The Circulation of the Atmosphere and Oceans

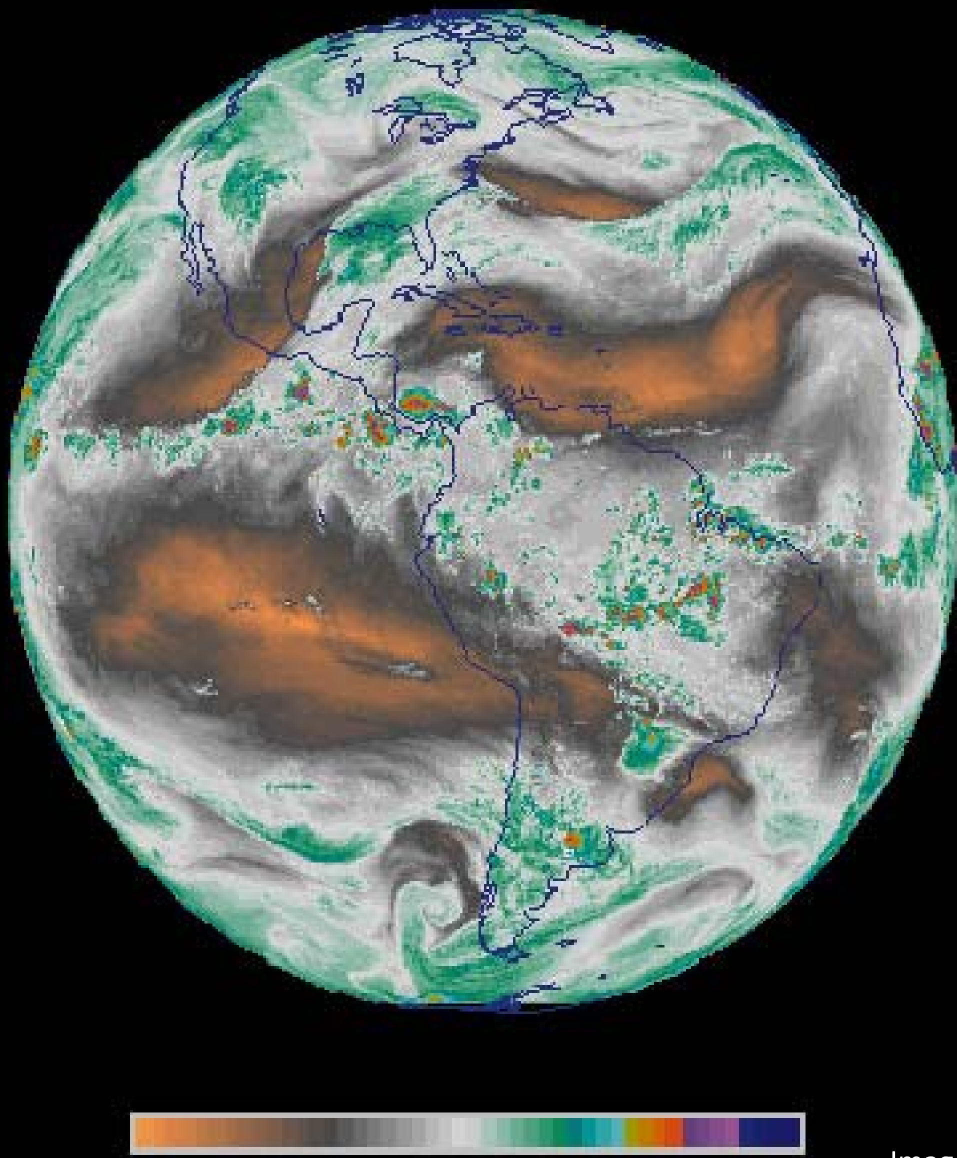


Image Credit: *NOAA*

The Real World Environment Varies in All Three Spatial Dimensions and Time

Solar Forcing Variations with Latitude and Time

Seasonal variation of solar radiation

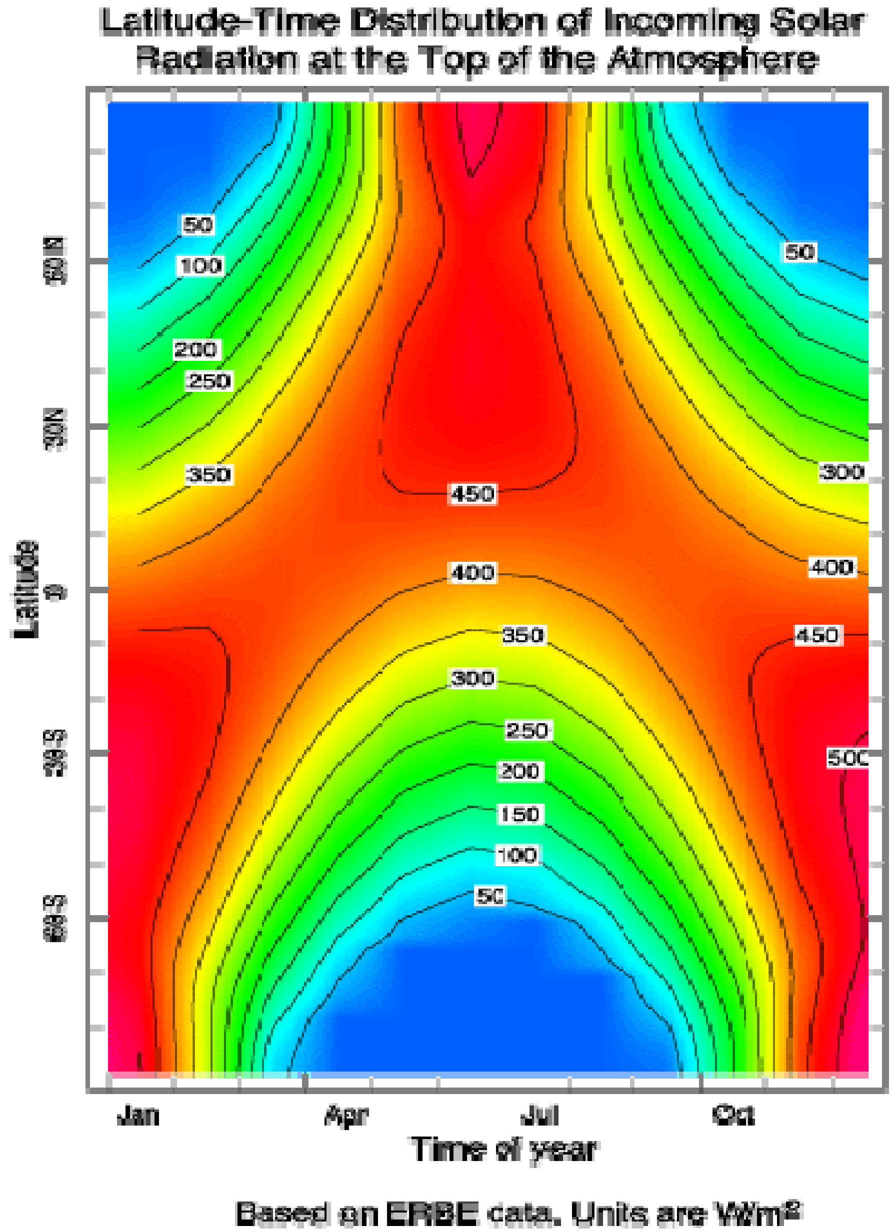


Image credit: *Lamont-Doherty Earth Observatory/Columbia University*

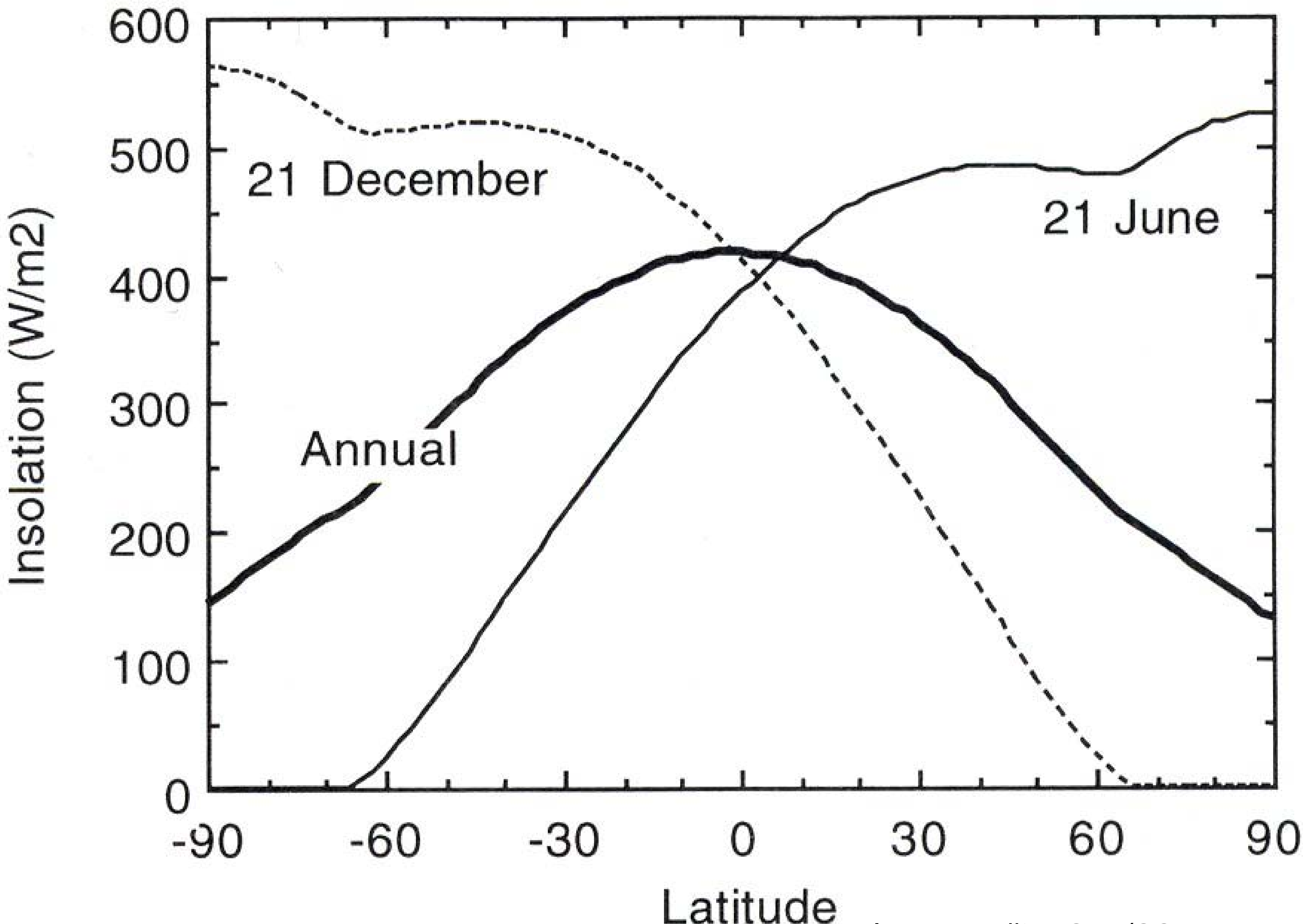


Image credit: *UCAR/COMET*

Response of the Earth System

Sea Surface Temperature

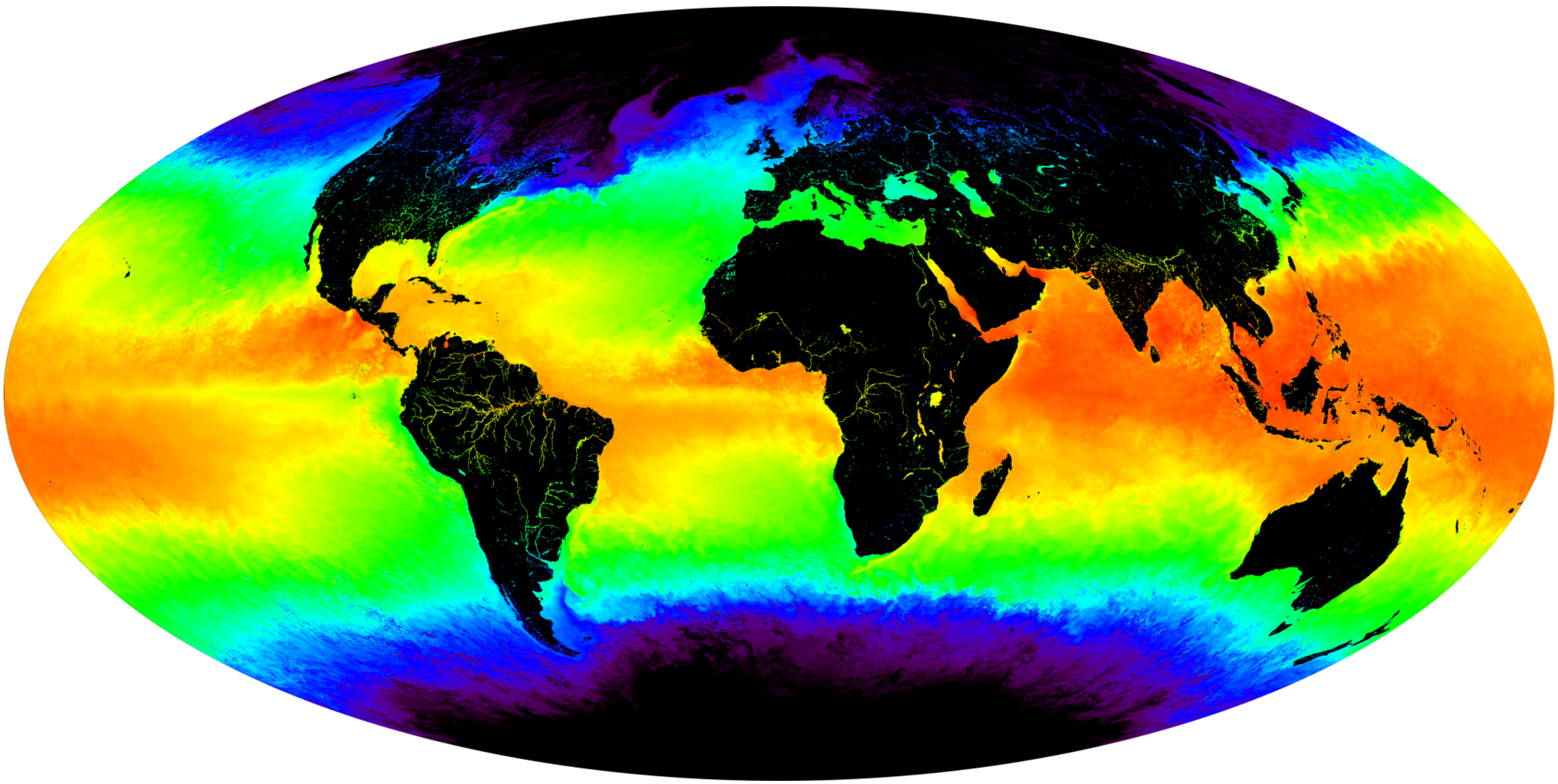
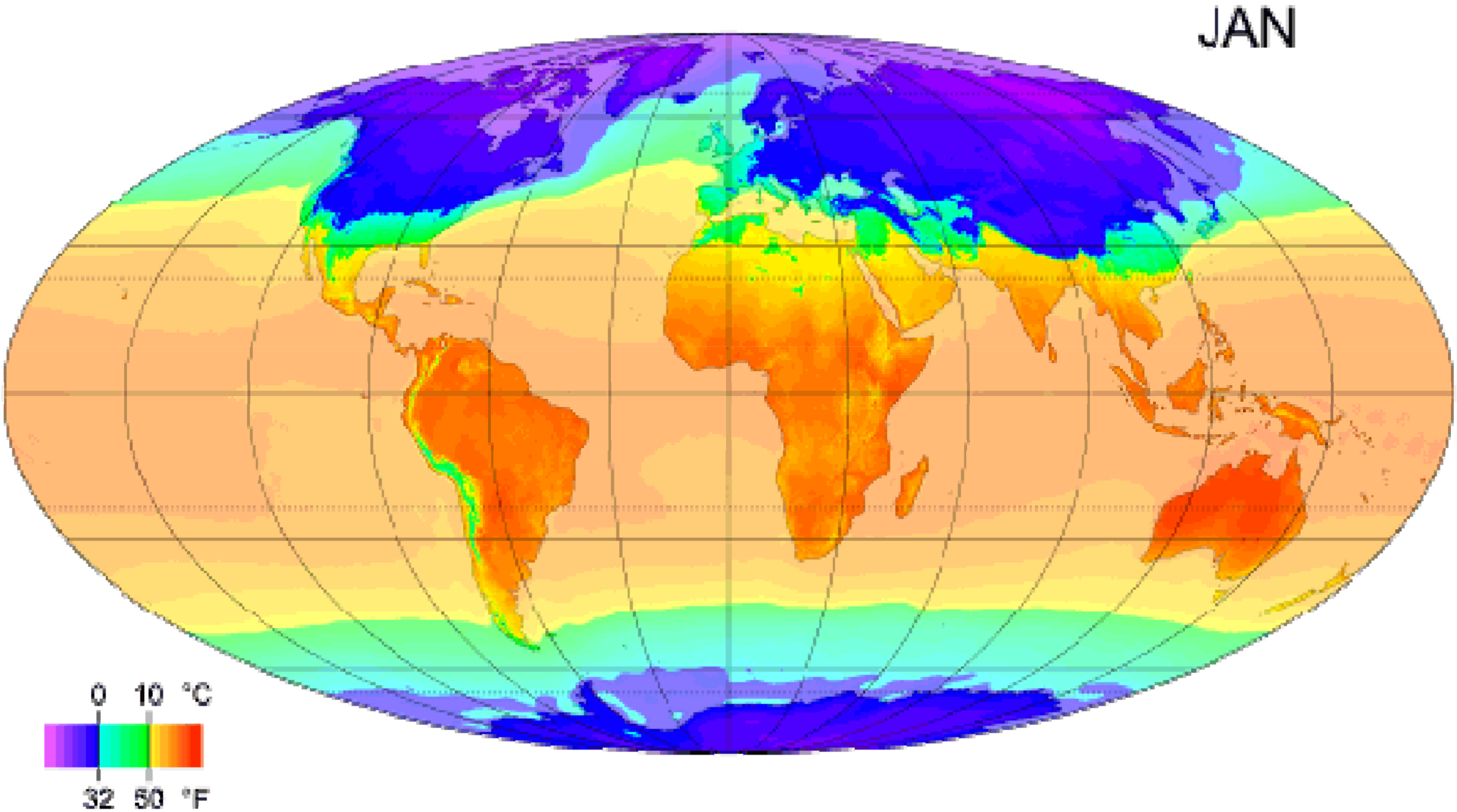


