Decadal changes of the Hadley circulation

Yongyun Hu

Dept. of Atmospheric and Oceanic Sciences
School of Physics, Peking University

Collaborators:
Lijun Tao, Jiping Liu, Chenggong Wang, Han Huang

AOS-EPS Summer School, Beijing, Aug. 1, 2017

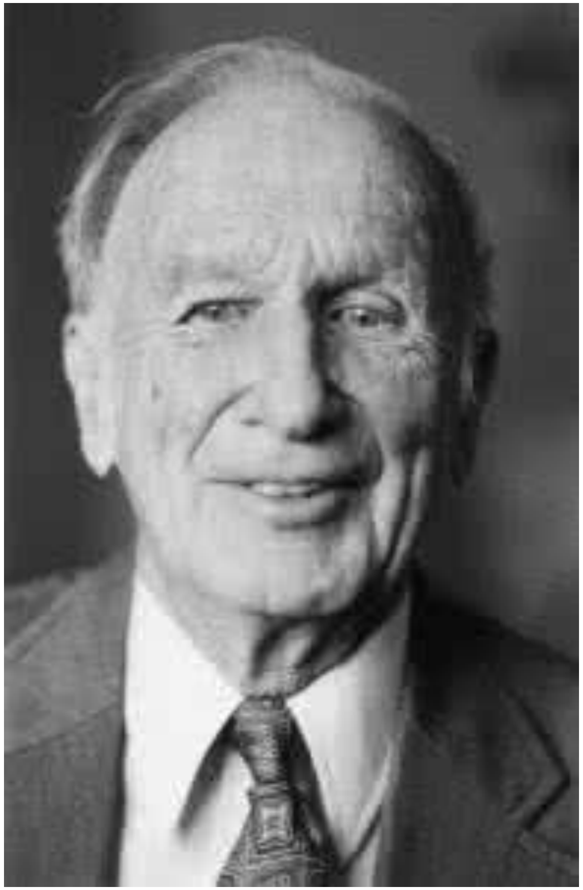
Contents

1. A brief history of the Hadley circulation,
2. Observations of widening of the Hadley circulation,
3. Climate effects of widening of the Hadley circulation,
4. What cause widening of the Hadley circulation?
5. Questions or homework.

1. A brief history of the Hadley circulation

The Nature of the global Circulation of the Atmosphere

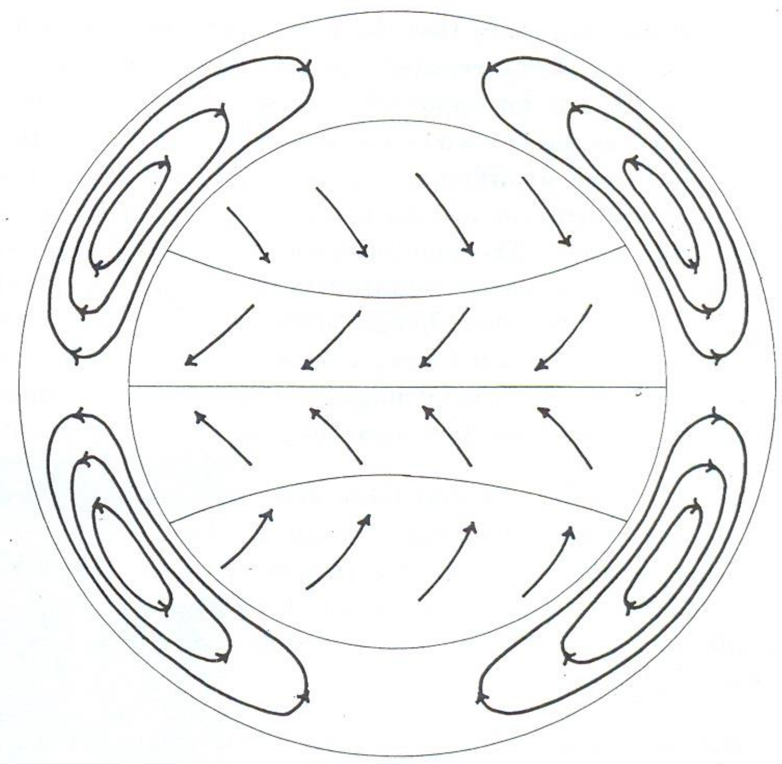
——Ed. Lorenze, 1969



Hadley's circulation model (1735)

Greater solar heating in low latitudes lead to rising motion near the equator and sinking near the poles, with equatorward motion at low levels and poleward motion aloft completing the circuit.

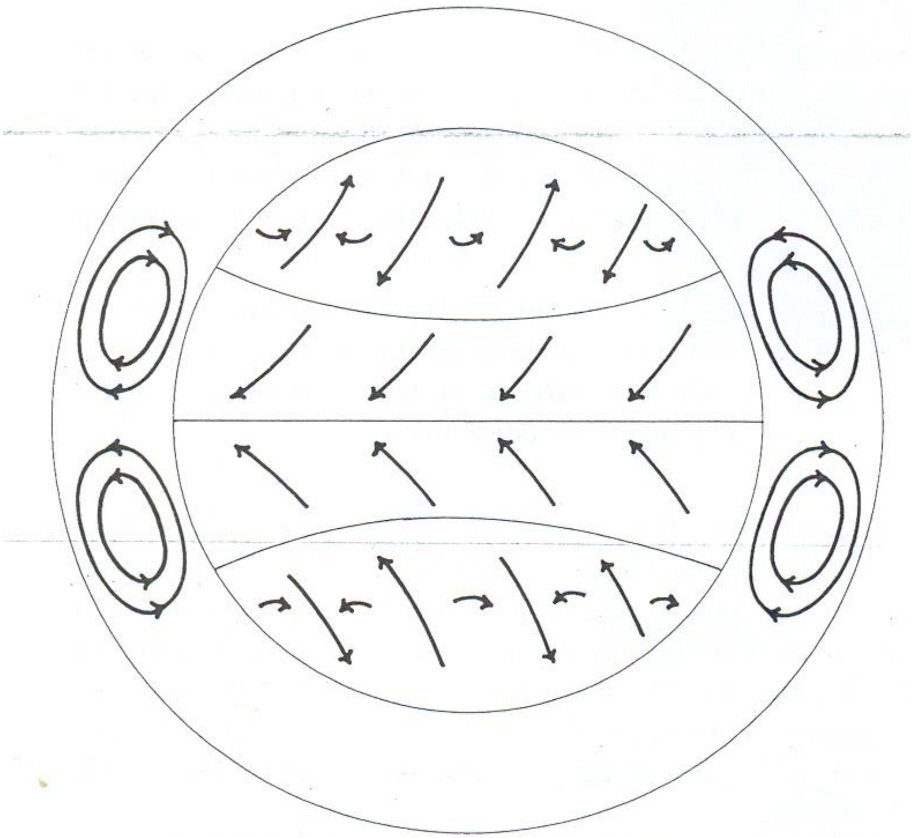
Hadley did not realize that the conservation involved is absolute angular momentum, rather than velocity. He was also unaware of the effect of the Coriolis force, which would turn the poleward flow westerly.



Dove's circulation view (1837)

Heindrich Wilhelm Dove's circulation is close to the current view of the Hadley circulation at low latitudes.

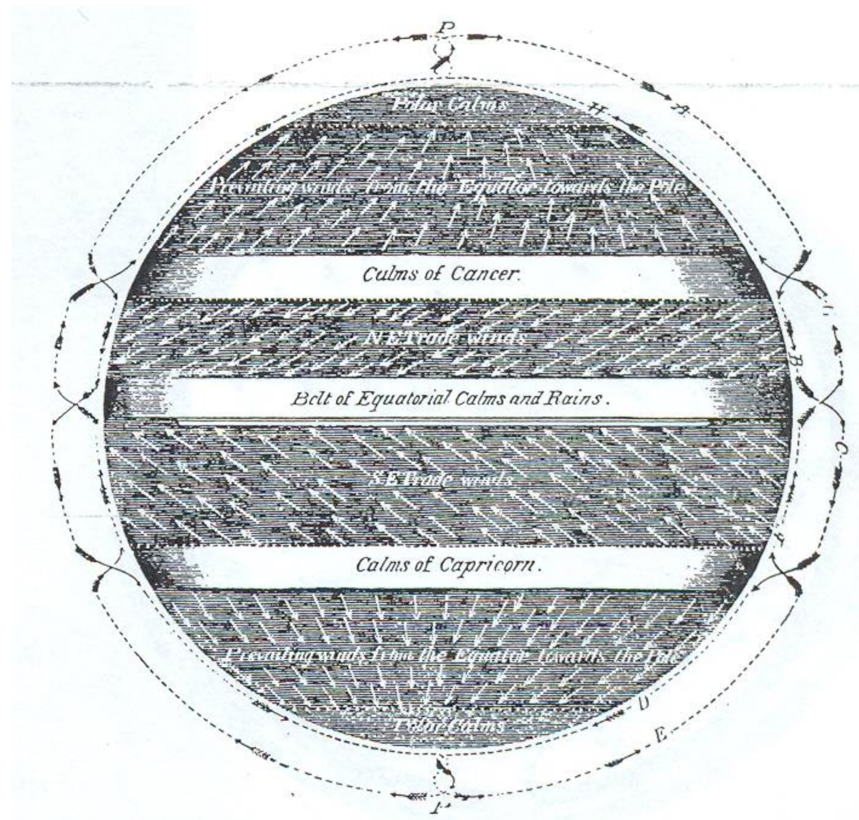
However, he did not realize that at middle and high latitudes the north-east winds are over the south-west winds.



Maury's circulation (1855)

Naval officer Matthew Maury proposed a circulation, which is closer to the present view, but missing the polar cell.

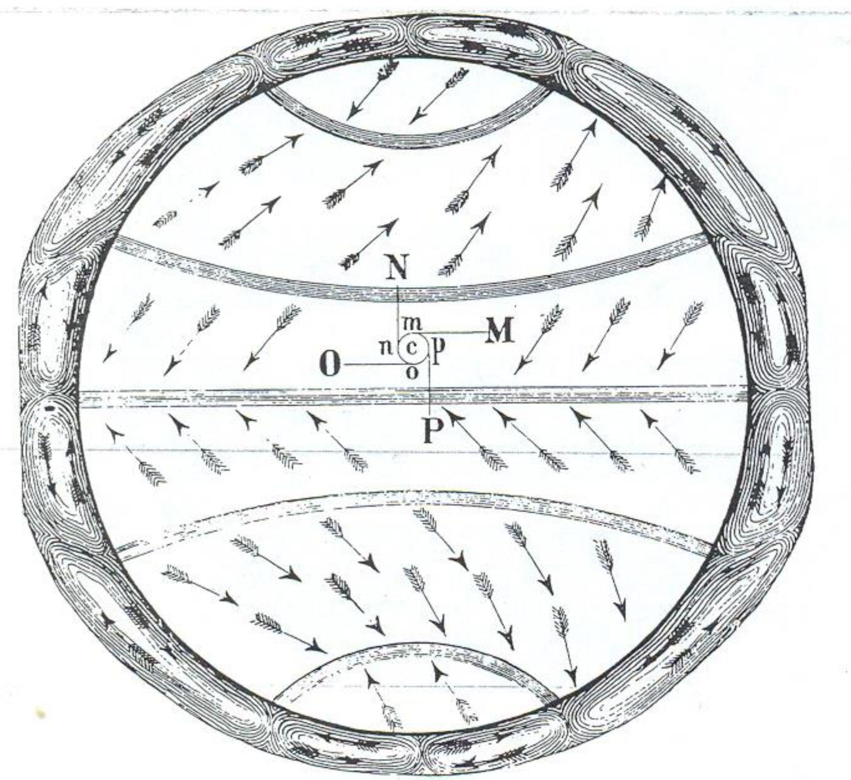
He could not explain why the circulation is like that.



Ferrel's circulation model (1856)

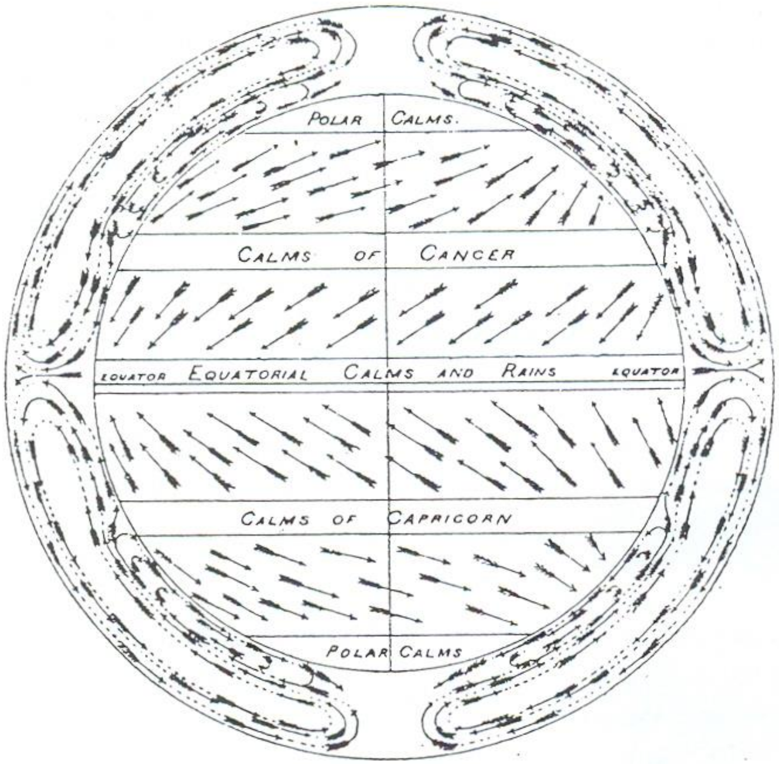
Ferrel (1856) suggested a circulation which is almost the same as the present view.

He could be the first to realize the role of the Coriolis force in atmospheric circulations.



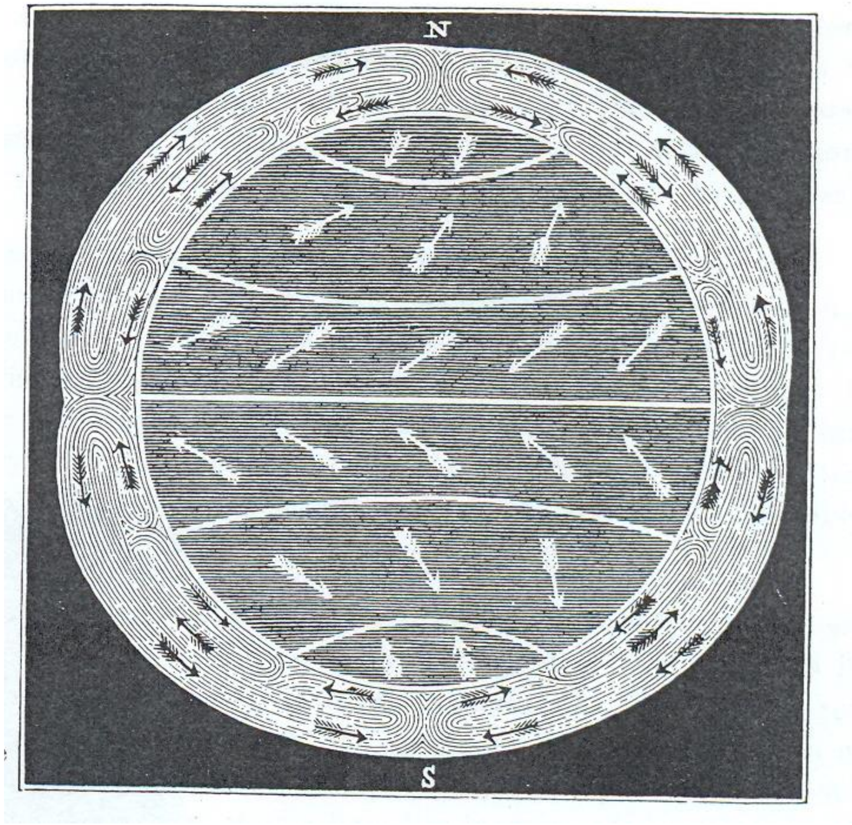
Thomson's view (1857, 1892)

James Thomson (1857, 1892) suggested a large direct cell like Hadley's occupied the bulk of each hemisphere, but in middle and higher latitudes there was a shallow indirect cell, with poleward flow close to the ground and equatorward flow at an intermediate level.



Ferrel’s second version (1859)

Ferrel somehow modified his first version of the global circulation. His second version is close to Thomson’s, except for that he had a polar cell.



