ENVIROMIS 2012, Irkutsk

Investigation of a global climate change influence on Northern Hemisphere storm-track evolution using idealized model of climate system

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Outline

- **Introduction**
  - Background
  - Role of storm tracks in weather and climate
- **Focus is on:** Connections between climate forcing (increasing CO_2) and storm tracks
- Scenarios of experiments . Midlatitude storm track response in a warmer climate in climate system model «Planet Simulator» (*Fraedrich K., Jansen H., et al.,2005)*
- Examples storm tracks dynamics from climate change (preliminary results)
- Summary and Future work

Background

The general circulation and climate change

An evidence of our understanding of the general circulation is whether we can predict changes in the general circulation that might be associated with past or future climate changes. It would be especially useful to predict changes associated with global warming.

Changes in the location, intensity or seasonality of major climatological features of the general circulation could be more important than average temperature changes, particularly where these changes might affect local hydrologic, energy balances and etc.

THE POLEWARD EXPANSION OF THE TROPICAL CIRCULATION

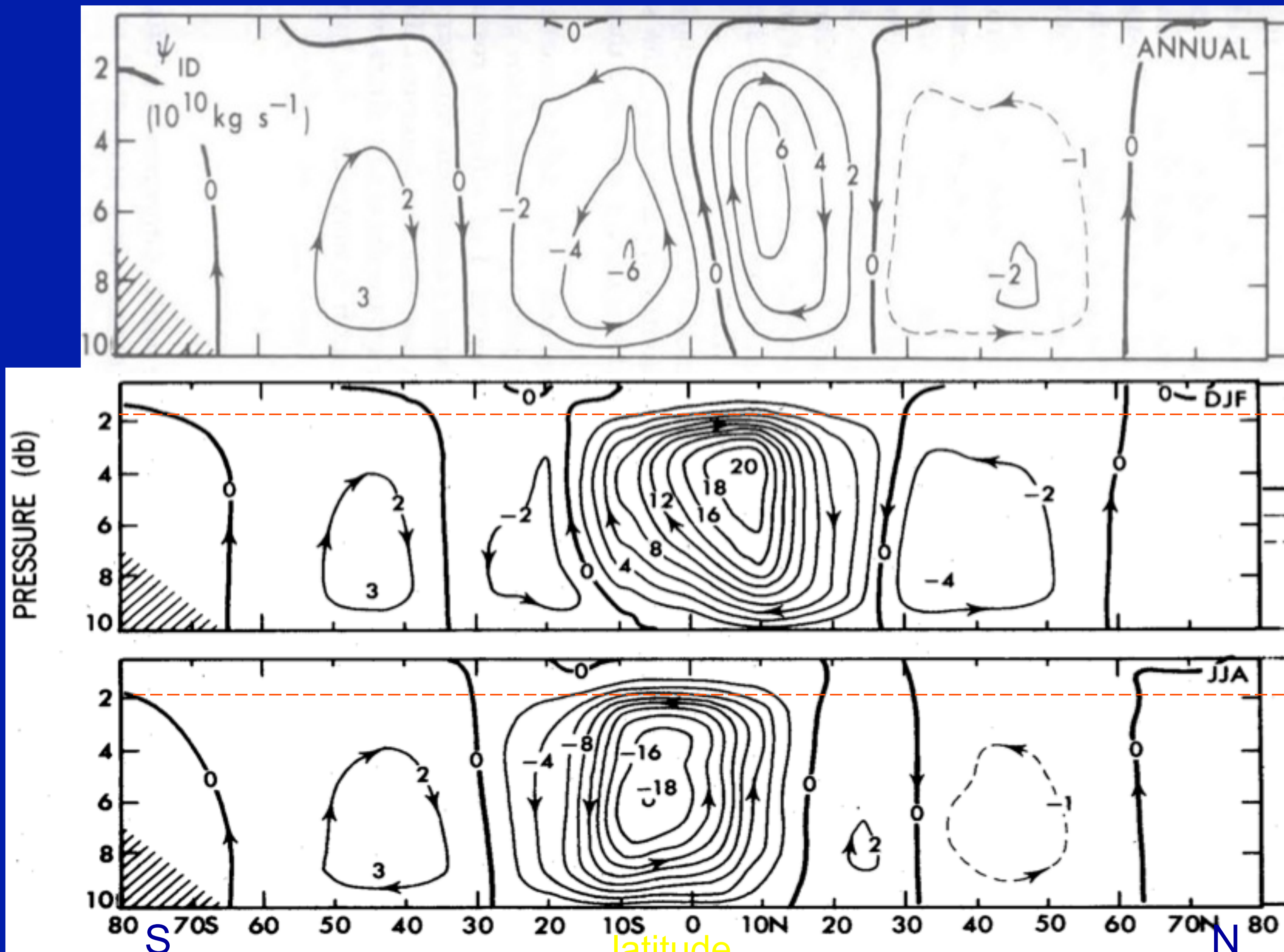
ANNUAL

200 mb (hPa)

DJF

200 mb (hPa)

JJA

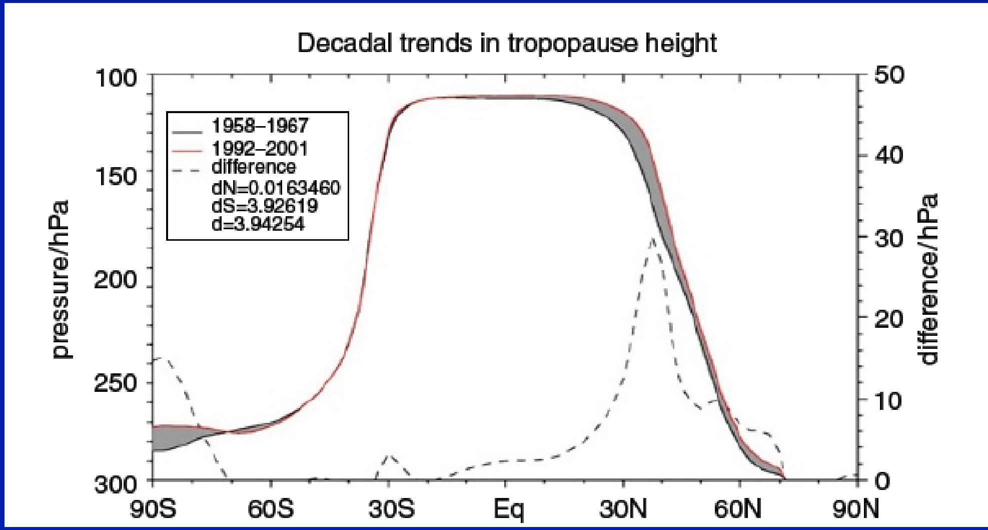


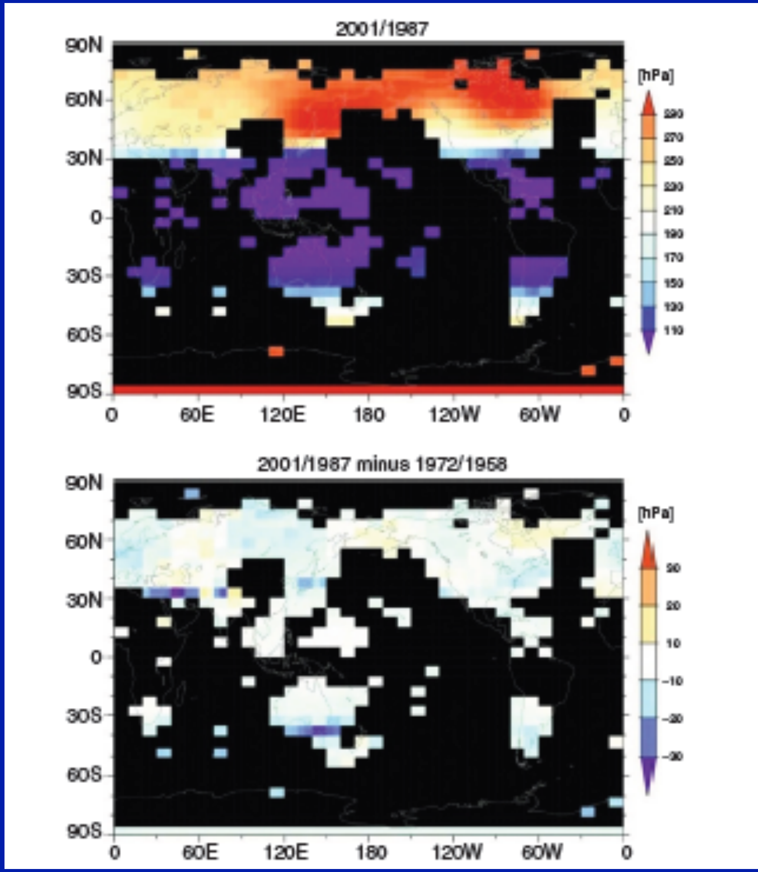
Total Meridional circulation - streamfunction units: 10^{10} kgm/sec

