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

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Lecture-2

Driver and Maintenance of the Mean Climate: Complexity in Climate Science

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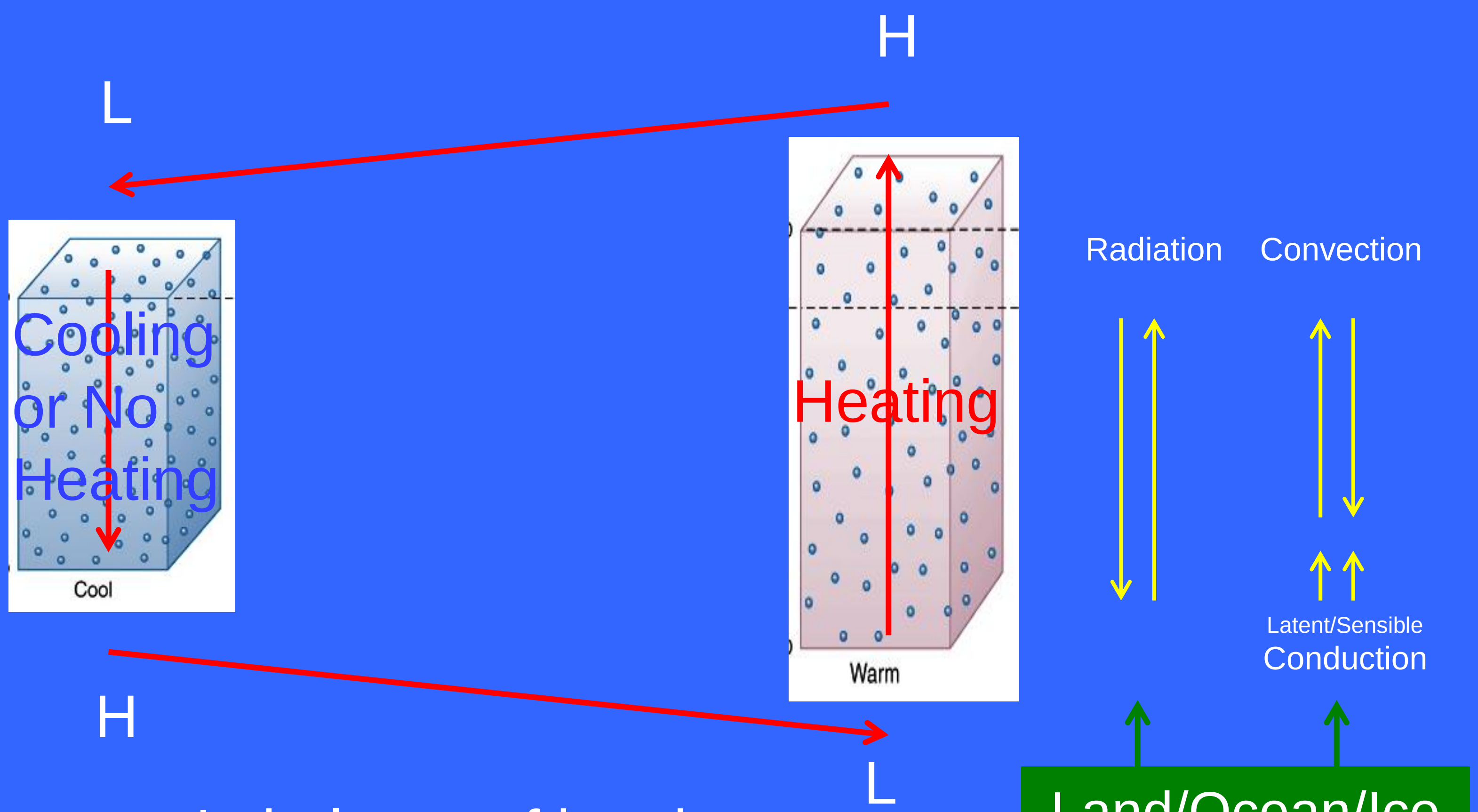
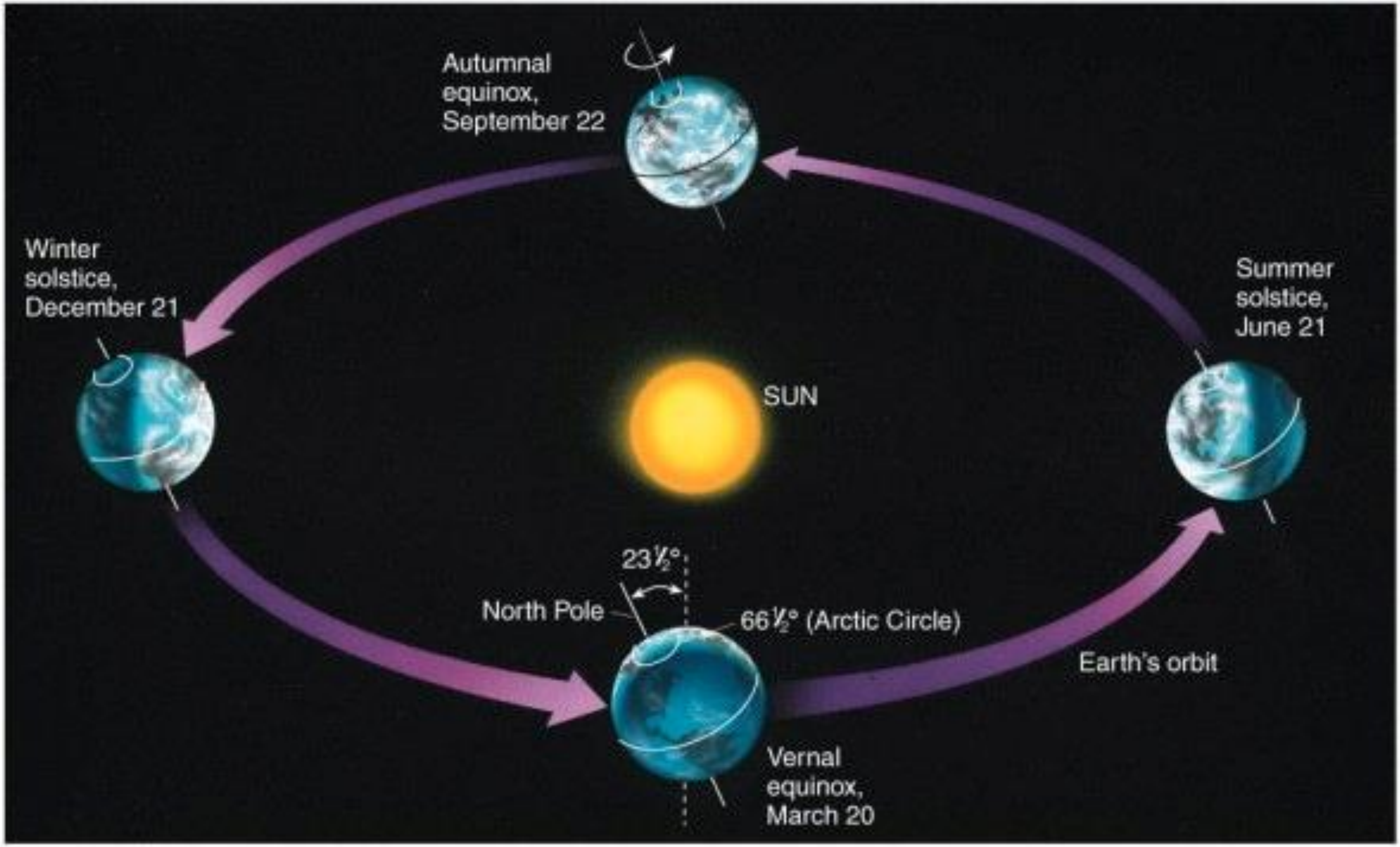
The motion in the atmosphere (winds) is caused by Heating gradients.

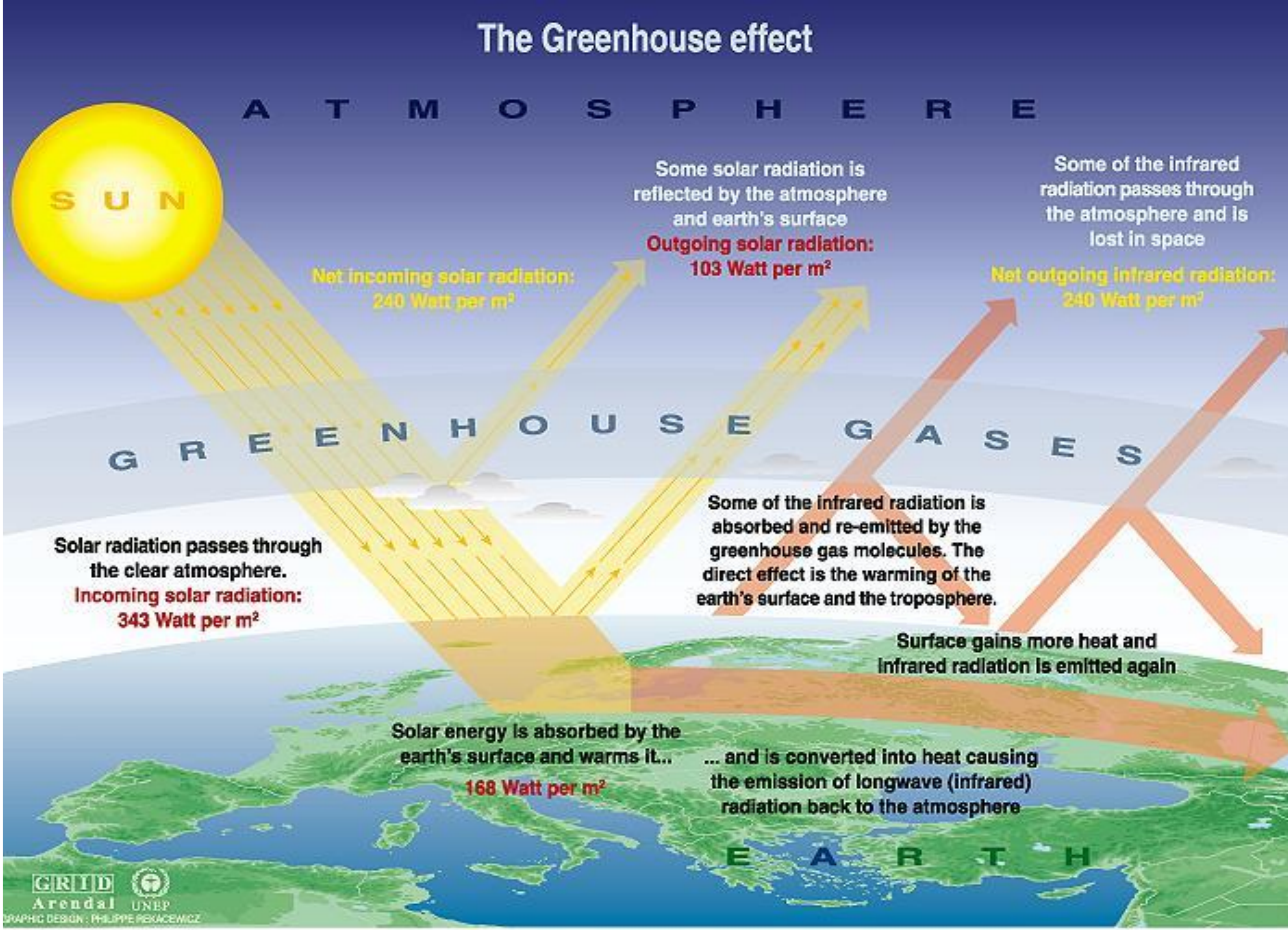


Imbalance of heating
→ Imbalance of temperature
→ Imbalance of pressure
→ Wind

Heating gradients on earth are produced by radiation balance from the Sun



Geometry of the sun-earth system



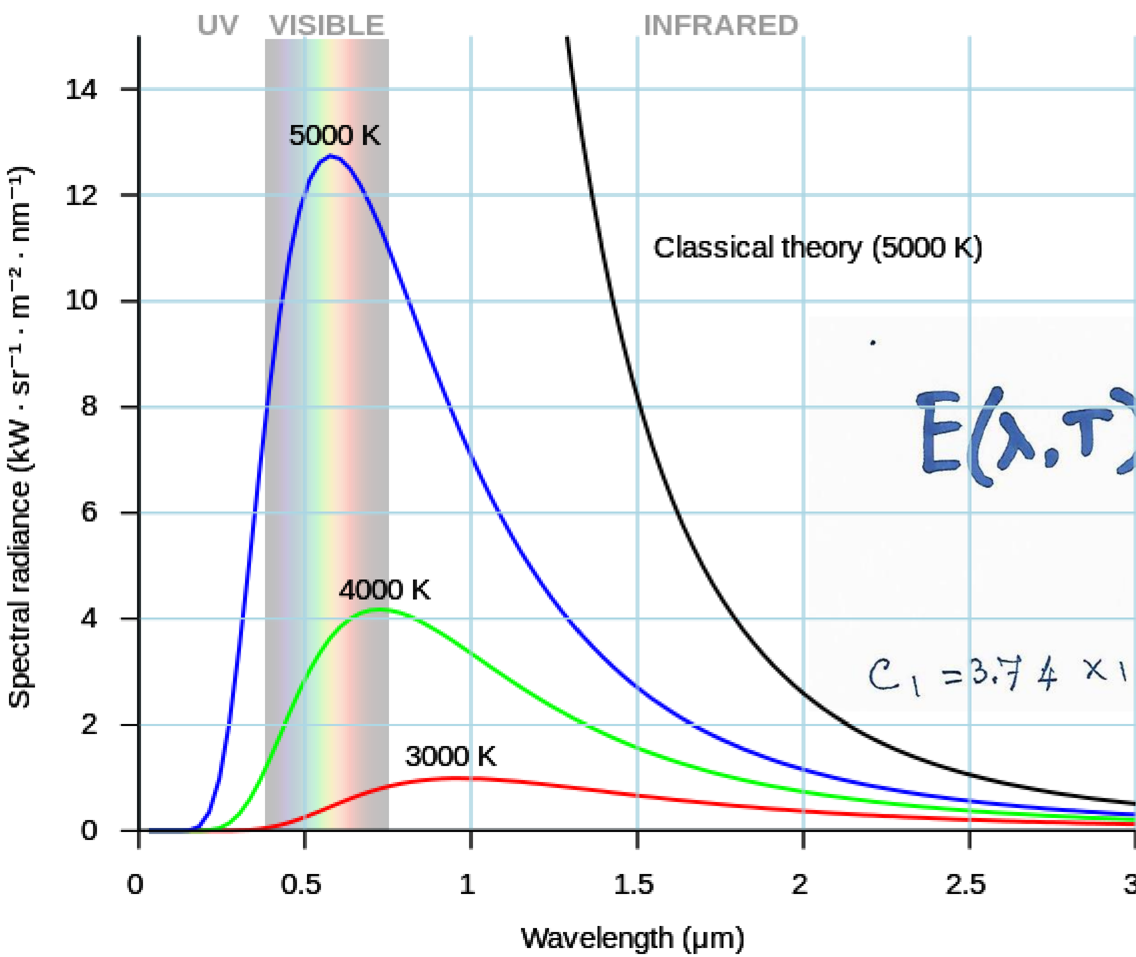
Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the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

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

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,



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

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

Blackbody Radiation

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.

