Lecture 2:

Stationary Waves in the Atmosphere

*(or: **Permanent zonal asymmetries: their configuration and role in energy transport**)*

-- Concept of "eddy" = zonal asymmetry

-- Horiontal configuration of stationary eddies:

- Aleutian and Icelandic Lows
- Subtropical Highs (think of the Hadley cell !!!)
- Indian Monsoon

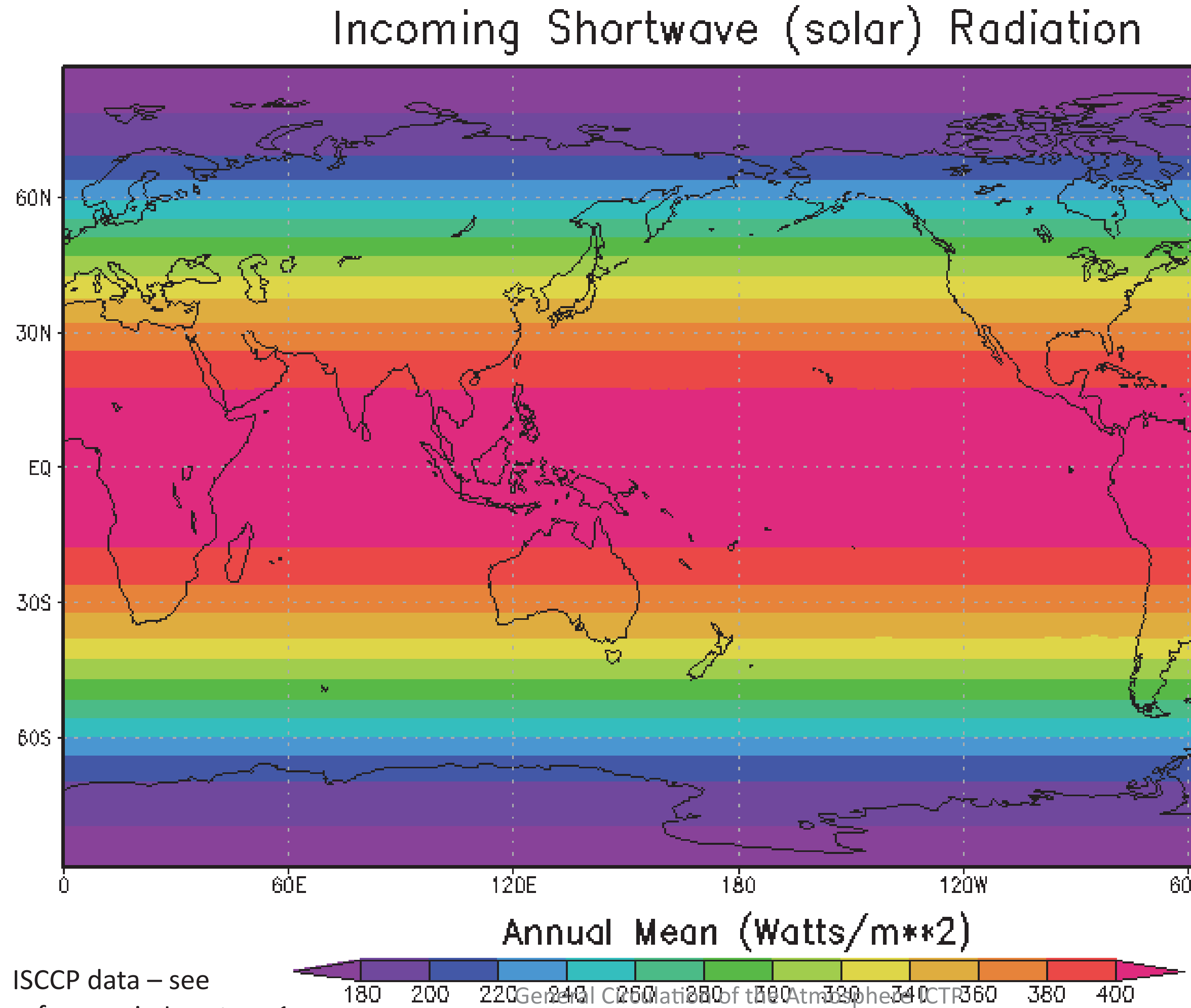
-- Poleward transport of heat

-- Cause of stationary eddies:

- Mountains
- Asymmetry of diabatic heating
- Relationship to ocean and surface heating

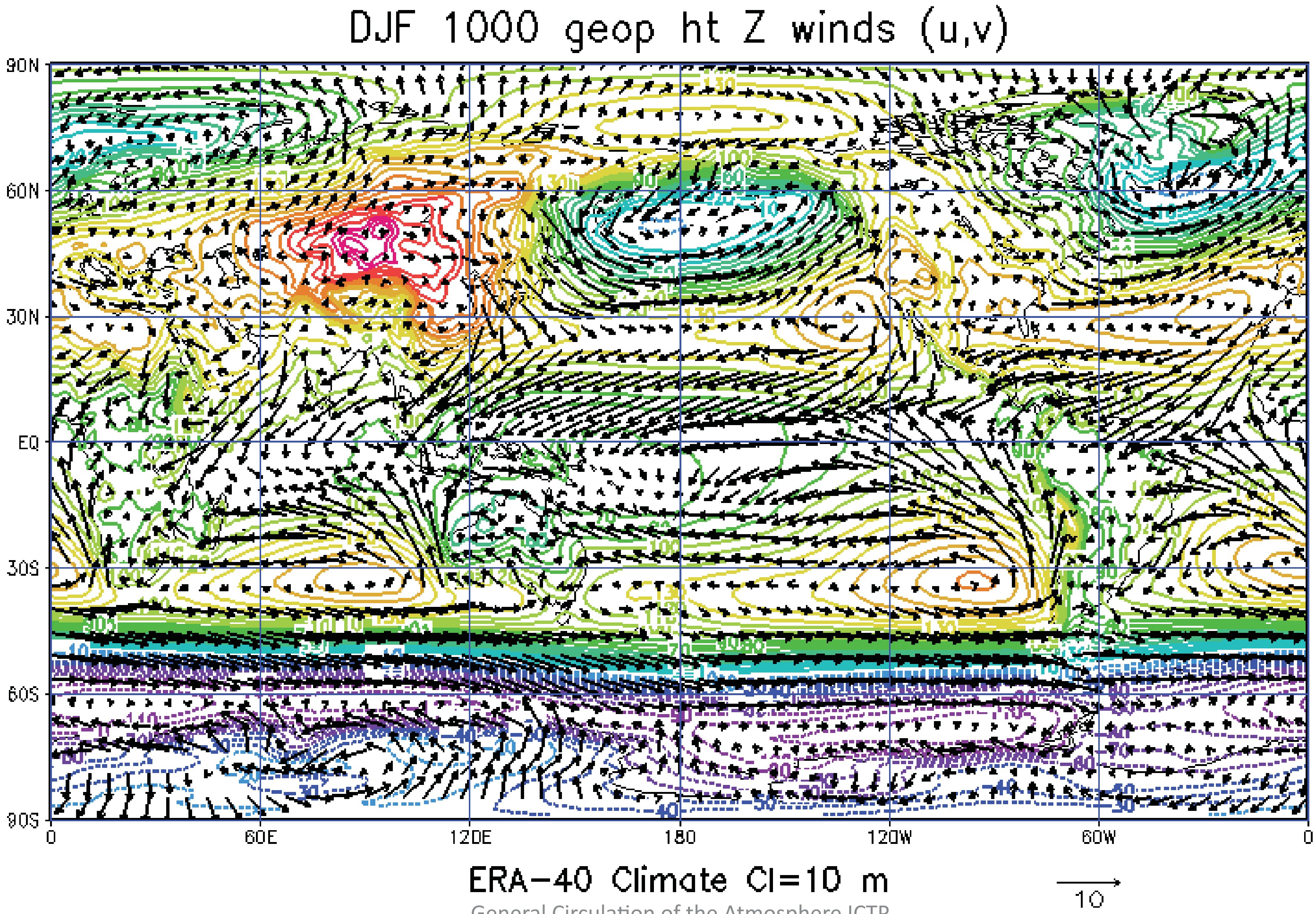
-- Relationship to cloudiness and radiative forcing and to storm tracks

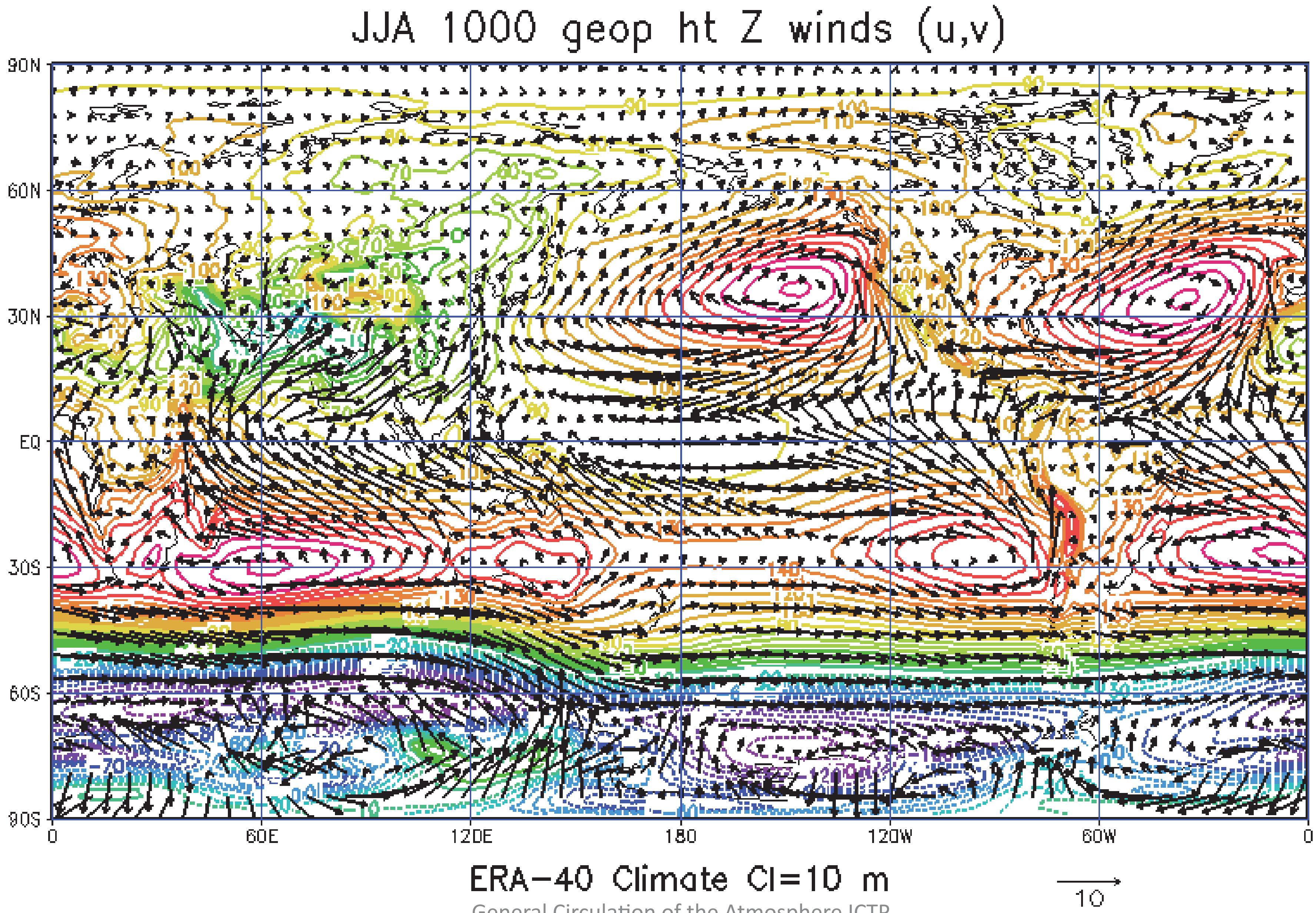
A field with Zonal symmetry: No dependence on longitude! $F(\lambda,\phi)=[F](\phi)$