Image credit: NASA Visible Earth (MODIS Oceans Group, NASA Goddard Space Flight Center)


JAN
0
10
°C
32
50
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January mean surface wind speed and direction

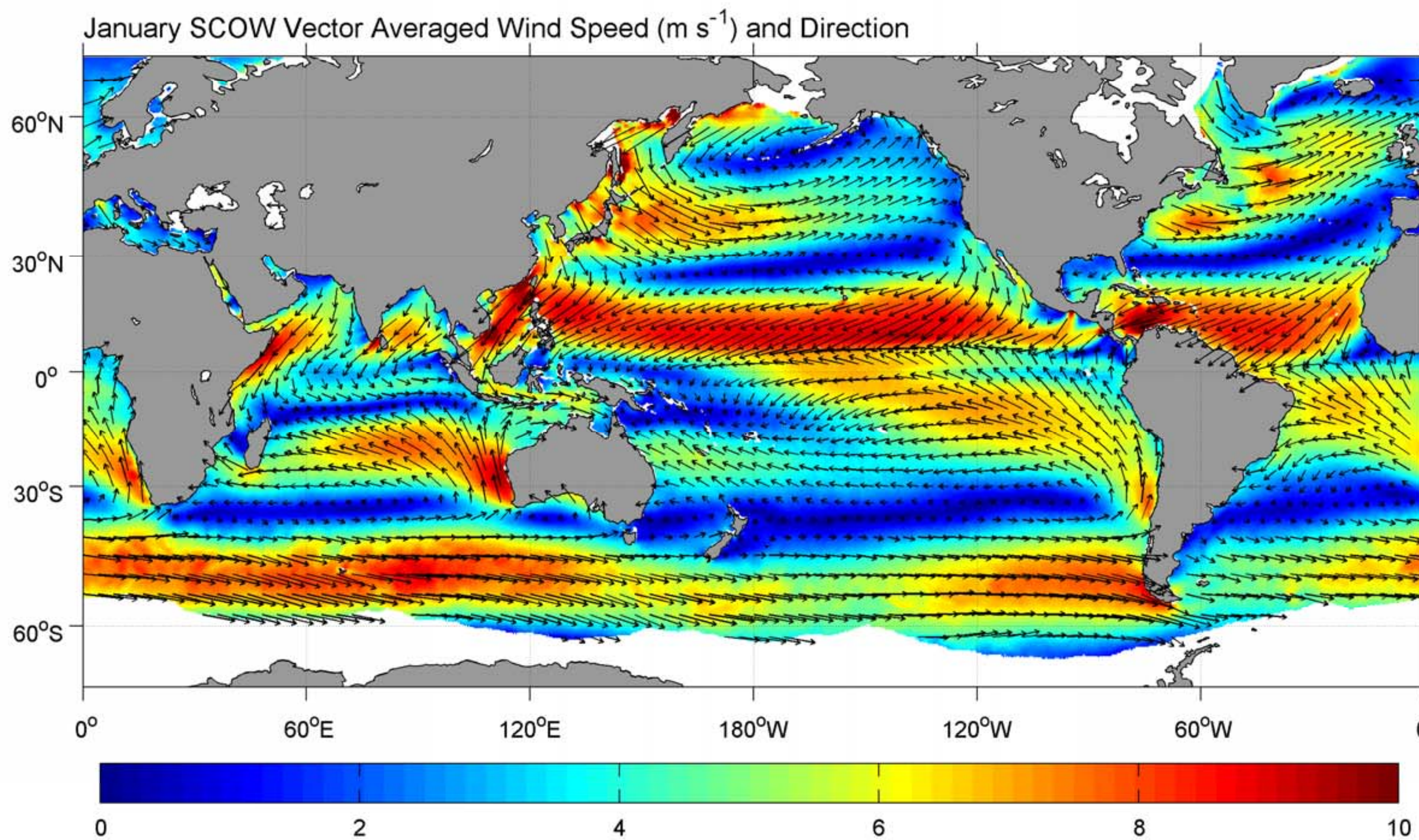


Image credit: Risien, C.M., and D.B. Chelton, 2008: A Global Climatology of Surface Wind and Wind Stress Fields from Eight Years of QuikSCAT Scatterometer Data. J. Phys. Oceanogr., 38, 2379-2413.

