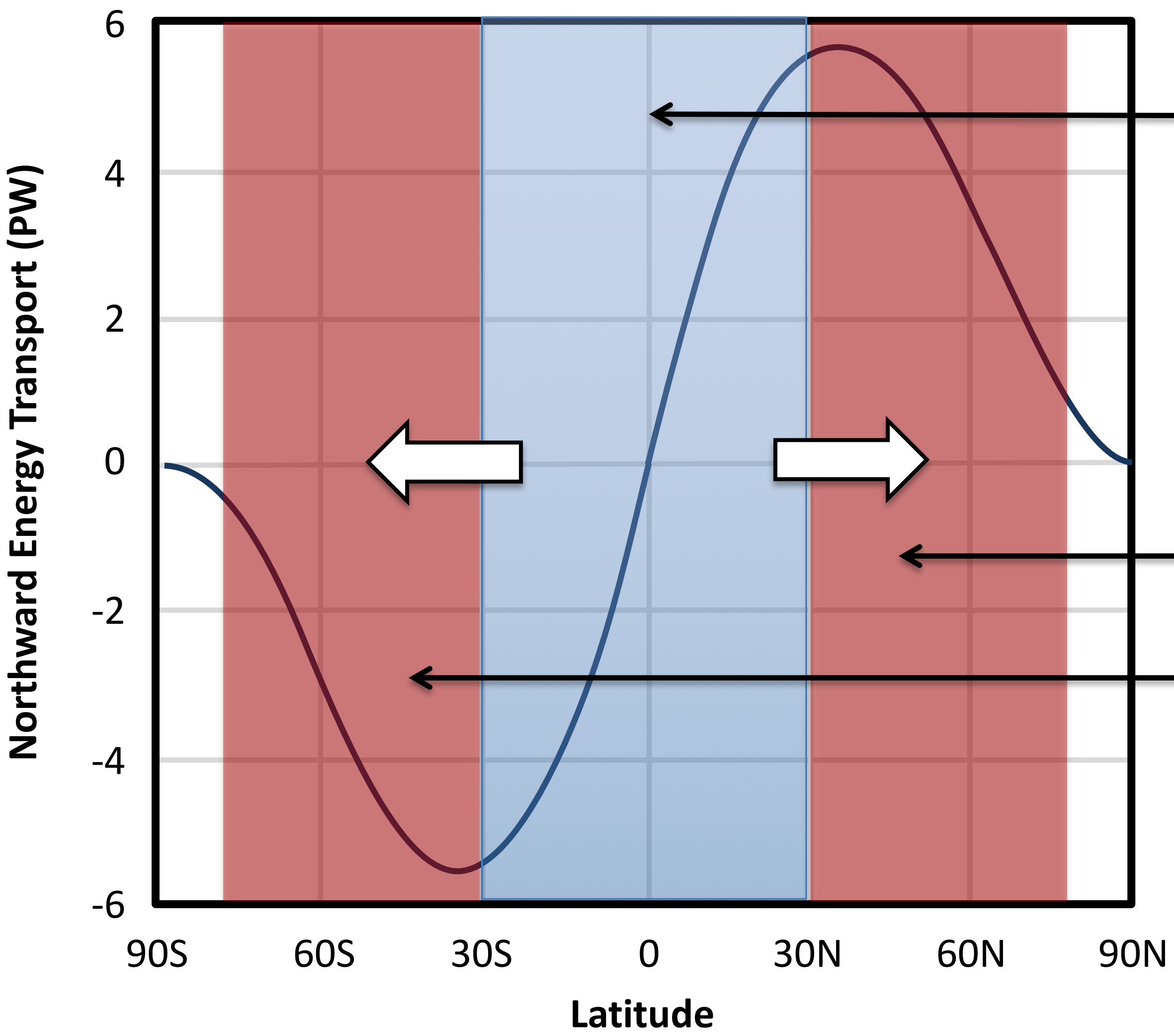


Figure: Satellite images of total column water vapor showing multiple atmospheric rivers (NASA).

Global Heat Transport



Heat transport **dominated by Hadley circulation**

Heat transport **dominated by eddy flux (extratropical cyclones)**: Recall eddy flux is strongest in the winter when the gradients of temperature are strongest

Wind Temperature Relationship

The Thermal Wind

Definition: The thermal wind is the **vector difference** between the geostrophic wind $\mathbf{u}_g$ at an upper level and a lower level (note that in this sense it is not a real wind).