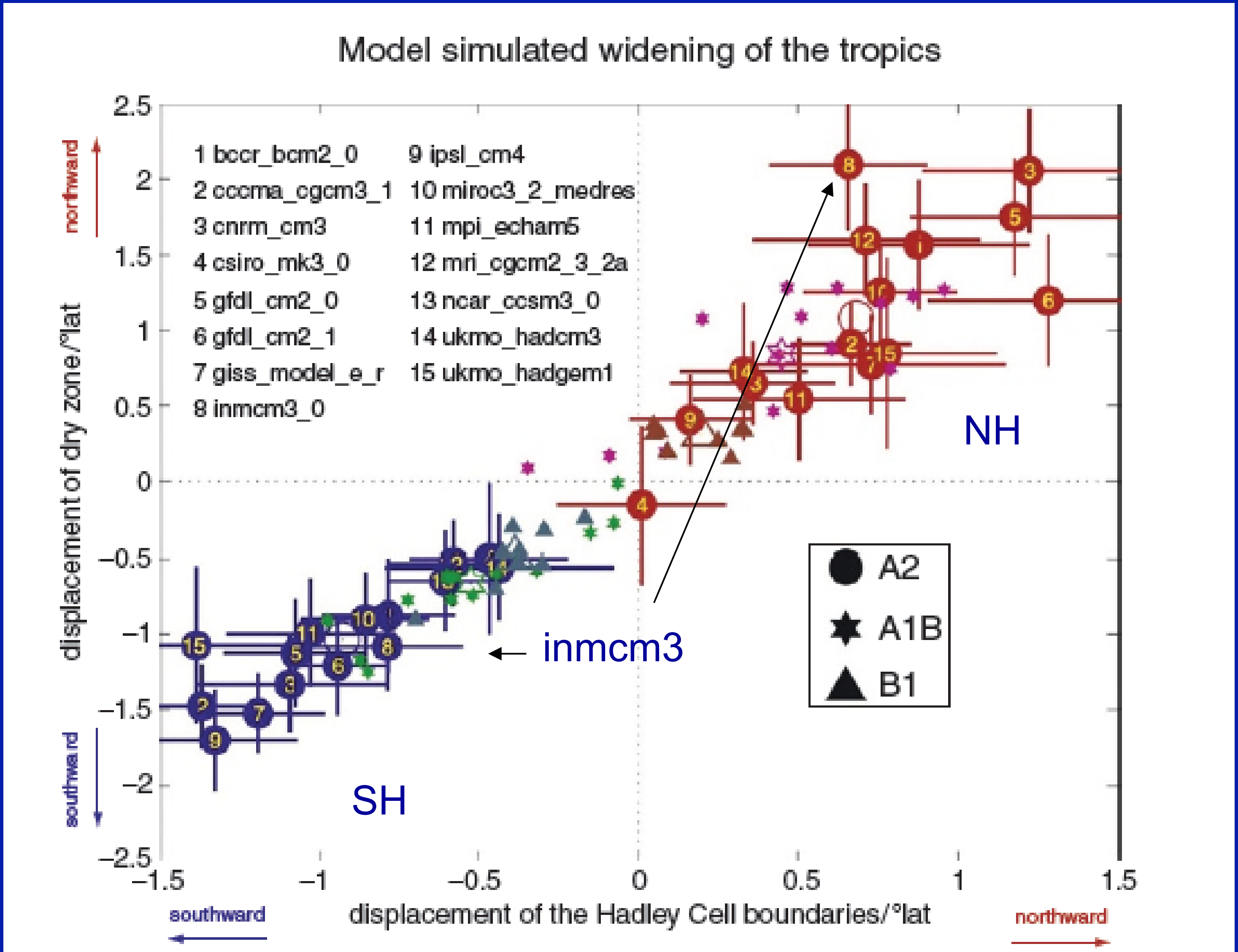
Tropical Tropopause Heights

- Analysis of radiosonde and reanalysis data shows that the height of the global tropopause has increased over the past decades, and

- GCM experiments indicate that climate change is likely responsible for this increase. This increase has been suggested as a possible reason for the poleward expansion of the tropical circulation.







Model simulated widening of the tropics - A2, A1B, and B1 scenarios of the IPCC-AR4 simulations.

Extratropical Eddies

- The recent increase in global tropopause heights is closely associated with systematic temperature changes below and above the tropopause temperatures have been warming in the troposphere and cooling in the stratosphere. The pattern of warming and cooling also affects the zonal wind structure in the region of the subtropical upper troposphere and lower stratosphere (UTLS).
- At intermediate heights of the UTLS region (12–16 km) the tropics warm and the extratropics cool, leading to an increase in meridional temperature gradients, and, by the thermal wind relationship, to an increase of zonal wind speeds above.
- Extratropical tropospheric eddies play a central role in this mechanism. The eddies tend to move eastward with the zonal flow and equatorward toward the subtropics until they approach their critical latitudes, where their phase speed equals the speed of the background zonal flow.

Remark: In paper (G. Chen and I.Held, 2007) a mechanism was proposed that establishes a connection between the pattern of warming and cooling in the UTLS region, the associated zonal wind anomalies, and the poleward movements of the jets.

Static Stability

- Changes in the vertical temperature structure of the atmosphere provide yet another explanation for the tropical widening. Such changes are related to the vertical non-uniformity of the tropospheric global warming signal.
- Observations as well as model experiments indicate that the global warming signal in the upper troposphere is stronger than in the lower troposphere and that it maximizes in the tropical upper troposphere

The Role of SST Forcing

- Surface temperatures over the tropical oceans undergo changes over time, which have been shown to have important consequences for the global atmospheric circulation. These SST changes are primarily related to the natural ENSO phenomenon.

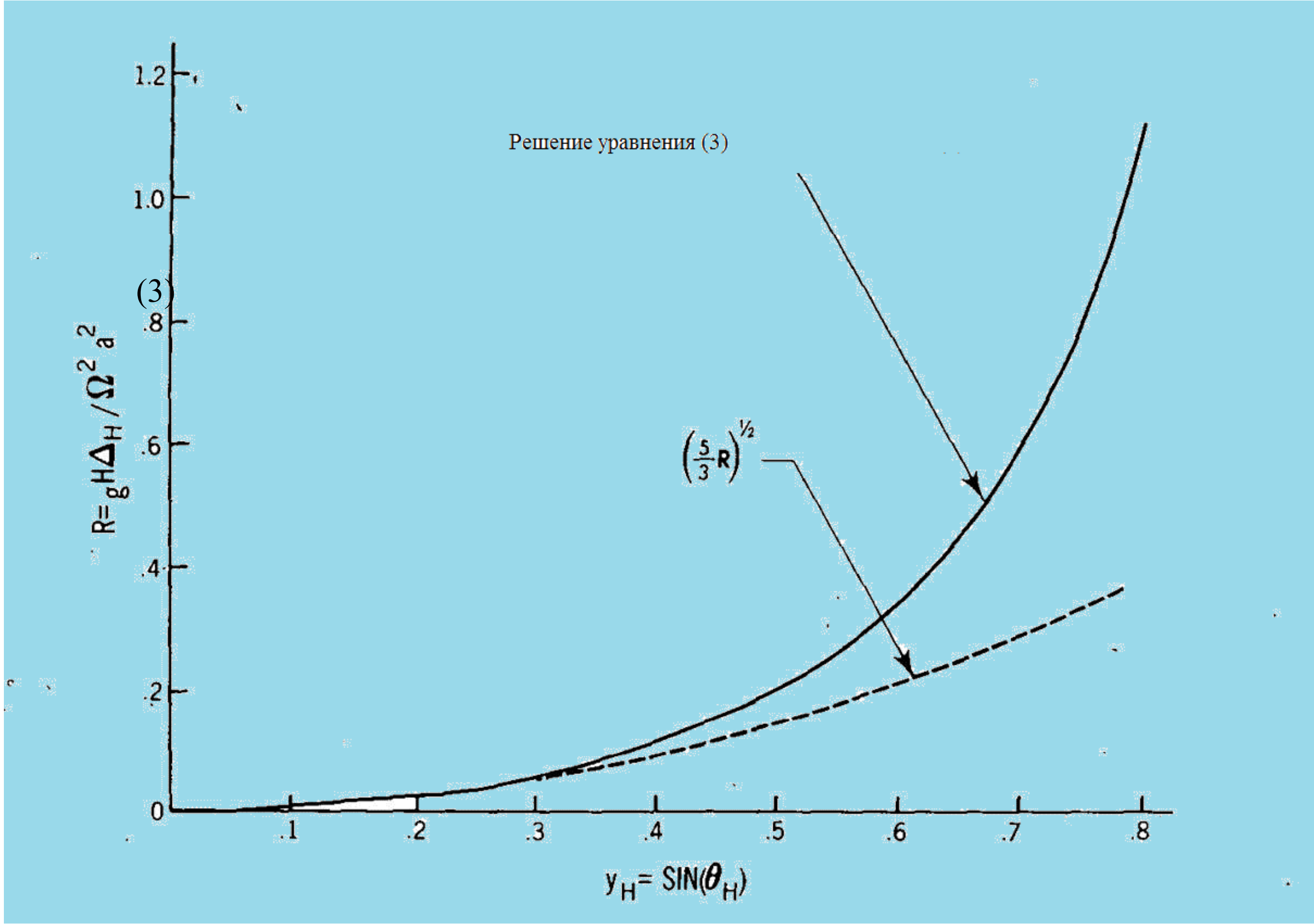
- Various studies have demonstrated that the tropics are contracting during the warm phase of ENSO (El Nin˜o), as indicated by equatorward displacements of the jet, storm track, eddy momentum divergence, and edge of the HC.

Dependence of tropical edges on height tropopause. In approach of small angles $y_H = \sin(\theta_H)$ (Held and Hou, 1980)

$$\Theta_H^2 = \frac{5}{3} \cdot R, \quad R = 1 \quad \varphi_H \approx \left(\frac{5}{3} \cdot \frac{gH_t}{\Omega^2 a^2} \cdot \frac{\Delta_h}{T_0} \right)^{\frac{1}{2}}$$

$$y_H^3 - \frac{y_H^5}{(1-y_H^2)} - y_H + \frac{1}{2}\ln\left(\frac{1+y_H}{1-y_H}\right) = 0$$

$$y_H = \sin\varphi_H$$



One question is whether climate change will significantly affect the location and intensity of midlatitude storm tracks and associated jets.

Because the wave, mean-flow interaction in midlatitudes produces low-frequency variations in the latitude of the jets, it is reasonable to think that a modest climate change might significantly affect the position of jets and their associated storm tracks.

Modeling of the response of midlatitude jets to greenhouse gas induced warming suggests that a drop of sea level pressure over the poles and a northward shift of the midlatitude jets is likely (Bengtsson *et al.* 2006; Miller *et al.* 2006), but this signal is affected by the response of ENSO to global warming, which is less certain (Yamaguchi and Noda 2006).