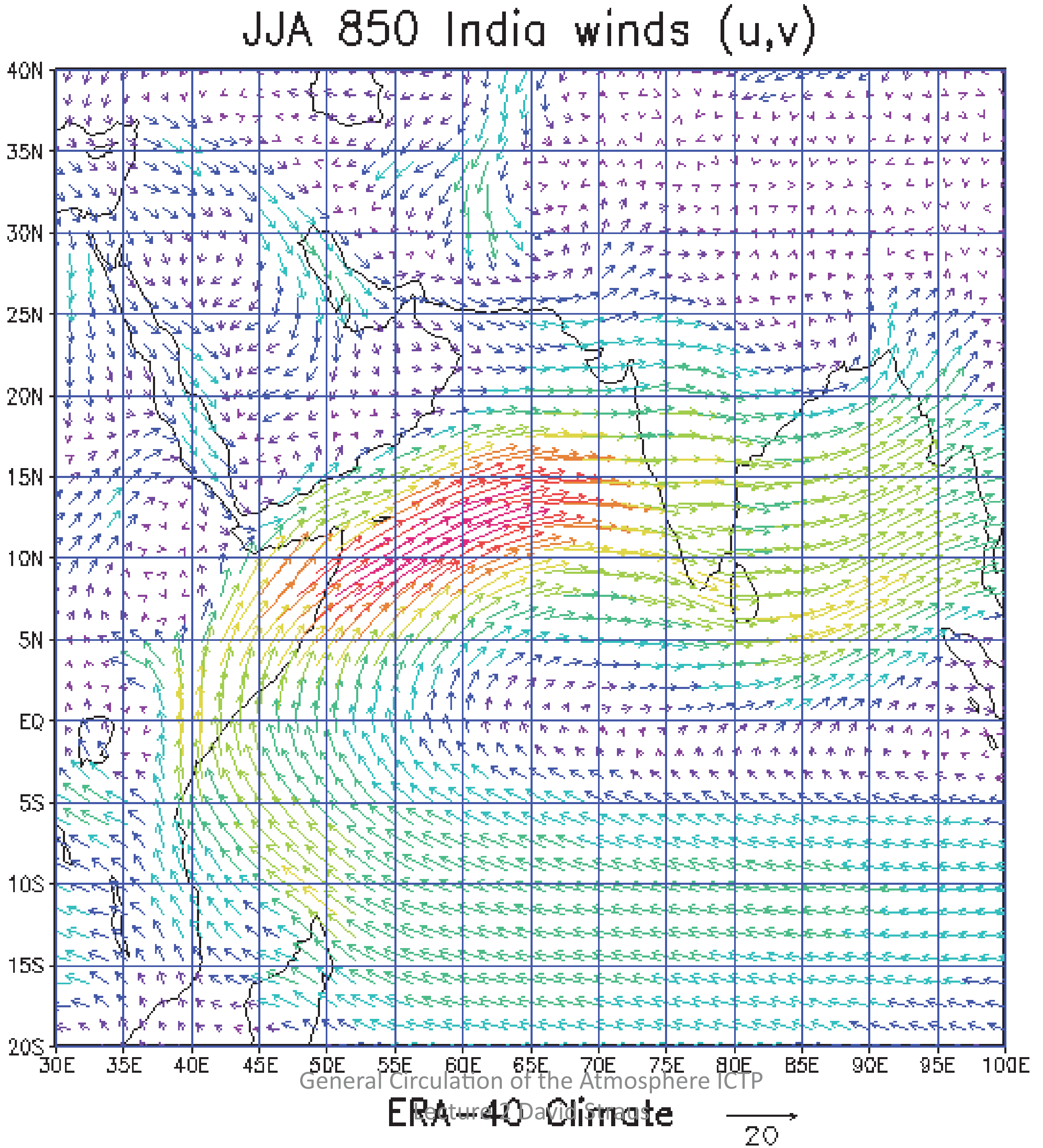


ISCCP data – see reference in Lecuture 1

Fields with zonal asymmetry: The time mean height and winds for DJF




JJA 1000 geop ht Z winds (u,v)
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
ERA-40 Climate CI=10 m
10