The thermal wind vector points such that cold air is to the left and warm air is to the right, parallel to isotherms in the northern hemisphere. Cold air to right / warm air to left in southern hemisphere

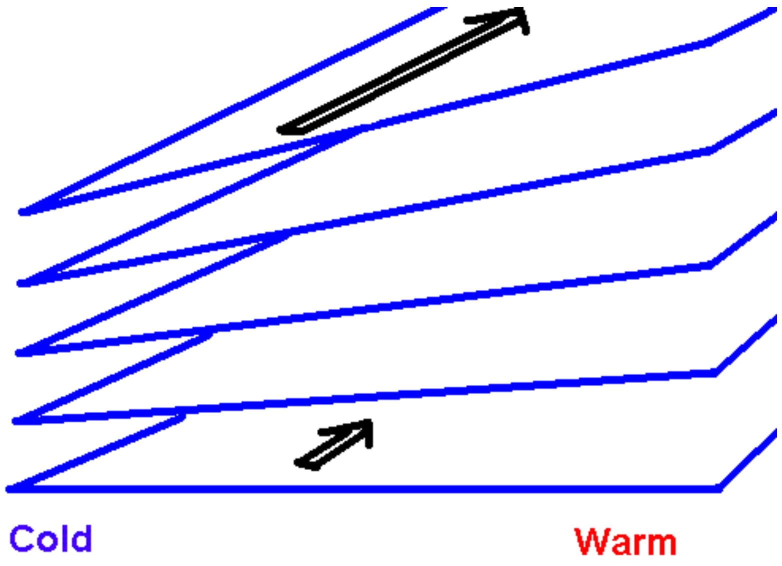


Figure: Thickness of layers related to temperature, causes a tilt in the pressure surfaces.

Change in magnitude of horizontal gradient of pressure then leads to vertical wind shear.

(Source: Brad Muller)

Thermal Wind Relationship

Starting point:

$$u_g = -\frac{1}{f}\left(\frac{\partial \Phi}{\partial y}\right)_p \qquad v_g = \frac{1}{f}\left(\frac{\partial \Phi}{\partial x}\right)_p$$

Differentiate with respect to p:

$$\frac{\partial u_g}{\partial p} = -\frac{1}{f}\frac{\partial}{\partial y}\frac{\partial \Phi}{\partial p} \qquad \frac{\partial v_g}{\partial p} = \frac{1}{f}\frac{\partial}{\partial x}\frac{\partial \Phi}{\partial p}$$

Use $$\frac{\partial \Phi}{\partial p} = g\frac{\partial z}{\partial p} = -\frac{1}{\rho} = -\frac{RT}{p}$$

(Recall we are on constant pressure surfaces)

Thermal wind relationship:

$$\frac{\partial u_g}{\partial p} = \frac{R}{pf}\left(\frac{\partial T}{\partial y}\right)_p \qquad \frac{\partial v_g}{\partial p} = -\frac{R}{pf}\left(\frac{\partial T}{\partial x}\right)_p$$

The Thermal Wind

Thermal wind relationship: $$\frac{\partial u_g}{\partial p} = \frac{R}{pf}\left(\frac{\partial T}{\partial y}\right)_p \qquad \frac{\partial v_g}{\partial p} = -\frac{R}{pf}\left(\frac{\partial T}{\partial x}\right)_p$$

The thermal wind itself is a vector difference. Rewrite thermal wind relationship as:

$$\frac{\partial u_g}{\partial(\log p)} = \frac{R}{f}\left(\frac{\partial T}{\partial y}\right)_p \qquad \frac{\partial v_g}{\partial(\log p)} = -\frac{R}{f}\left(\frac{\partial T}{\partial x}\right)_p$$

Then integrate:

Layer mean temperature

$$u_T = u_g(p_2) - u_g(p_1) = -\frac{R}{f}\left(\frac{\partial \langle T \rangle}{\partial y}\right)_p \log\left(\frac{p_1}{p_2}\right)$$

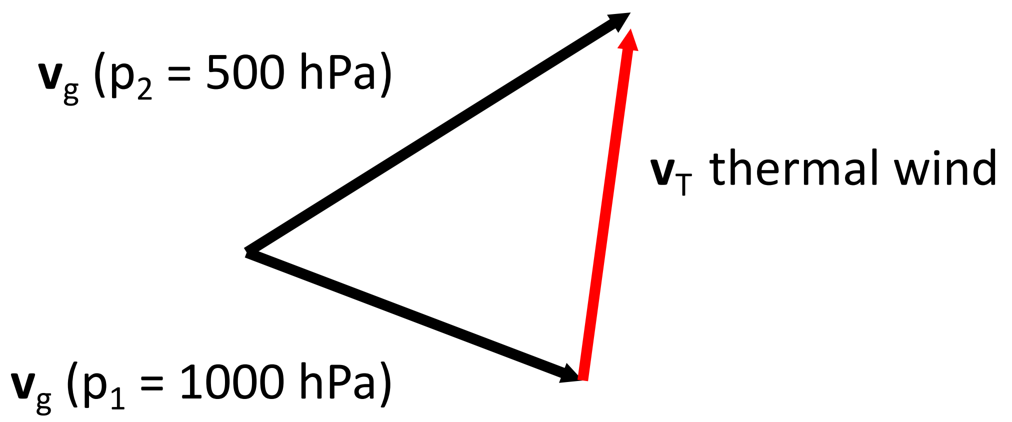
$$v_T = v_g(p_2) - v_g(p_1) = \frac{R}{f}\left(\frac{\partial \langle T \rangle}{\partial x}\right)_p \log\left(\frac{p_1}{p_2}\right)$$