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

T→ temp. in ^oK

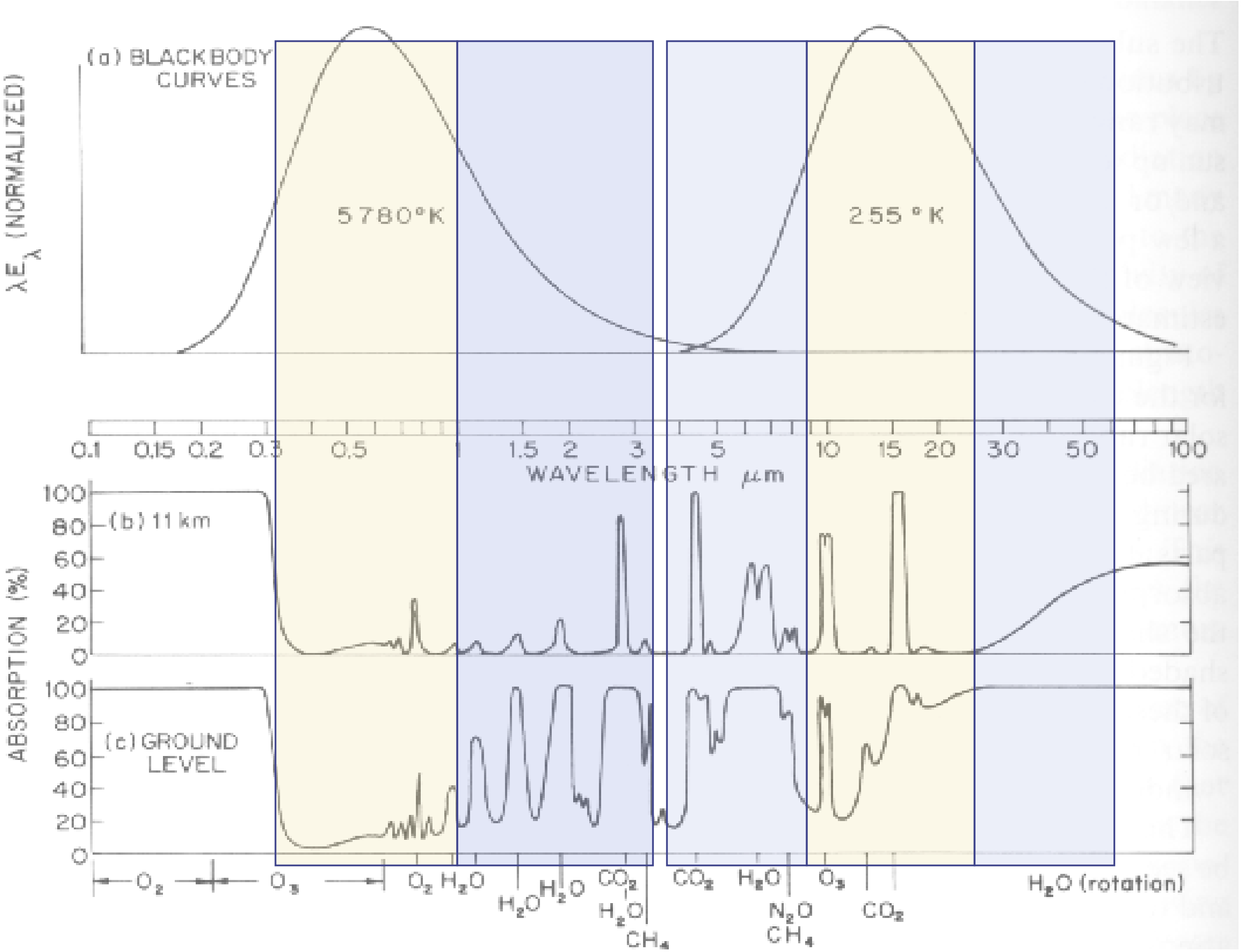
The Stephen-Bolzmann Law:

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

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

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

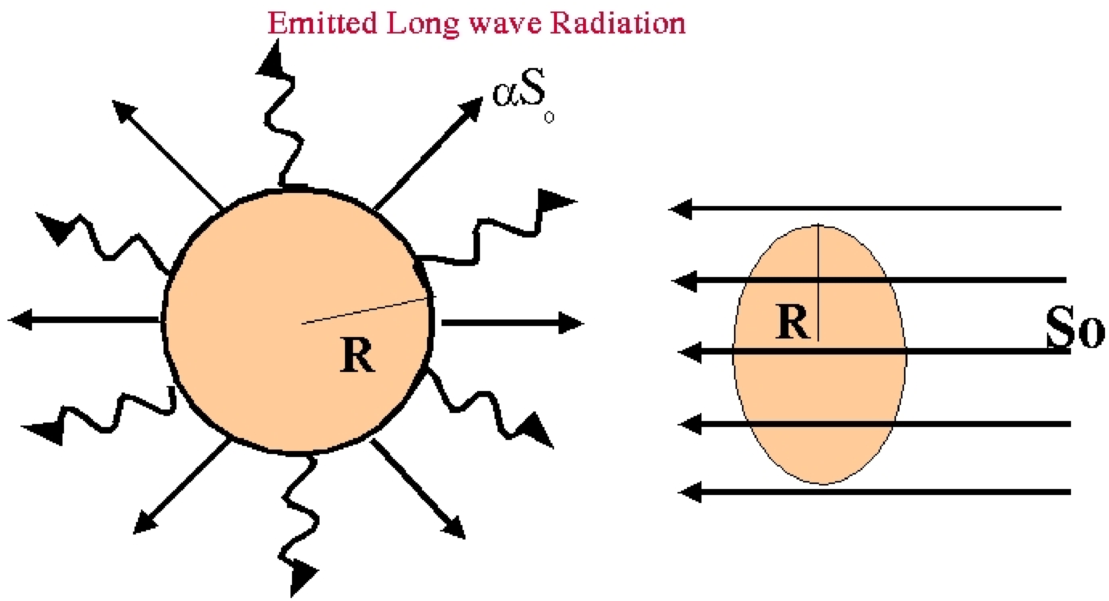
Fundamentals of the Greenhouse Effect



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

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

BASIC ENERGY BALANCE



Te- Equilibrium temperature.

Emitted Radiation = Absorbed Radiation

$$4\pi R^2 \tau \sigma T_e^4 = \pi R^2 (1-\alpha) S_o$$

Atmospheric Transmissivity Variations

Atmospheric Reflectivity Variations

Solar Energy Variations

Calculation of Radiative Equilibrium Temperature

LW radiation lost = Incoming solar radiation

$$\tau 4\pi R^2 \sigma T_e^4 = \pi R^2 (1-\alpha) S_0$$

Solar constant $S_0 \approx 1365$ W m^{-2}

Albedo $\alpha = 0.3$

T_e – Radiative equilibrium temperature

τ – Infrared transmissivity (assuming no atmosphere, $\tau = 1.0$)

$$\sigma T_e^4 = \frac{1}{4}(1-\alpha) S_0 = 238 \text{ W m}^{-2}$$

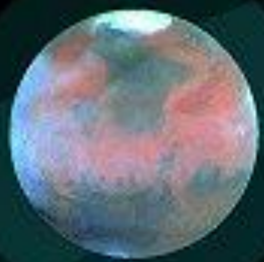
or $T_e = 255$ K (-18 $^\circ$ C) where $\sigma = 567 \times 10^{-8}$ W m^{-2} K^{-4}

Our current global mean surface temperature $T_{sfc} \approx 288$ K

ΔT = (288 - 255) = 33 K is the natural greenhouse effect of the earth's atmosphere.

A Tale of Three Planets

MARS
Sun Distance = 1.56 AU
F = 592 W/m^2
Albedo = 17%
T_{sfc} = 210 K
(1.0-0.17)F= **491.4**W/m^2



Mars: −63^{o}C

EARTH
Sun Distance = 1.00 AU
F = 1367 W/m^2
Albedo = 30%
T_{sfc} = 288 K

Earth: 15^{o}C (59^{o}F)

VENUS
Sun Distance = 0.72 AU
F = 2639 W/m^2
Albedo = 78%
T_{sfc} = 737 K
(1.0-0.78)F = **580.6** W/m^2

Venus: 464^{o}C

Surface Temperature

Sources: Calvin J. Hamilton, Views of the solar system, www.planetscapes.com; Bill Arnett , The nine planets, a multimedia tour of the solar system, www.seds.org/billa/tnp/nineplanets.html

Characteristics of atmospheres of four planets

R – Radius in units of earth's radius

A – Albedo

Te – Radiative equilibrium temp.

Tm – Approx. measured temp. at the top of the atmosphere.

Mr – Molecular weight of the air.

	Mean surface temperature (K)	Surface pressure (atm)	Accn due to gravity	Main constituents	
Venus	750	90	8.84	CO_2 96% N_2 4%	Deep clouds complete cover
Earth	280	1	9.81	N_2 78% O_2 21%	50% cover H_2O clouds
Mars	218	0.006	3.76	CO_2 95% N_2 3%	Some very thin H_2O clouds
Jupiter	134	2	26	H_2, He	NH_3 clouds

	R	A	T_e(K)	T_m(K)	M_r	Period of rotation (days)
Venus	0.72	0.77	277	230	44	243
Earth	1.00	0.30	256	250	28.8	1.00
Mars	1.52	0.15	216	220	44	1.03
Jupiter	5.20	0.58	98	130	2	0.41

Note: Mars atmosphere is very thin, about 100 times thinner than that of earth!

Role of the Atmosphere

- **Decreases Long Wave (LW) radiation loss to space**
- **Depends on clouds, Water vapor, and CO_2 distributions**

Equilibrium Temperature for Venus

For Venus, S_0 = 2643 W m^2. It is almost covered with thick CO_2 clouds. Therefore α = 0.77.

If the Venus atmosphere were transparent to LW radiation, the equilibrium temperature would be

$\sigma T_e^4 = \frac{(1-\alpha)S_0}{4} \approx$ 277 K

However, the surface temperature is 750 K. Thus the greenhouse effect of Venus atmosphere is 750 - 277 = 473 K !

However, if the earth had one uniform temperature, there would be no pressure gradient and no motion (winds)!

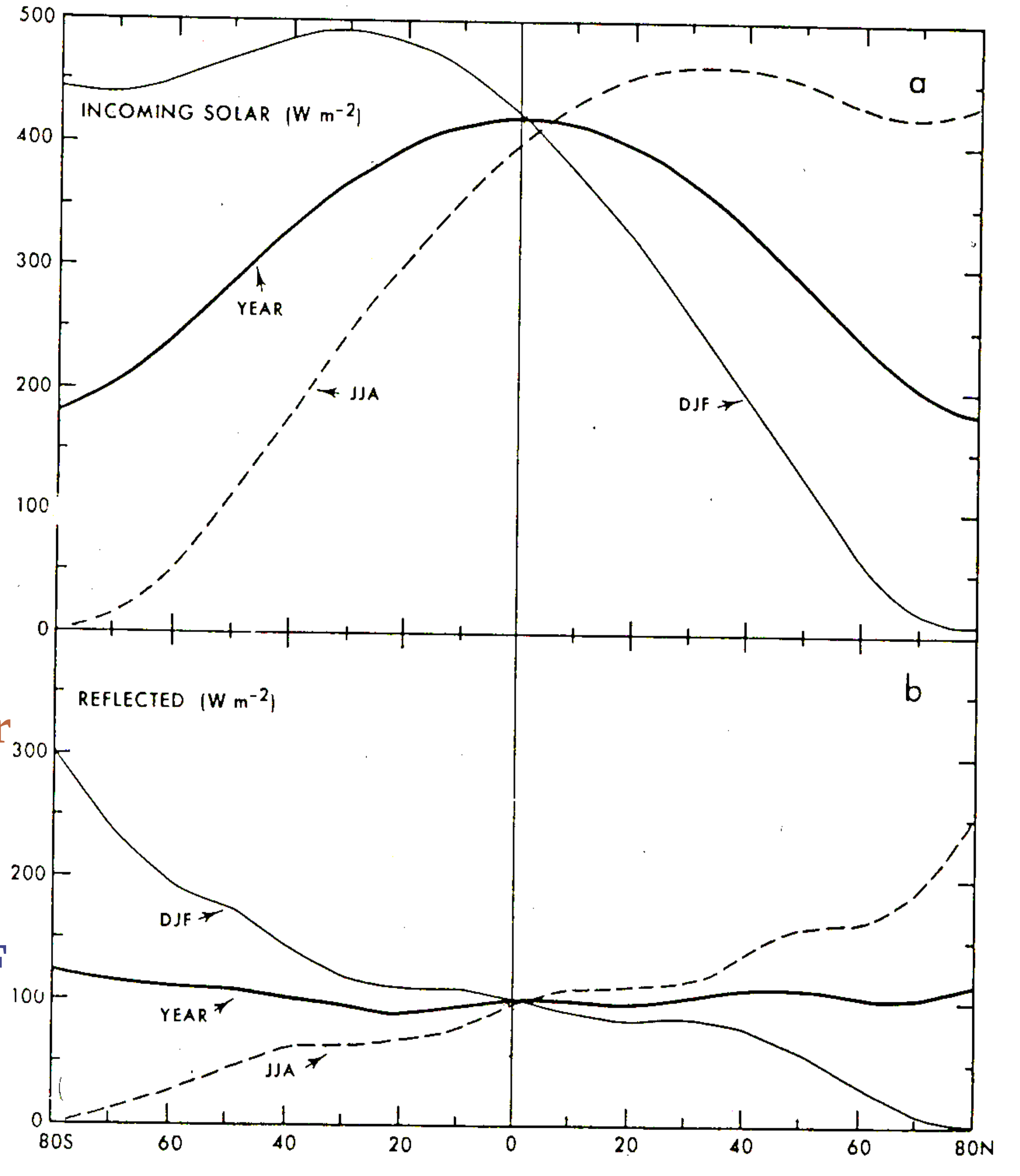
So, the energy balance model, just described is only a zero-order model of the earth's climate!

In reality, due to the sphericity of the earth and its inclination of its axis in the ecliptic plane, radiation received varies with latitude.

Next, the latitudinal variation of radiation balance is described.

Zonal mean incoming solar radiation (W m $^{-2}$) at the top of the atmosphere, annual mean (thick solid), JJA (dashed line) and DJF (thin solid) as a function of latitude.

Zonal mean reflected solar radiation (W m $^{-2}$) at the top of the atmosphere, annual mean (thick solid), JJA (dashed line) and DJF (thin solid) as a function of latitude.