JJA 850 India winds (u,v)
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20S
30E 35E 40E 45E 50E 55E 60E 65E 70E 75E 80E 85E 90E 95E 100E
ERA-40 Climate
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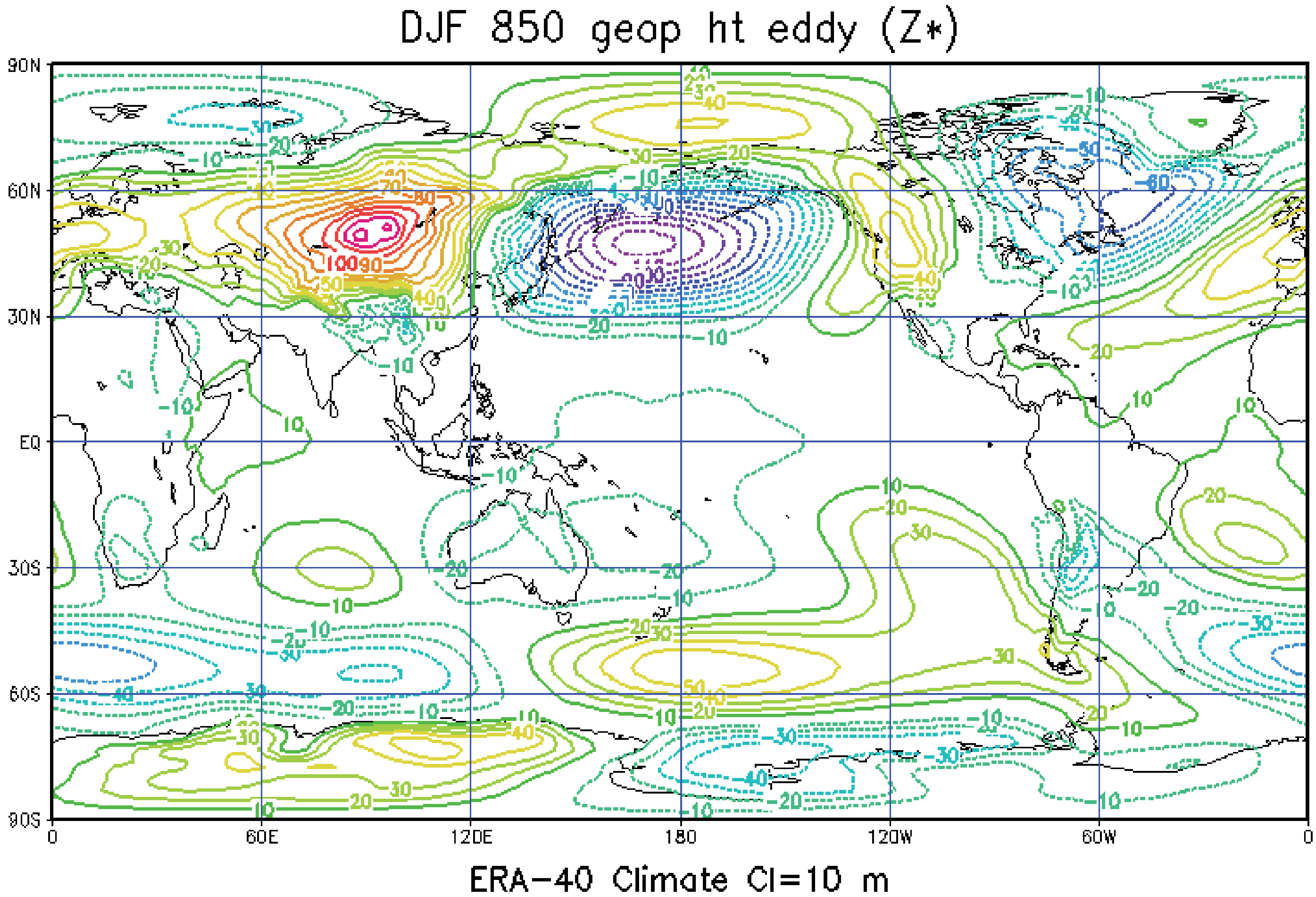
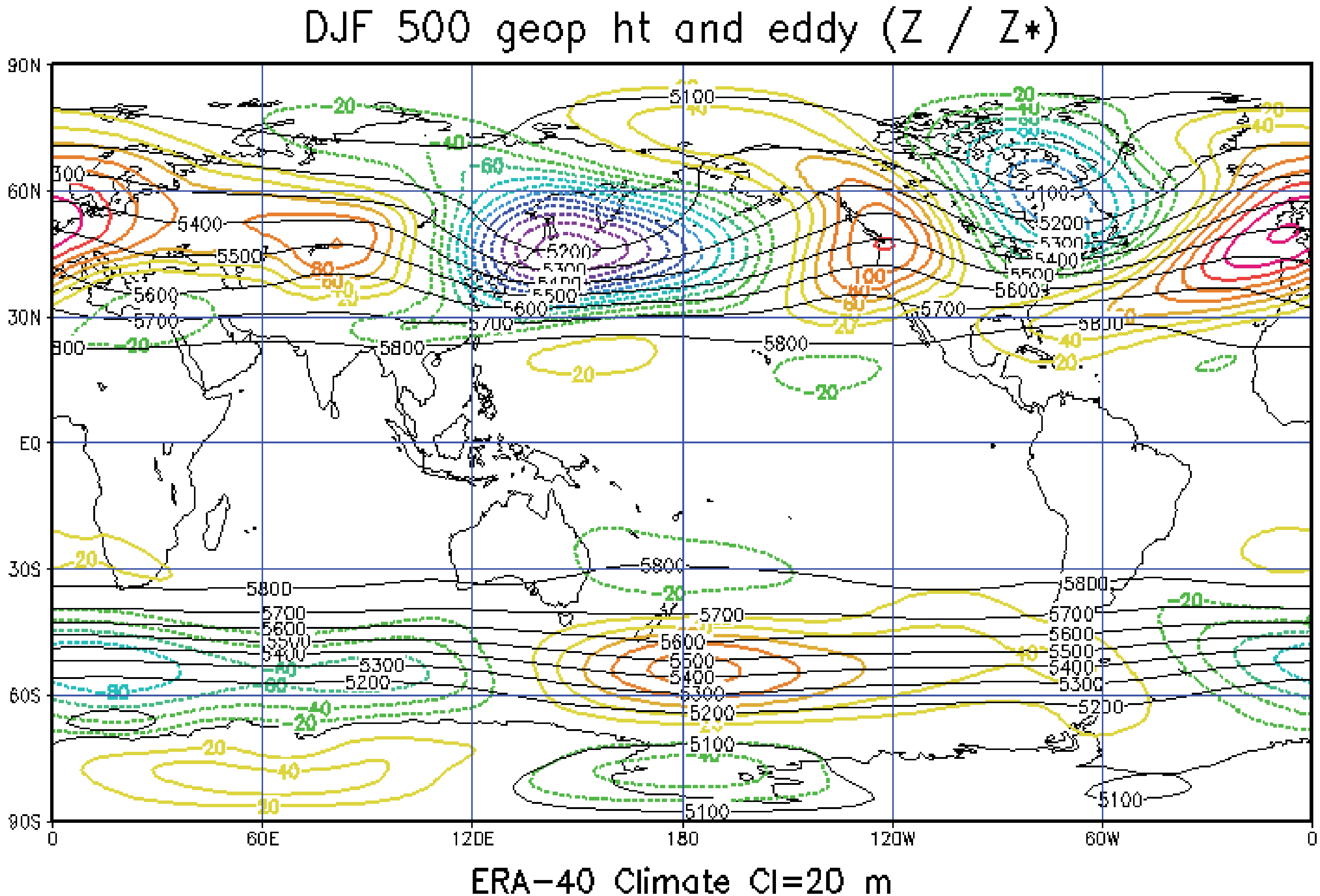
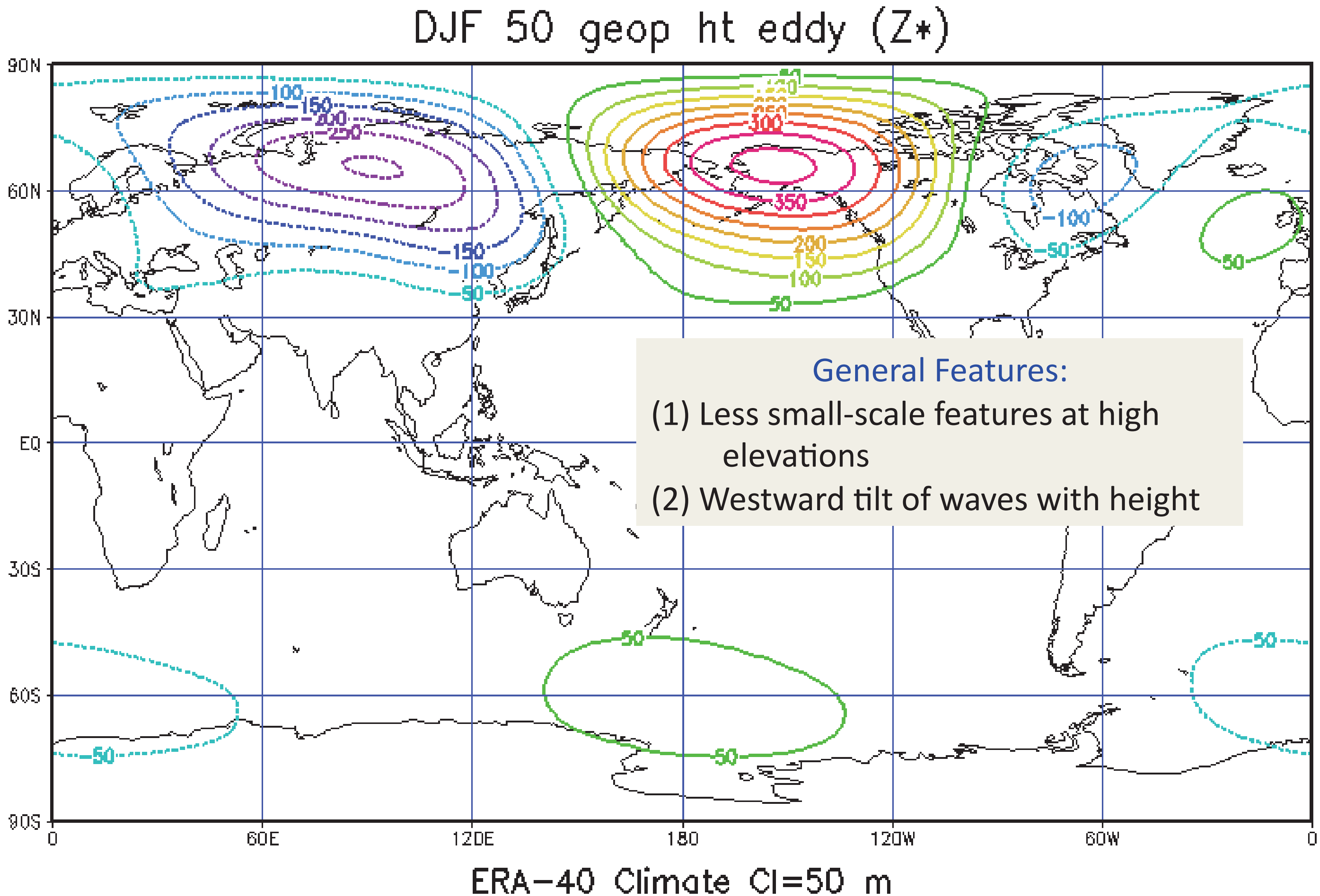
Eddies are defined as the deviaton from zonal mean: $Z^* = Z - [Z]$



Z Field – black contours ; Eddy (Z*) Field – colored contours





General Features:

(1) Less small-scale features at high elevations

(2) Westward tilt of waves with height

Longitude / Pressures sections of DJF Mean Z* fields from NCEP reanalysis.

Vertical coordintae is Log(pressure)
Horizontal coordinate is longitude.

In mid-latitudes, clear westward tilt with height is seen.

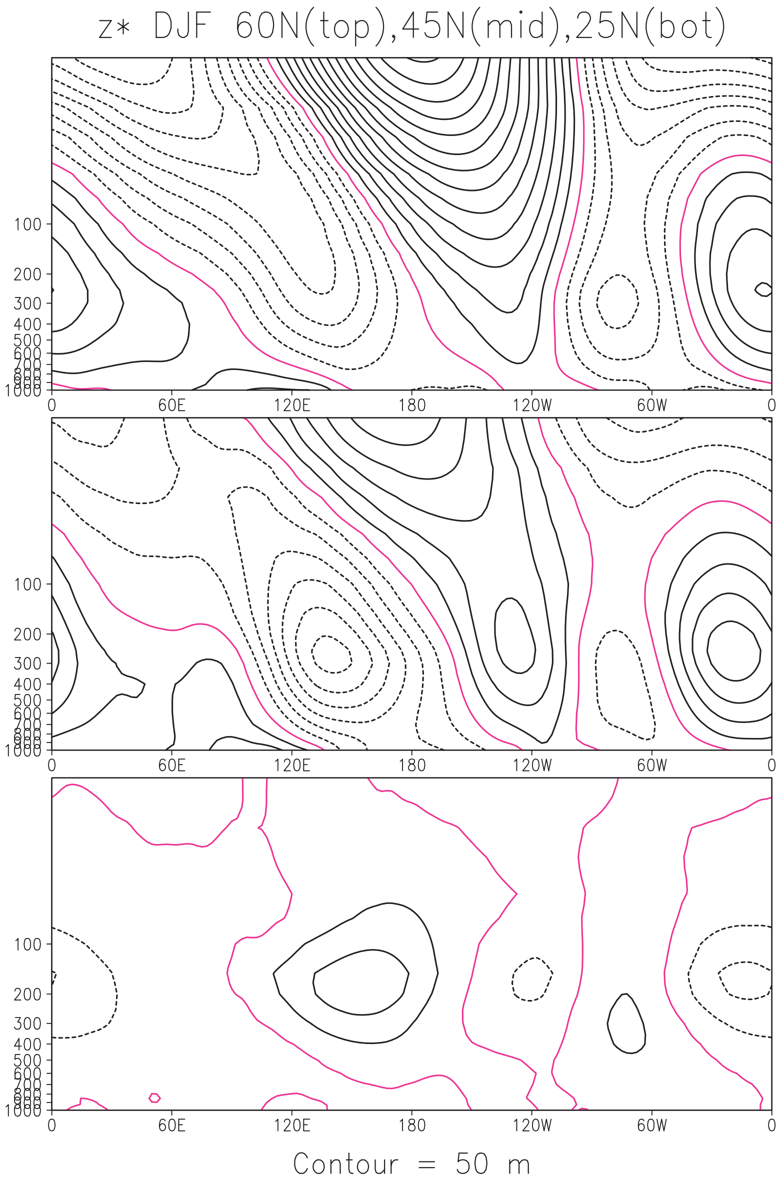


Figure 4: **Longitude/Pressure sections of DJF Z* at 60N (top), 45N(mid), and 25N(lower) .**

1 Stationary Wave Description: Zonal Waves and Poleward Heat Transport

We use the geostrophic approximation for the time mean eddy components of the horizontal wind (u, v) and use the hydrostatic approximation for the time mean eddies, all in log-pressure coordinates:

$$\frac{f}{g}u^* = -\frac{1}{a}\frac{\partial z^*}{\partial \phi} \quad (1)$$

$$\frac{f}{g}v^* = +\frac{1}{a\cos\phi}\frac{\partial z^*}{\partial \lambda} \quad (2)$$

$$\frac{\partial z^*}{\partial Z} = \frac{RT^*}{gH} \quad (3)$$

where z is the geopotential height, and as before

$$Z = H\,log\left(\frac{p_0}{p}\right)$$

with $H = 10$ km, and $p_0 = 1000hPa$.

1

Since for each latitude and level, the wind and height fields are periodic in longitude e.g. $z(\lambda = 2\pi) = z(\lambda = 0)$ we can expand z in harmonic coefficients:

$$
\begin{aligned}
z^* &= \sum_{m>0}^{m=M} \left(A_m \cos(m\lambda) + B_m \sin(m\lambda)\right) \\
&= \sum_{m>0}^{m=M} \mathcal{A}_m \cos\left(m\lambda - \Psi_m\right) \qquad (4)
\end{aligned}
$$

The harmonic coefficients A and B depend on the integer zonal wavenumber m, as do the amplitude $\mathcal{A}$ and phase Ψ. The truncation limit $m = M$ can be taken to be quite modest $M \sim 10$ for all time mean upper air fields (excepting ω), since they are smooth.