Vilhelm Bjerknes's version (1921)

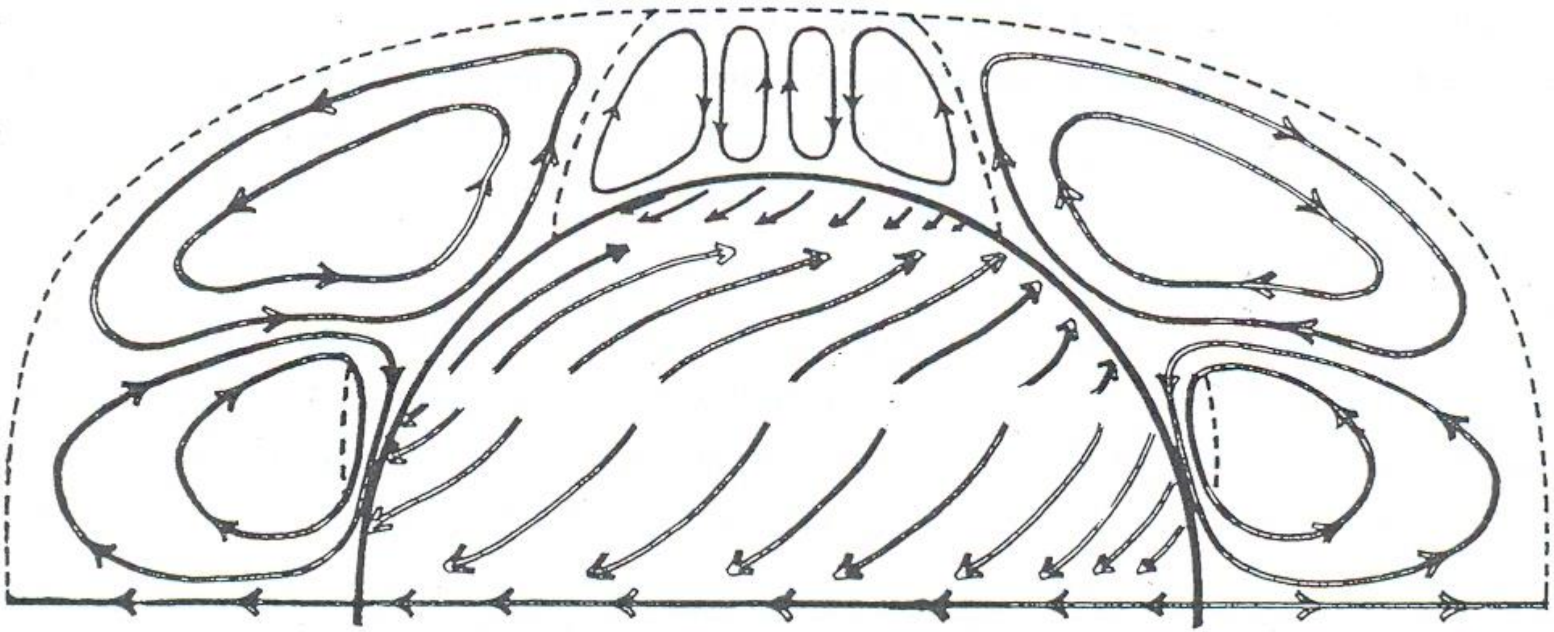


Figure 36. — A schematic representation of the zonally averaged circulation according to Bjerknes (1921)

Jacob Bjerknes's version (1921)

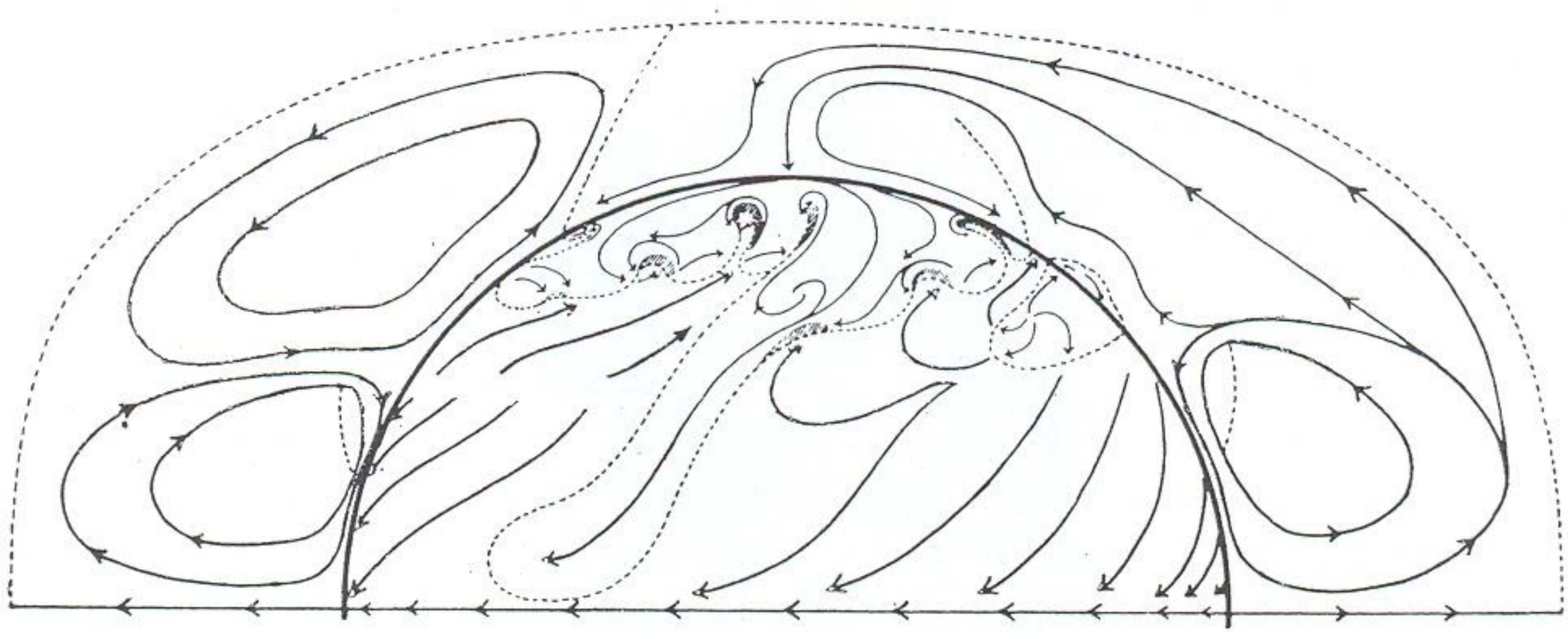
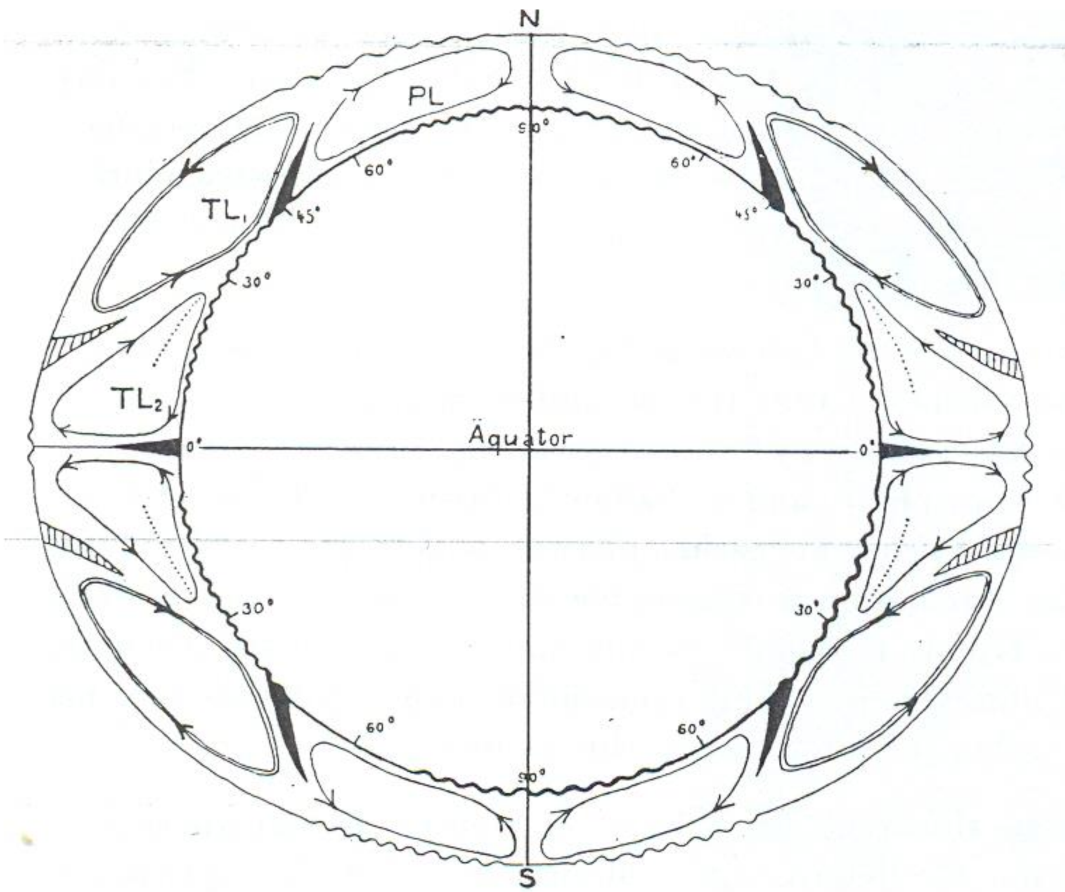


Figure 37. — A schematic representation of the general circulation of the atmosphere according to Bjerknes (1921)

Bergeron's view (1928)



Williams's version (1968)

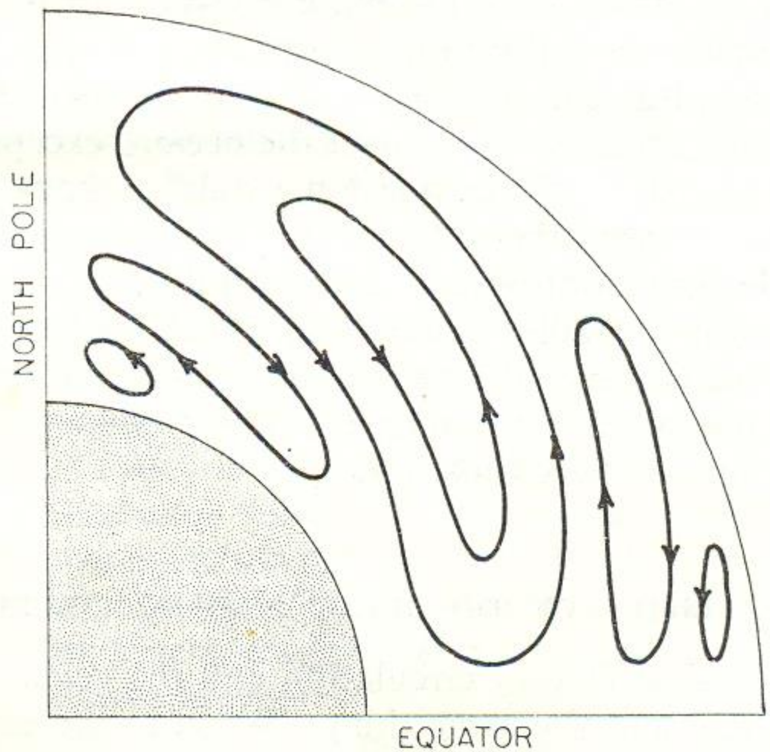


Figure 3. Schematic representation of the mean meridional circulation as determined numerically by Williams (1968). The computations were for a rotating cylindrical annulus with frictionless side walls, but the diagram is transcribed to a sphere for comparison with Figs. 1 and 2.

Shaowu Wang's view（1976）

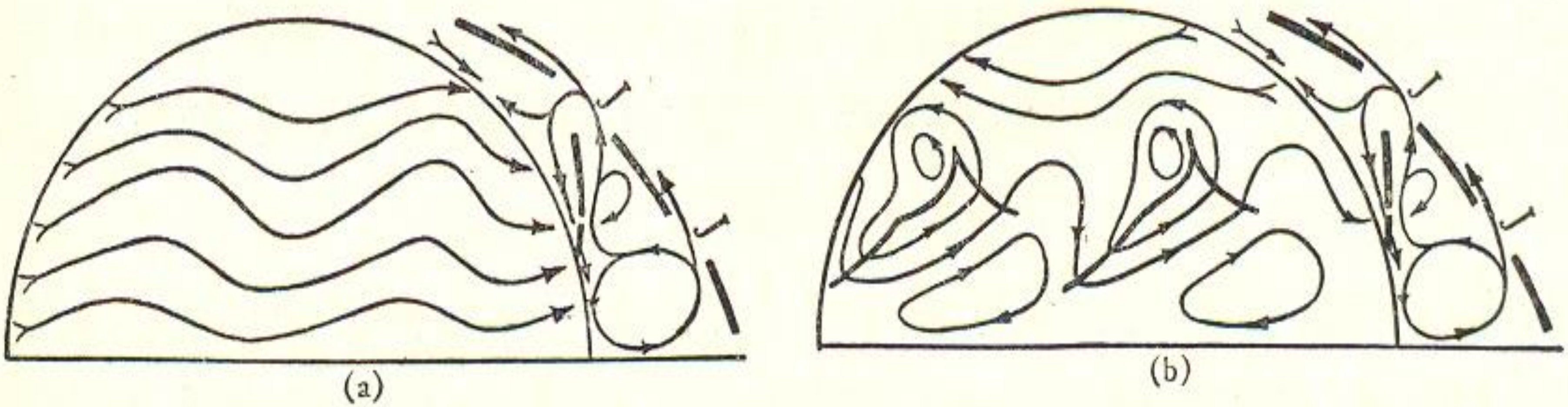
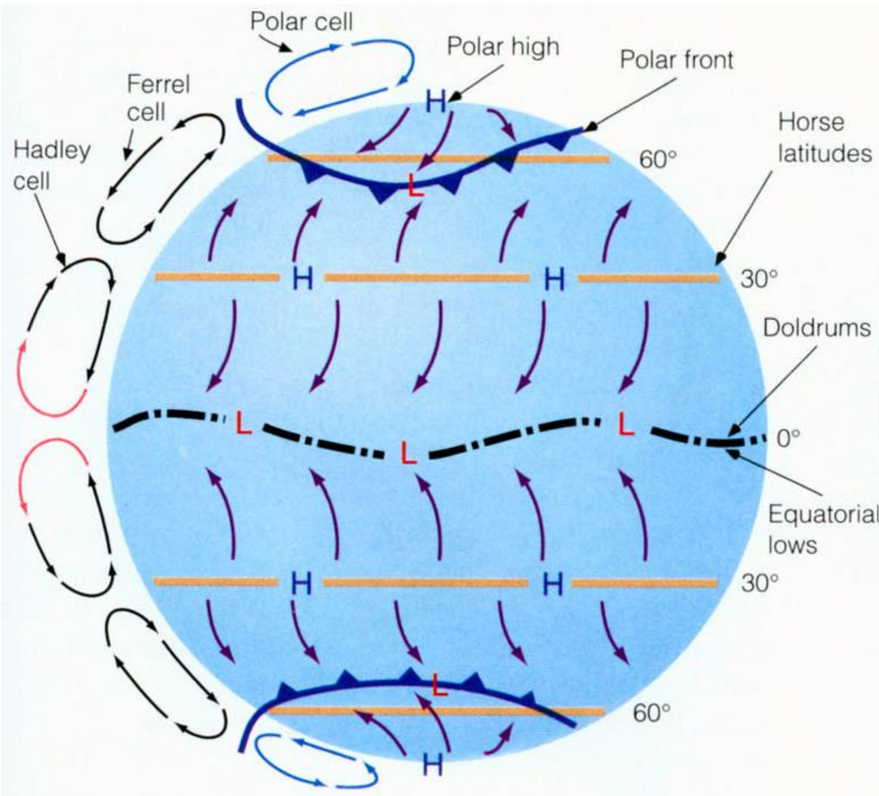
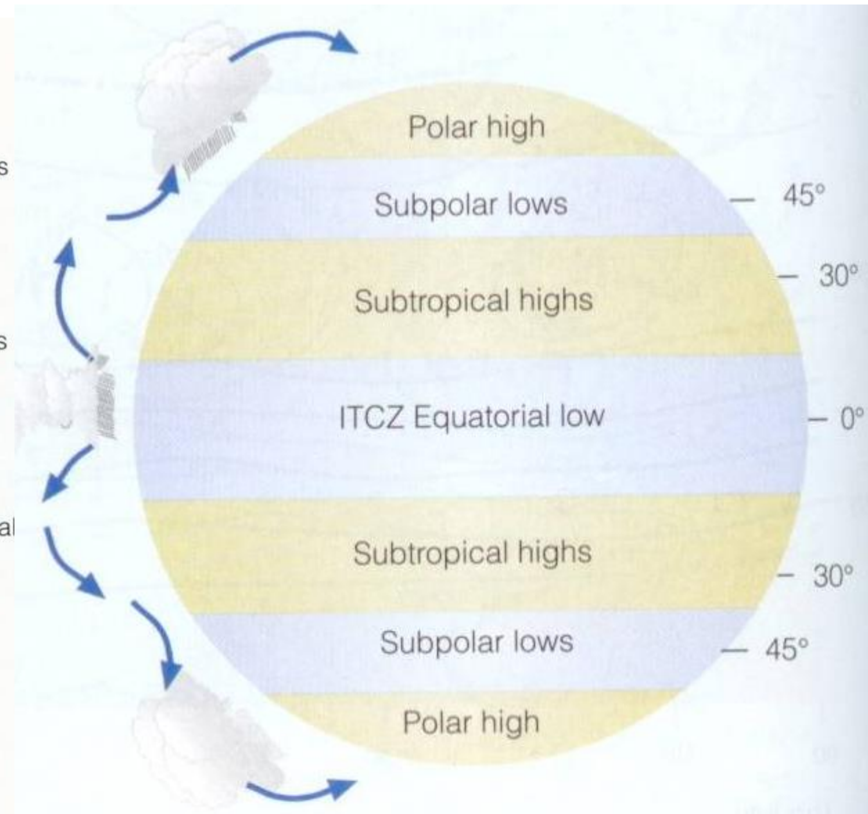


图 16·3　最简单的可能的"三圈环流"及其相应的高空(a)，地面(b)流场
(粗实线为锋区或对流顶，J 为西风急流)

A commonly present view of the global meridional circulation





We need a theory

- There had been no a theory of what govern the Hadley circulation from 1735 to 1980.

- All the above works are qualitative descriptions.

- An incomplete, but nice theory came out in 1980. It the paper by Held and Hou (1980).

