The Present Day Climate and how it is Driven and Maintained?

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Lecture-1

Observed 3-D structure of Present day Mean Climate

(Mean structure of Circulation + statistics of transients)

Background and Philosophy Behind the Lectures

Introductory :

- Meant for uninitiated in Climate Science
- Focus on Phenomenology rather than GFD
- My apologies to all the senior Physicists and Climate scientists that are joining the Course.

Theme : "Complexities' in Climate Science and Indian Monsoon

Acknowledgements:

Based on work with and what I learned from my colleagues and students at the IISC, Bangalore, IITM, Pune and Cotton University, Guwahati. Thanks to SERB, Government of India for a Fellowship and support.

CLIMATE…

IS WHAT YOU EXPECT,

WEATHER …

IS WHAT YOU GET.

Or,

WEATHER IS WHAT WE EXPERIENCE OVER THE COURSE OF HOURS, DAYS, AND WEEKS.

CLIMATE IS THE AVERAGE OF WEATHER OVER YEARS, DECADES, AND LONGER.

How do we characterize the atmosphere?

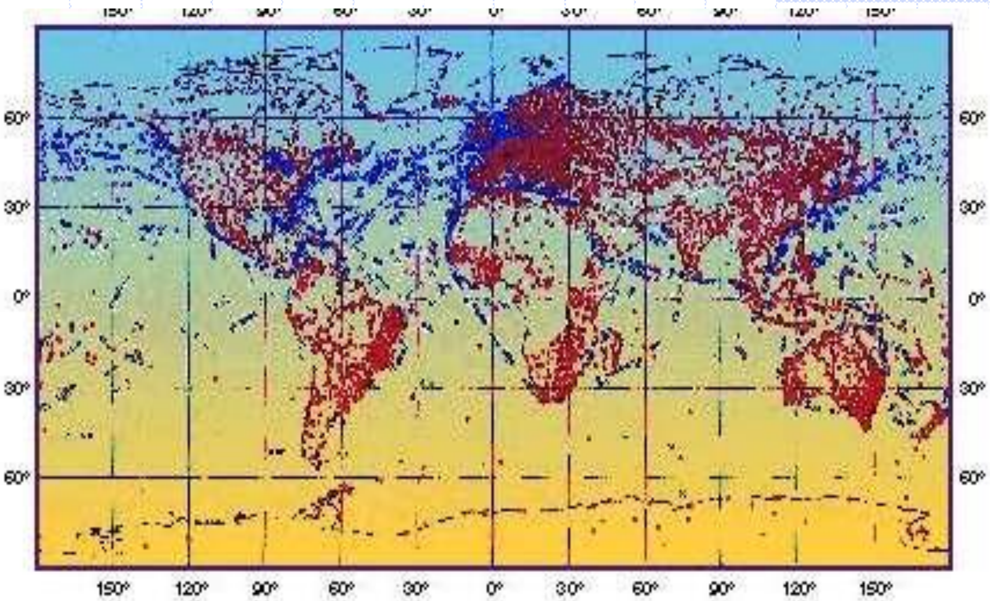
Winds Temperature Humidity Rainfall Pressure

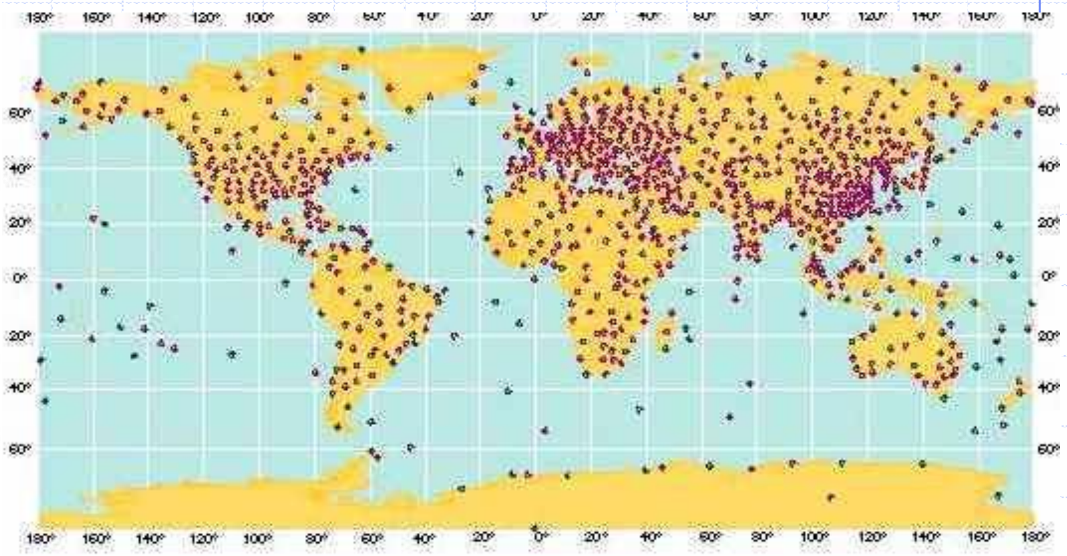
How do we observe the atmosphere?

Conventional observing network

- Upper Air observations with Radiosonde
  - **Backbone of monitoring 3-D structure of Atmosphere even today.**

- Surface Observations
- Wind speed, direction
- Temp. humidity, pressure
- **AWS, Raingauge**





Surface observations

The backbone of the surface-based sub-system continues to be about 11,000 stations on land making observations at or near the Earth's surface, at least every three hours and often hourly, of meteorological parameters such as atmospheric pressure, wind speed and direction, air temperature and relative humidity.

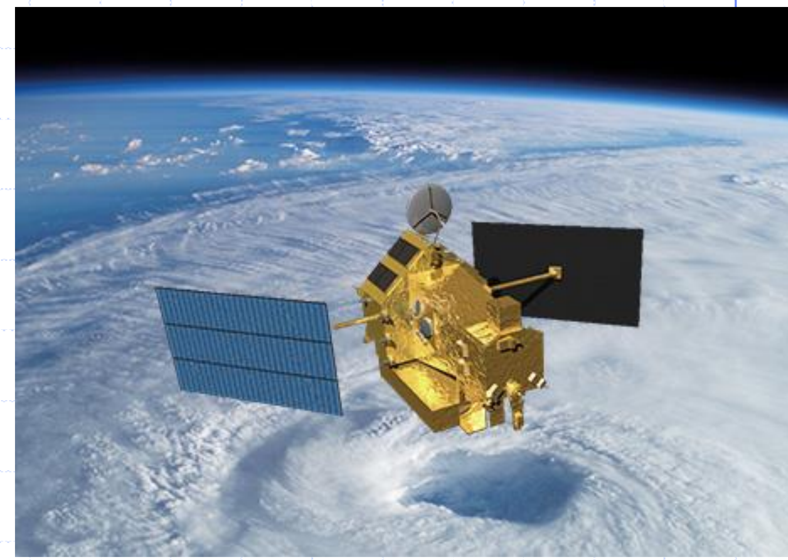
Upper Air Observations:

From a network of roughly 900 upper-air stations, radiosondes, attached to free-rising balloons, make measurements of pressure, wind velocity, temperature and humidity from just above ground to heights of up to 30km. Over two thirds of the stations make observations at 0000UTC and 1200UTC. Between 100 and 200 stations make observations once per day, while about 100 have "temporarily" suspended operations. In ocean areas, radiosonde observations are taken by 15 ships, which mainly ply the North Atlantic, fitted with automated shipboard upper-air sounding facilities.

How do we observe the atmosphere?

➢ Space based platforms : remotely sensed

TRMM-satellite



GOES-8, an USA Weather satellite

Sensors could be

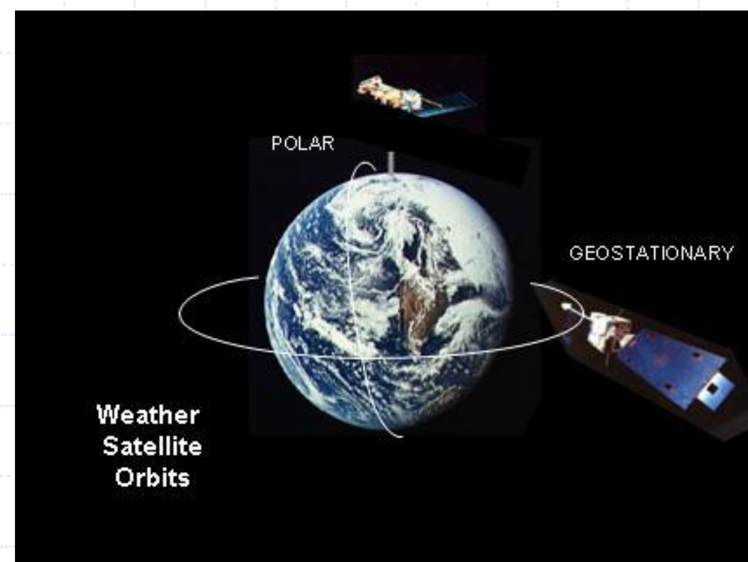
- Passive
- active

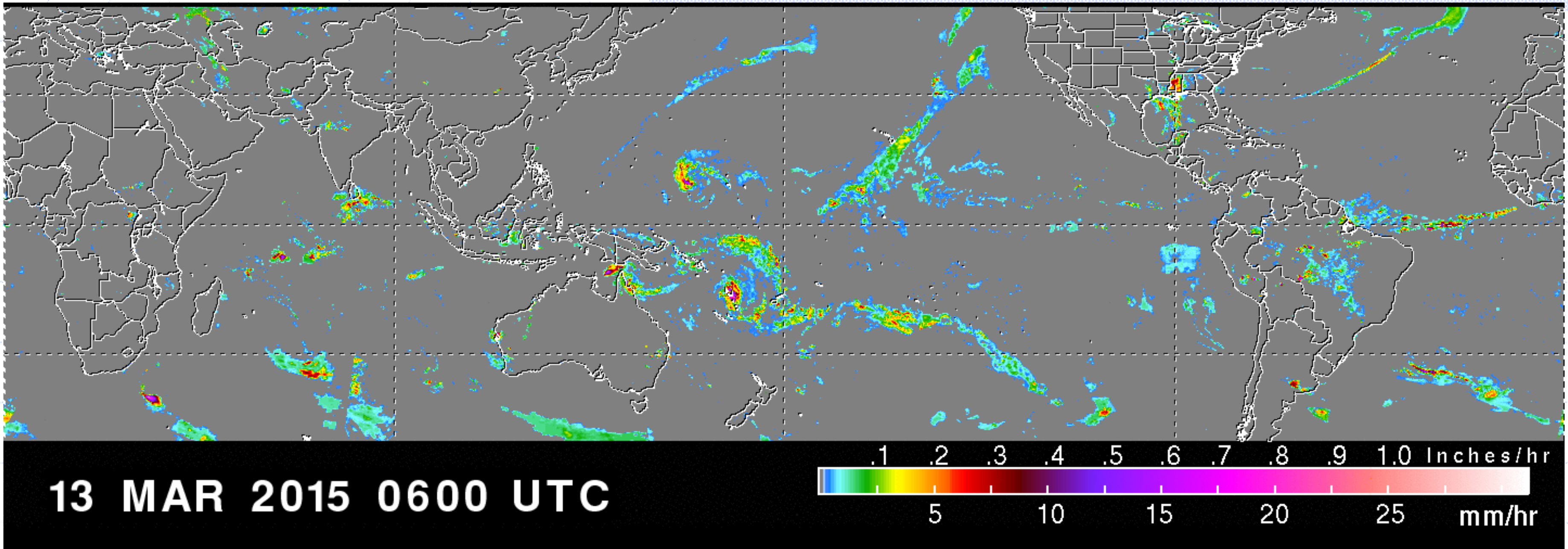
Sensors are based on

- Visible spectrum of radiation
- Infrared spectrum and
- Microwave spectrum

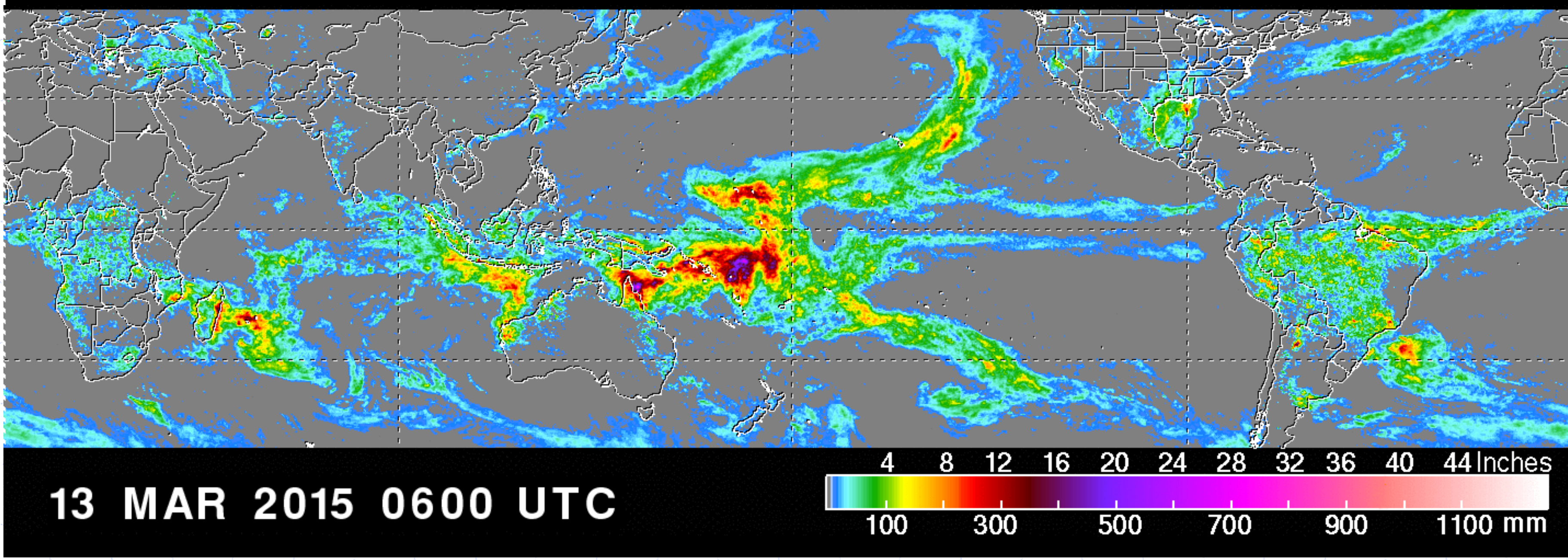
The satellite platform :

- Geostationary
- Polar orbiting





3-hourly



Monthly accumulated

Some recent observations of precipitation from TRMM

Observed mean structure of the Atmosphere

- Observed vertical and horizontal structure of the atmosphere.
- Temperature, winds and humidity fields.
- What maintains this distribution?
- Solar radiation and earth's radiation and radiation balance.
- Simple estimate of global mean surface temperature.
- Greenhouse effect and examples of surface temperature of some other planets and their radiative equilibrium.

Why 'Mean' ? What 'Mean' ?

- The atmosphere variables fluctuates in a wide range of time scales
- In this lecture, we do not address the variation but concentrate on 'time mean' state of the atmosphere
- However, there are clear differences between ***summer*** and ***winter***. Therefore time mean will refer to seasonal mean. We shall show summer and winter separately

The atmosphere has a 3-dimensional structure

- There are east-west variations, north-south variations and variations in the vertical

SOME NOMENCLATURE

$x \longrightarrow +ve$ eastward

$y \longrightarrow +ve$ northward

$z \longrightarrow +ve$ upward

Winds:

x - component : $u \longrightarrow$ often called **Zonal Winds**

y - component : $v \longrightarrow$ often called **Meridional Winds**

z - component : $w \longrightarrow$ **Vertical Velocity**

$u \longrightarrow +ve$: west to east winds are also called **WESTERLY**

$u \longrightarrow -ve$: east to west wind are also called **EASTERLY**

$v \longrightarrow +ve$ northward $\longrightarrow$ **SOUTHERLY**

$v \longrightarrow -ve$ southward $\longrightarrow$ **NORTHERLY**

DEFINITIONS

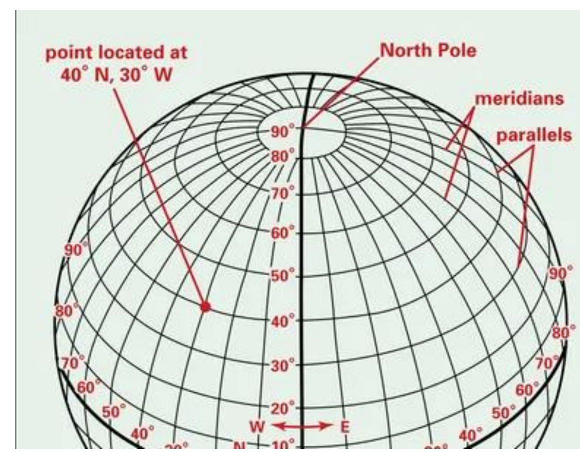
$\bar{A} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} A dt \longrightarrow$ time mean of A

$A' = A - \bar{A} \longrightarrow$ deperture from the time mean or the transient eddies.

By definition $\overline{A'} = 0$

$[A] = \frac{1}{2\pi} \int_0^{2\pi} A d\lambda \longrightarrow$ Zonal mean of A

$A^* = A - [A] \longrightarrow$ deperture from the Zonal mean or the stationary eddies.



By definition $[A^*] = 0$

However $\overline{A^*}$ = Time mean of the Zonal deviation $\neq$ 0.