Using equation 4 in equation 2 and equation 3, we obtain expansions

2

for the eddy wind components and temperature:

$$\frac{f}{g}u^* = -\frac{1}{a}\sum_{m>0}\left(\frac{\partial \mathcal{A}_m}{\partial \phi}\cos(m\lambda - \Psi_m) + \mathcal{A}_m \sin(m\lambda - \Psi_m)\frac{\partial \Psi_m}{\partial \phi}\right)$$

$$\frac{f}{g}v^* = +\frac{1}{a\cos\phi}\sum_{m>0}(-m\mathcal{A}_m \sin(m\lambda - \Psi_m)) \tag{5}$$

$$\frac{R}{gH}T^* = \sum_{m>0}\left(\frac{\partial \mathcal{A}_m}{\partial Z}\cos(m\lambda - \Psi_m) + \mathcal{A}_m \sin(m\lambda - \Psi_m)\frac{\partial \Psi_m}{\partial Z}\right) \tag{6}$$

in which the derivatives of the amplitude and phase of each harmonic component enter.

From these equations it is not hard to obtain:

$$\frac{R}{gH}\frac{f}{g}[v^*T^*] = -\frac{1}{a\cos\phi}\frac{1}{2}\sum_{m>0} m(\mathcal{A}_m)^2\frac{\partial \Psi_m}{\partial \tilde{Z}} \tag{7}$$

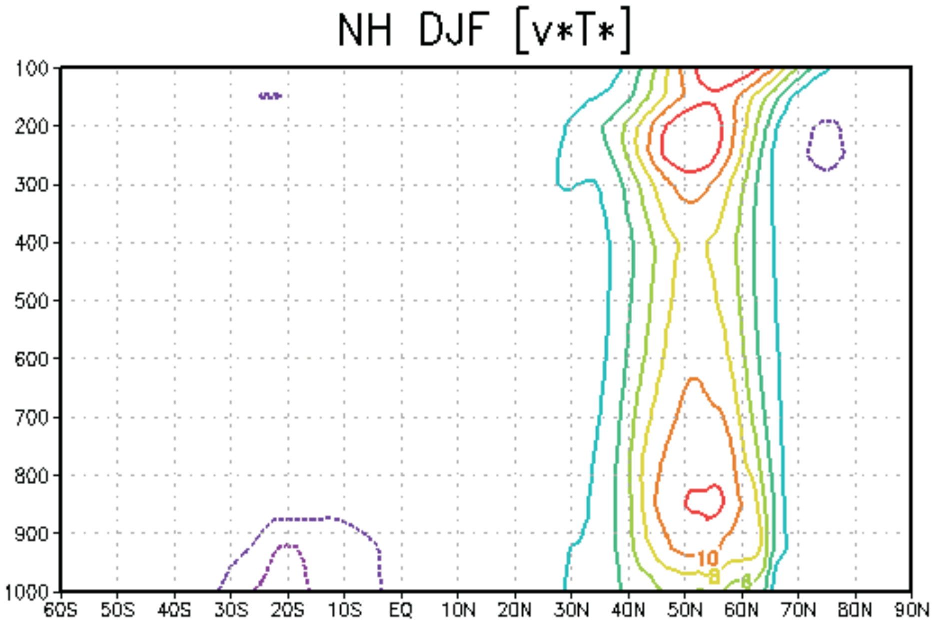
where both sides are dimensionless. *Note that poleward heat flux is associated with a negative shift of the phase* Ψ *with height.* This is equivalent to a *westward* shift with height.

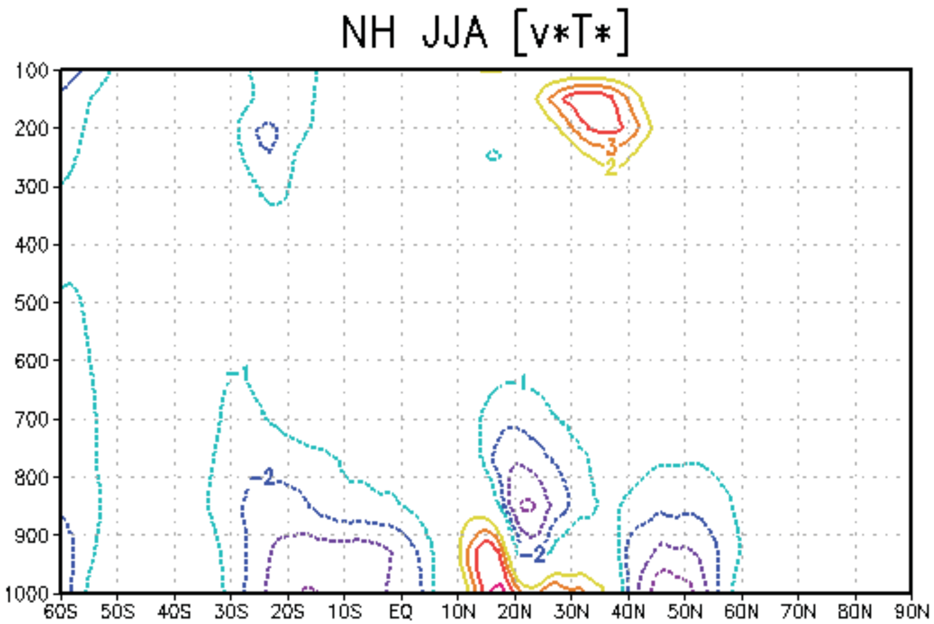
From ERA40:
Compute long term means of v and T.

Compute the eddy component at each point.

Compute the zonal mean of the product of eddy fields

$$\left[\bar{v}^{*}\bar{T}^{*}\right]$$





From NCEP reanalysis

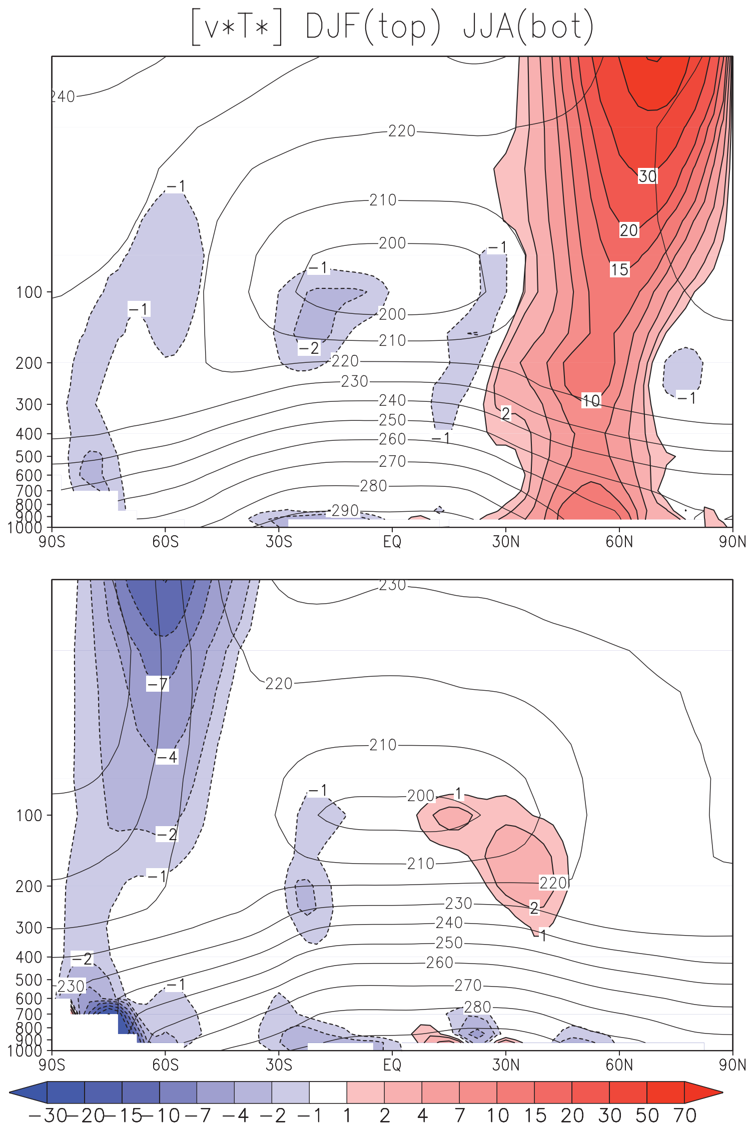


Figure 23: **Stationary Eddy heat flux $[v^*T^*]$ (shaded) and mean T (contour) for DJF (top) and JJA (bottom).**