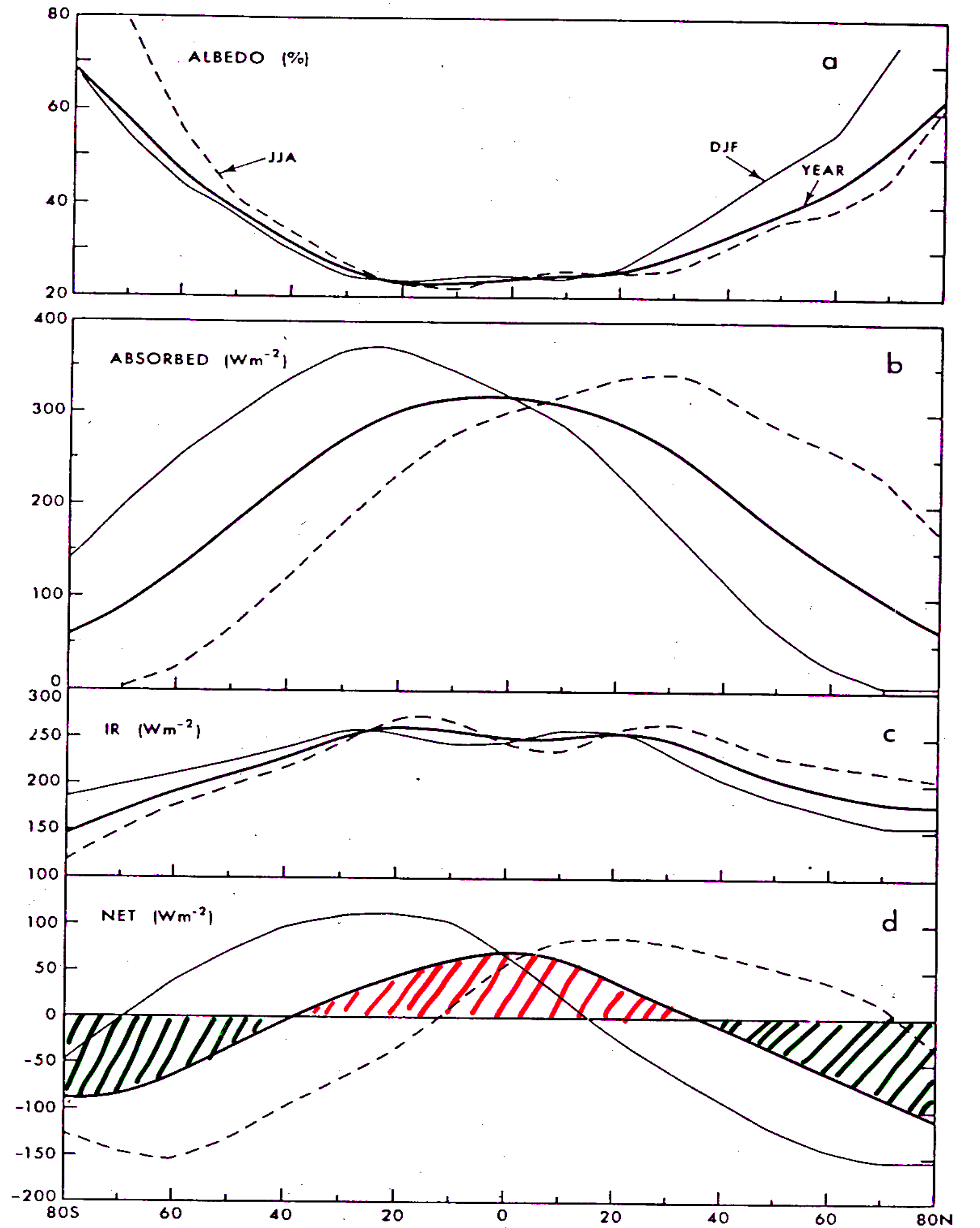


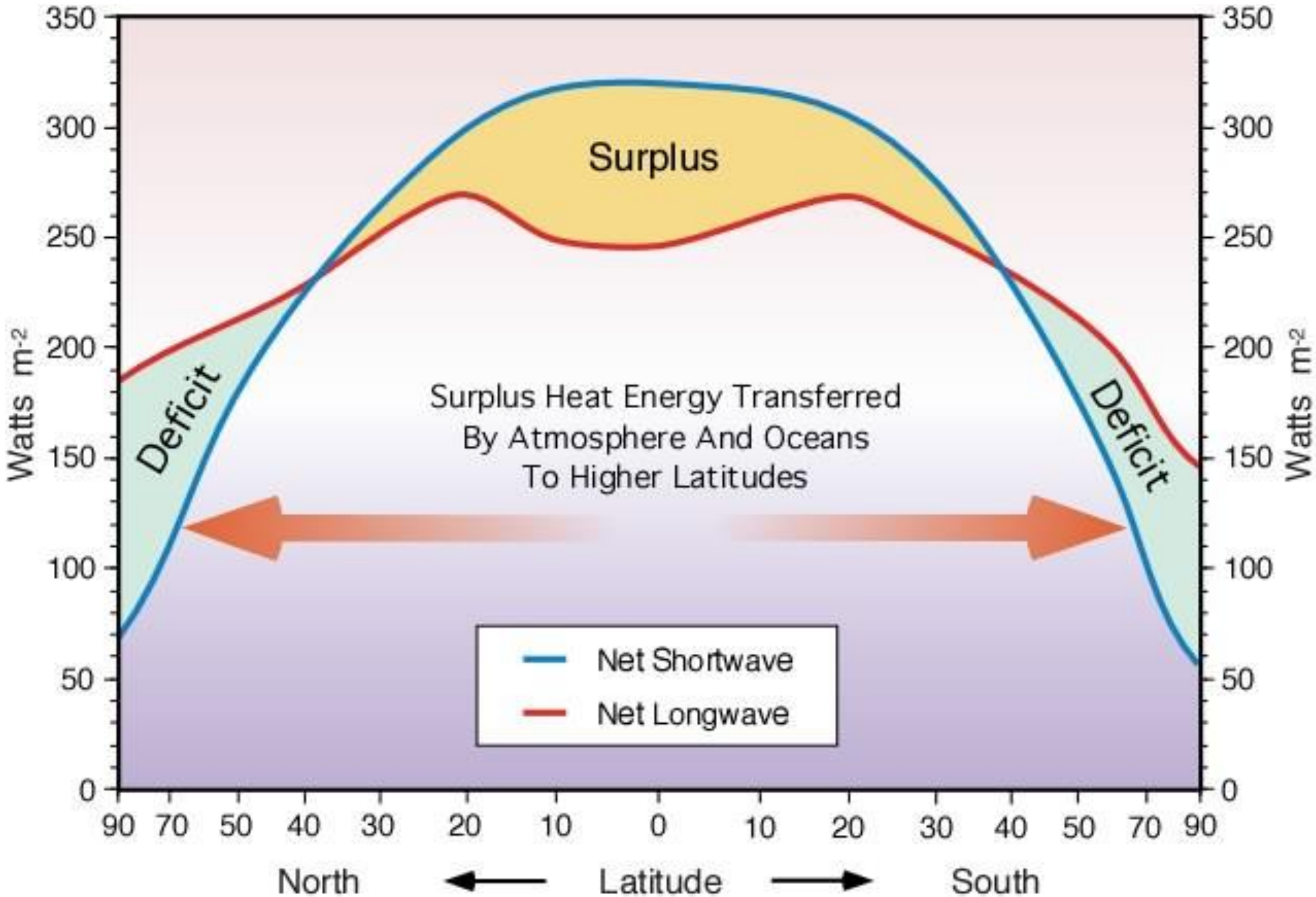
Zonal mean Albedo (%) at the top of the atmosphere, annual mean (thick solid), JJA (dashed line) and DJF (thin solid) as a function of latitude.

Zonal mean absorbed radiation (W m $^{-2}$), annual mean (thick solid), JJA (dashed line) and DJF (thin solid) as a function of latitude.

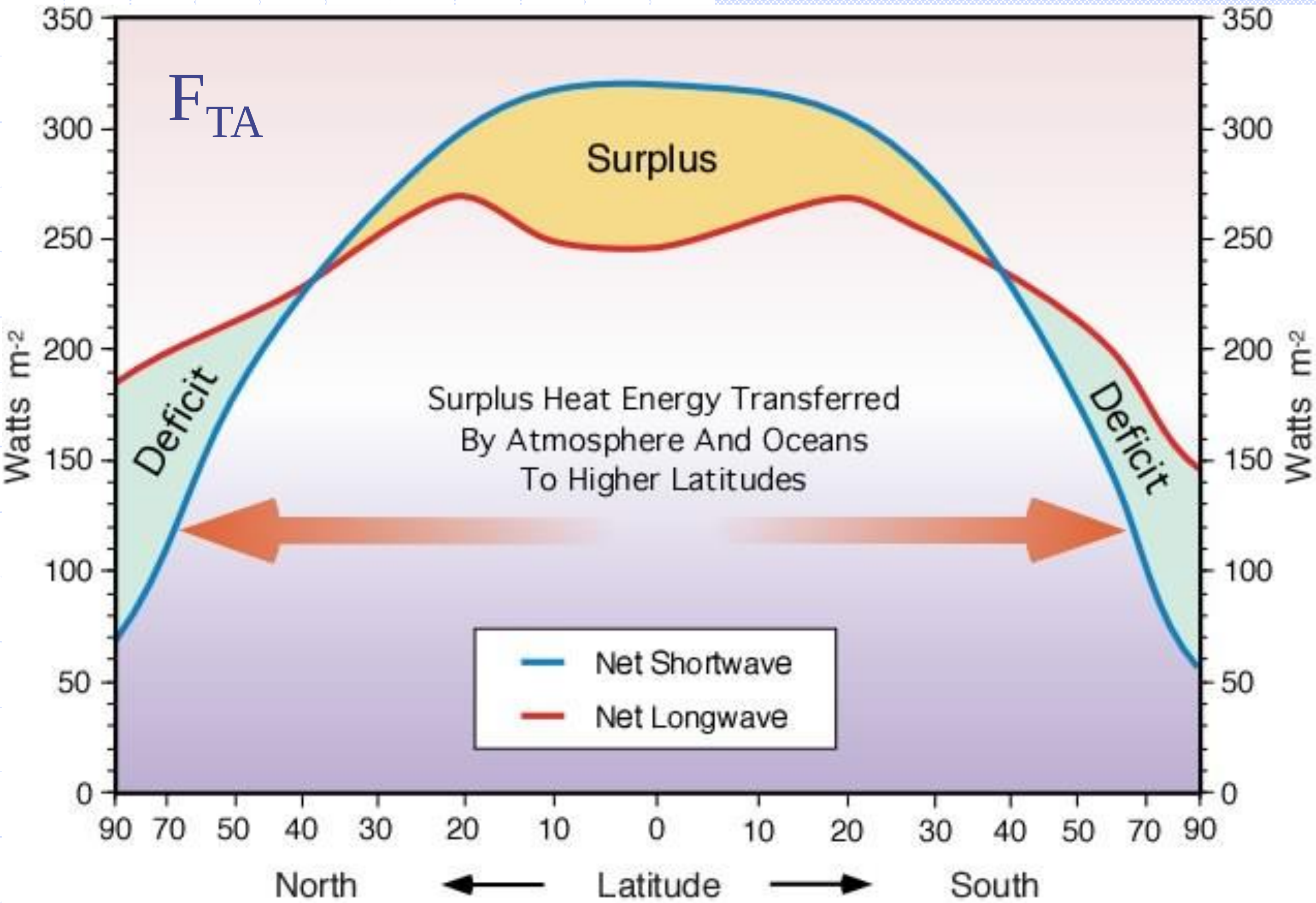
Zonal mean emitted radiation (W m $^{-2}$), annual mean (thick solid), JJA (dashed line) and DJF (thin solid) as a function of latitude.

Zonal mean net radiation (W m $^{-2}$) at the top of the atmosphere, annual mean (thick solid), JJA (dashed line) and DJF (thin solid) as a function of latitude.





- **Positive net heat flux at the top of the atmosphere and negative net heat flux over the polar region indicates that,**
- **Air should rise over the tropics and sink over the polar region.**
- **One large meridional cell?**
- **Early attempts to explain the general circulation assumed a single meridional circulation.**
- **But this cannot explain westerlies in the middle latitude. In this case we should have easterlies at the surface over the whole globe.**



The net heat balance at the TOA also indicates that, for the earth's climate to be in equilibrium, there must be mechanisms in place that continously transports heat from equatorial regions to the polar regions.

Required Heat Transport

$$T_A + T_O = -\int_{\phi_1}^{\pi/2} 2\pi r \cos\phi F_{TA}\, d\phi$$

Atmospheric transport

Oceanic transport

How are the Atmospheric motions generated?

Positive net heating in Tropics & negative net heating in Polar regions

→Warmer tropics & Colder polar regions

→Lower Pressure in the tropics and higher pressure in the polar regions

→Air moves under the action of the pressure gradient force and motion is generated.

→As the earth is rotating, Coriolis force modifies this motion and observed circulation is generated.

Governing Equations

The equations of motion in a relative framework can be written as

$$\frac{d\mathbf{V}}{dt} = -2\Omega \times \mathbf{V} - \frac{1}{\rho}\nabla p + \mathbf{g} + \mathbf{F}$$

$-2\Omega \times \mathbf{V}$ is the Coriolis term

$\mathbf{F}$ is the friction

$\frac{1}{\rho}\nabla p$ is the pressure gradient term

$\mathbf{g}$ is the gravity term

$\mathbf{V}$ is the three dimensional velocity vector

The equation of conservation of energy can be expressed by the first law of thermodynamics can be written as

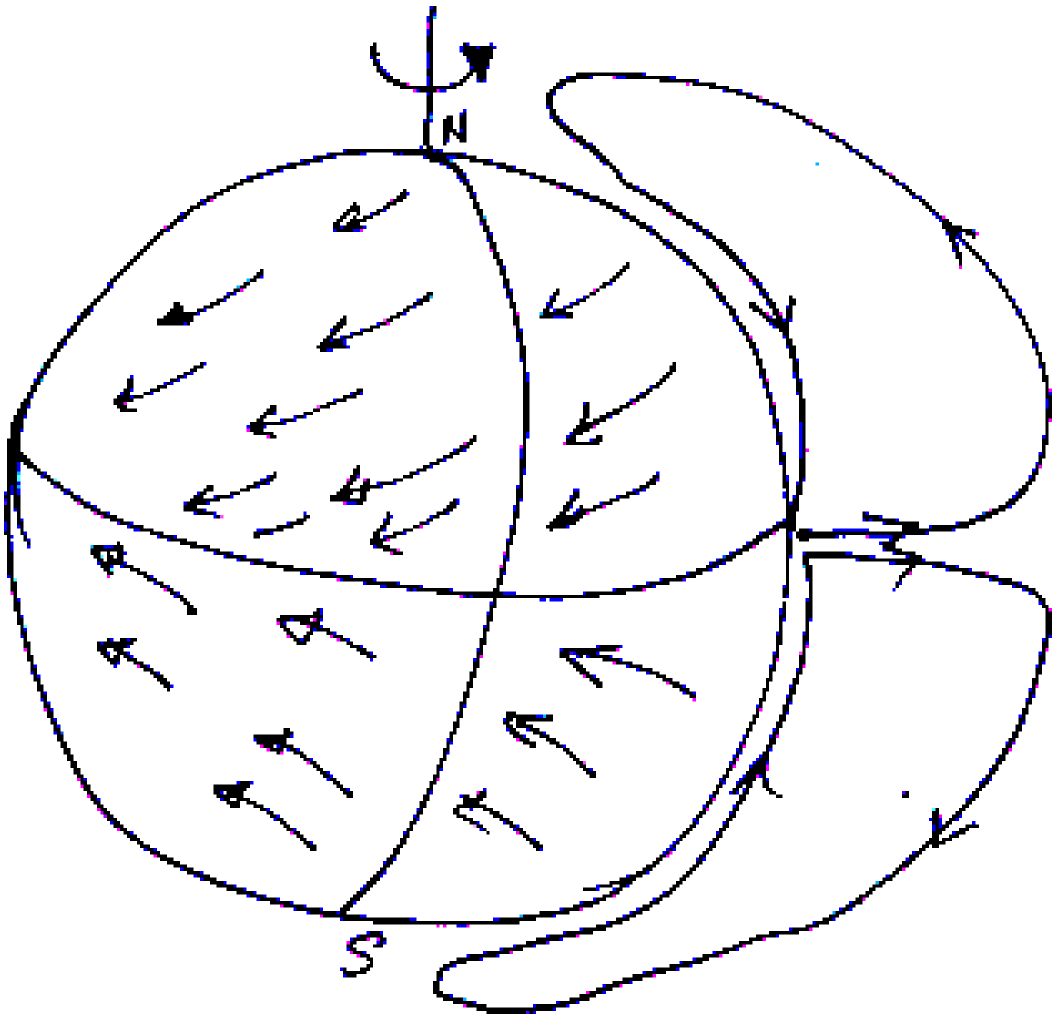
$$c_p \frac{T}{\theta}\frac{d\theta}{dt} = Q$$