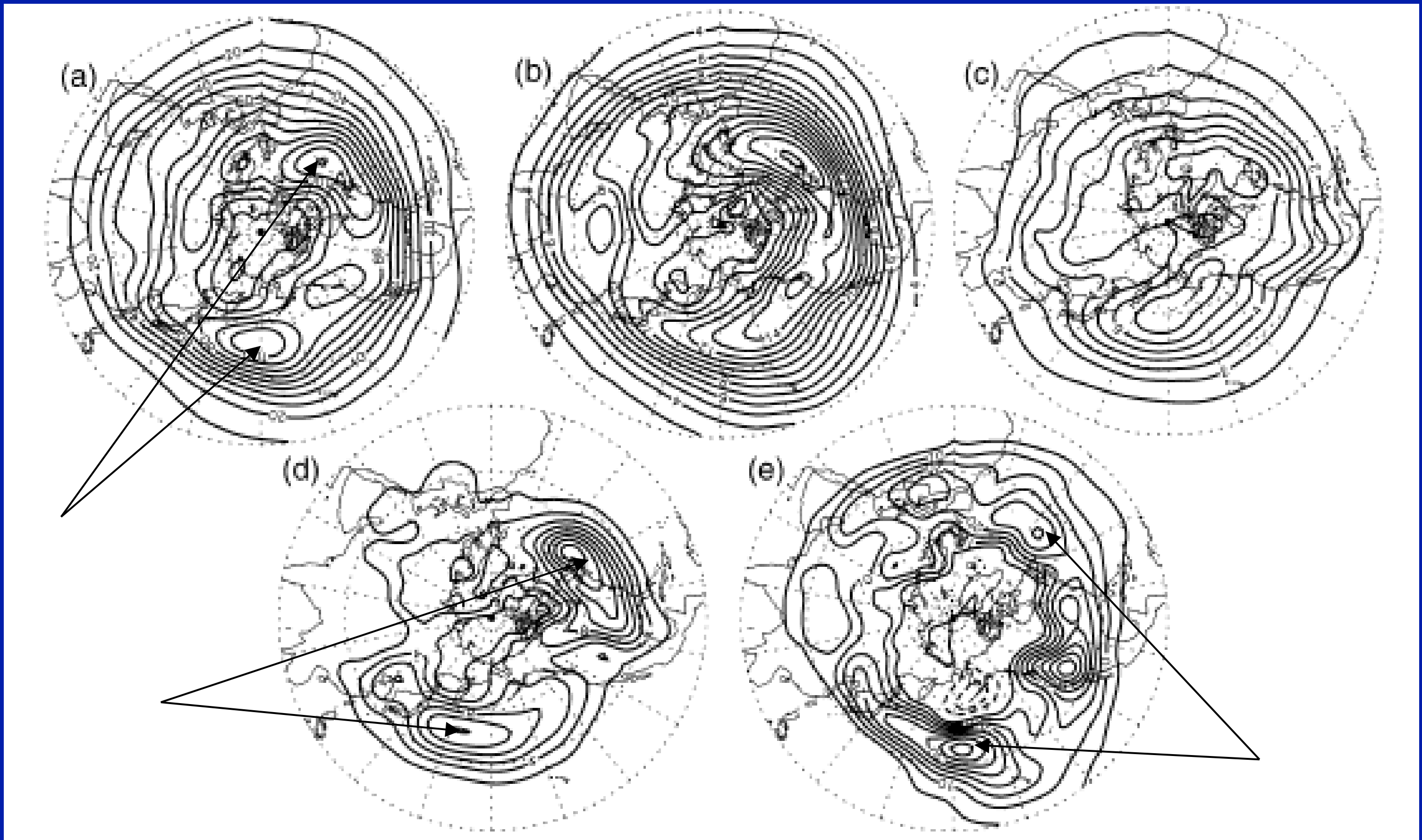
Background

Storm Tracks

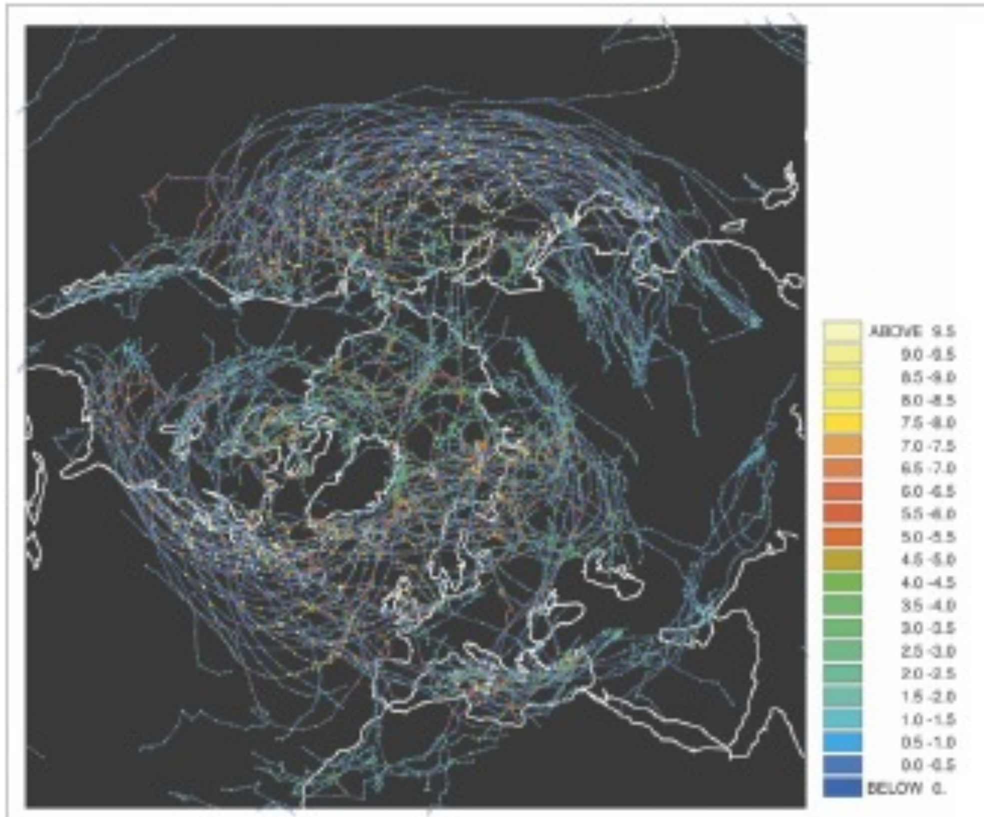
Band-pass filters that emphasize the 2.5 to 6-day variance tend to be associated with baroclinic wave development and zonally elongated patterns of maximum variance in this frequency band were identified

as the storm tracks.

The variables often considered for analyzing the storm tracks include the geopotential height, vorticity, geostrophic wind components, temperature, eddy momentum flux, eddy heat flux and eddy kinetic energy, etc.



Bandpass statistics from the NCEP–NCAR reanalysis.
(a) std devs of 250-hPa *Z* (contour 10 m),
(b) (b) 300-hPa U (contour 2 m s-1), and
(c) (c) SLP (contour 1 hPa).
(d) Poleward fluxes of a heat at 850-hP (contour 2 K m s-1) and
(e) 250-hPa westerly momentum (contour 5 m2 s-2).



Example of
extratropical cyclone tracks for the DJF winter of 2002-2003 from ERA-40 based on the relative vorticity at 850hPa.

Only systems that **last longer than 2 days and travel farther than 1000 km are included.** Tracks are the blue lines and the colored dots indicate the intensity along the track in units of 10−5 *s*−1. [from Bengtsson et al. (2006)]

Why do we need to study dynamics of storm tracks?

Through radiative forcing by increased atmospheric carbon dioxide and water vapor and increased solar absorption due to less low cloud cover in the subtropics, more energy is gained within the tropics and subtropics, while in the middle and high latitudes energy is reduced through increased outgoing terrestrial radiation in the Northern Hemisphere and increased ocean heat uptake in the Southern Hemisphere.

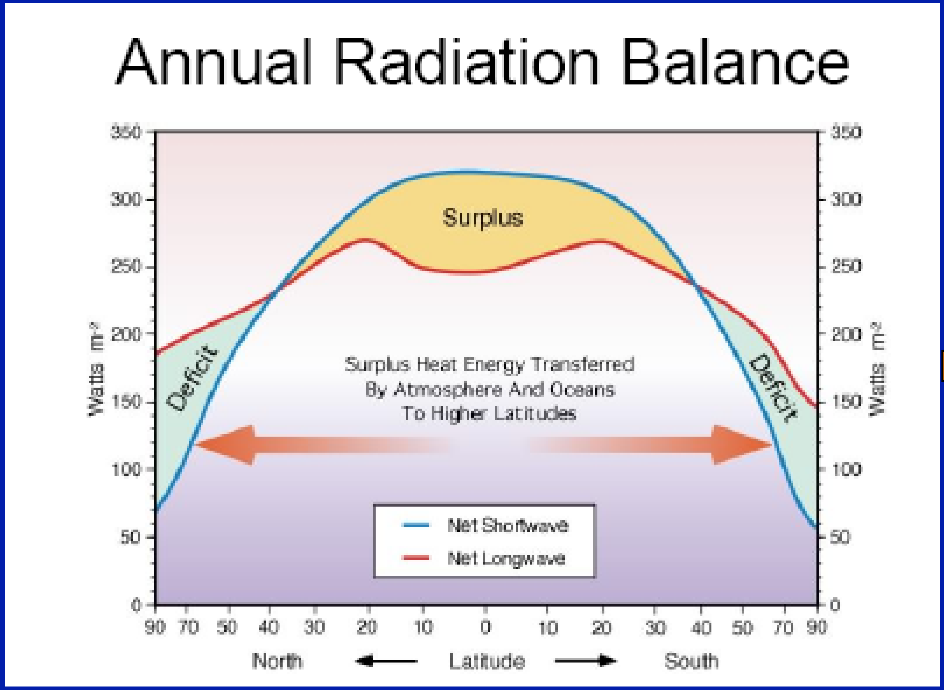
This enhanced energy imbalance in the future climate requires larger poleward atmospheric energy transports in the midlatitudes which are partially accomplished by the intensifed storm tracks. This strong connection between intensifed storm track energy transports and intensifed energy imbalance in the atmosphere is also confrmed in CMIP3/IPCC AR4 models.