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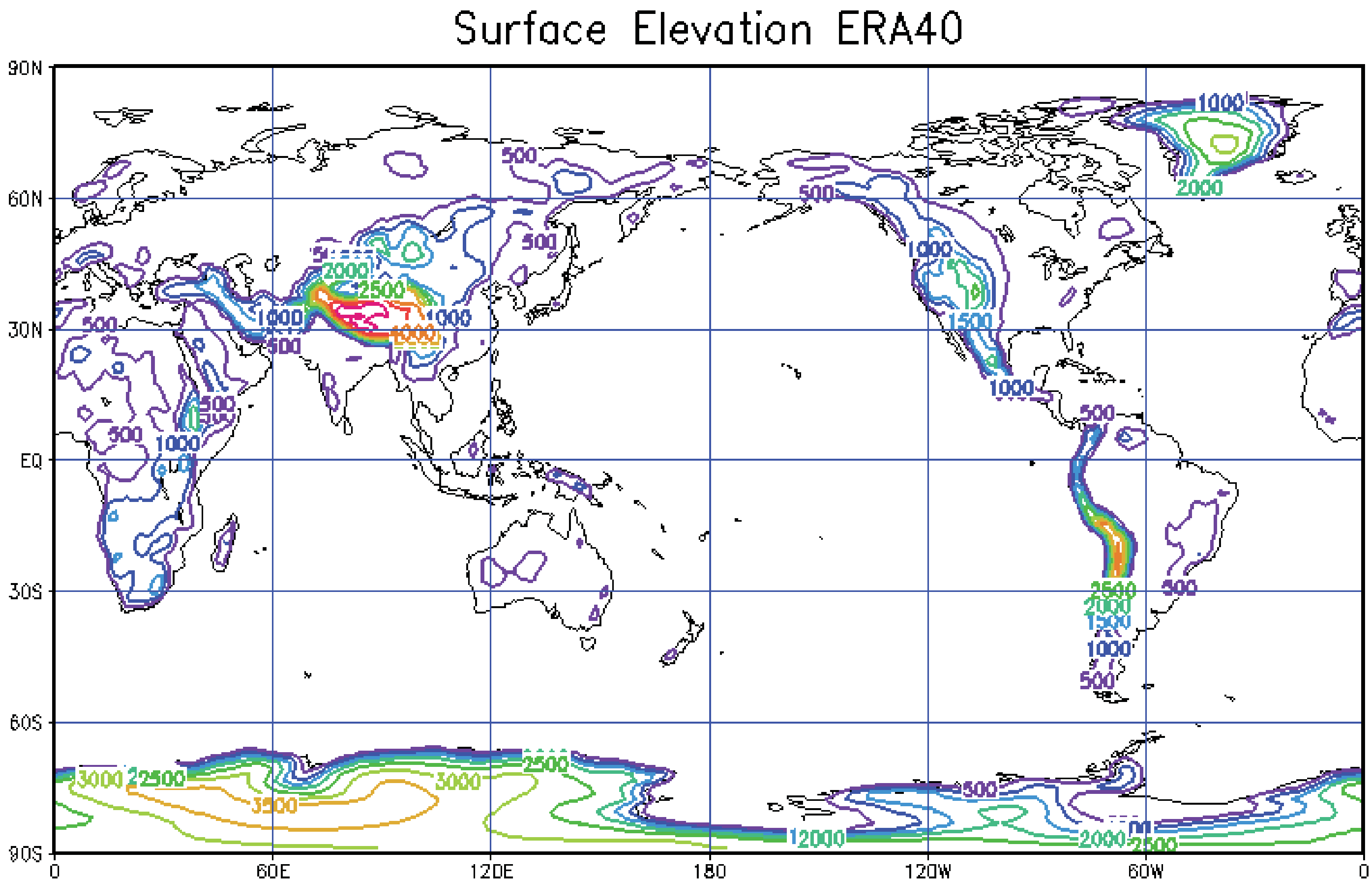
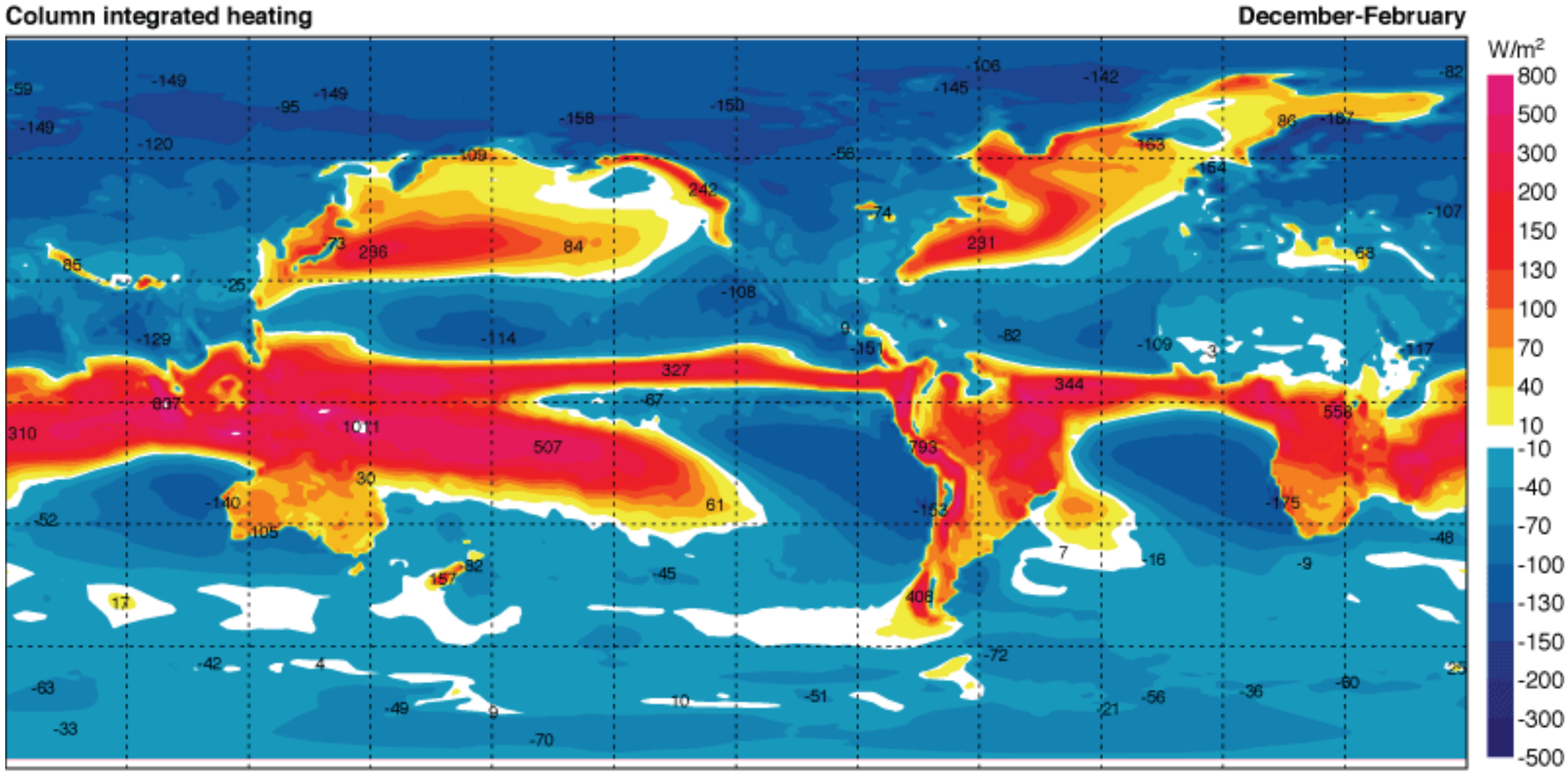
Cause (1) of Stationary Waves: Mountains !



(Traditional) Cause (2) of Stationary Waves: Diabatic Heating Q

$T\,ds/dt = (p/p_0)^k\, C_p\, d\Theta/Dt = Q$

Plot shows mass-weighted vertical integral of Q for DJF



http://www.ecmwf.int/research/era/ERA-40_Atlas/docs/section_C/parameter_cih.html

(Traditional) Cause (2) of Stationary Waves: Diabatic Heating Q

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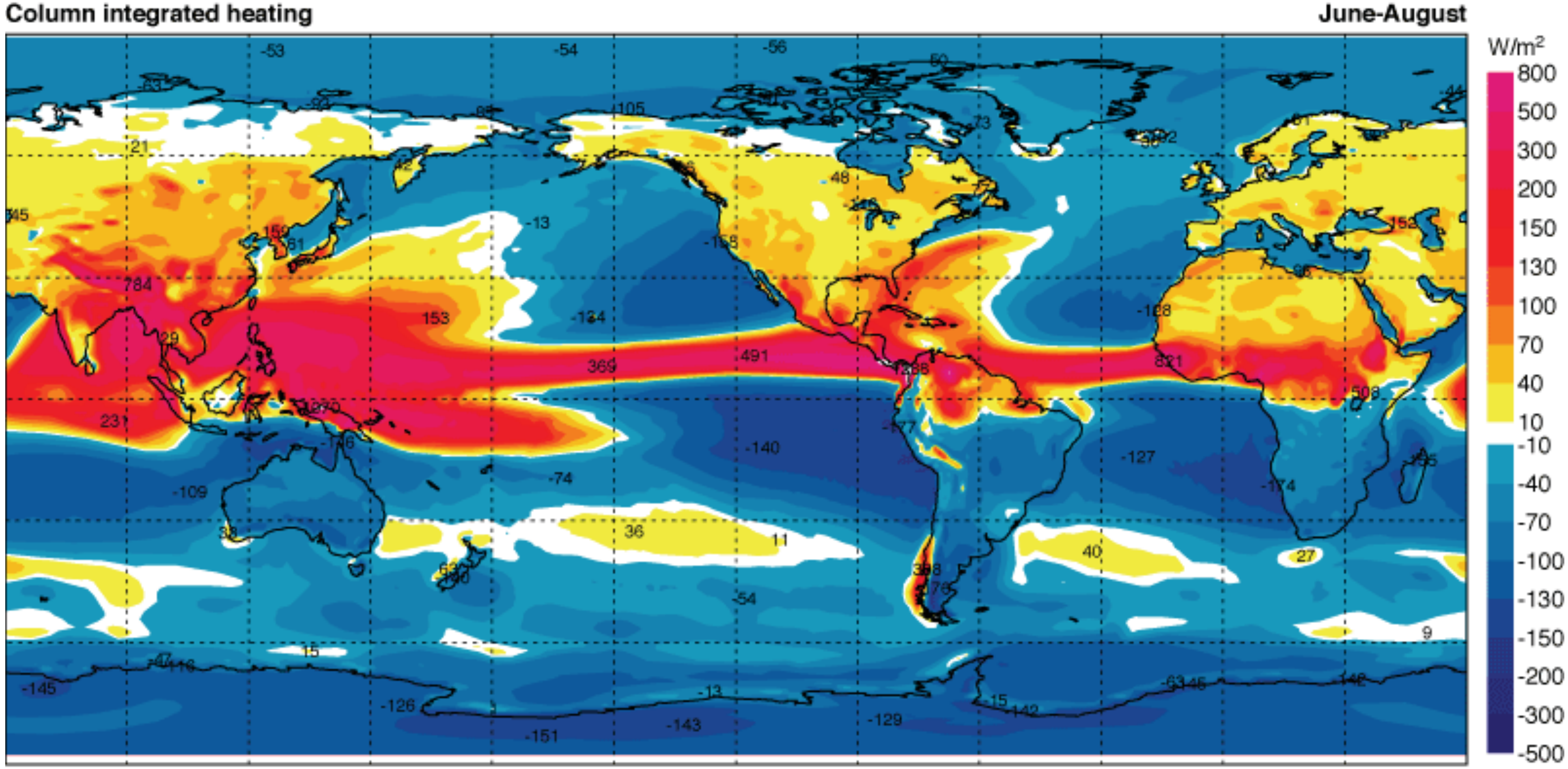
Plot shows mass-weighted vertical integral of Q for JJA