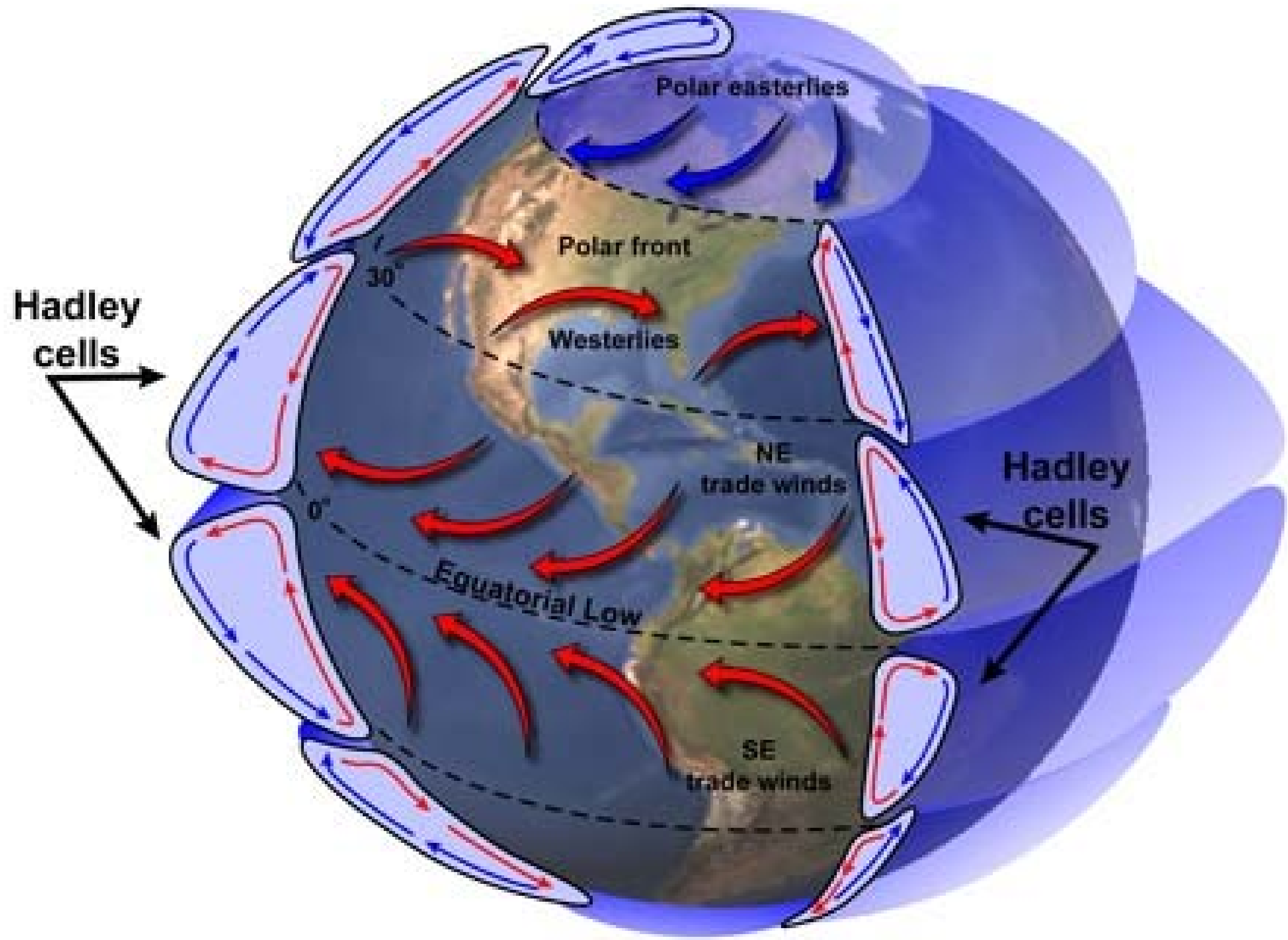


Image credit: *NASA*

Instantaneous Surface Wind

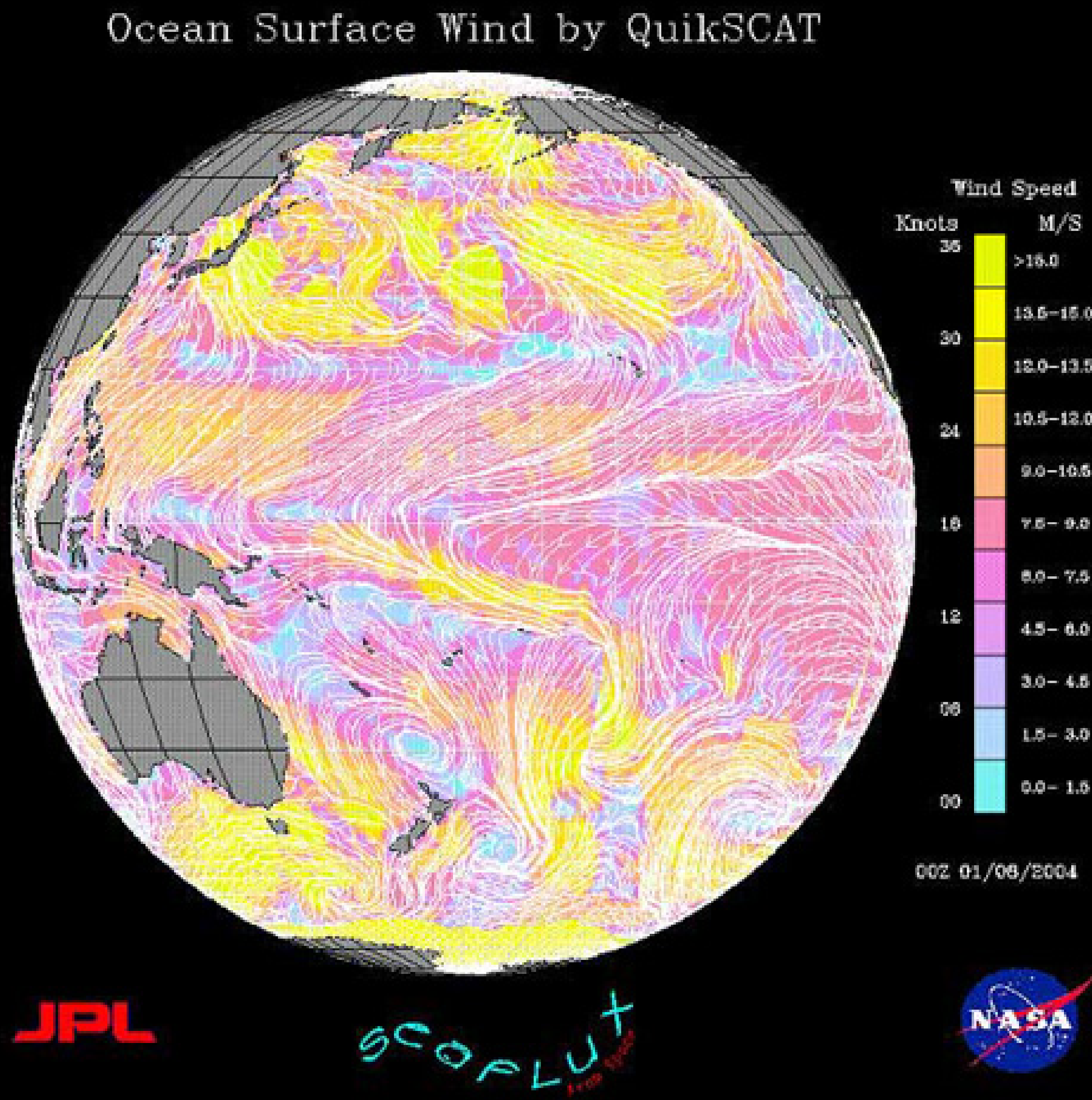


Image credit: *NASA/JPL*

Global Surface and 250 hPa Winds

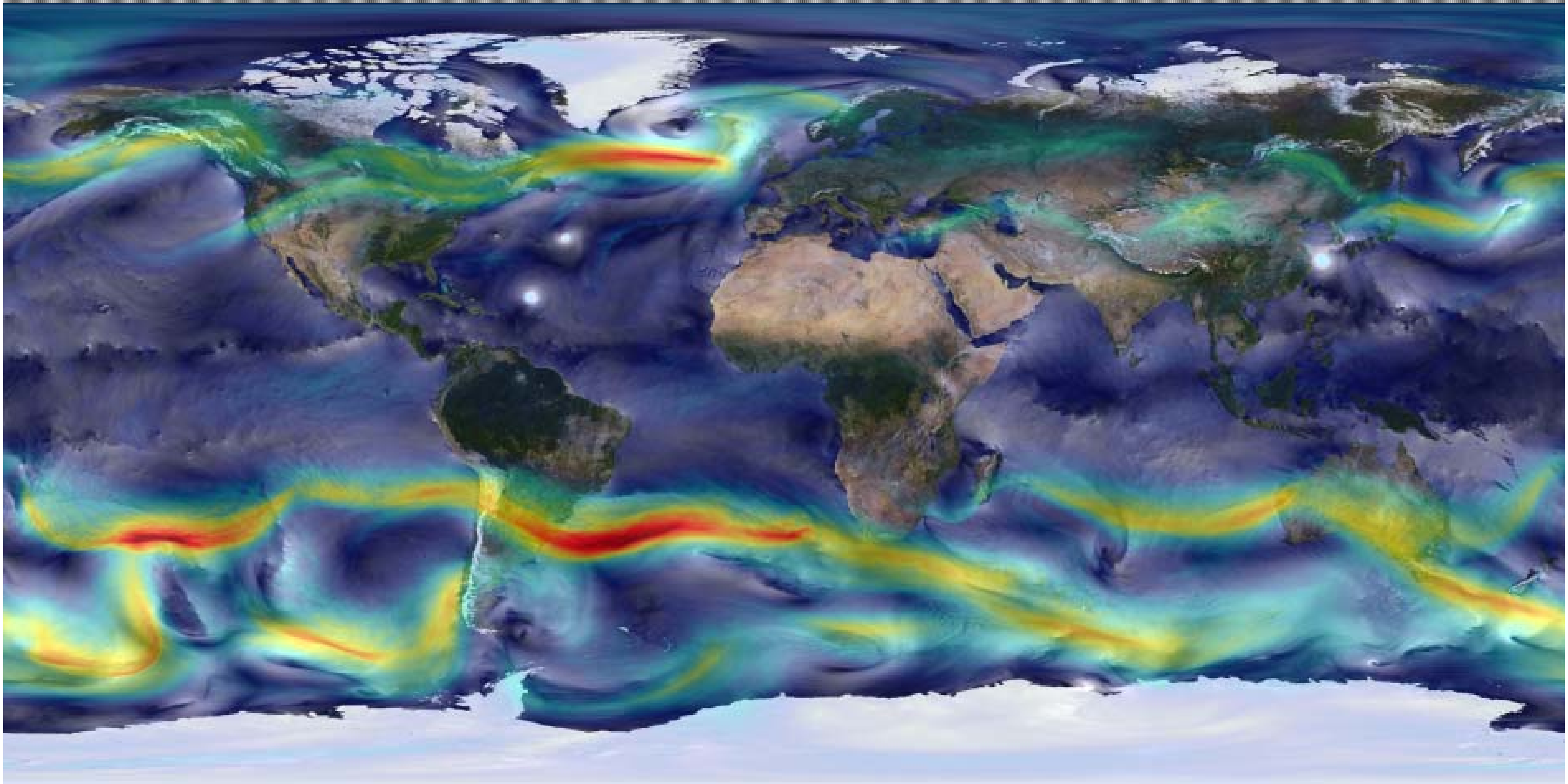
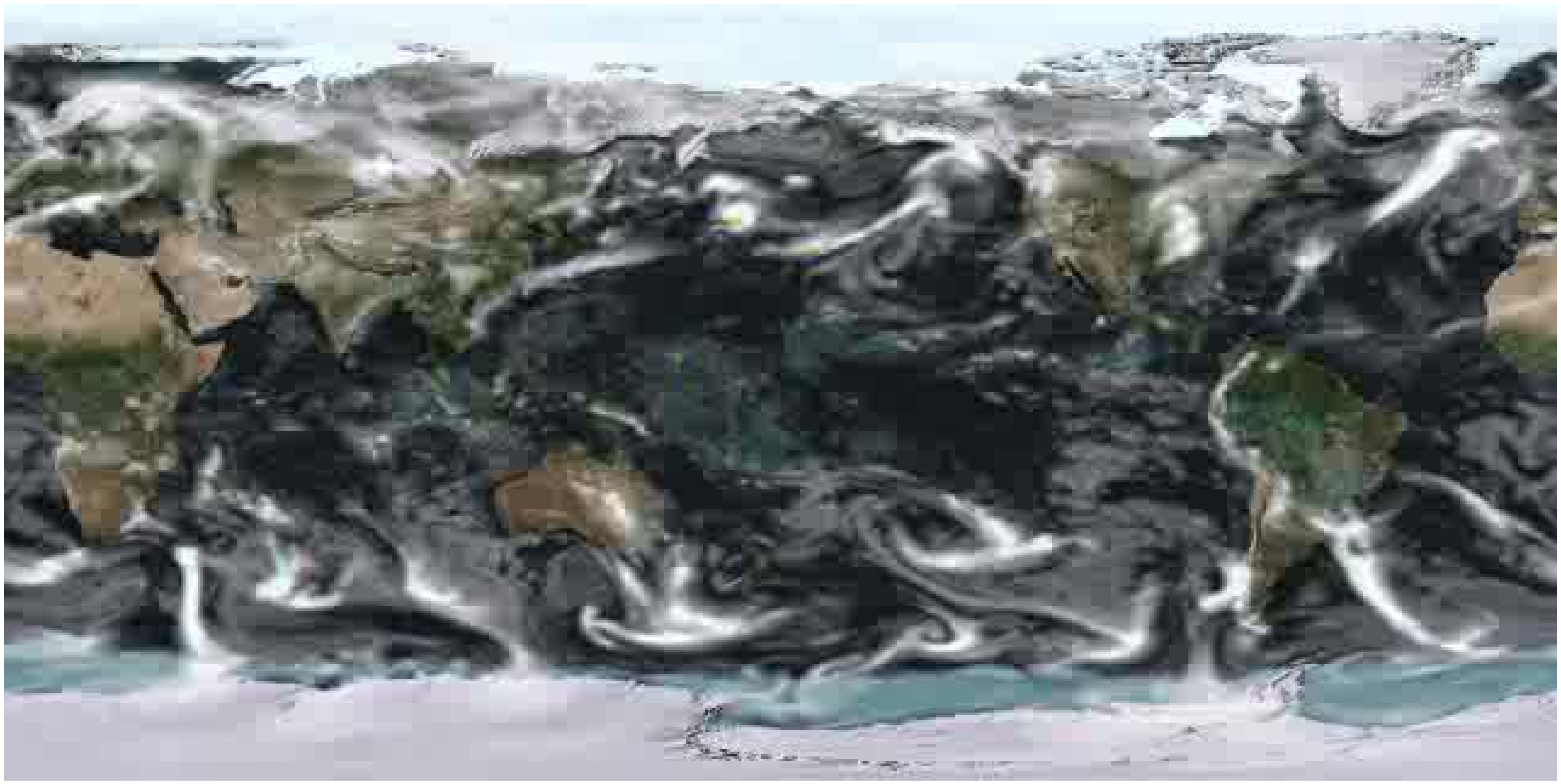
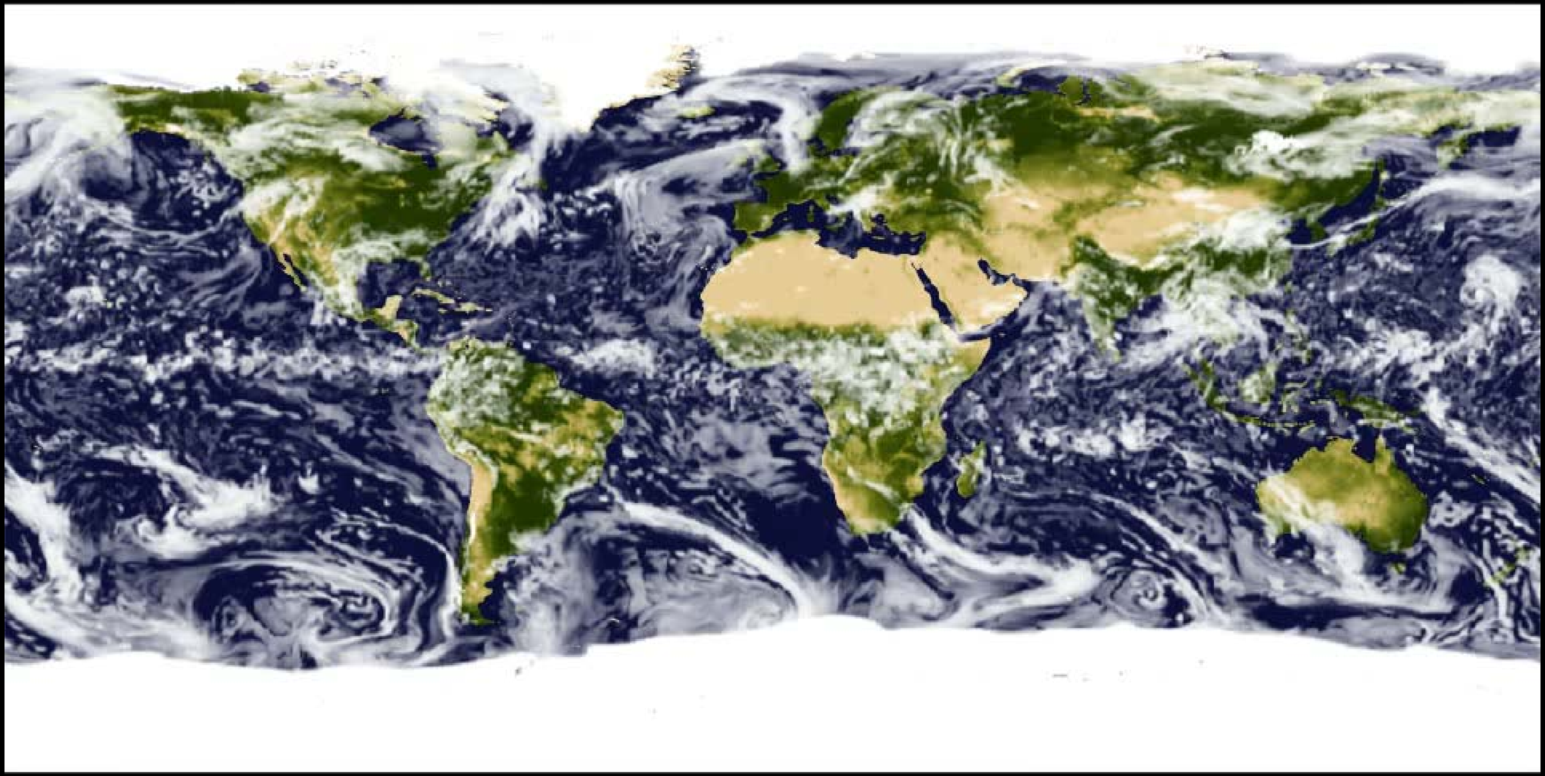


Image Credit: *William Putman/NASA Goddard Space Flight Center*



Simulation:
Urs Beyerle, Institute for Atmospheric and Climate Science, ETH Zurich

Visualization:
Thierry Corti, Center for Climate Systems Modeling, ETH Zurich



C2SM
Center for Climate
Systems Modeling

12 Sep 00 h

Ocean Circulation

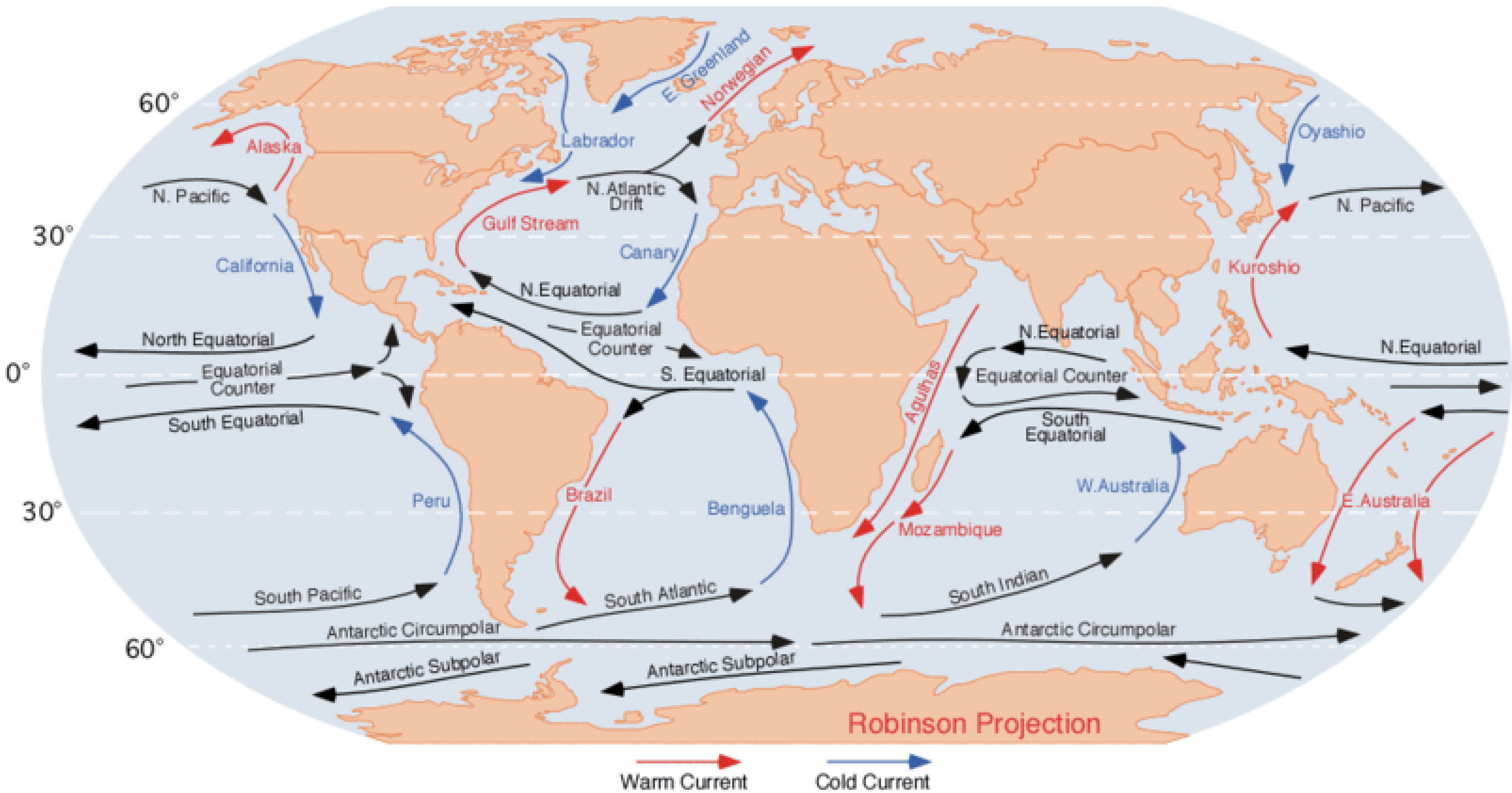


Image credit: *Dr. Michael Pidwirny*

Ocean Circulation

Worth watching all of

http://svs.gsfc.nasa.gov/vis/a000000/a003800/a003827/prepetual_ocean_1080p30.mp4

Movie on following slide created from the MITgcm, an ocean model developed at MIT. Credit also to NASA; see link above.

Effects of Atmospheric Circulation

- Vertical and lateral energy transport
- Vertical and lateral transport of water
- Transport of trace gases, including greenhouse gases
- Transport of aerosols
- Large-scale condensation/evaporation of water

Global Energy Balance

Steady Flow:

$$\nabla \bullet \left[F_{rad}\hat{k} + F_{conv}\hat{k} + \rho \mathbf{V} E \right] = 0,$$

$$where$$

$$E \equiv c_p T + gz + L_v q + \frac{1}{2} |\mathbf{V}|^2$$

Integrate from surface to top of atmosphere:

$$\nabla_2 \bullet \overline{\rho \mathbf{V} E} + F_{rad_{TOA}} - \left(F_{rad} + F_{conv} \right)_{surface} = 0$$

Lateral Heat Transport by Atmosphere and Oceans

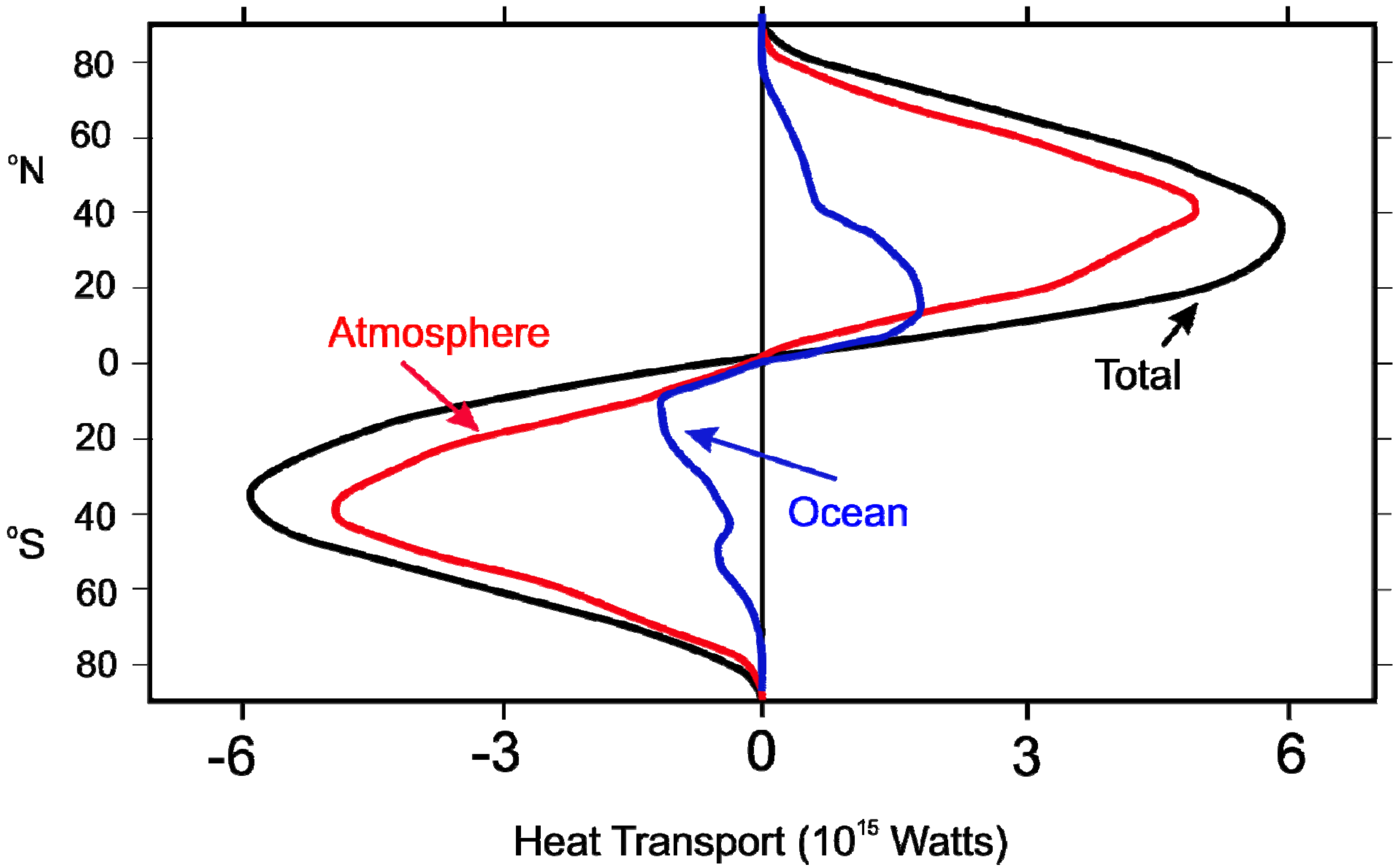


Image credit: After Fasullo, John T., Kevin E. Trenberth, 2008: The Annual Cycle of the Energy Budget. Part II: Meridional Structures and Poleward Transports. *J. Climate*, **21**, 2313–2325.