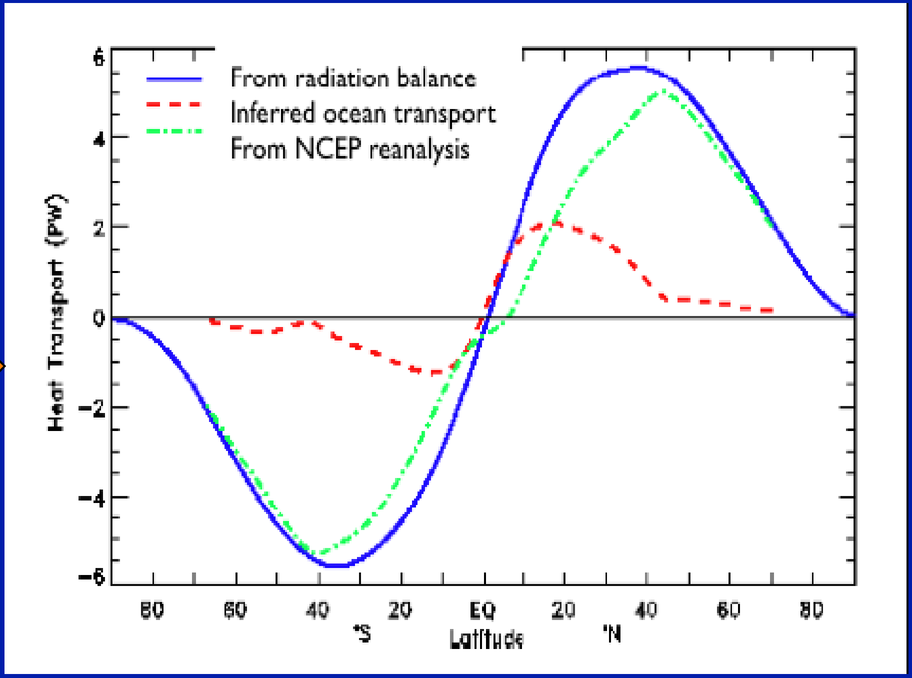
The meridional gradient in Absorbed Solar Radiation (ASR) drives circulation.

In an equilibrium, the resultant Meridional Heat Transport (MHT) is such that

ASR = OLR + MHT

OLR is the Outgoing Longwave Radiation at the TOA





Northward heat transport in the atmosphere for:
whole YEAR
DJF
JJA

Total

This total is made up of the sum of the following motions:

Transient eddies

Standing eddies

Mean meridional circulation

Energy flux units: 0.4cos(lat) PW

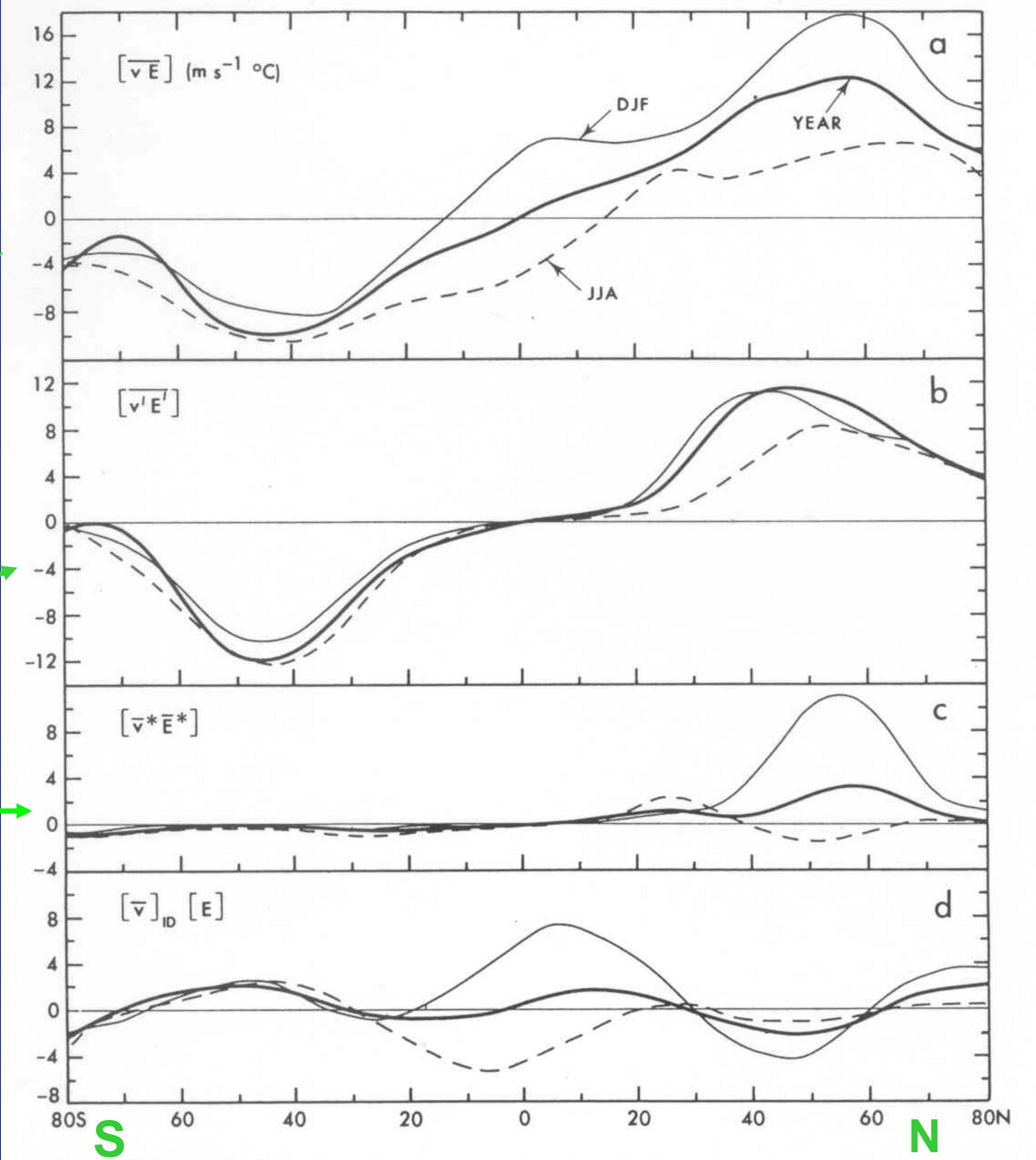


FIGURE 13.11. Meridional profiles of the zonal- and vertical-mean northward transport of energy by all motions (a), transient eddies (b), stationary eddies (c), and mean meridional circulations (d) in °C m s^{-1} [to convert to units of 10^{15} W multiply values by $2\pi R \cos\phi\, c_p(p_0/g) \approx 0.4 \cos\phi$; from Oort and Peixoto, 1983].

The role of the storm - the tracks in the dynamics of weather and climate

Example: The winter climate of Europe and the Mediterranean is dominated by the weather systems of the midlatitude storm tracks. The behaviour of the storm tracks is highly variable, particularly in the eastern North Atlantic, and has a profound impact on the climate of the Mediterranean region. (D. J. Brayshaw et al., 2011)

The storm - the tracks are defined as the region of strong baroclinicity (maximum meridional temperature gradient), which are determined on the basis of eddy statistics like eddy fluxes of angular momentum, energy, and water (with the use of high - band pass - filter).

In the Northern Hemisphere, there are two major storms in the region - Label: Atlantic and Pacific.

Baroclinic eddies:

-bring heavy rains and other hazardous weather phenomena in the middle latitudes;

-play an important role in the global energy cycle and the hydrological cycle

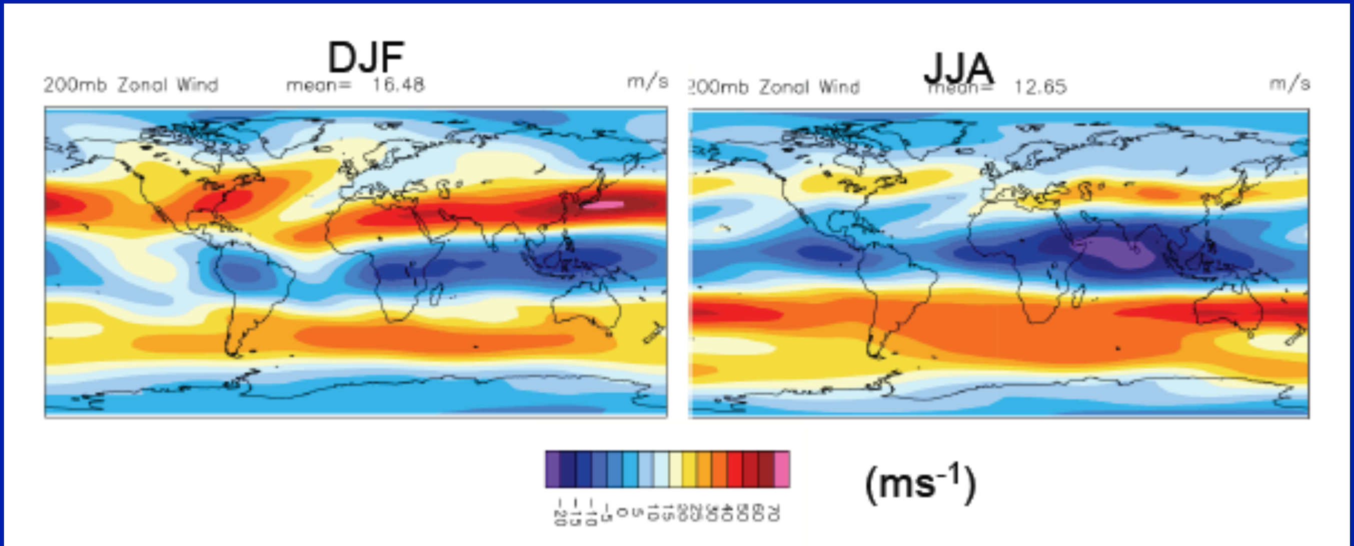
- Fluxes of heat, momentum, and water vapor shape Earth's temperature, wind, and net precipitation distribution.

- In the extratropics in the zonal mean, these fluxes are dominated by transient eddies (Peixoto and Oort 1992).