Held and Hou's theory (1980)

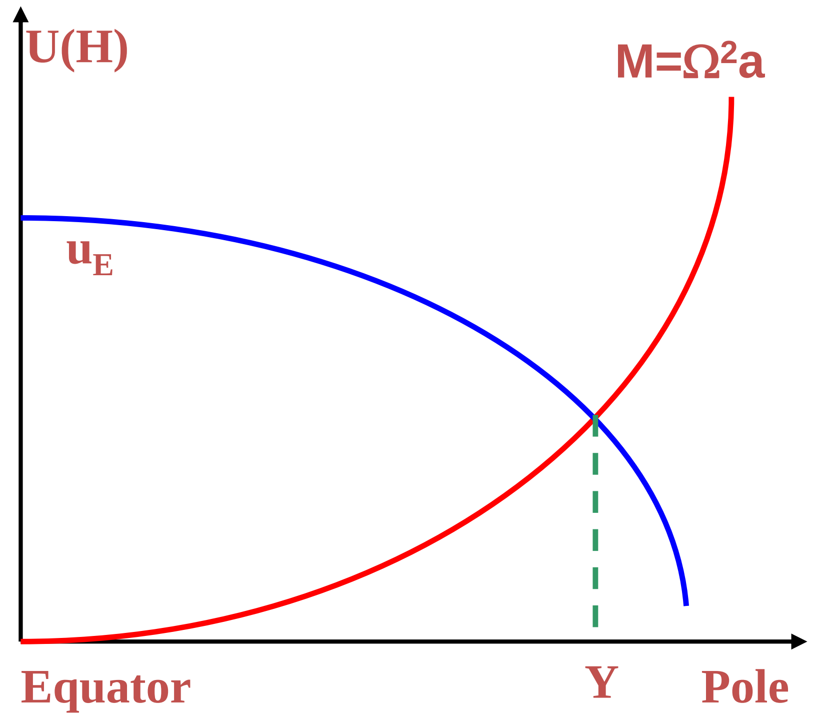
1. Angular momentum conservation

$$M = \Omega a^2 = (\Omega a \cos\phi + \bar{u}) a \cos\phi$$

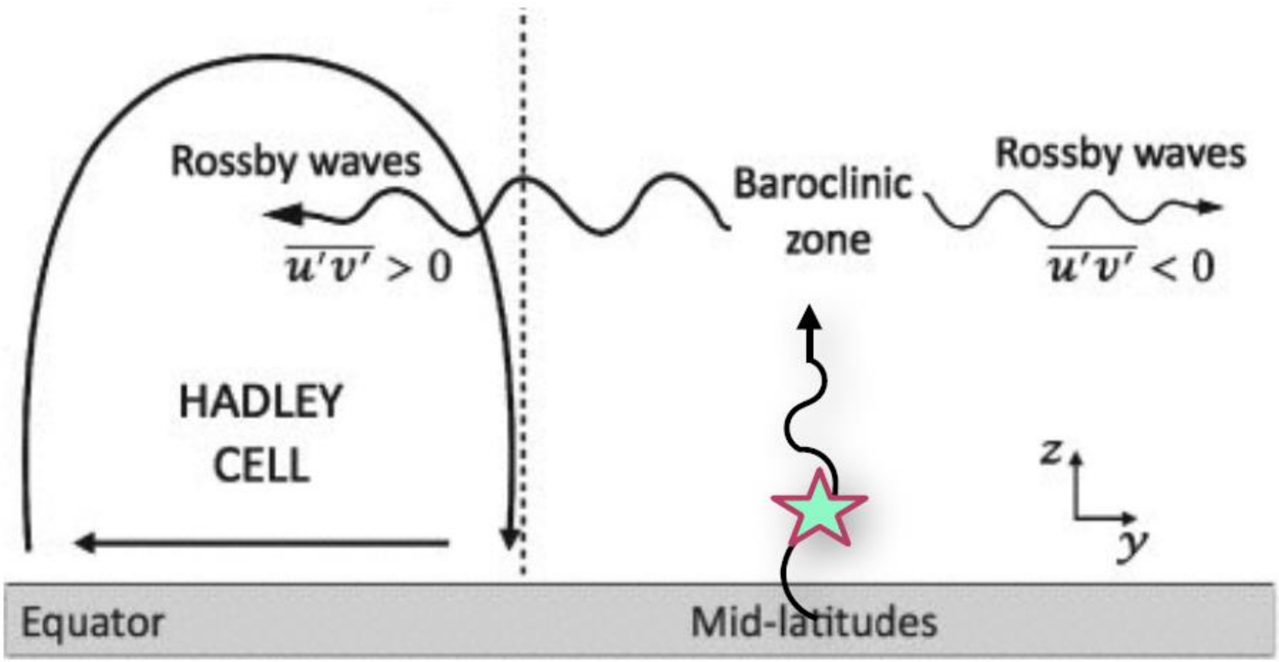
$$\bar{u} = \Omega a \frac{\sin^2\phi}{\cos\phi}$$

2. Thermal wind balance

$$\frac{\partial u}{\partial z} = -\frac{g}{f\theta_0}\frac{\partial \theta}{\partial y}$$



Held (2000)
The Hadley circulation and mid-latitude eddies



Held (2000)

In the Lagrangian view (considering an air parcel moving over an isentropical surface), there is indeed a single Hadley cell extending to the polar region.

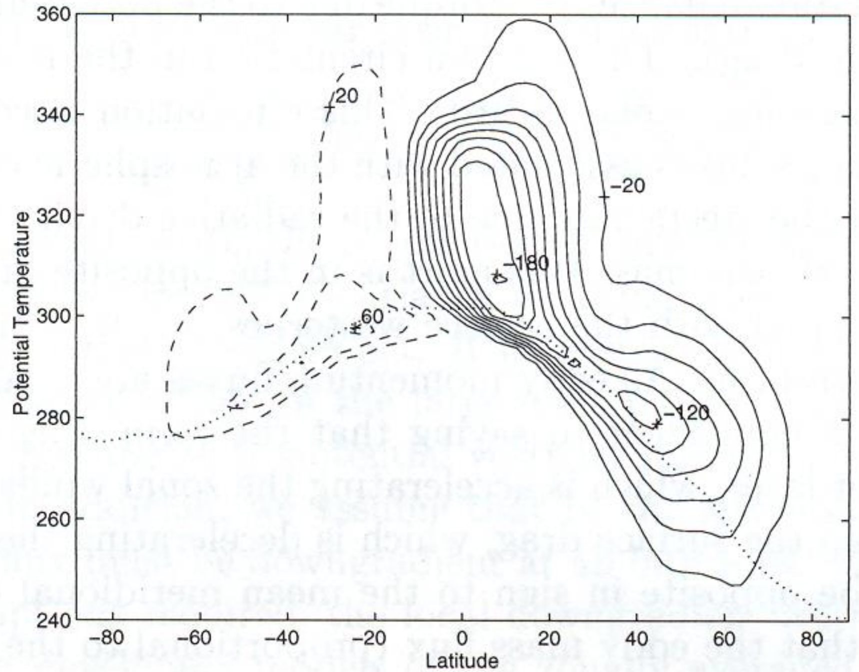
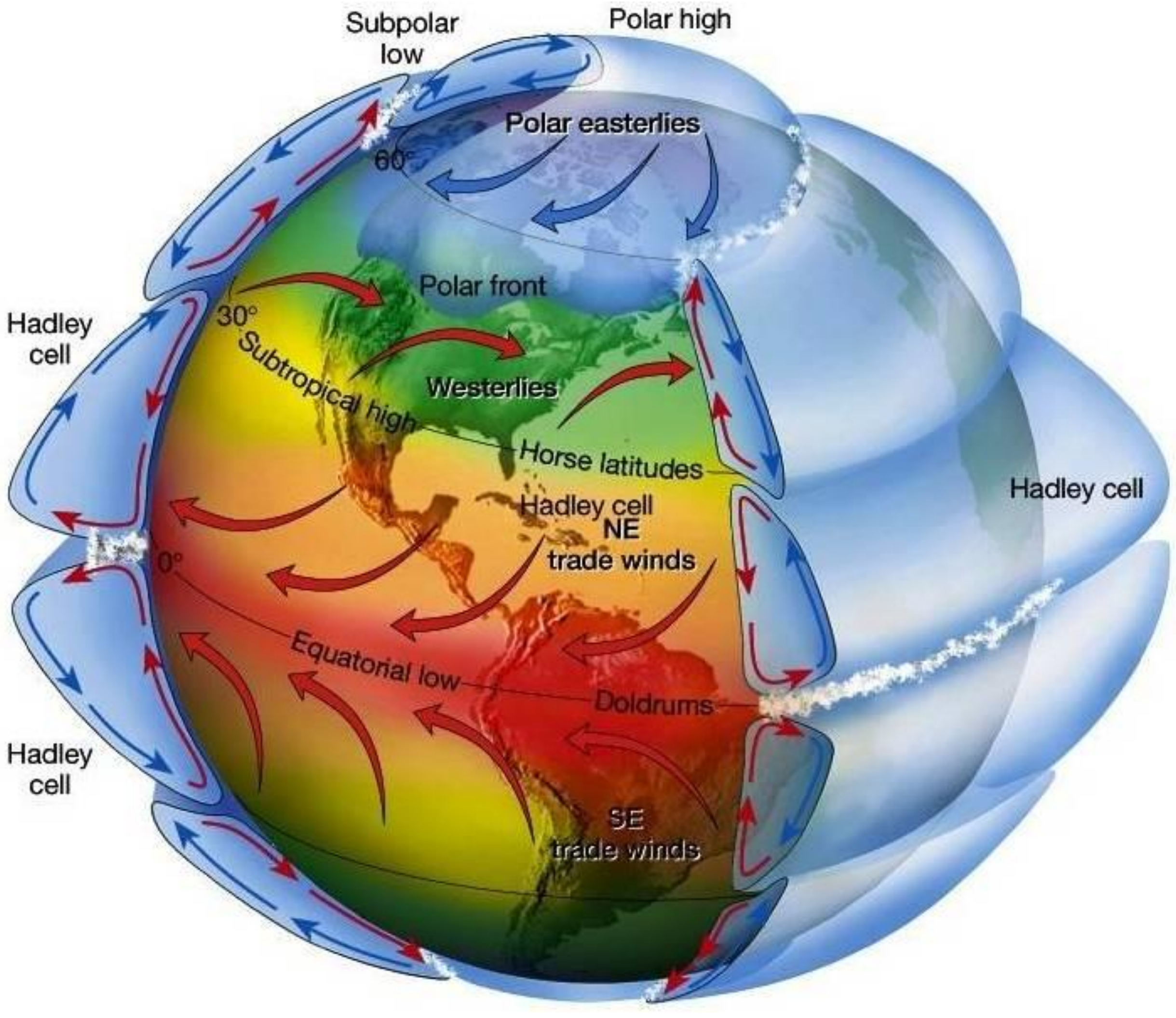
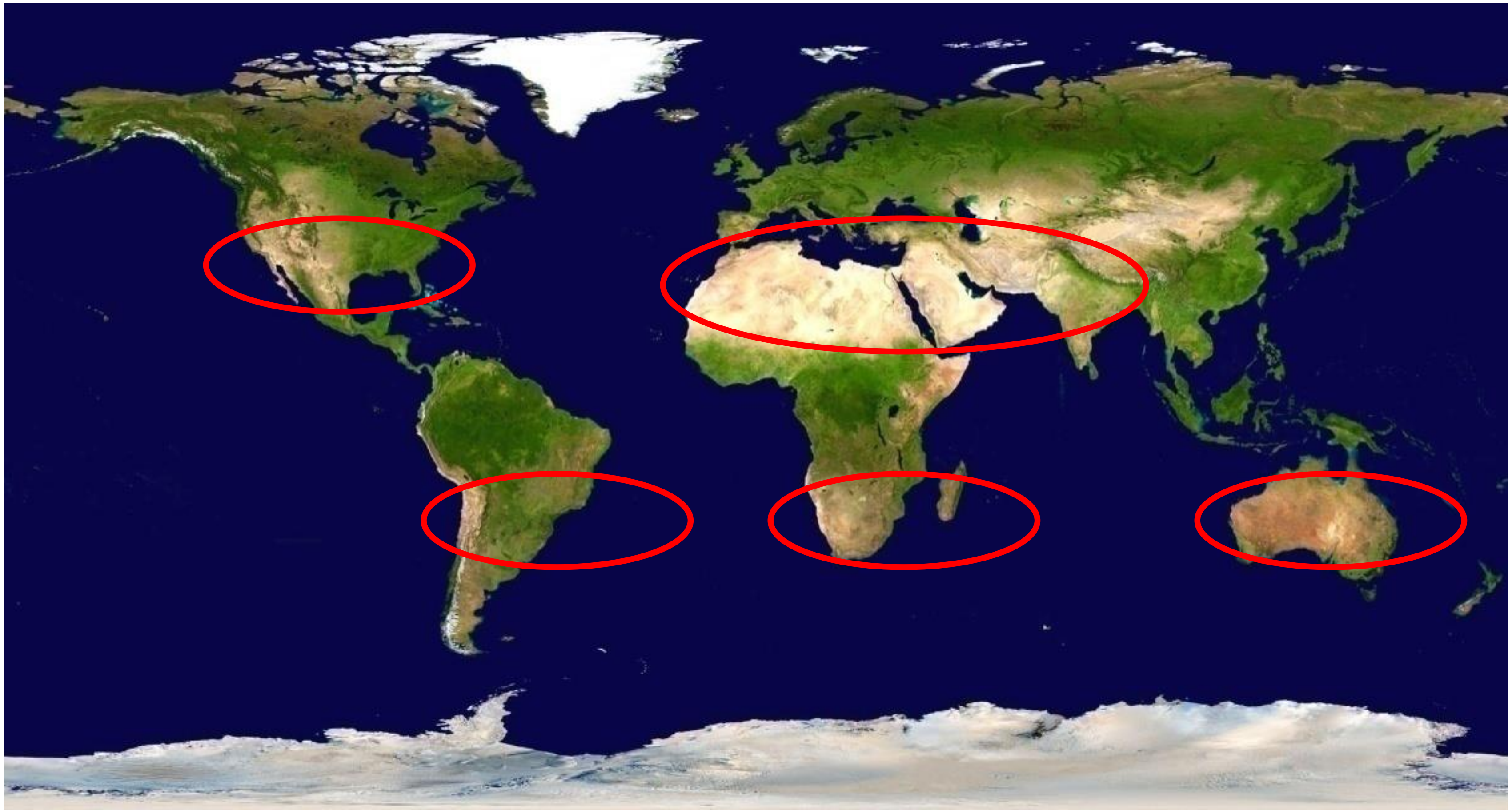


Figure 6: The mass transport streamfunction as a a function of potential temperature and latitude, in January, as computed from a GCM, from [6]. The dotted line is the median surface temperature.

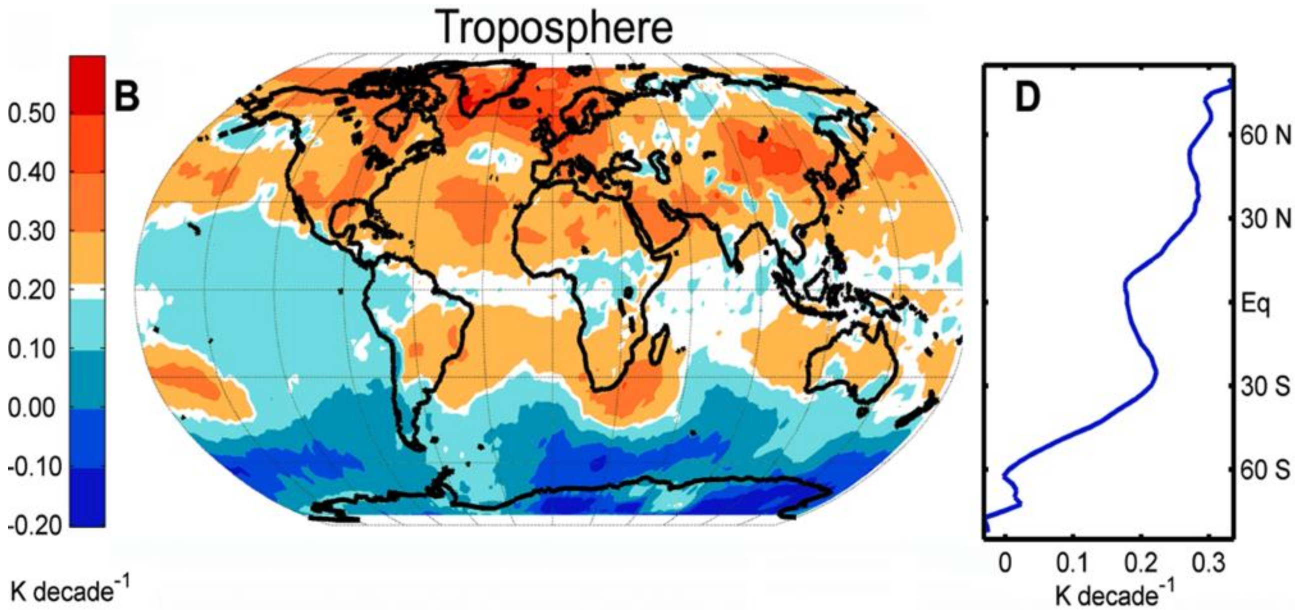
2. Observations of widening of the Hadley circulation



Subtropical dry zones

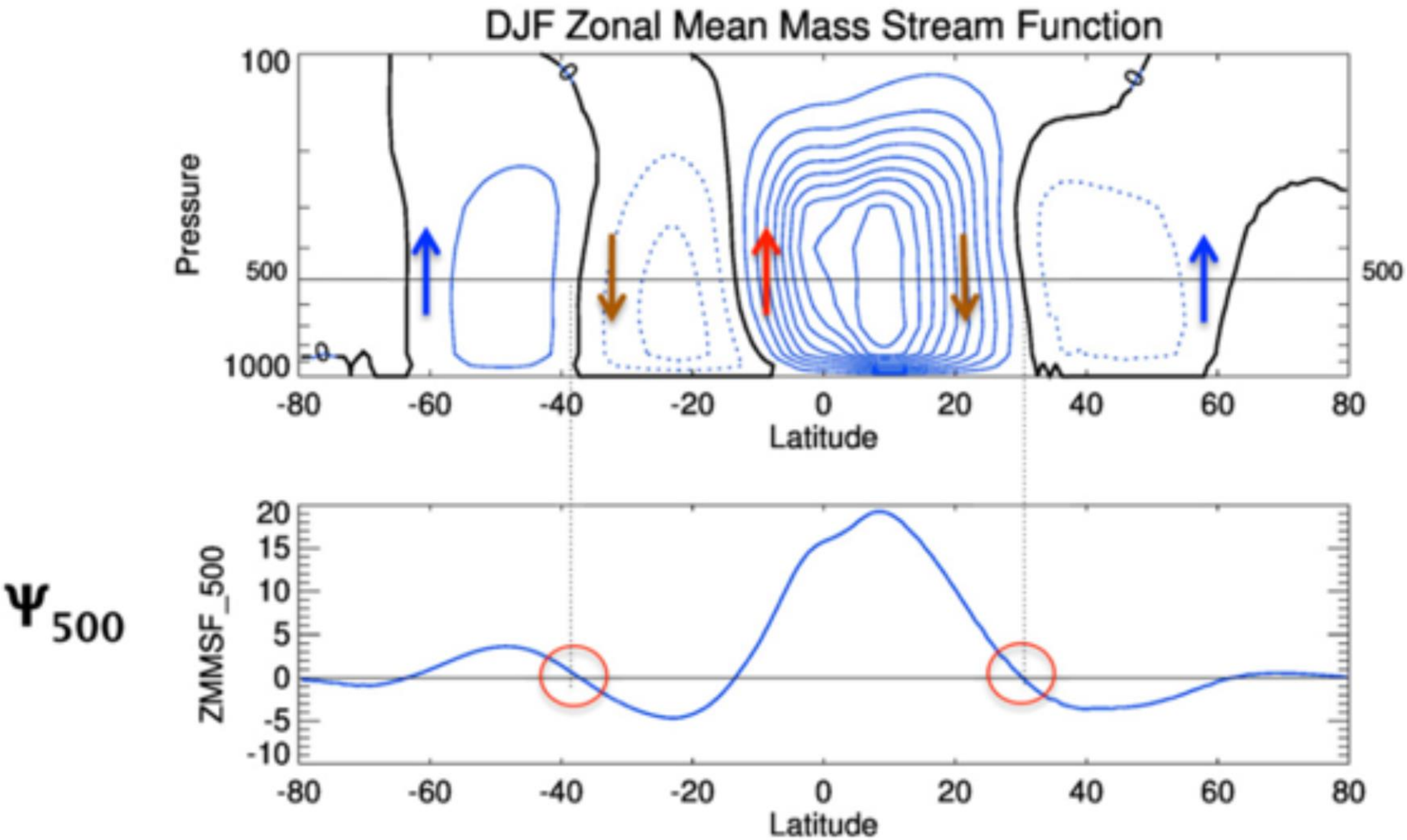


Warmer subtropics → poleward shift of subtropical jets → poleward expansion of the Hadley circulation