where θ is the potential temperature defined by

$$\theta = T\Big(\frac{p_{00}}{p}\Big)^{\kappa}$$

and Q = Net radiation + Latent heat + Sensible heat

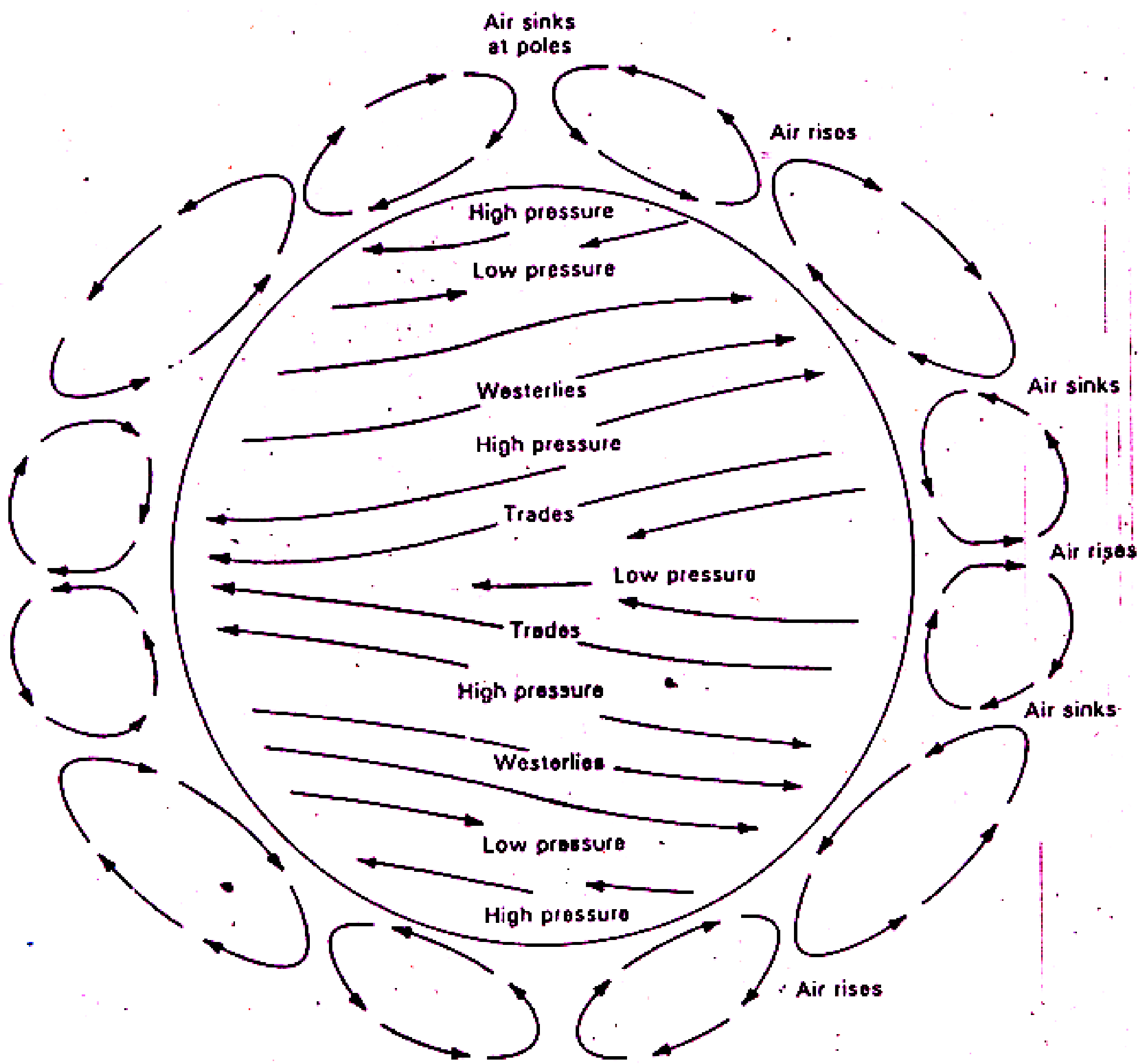
Thus, if air rises at the equator and moves to the poles and sink and return to the equator near the surface it would set up ONE huge N-S cell in each hemisphere. What would happen to the surface winds?



If the surface winds were easterlies everywhere as shown, what would happen to the rate of rotation of the earth?

Surface winds if there were only one meridional cell.

How do we explain surface easterlies in tropics and westerlies in middle latitudes? A three cell meridional circulation is required.



How is a three cell meridional structure is maintained?

- **The middle cell where ascending motion takes place around 60 deg where the surface is relatively warmer and descending motion takes place around 30 deg where the surface is relatively warmer is a thermally ‘indirect’ cell, also called Ferrel cell (William Ferrel, 1817-1891, American Meteorologist).**

- **What is responsible for the ‘indirect’ Ferrel cell? What makes air to rise over a surface which is colder than over its descending region?**

So, What is responsible for the 'indirect meridional cell?

I mentioned earlier that large amplitude Rossby waves are important part of middle latitude circulation. Could these waves play a role is causing the 'indirect' meridional cell?

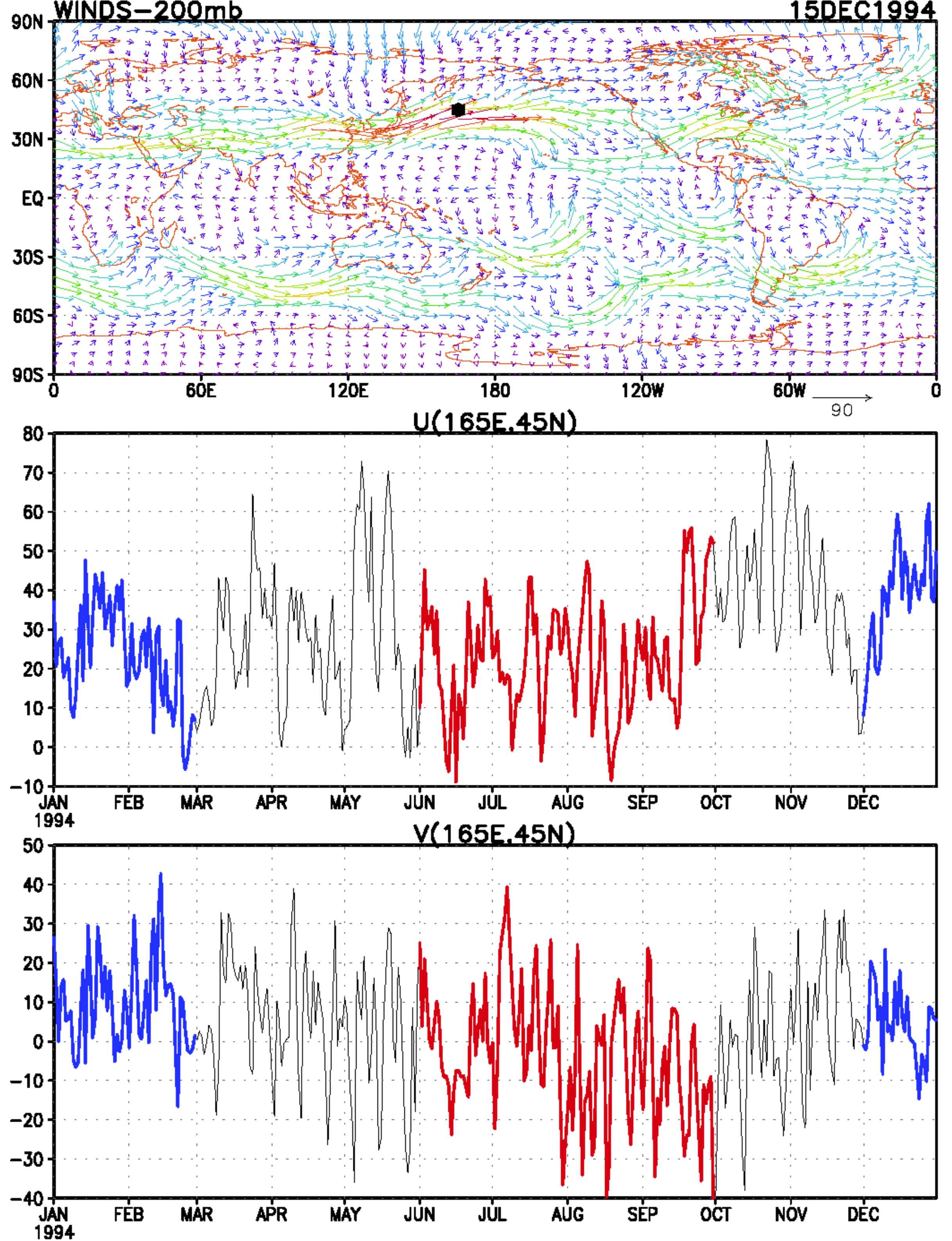
What are the amplitudes of these waves? Plot standard deviation.

Can they transport heat and momentum? We shall calculate transport of heat ($[\overline{v't'}]$) and $[\overline{v'u'}]$.

An example of amplitude daily fluctuations of wind at 200 hPa level at a point in middle latitude (shown by the dot)

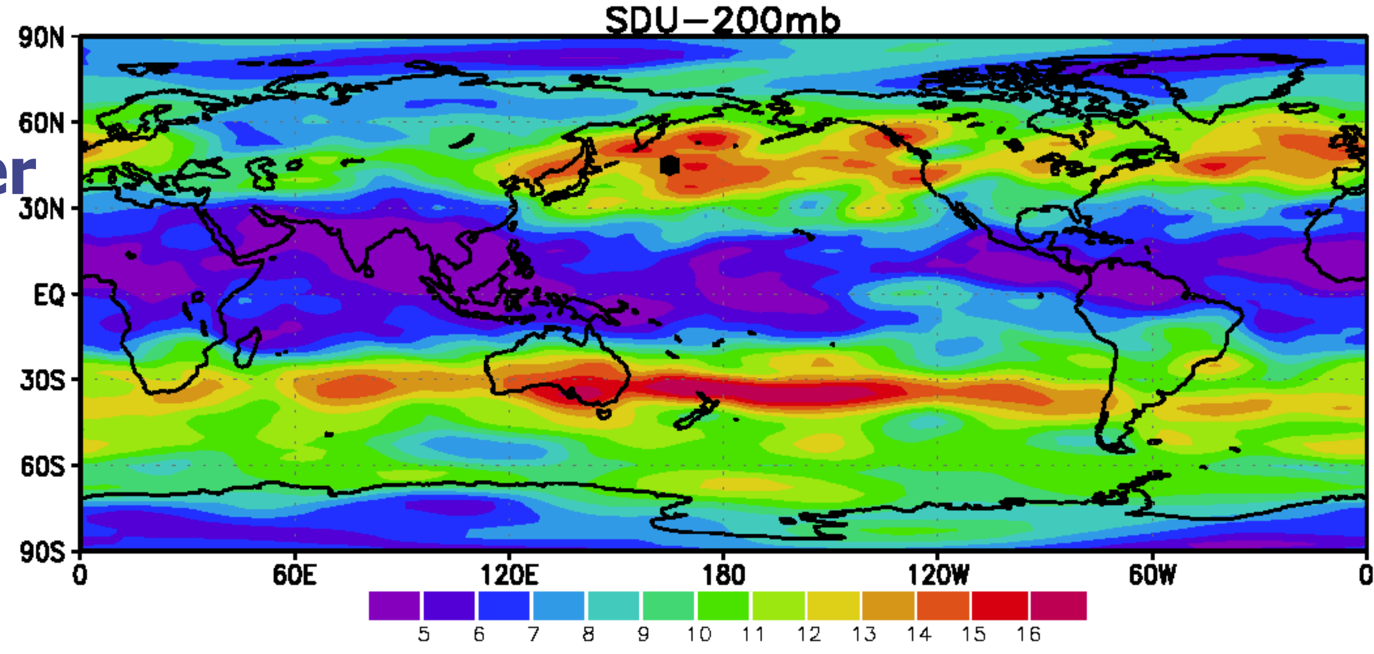
U and V winds during summer (red) and winter (blue) are highlighted.

It may be noted that 20-40 m/s wind variation from one day to another takes place.



Standard deviation of daily fluctuations of U wind at 200 hPa level during summer season over all grid points

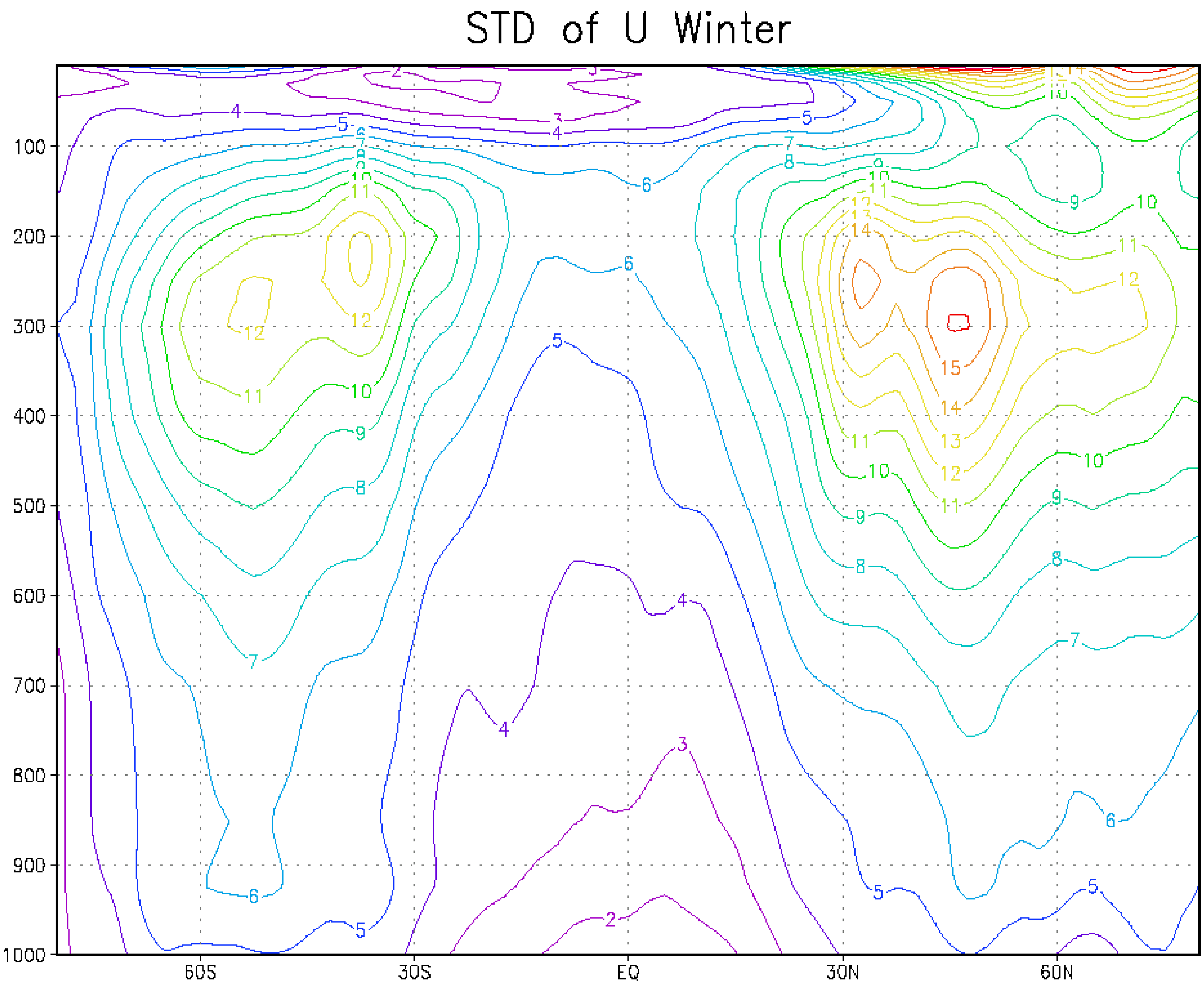
JJAS



Note that S.D. is generally uniform along a latitude circle.