- The winter jets are stronger than the summer jets

- The jets in the NH are localized, while the jet in the SH is nearly zonally symmetric

- Jets demark regions of strong temperature gradients. Hence they are regions with high potential energy and flow instability ---> the storm tracks which transport heat polewards (3PW NH and 5.5PW in SH)



- usually transient baroclinic waves are developed in the vicinity of the entrance to the jet stream, are carried downstream and destroyed at the exit of the jet (a somewhat simplified view of their relationship with the jet stream and the life cycle of the wave);

- their role in the maintenance of the jet stream is complicated enough, eddies fluxes of heat in a storm - tracks directed to the pole, and apparently acts to weaken the jet;

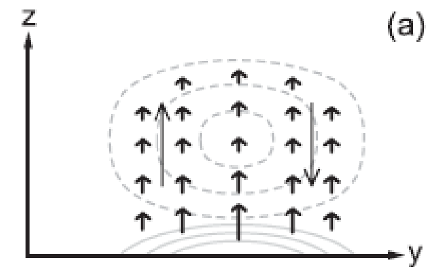
- transient eddies in midlatitude storm-track is an important mechanism of energy, moment and moisture transport in climate system.

$$\frac{\partial \bar{u}}{\partial t} - f\bar{v}^* = (\rho_0 a \cos\varphi)^{-1}\nabla \cdot \mathbf{F}$$

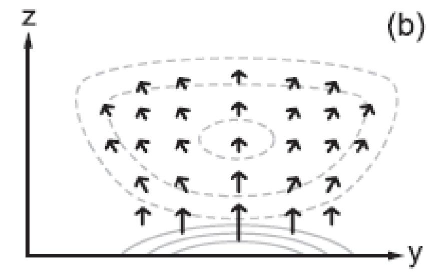
$$\frac{\partial \bar{\theta}}{\partial t} + \overline{w}^* \frac{\partial \bar{\theta}}{\partial z} = \bar{Q} \qquad \overline{w}^* = \overline{w} + \frac{\partial}{\partial y}\left(\overline{v'\theta'}\left(\frac{\partial \bar{\theta}}{\partial z}\right)^{-1}\right)$$

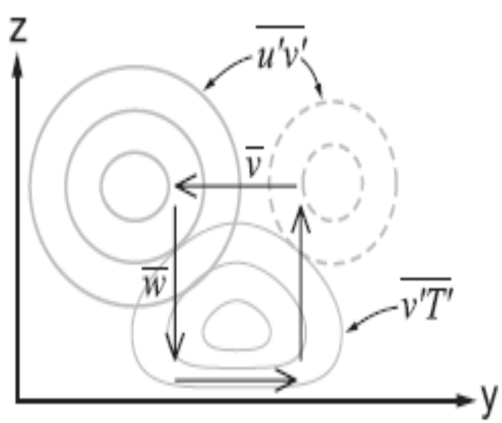
Eliassen-Palm Flux vector, F =
$$F_\varphi = -\rho_0 a \cos\varphi\, \overline{u'v'}$$
$$F_z = f\rho_0 a \cos\varphi\, \overline{v'\theta'}/\bar{\theta}_z$$

wave fluxes that propagate upward and converge,

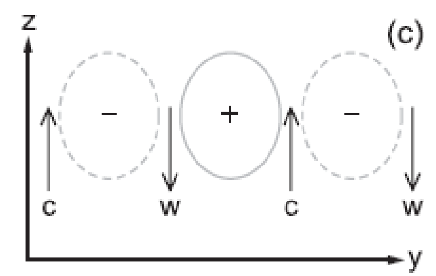


wave fluxes that propagate upward and then meridionally outward,



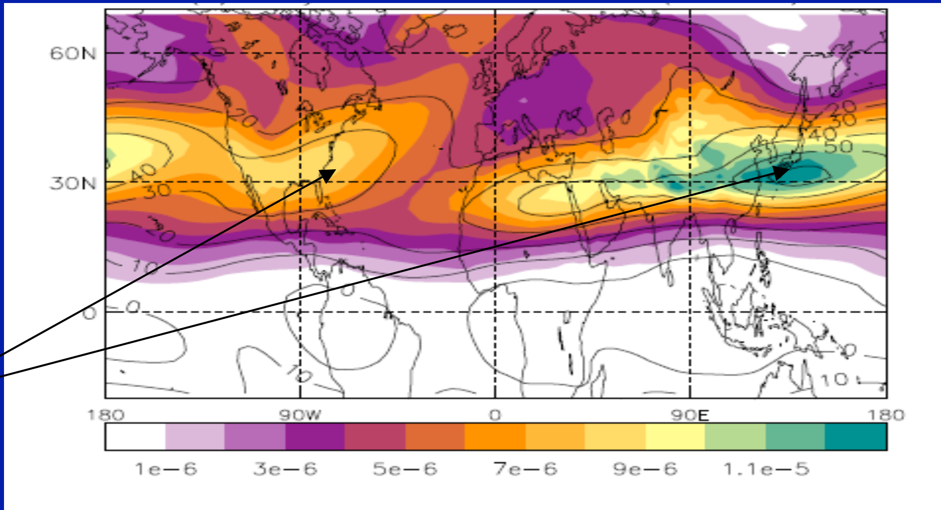


the difference in EP flux convergence
and residual vertical velocity



(D. Hartmann, 2007)

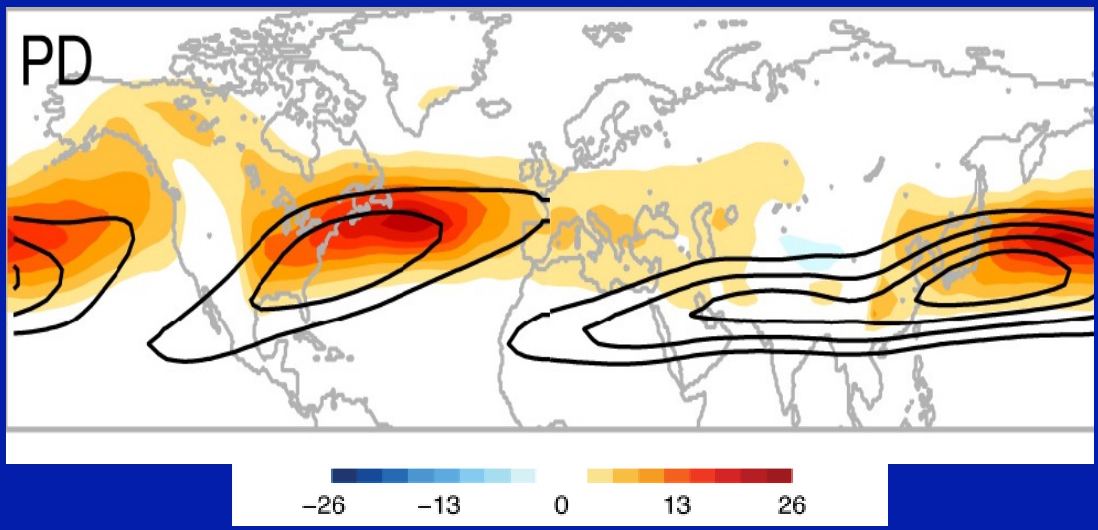
- for the baroclinic waves in a storm - tracks we have the following estimate of the maximum linear growth rate (estimated by R. Lindzen, B. Farrell, 1980, in the problem of instability baroclinic flow)

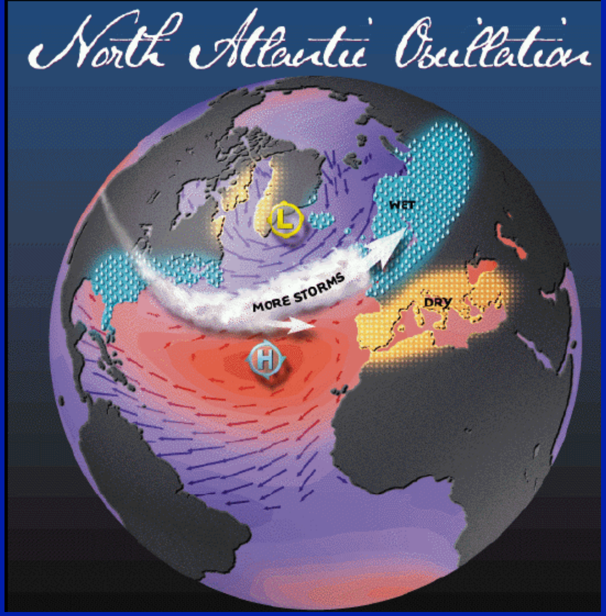


$$(kc_i)_{\max} = \sigma_E \approx -0.3125 \cdot \frac{g}{N \cdot \bar{T}} \cdot \left. \frac{d\bar{T}}{dy} \right|_{surf}$$

Eady growth rate (measured between 300 and 700 hPa) (colours, s−1) (from D. J. Brayshaw et al., 2011)

poleward heat flux 850mb (Km/s)





Positive Phase NAO

Climate variability associated with storm tracks

1) In the midlatitudes, climate variability is due to storm-track dynamics that are intrinsic to the atmosphere

2) The dynamical time scale associated with these modes is ~ 5 days, and is set by the interactions between the storms and the jets that form them