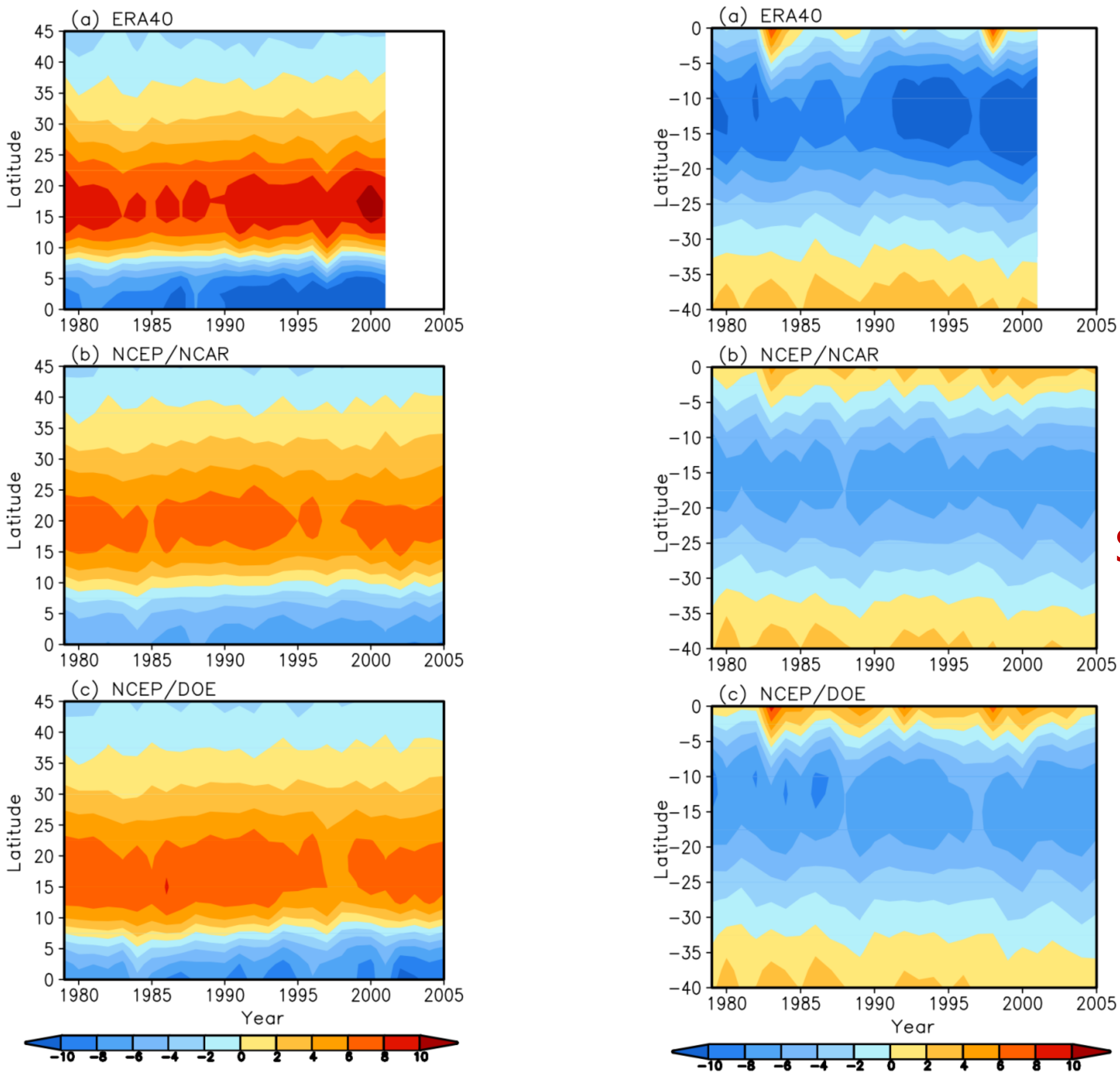
Fu et al. (2006)

Define the boundary of the Hadley circulation



Widening of the Hadley circulation in reanalysis

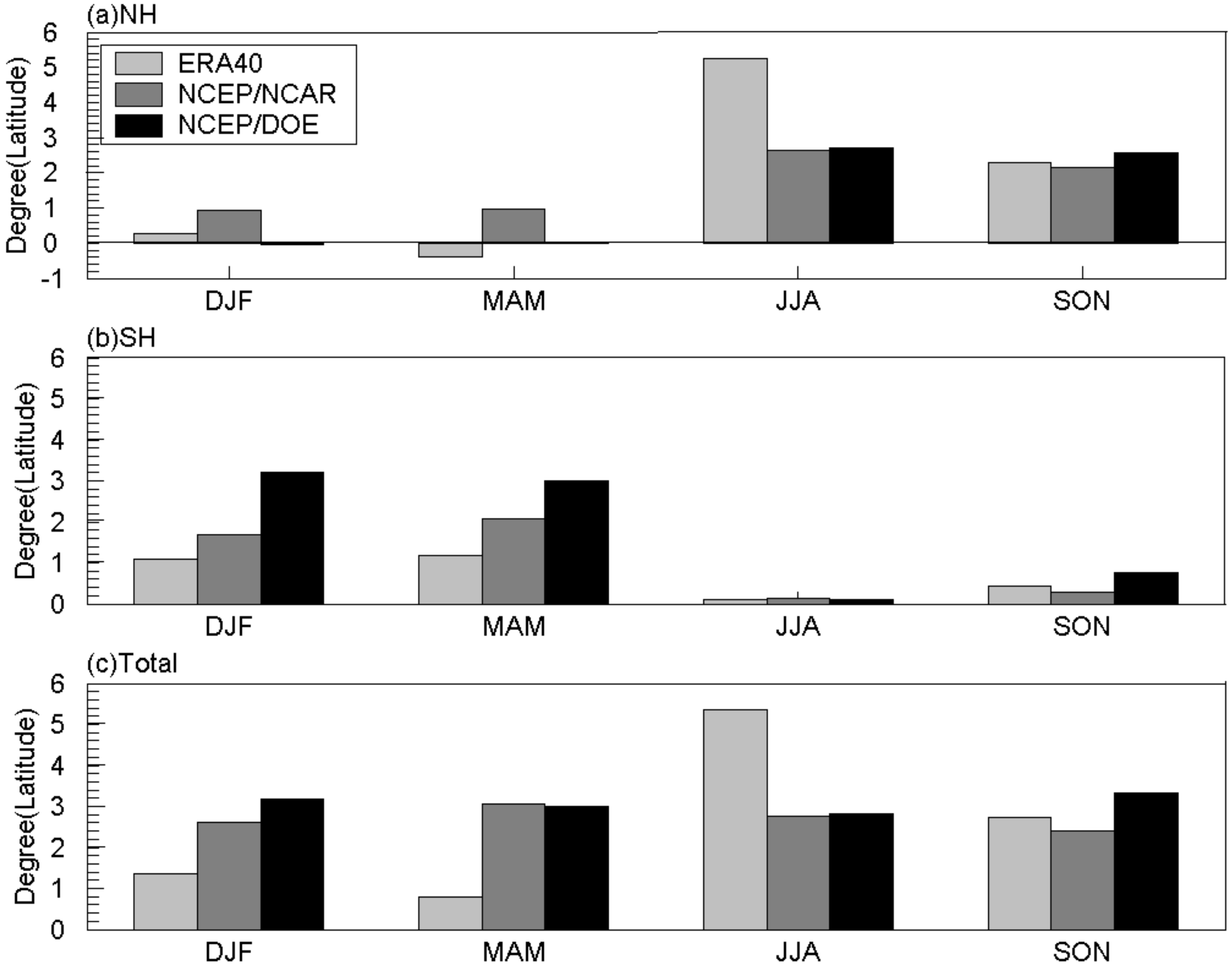
NH



SH

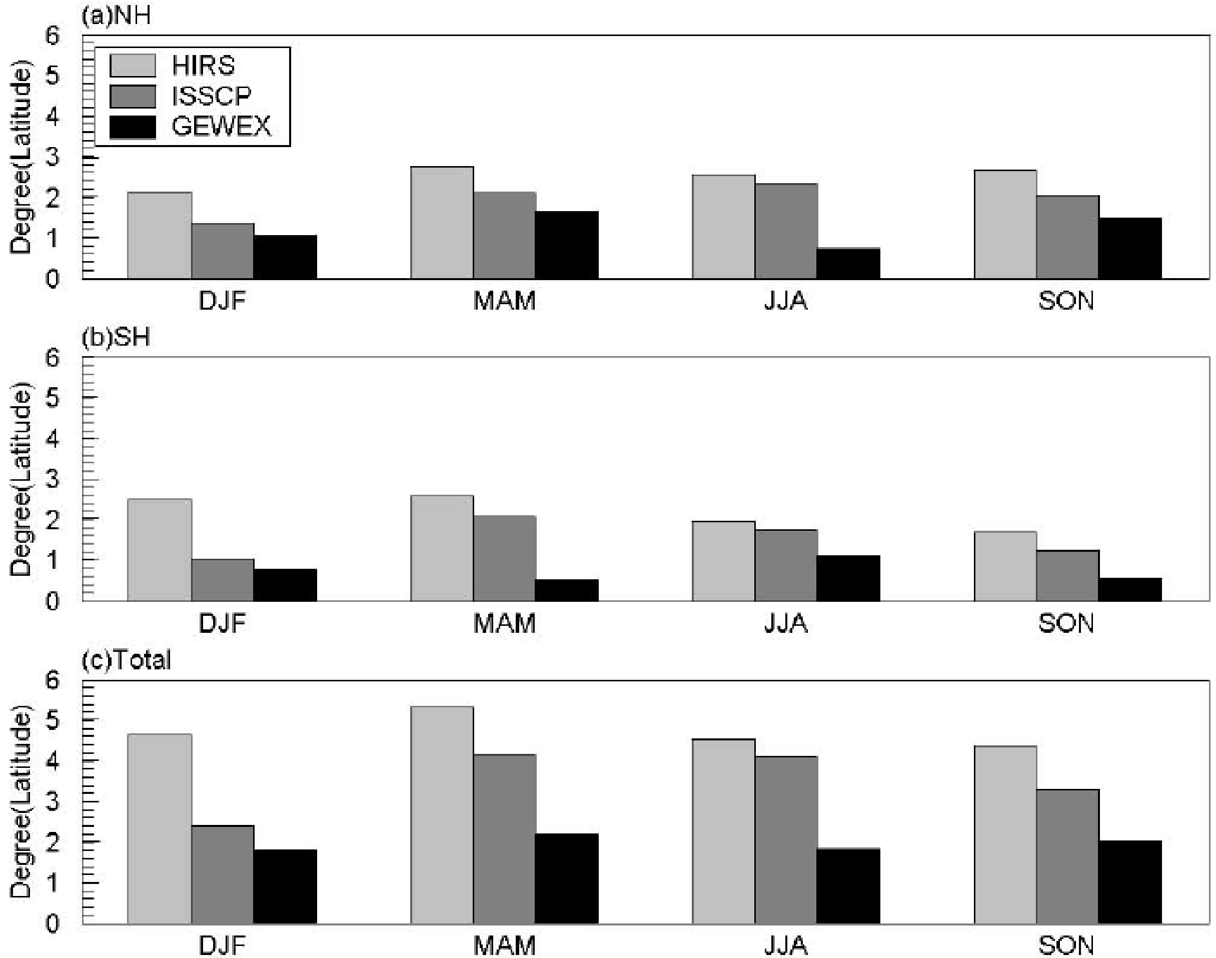
Hu and Fu (2007, ACP)

Widening of the Hadley circulation in reanalysis (1979-2005)



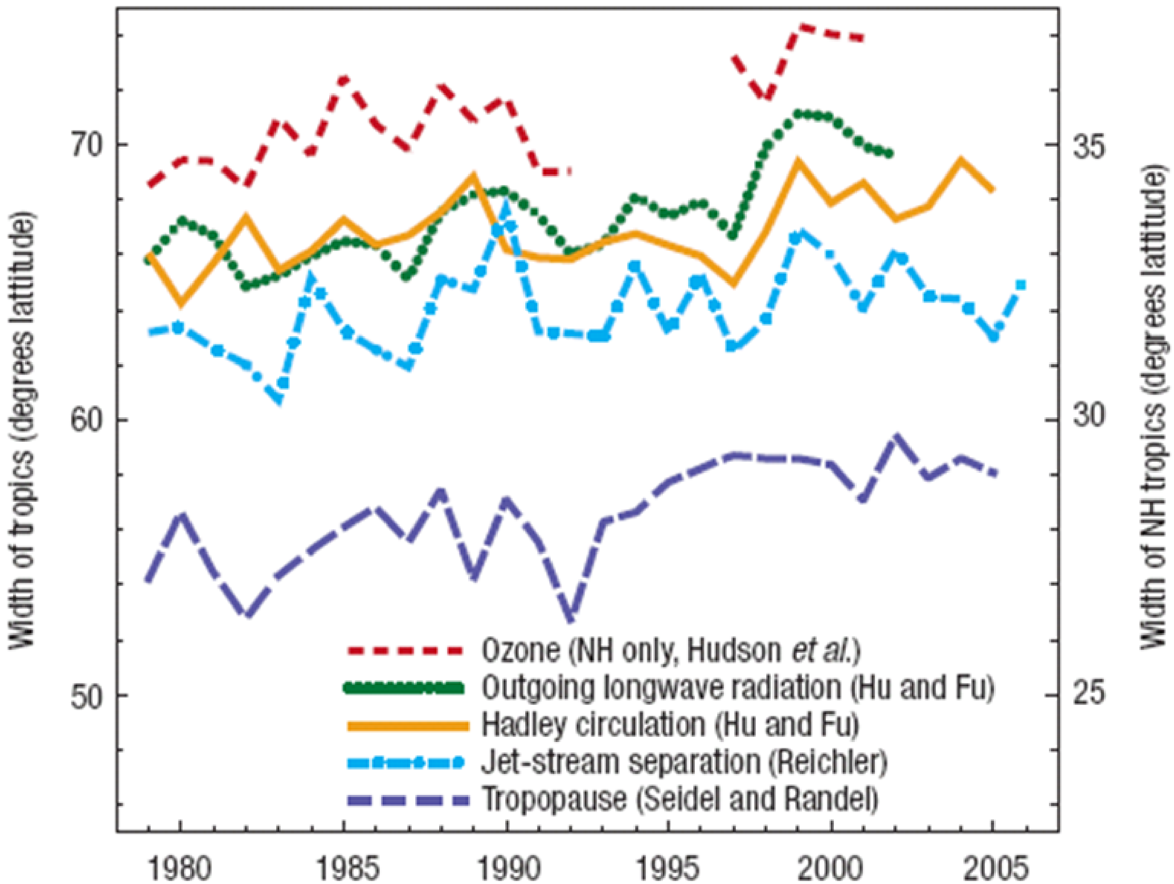
Hu and Fu (2007, ACP)