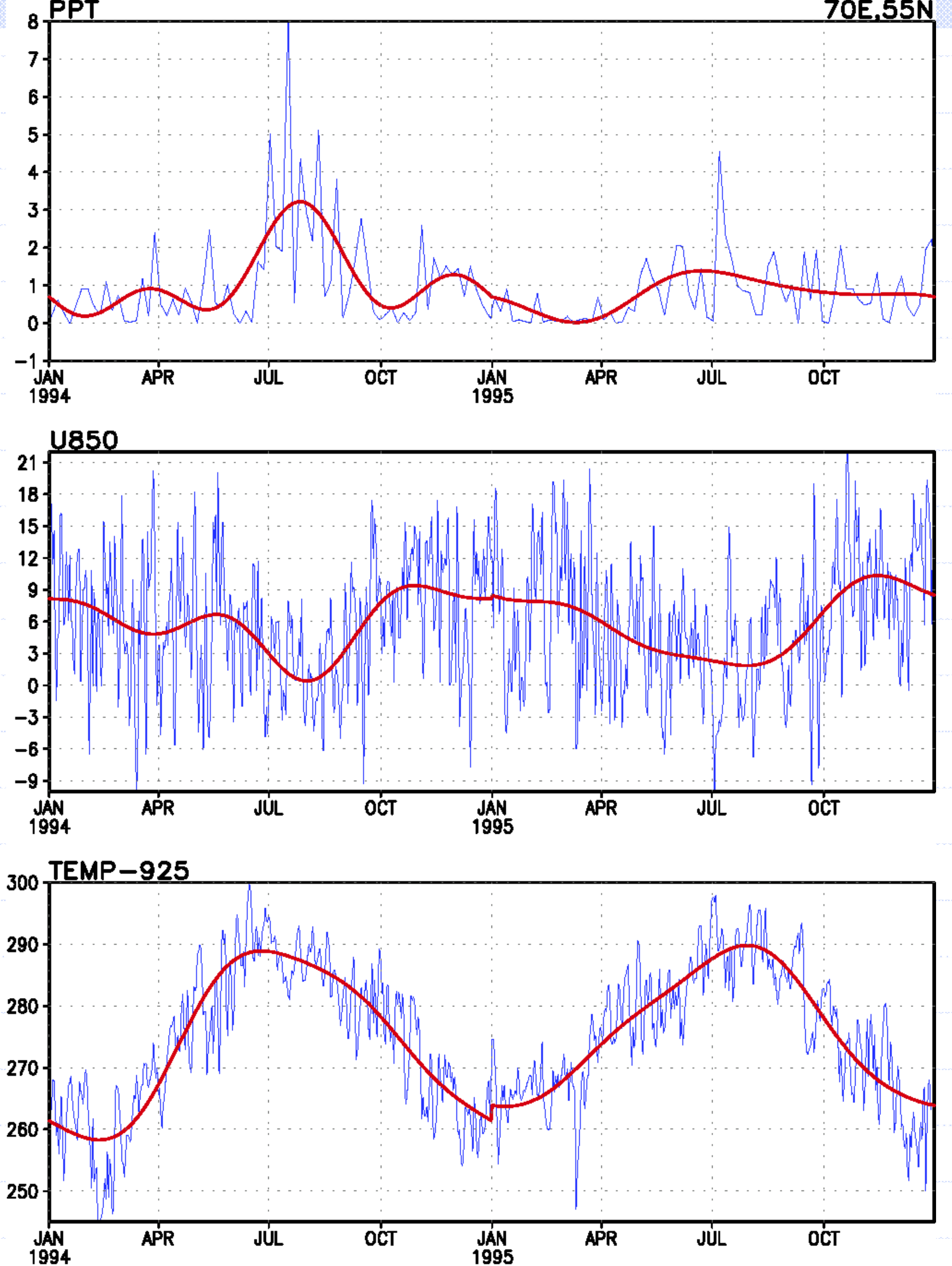
$[\overline{V'A'}] \Rightarrow$ Meridional transport of A resulting from transient eddies.

$[\overline{V^*}\ \overline{A^*}] \Rightarrow$ Meridional transport of A resulting from the stationary eddies.

$[\bar{V}]\ [\bar{A}] \Rightarrow$ Meridional transport of A resulting from mean meridional circulation.

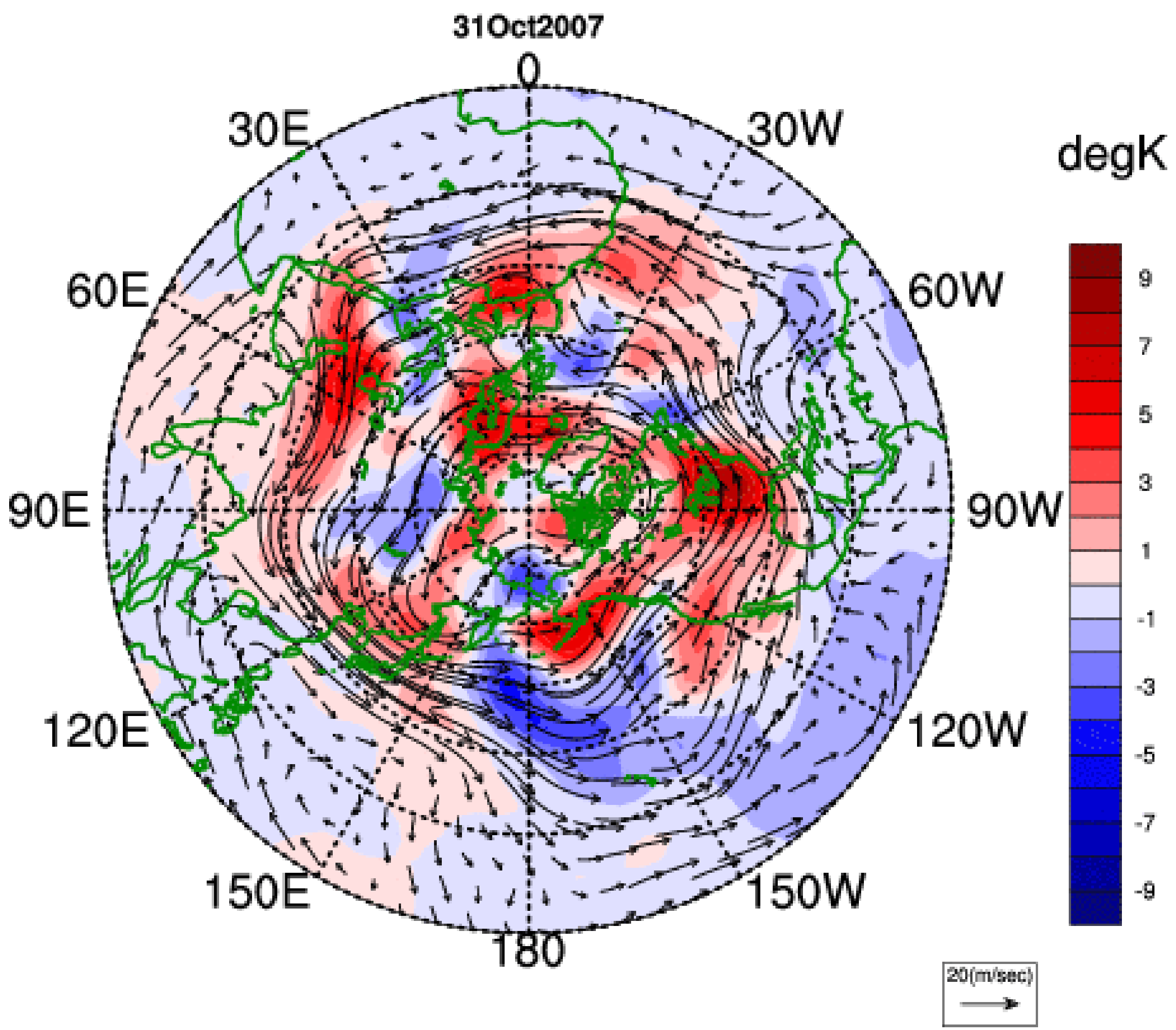
Another example of weather and climate

Daily time series of precipitation (PPT), eastward component of wind at 850 hPa level (U850) and temperature near the surface at 925 hPa at a high latitude station (70E,55N). The red line is the annual cycle or expected values.



Total Wind vectors and temperature anomalies (shading) at 200 hPa for 2007, Nov-Feb (everyday)

(The Rossby Waves that produces Extratropical Weather)



Two important tenets of Weather

It became clear early on that the weather disturbances with 3-5 day time scale were the most energetic events after the Annual Cycle.

Weather

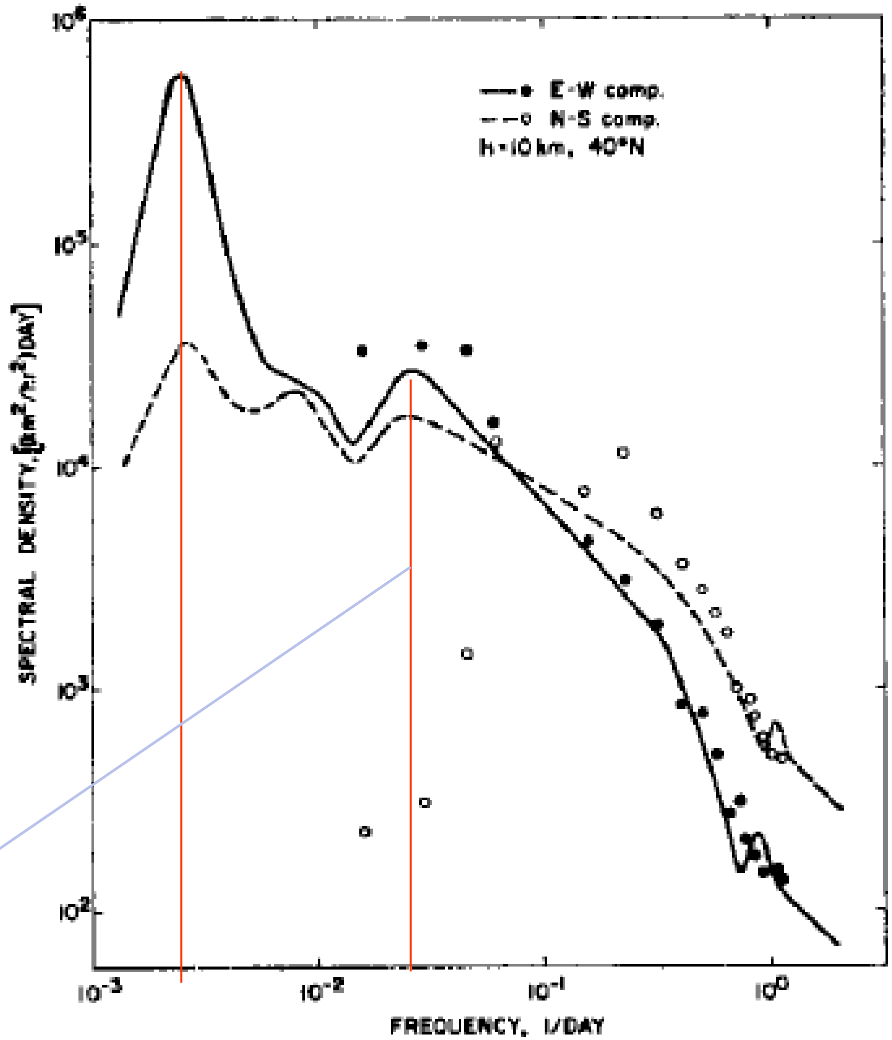
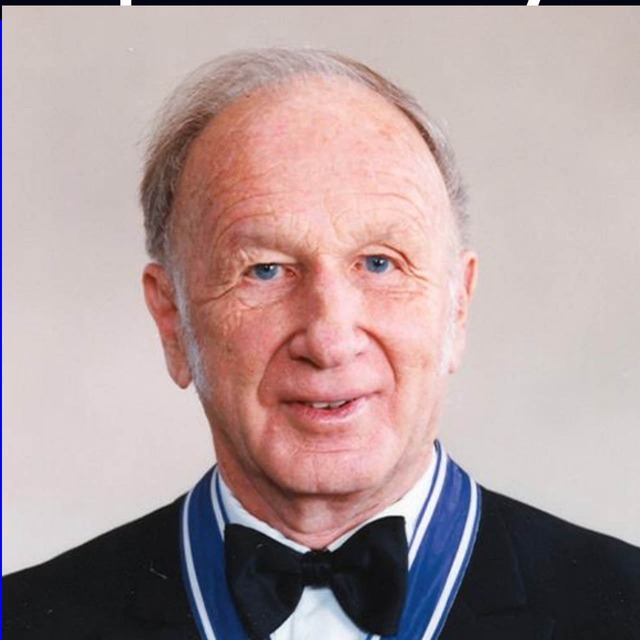


Fig. 1. Spectral density of E–W (solid line) and N–S (dashed line) wind components at 10 km altitude over Washington, D.C. station. Solid and open circles represent a replot of Figure 2 data (see text).

Vennichenko, N. K., 1970: Tellus, 22, 158-

It also became clear that the Weather is Chaotic and could not be predicted beyond a couple of weeks…



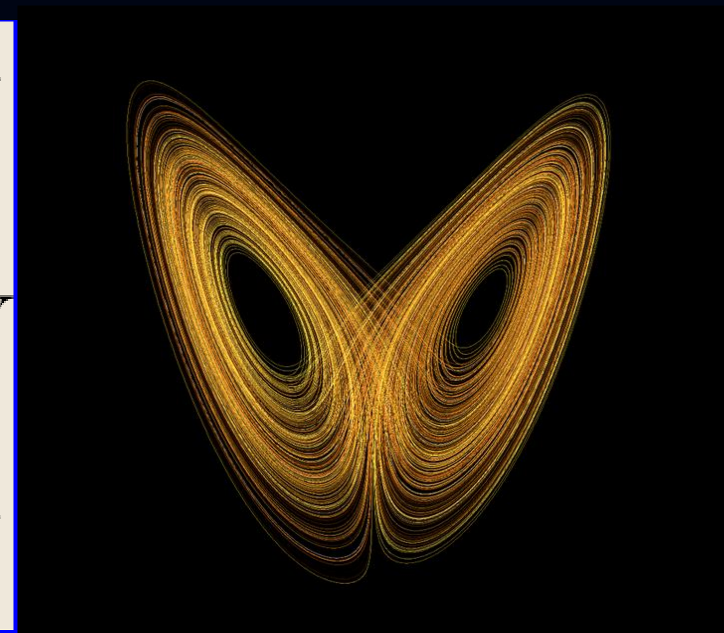
E. N Lorenz, 1917-2008

$$\frac{dX}{d\tau} = -\sigma X + \sigma Y$$

$$\frac{dY}{d\tau} = -XZ + rX - Y$$

$$\frac{dZ}{d\tau} = XY - bZ$$

Lorenz Equations



& Butterfly Effect??

One of the most influential paper in weather and climate science (cited over 24000 times!)

➔ Sensitivity to initial conditions and limit on predictability.

130 JOURNAL OF THE ATMOSPHERIC SCIENCES VOLUME 20

Deterministic Nonperiodic Flow[1]

EDWARD N. LORENZ

Massachusetts Institute of Technology

(Manuscript received 18 November 1962, in revised form 7 January 1963)

ABSTRACT

Finite systems of deterministic ordinary nonlinear differential equations may be designed to represent forced dissipative hydrodynamic flow. Solutions of these equations can be identified with trajectories in phase space. For those systems with bounded solutions, it is found that nonperiodic solutions are ordinarily unstable with respect to small modifications, so that slightly differing initial states can evolve into considerably different states. Systems with bounded solutions are shown to possess bounded numerical solutions.

A simple system representing cellular convection is solved numerically. All of the solutions are found to be unstable, and almost all of them are nonperiodic.

The feasibility of very-long-range weather prediction is examined in the light of these results.

Complexity in Climate Science

Interconnectedness between Chaotic Weather and Annually Fluctuating Climate

First, let us get an idea of the ***time mean*** climate during northern summer (JJA) and winter (

Figures shown here of the 3-D structure of the atmosphere are from **NECP/NCAR Reanalysis** (Kalnay et al. 1996: The NCEP/NCAR Reanalysis Project, BAMS, https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2 Cited > 32000 times, larger than Lorenz's Chaos paper!)

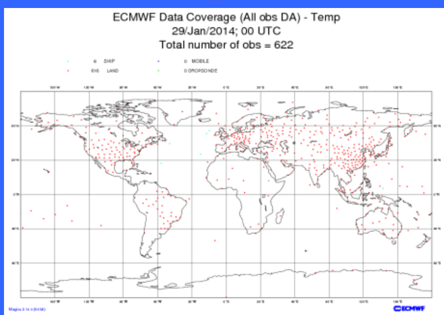
What is a Reanalysis?
To understand Reanalysis, we must understand,

What is an Analysis:
As shown earlier, there are many 'data gap' regions in the actual observations. An analysis is a way to 'interpolate' the observations to fill the data gaps in way 'consistent with dynamical equations governing them'. This is where the 'Operational forecasting model' comes in.

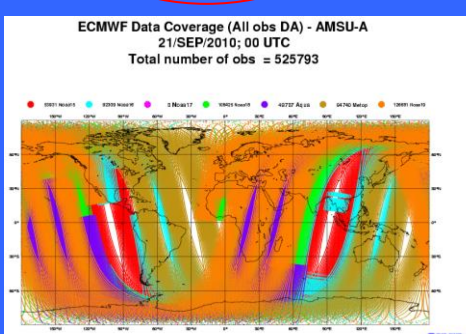
Therefore, **Reanalysis** is:
Analyzed spatially inhomogeneous 'Observations' into a uniform 'grids' using a latest modern day 'weather prediction' model' going backward in time and including all available observations that came in delayed mode even after the 'cut-off' time for operational forecasts.