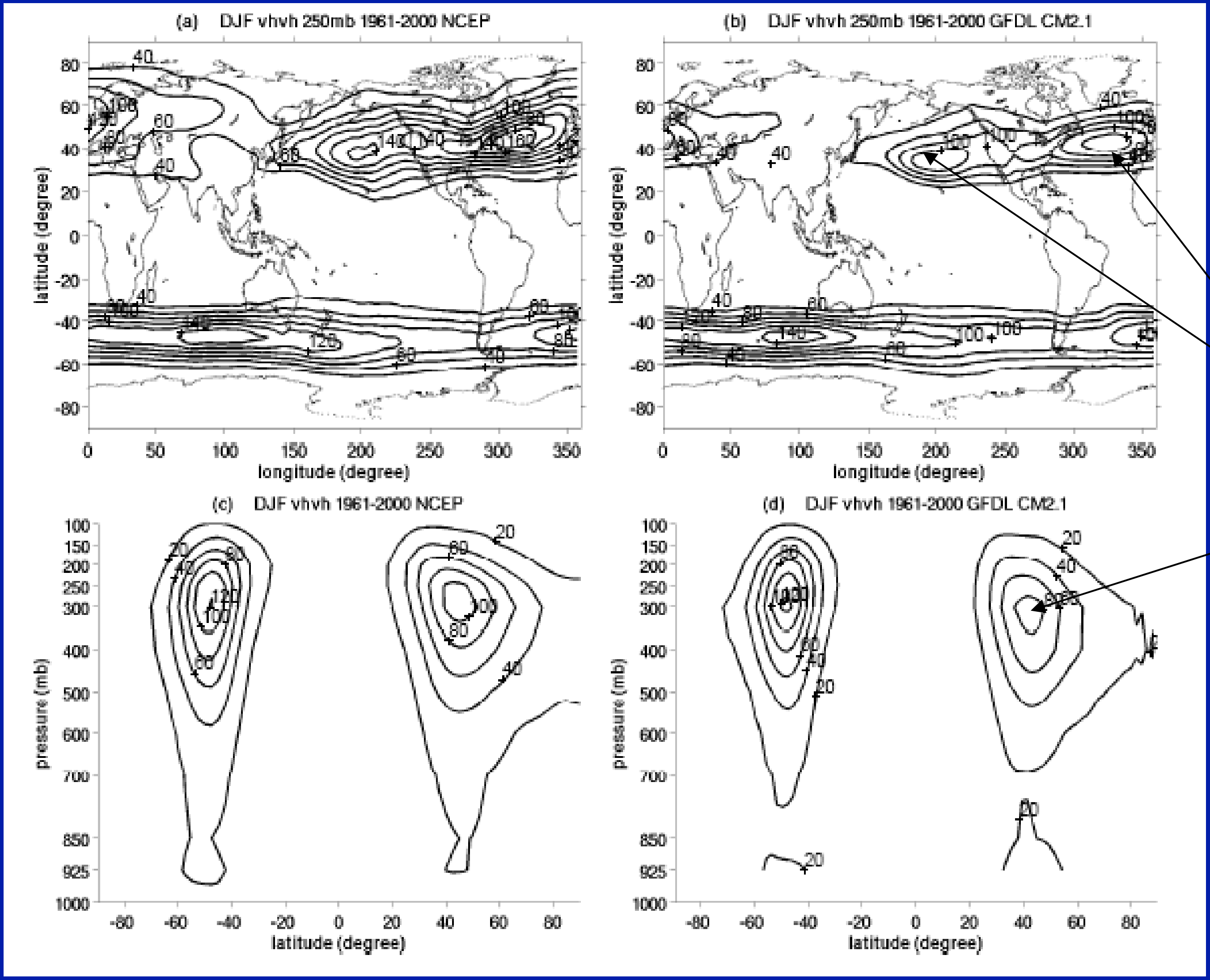
3) Key patterns of climate variability (the 'modes') are co-located with the jets, which are determined by rotation rate, orography, gross land-sea contrasts, etc.

These modes include:

- The North Atlantic Oscillation (NAO)
- The North Pacific Oscillation (NPO)
- The Northern Annular Mode (NAM aka AO)

The variance of eddy meridional velocity **(v'v')** at 250 mb

NCEP-NCAR



GFDL CM2:1

Comparison of band-pass filtered variance of meridional velocity, produced in the GFDL CM2:1 model simulations (right column) with that derived in the NCEP-NCAR reanalysis (left column).

The aim of our work is investigation of the intensity and major transient eddies propagation paths change through the global climate change.

Scenarios of experiments

Scenario:

Control — concentration CO_2 is constant (360 ppm);

SRES A2 — concentration CO_2 exponential grows, increasing to the end of modelling almost twice;

minus SRES A2 — mirror display SRES A2.

The period of modelling: 90 + 20 + 90 years

Filtration: filter (*Blackmon M.L, 1976)*, high-frequency. Waves with periodicity of 2-8 day (synoptic scale) are selected.

Considered characteristics:

averages on time of value meridional sensible heat flux ($v'T'$) and variance of eddy meridional velocity ($v'v'$) and their trends for 90 years.

We provide our study using the idealized climatic system model «Planet Simulator» (*Fraedrich K., Jansen H., et al., 2005*).

Three equilibrium states (CONTR, SRES-A2 and minus SRES-A2 is compared for the estimation of climatic system reaction.

Together with sensitivity of storm-track dynamic other features of “warm” climate in comparison with “current” climate dynamic is considered.

Model Dynamics

Conservation of momentum (vorticity and divergence equation)

$$\frac{\partial \zeta + f}{\partial t} = \frac{1}{(1-\mu^2)}\frac{\partial F_\nu}{\partial \lambda} - \frac{\partial F_u}{\partial \mu} + P_\zeta$$

$$\frac{\partial D}{\partial t} = \frac{1}{(1-\mu^2)}\frac{\partial F_u}{\partial \lambda} + \frac{\partial F_\nu}{\partial \mu} - \nabla^2 E - \nabla^2(\phi + T_0 \ln p_s) + P_D$$

Hydrostatic approximation (using the equation of state)

$$0 = \frac{\partial \phi}{\partial \ln \sigma} + T$$

$$\frac{\partial \ln p_s}{\partial t} = -\int_0^1 A d\sigma$$

Thermodynamic equation

$$\frac{\partial T'}{\partial t} = F_T - \dot{\sigma}\frac{\partial T}{\partial \sigma} + \kappa W T + \frac{J}{c_p} + P_T$$

Conservation of mass (continuity equation)

$$\frac{\partial \ln p_s}{\partial t} = -\int_0^1 A d\sigma$$

Thermodynamic equation

$$\frac{\partial T'}{\partial t} = F_T - \dot{\sigma}\frac{\partial T}{\partial \sigma} + \kappa W T + \frac{J}{c_p} + P_T$$

Spectral Transform method

The prognostic variables are represented in the horizontal by truncated series of spherical harmonics (Q stands for ζ, D, T and $\ln p_s$)

$$Q(\lambda, \mu, \sigma, t) = \sum_{m=-M}^{M} \sum_{n=|m|}^{M} Q_n^m(\sigma, t) P_n^m(\mu) e^{im\lambda}$$

$$= Q_n^0(\sigma, t) P_n^0(\mu) + 2 \textstyle\sum_{m=1}^{M} \sum_{n=m}^{M} Q_n^m(\sigma, t) P_n^m(\mu) e^{im\lambda}$$

Vertical discretization

$$(\dot{\sigma}\frac{\partial Q}{\partial \sigma})\hat{=}\frac{1}{2\Delta\sigma_r}[\dot{\sigma}_{r+0.5}(Q_{r+1}-Q_r)+\dot{\sigma}_{r-0.5}(Q_r-Q_{r-1})]$$

$$\frac{\partial \phi}{\partial \ln \sigma}+T\hat{=}\phi_{r+0.5}-\phi_{r-0.5}+T_r\cdot\ln\frac{\sigma_{r+0.5}}{\sigma_{r-0.5}}$$

$$\phi_r=\phi_{r+0.5}+\alpha_r T_r$$

$$\text{with } \alpha_r=1-\frac{\sigma_{r-0.5}}{\Delta\sigma_r}\ln\frac{\sigma_{r+0.5}}{\sigma_{r-0.5}} \text{ and } \Delta\sigma_r=\sigma_{r+0.5}-\sigma_{r-0.5}$$

Semi-implicit time stepping

Model Physics – Parameterizations:

Surface Fluxes and Vertical Diffusion

Radiation

Moist Processes and Dry Convection

Land Surface and Soil

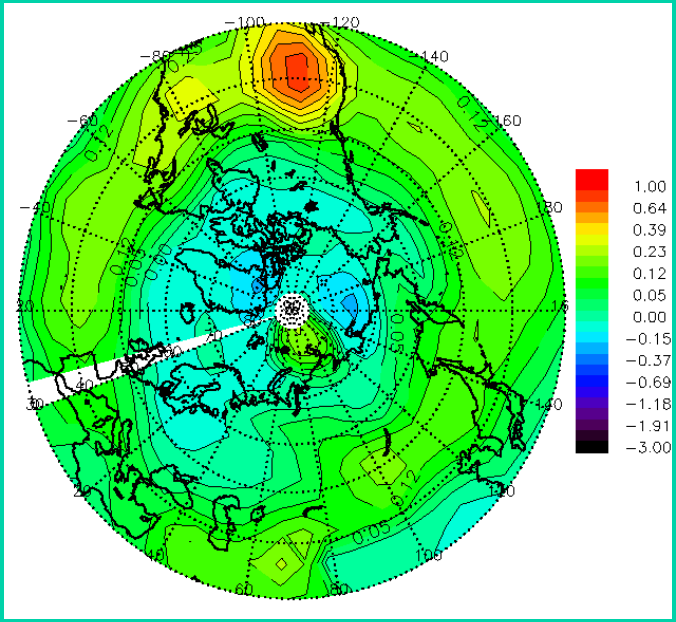
Sea Surface

Ocean: Mixed Layer   Slab Ocean Model   Sea ice model

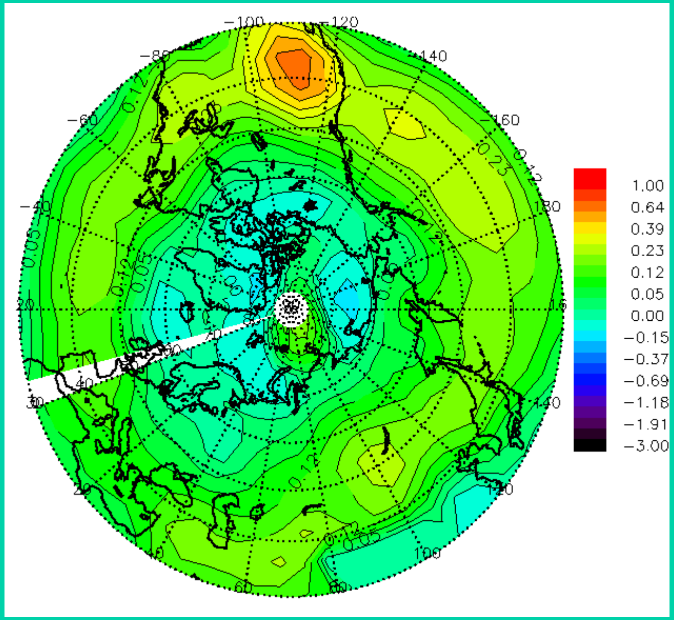
Dynamic Vegetation

Meridional sensible heat flux **(v'T')** at 700 mb

Winter



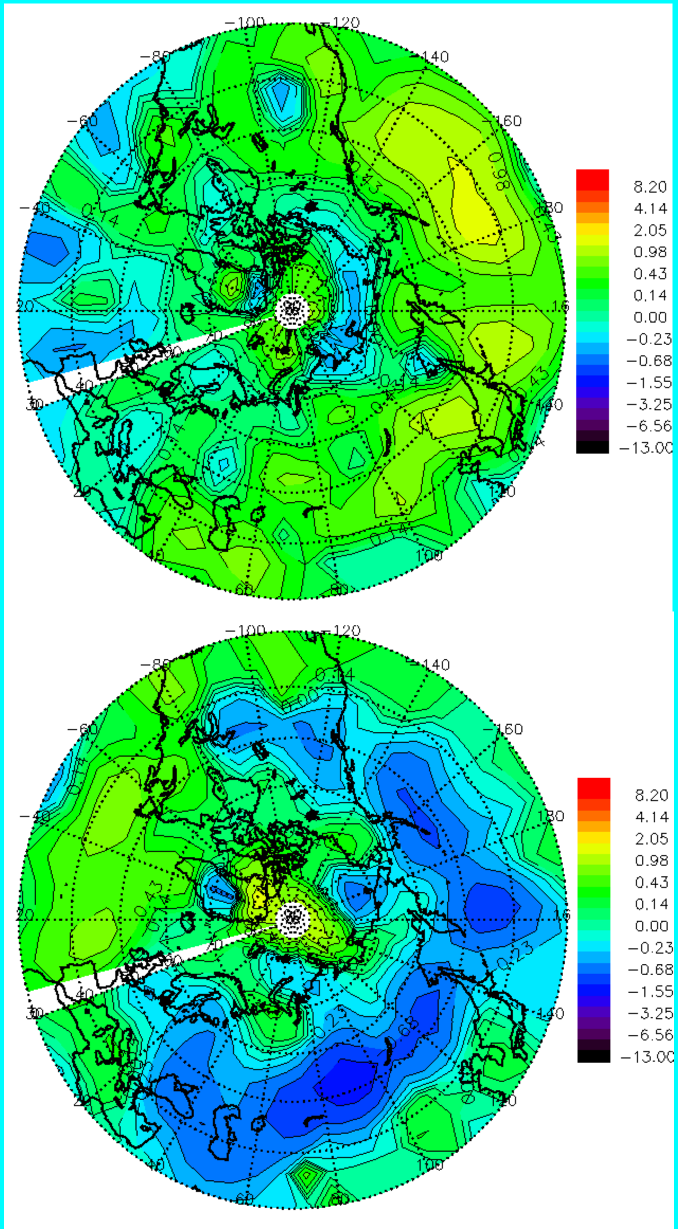
Control



SRES A2

Trend: meridional sensible heat flux **(v'T')** at 700 mb

winter

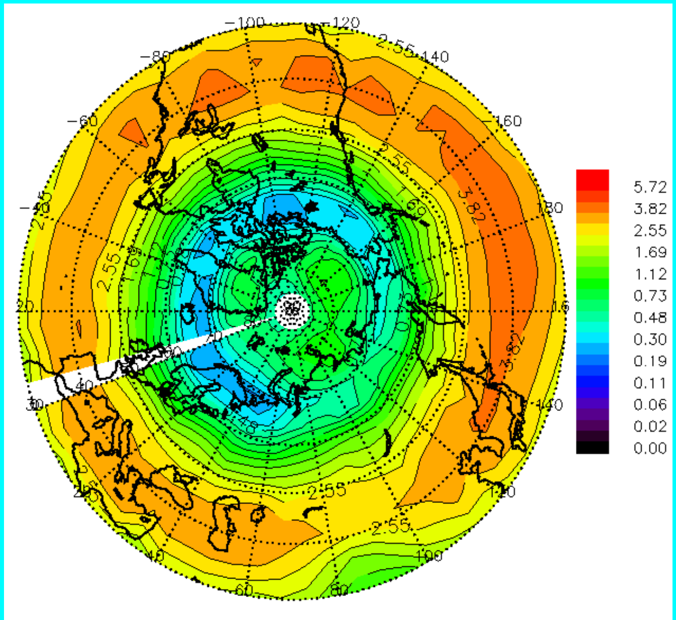


SRES A2

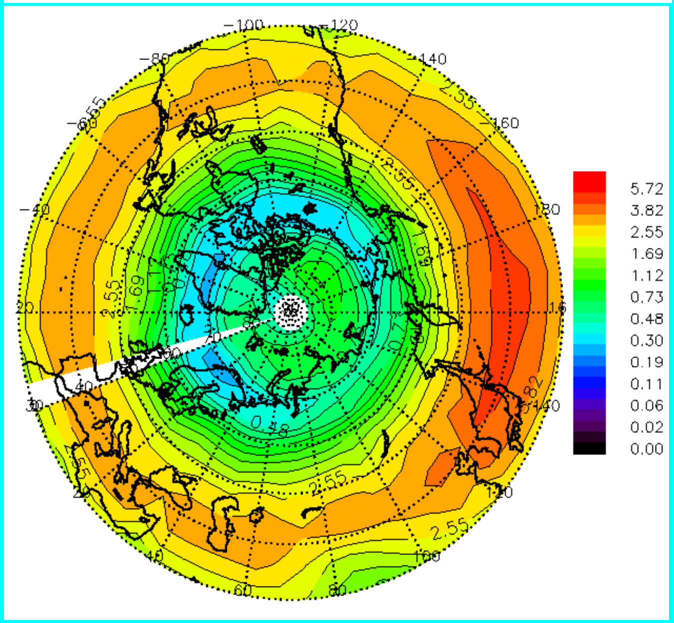
- (SRES A2)