Also note that the S.D is small in tropics and large in middle latitudes.

H
E
I
G
H
T

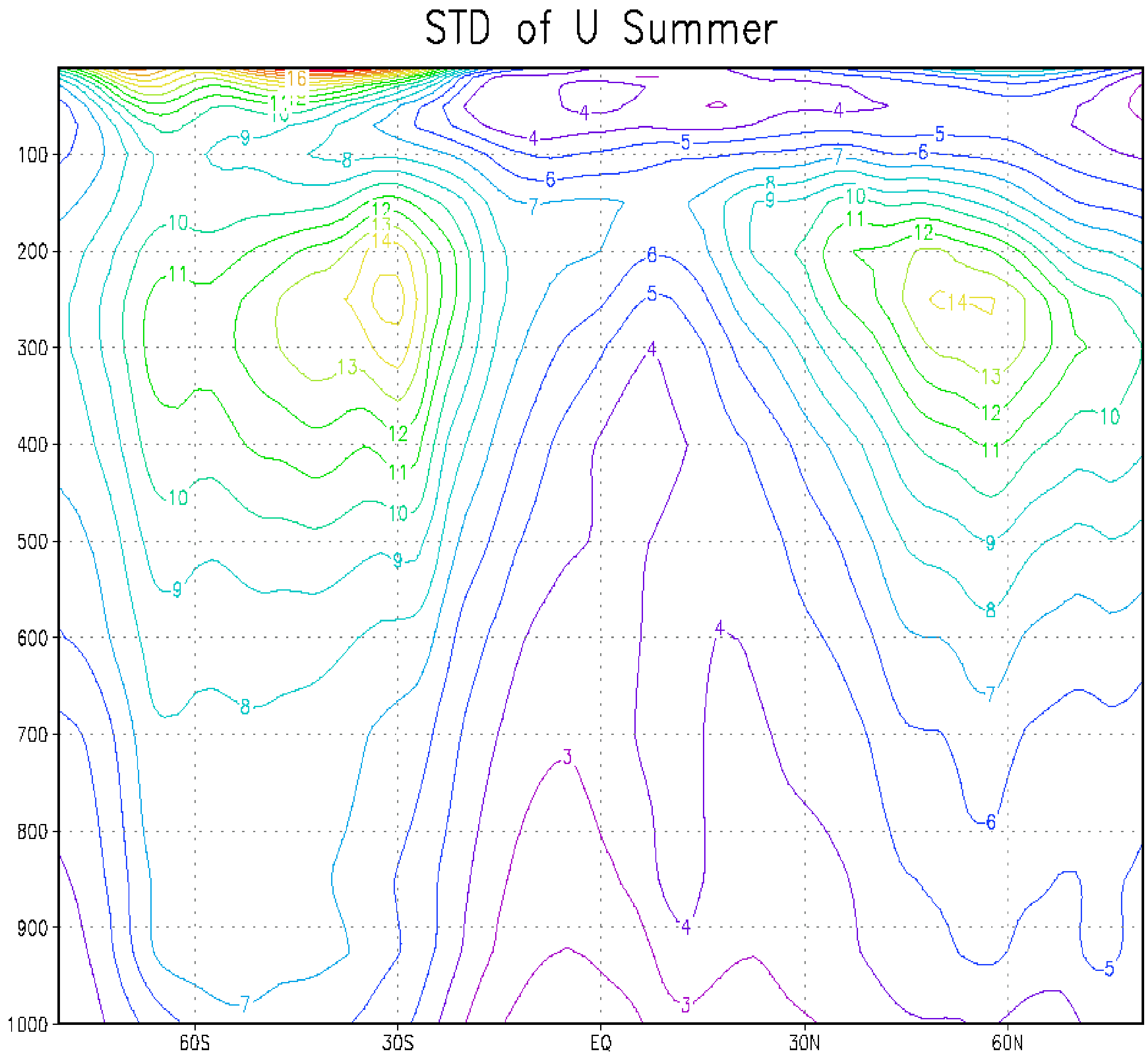


Note large day-to-day fluctuations (~15 m/s) of zonal winds in middle lat. Upper atmos. In the exit region of the subtropical westerly jets.

It is small in the tropics (~3-5 m/s)

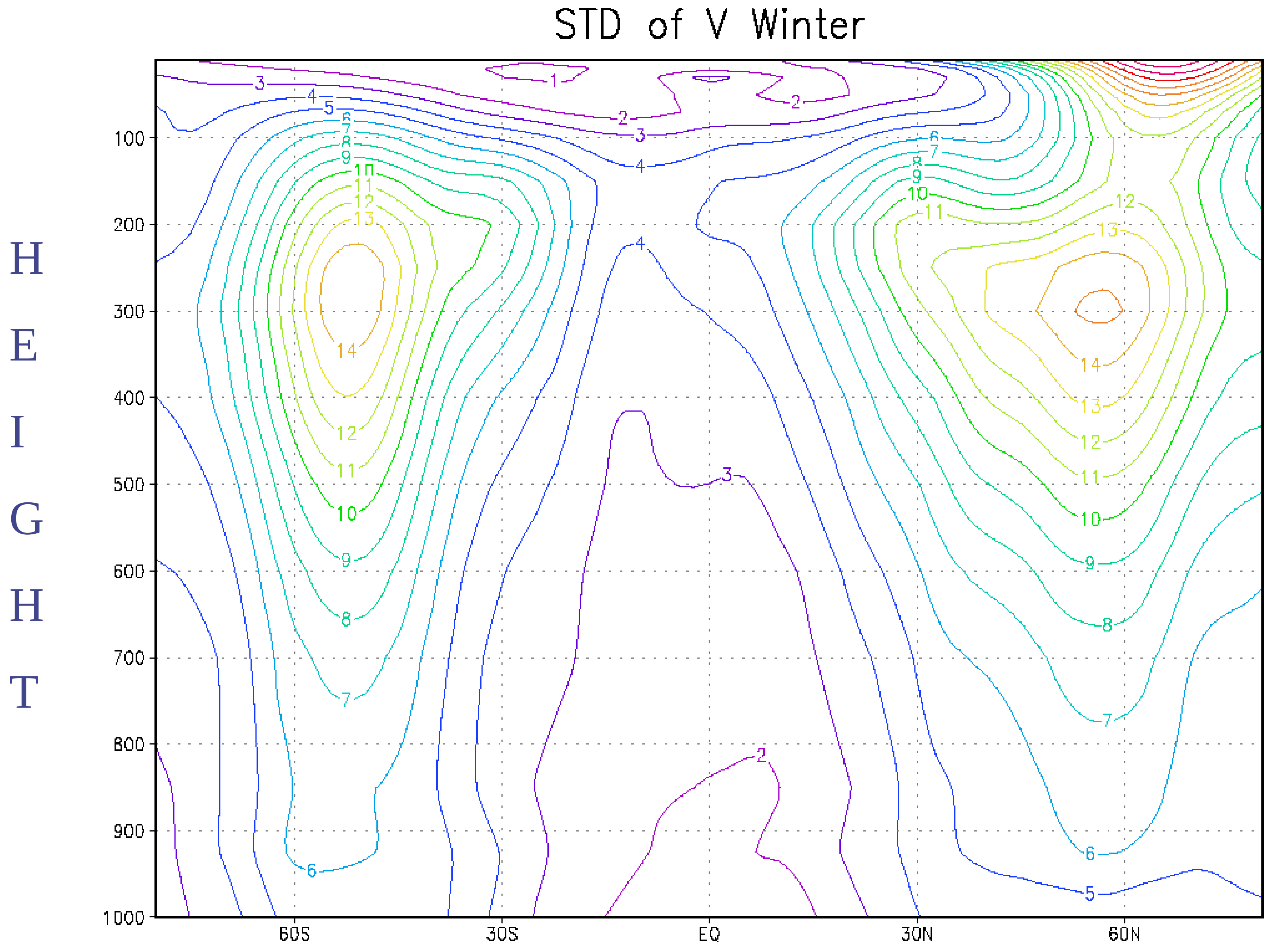
Standard Deviation of east-west component of wind (m/s) during northern winter (DJF) averaged over each latitude circle

H
E
I
G
H
T

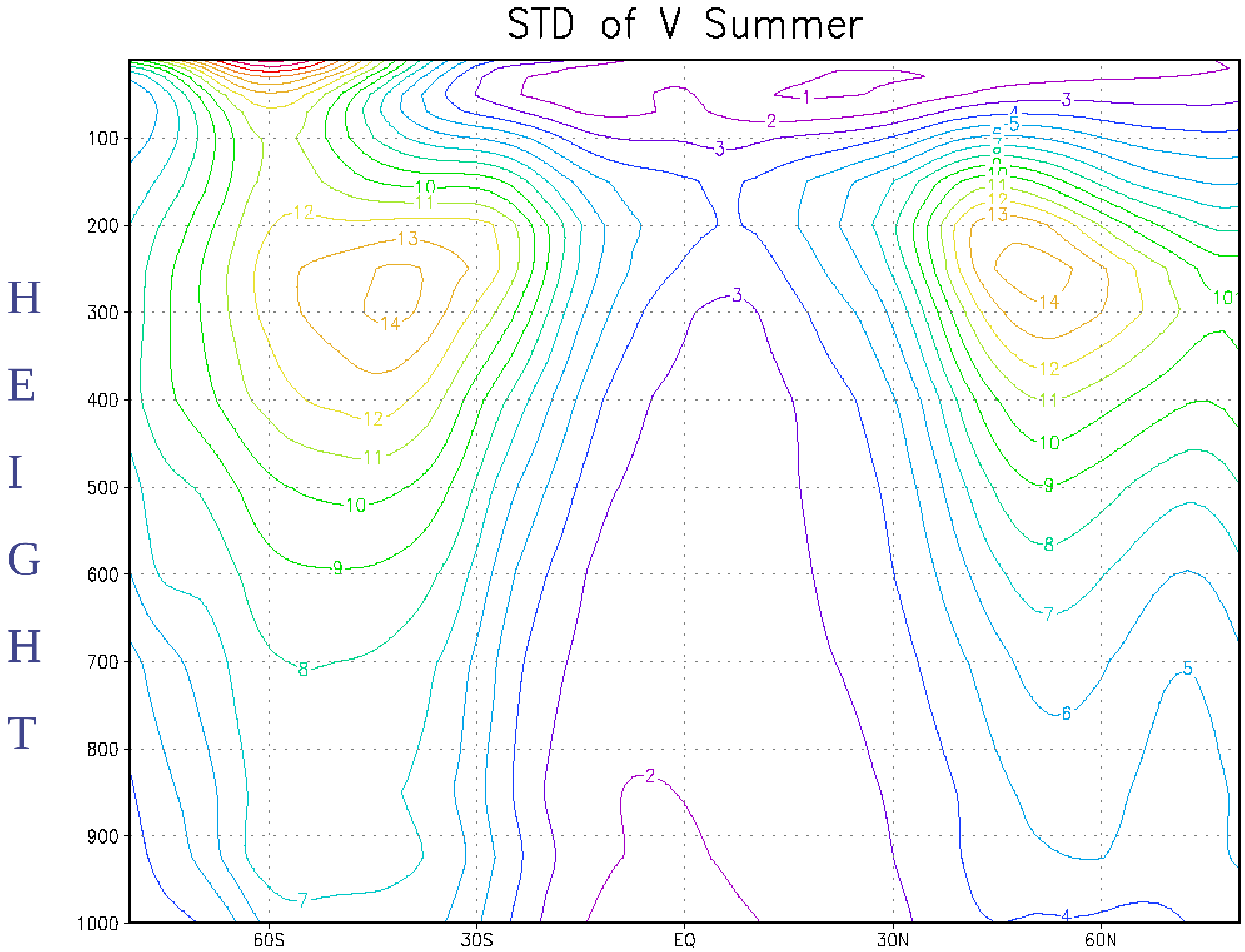


Similar to the distribution during winter (previous figure). However, there is one major difference in the distribution. What is it?

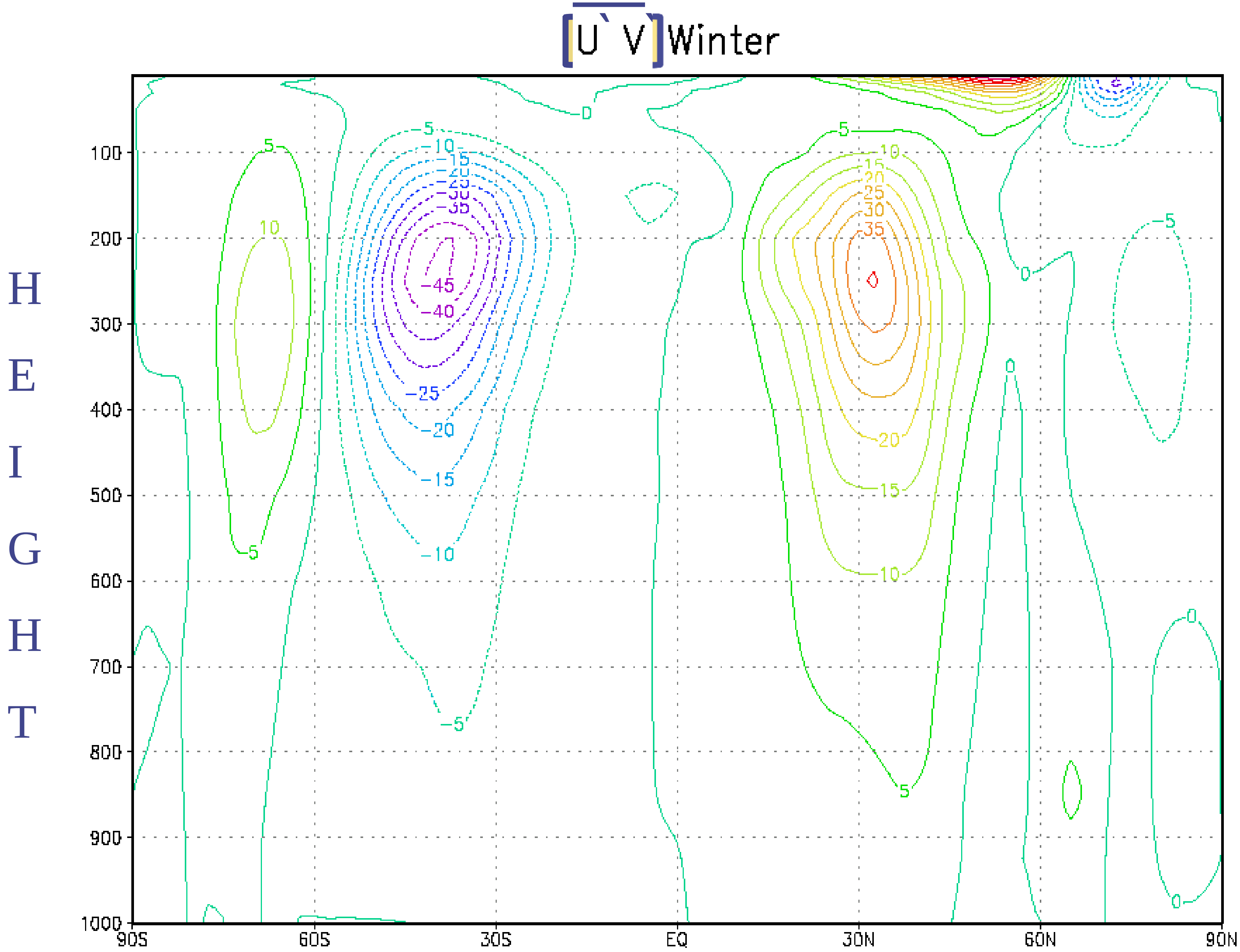
Standard Deviation of east-west component of wind (m/s) during northern summer (JJA) averaged over each latitude circle