A Weather Prediction System: Backbone of ‘Analysis’

Initial Conditions:

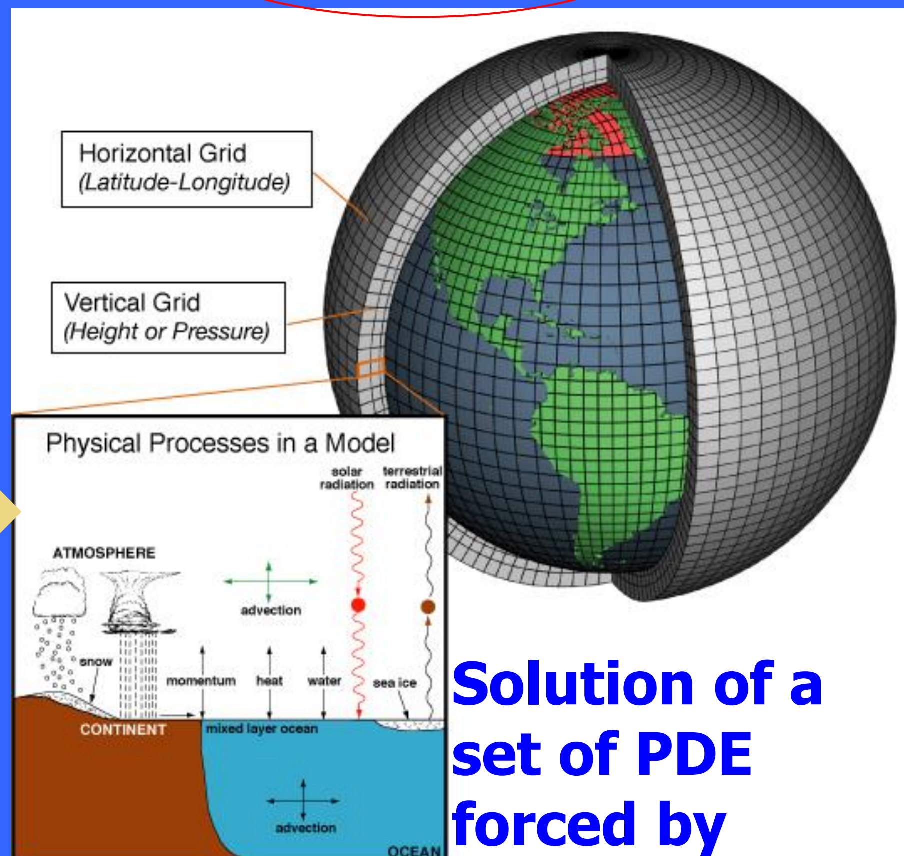


Analysis of conventional and satellite Obs. & Data Assimilation



U V W T Q P etc

Forecast Model



Solution of a set of PDE forced by Heat Balance

Forecasts

Time Marching

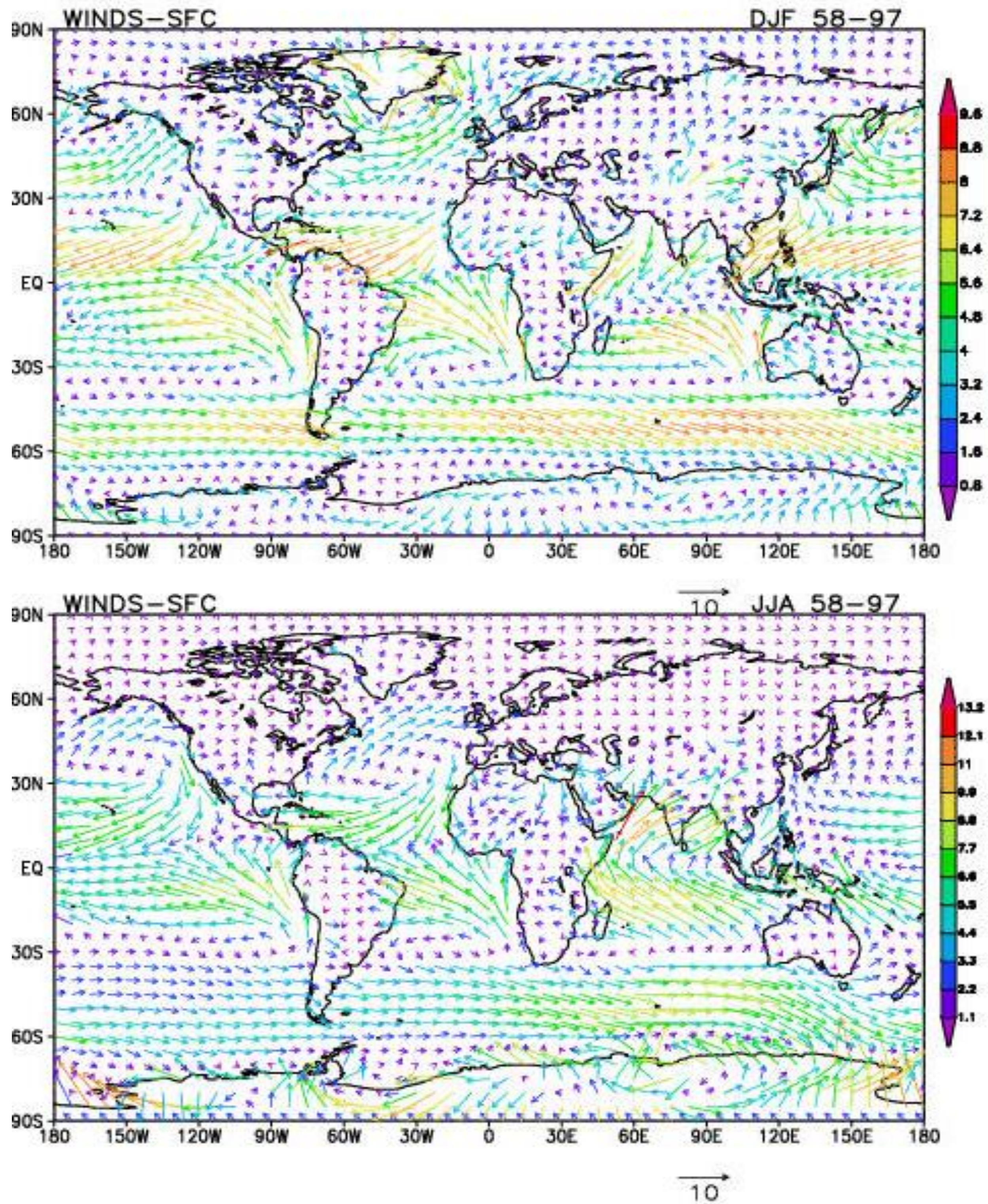
U V W T Q P etc

Met. Parameters

Long term mean seasonal average vector winds during NH winter (DJF) and summer (JJA) at the surface. This is based on 40 years of NCEP/NCAR reanalysis. Colors indicate wind magnitude.

Easterlies in the tropics and westerlies in the middle latitudes may be noted.

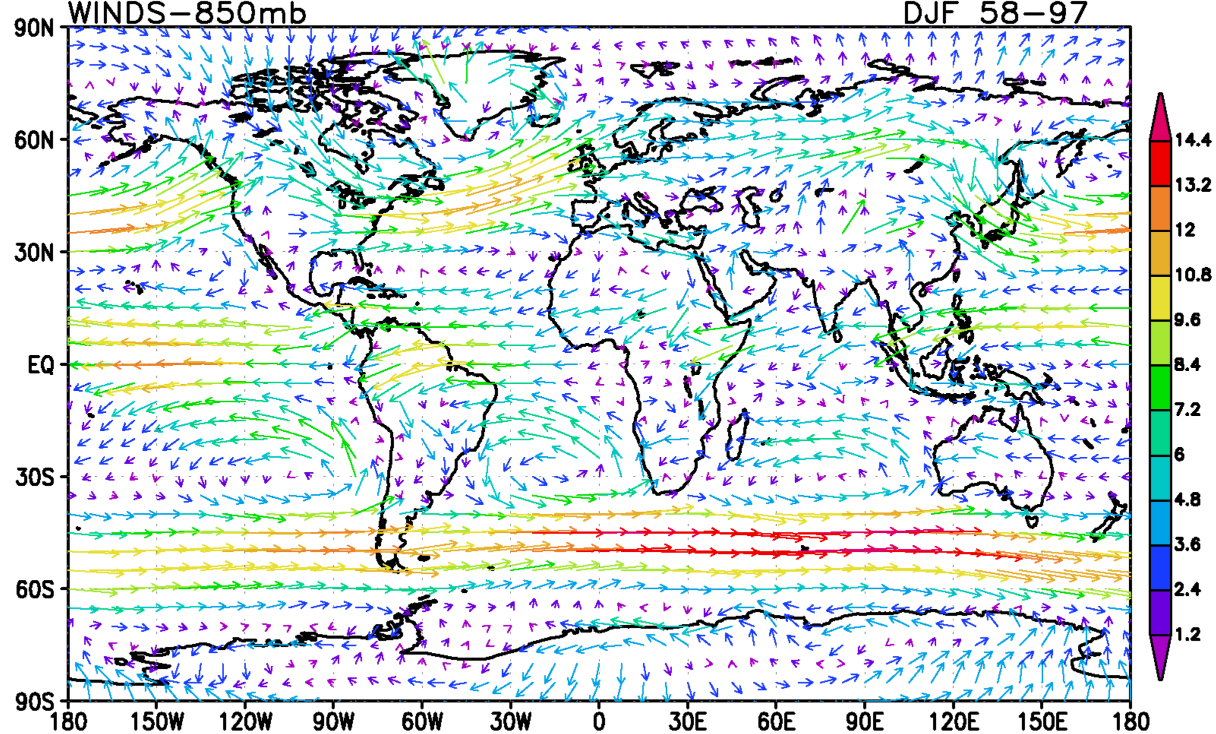
Reversal of winds between the two seasons over the monsoon regions is seen.

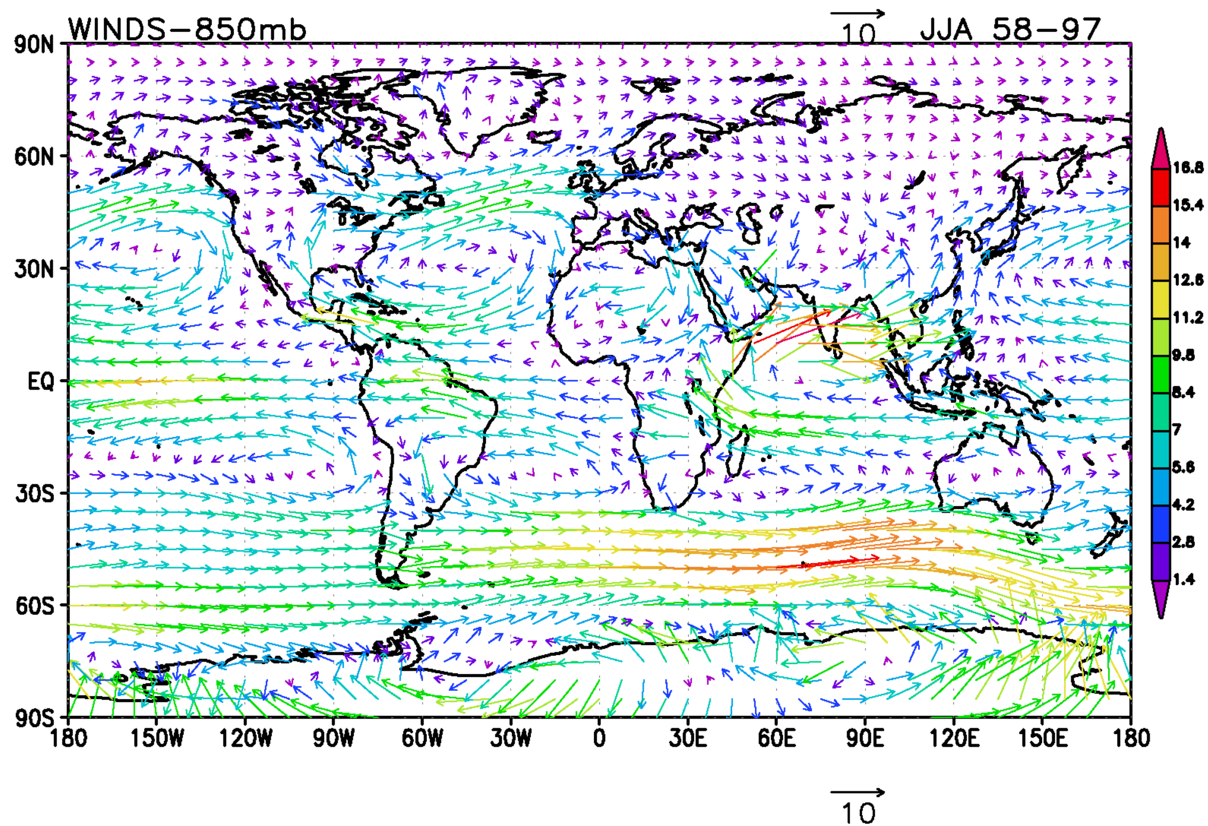


Long term mean seasonal average vector winds during NH winter (DJF) and summer (JJA) at 850 hPa. This is based on 40 years of NCEP/NCAR reanalysis. Colors indicate wind magnitude.

Easterlies in the tropics and westerlies in the middle latitudes may be noted.

Reversal of winds between the two seasons over the monsoon regions is seen.

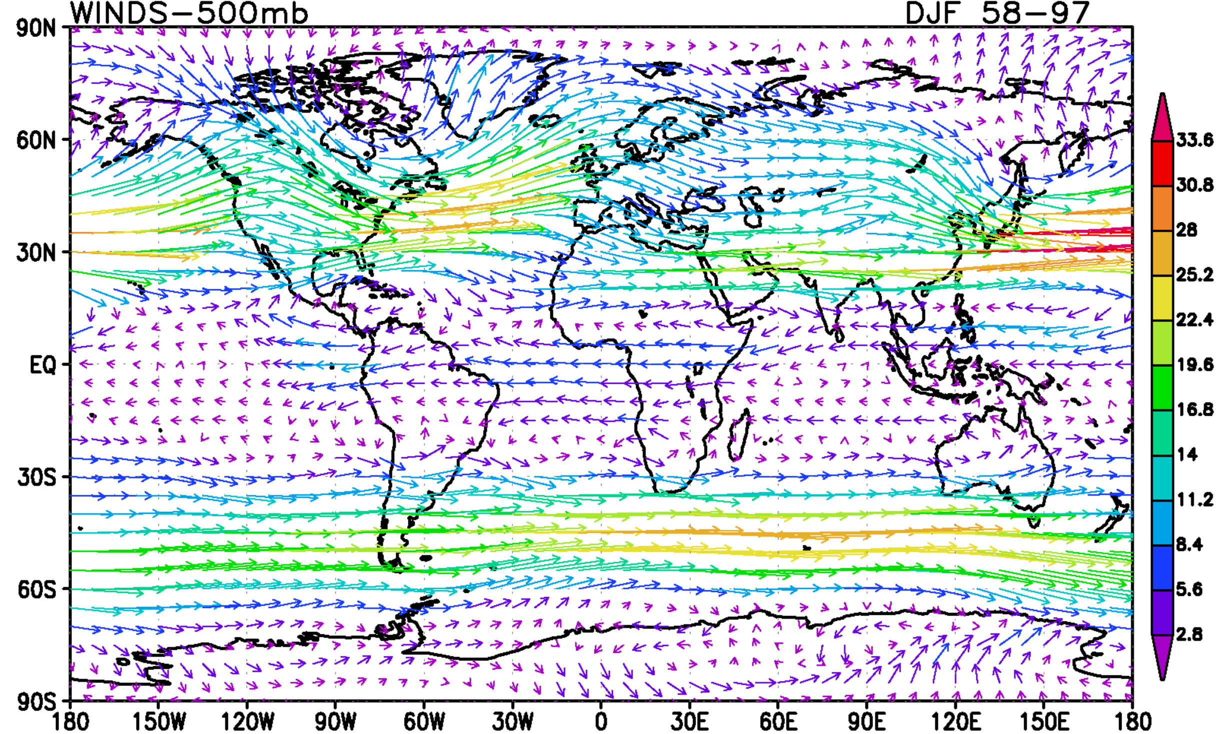


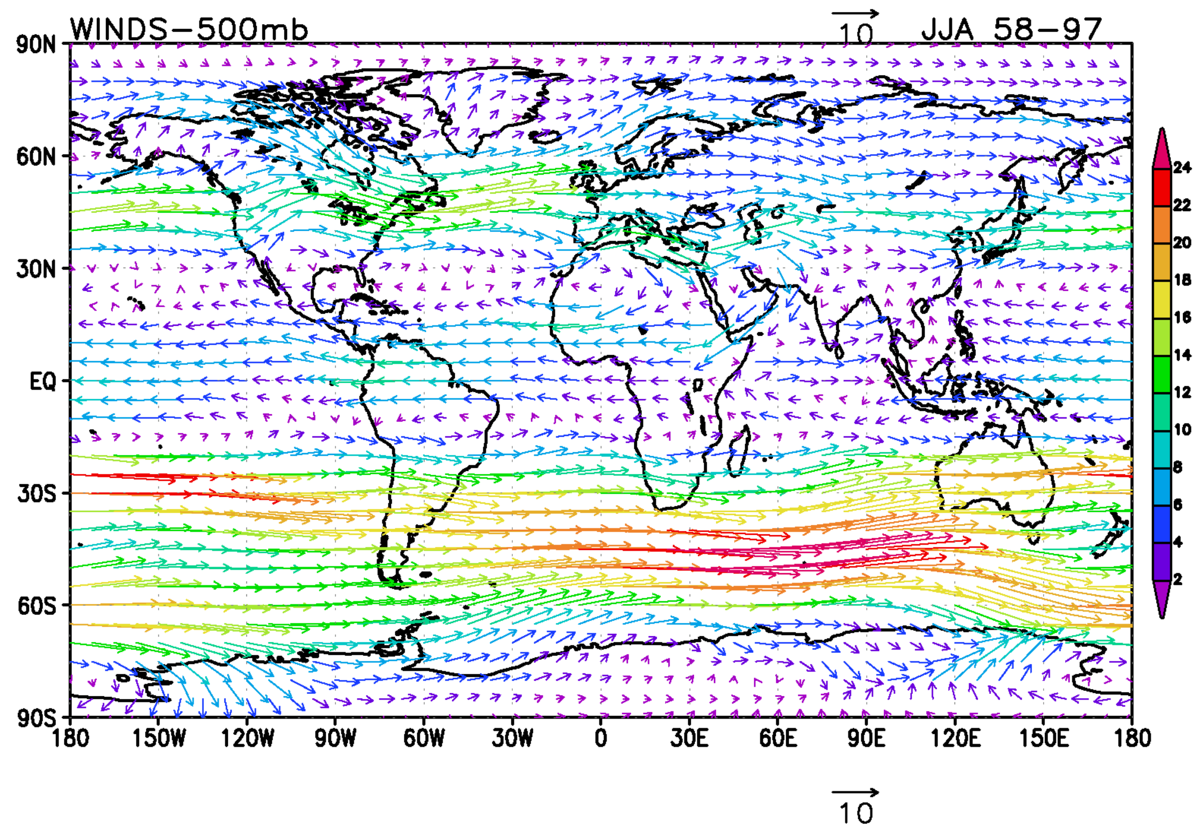


Long term mean seasonal average vector winds during NH winter (DJF) and summer (JJA) at 500 hPa. This is based on 40 years of NCEP/NCAR reanalysis. Colors indicate wind magnitude.

Easterlies in the tropics and westerlies in the middle latitudes may be noted.

Winds at this level over the monsoon regions are weak during both seasons.