The variance of eddy meridional velocity **(v'v')** at 250 mb

winter

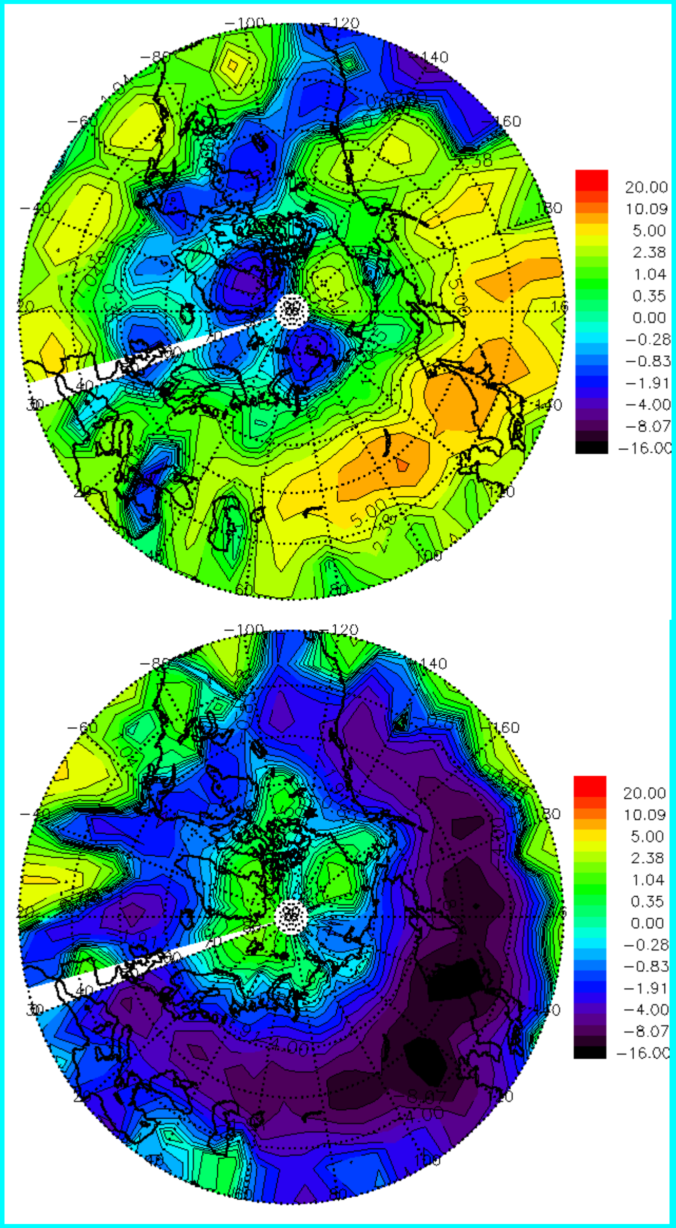


Control



SRES A2

Trends: The variance of eddy meridional velocity **(v'v')** at 250 mb

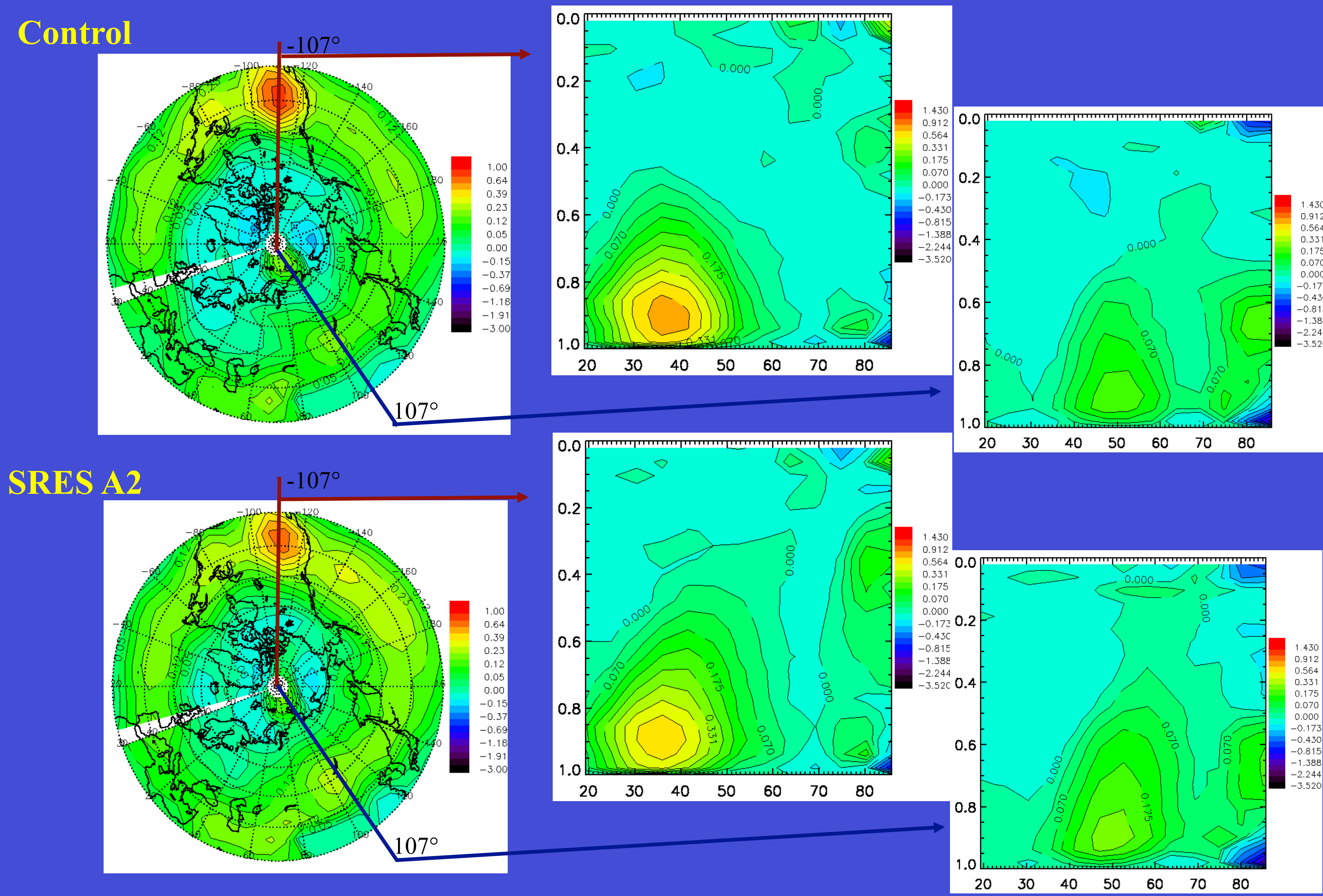


SRES A2

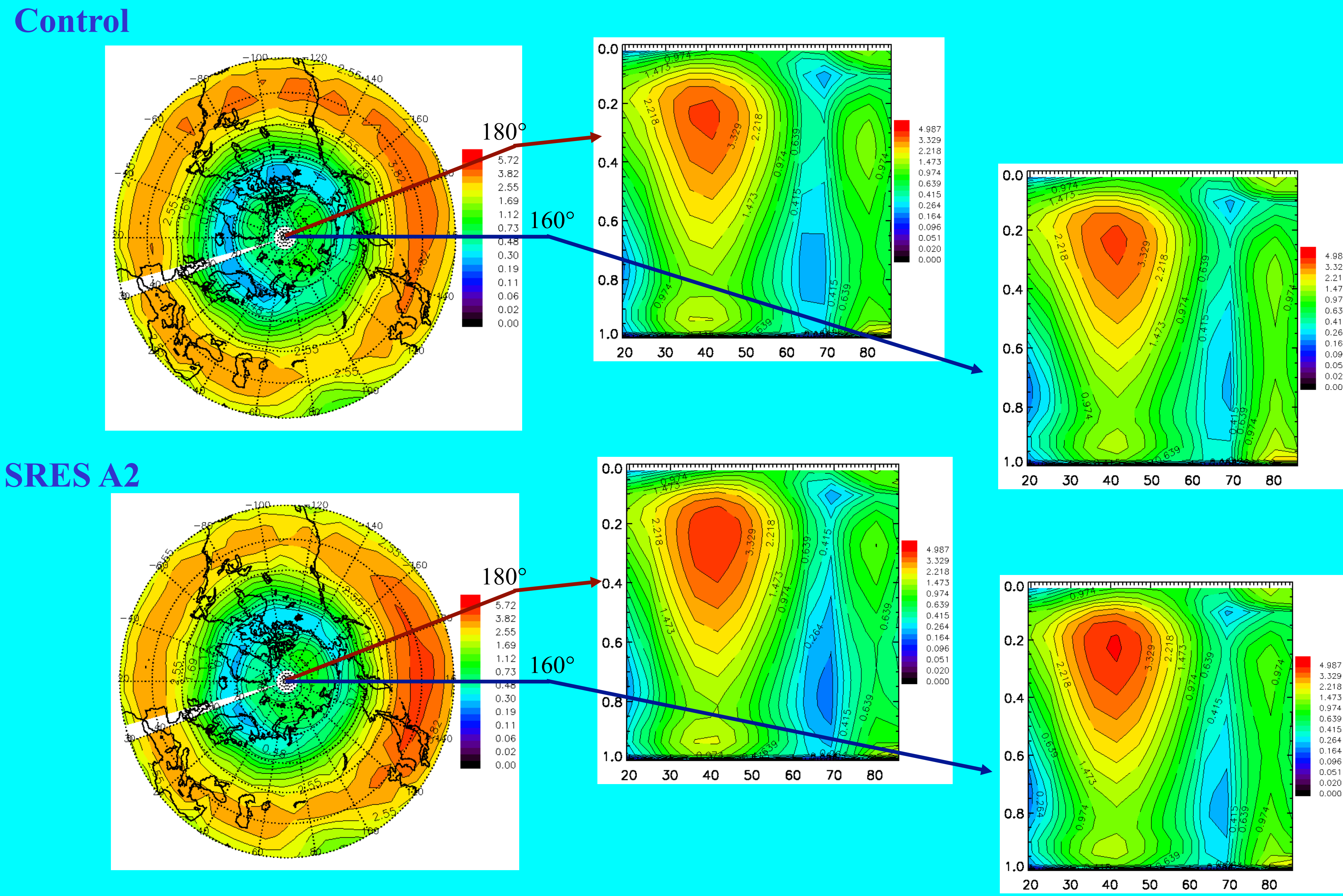
winter

- (SRES A2)

(v'T') at 700 mb, winter



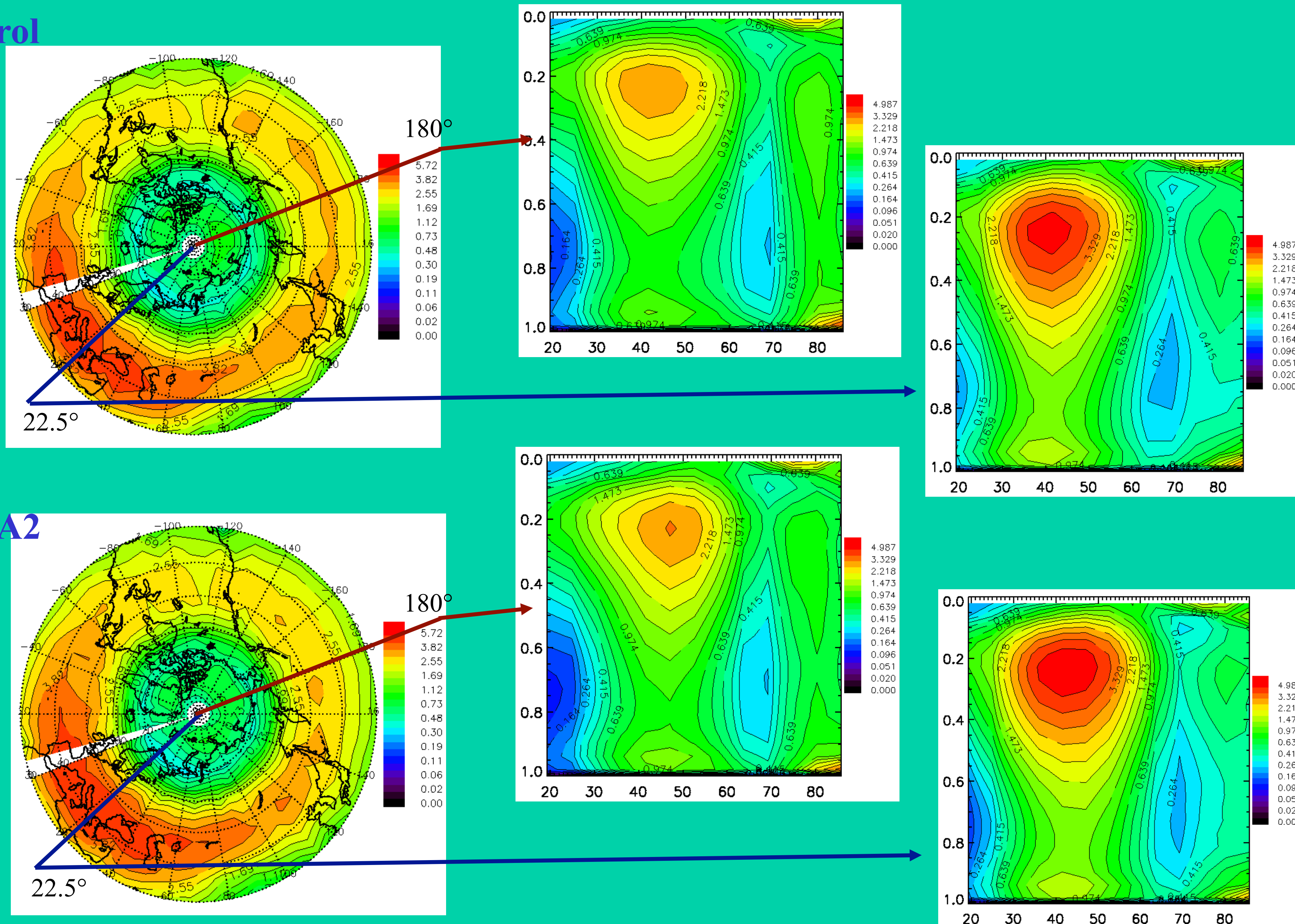
(v'v') at 250 mb, winter



(v'v') at 250 mb, summer

Control

SRES A2



Summary and Future work

In this paper we have examined the future projections in the location and amplitude of the storm tracks from the global coupled climate model simulations, the A2 and – A2 scenarios.

We have identified a poleward expansion, and intensification on the poleward flank, of storm tracks in the future climate from band-pass filtered transient eddy statistics.

The future projections in transient eddy activity and its heat transport well correspond to the changes in baroclinic instability.

As have been noted, the enhanced planetary energy imbalance is primarily radiative driven and provides more available potential energy in the atmosphere.

However, till now there is no general point of view on that as distribution and intensity a storm – tracks will vary at change of a climate in 21 century, i.e. can the transient eddies maintain themselves in forming the storm track, or are they controlled by other sources such as diabatic heating, surface damping, or stationary waves?

Storm tracks are key link between patterns of climate variability (ENSO, NAO, etc.) and extreme weather. It is necessary for investigating this in large ensemble of GCM climate change experiments

Thank You