What causes atmospheric circulation?

Much non-convective atmospheric motion can be grouped into two categories:

1. Large-scale, quasi-steady overturning motion in the Tropics
2. Eddies with horizontal dimensions of ~ 3000 km in middle and high latitudes

First consider a hypothetical planet like Earth, but with no continents and no seasons and for which the only friction acting on the atmosphere is at the surface.

This planet has an exact nonlinear equilibrium solution for the flow of the atmosphere, characterized by:

1. Every column is in radiative-convective equilibrium
2. Wind vanishes at planet's surface
3. Horizontal pressure gradients balanced by *Coriolis accelerations*

Hydrostatic balance:

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

$$\rho = \frac{p}{RT}$$ Ideal Gas Law

→ **Pressure decreases upward more slowly at higher temperature**

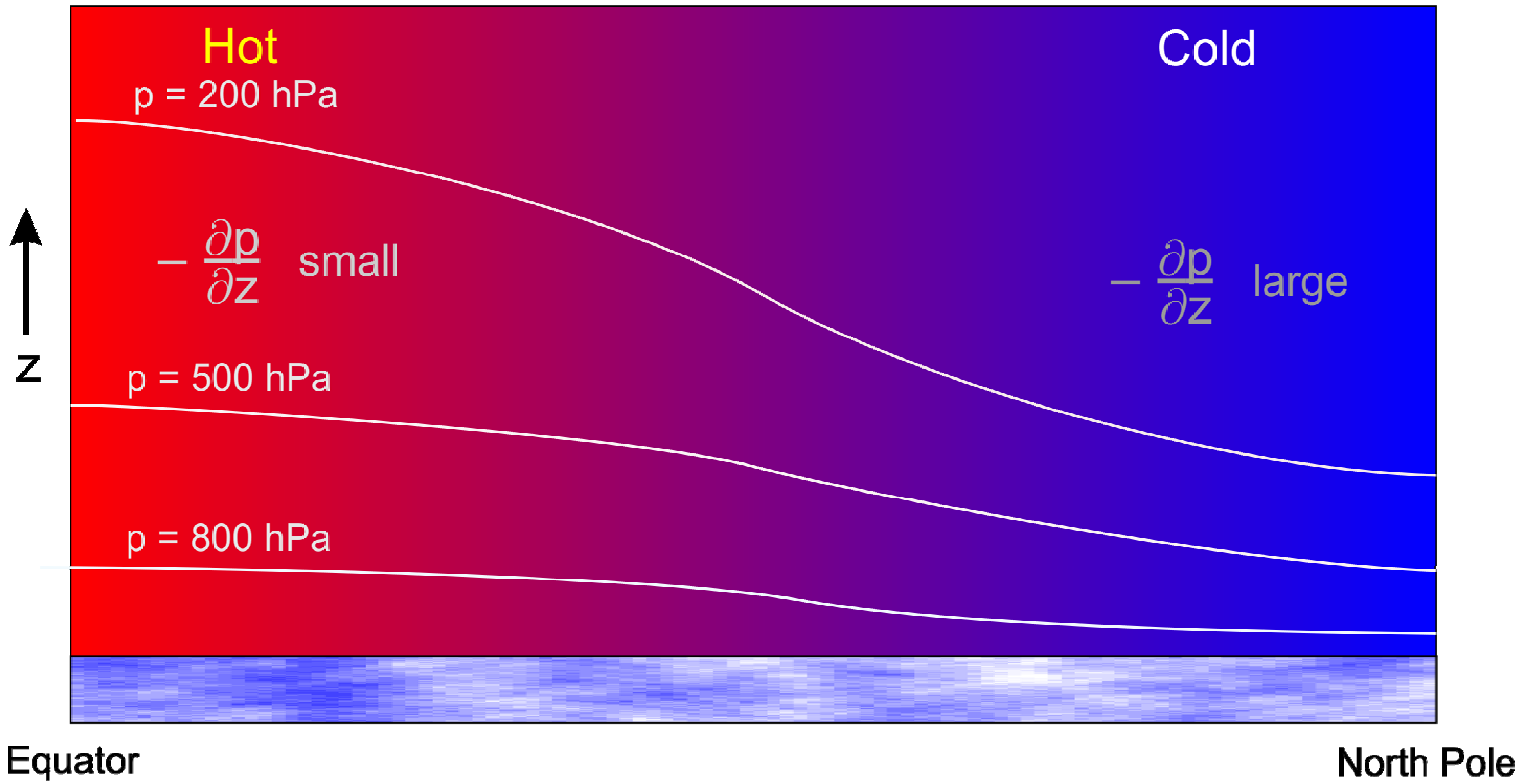


Image credit: *Kerry Emanuel*

Horizontal force balance in *inertial* reference frame:

$$\frac{du}{dt} = -\alpha \frac{\partial p}{\partial x}, \qquad \frac{dv}{dt} = -\alpha \frac{\partial p}{\partial y}$$

Air accelerates DOWN the pressure gradient

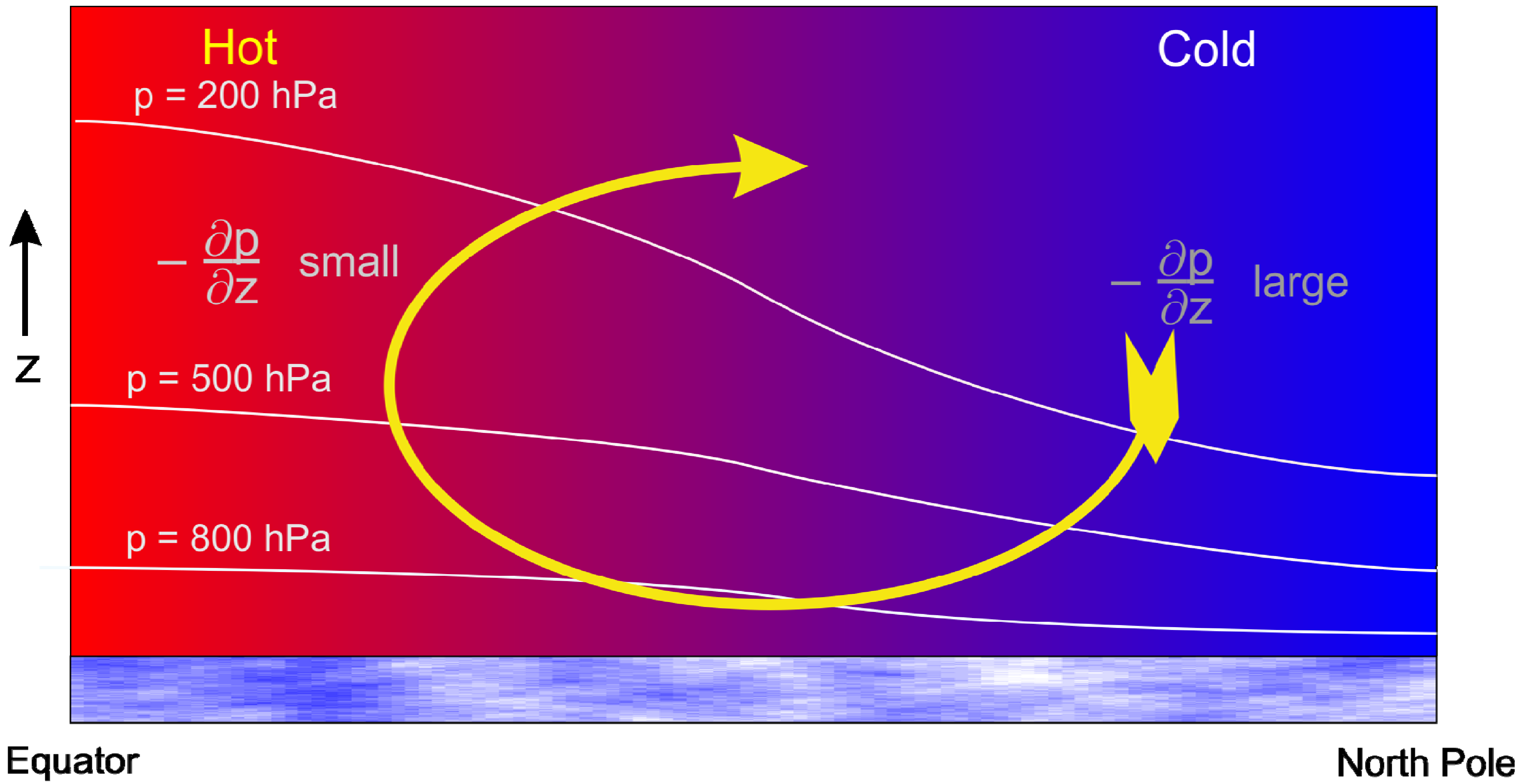
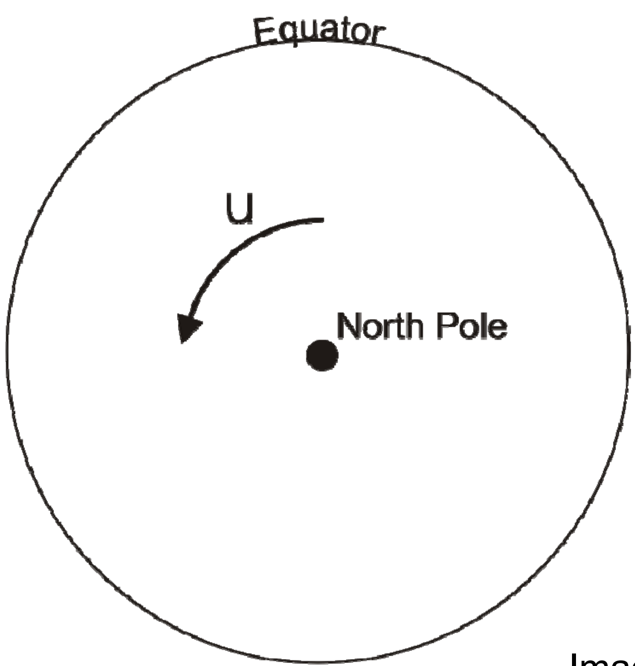


Image credit: *Kerry Emanuel*

Horizontal force balance in *inertial* reference frame:

$$\frac{du}{dt} = -\alpha \frac{\partial p}{\partial x}, \qquad \frac{dv}{dt} = -\alpha \frac{\partial p}{\partial y}$$

Rotating reference frame of Earth:



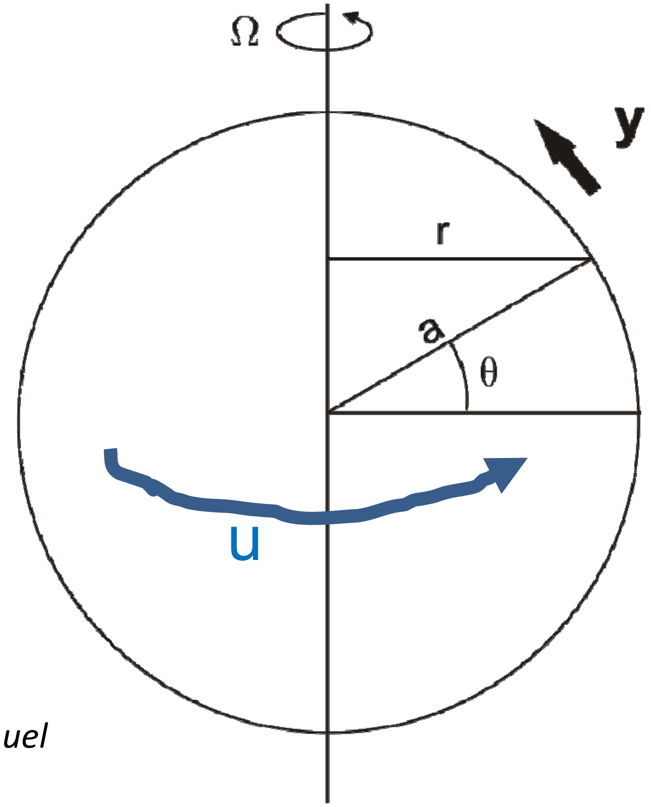
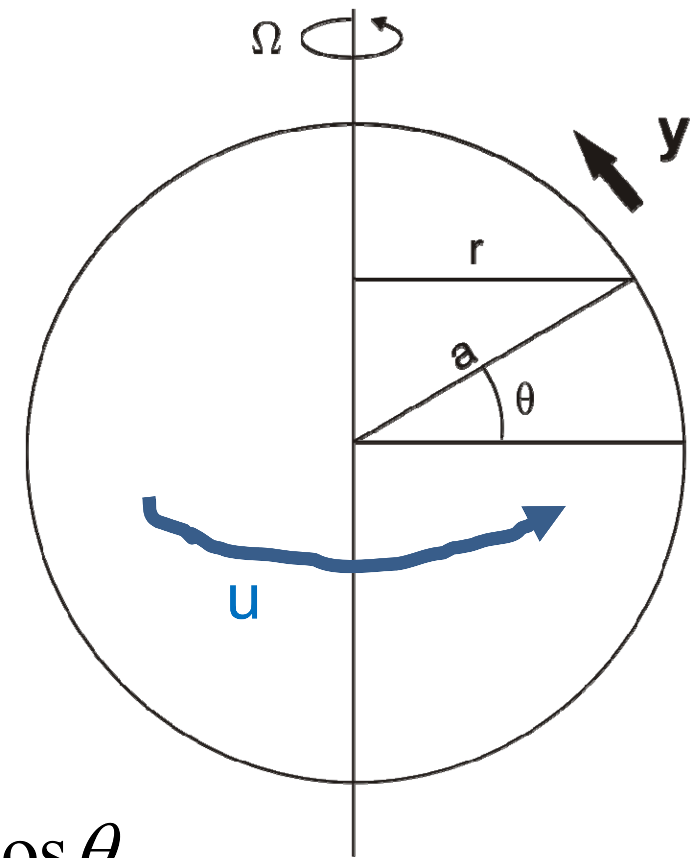


Image credit: *Kerry Emanuel*

$$\frac{dv}{dt} = -\alpha \frac{\partial p}{\partial y} - \frac{u^2}{r} \sin\theta$$



$$u = \Omega a \cos\theta + u_{rel}, \qquad r = a\cos\theta$$

$$\rightarrow \frac{dv}{dt} = -\alpha \frac{\partial p}{\partial y} - \underbrace{\Omega^2 a \cos\theta \sin\theta} - 2\Omega \sin\theta u_{rel} - \frac{u_{rel}^2}{a} \tan\theta$$

Constant acceleration toward equator!

$$\frac{dv}{dt} = -\alpha \frac{\partial p}{\partial y} - \frac{u^2}{r} \sin\theta$$

$$u = \Omega a \cos\theta + u_{rel}, \qquad r = a\cos\theta$$

$$\rightarrow \frac{dv}{dt} = -\alpha \frac{\partial p}{\partial y} - \underbrace{\Omega^2 a \cos\theta \sin\theta} - 2\Omega \sin\theta u_{rel} - \frac{u_{rel}^2}{a} \tan\theta$$

Bracketed term absorbed into definition of gravity:

$$\frac{dv}{dt} = -\alpha \frac{\partial p}{\partial y} - 2\Omega \sin\theta u_{rel} - \frac{u_{rel}^2}{a} \tan\theta$$

$$\cong -\alpha \frac{\partial p}{\partial y} - 2\Omega \sin\theta u_{rel}$$

Very small

$$\equiv -\alpha \frac{\partial p}{\partial y} - f u_{rel}, \quad \text{where } f \equiv 2\Omega \sin\theta$$