Standard Deviation of north-south component of wind (meridional wind , m/s) during northern winter averaged over each latitude circle



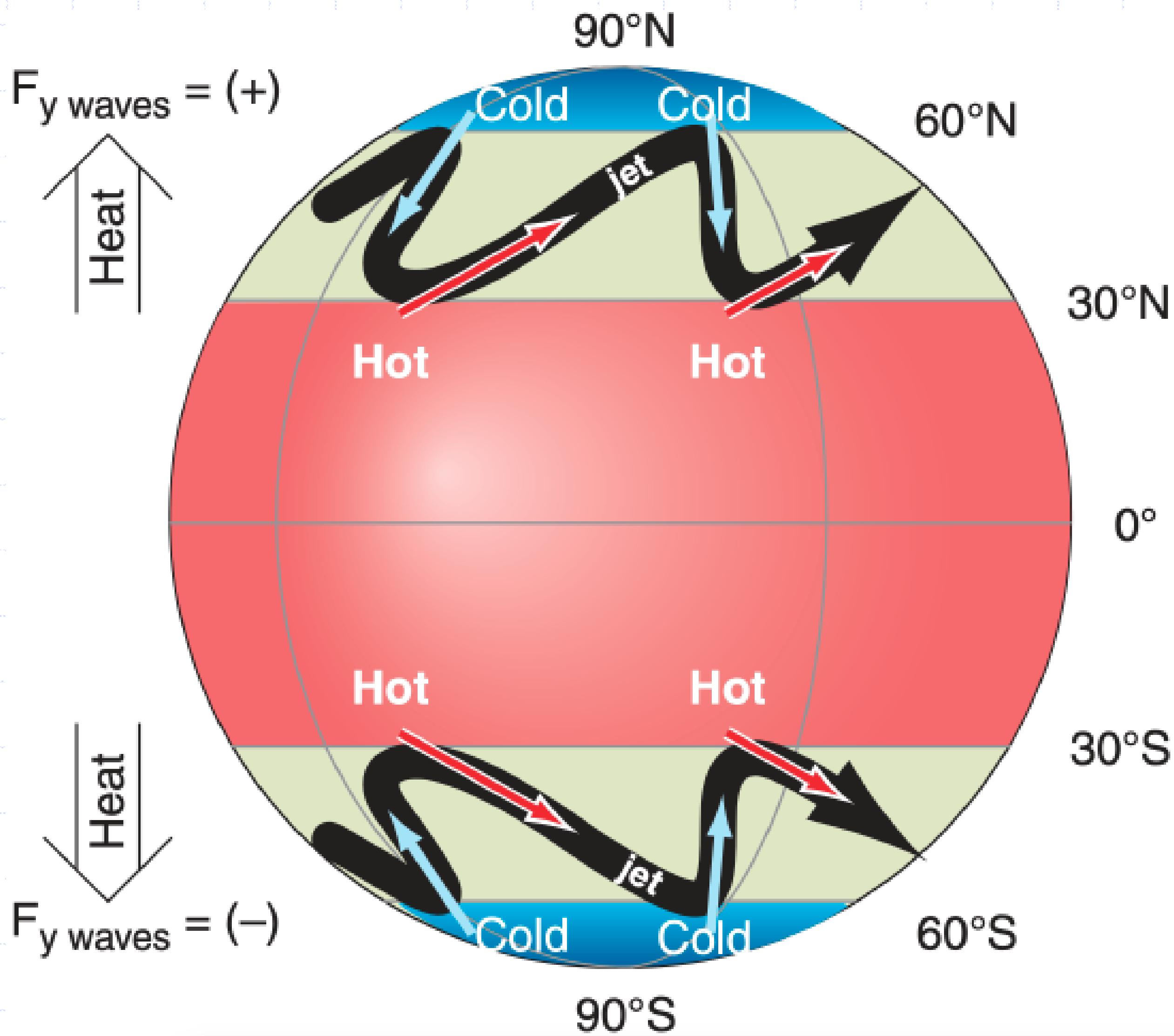
Standard deviation of north-south component of wind (meridional wind, m/s) during northern summer averaged over each latitude circle.



Northern winter mean zonally averaged northward transport of zonal momentum by transient eddies [u'v']bar, (m^2/s^2)

Thus, there is no doubt that the transient waves transport heat pole ward in both hemispheres. However, how do the waves achieve this?

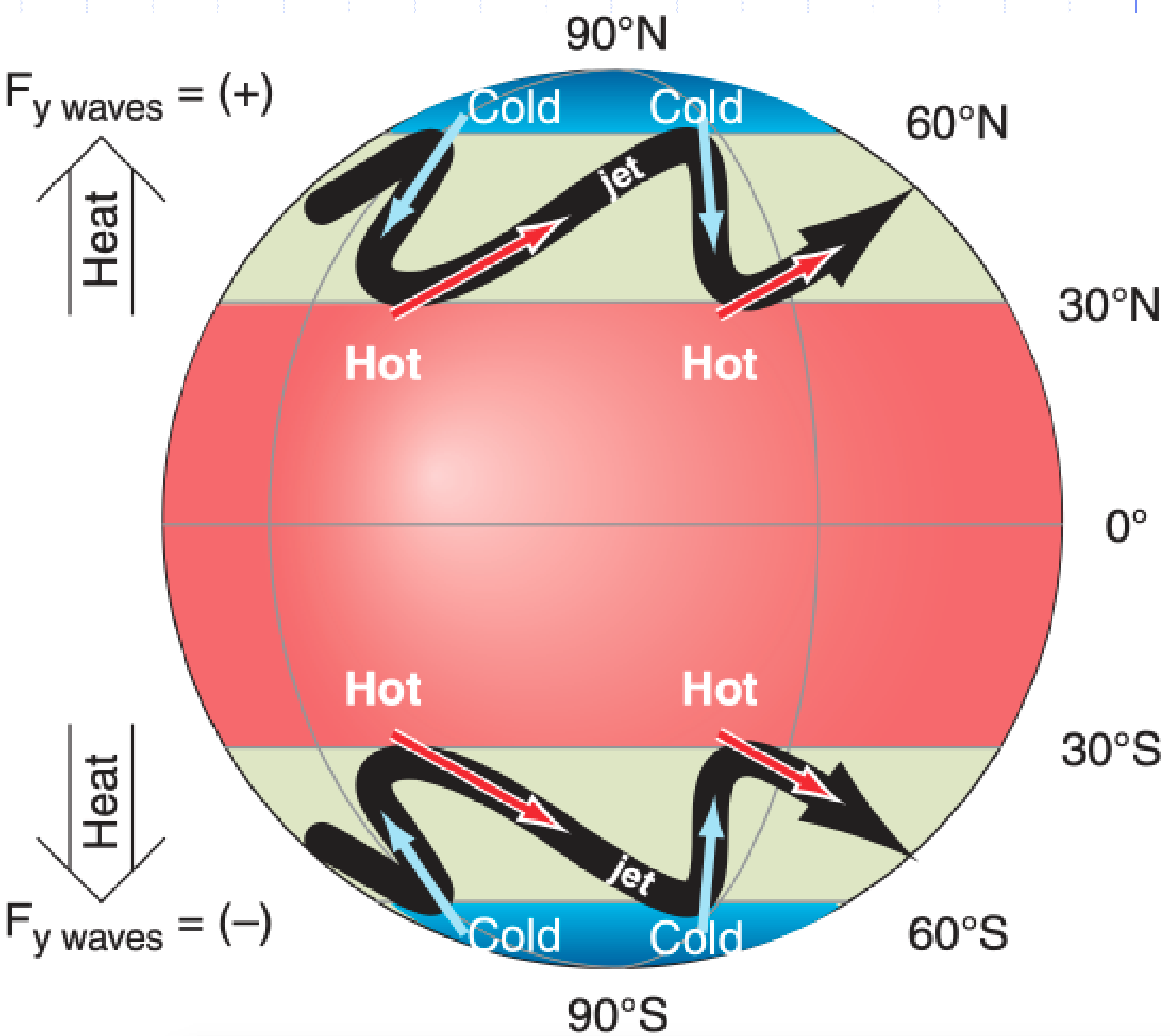
Northward movement (v' = +) of warm air (T' = +) in the N. Hemisphere contributes to a positive (northward) heat flux $v'T'$. This is a kinematic flux, because units are K·m/s. Similarly, southward movement (v' = –) of cold air (T' = –) also contributes to a positive heat flux $v'T'$ (because negative times negative = positive).



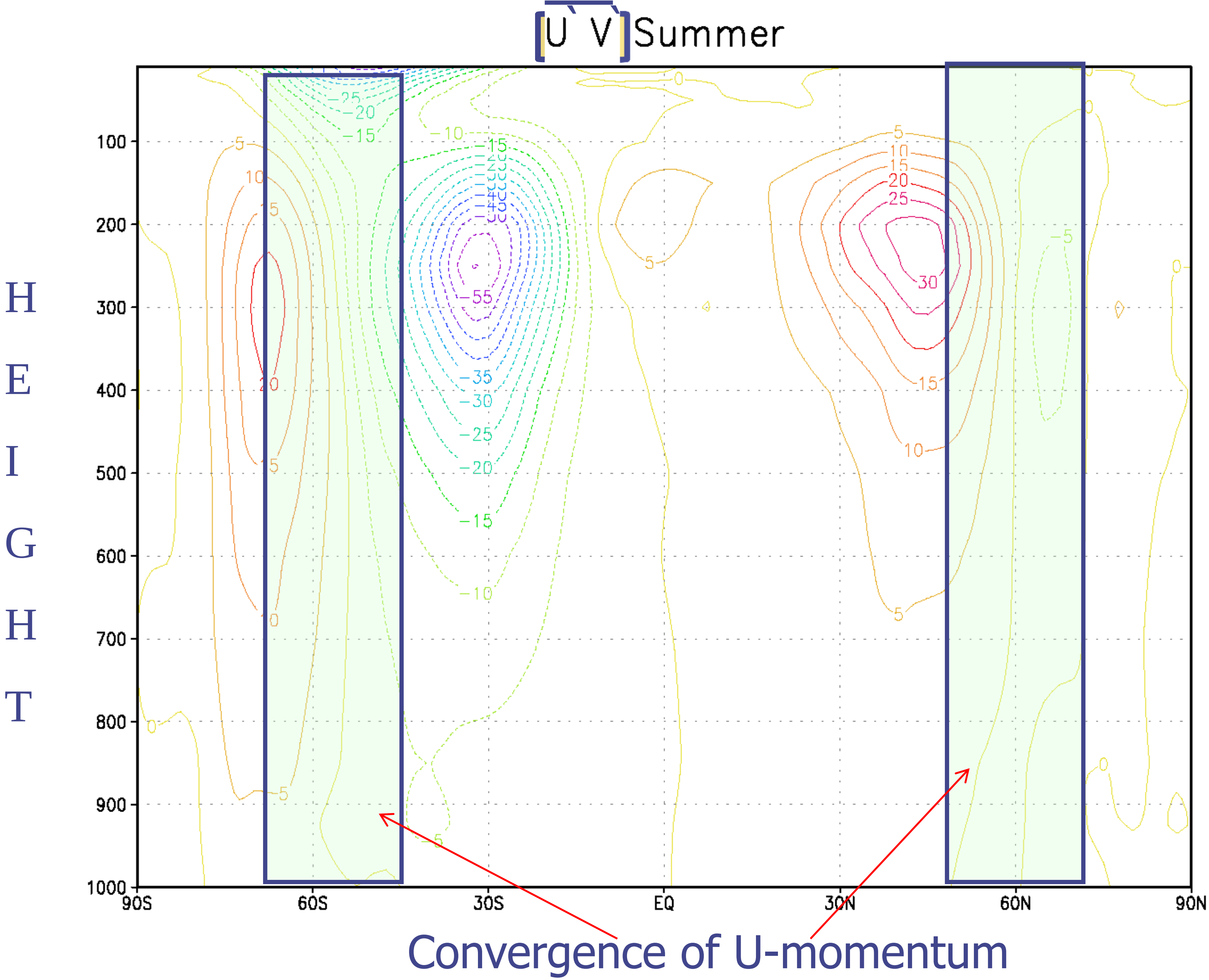
Thus, the shape of the wave and troughs and ridges is important.

Thus, there is no doubt that the transient waves transport U-momentum pole ward in both hemispheres. However, how do the waves achieve this?

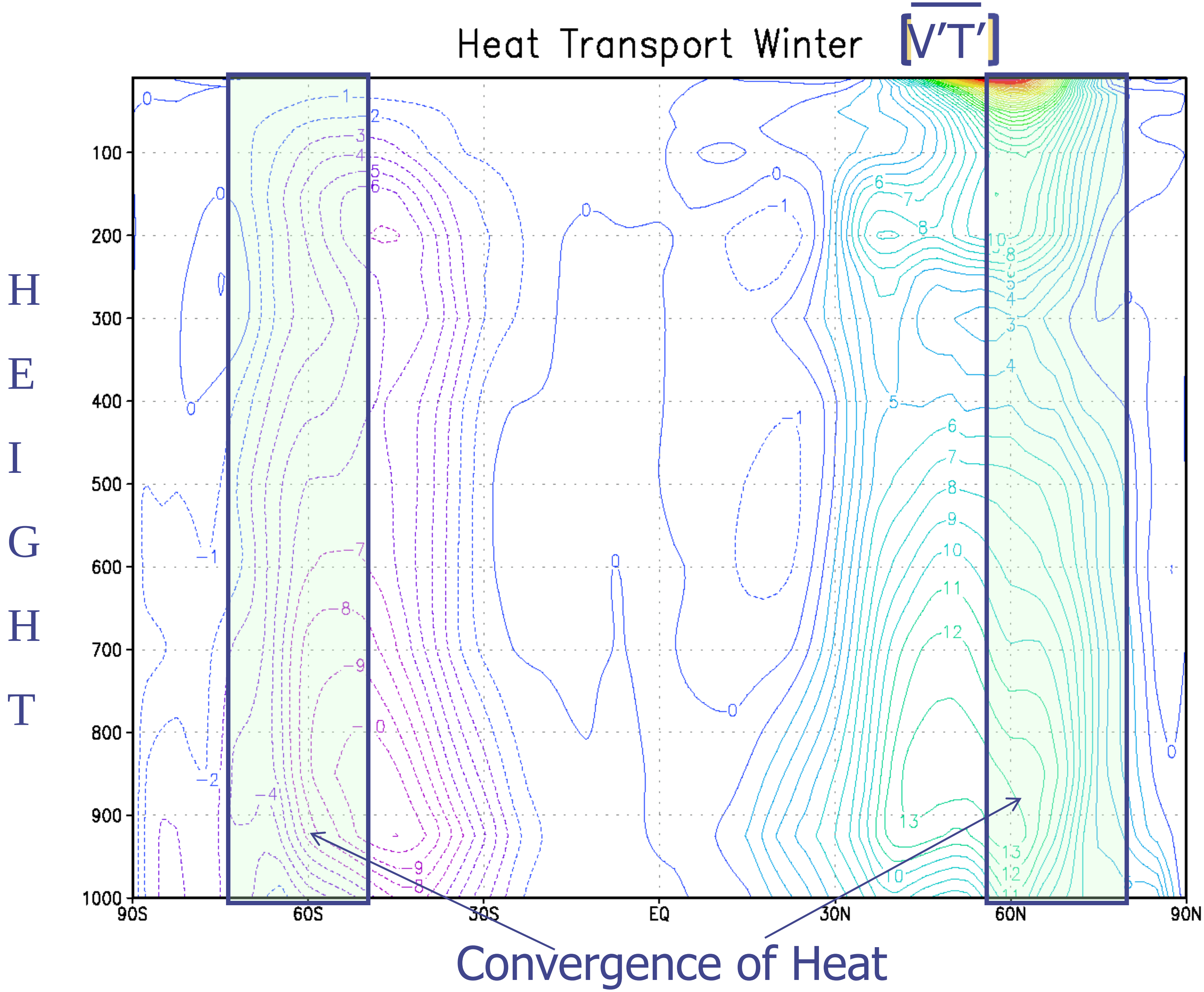
Northward movement (v' = +) of westerly flow (u' = +) in the N. Hemisphere contributes to a positive (northward) heat flux v'u". Similarly, southward movement (v' = –) of easterly zonal winds (u' = –) also contributes to a positive heat flux v'u' (because negative times negative = positive).