Widening of the tropical belt characterized by OLR



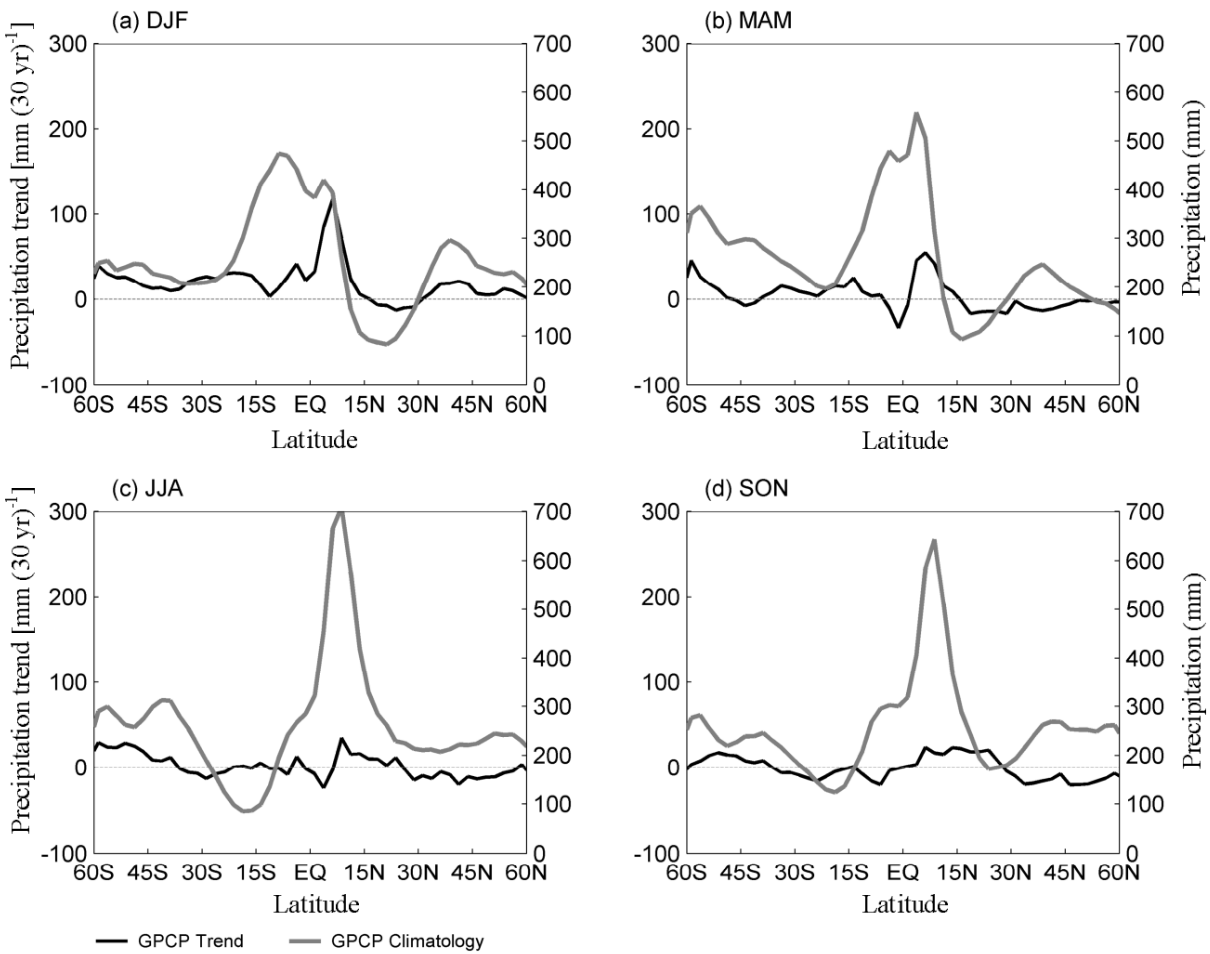
Hu and Fu (2007, ACP)

Widening of tropical belt in multiple independent datasets



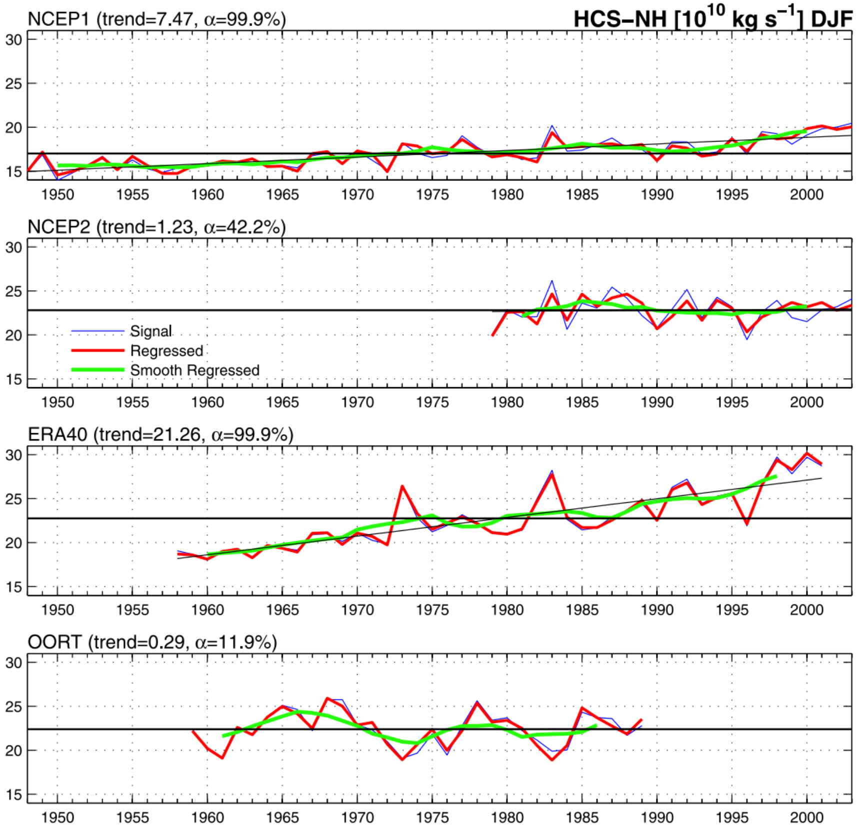
Seidel et al. (2008, *Nature Geoscience)*

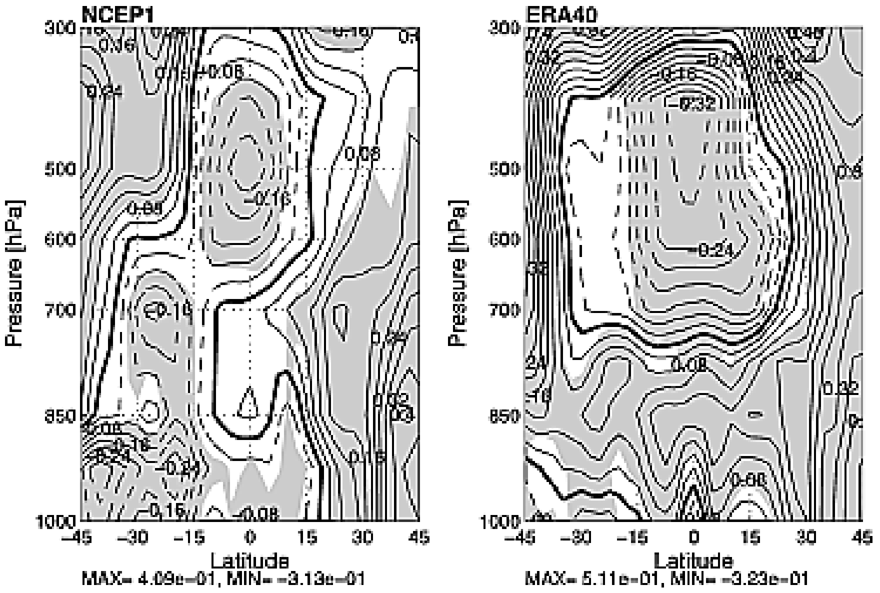
Zonal-mean precipitation and trends



Hu and Zhou (2011)

Changes in strength





Mitas and Clement (2005, 2006)

Too large trends in ERA-40 tropical precipitation

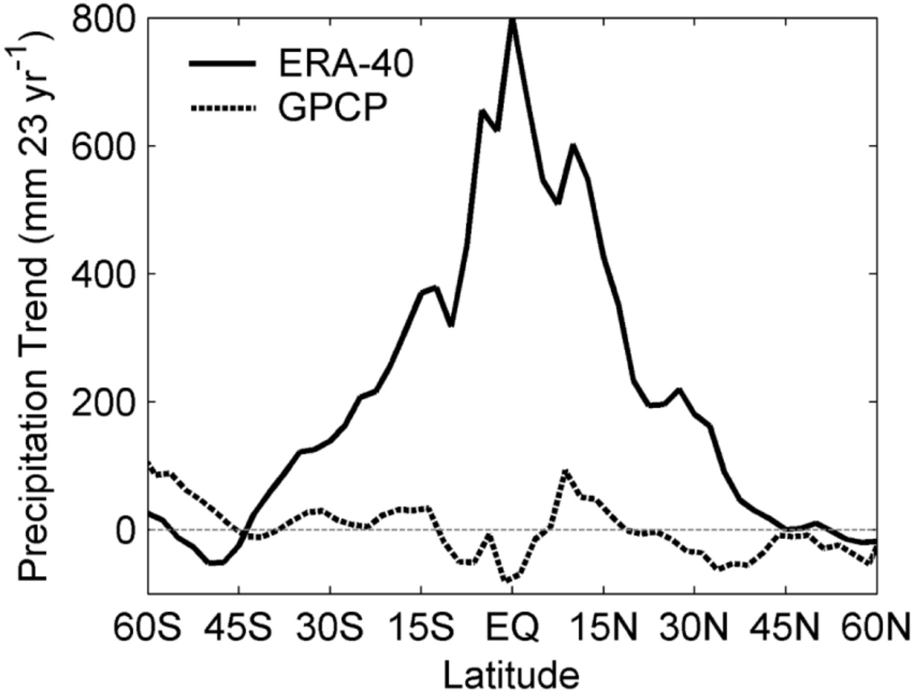
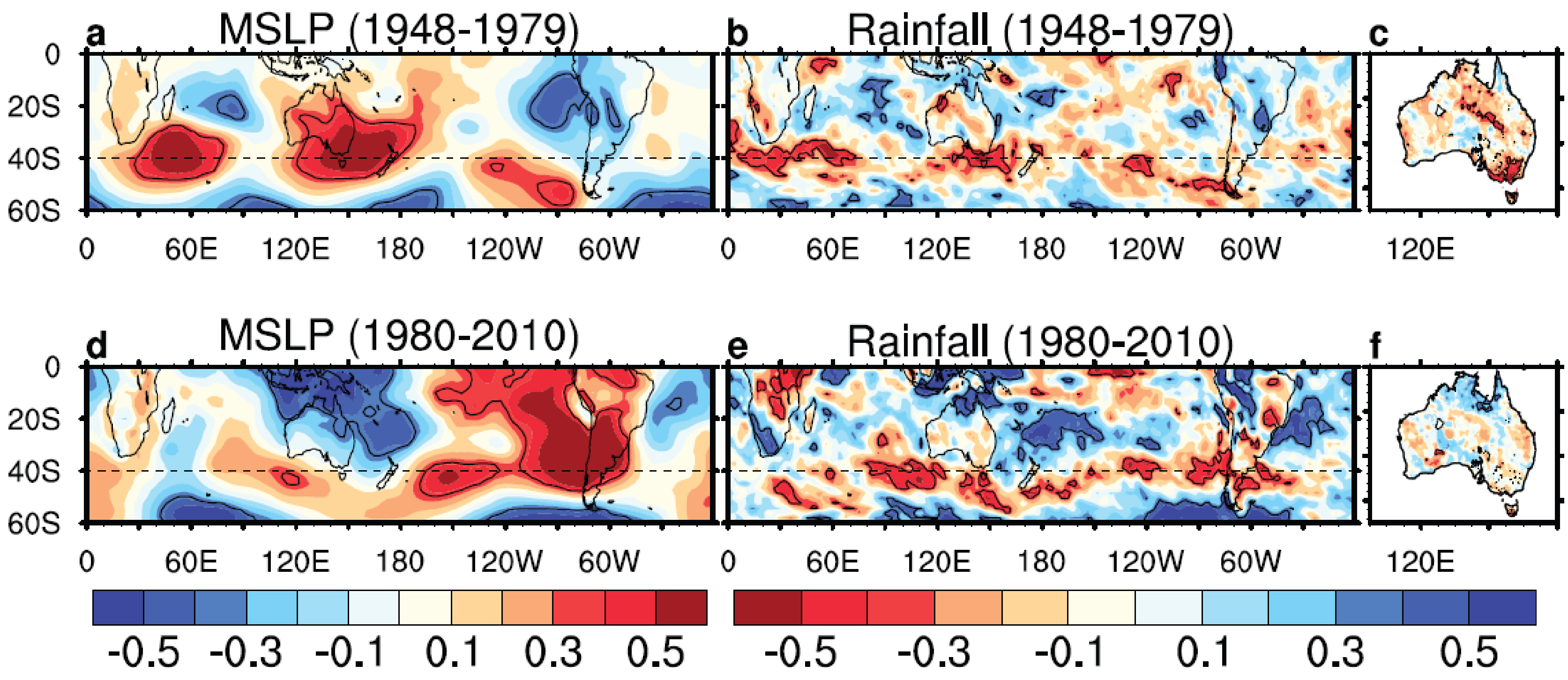


Fig. 12. Comparison of annual and zonal mean trends in precipitation between GPCP and ERA40 data over the period 1979–2001.

Hu et al. (2011)

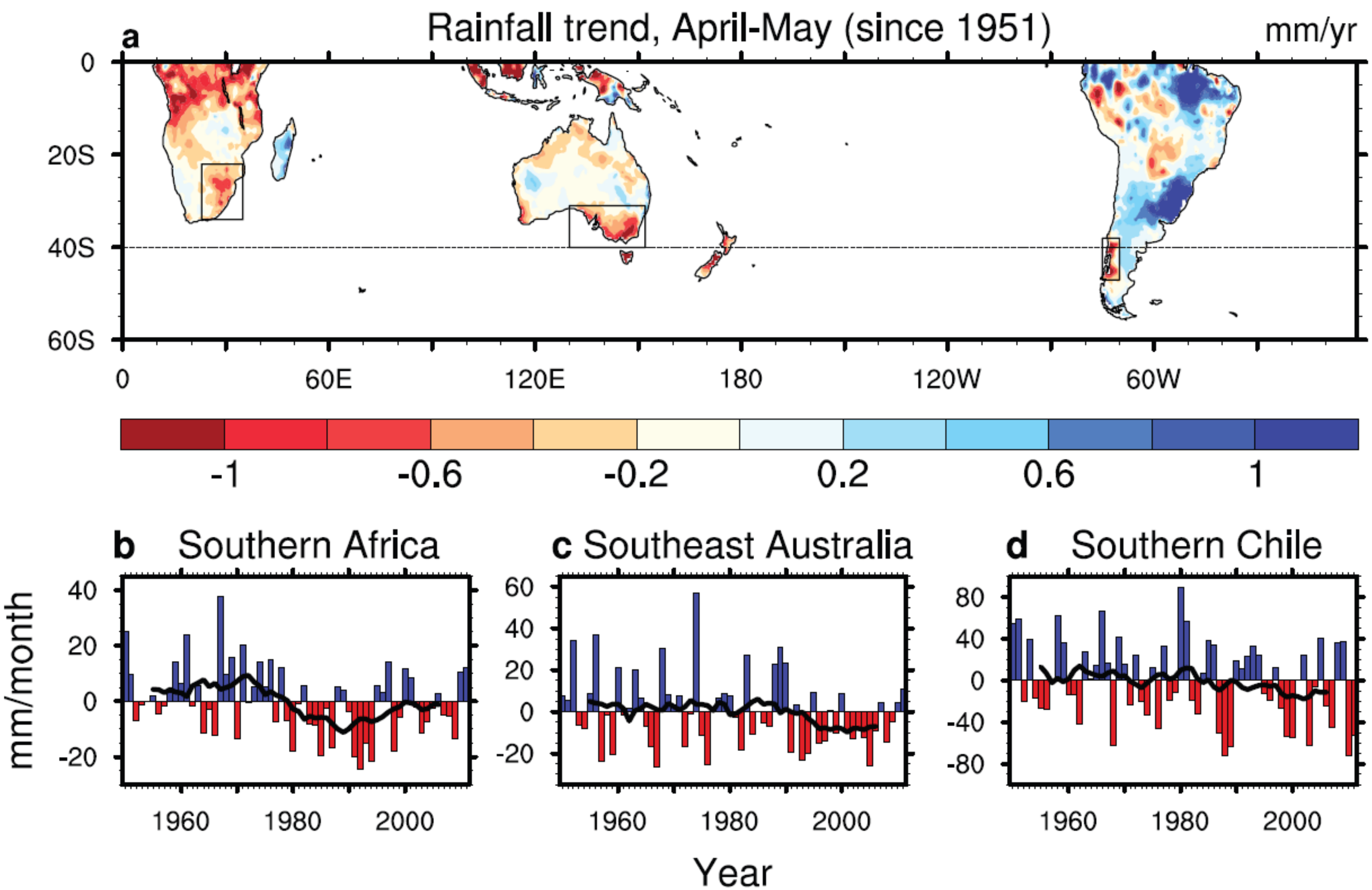
3. Climate effects of widening of the Hadley circulation

Poleward shift of the subtropical dry zone



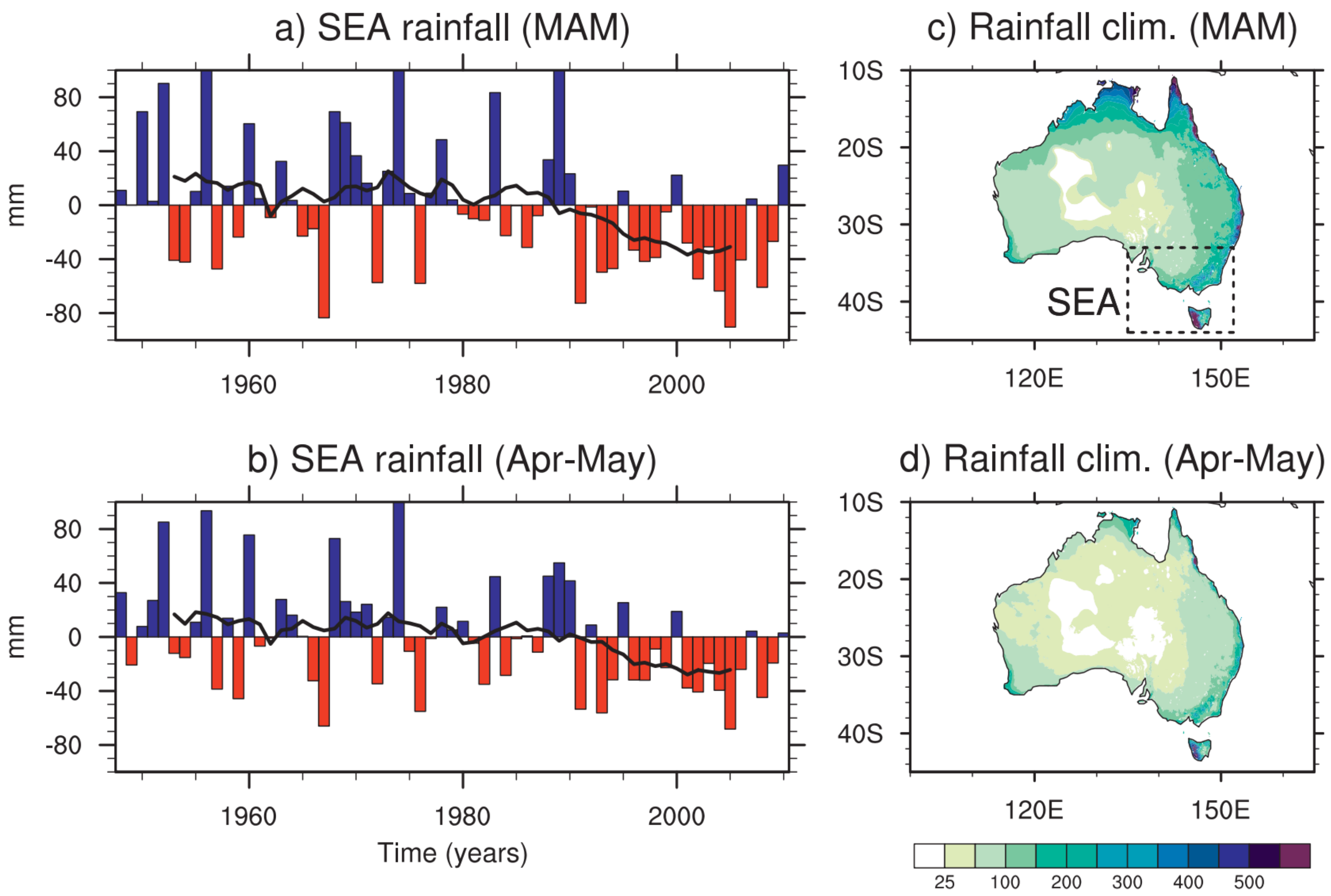
Cai et al. (2012, SREP)