The Thermal Wind

$$u_T \approx u_g(p_2) - u_g(p_1) = -\frac{R}{f}\left(\frac{\partial \langle T \rangle}{\partial y}\right)_p \log\left(\frac{p_1}{p_2}\right)$$

$$v_T \approx v_g(p_2) - v_g(p_1) = \frac{R}{f}\left(\frac{\partial \langle T \rangle}{\partial x}\right)_p \log\left(\frac{p_1}{p_2}\right)$$

Example: Thermal wind v_T between 500 hPa and 1000 hPa



The Thermal Wind

$$u_T \approx u_g(p_2) - u_g(p_1) = -\frac{R}{f}\left(\frac{\partial \langle T \rangle}{\partial y}\right)_p \log\left(\frac{p_1}{p_2}\right)$$

$$v_T \approx v_g(p_2) - v_g(p_1) = \frac{R}{f}\left(\frac{\partial \langle T \rangle}{\partial x}\right)_p \log\left(\frac{p_1}{p_2}\right)$$

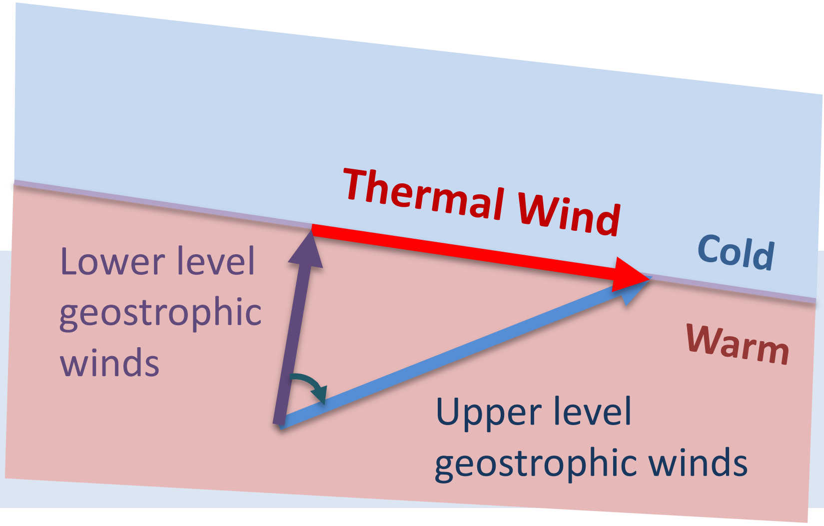
Thermal wind always points parallel to lines of constant temperature:

$$\mathbf{u}_T \cdot \nabla \langle T \rangle = \frac{R}{f} \log\left(\frac{p_1}{p_2}\right)\left[-\frac{\partial \langle T \rangle}{\partial y}\frac{\partial \langle T \rangle}{\partial x} + \frac{\partial \langle T \rangle}{\partial x}\frac{\partial \langle T \rangle}{\partial y}\right] = 0$$

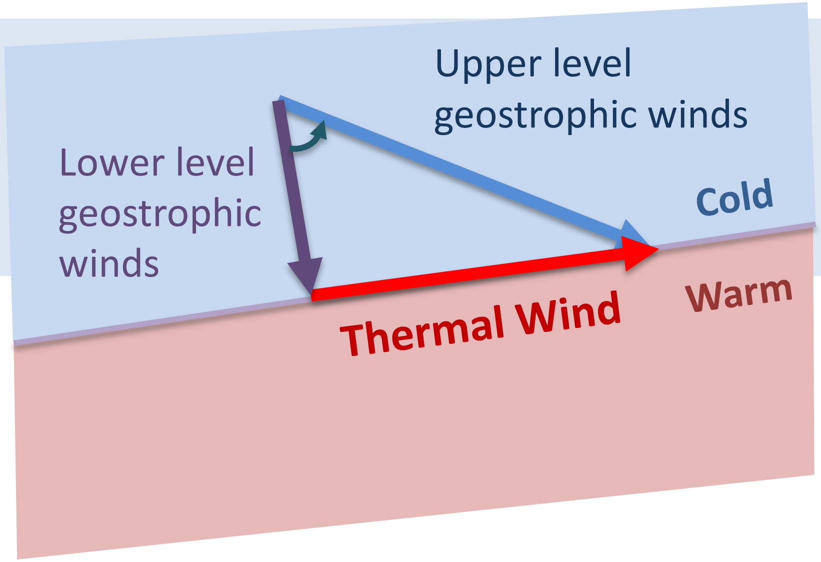
The Thermal Wind

Thermal wind always points parallel to lines of constant temperature (also lines of constant layer thickness):

Definition: Veering winds are associated with clockwise rotation with height and warm air advection.