www.ecmwf.int/research/era/ERA-40_Atlas/docs/section_C/parameter_cih.html

Some difficulties with cause-and-effect

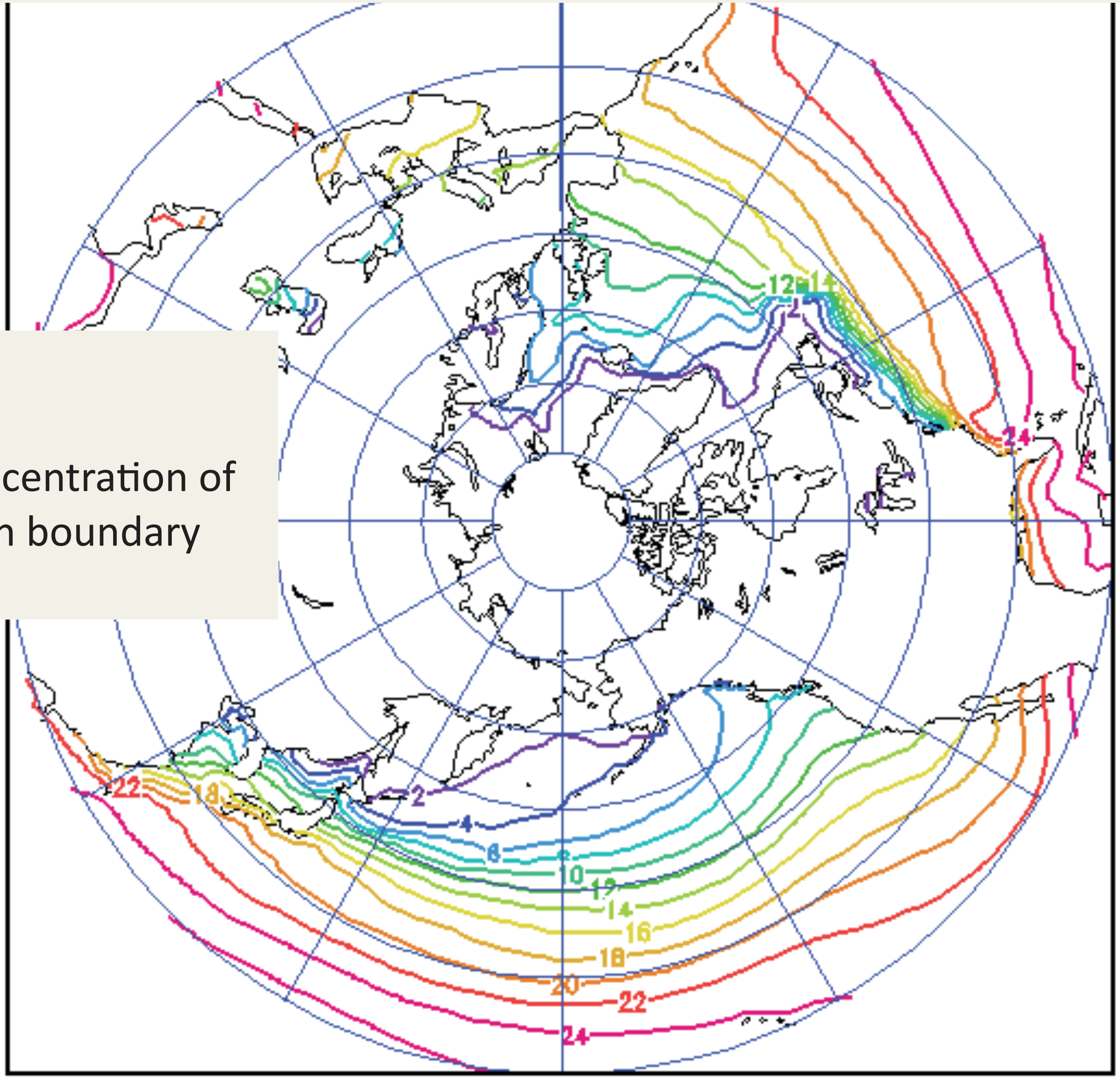
(1) The horizontal distribution of Diabatic Heating is a result of stationary waves as much as a cause!

(2) Mid-latitude diabatic heating in storm track regions due to transients, which strongly interact with the stationary eddies, making cause and effect hard to disentangle. (More on this in Lecture 3)

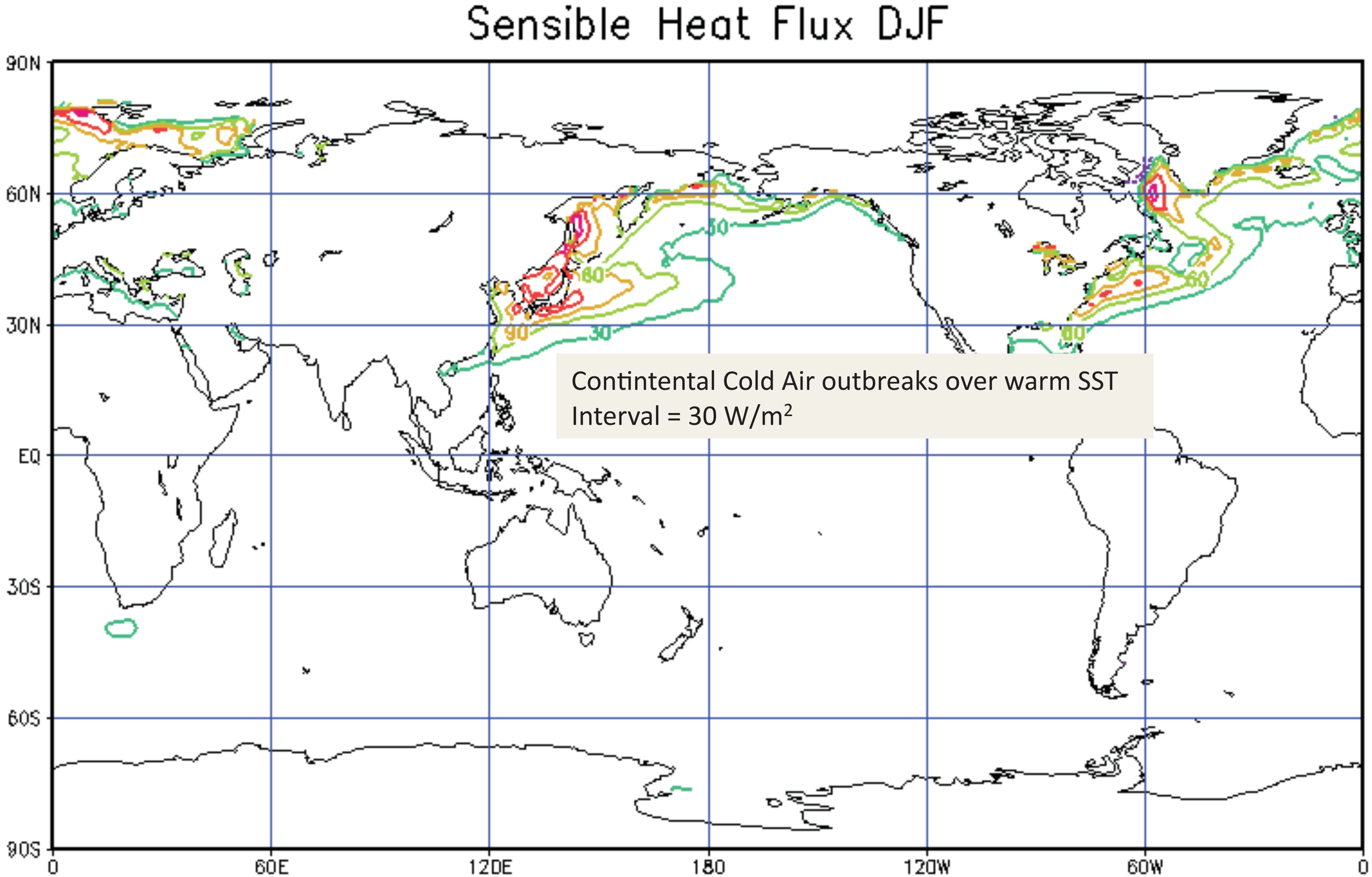
Cause (3) of Stationary Waves: Land-Sea Distirbution – (3a) Effect on SST

NH SST in DJF

Note strong concentration of dT/dy in western boundary current regions



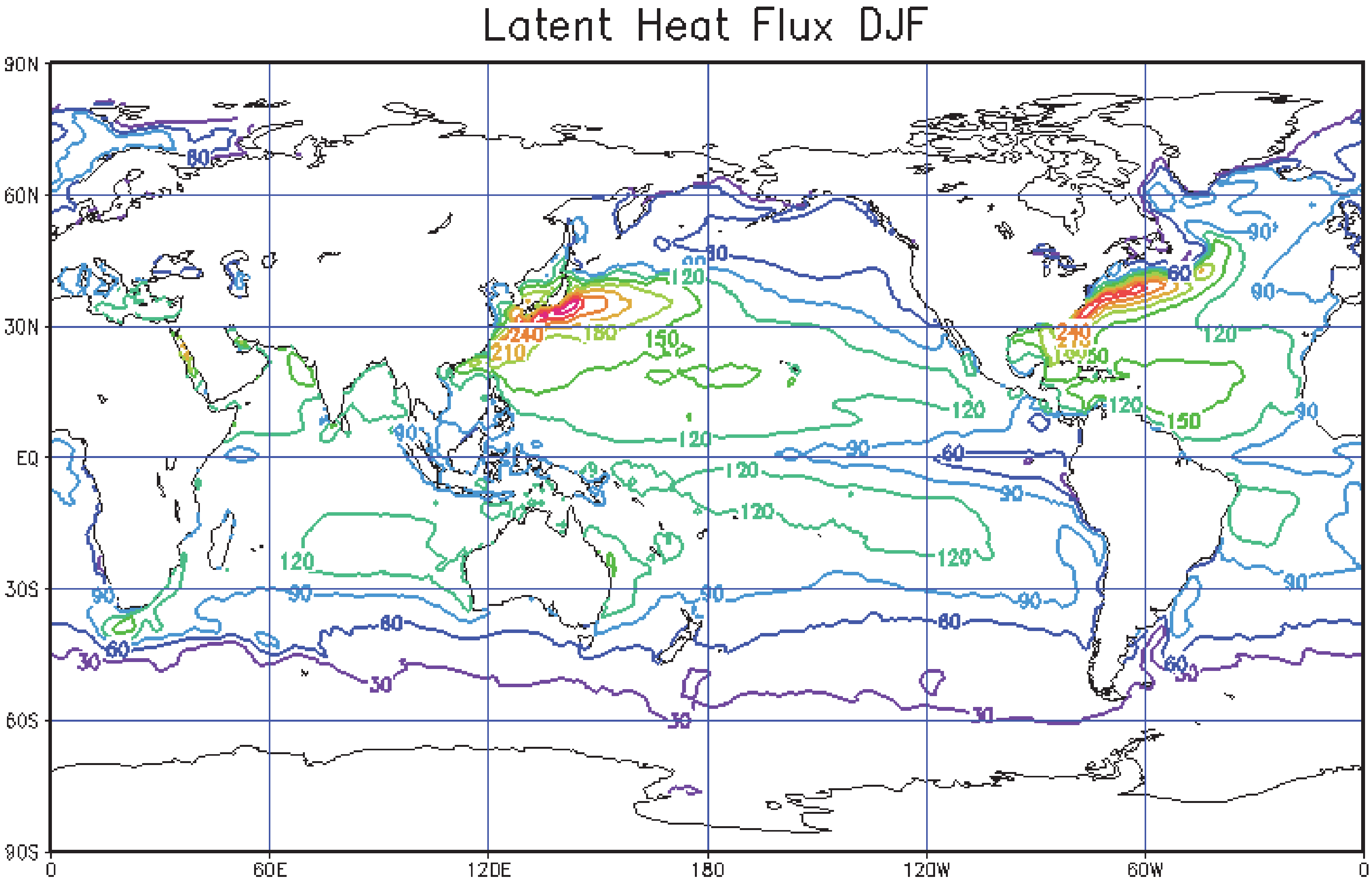
Cause (3) of Stationary Waves: Land-Sea Distirbution –(b) Effect of Ocean Thermal Heating of overlying atmosphere (Sensible Heat Flux) DJF



Contintental Cold Air outbreaks over warm SST
Interval = 30 W/m^2

Yu, L., and R. A. Weller, 2007: Objectively Analyzed air-sea heat Fluxes (OAFlux) for the global oceans. Bull. Ameri. Meteor. Soc., 88, 527-539.