SH Rainfall trends



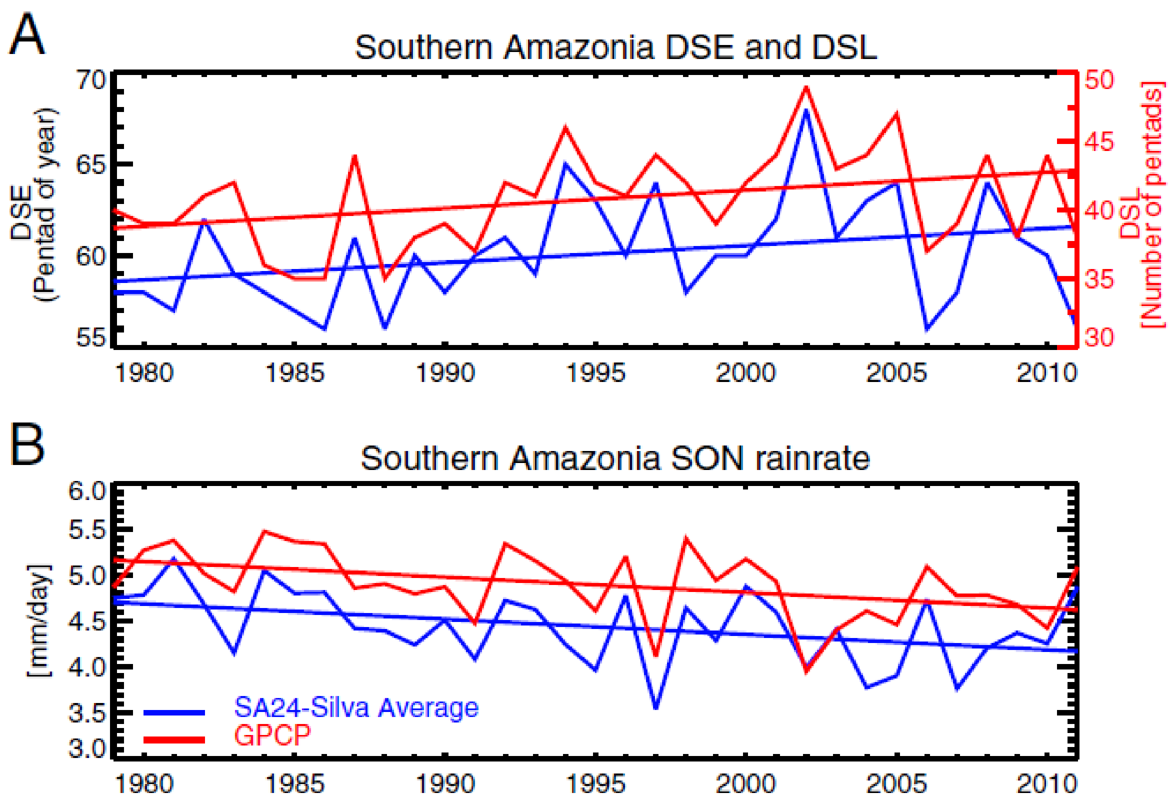
Cai et al. (2012, SREP)

Decreasing rainfall in Southeast Australia



Cai and Cowan (2013, J. Climate)

Poleward shift of the subtropical dry zone



Fu et al. (2012, PNAS)

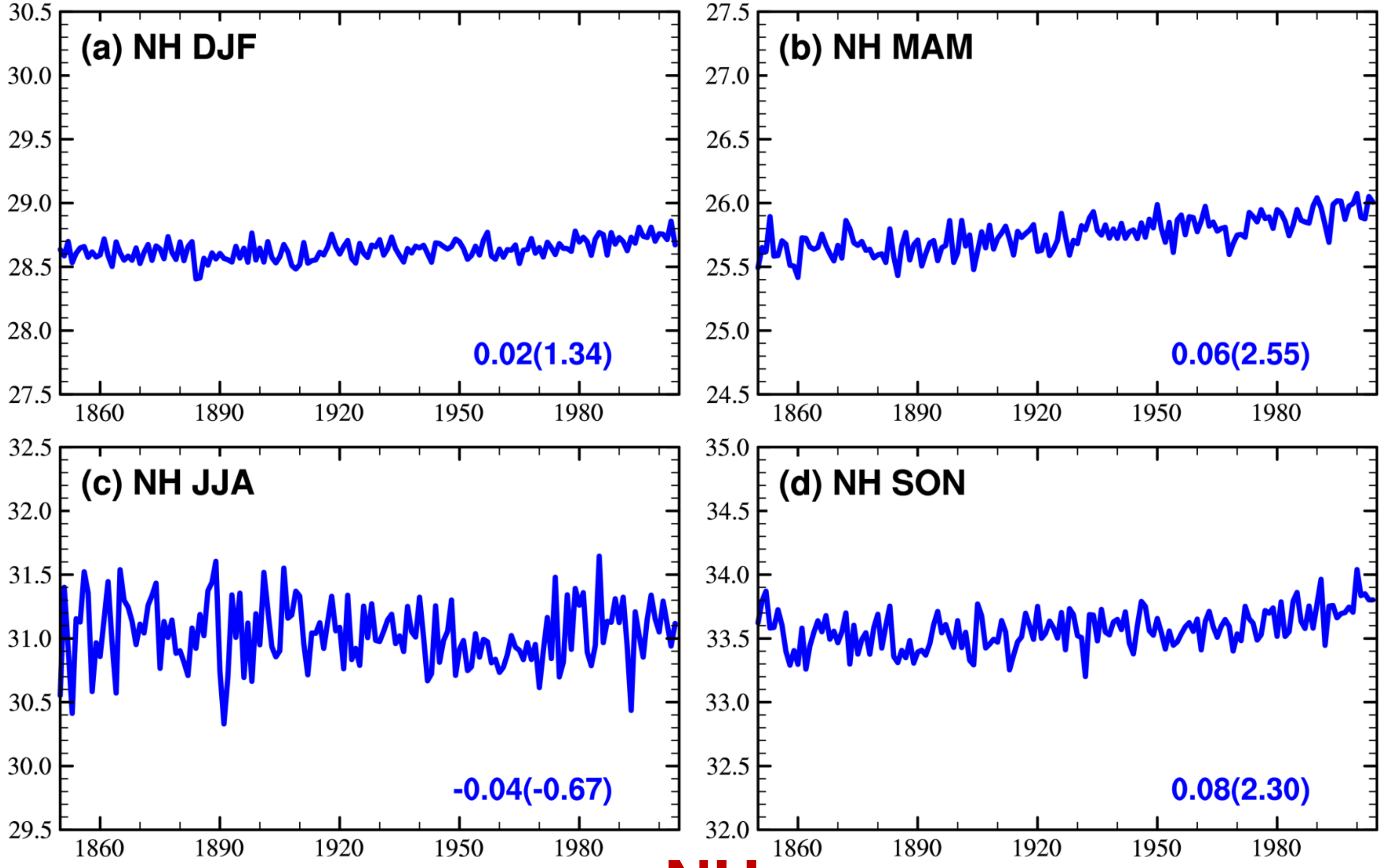
3. What cause widening of the Hadley circulation?

- **Question:**
  - **What forced the observed widening of the Hadley circulation?**

- **Data:**
  - **CMIP5 simulations (historical, individual forcing, projection)**

Num	Models	All	GHG	Oz	AA	RCP2.6	RCP4.5	RCP6.0	RCP8.5
1	ACCESS1-0	1					1		1
2	ACCESS1-3	2					1		1
3	bcc-csm1-1	3	1			1	1	1	1
4	bcc-csm1-1-m	3				1	1	1	1
5	BNU-ESM	1	1			1	1		1
6	CanESM2	5	5		5	5	5		5
7	CCSM4	6	3	2	3	6	6	6	6
8	CESM1-BGC	1					1		1
9	CESM1-CAM5	3				3	3	2	3
10	CESM1-CAM5-1-FV2		2		2				
11	CESM1-WACCM	4				1	1		1
12	CMCC-CESM	1							1
13	CMCC-CM	1					1		1
14	CMCC-CMS	1					1		1
15	CSIRO-Mk3-6-0	10	5		5	10	10	10	10
16	EC-EARTH	2				1	3		3
17	FGOALS-g2	5	1	1	2	1	1		1
18	FGOALS-s2	3				1		1	3
19	FIO-ESM	3				3	3	3	3
20	GFDL-CM3	5			3	1	1	1	1
21	GFDL-ESM2G	1				1	1	1	1
22	GFDL-ESM2M	1	1		1	1	1	1	1
23	GISS-E2-H	6	5	11	5	1	5	1	1
24	GISS-E2-R	6	5	10	5	1	6	1	1
25	HadGEM2-AO	1				1	1	1	1
26	HadGEM2-CC	3					1		3
27	HadGEM2-ES	5	4			4	4	4	3
28	inmcm4	1					1		1
29	IPSL-CM5A-LR	6			1	4	4	1	4
30	IPSL-CM5A-MR	3				1	1	1	1
31	IPSL-CM5B-LR	1					1		1
32	MIROC5	5				3	3	3	3
33	MIROC-ESM	3				1	1	1	1
34	MIROC-ESM-CHEM	1				1	1	1	1
35	MPI-ESM-LR	3				3	3		3
36	MPI-ESM-MR	3				1	3		1
37	MRI-CGCM3	3				1	1	1	1
38	NorESM1-M	3			1	1	1	1	1
39	NorESM1-ME	1				1	1	1	1
	Model ensemble	38	11	4	11	29	36	22	38

All forcing

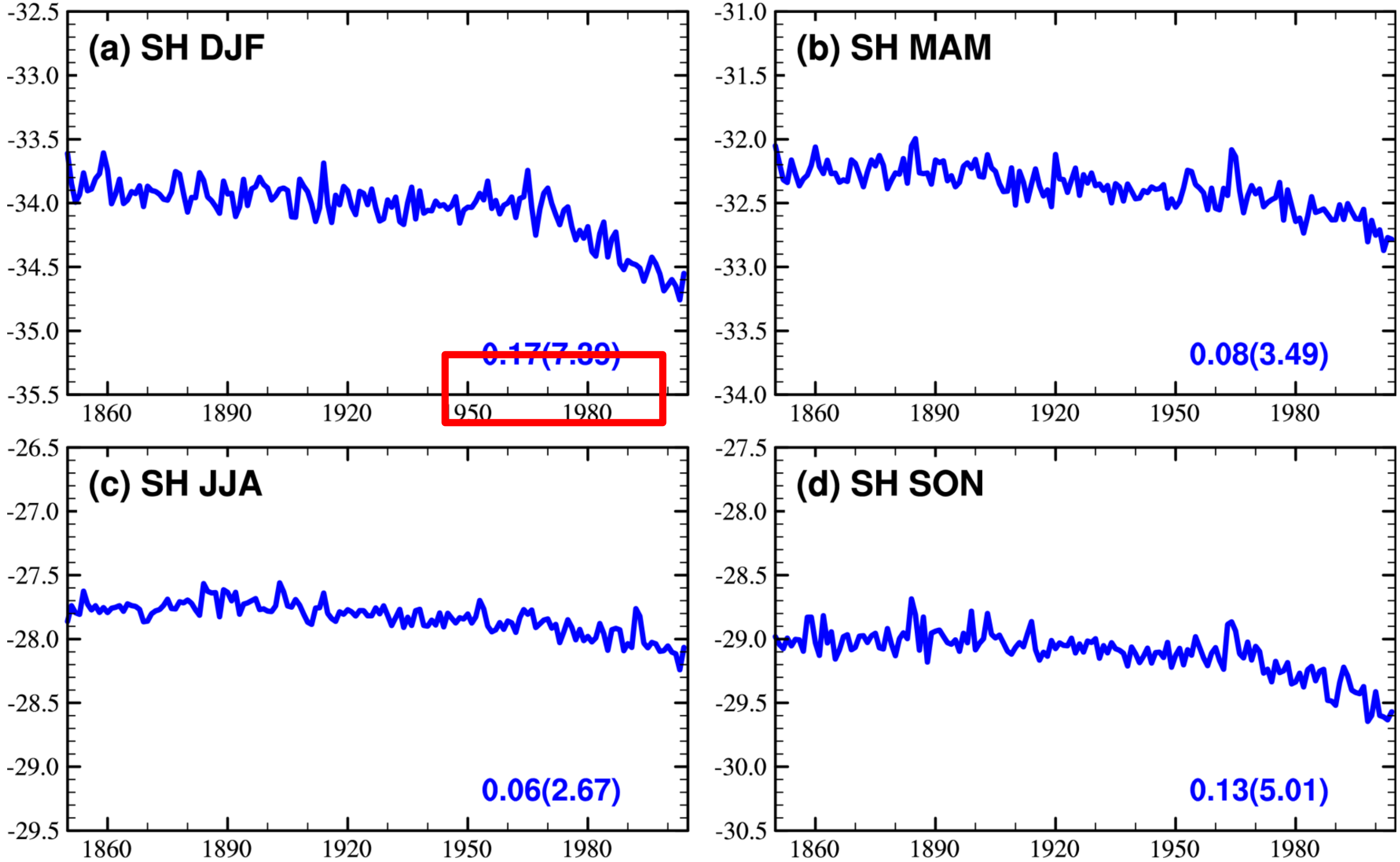


NH

HC width does not follow the global mean surface temperature.

Tao et al. (2016, Climate Dynamics)

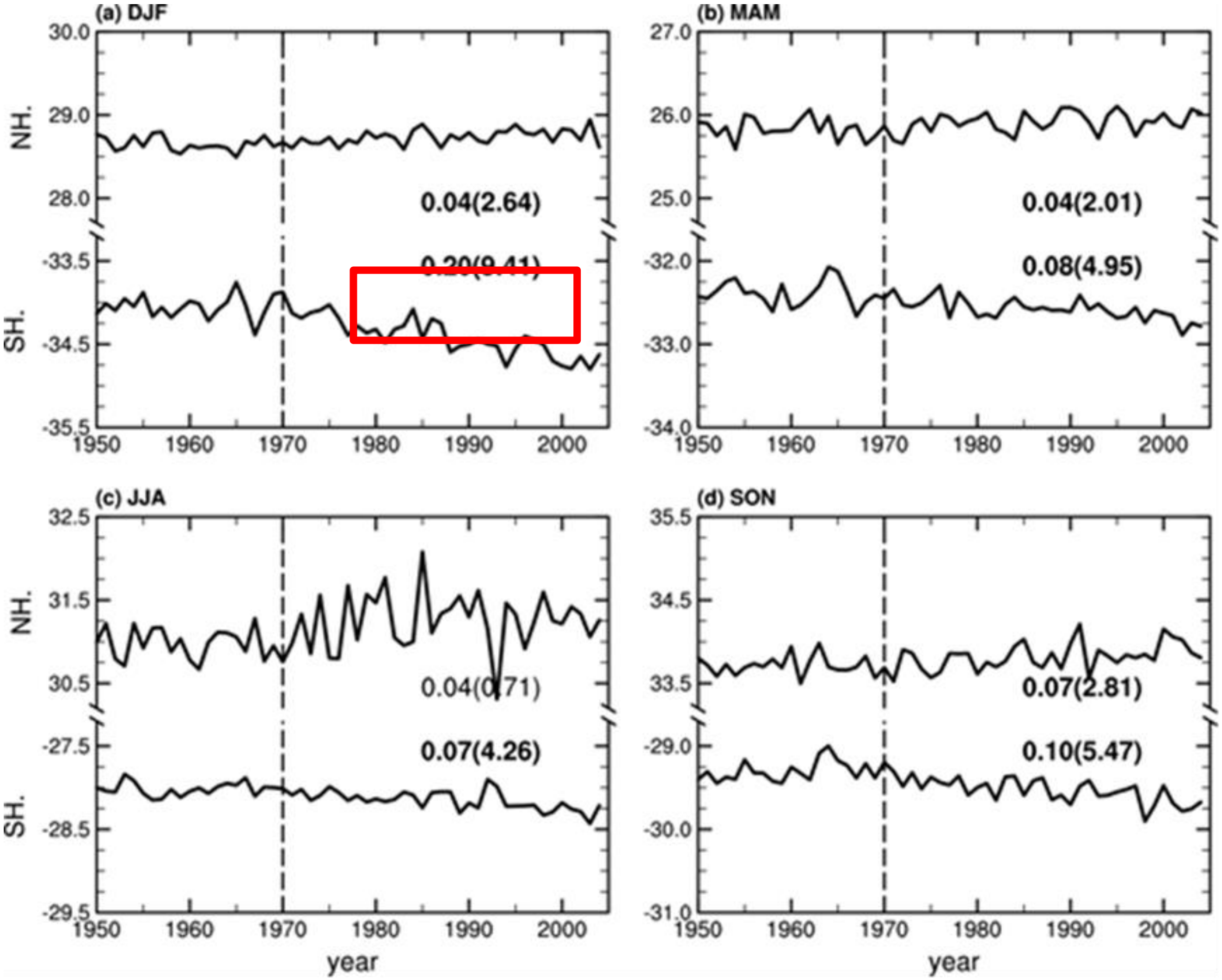
All forcing



SH

Tao et al. (2016, Climate Dynamics)