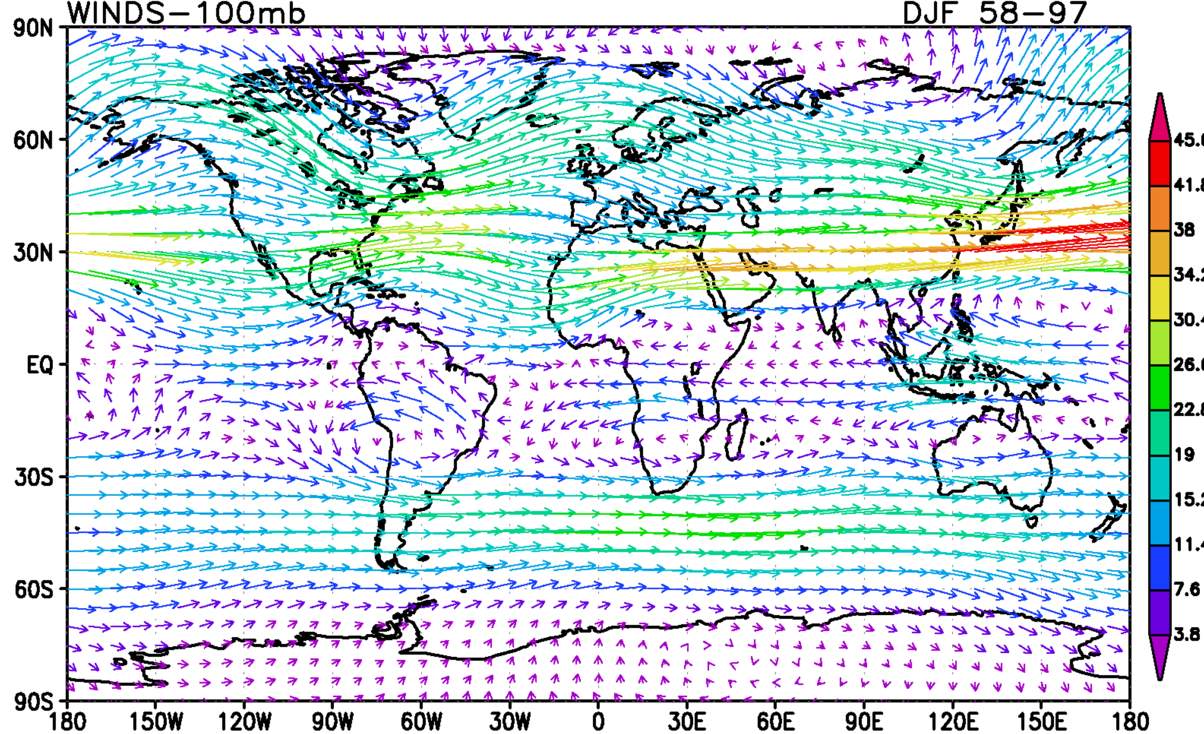


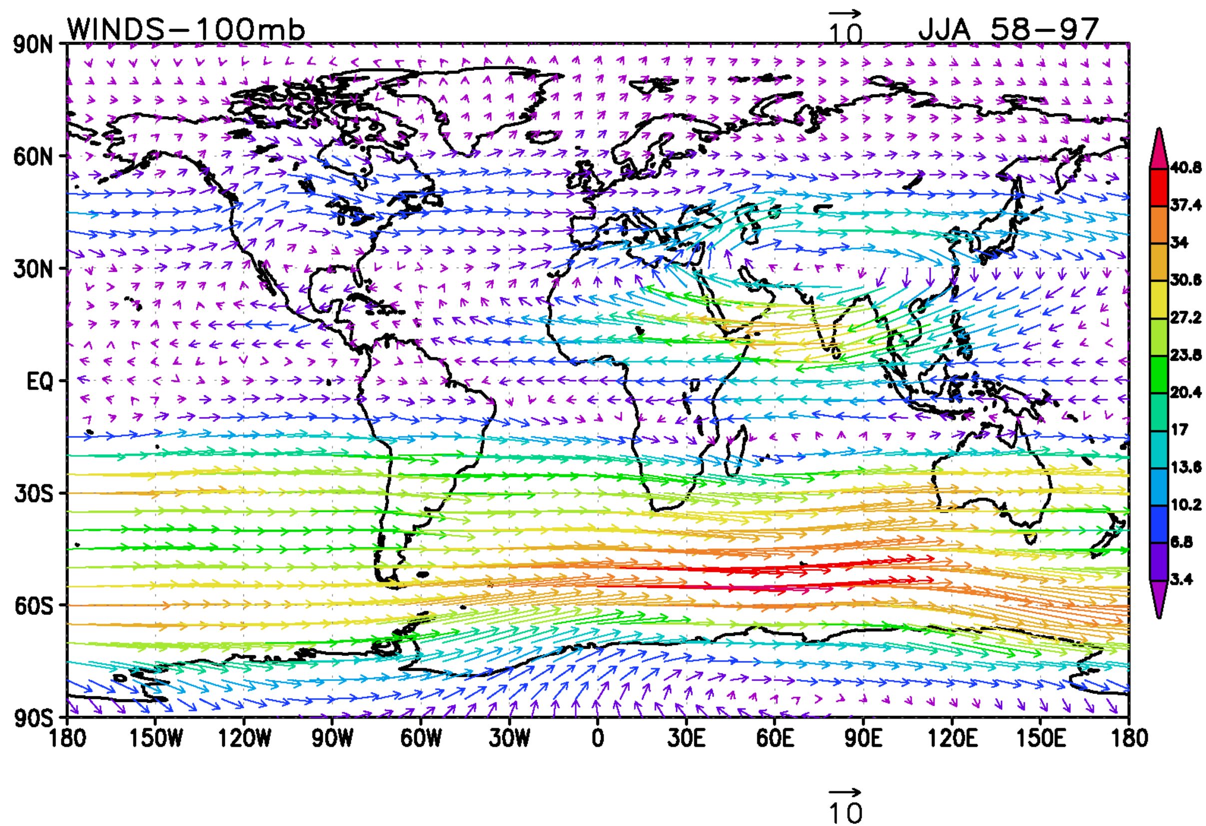
Long term mean seasonal average vector winds during NH winter (DJF) and summer (JJA) at 100 hPa. Colors indicate wind magnitude.

Easterlies in the tropics and jet-like strong westerlies are seen in the sub-tropics.

An easterly jet over the equatorial monsoon region during summer.

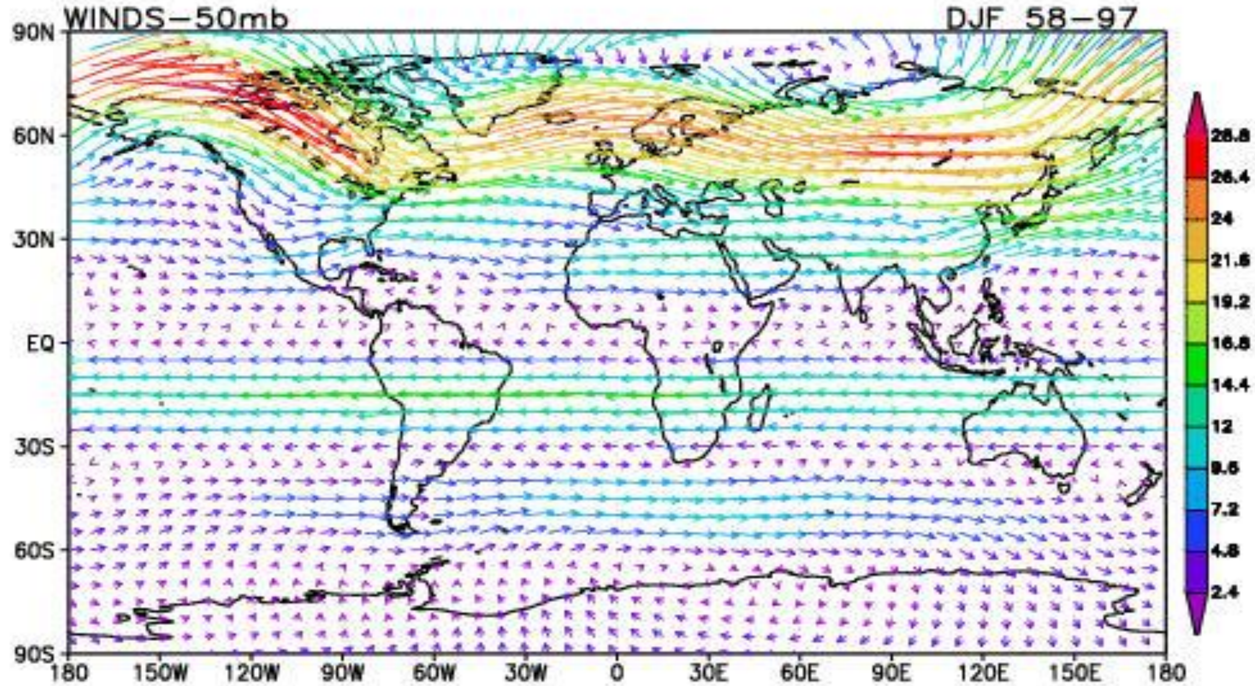
Also a massive anticyclonic circulation sits over the Tibet during summer.

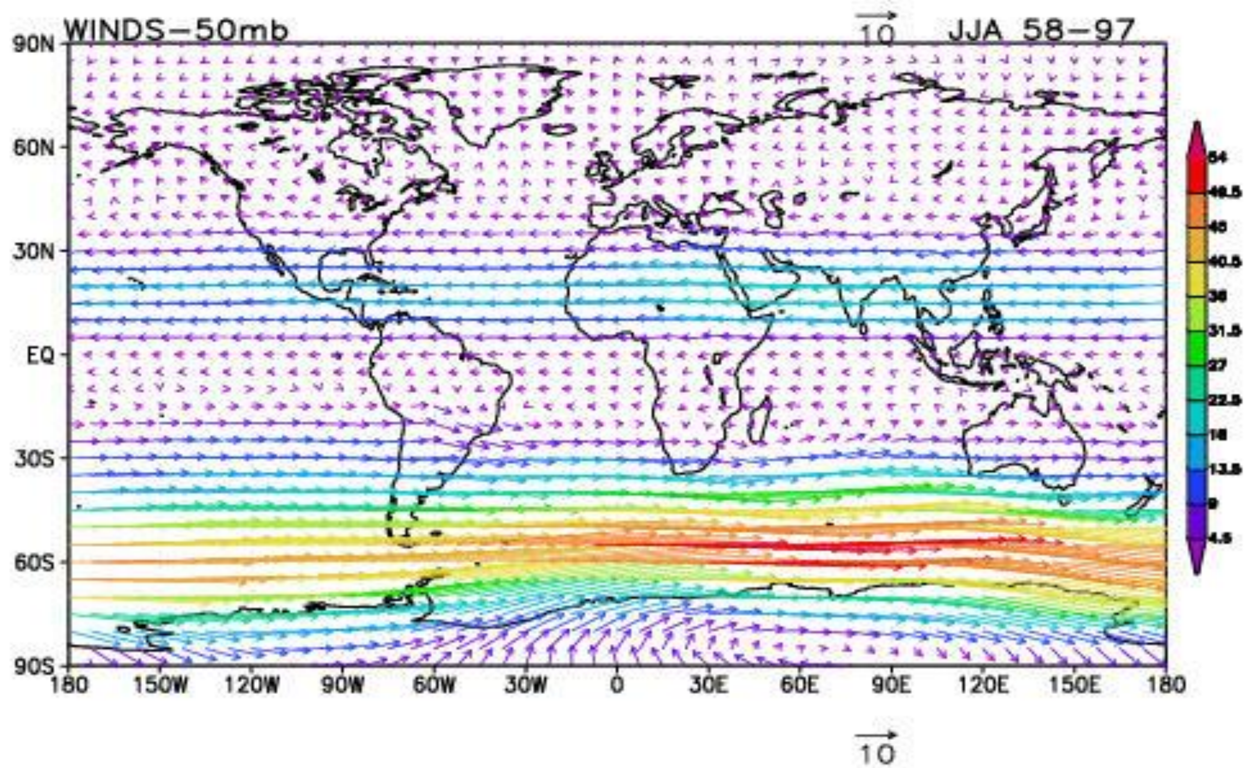




Long term mean seasonal average vector winds during NH winter (DJF) and summer (JJA) at 50 hPa (lower stratosphere). Colors indicate wind magnitude.

The striking feature is that westerly jet is asymmetric about the equator at this level. Summer hemisphere does not have westerly jet and the jet is located closer to the winter hemispheric polar region.

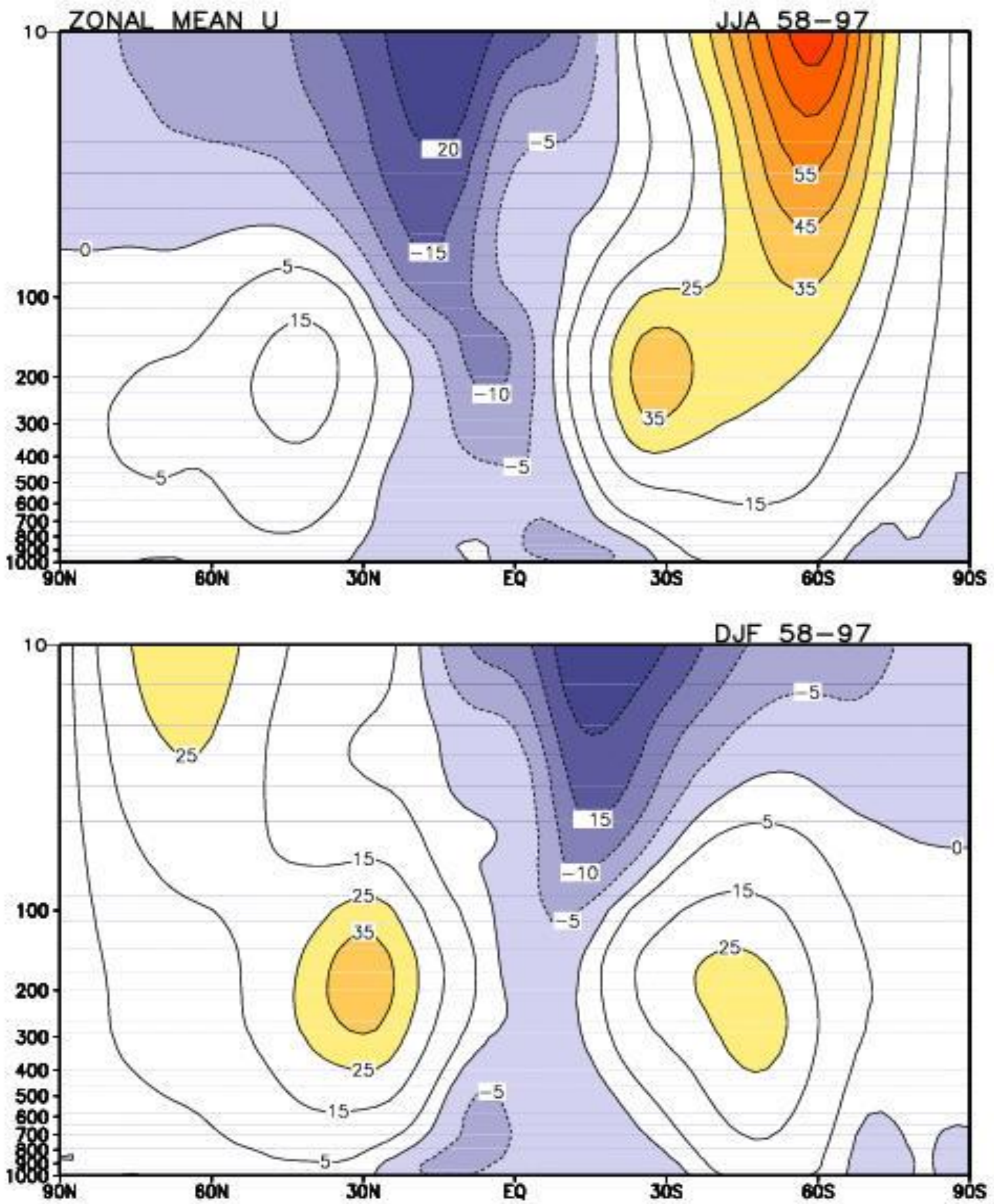




Eastward component of the winds (zonal winds, u) averaged along a latitude circle (zonal average) as a function of latitude and height (represented in pressure from 1000 hPa to 10 hPa.

In the troposphere (below 100 hPa), subtropical westerly jets in both hemispheres may be seen.