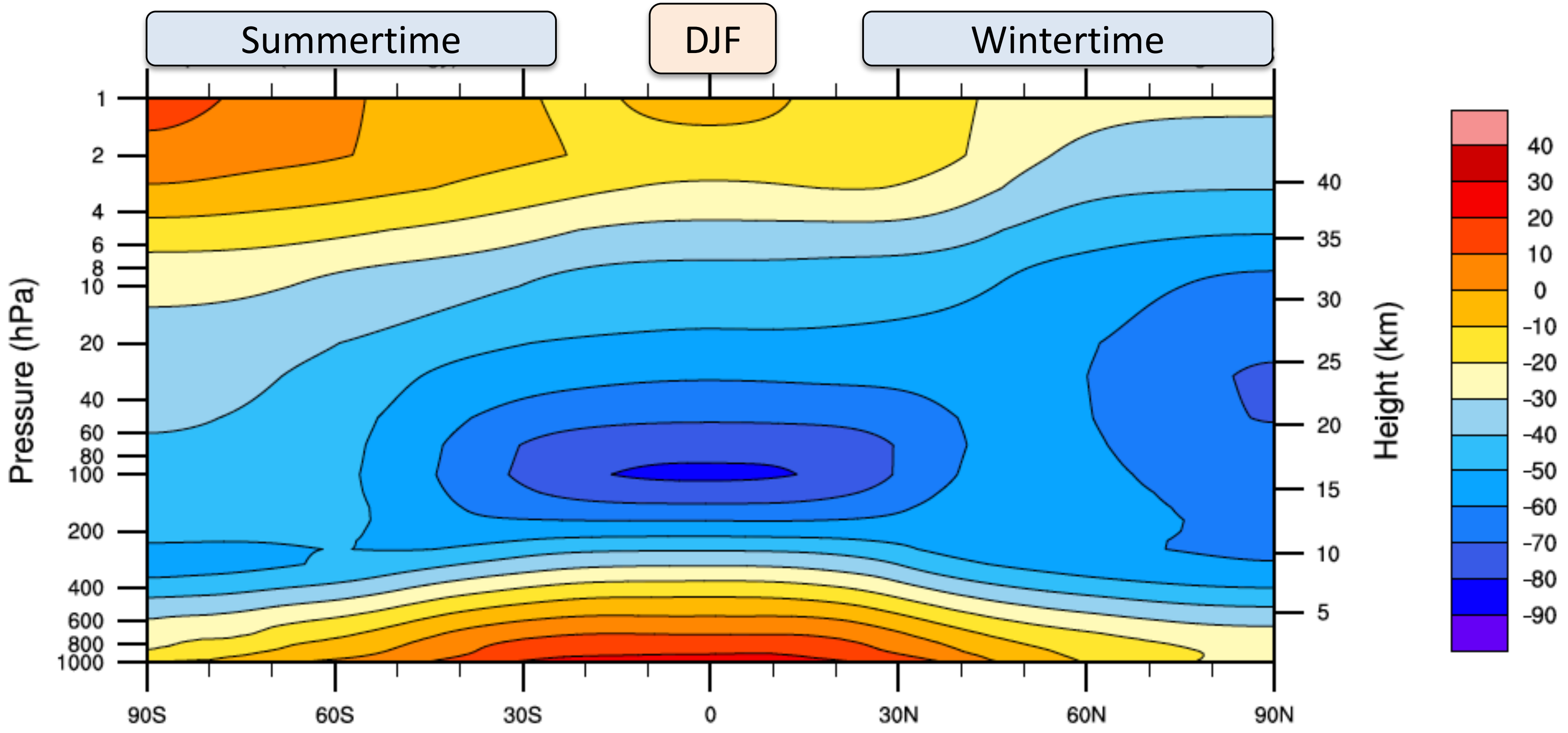
Definition: Backing winds are associated with counterclockwise rotation with height and cold air advection.



The Thermal Wind

The thermal wind determines the relationship between meridional temperature gradients and zonal winds.

Question: Given zonal mean temperature below, where are zonal jets?