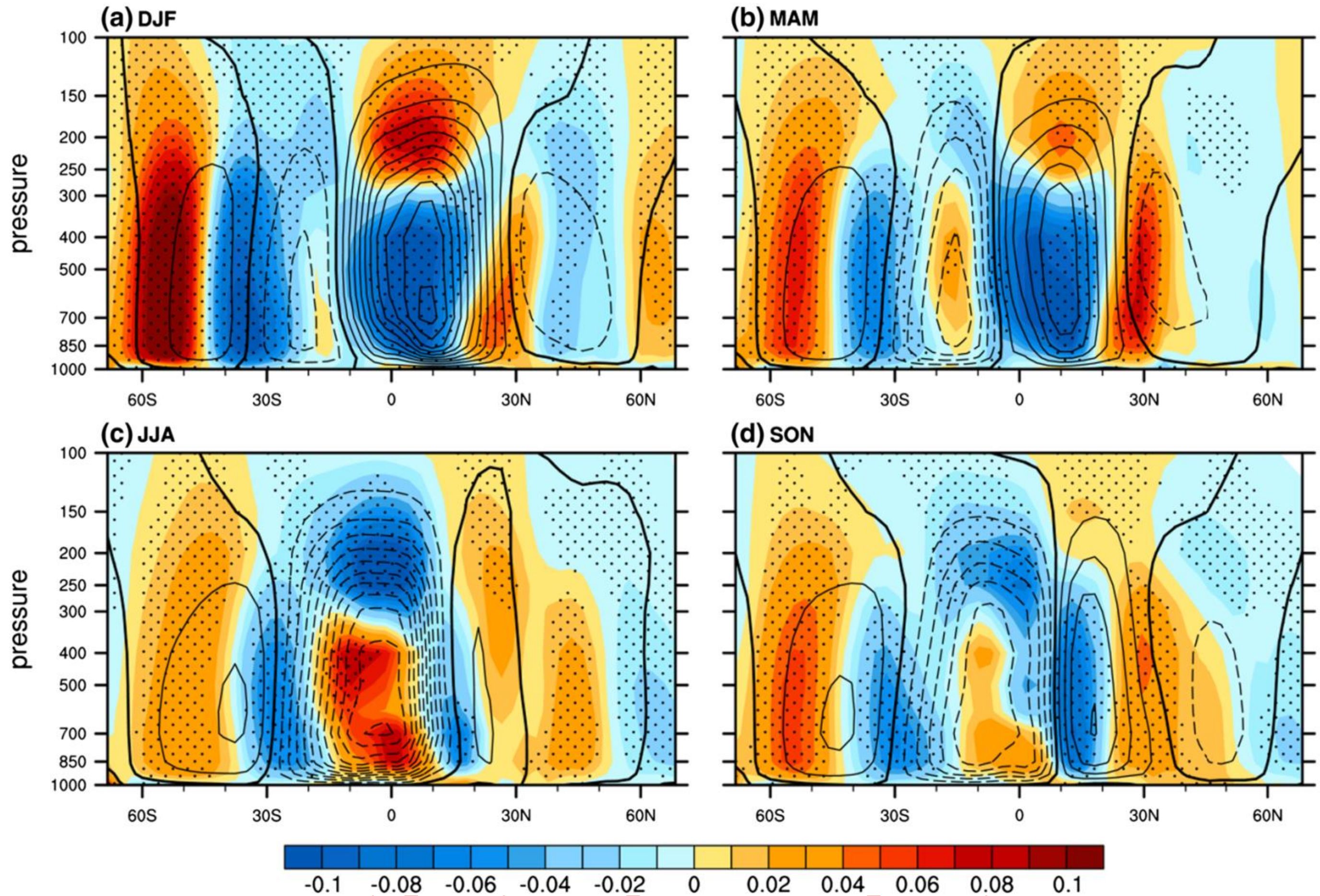
All forcing



Tao et al. (2016, Climate Dynamics)

Trends in mass streamfunction:

All forcing (1970-2005)

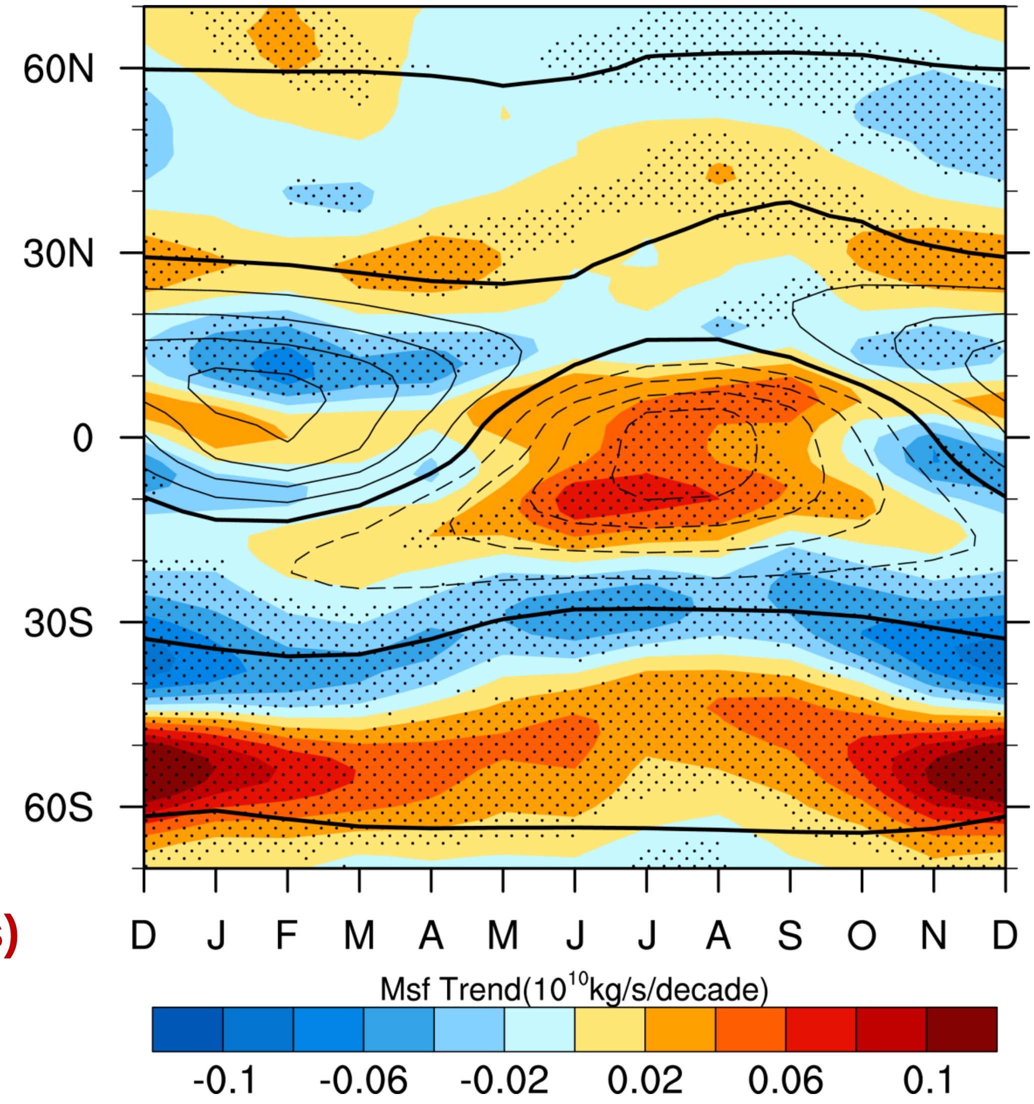


Widening, but weakening

Tao et al. (2016, Climate Dynamics)

Mass streamfunction trend at 500 hPa

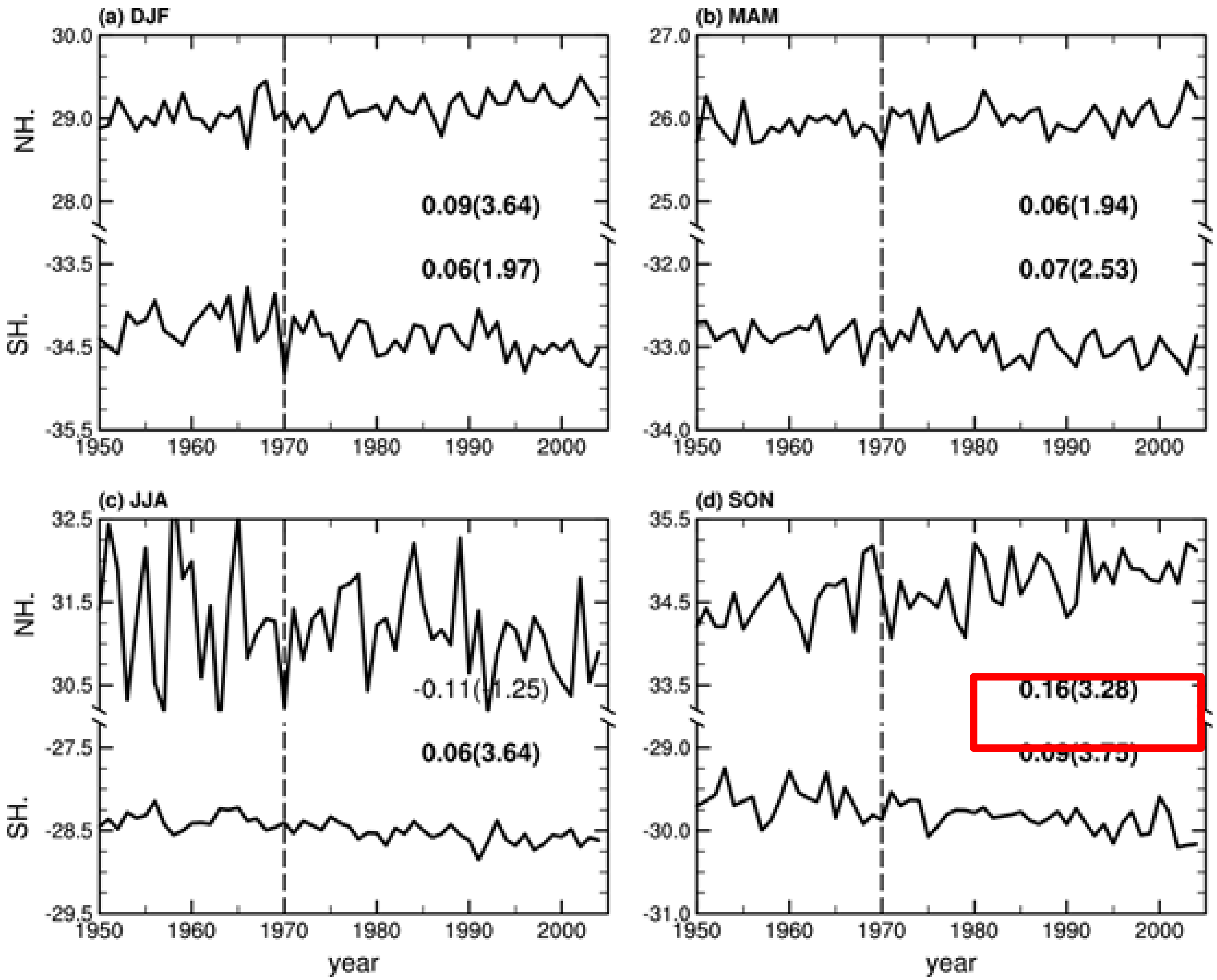
(All forcing, 1970-2005)



Widening,
But weakening

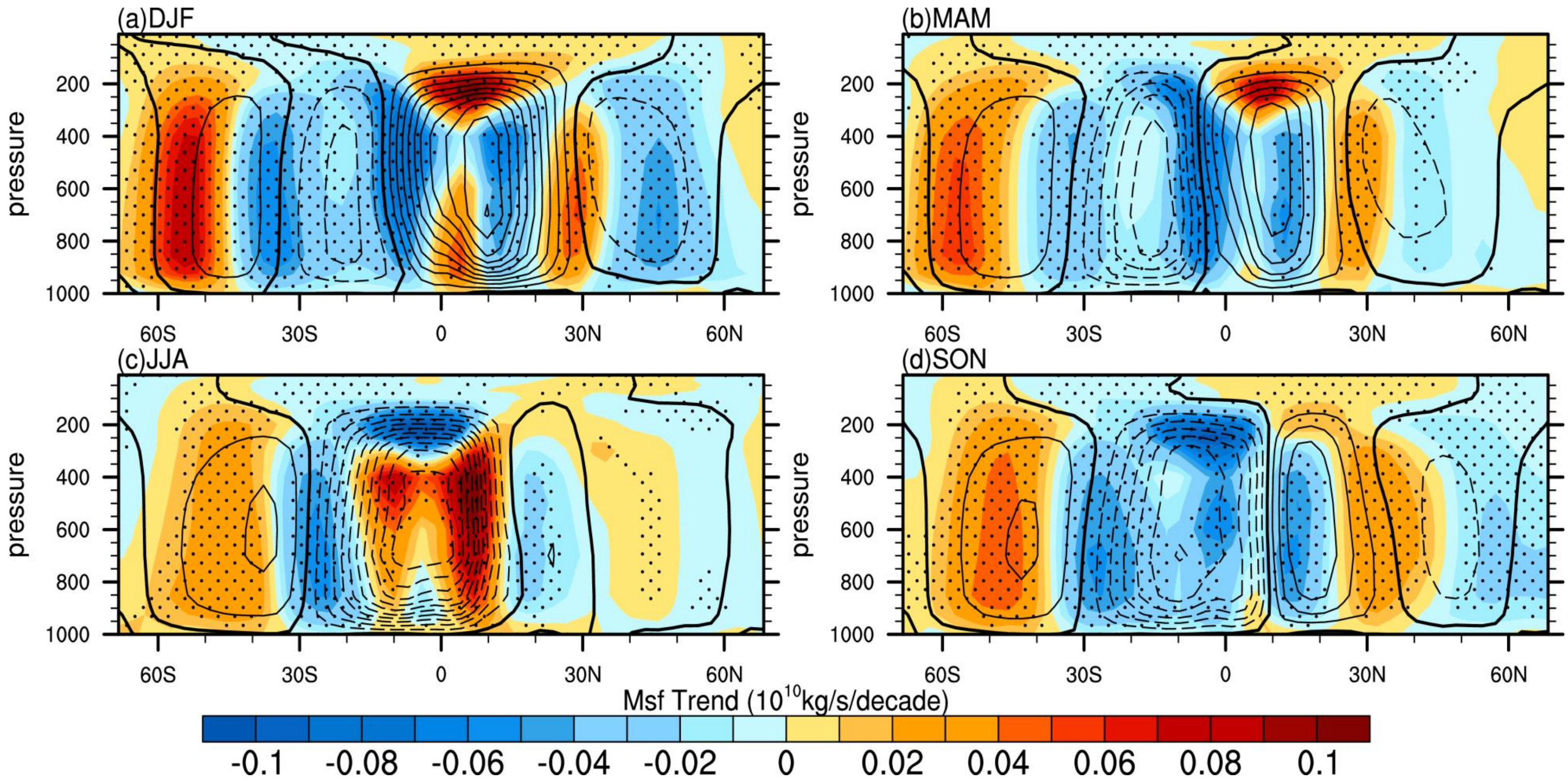
Tao et al. (2016, Climate Dynamics)

GHG-only



Tao et al. (2016, Climate Dynamics)

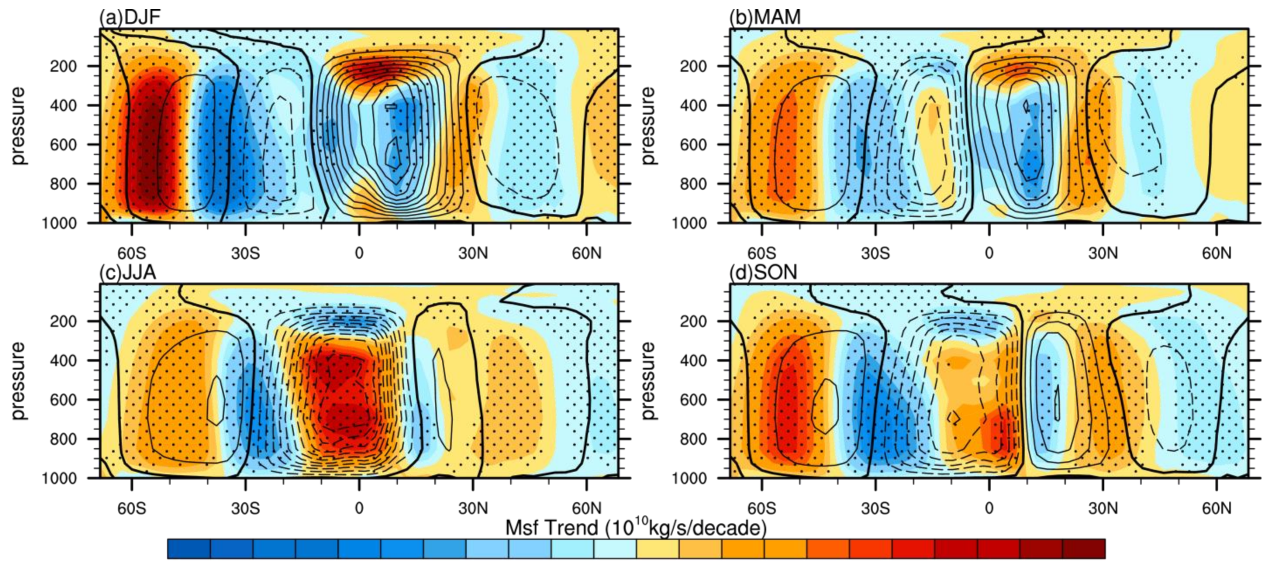
GHG-only forcing (1970-2005)