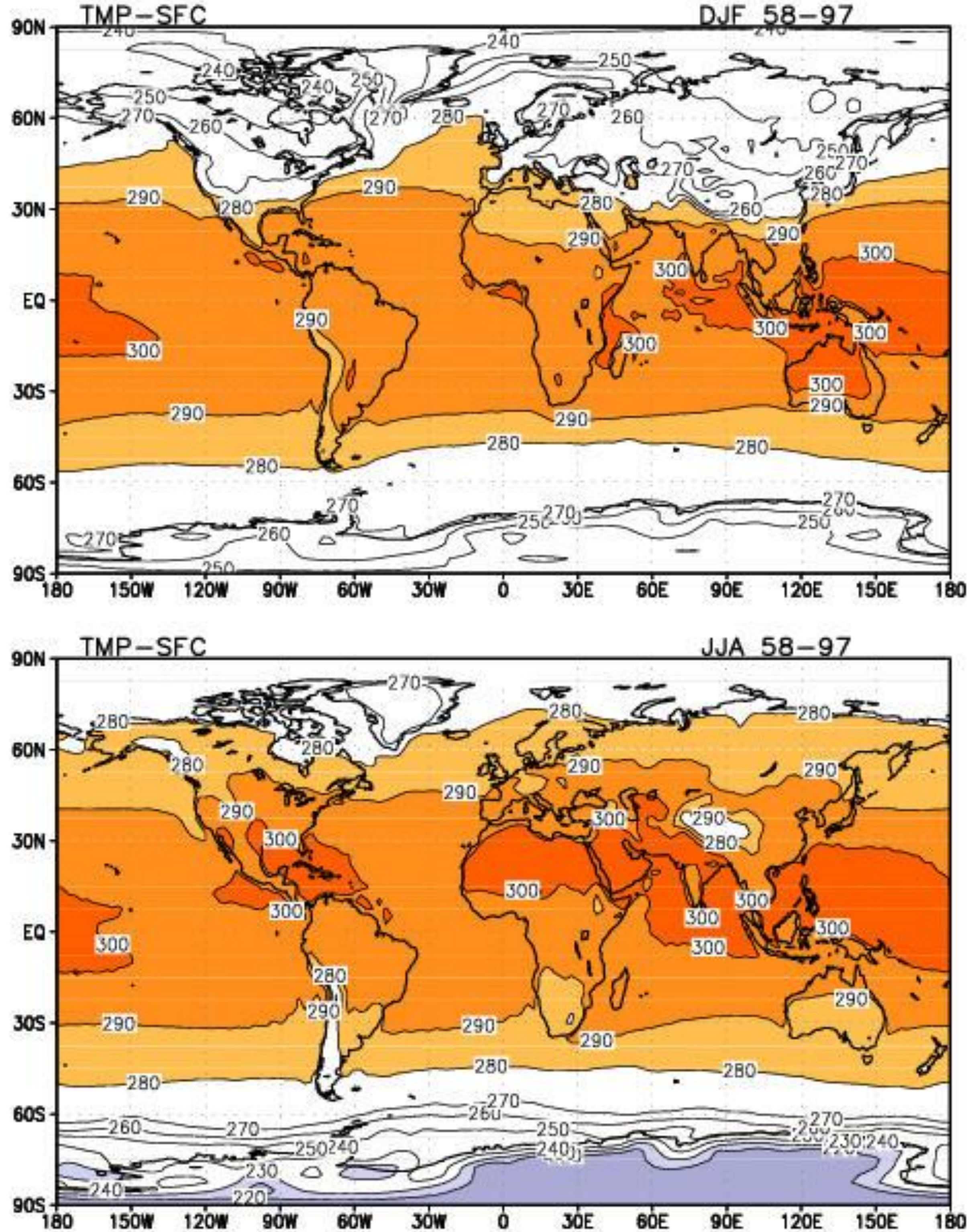
Westerly jet in the summer hemisphere and easterly jet in the winter hemisphere are seen the stratosphere.



Long term mean seasonal average temperature (K) during NH winter (DJF) and summer (JJA) at the surface. This is based on 40 years of NCEP/NCAR reanalysis.

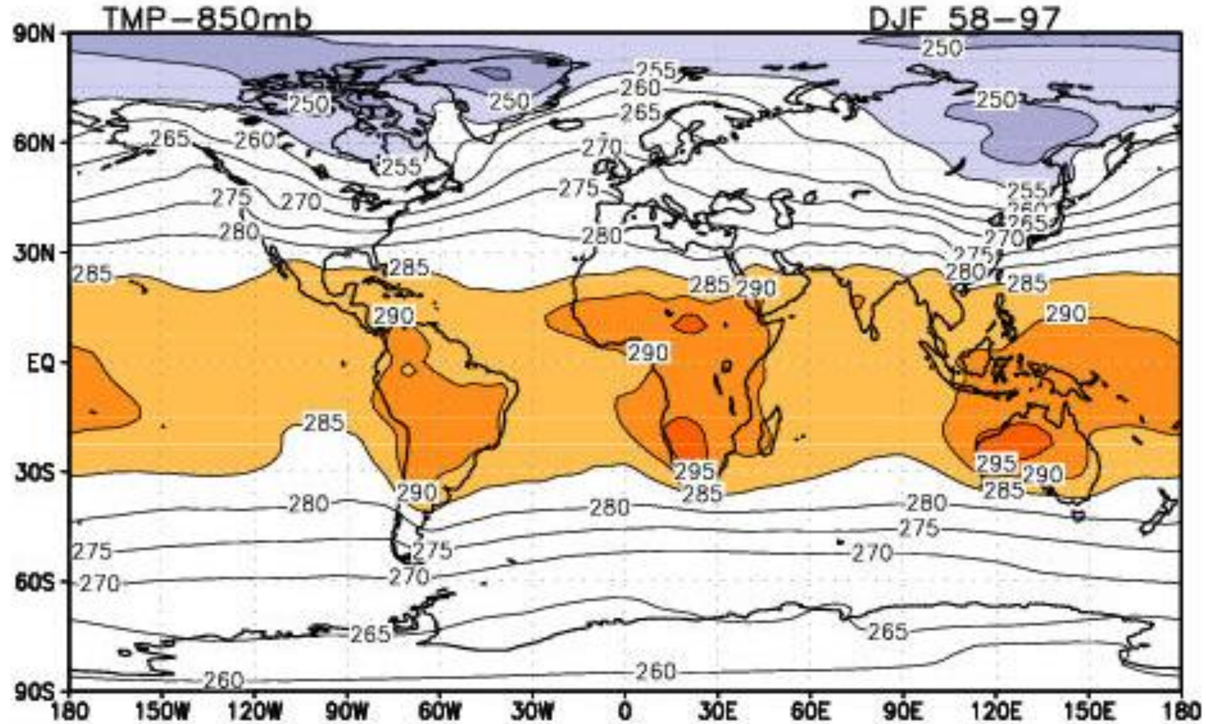
In the tropics (between 30S and 30N), latitudinal variations of temp. is very weak. It is rapid in the middle latitude.

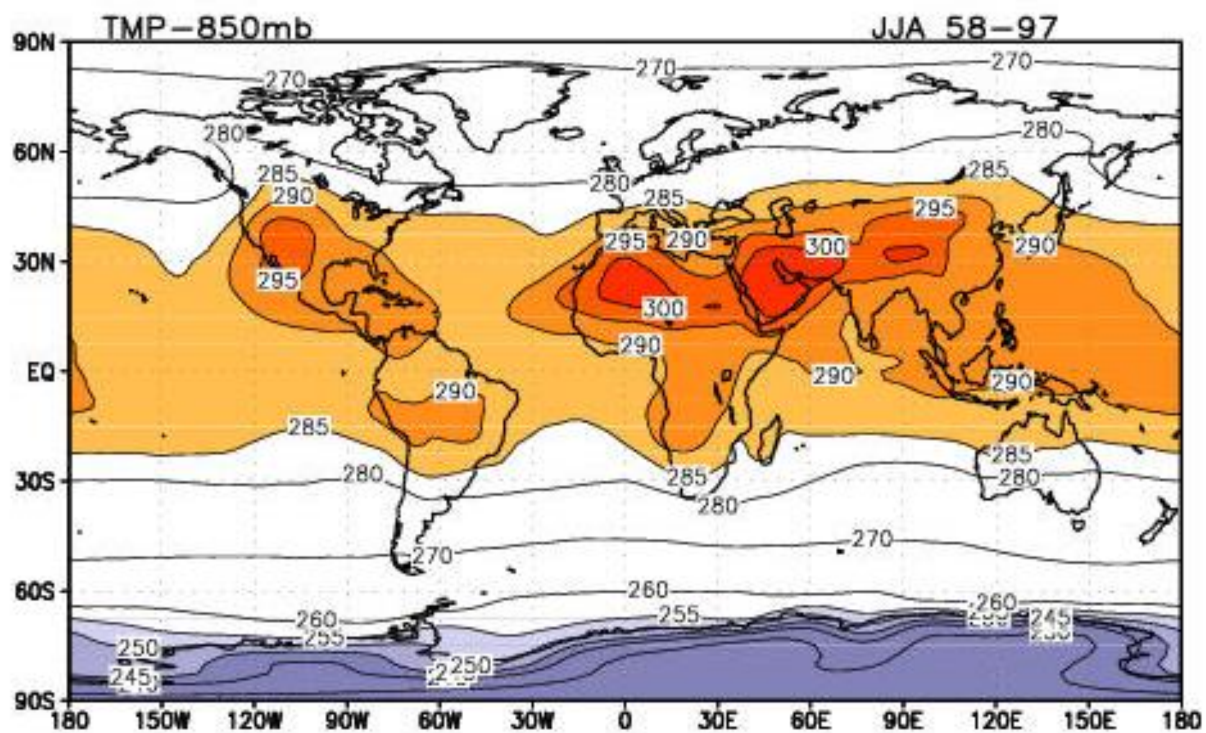
The equator-to-pole temp. difference is around 60K (40K)in winter (summer) hemisphere.



Long term mean seasonal average temperature (K) during NH winter (DJF) and summer (JJA) at 850 hPa.

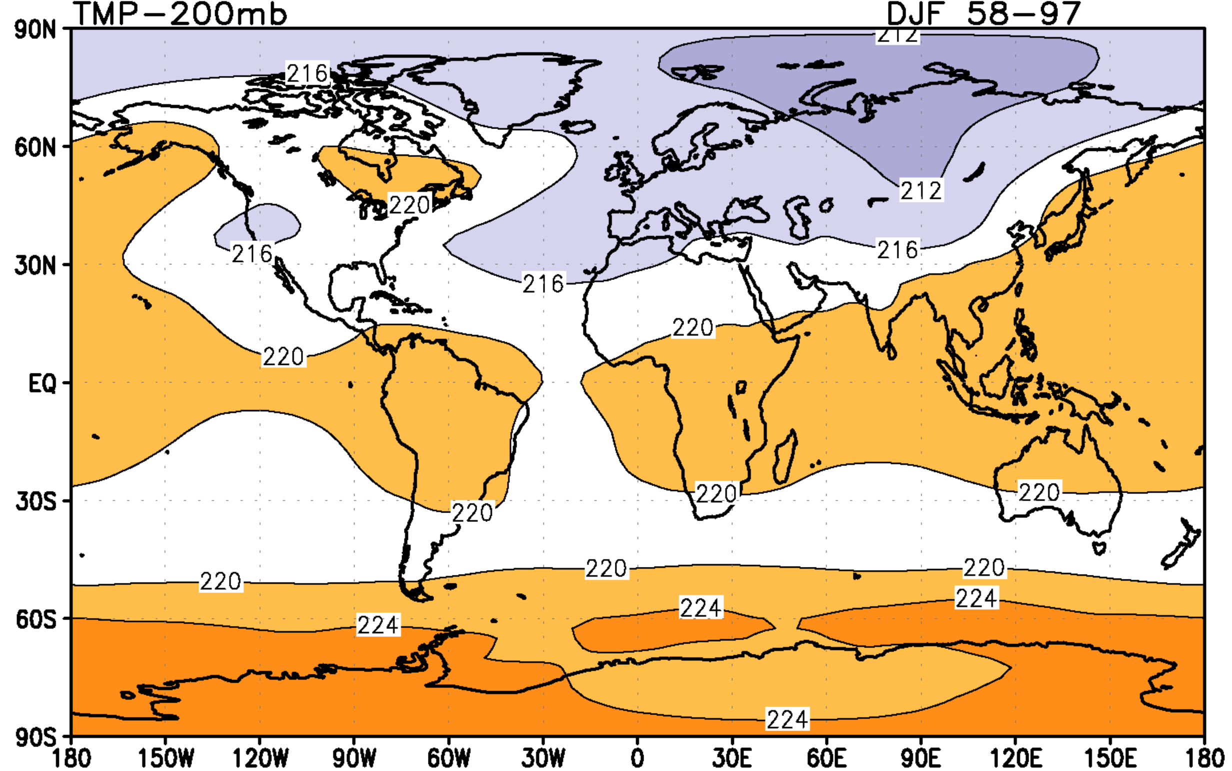
Similar to that at surface but the magnitude has decreased. The wave like structure of Temp. contours in NH winter (DJF) is due to land-ocean contrasts.

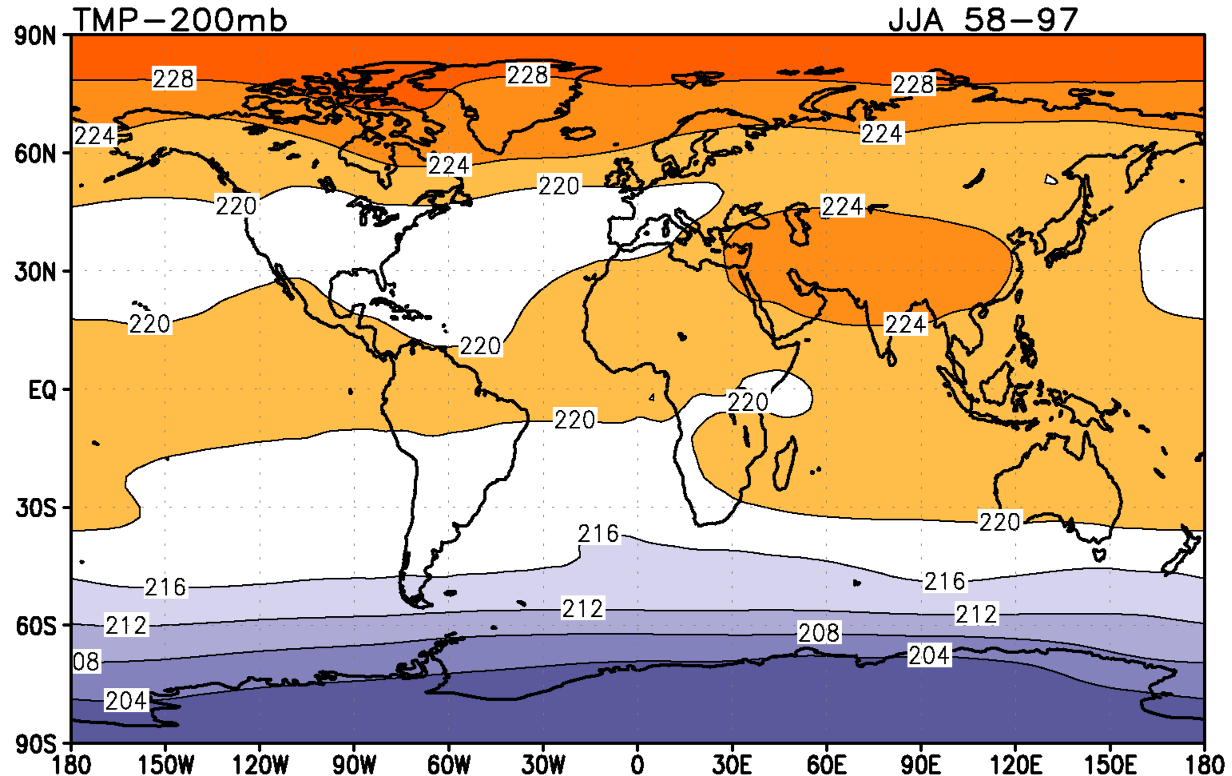




Long term mean seasonal average temperature (K) during NH winter (DJF) and summer (JJA) at 200 hPa.

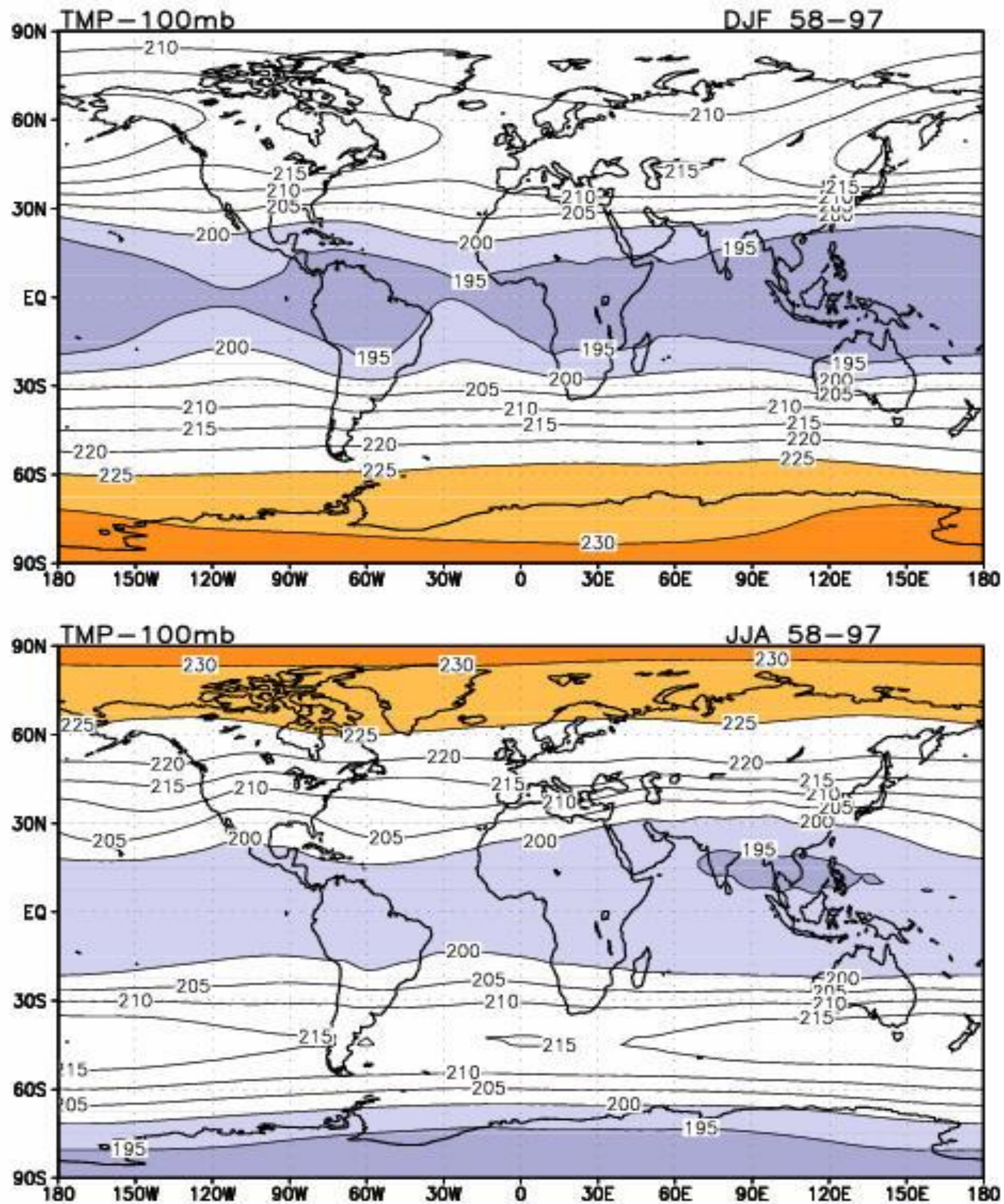
Magnitudes decrease with height. But at this level there is a inter hemispheric asymmetry. One pole is warmer than the other that reverses with season.