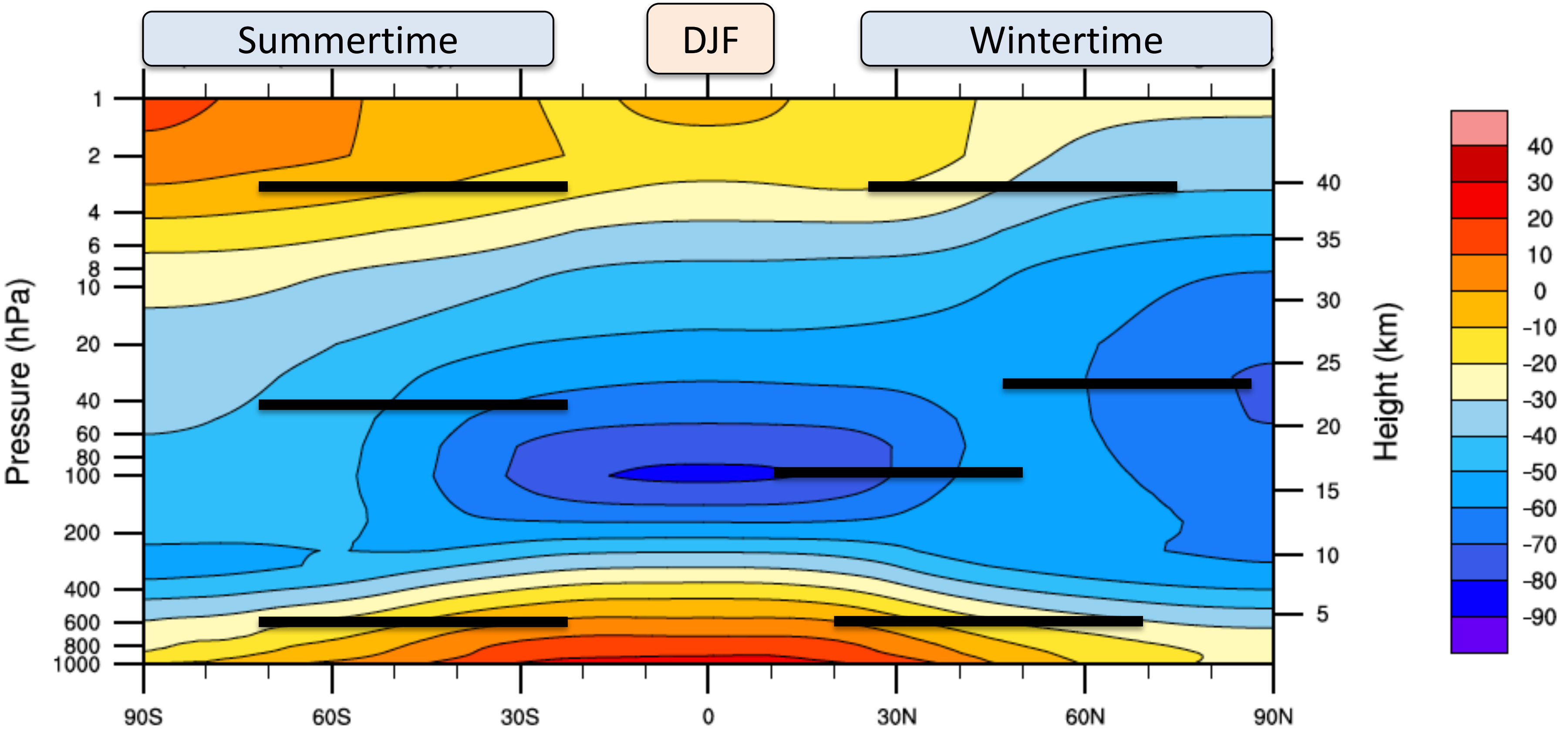


The Thermal Wind

Question: Given zonal mean temperature below, where are zonal jets?

Obtain from thermal wind relationship: $$\frac{\partial u_g}{\partial p} = \frac{R}{pf}\left(\frac{\partial T}{\partial y}\right)_p$$

$\frac{\partial T}{\partial y}$?