Geostrophic Balance

$$\alpha \frac{\partial p}{\partial y} = -fu_{rel}, \quad where\ f \equiv 2\Omega \sin\theta$$

$\boldsymbol{f}$ is the *Coriolis Parameter*

Similarly,

$$\alpha \frac{\partial p}{\partial x} = fv_{rel}$$

Thermal Wind Equation

$$\alpha \frac{\partial p}{\partial y} = -fu_{rel} \qquad \textit{geostrophic}$$

$$\alpha \frac{\partial p}{\partial z} = -g \qquad \textit{hydrostatic}$$

Eliminate p:

$$f \frac{\partial u}{\partial z} = -g\left(\frac{\partial \ln(\alpha)}{\partial y}\right) = -g\left(\frac{\partial \ln(T)}{\partial y}\right)_p \qquad \textit{Thermal wind}$$

Zonal wind increases with altitude if temperature decreases toward pole

Thermal Wind Balance

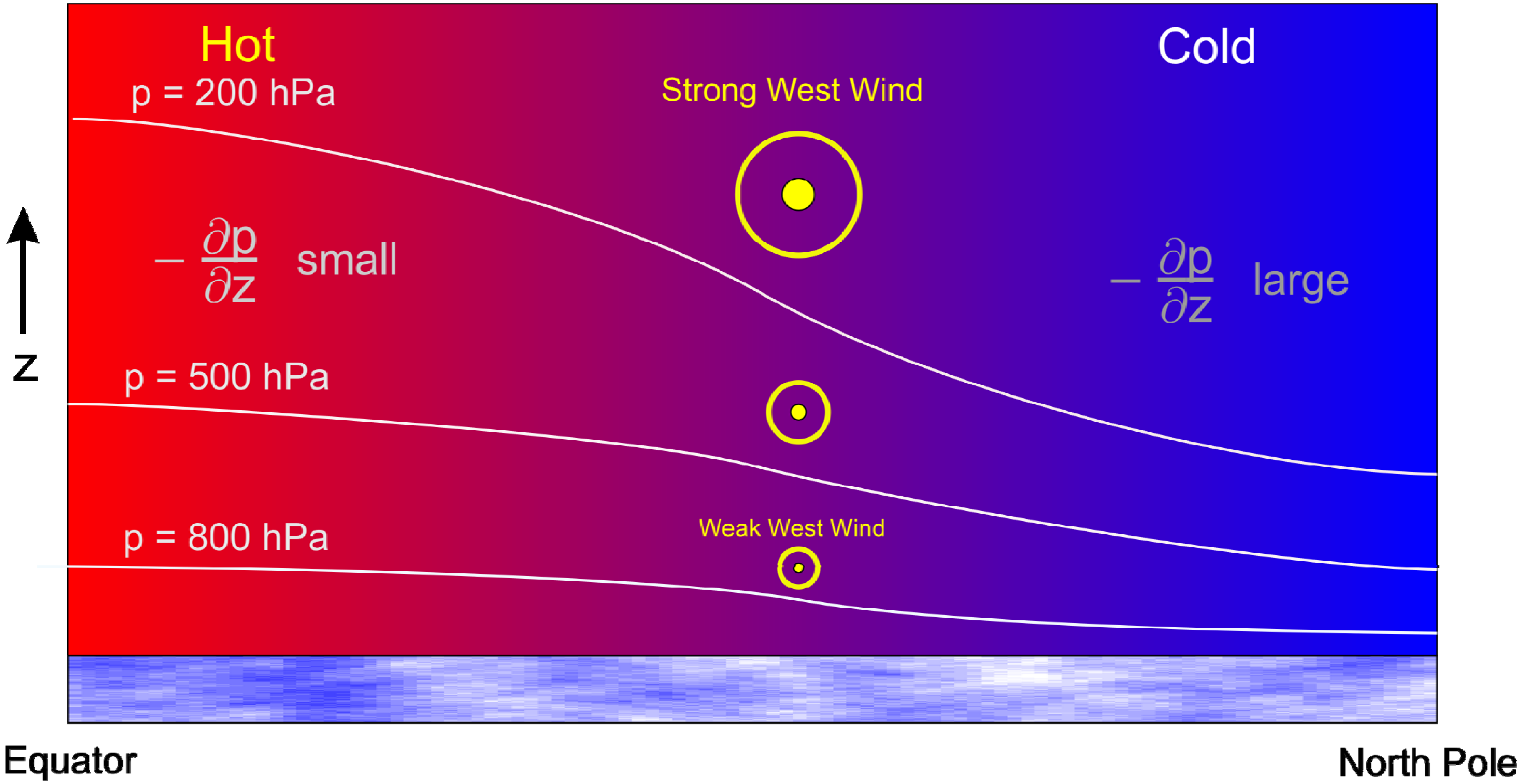
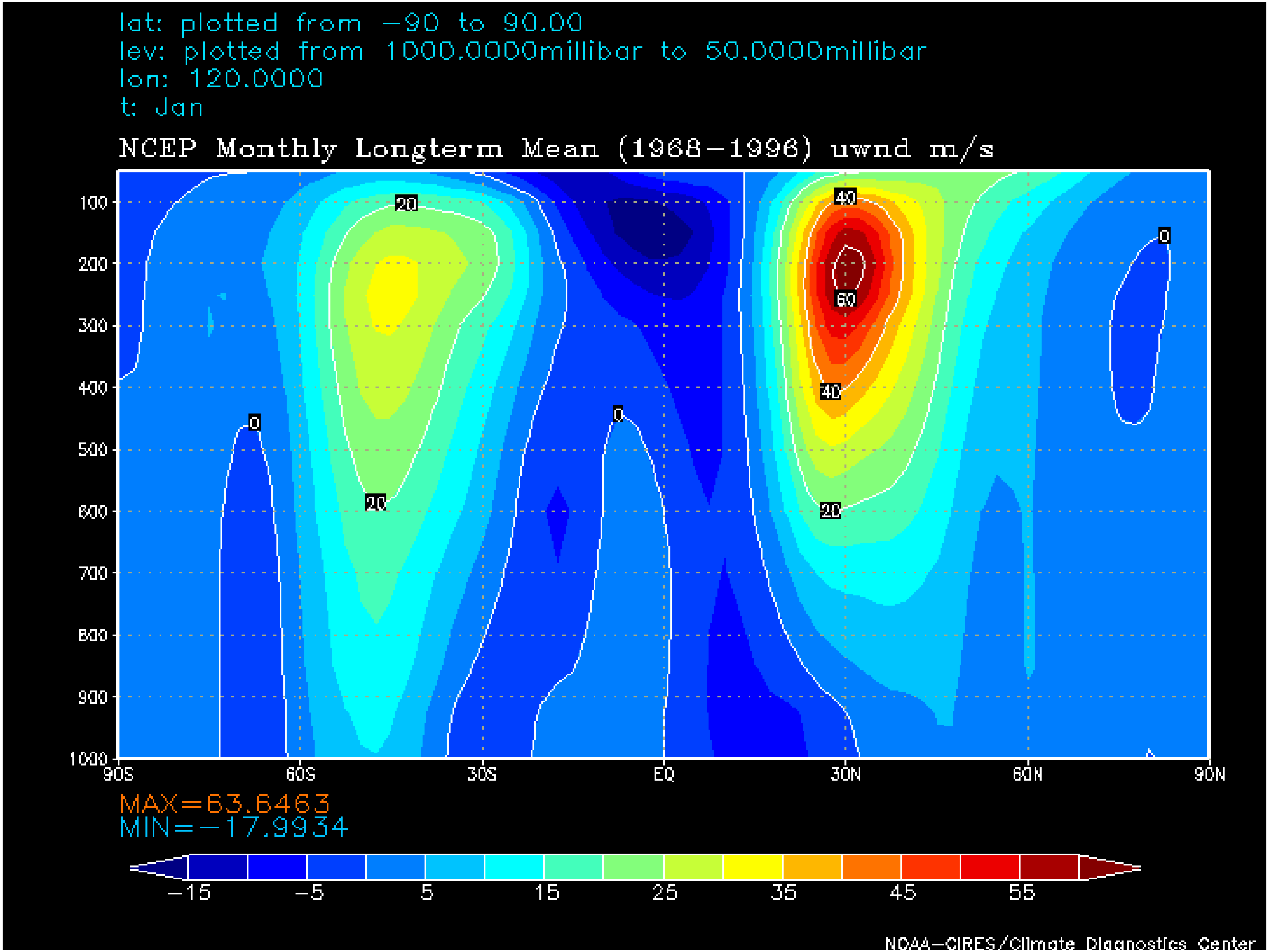


Image credit: *Kerry Emanuel*



lat: plotted from -90 to 90.00
lev: plotted from 1000.0000millibar to 50.0000millibar
lon: 120.0000
t: Jan
NCEP Monthly Longterm Mean (1968-1996) uwnd m/s
100
200
300
400
500
600
700
800
900
1000
90S
60S
30S
EQ
30N
60N
90N
20
40
60
0
MAX=63.6463
MIN=-17.9934
-15
-5
5
15
25
35
45
55
NOAA-CIRES/Climate Diagnostics Center

Exact Solution!

- Every individual column of the atmosphere and the surface beneath it are in radiative-convective equilibrium
- Surface pressure is constant
- Pressure above the surface decreases poleward, more rapidly at higher altitudes
- Pressure gradient in geostrophic balance with a west wind

Two potential problems with this solution:

1. Not enough angular momentum available for required west-east wind

2. Equilibrium solution may be unstable

Angular momentum per unit mass:

$$M = a\cos\theta\left(\Omega a\cos\theta + u\right)$$

$$a = radius\ of\ earth$$

$$\theta = latitude$$

$$\Omega = angular\ velocity\ of\ earth$$

$$u = west-east\ wind\ speed$$

Moist adiabatic atmosphere:

$$s^* = constant$$

$$\alpha = \alpha\left(s^*, p\right)$$

$$\rightarrow \left(\frac{\partial \alpha}{\partial y}\right)_p = \left(\frac{\partial \alpha}{\partial s^*}\right)_p \frac{\partial s^*}{\partial y}$$

$$Maxwell: \quad \left(\frac{\partial \alpha}{\partial s^*}\right)_p = \left(\frac{\partial T}{\partial p}\right)_{s^*}$$

$$\rightarrow f \frac{\partial u}{\partial p} = \left(\frac{\partial T}{\partial p}\right)_{s^*} \frac{\partial s^*}{\partial y}$$

Integrate from surface to tropopause, taking u=0 at surface:

$$fu_T = -\left(T_s - T_T\right)\frac{\partial s^*}{\partial y} = -\left(T_s - T_T\right)\frac{\partial s_b}{\partial y}$$

$$\boxed{u_T = -\frac{\left(T_s - T_T\right)}{2\Omega \sin\theta}\frac{\partial s_b}{\partial y}}$$

Implies strongest west-east winds where entropy gradient is strongest, weighted toward equator

Angular momentum per unit mass:

$$M = a\cos\theta\left(\Omega a\cos\theta + u\right)$$

At tropopause:

$$M_T = a\cos\theta\left(\Omega a\cos\theta + u_T\right)$$

$$= a\cos\theta\left(\Omega a\cos\theta - \frac{\left(T_s - T_T\right)}{2\Omega a\sin\theta}\frac{\partial s_b}{\partial\theta}\right)$$

Maximum possible value of M is its resting value at equator:

$$M_{\max} = \Omega a^2$$

We require that $M \le M_{\max}$:

$$-\frac{\partial s_b}{\partial \theta} < \frac{2\Omega^2 a^2}{T_s - T_T} \sin^2\theta \tan\theta$$

Violated in much of Tropics

What happens if there is not enough angular momentum at the equator to provide the zonal wind speeds needed to achieve thermal wind balance?

Thermal Wind Balance

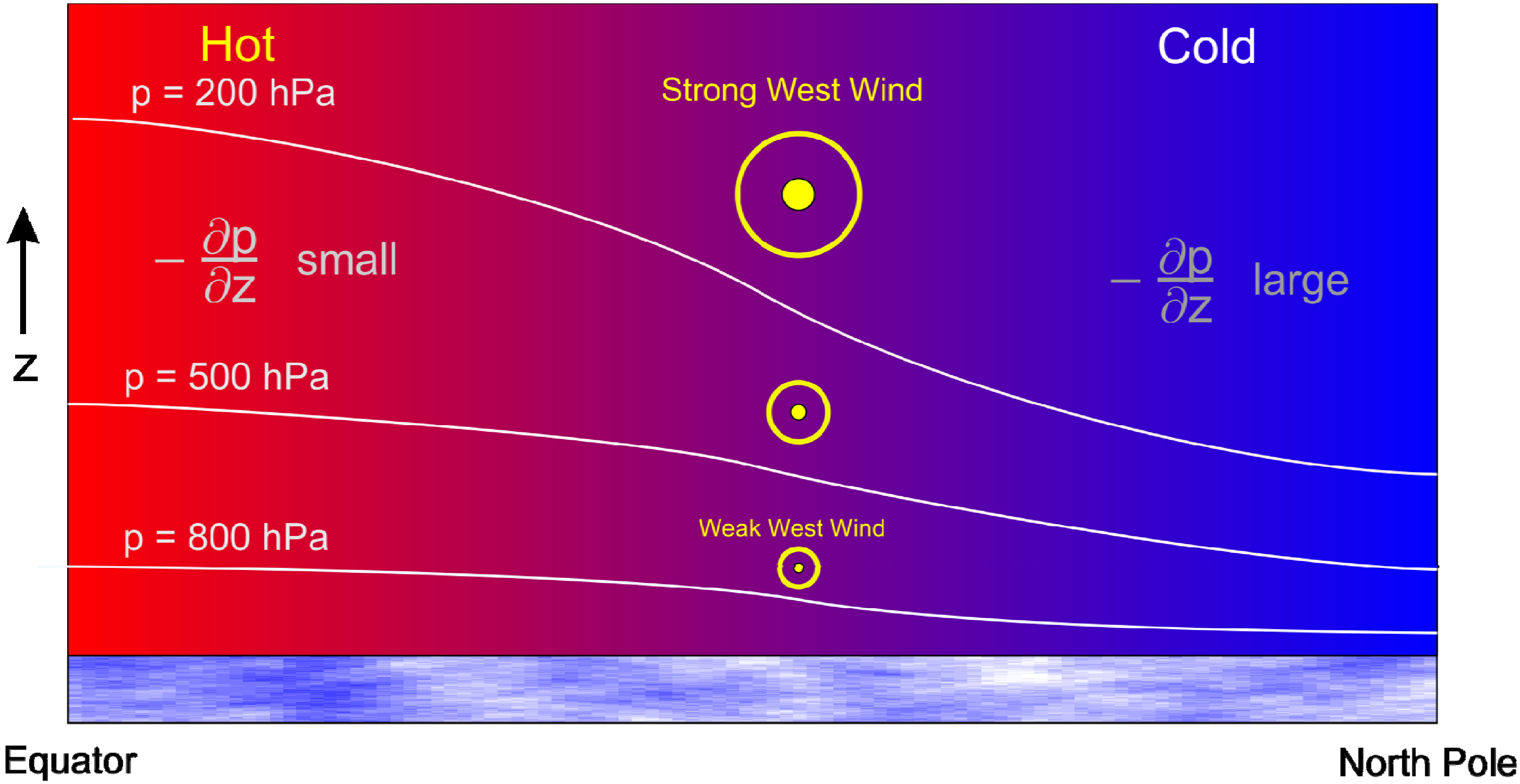


Image credit: *Kerry Emanuel*

Overturning Circulation Develops that Drives Temperature Gradient Back Towards a ***Critical Value*** such that there is Just Enough Angular Momentum to Provide Thermal Wind Balance:

Hot air rising, cold air sinking, with weaker westerlies, smaller T gradient

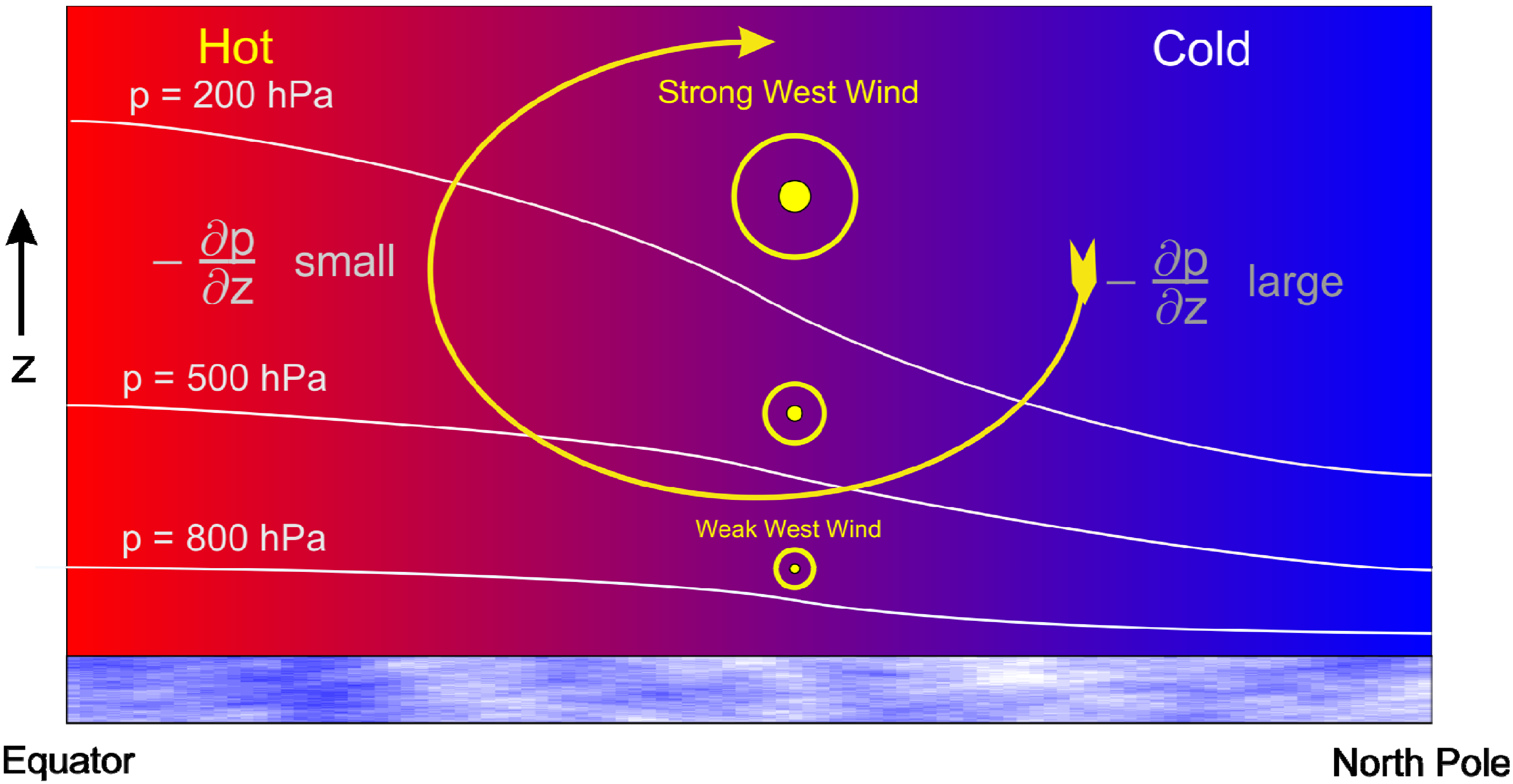


Image credit: *Kerry Emanuel*

December - February

Vertical (pressure) Velocity 10^{-3} Pa s^{-1}

June-August

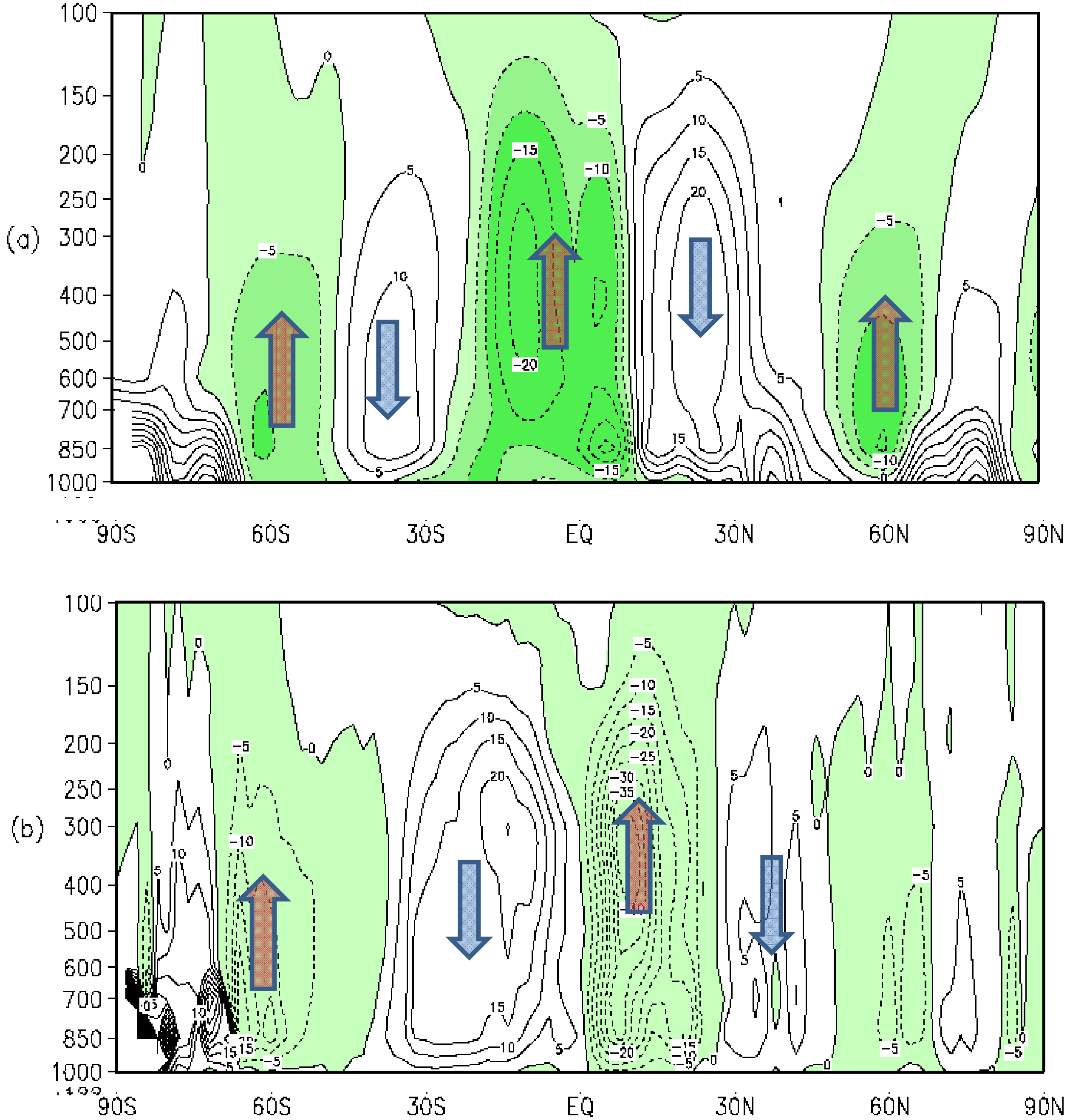


Image credit: *NOAA*

July Average Pressure Velocity at 500 hPa

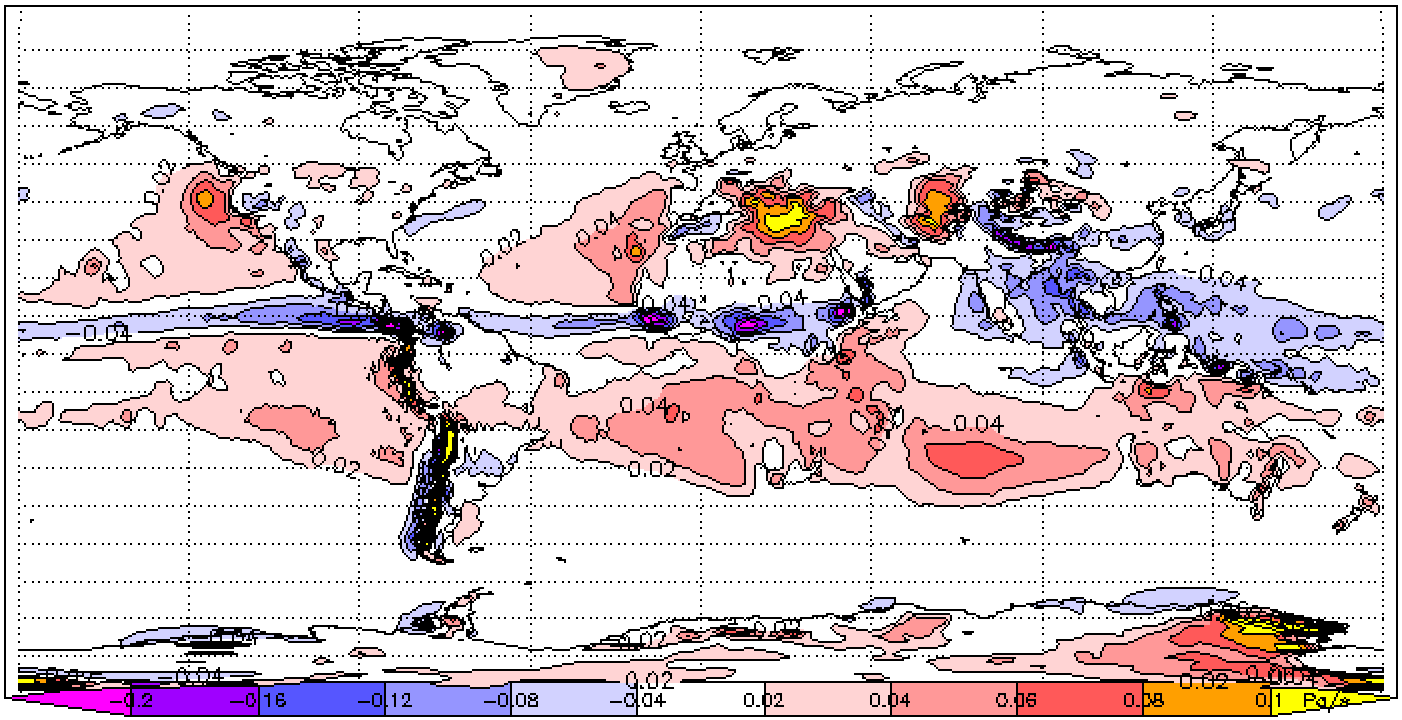
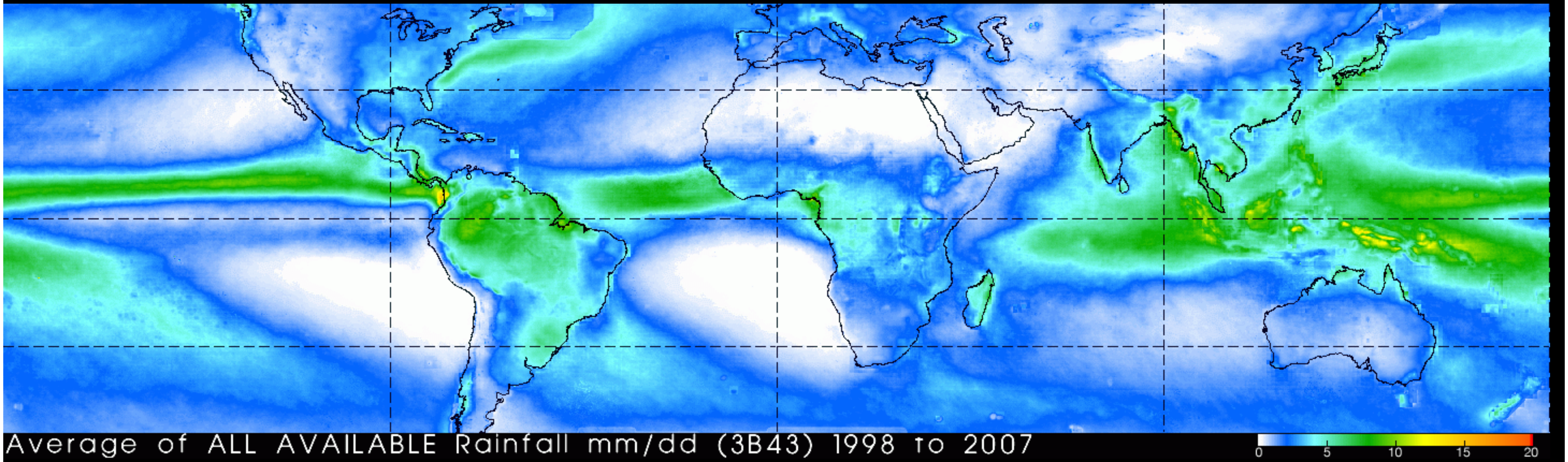


Image credit: *William M. Connolley*

Tropical Precipitation Climatology



Rainfall (mm/day) as measured from satellite, averaged over 1998-2007

Image Credit: NOAA/NSF/U. of Wisconsin CIMMS/SSEC

Other Large-Scale Tropical Circulations:

- The Walker Cell

The Walker Circulation

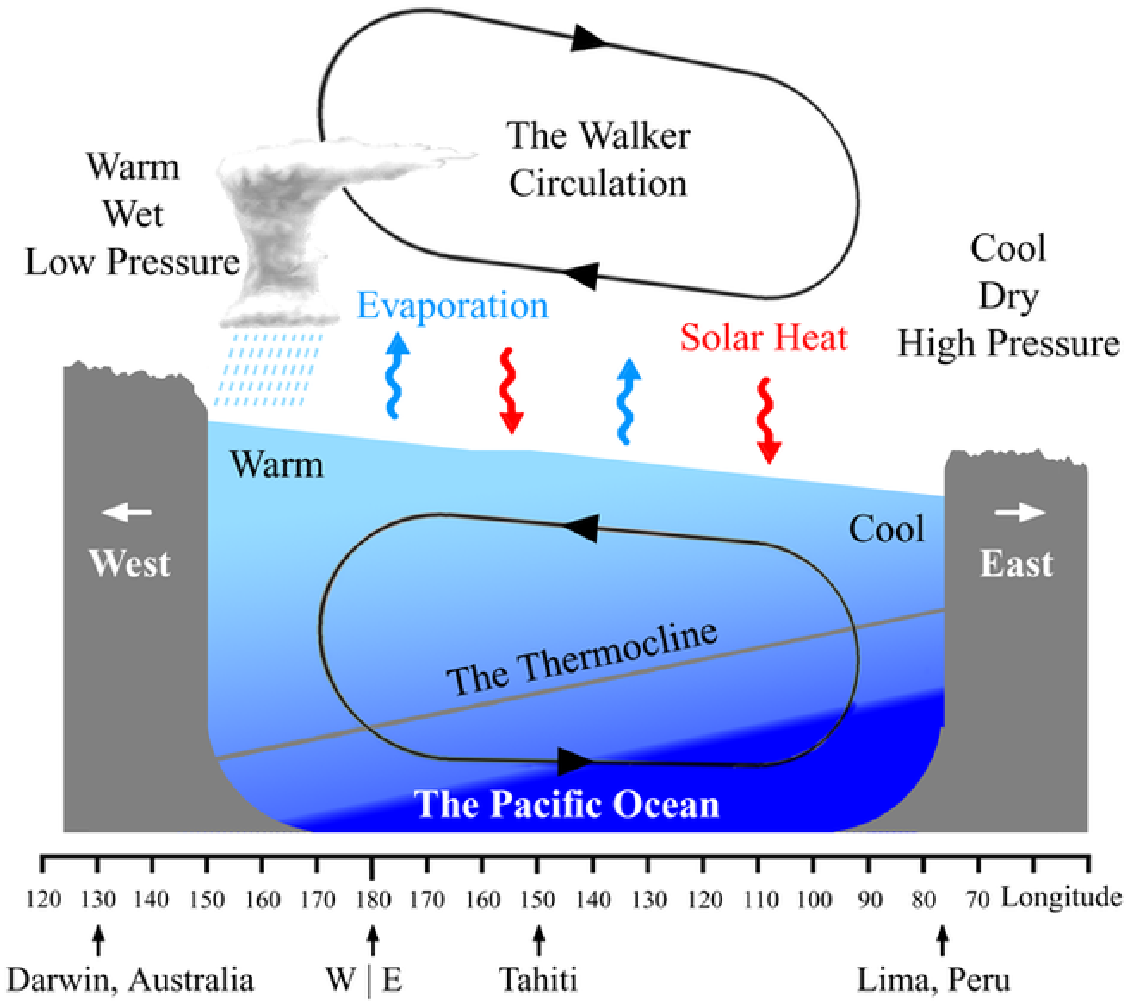
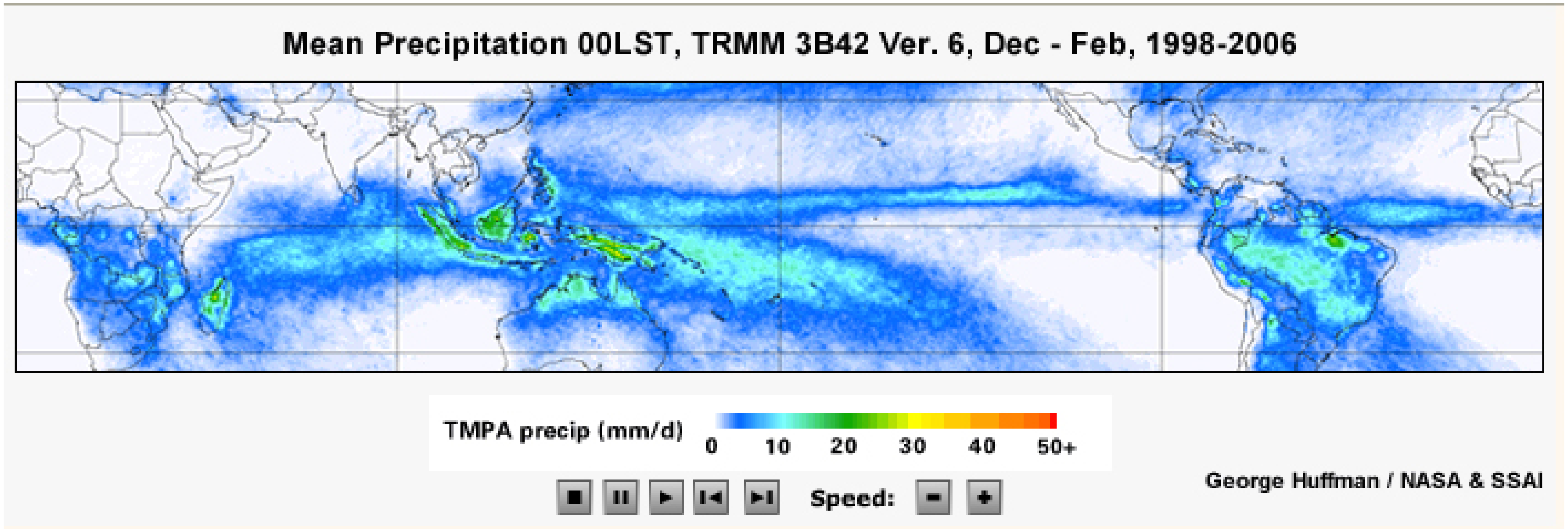