Long term mean seasonal average temperature (K) during NH winter (DJF) and summer (JJA) at 100 hPa.

It may be noted that at this level, the equator is colder than the polar region reversing the equator to pole temperature gradient at this level compared to that at the surface.

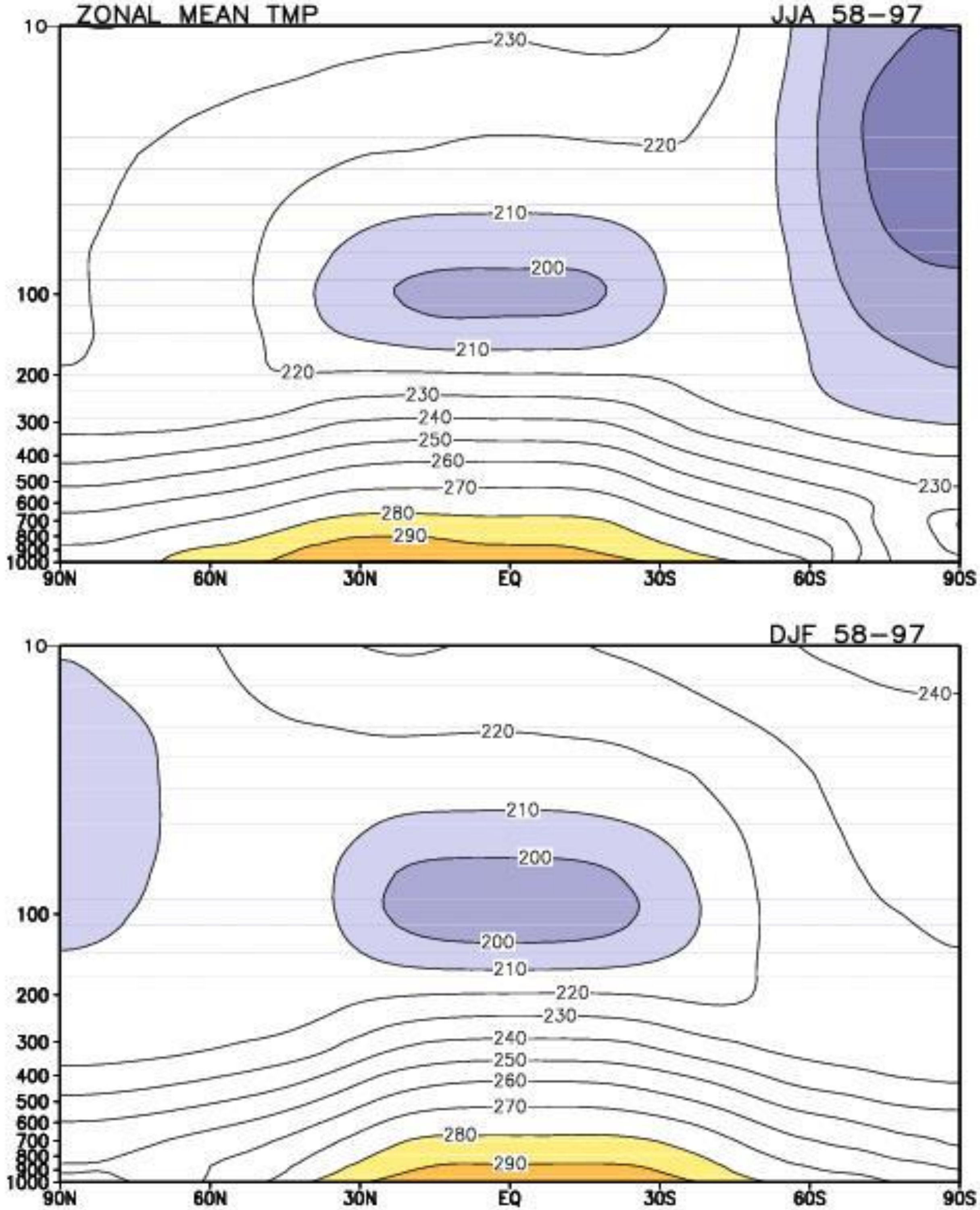


Temperature (K) averaged along a latitude circle (zonal average) as a function of latitude and height (represented in pressure from 1000 hPa to 10 hPa.

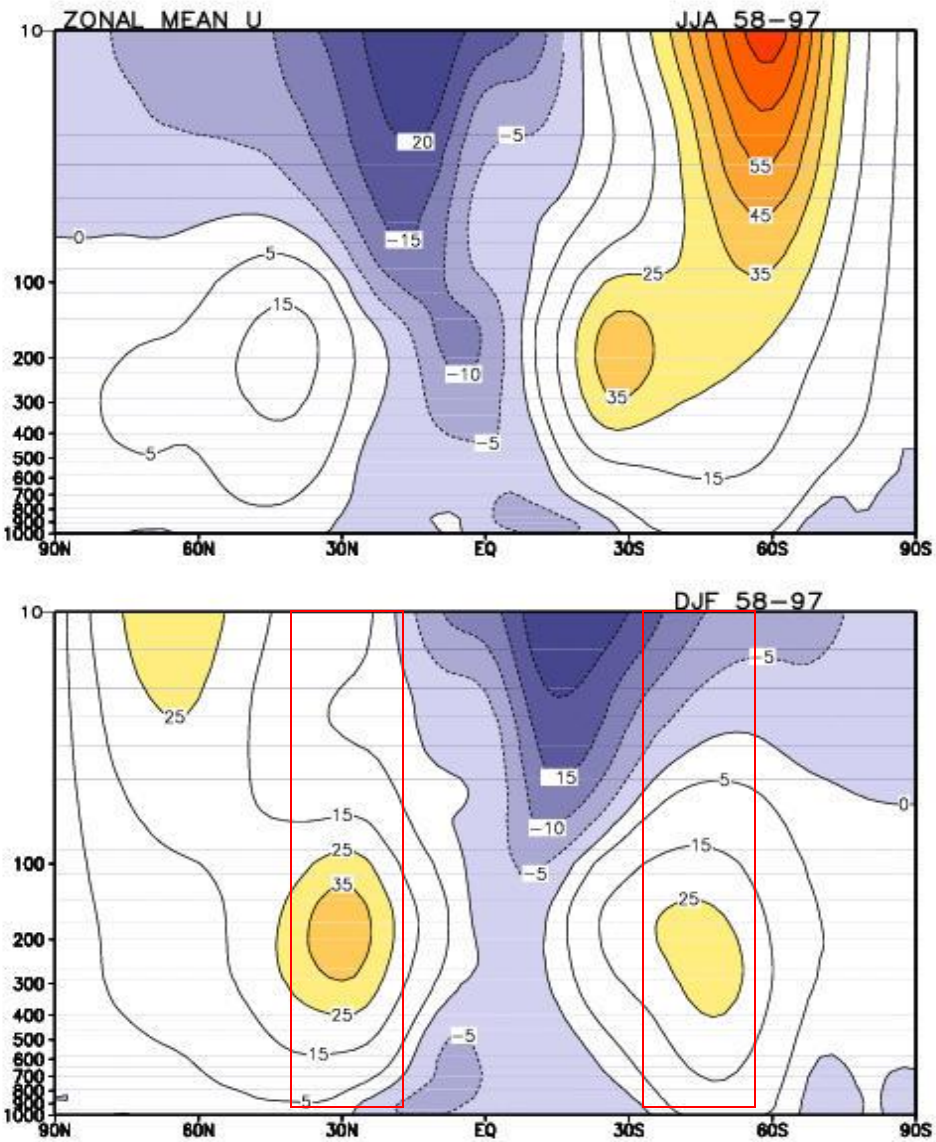
The temperature decreases to a height (tropopause) and increases thereafter.

Height of the tropopause in the tropics is about 100 hPa while it is 300 hPa in polar regions.

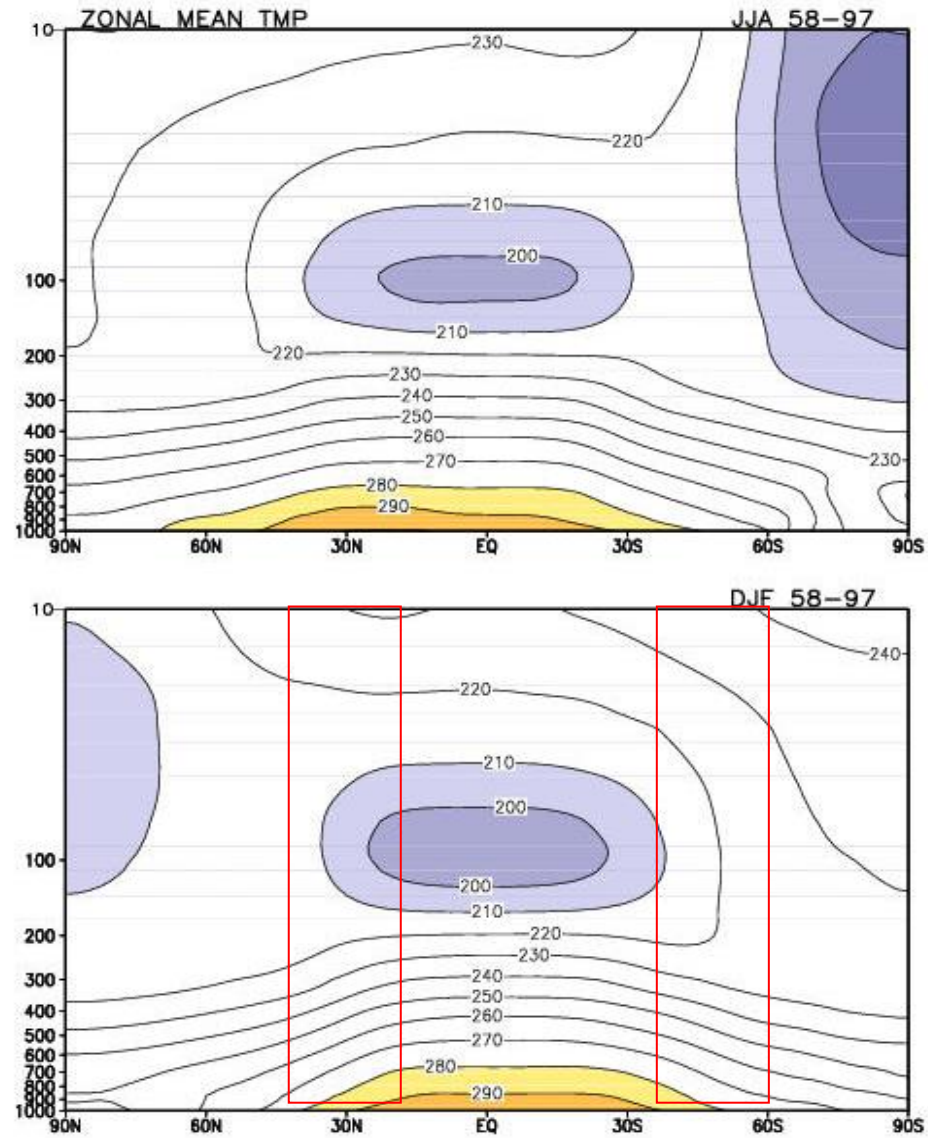
The symmetry of the temperature profile around the equator in the troposphere and its asymmetry in the stratosphere may be noted.



Climatological zonal mean U



Climatological zonal mean T



It may be noted that zonal mean zonal winds and temperature are strongly coupled. Meridional gradient of T is proportional to vertical shear of zonal winds.

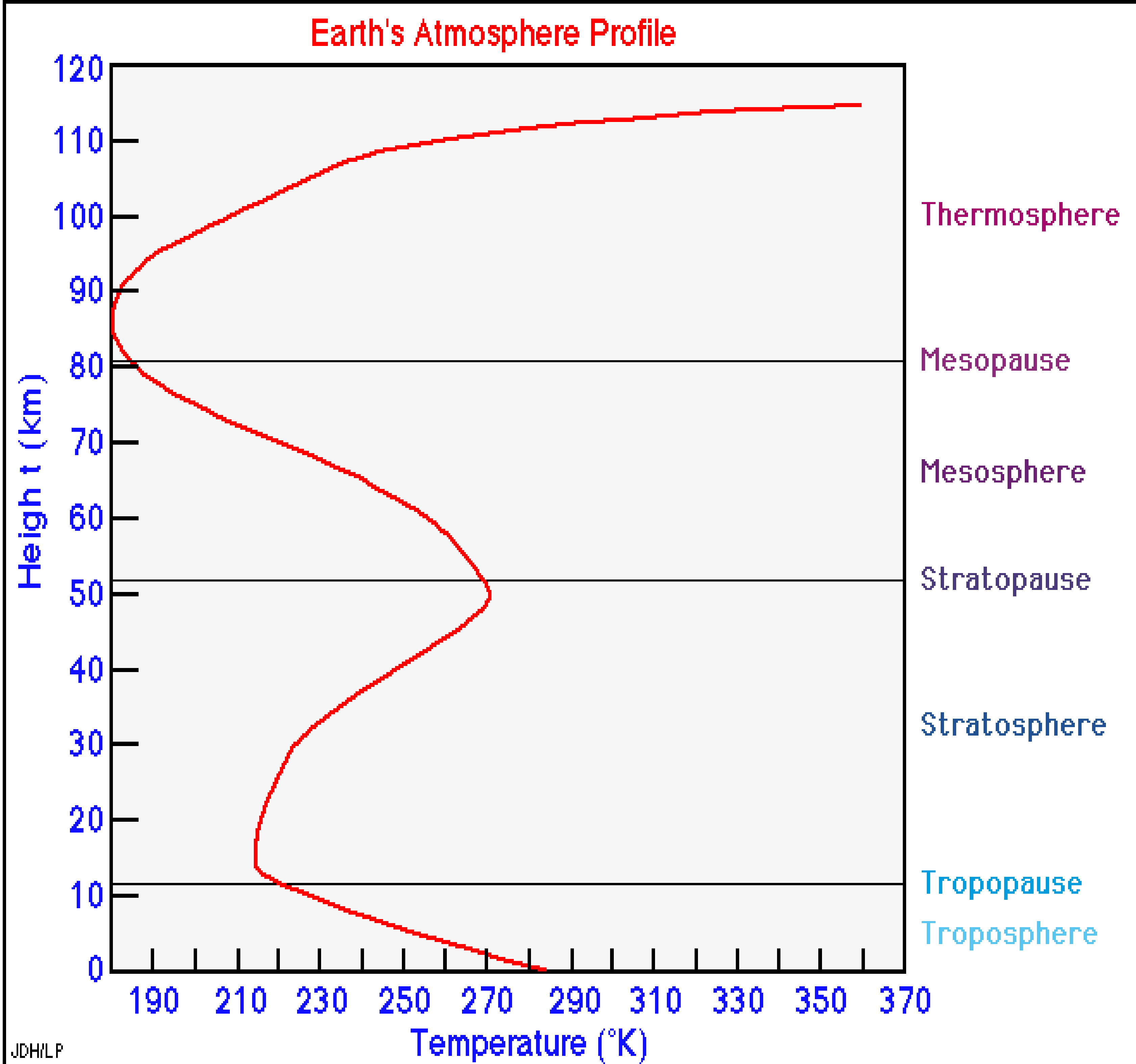
On large scales, the winds are largely in geostrophic balance where the Coriolis force is in balance with pressure gradient force. The geostropic balance, together with hydrostatic relation for such scales indicate that winds are in Thermal wind balance. That means that the 'vertical shear of zonal mean winds are proportional to north-south gradient of mean temperatures as,

$$\bar{u}_z = -R(H\beta y)^{-1}\,\bar{T}_y$$

at Eq.

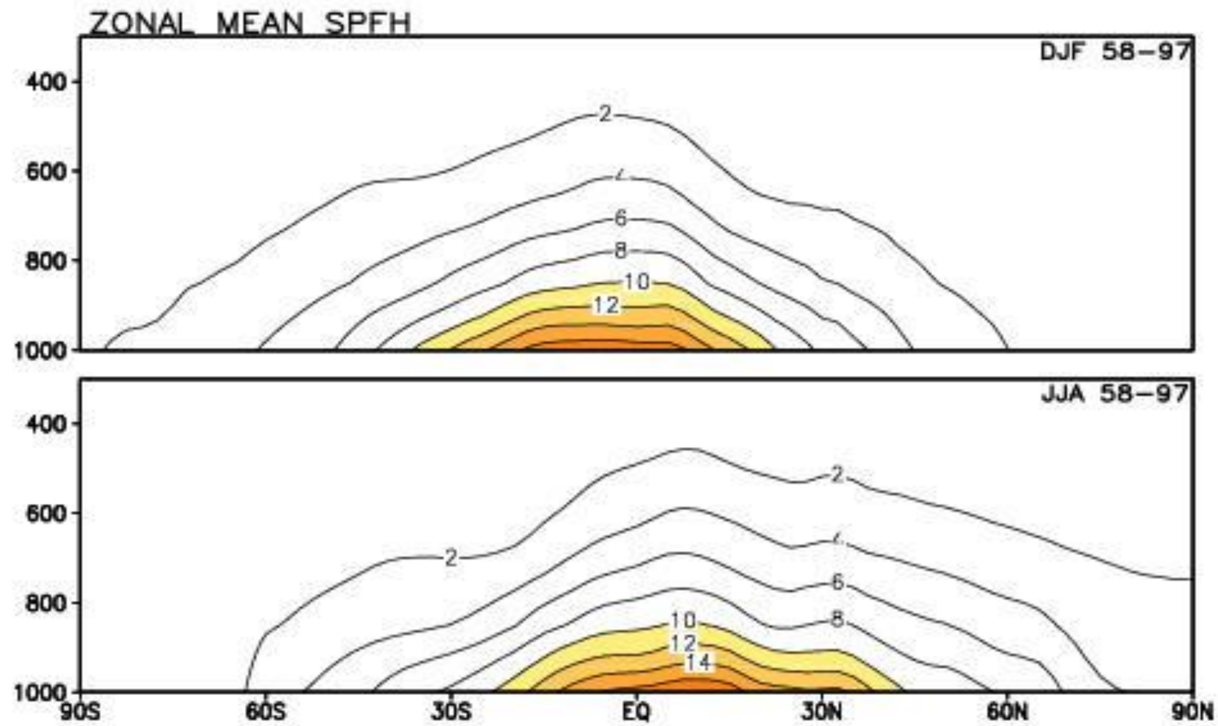
$$\bar{u}_z = -R(H\beta)^{-1}\,\bar{T}_{yy}$$