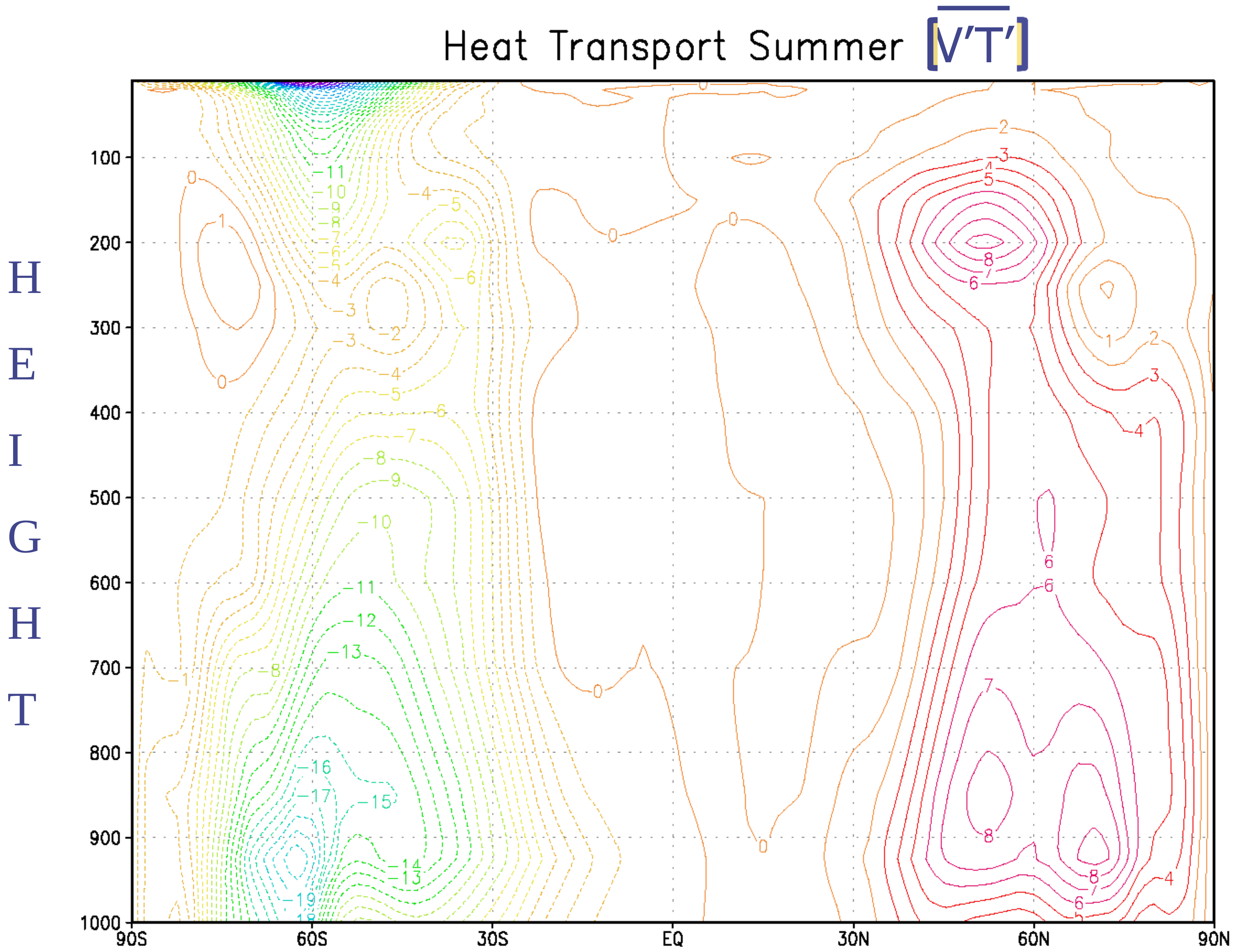
Thus, the shape of the wave and troughs and ridges is important.



Northern summer mean zonally averaged northward transport of zonal momentum by eddies [u’v’]bar, (m^2/s^2)



Northern winter mean zonally averaged northward transport of heat by the transient eddies, [v't']bar, (m.k/s)



Northern summer mean zonally averaged northward transport of heat by the transient eddies, [v't']bar.

If T = $\bar{T}$ + T′ + T*, then an equation for [$\bar{T}$] can be written as,

$$\frac{\partial[\bar{T}]}{\partial t} = 0 = -[\Gamma_d - \Gamma][\bar{W}] + P + Q \qquad (11)$$

where,

Γ = observed lapse rate = $\frac{\partial[\bar{T}]}{\partial t}$

Γ_d = dry adiabatic lapse rate

W = vertical velocity

P = eddy heat flux divergence

$= -\frac{\partial}{\partial y}\left\{[\bar{v^*}\bar{T^*}] + [(\overline{v'T'})]\right\}$

Q= time and zonal averaged diabatic heating rate. $=[\bar{Q}_R] + [\bar{Q}_{Latent}]$

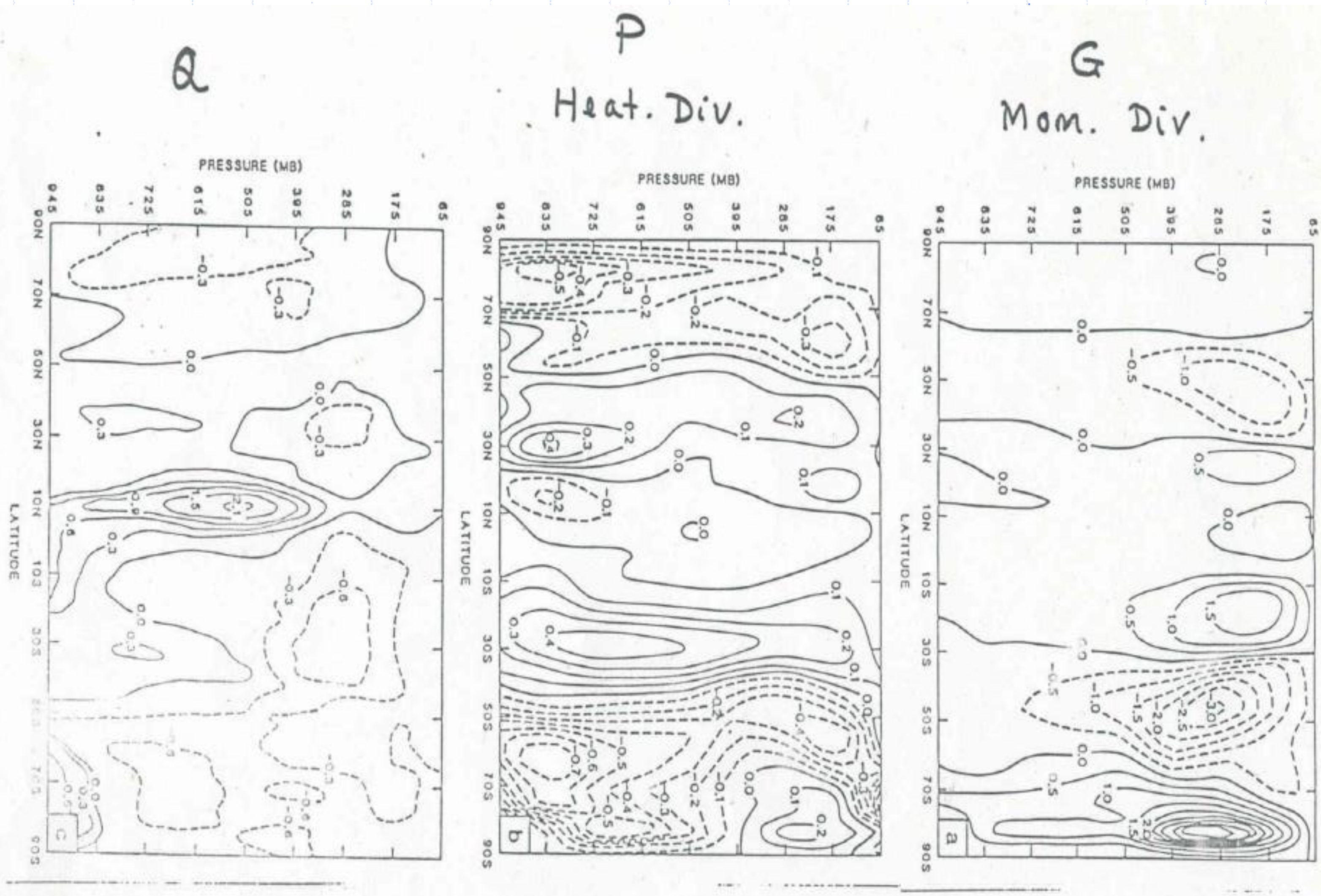
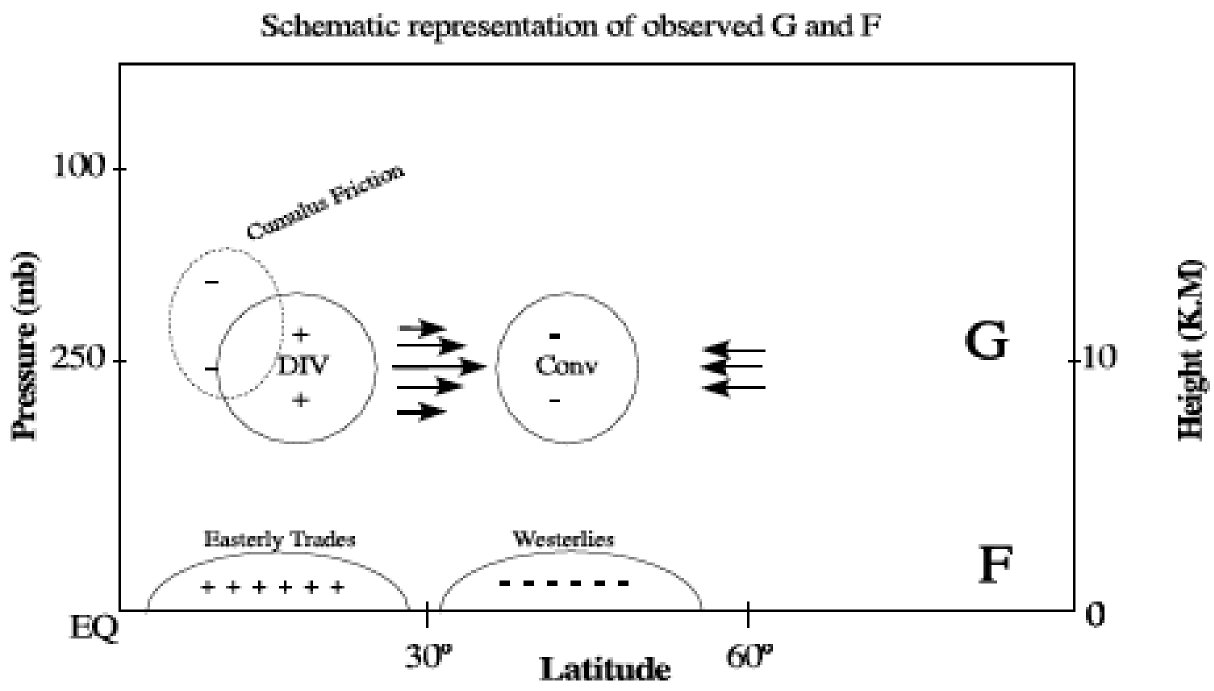
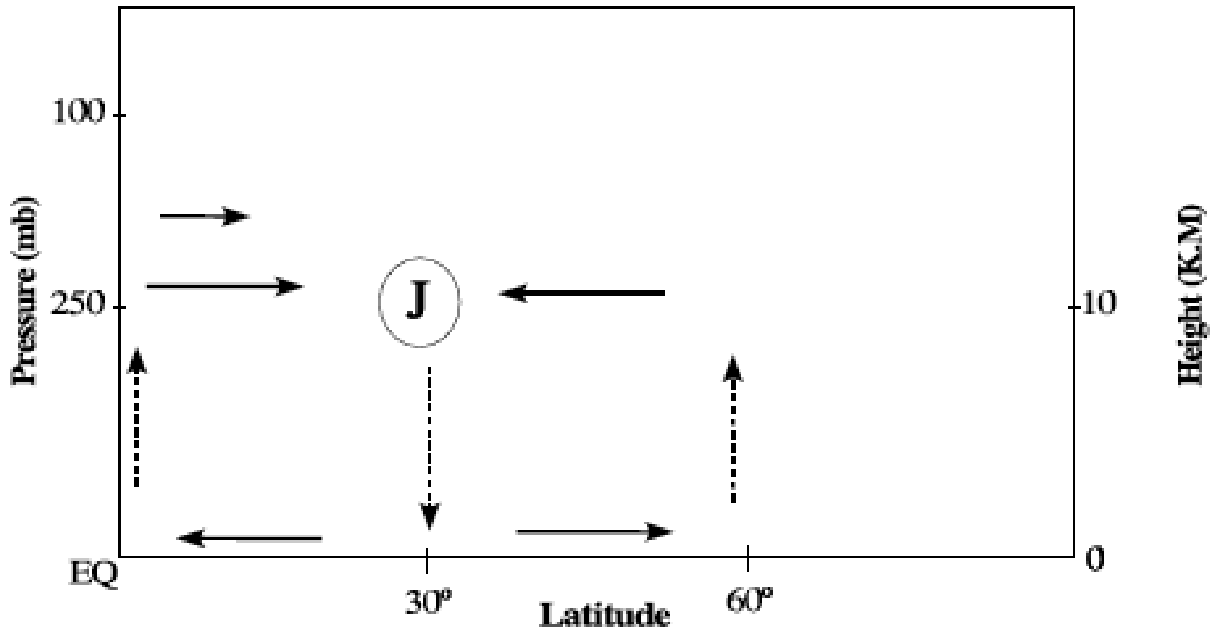


Figure 9. a) G x 8·64 x 10^4 ms^{-2}; b) P x 8·64 x 10^4 s^{-1} deg. c) total diabatic heating for the model, deg day^{-1}.