Image credit: *PAR, Wikipedia*

Other Large-Scale Tropical Circulations:

- The Walker Cell
- Monsoons

Satellite-Derived Precipitation for Dec-Feb (top), and Jun-Aug (bottom) 1998-2006



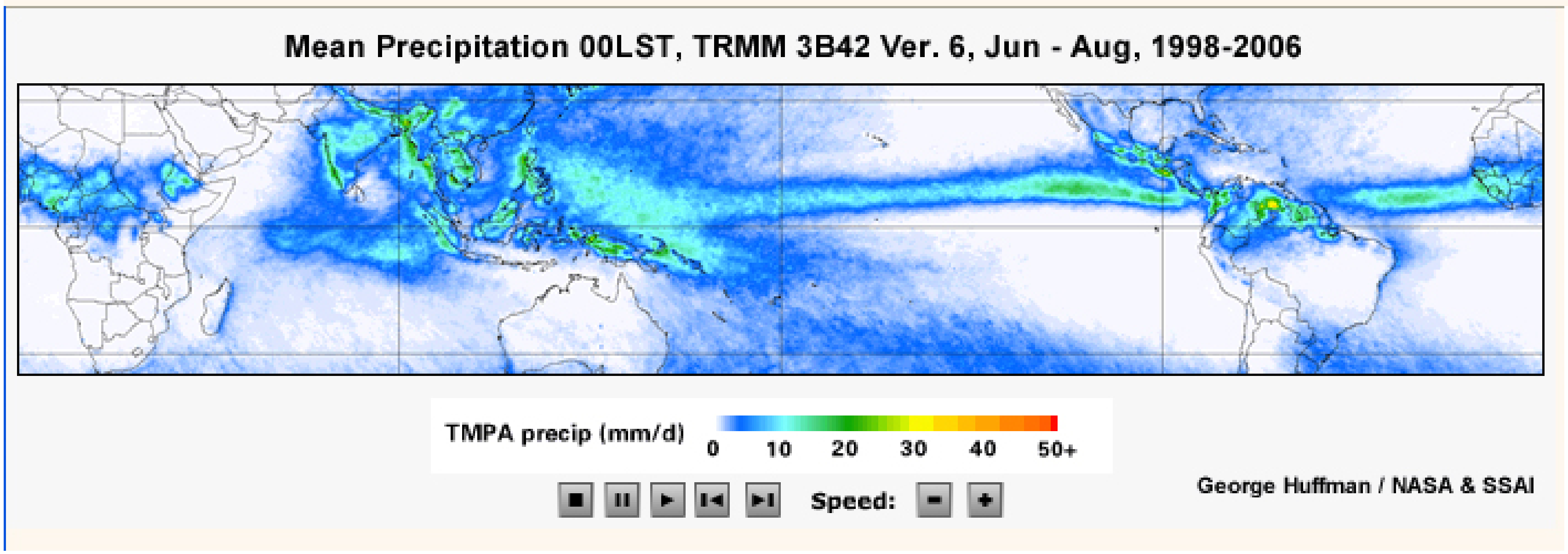


Image credit: *George Huffman/NASA*

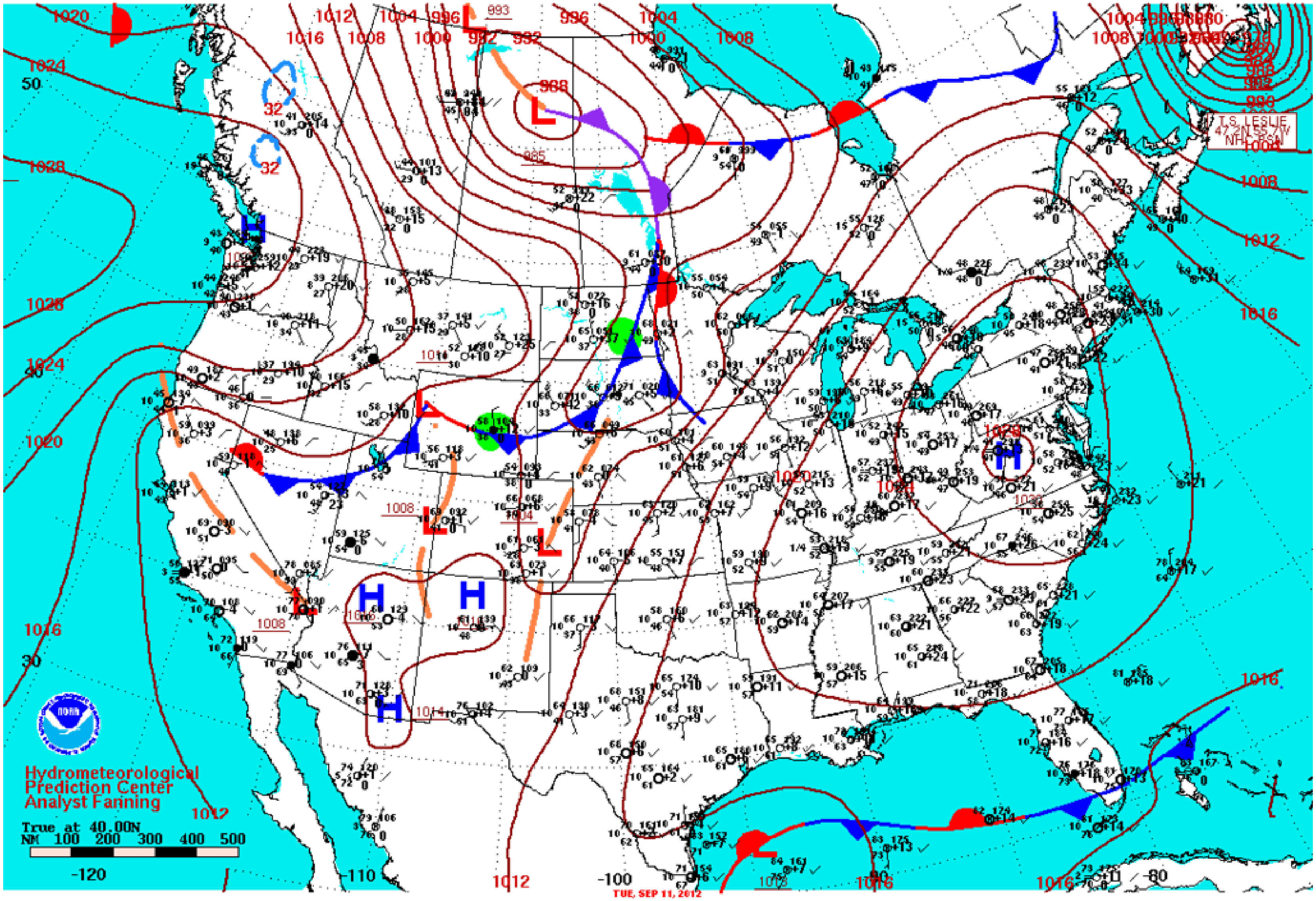
What causes atmospheric circulation?

Much non-convective atmospheric motion can be grouped into two categories:

1. Large-scale, quasi-steady overturning motion in the Tropics

2. **Eddies with horizontal dimensions of ~ 3000 km in middle and high latitudes**

Surface Weather Map for September 11th 2012



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Image credit: *NOAA/National Centers for Environmental Prediction*

Temperature at the Tropopause, Northern Hemisphere, November 24th 2013

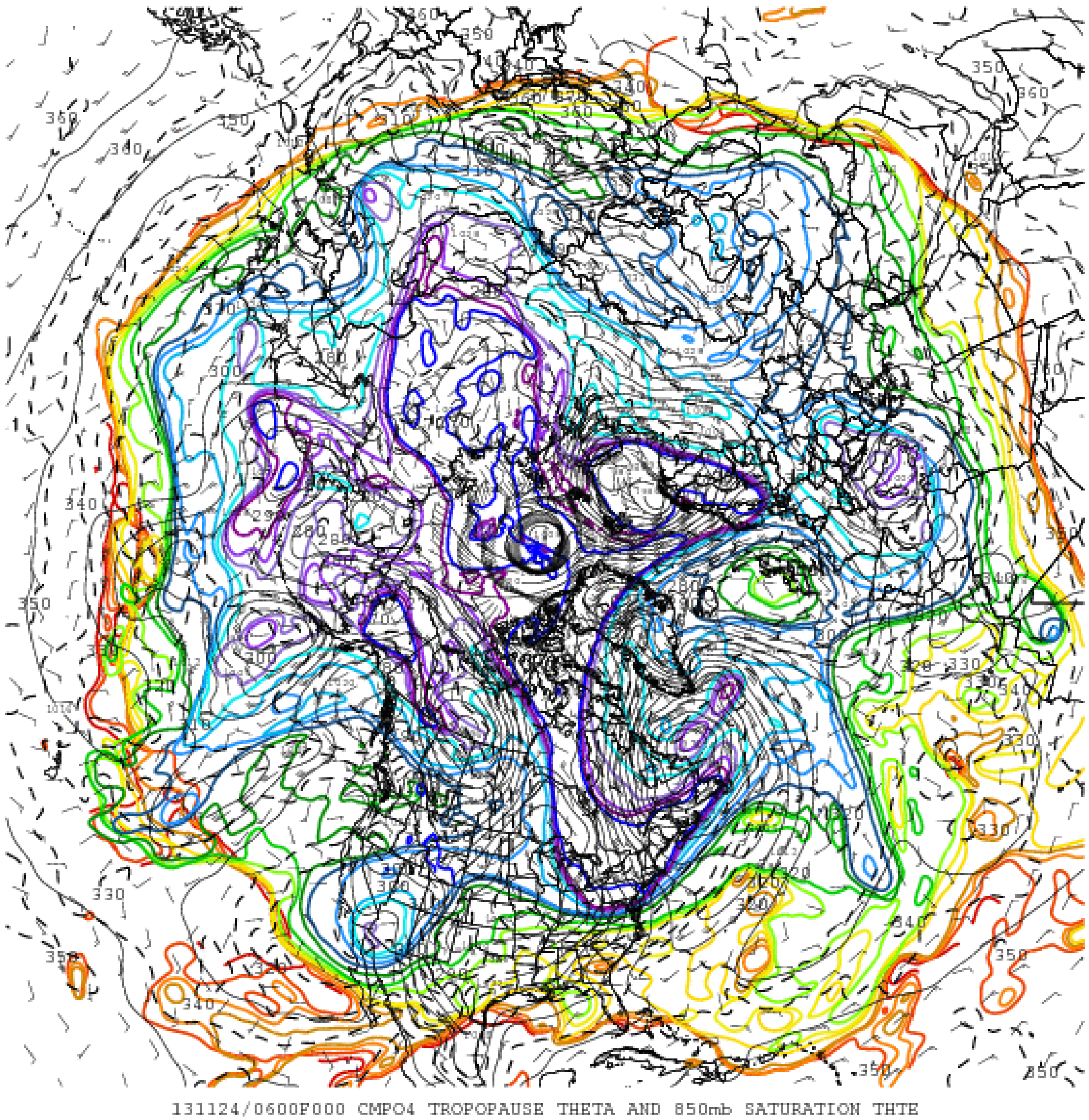


Image credit: *PAOC/MIT*

Play movie for today's weather at

http://wind.mit.edu/~reanal/pv.html

Northern hemisphere temperature animation

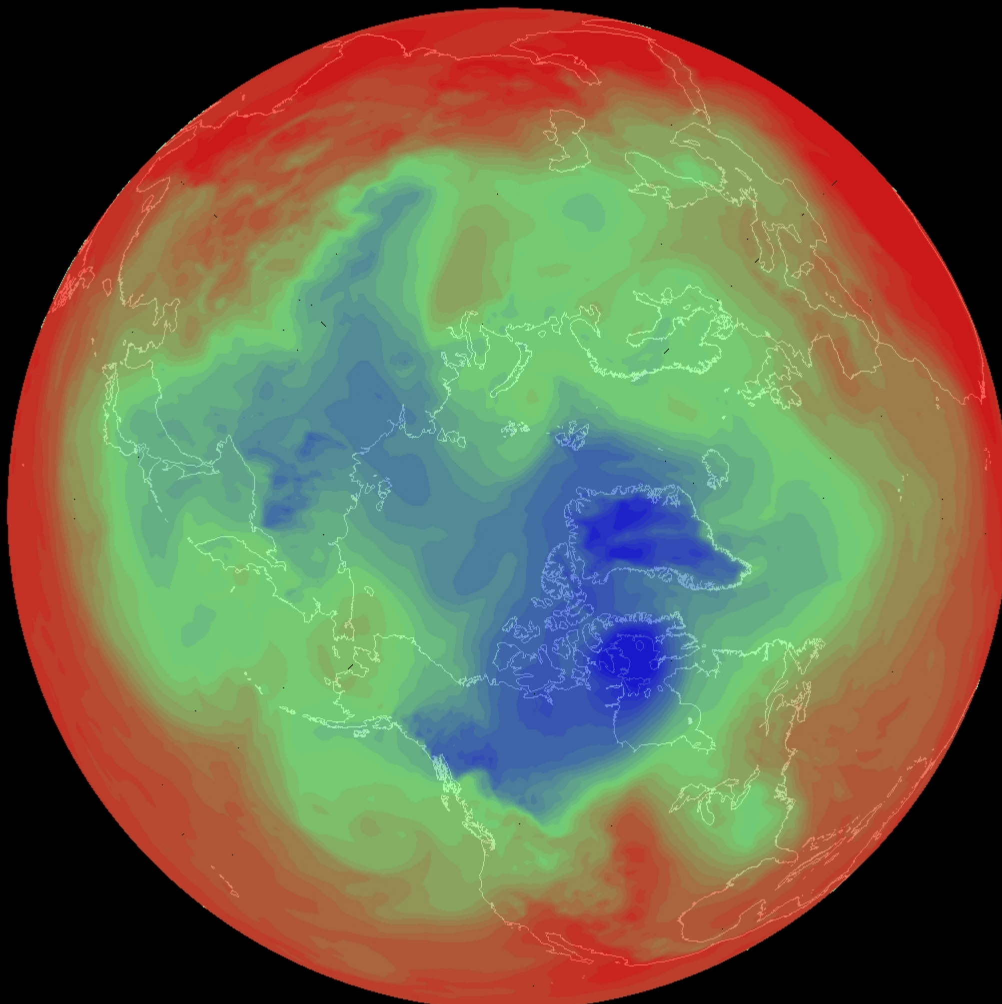


Image credit: *PAOC/MIT*

Eddies:
Thermal Wind Solution is ***Unstable*** in Middle and High Latitudes

Concept of Stability and Instability:

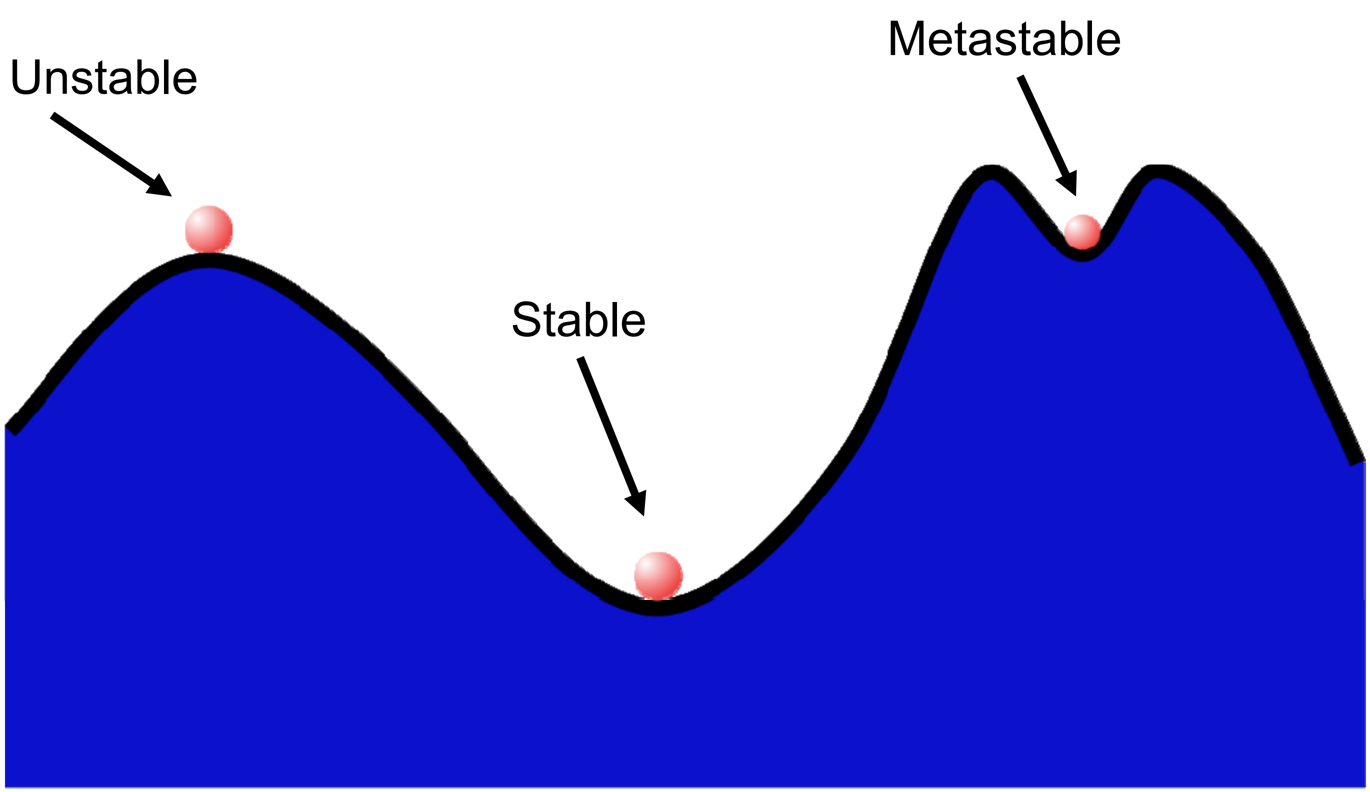


Image credit: *Kerry Emanuel*

Baroclinic Instability

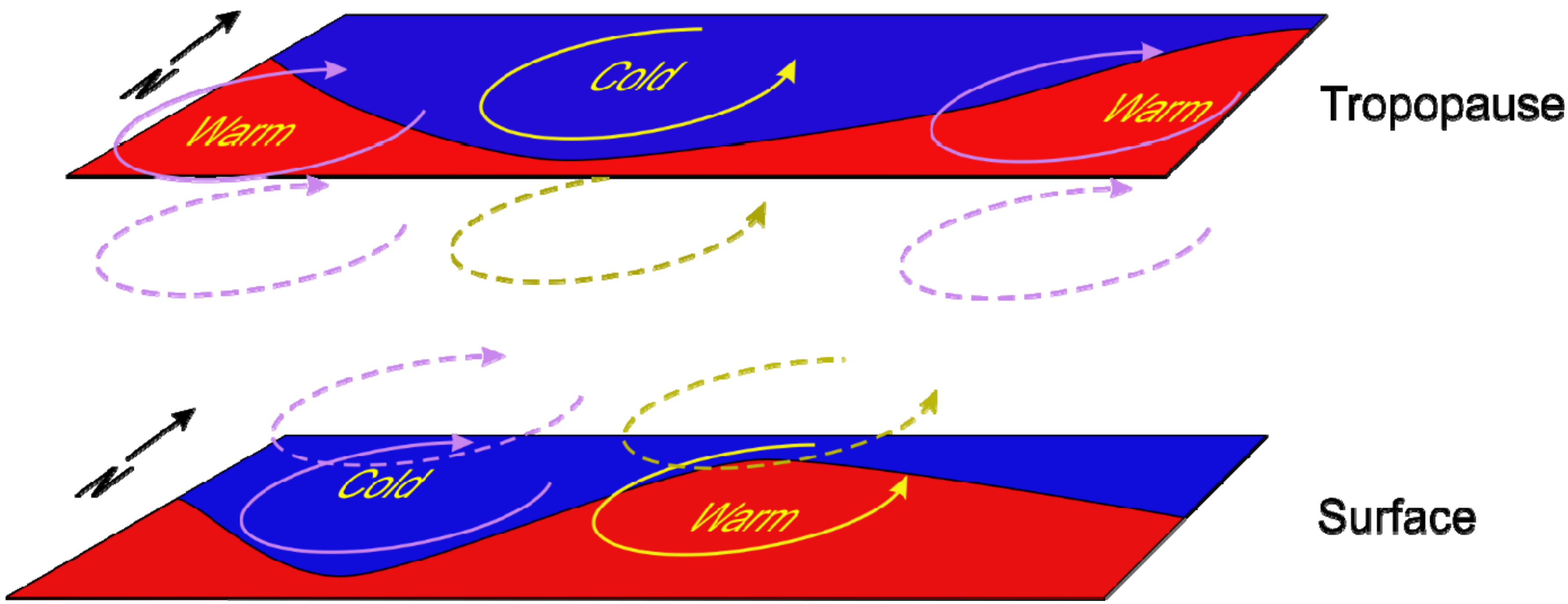
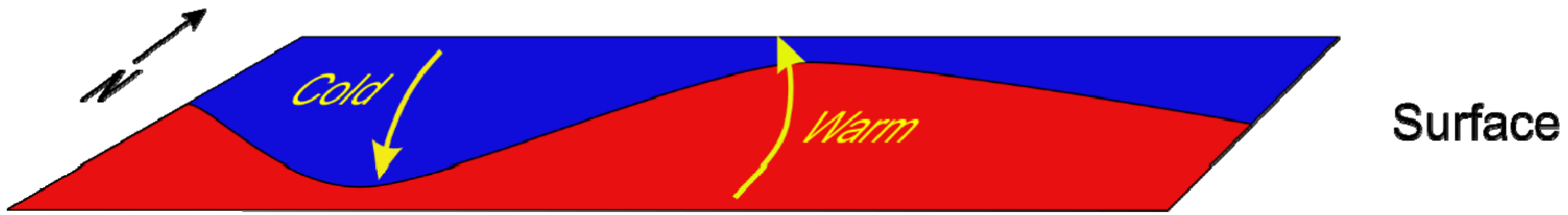


Image credit: *Kerry Emanuel*

Baroclinic cyclone off the eastern U.S.

Image credit: *NOAA*

Concept of eddy fluxes:



Warm, moist air moves poleward; cold, dry air moves equatorward

Image credit: *Kerry Emanuel*

Formulation of eddy fluxes:

$$\nabla \bullet \overline{\rho \mathbf{V} E} + F_{rad_{TOA}} - \left(F_{rad} + F_{conv}\right)_{surface} = 0$$

$$\rho \mathbf{V} = \{\rho \mathbf{V}\} + \rho \mathbf{V}',$$

$$E = \{E\} + E',$$

$$where \ \ \{X\} \equiv \frac{1}{2\pi}\int_0^{2\pi} X d\lambda$$

$$\rightarrow \nabla \bullet \left[\overline{\{\rho \mathbf{V}' E'\}} + \overline{\{\rho \mathbf{V}\}\{E\}}\right] + F_{rad_{TOA}} - \left(F_{rad} + F_{conv}\right)_{surface} = 0$$

Annual Mean Eddy Heat Flux from a Climate Model

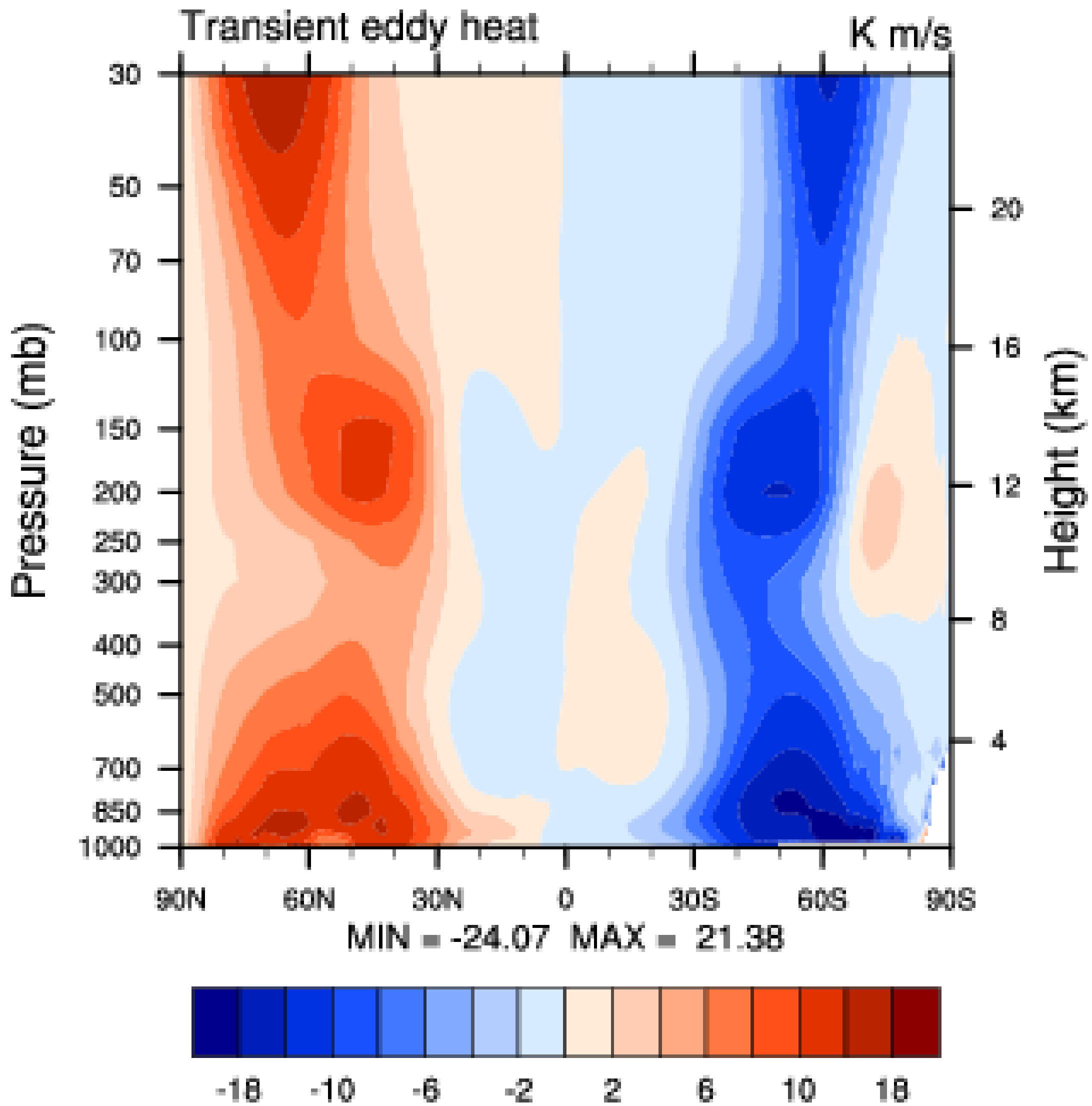
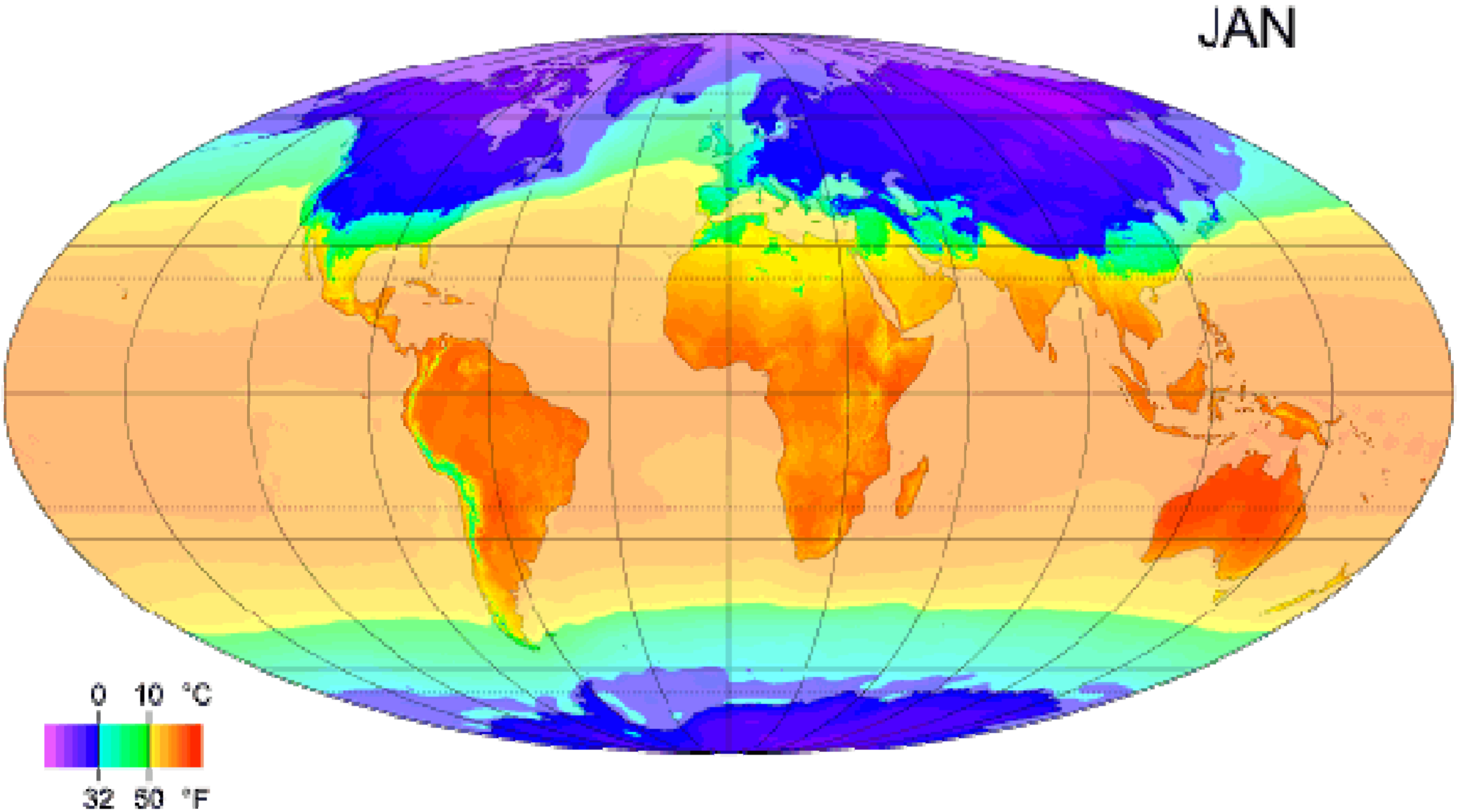


Image credit: *NSF/University Corporation for Atmospheric Research*

Eddy heat fluxes are not efficient enough to prevent temperature gradients from developing


JAN
0
10
°C
32
50
°F

Issues

- Temperature gradient controlled by eddies of horizontal dimensions ~ 3000 km
- Familiar highs and lows on weather maps
- Eddy physics not simple
- Concept of criticality does not apply...critical T gradient = 0 (not observed)
- While eddies try to wipe out T gradient, they do not succeed

Global Warming Effects on Atmospheric Circulation

- Hadley circulation seems to weaken but expands poleward

- Temperature gradient decreases at surface but increases at tropopause; former would decrease eddy strength while latter would increase it