Where, R➔ specific Gas Constant for air
H➔ scale height
β➔gradient of Coriolis parameter

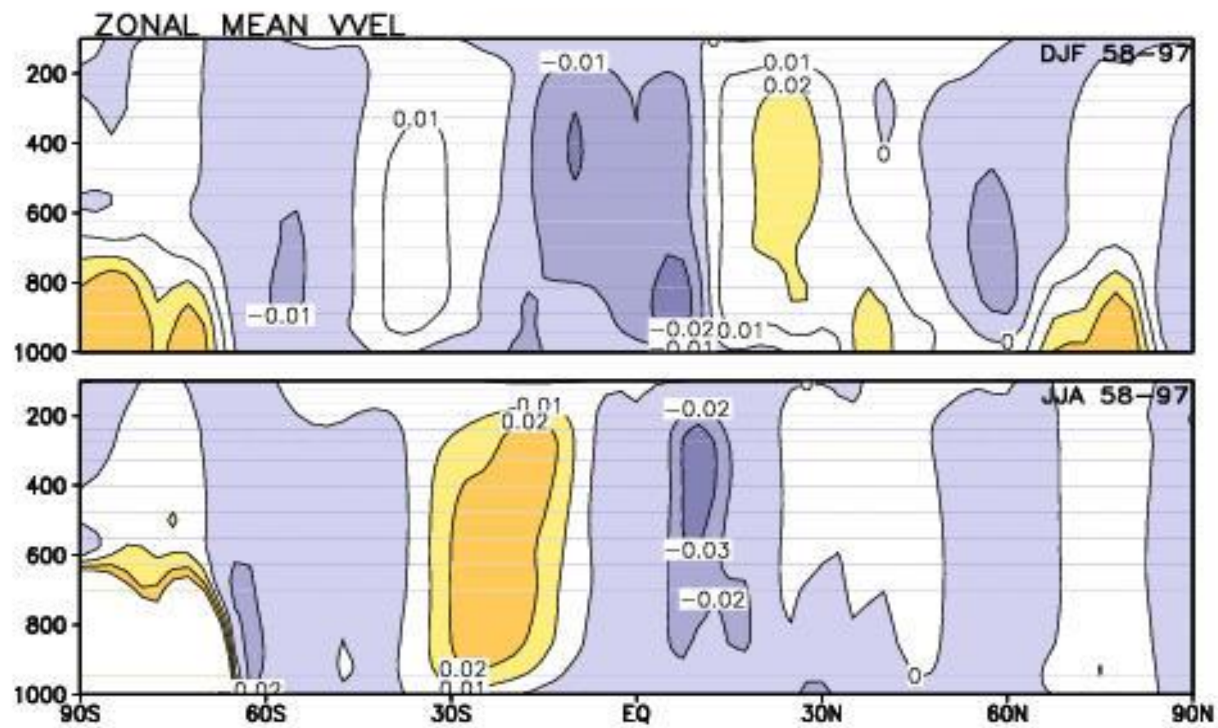


Earth's Atmosphere Profile
Height t (km)
120
110
100
90
80
70
60
50
40
30
20
10
0
190
210
230
250
270
290
310
330
350
370
Temperature (°K)
Thermosphere
Mesopause
Mesosphere
Stratopause
Stratosphere
Tropopause
Troposphere
JDH/LP

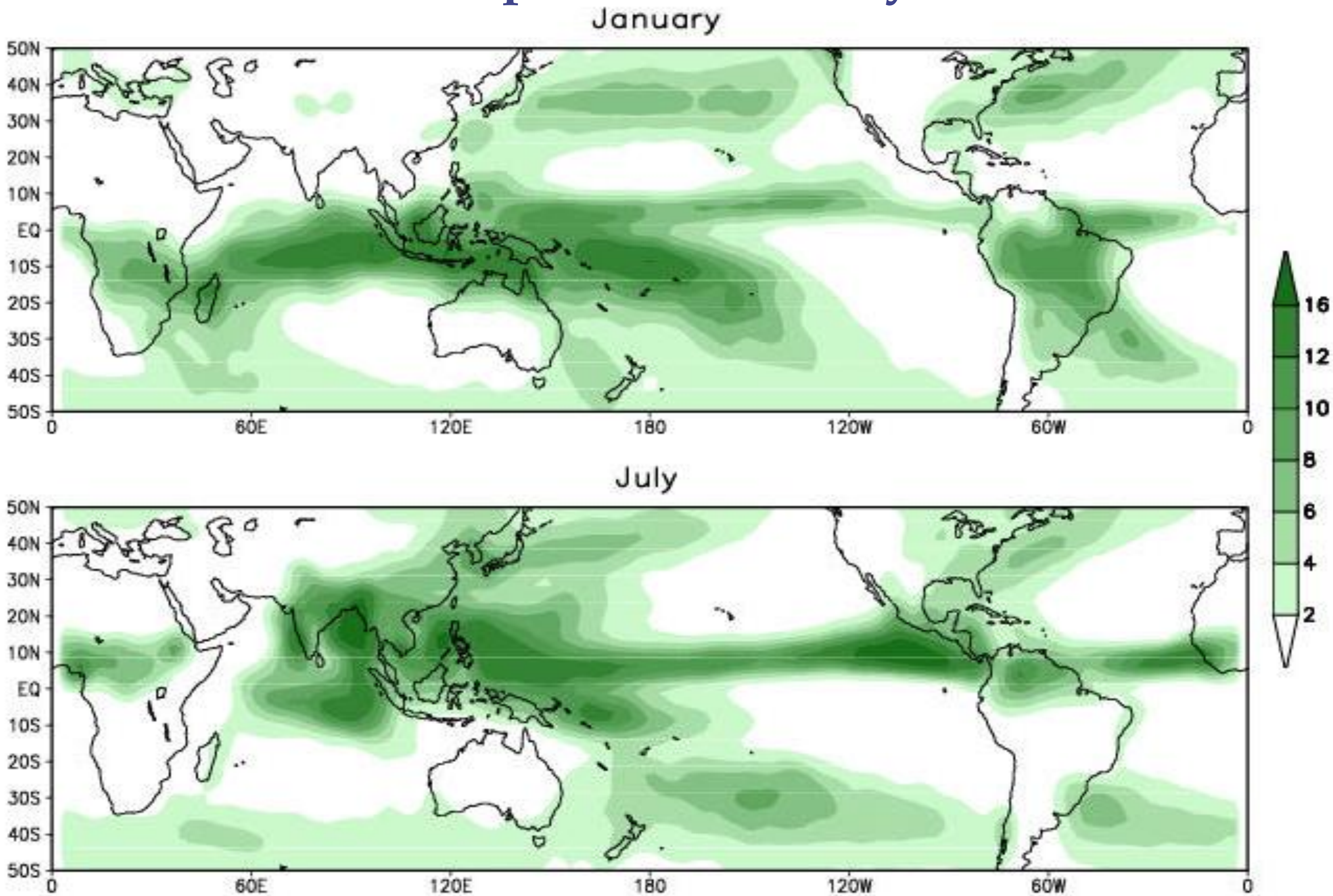
Specific humidity (g/kg) averaged along a latitude circle (zonal average) as a function of latitude and height (represented in pressure from 1000 hPa to 300 hPa.



Pressure vertical velocity (hPa/s) averaged along a latitude circle (zonal average) as a function of latitude and height (represented in pressure from 1000 hPa to 100 hPa. Negative values represent upward motion.

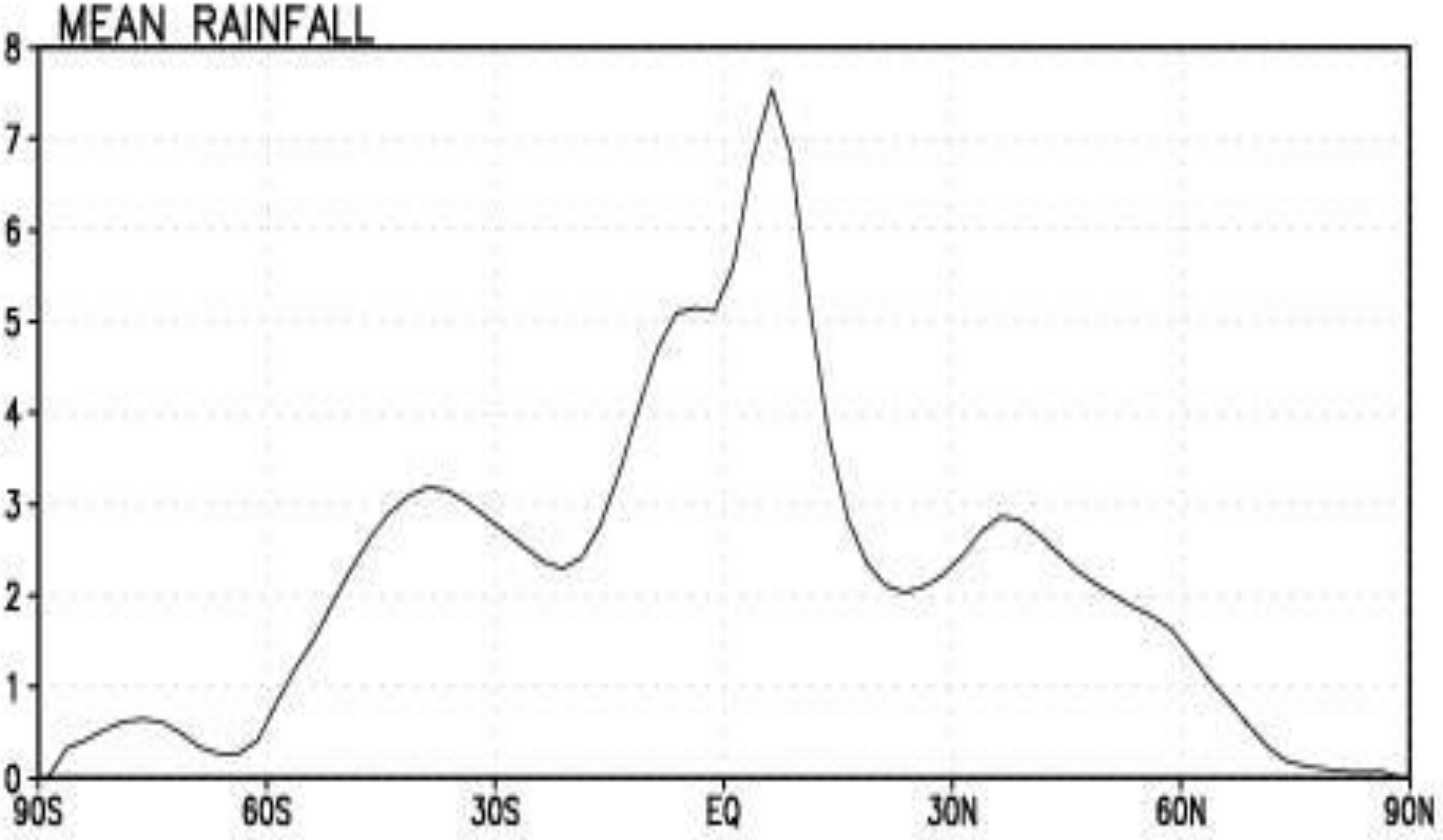


Precipitation (mm day^{-1})



Climatological mean precipitation (mm day^{-1}) for January and July.

Zonal Mean Annual Precipitation (mm day^{-1})



Some important features of the observed Mean condition of the atmosphere

- **Surface easterlies in the tropics & surface westerlies in the middle latitudes**

- **Westerly jet stream in the upper atmosphere subtropics. Winter hemisphere jet tends to be stronger than the summer hemisphere one.**

- **Easterly jet in the upper atmosphere over the equatorial region during summer monsoon region**

- **Three cell meridional structure**

Some important features of the observed Mean condition of the atmosphere (contd.)

- **Equator to pole temperature difference is about 60^0K in the winter hemisphere and about 35^0K in the summer hemisphere**

- **The temperature gradient in the meridional direction is weak in the tropics and strong in the middle latitude.**

- **Height of the tropopause is much lower in the polar region as compared to the equatorial region**

What drives this temperature and wind distribution in the Atmosphere?

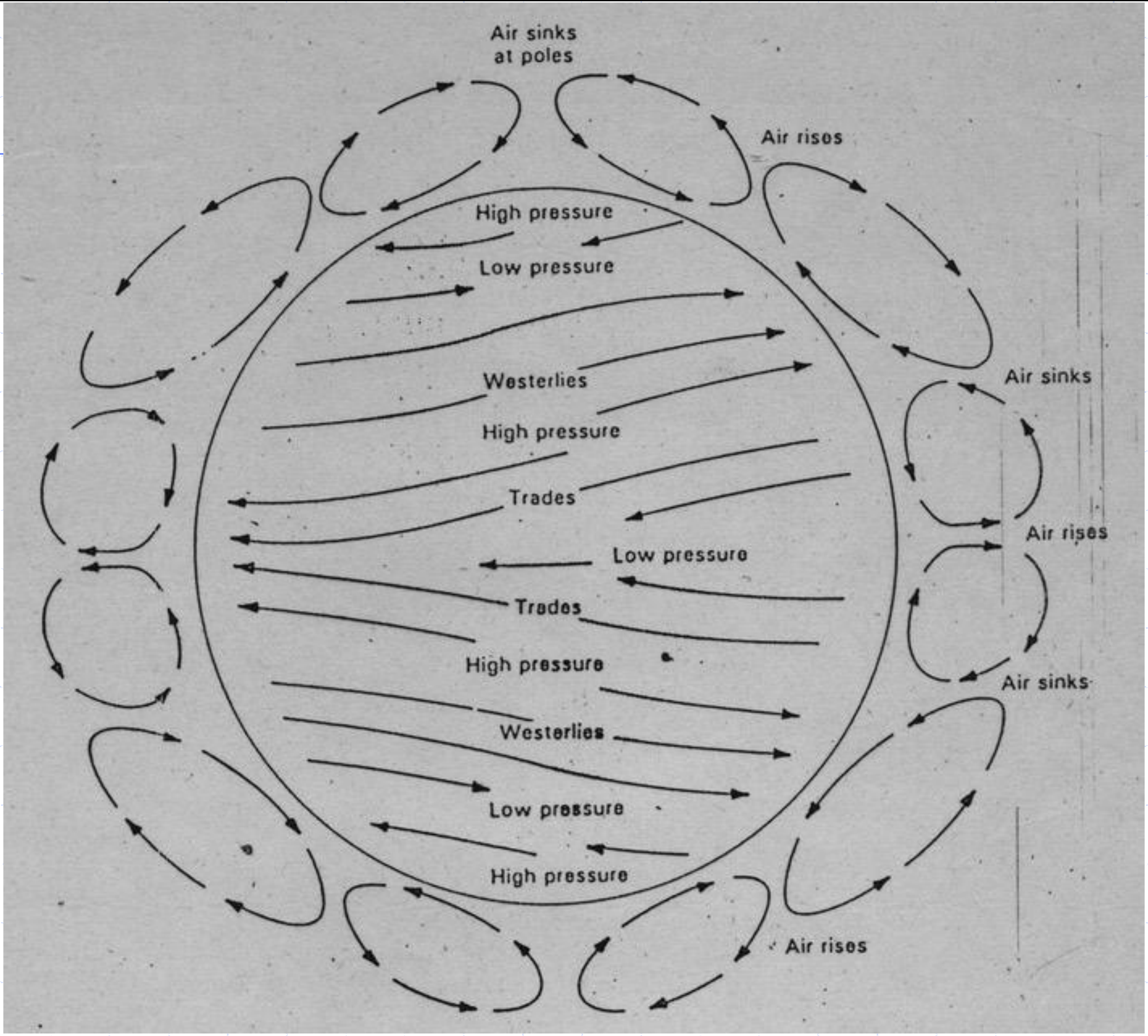
Importance of

- **The temperature gradient in the meridional direction is weak in the tropics and strong in the middle latitude.**

- **Weak temperature gradient in tropics➔ weak vertical shear of zonal winds➔ No Baroclinic Instability➔ tropical weather is largely initiated by Barotropic instability**

- **Strong temperature gradient in middle latitudes➔ large APE, large vertical shear of U wind➔Baroclinic Instability➔ extra-tropical weather is largely driven by Baroclinic Instability**

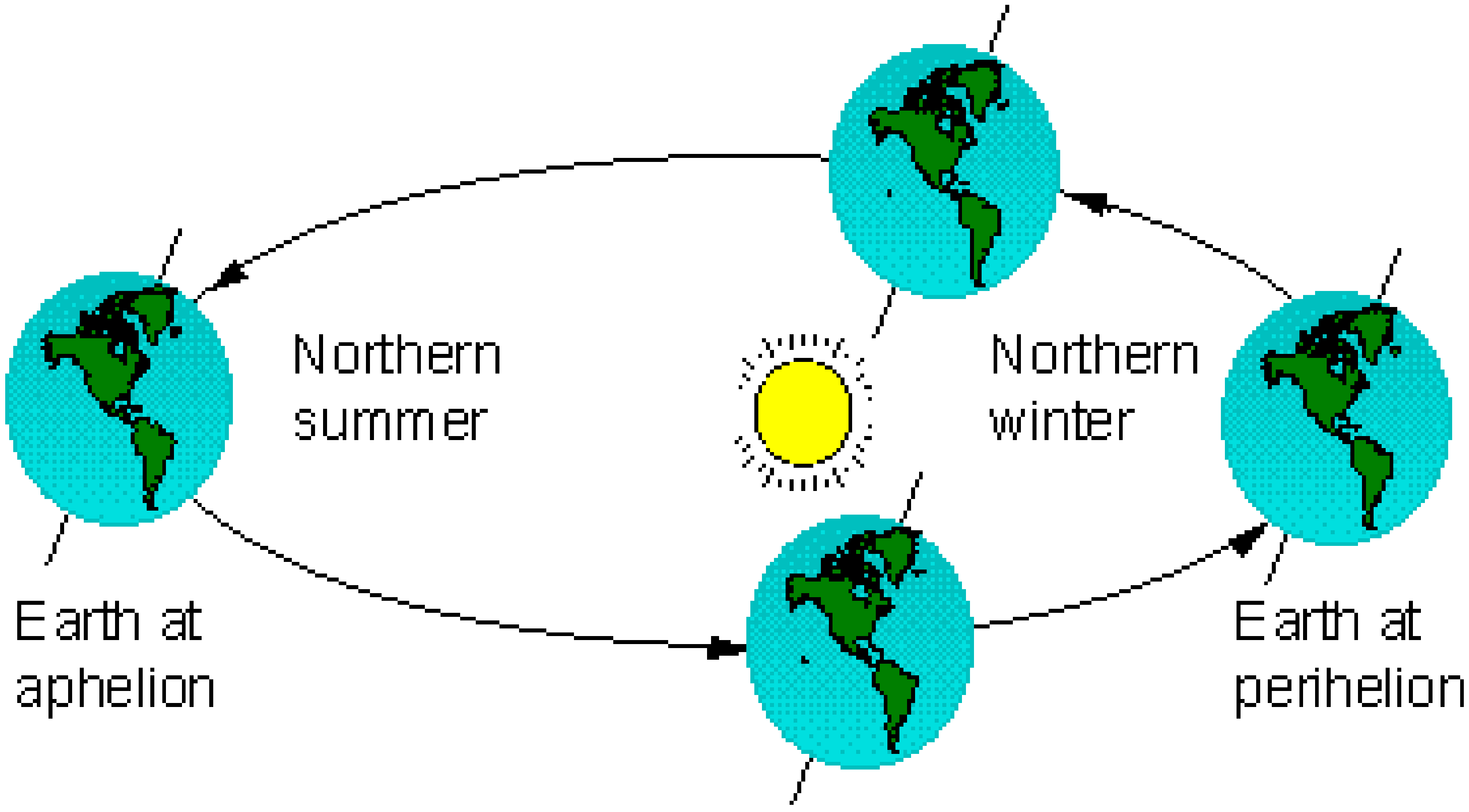
The observed 3-meridional cell structure of the circulation is essential for explaining the easterlies in tropics and westerlies in middle latitudes.