Schematic representation [$\bar{v}$] obtained from Eq(4)

Courtesy: M. J. Wallace, from his article in 'General circulation and Climate', NCAR workshop.

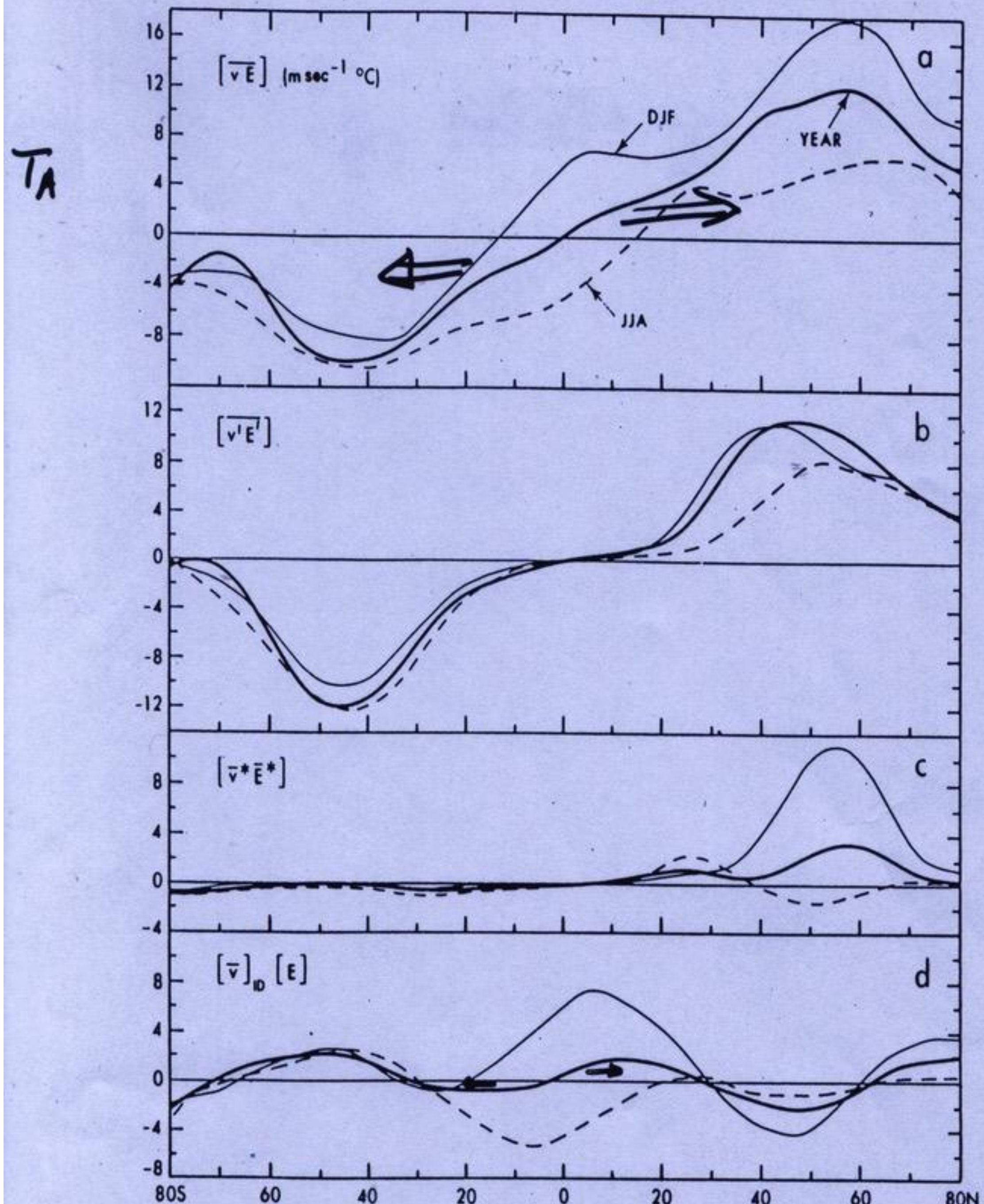


FIG. 39. Meridional profiles of the zonal and vertical mean northward transport of total energy by (a) all motions, (b) transient eddies, (c) stationary eddies, and (d) mean meridional circulations.

Relative contributions mean meridional circulation and the eddies in meridional transport of energy.

Transient eddy transport

Stationary eddy transport

MMC transport

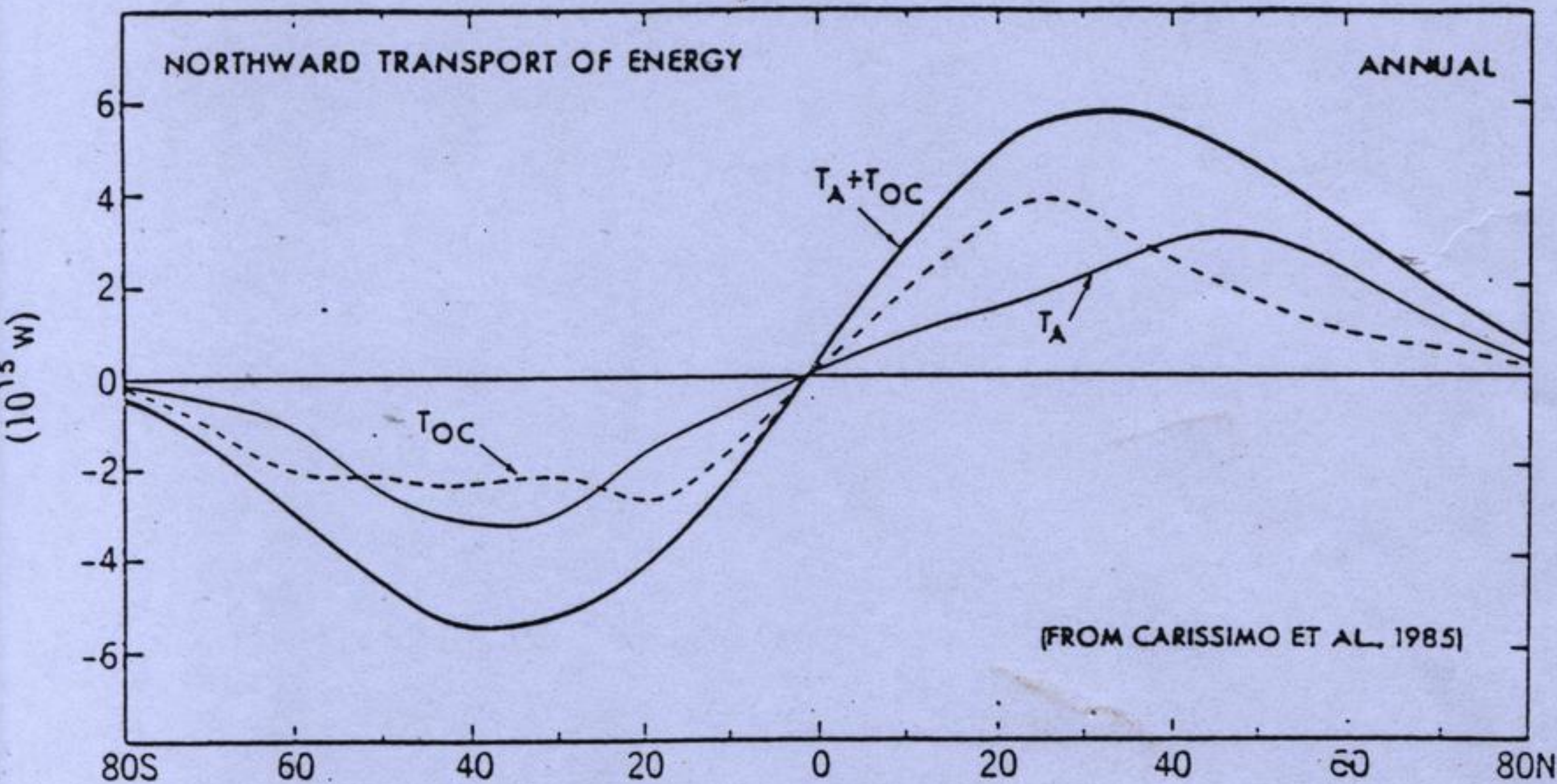
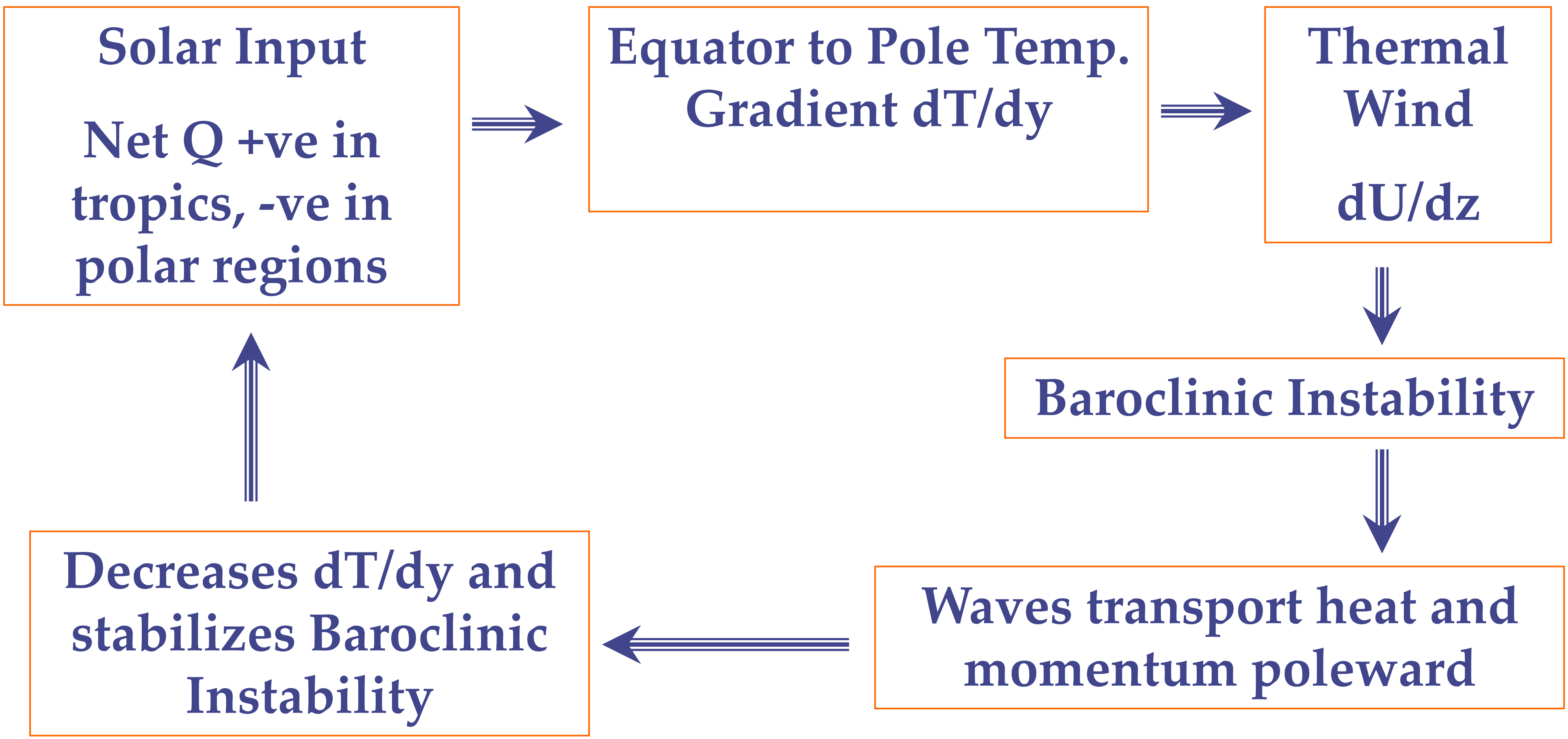


FIGURE 13.17. Meridional profiles of the northward transport of energy by the total system ($T_A + T_{OC}$), the atmosphere (T_A), and the oceans (T_{OC}) for annual-mean conditions in units of 10^{15} W (based on data from Carissimo *et al.*, 1985).

Maintenance of General Circulation of the Atmosphere



Thus, our mean circulation and climate is in vacillating dynamic equilibrium and non-stationary. Available potential energy (APE) due to equator-pole temperature gradient drive unstable Rossby waves (weather) that transport energy pole ward and weaken the temperature gradient that can not support them anymore reducing the transport. Radiation balance makes the Temp. gradient again strong and repeats the cycle.

Inherent "Complexity" Climate System

- **The 'Chaotic' weather disturbances (T~5 Day) transport most of excess heat energy from tropics to poles and maintain the 'Mean' (T>90 days) climate in equilibrium.**

- **However, 'weather disturbances' are instabilities on the 'mean flow' drawing energy from them!**

- **Neither can live (exist) without the other.**

Thus, the Climate or General Circulation is not just the 'time mean meridional circulation' but 'Time mean meridional circulation together with 'transient eddies' that accomplices required energy transports required to maintain the 'time mean''

In late 40's and early 50's there was an 'emotional debate' on whether the 'mean meridional circulation' or the 'turbulent eddies' were primary componet of the General circulation.

There were essentially two schools, with Rossby, Starr and others who viewed time and zonally averaged circulation as a response to forcing by large scale turbulent eddies while Palmen, Riehl, Nemias and others who sought to explain the gross features of the time mean circulation as a response to steady forcing by the time mean diabatic heating field and influence of orography.

In response to an article by Rossby and Starr, Palmen wrote a letter in J. Meteorology.

"It is not clear whether the authors intended to question the necessity of meridional circulations for the maintenance of the kinetic energy of the atmosphere. Such an intention would mean a complete change of the whole foundation of dynamic meteorology, and I doubt strongly that the genius of the authors, recognized by all meteorologists, will be sufficient for that goal."

Victor Starr wrote back in the same issue:

"Apprantely Palmen suspects me of highest heresy lest I suggest that the energy production process may also be accomplished without the aid of meridional circulations…… If to this we add Widger's result, the hypothesis that meridional cells are of small importance seems to be bearing fruit. Indeed if such are the fruits of heresy, then I say let us have more heresy...
Dr. Palmen speaks of "the whole foundation of dynamic meteorolgy." What does he mean by it? Certainly he does not mean the collection of sundry differential equations such as the hydrostatic equation, the continuity principle, etc., which is found in textbooks. Does he mean some rational solution of these equations which purports to give the essential mechanism of the general circulation? To the best of my information the problem is so diffucult that we have no such solution and cannot hope for one in the directly forseeable future. …"

Acknowledgements

1. E.N. Lorenz, 1967: The Nature and Theory of the general circulation of the atmosphere. WMO(WMO-NO.218,TP 115).

2. J.P.Peixoto and A.H.Oort, 1992: Physics of Climate, American Inst. Physics, pp 507

3. Most of the figures presented here are created from NCEP/NCAR Reanalysis by a student when I was at IISc.

4. I thank my friend J. M. Wallace whose article in 'The general Circulation, Theory, Modeling and Observations' Proceedings of a NCAR Colloquium deeply influenced the narrative I present here. I have used a few figures from the article.

Thank you