The Thermal Wind

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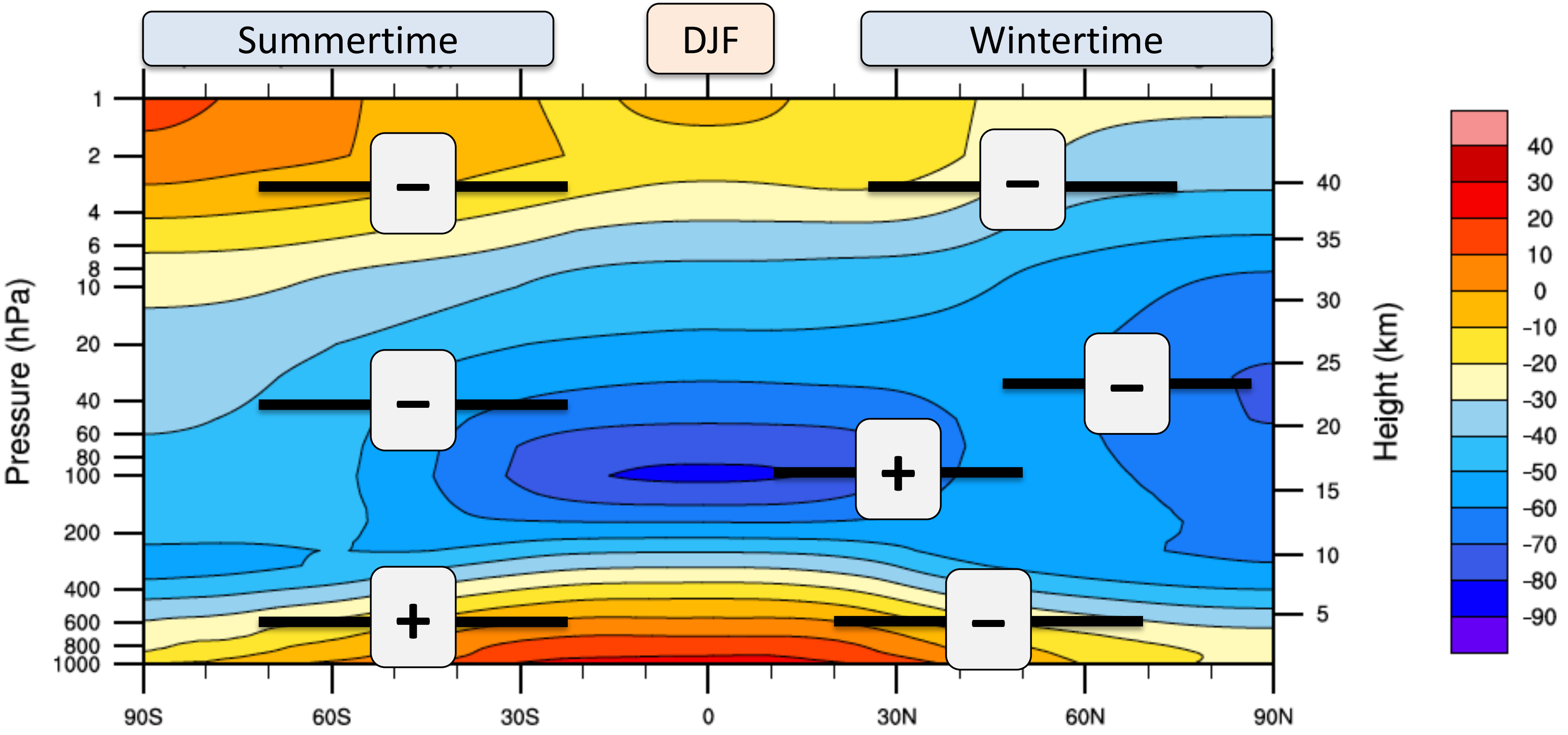


The Thermal Wind

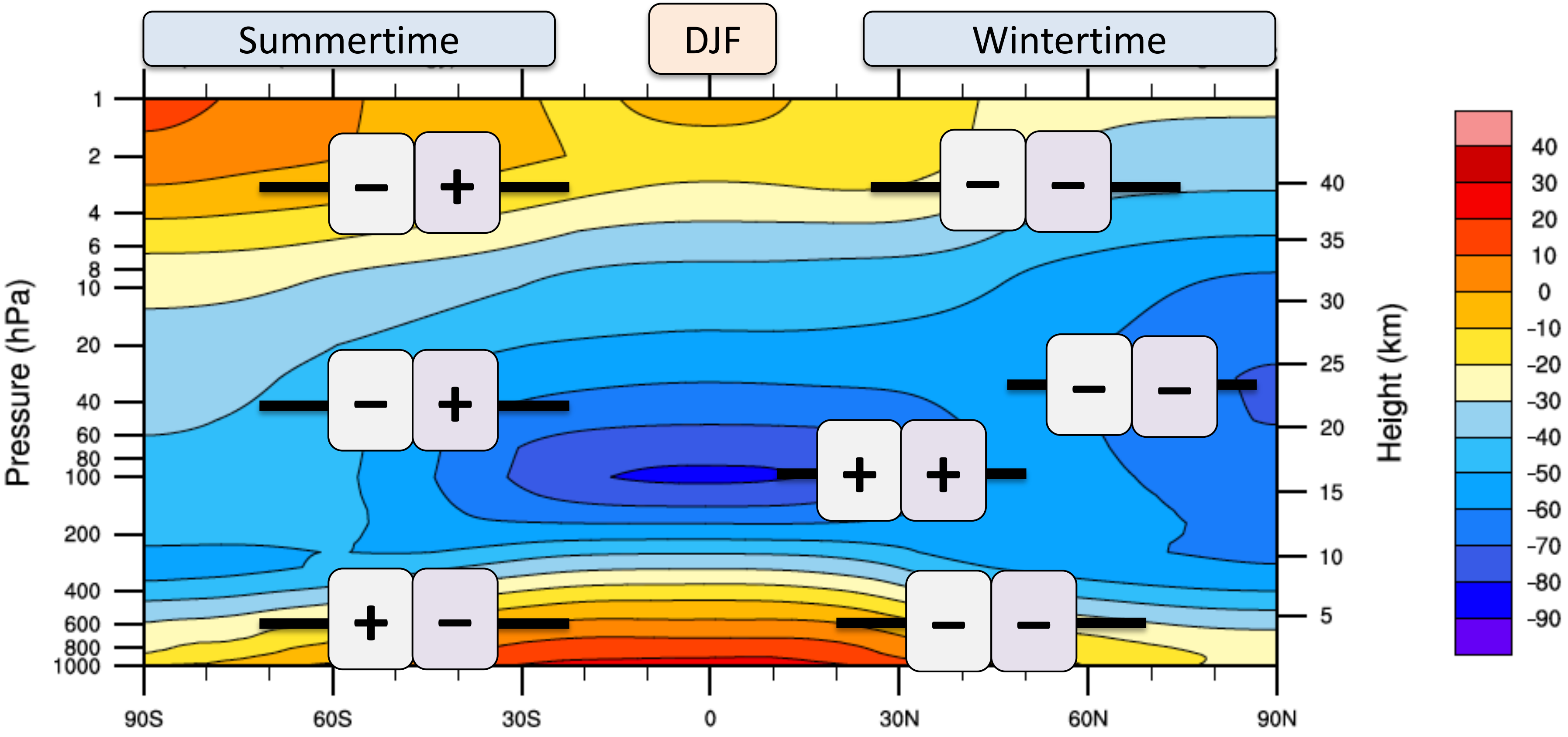
Question: Given zonal mean temperature below, where are zonal jets?