Cause (3) of Stationary Waves: Land-Sea Distirbution –(c) Ocean Flux of Latent Heat to overlying atmosphere (Evaporation) DJF



Yu, L., and R. A. Weller, 2007: Objectively Analyzed air-sea heat Fluxes (OAFlux) for the global oceans. Bull. Ameri. Meteor. Soc., 88, 527-539.

Discussion of Latent Heat Flux:

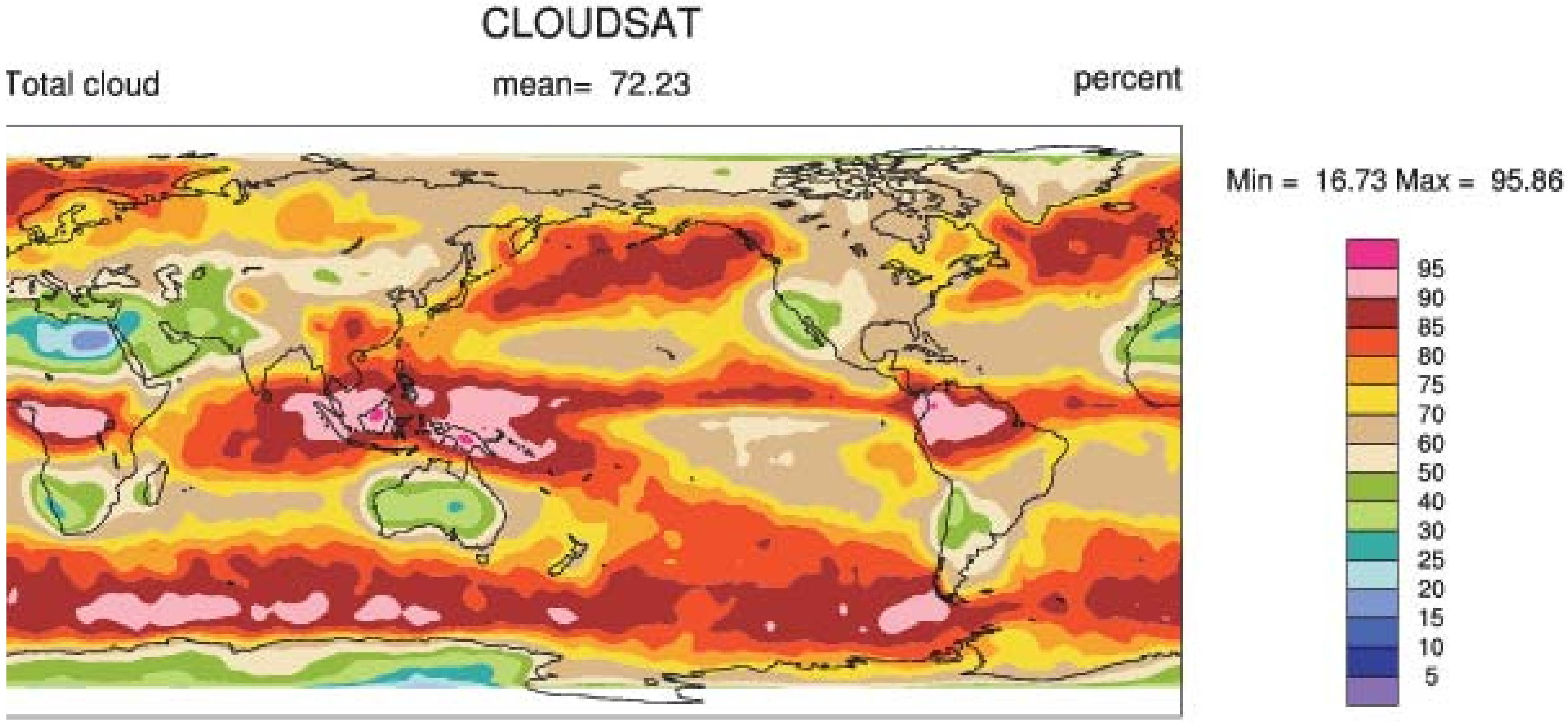
(1) Evidence of Contintental Cold Air outbreaks over warm SST

(2) (2) Broad maxima in regions of subsidence in subtropics

(3) Zonal mean evaporation shows maxima in subtropics – this is due to the Hadley cell subsidence branch

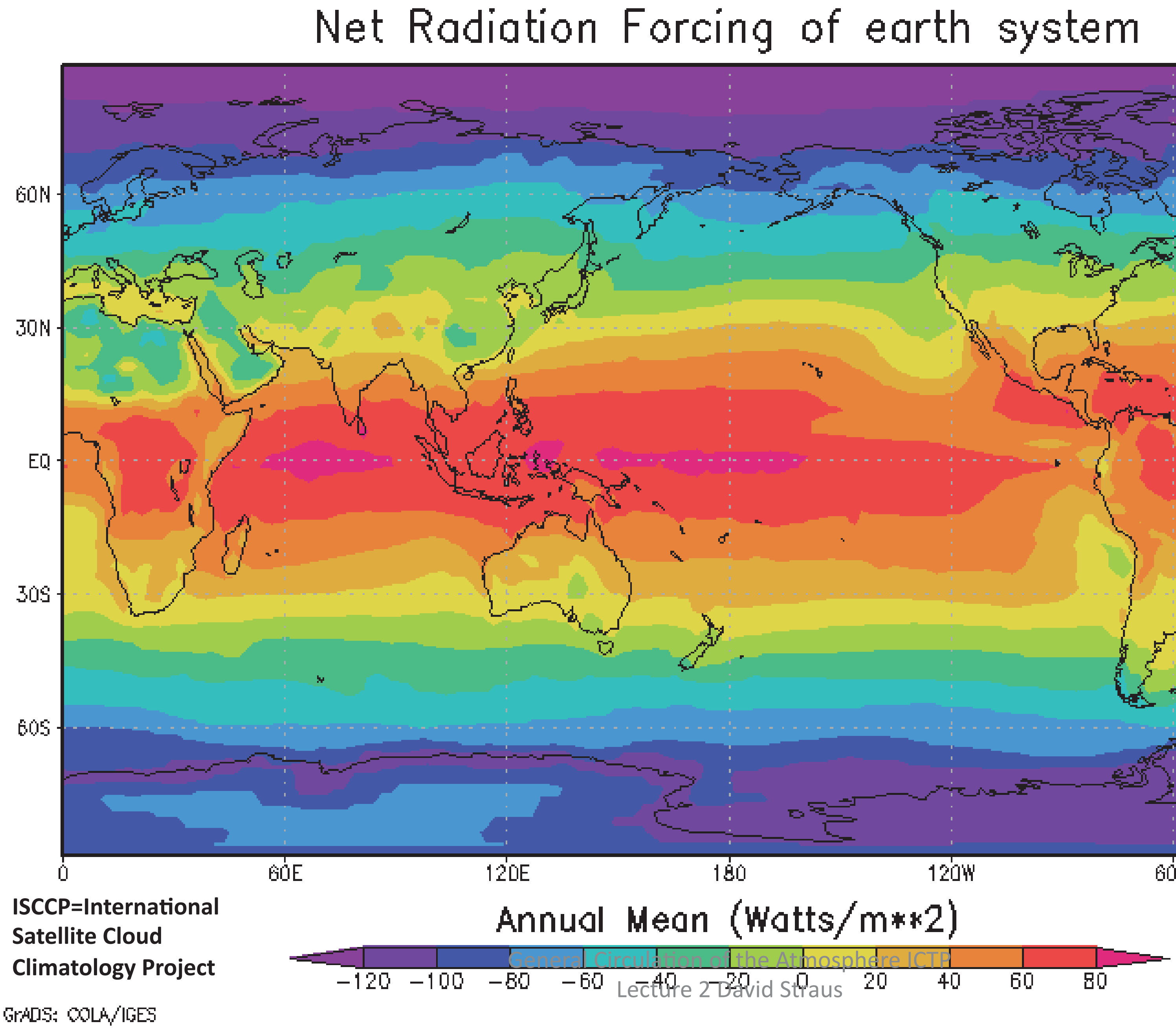
(4) Subsidence regions should have little cloudiness – see clouds in next picture!

Cloud amount shows tropical convection, subsidence zones, deserts and mid-latitude storm tracks