How is a three cell meridional structure is maintained?

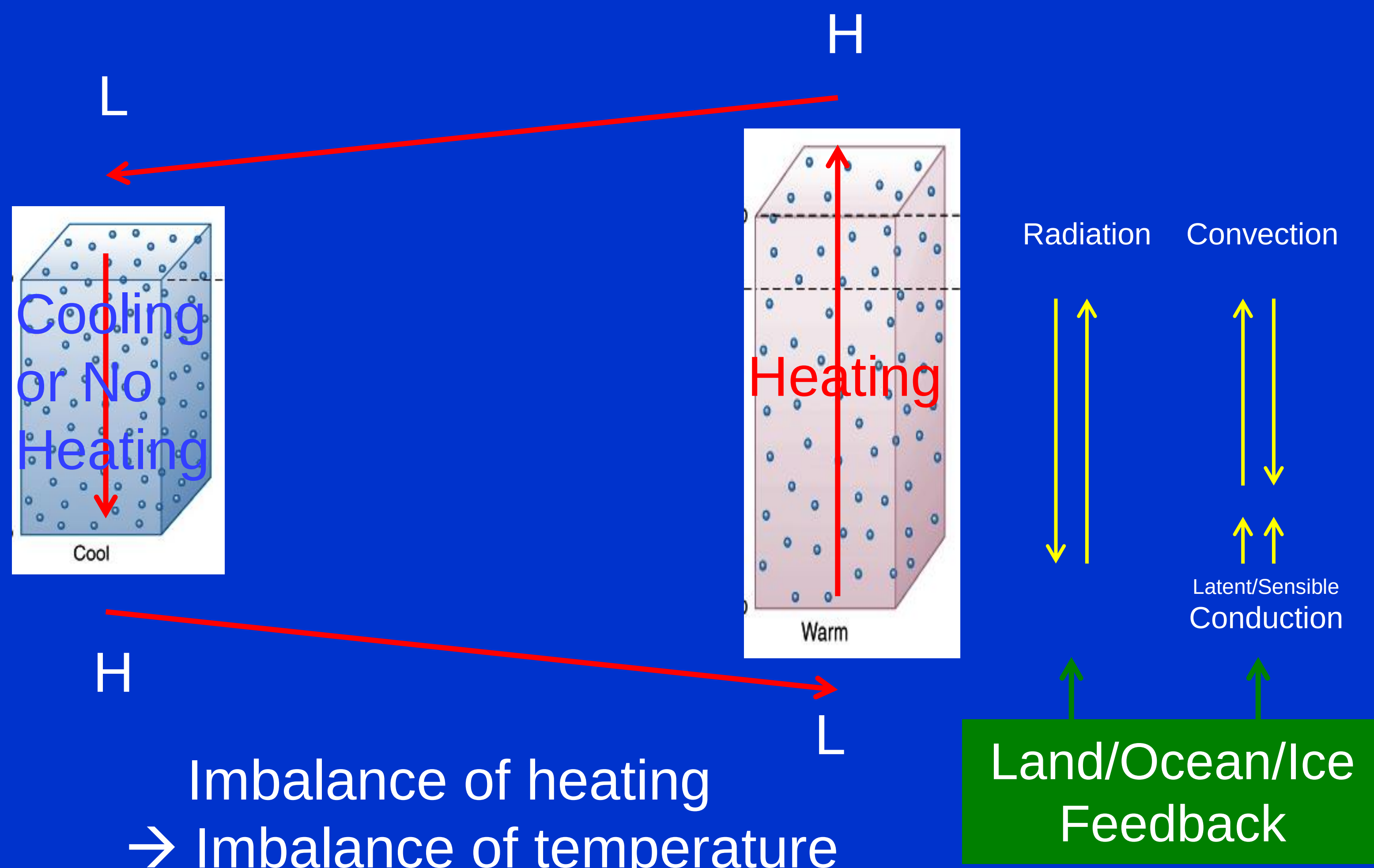
In particular, how is the thermally indirect Ferrel Cell maintained?

What drives the winds and temperature in the Atmosphere?



Geometry of the sun-earth system

The motion in the atmosphere (winds) is caused by Heating gradients.

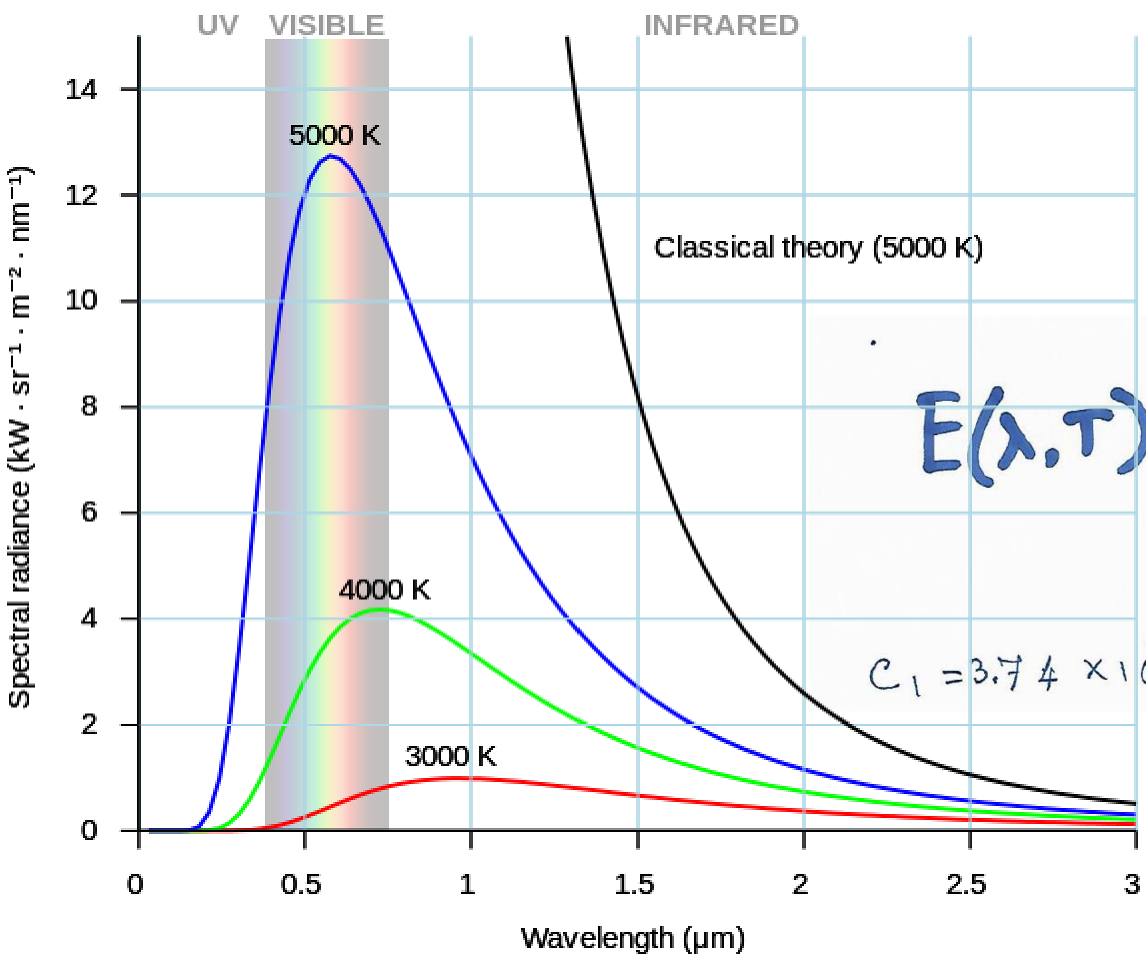


Imbalance of heating
→ Imbalance of temperature
→ Imbalance of pressure
→ Wind

Blackbody Radiation

Balance of Radiation received and lost by emission leads to Heating of atmosphere/earths surface. Need to review some basic concepts of Blackbody Radiation

Planck's Law: The amount of radiation emitted at wavelength λ by a blackbody at temperature T is given by Planck's Law by,



$$E(\lambda,T) = \frac{c_1}{\lambda^5\left(e^{\frac{c_2}{\lambda T}} - 1\right)} \qquad (1)$$

$c_1 = 3.74 \times 10^{-16}\ W\,m^{-2}$, $c_2 = 1.44 \times 10^{-2}\ m\,^{o}K$

Wein Displacement Law:

From the Planck's equation, we can derive that the wavelength at which maximum radiation is emitted by a blackbody is inversely proportional to Temperature, known as the Wein Displacement ;law.

$$\lambda_m = 2897/T \qquad (2)$$

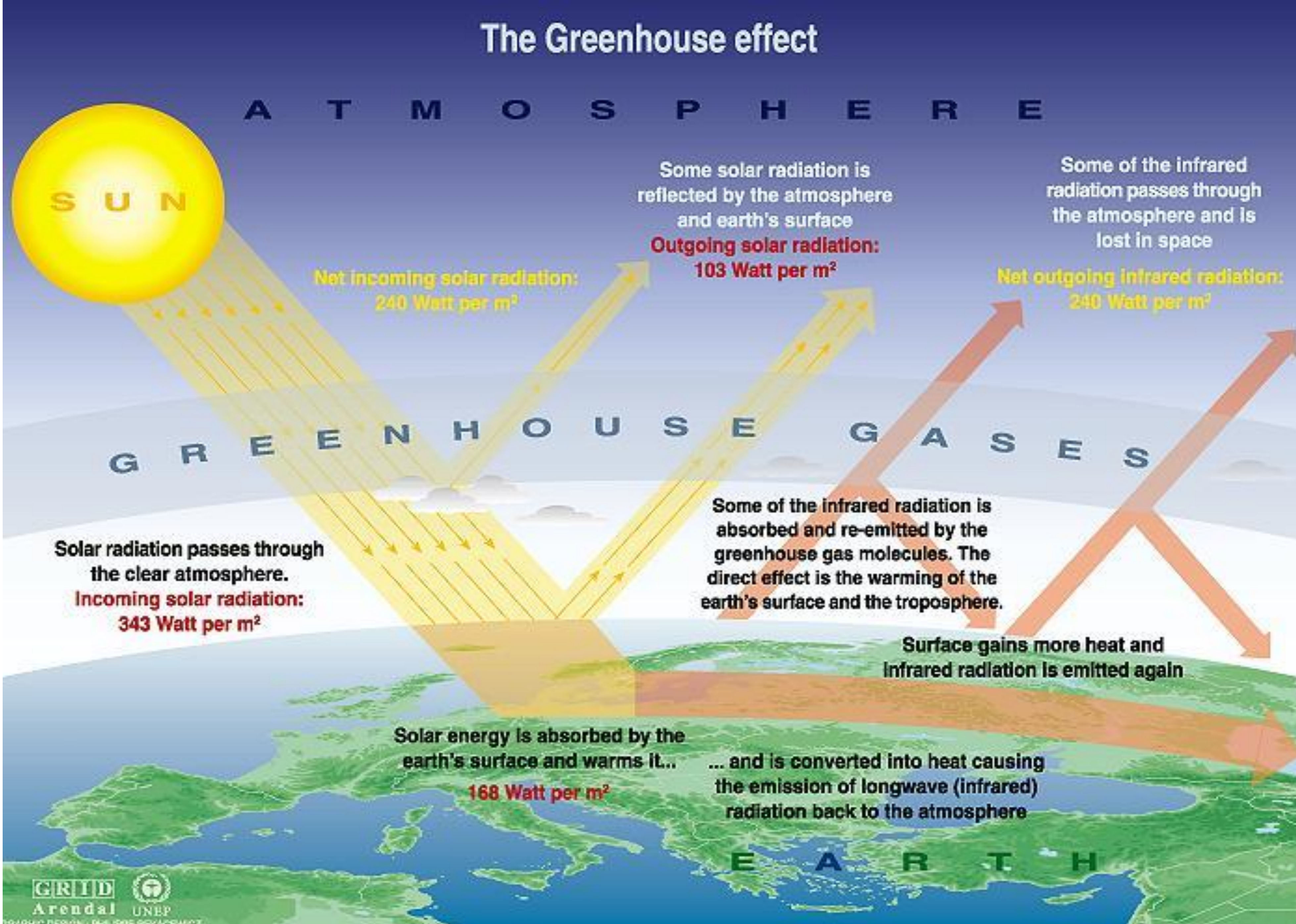
T→ temp. in ^{O}K

The Stephen-Bolzmann Law:

The radiance emitted by a black body can be obtained by integrating (1) over all wavelenghts, known as blackbody irradiance is given by,

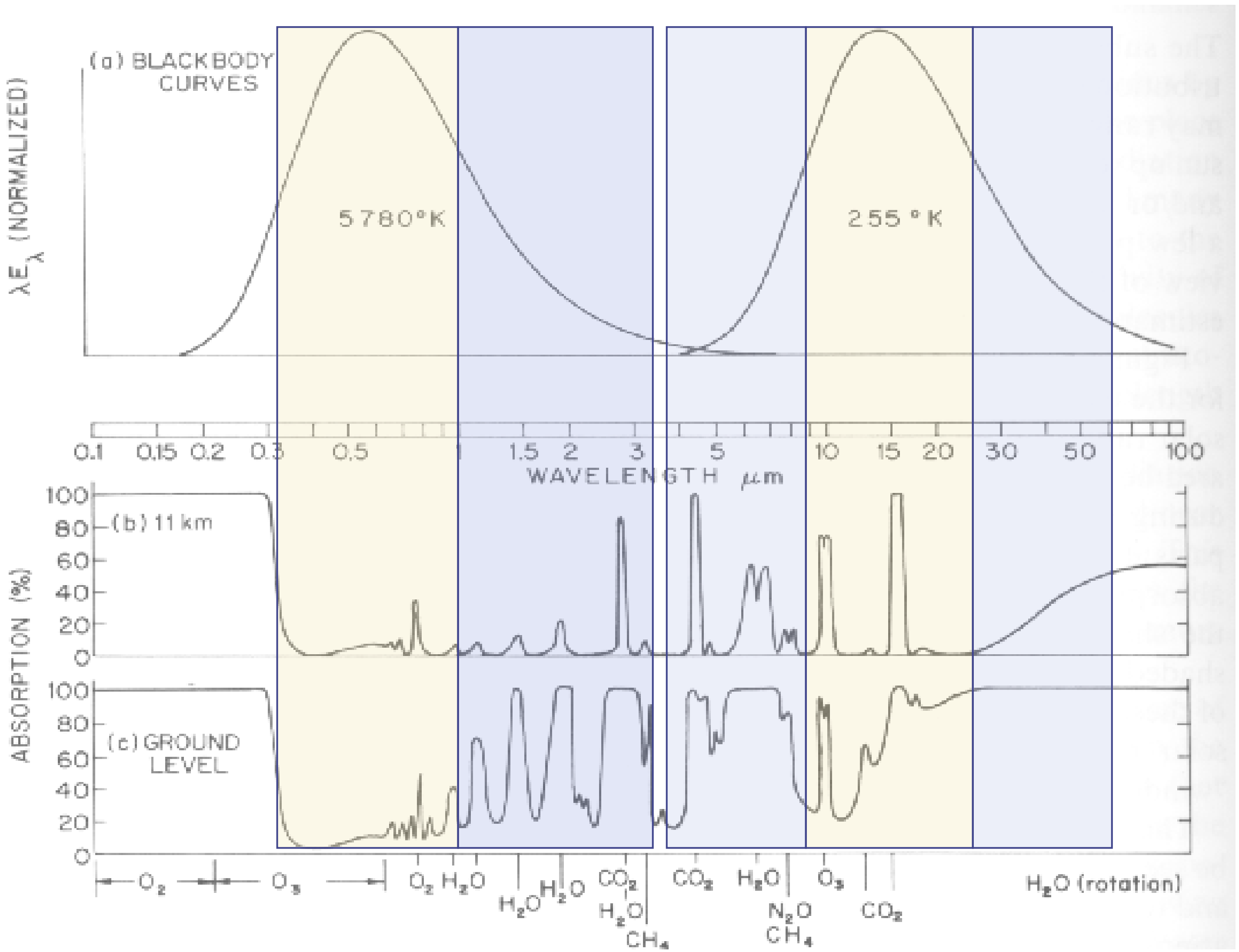
$$E^*(T) = \sigma T^4 \qquad (3)$$

$$\sigma = 5.67 \times 10^{-8}\ W m^{-2} deg^{-4}$$



Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996.

The Radiation Budget : Incoming Solar (SW) & outgoing LW



(Top) Normalized blackbody radiation for sun (left) and earth (right).

(Bottom) Absorption of solar radiation at 11 km and ground level.

The rest of the story on Climate in the next Lecture…

Thank You