Obtain from thermal wind relationship: $$\frac{\partial u_g}{\partial p} = \frac{R}{pf}\left(\frac{\partial T}{\partial y}\right)_p$$

Note: In southern hemisphere $f < 0$

$\frac{\partial T}{\partial y}$?

$\frac{\partial u_g}{\partial p}$?



The Thermal Wind

Question: Given zonal mean temperature below, where are zonal jets?

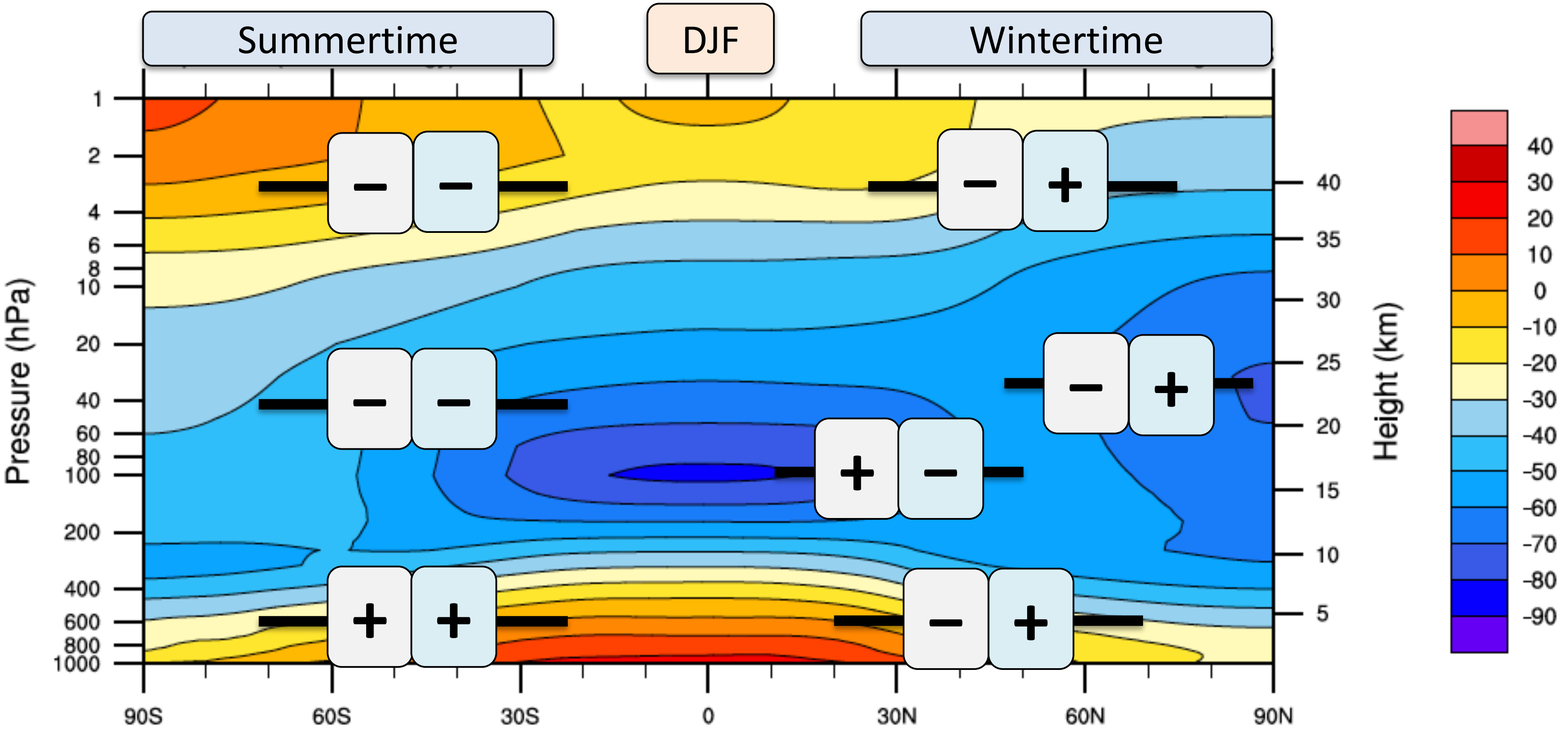
Obtain from thermal wind relationship: $$\frac{\partial u_g}{\partial p} = \frac{R}{pf}\left(\frac{\partial T}{\partial y}\right)_p$$

$\frac{\partial T}{\partial y}$?