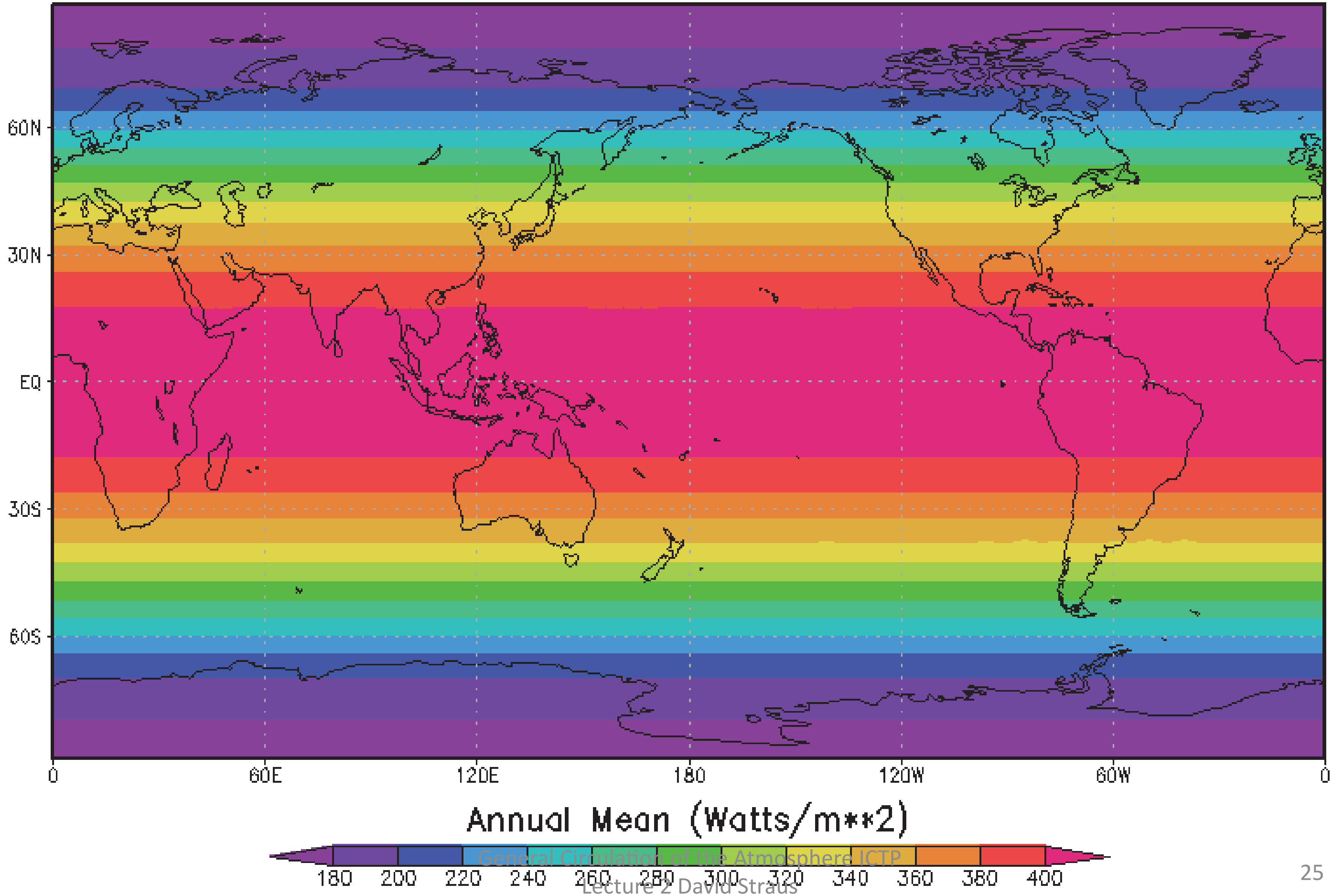
http://www.cesm.ucar.edu/experiments/cesm1.0/diagnostics/b40.t31x3.037/atm_451-500-obs/set5_6/set5_6.htm

A Review of the Time Mean, Global Mean Radiation Balance in the Horizontal

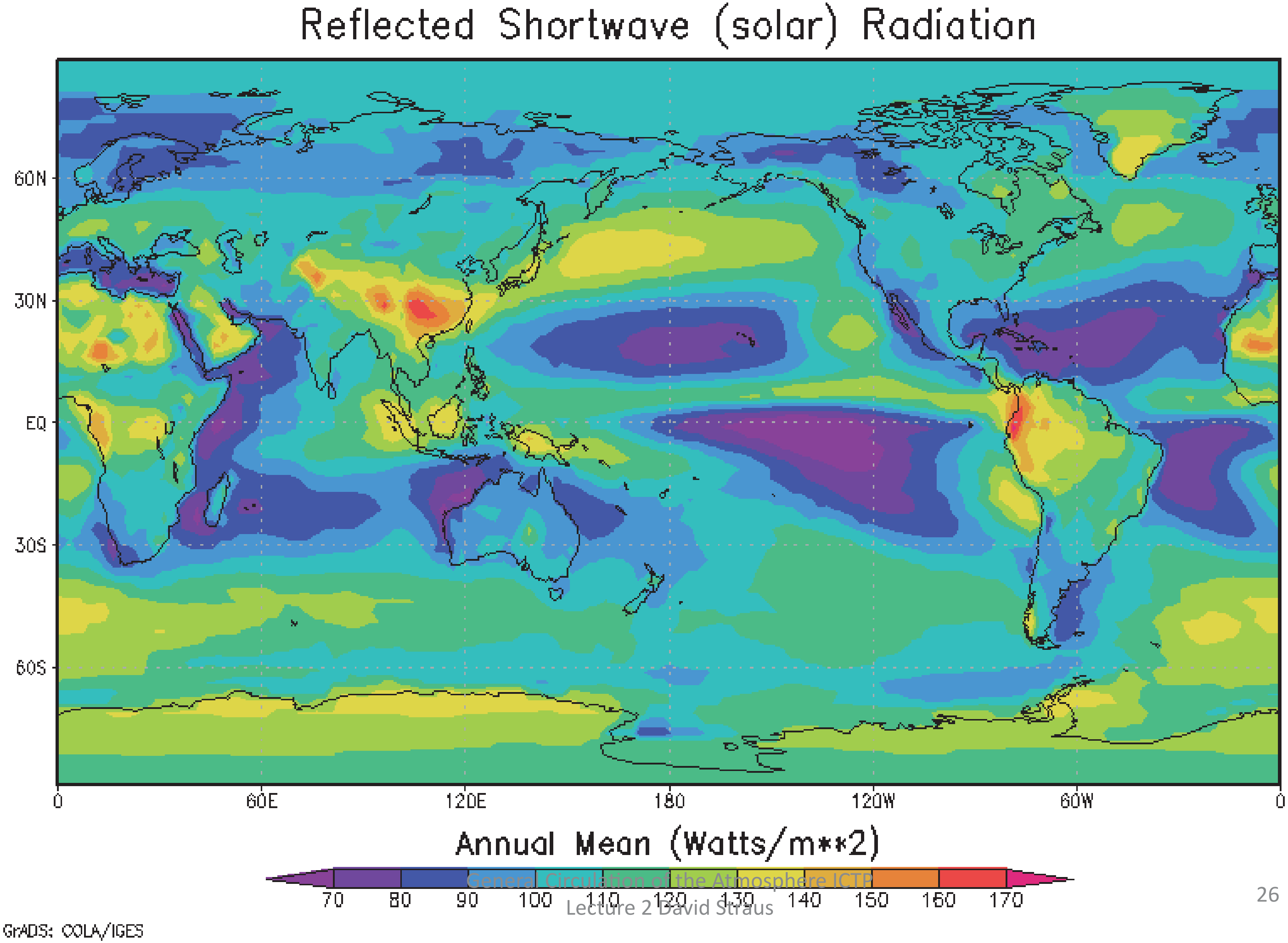


ISCCP=International Satellite Cloud Climatology Project

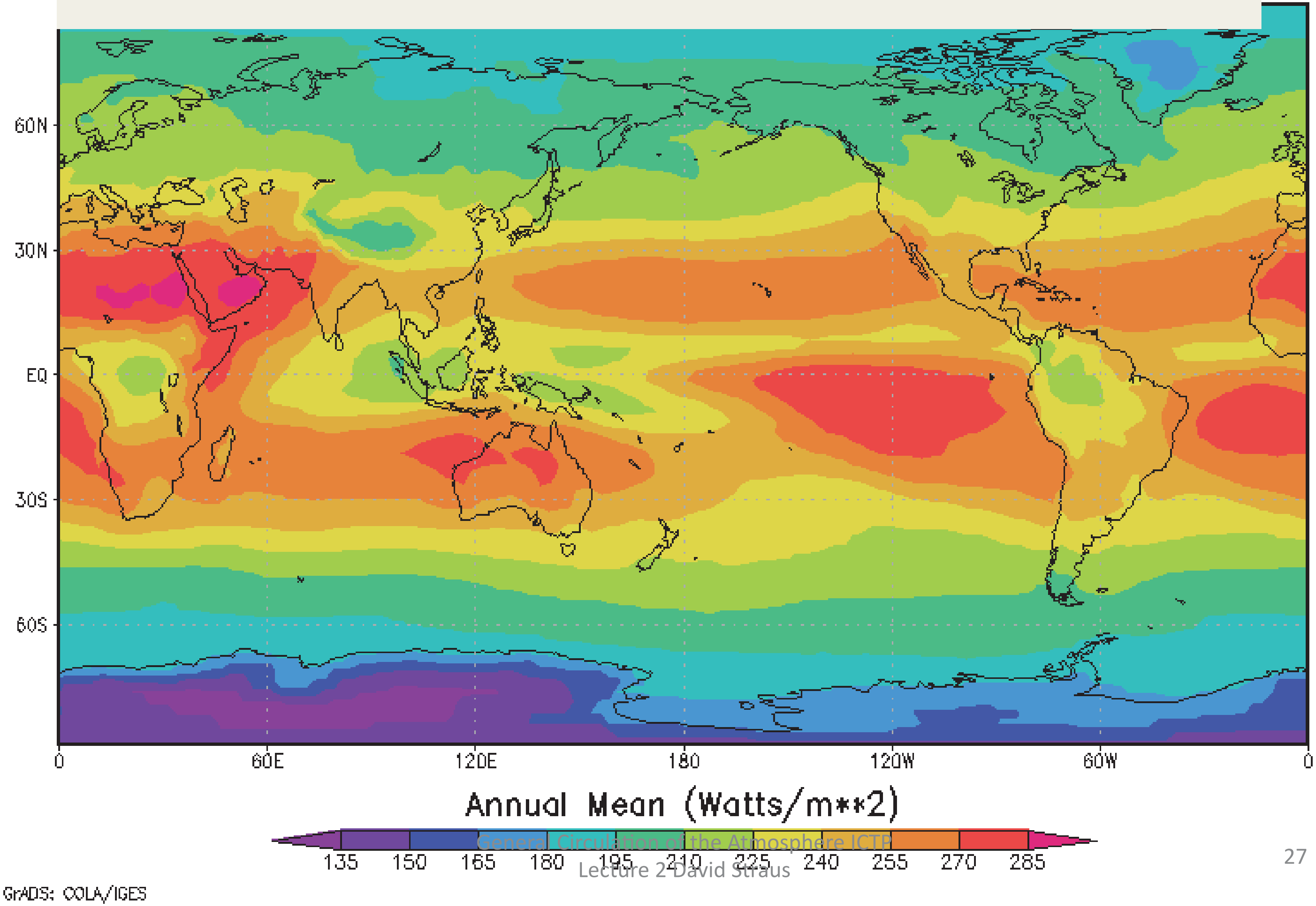
Incoming Shortwave (solar) Radiation



Reflected shortwave radiation is higher where there are clouds – smaller over the cloud-free oceanic regions – hence the oceanic subtropical highs – oceans are dark!



Outgoing long-wave radiation is sensitive to the temperature of the surface that radiates to space – hence to the height of the clouds! Deep clouds radiate to space from colder Temperature and hence have lower OLR



References:

Yu, L., and R. A. Weller, 2007: Objectively Analyzed air-sea heat Fluxes (OAFlux) for the global oceans. Bull. Ameri. Meteor. Soc., 88, 527-539.

Yu, L., X. Jin, and R. A. Weller, 2008: Multidecade Global Flux Datasets from the Objectively Analyzed Air-sea Fluxes (OAFlux) Project: Latent and sensible heat fluxes, ocean evaporation, and related surface meteorological variables. Woods Hole Oceanographic Institution, OAFlux Project Technical Report. OA-2008-01, 64pp. Woods Hole. Massachusetts.