$\frac{\partial u_g}{\partial z}$?

Recall that

$$\frac{\partial u_g}{\partial z} \sim -\frac{\partial u_g}{\partial p}$$

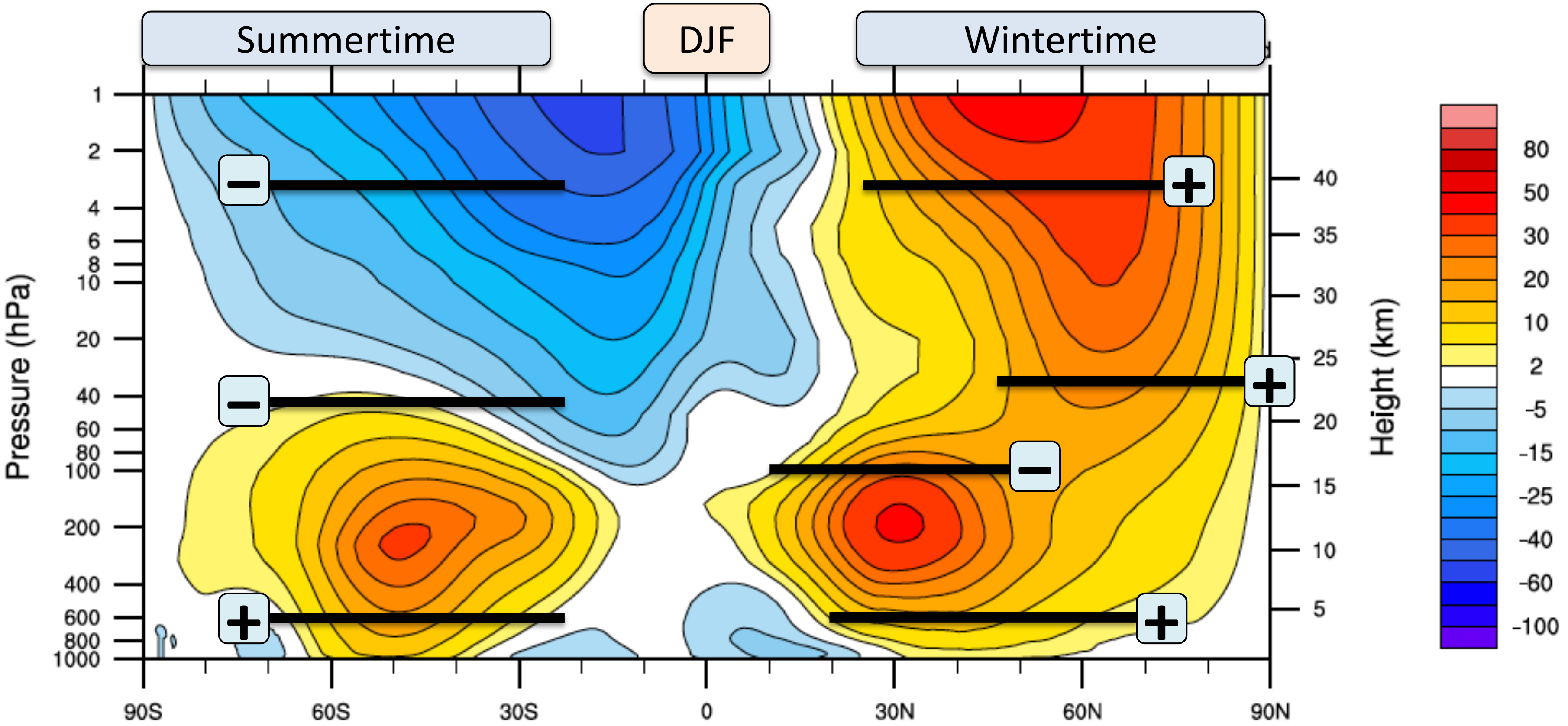


The Thermal Wind

Question: Given zonal mean temperature below, where are zonal jets?

Obtain from thermal wind relationship: $$\frac{\partial u_g}{\partial p} = \frac{R}{pf}\left(\frac{\partial T}{\partial y}\right)_p$$

$\frac{\partial u_g}{\partial z}$?



ATM 241 Climate Dynamics
Lecture 5
The General Circulation

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Thank You!