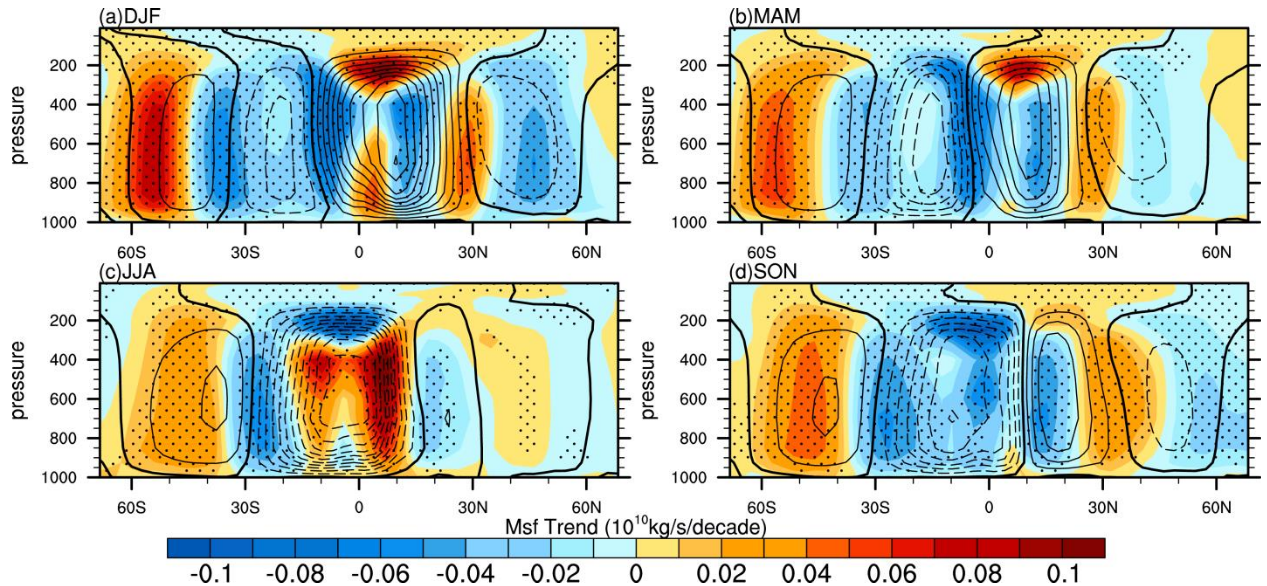
Tao, Hu and Liu (2015, Climate Dynamics)

All forcing vs. GHG-only

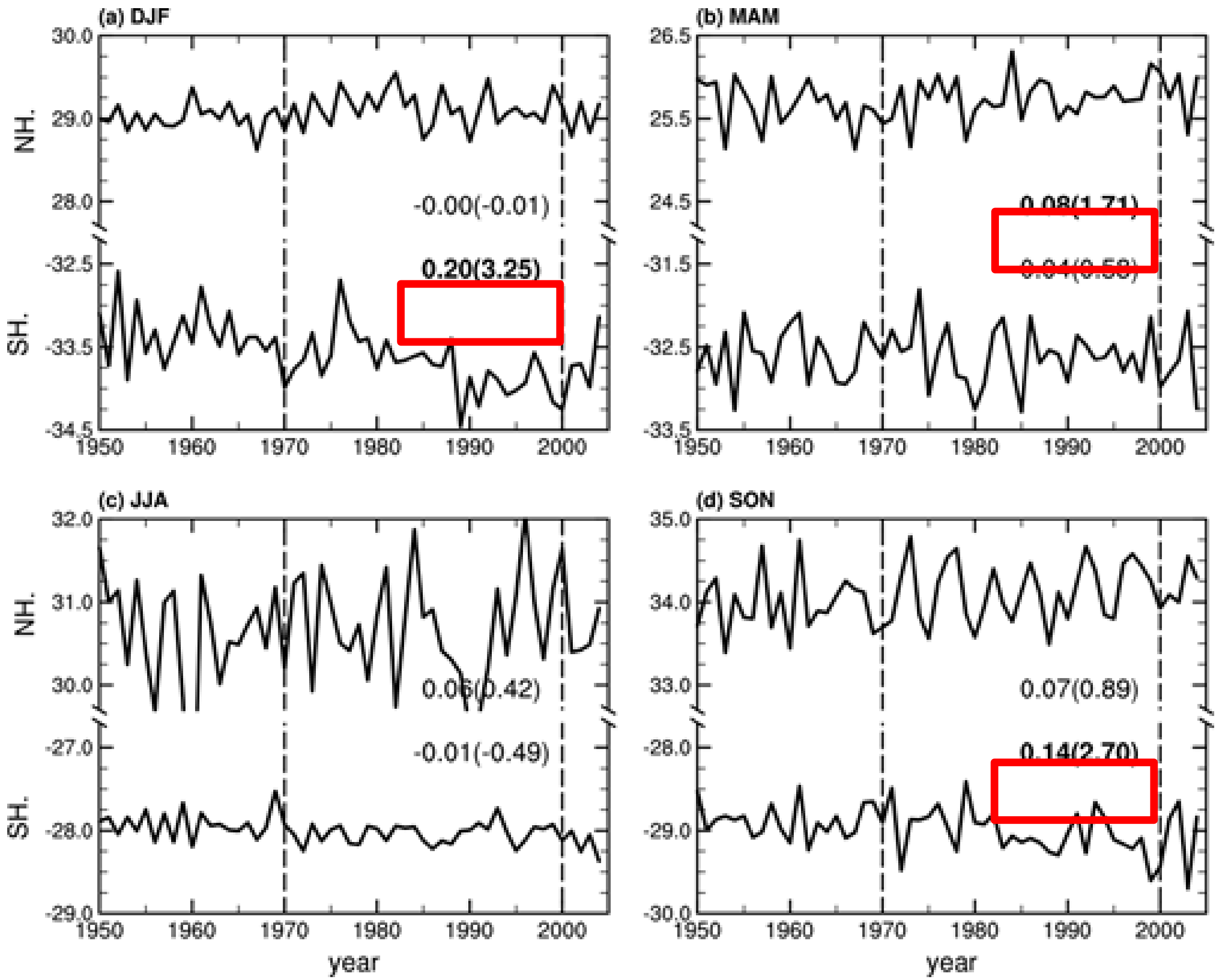
All forcing



GHG-only

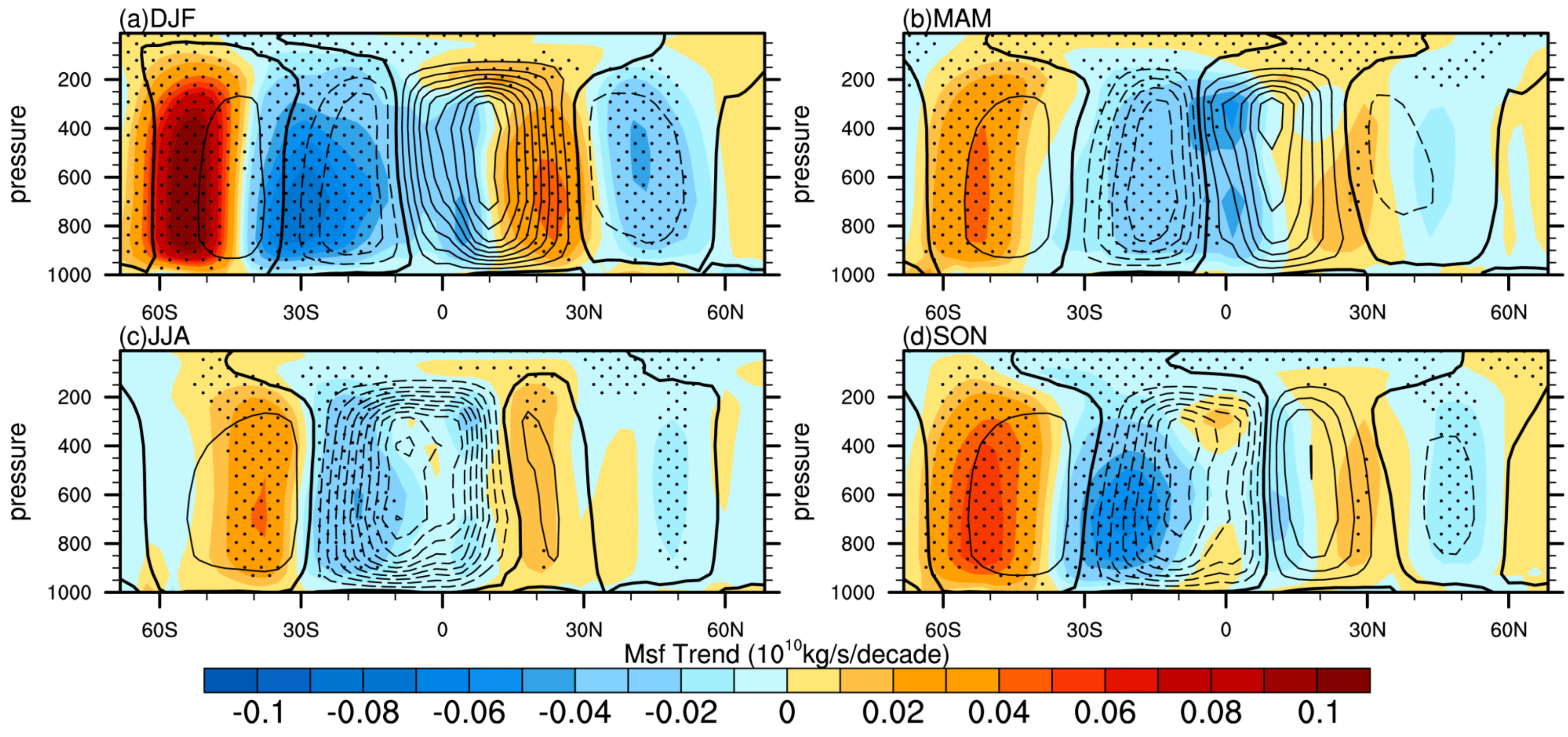


Ozone-only



Tao et al. (2016, Climate Dynamics)

Mass streamfunction trend
(ozone-only, 1950-2005)

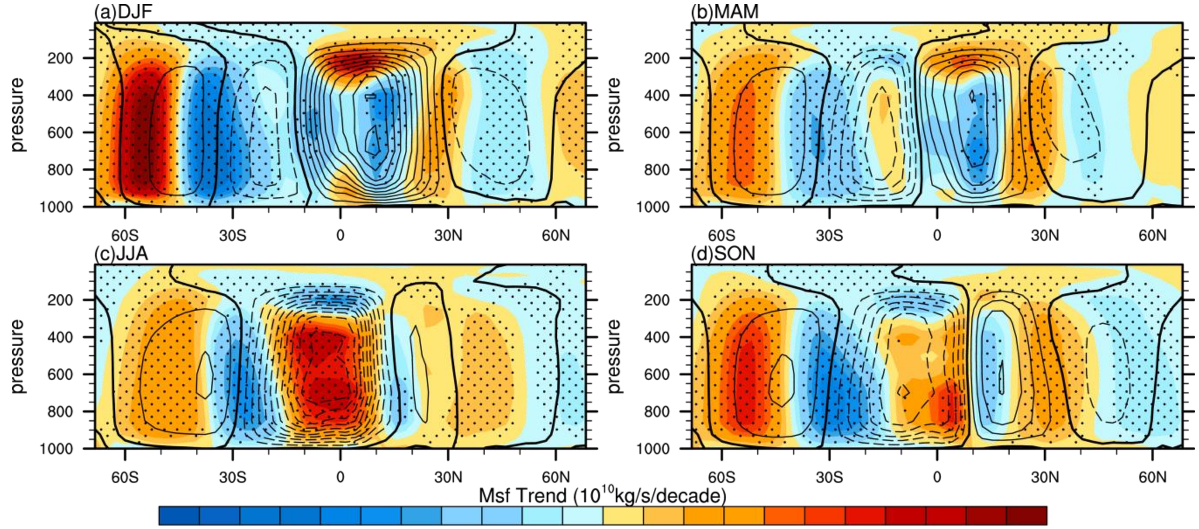


Widening and strengthening

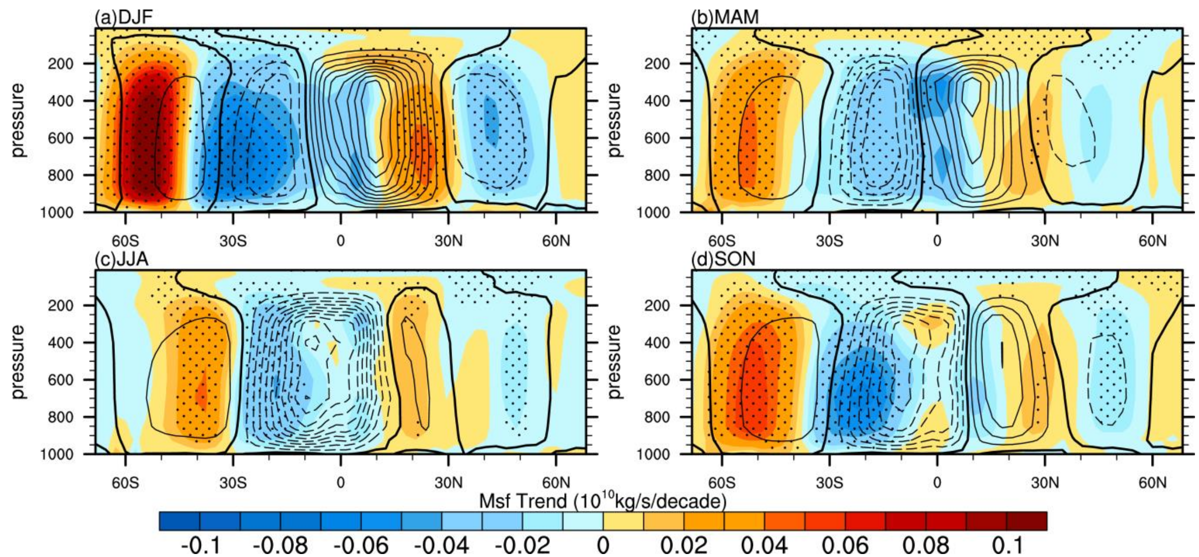
Tao et al. (2016, Climate Dynamics)

All forcing vs. ozone-only

All forcing

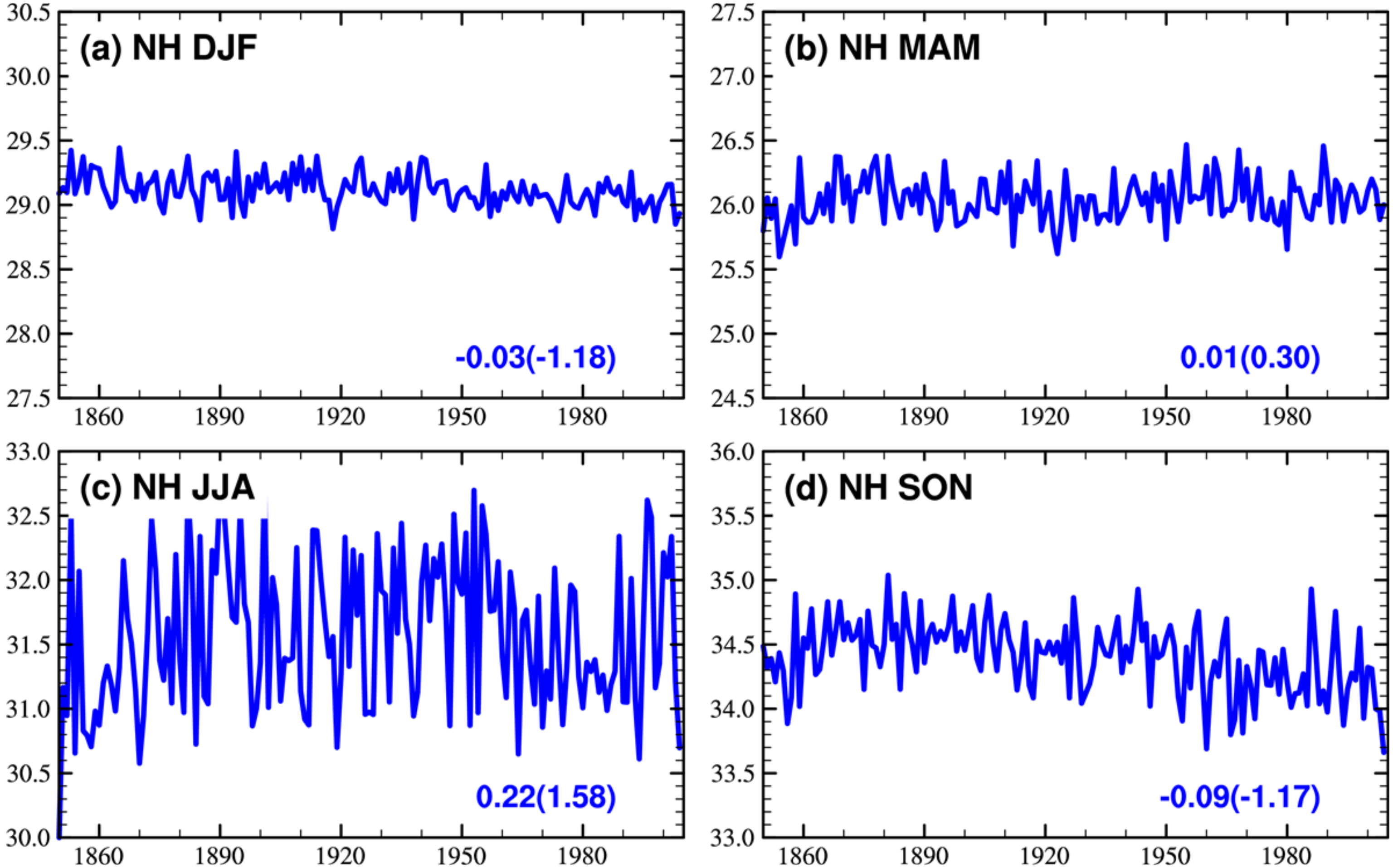


Ozone-only



Ozone depletion has different mechanism in causing HC changes from that of increasing GHGs?

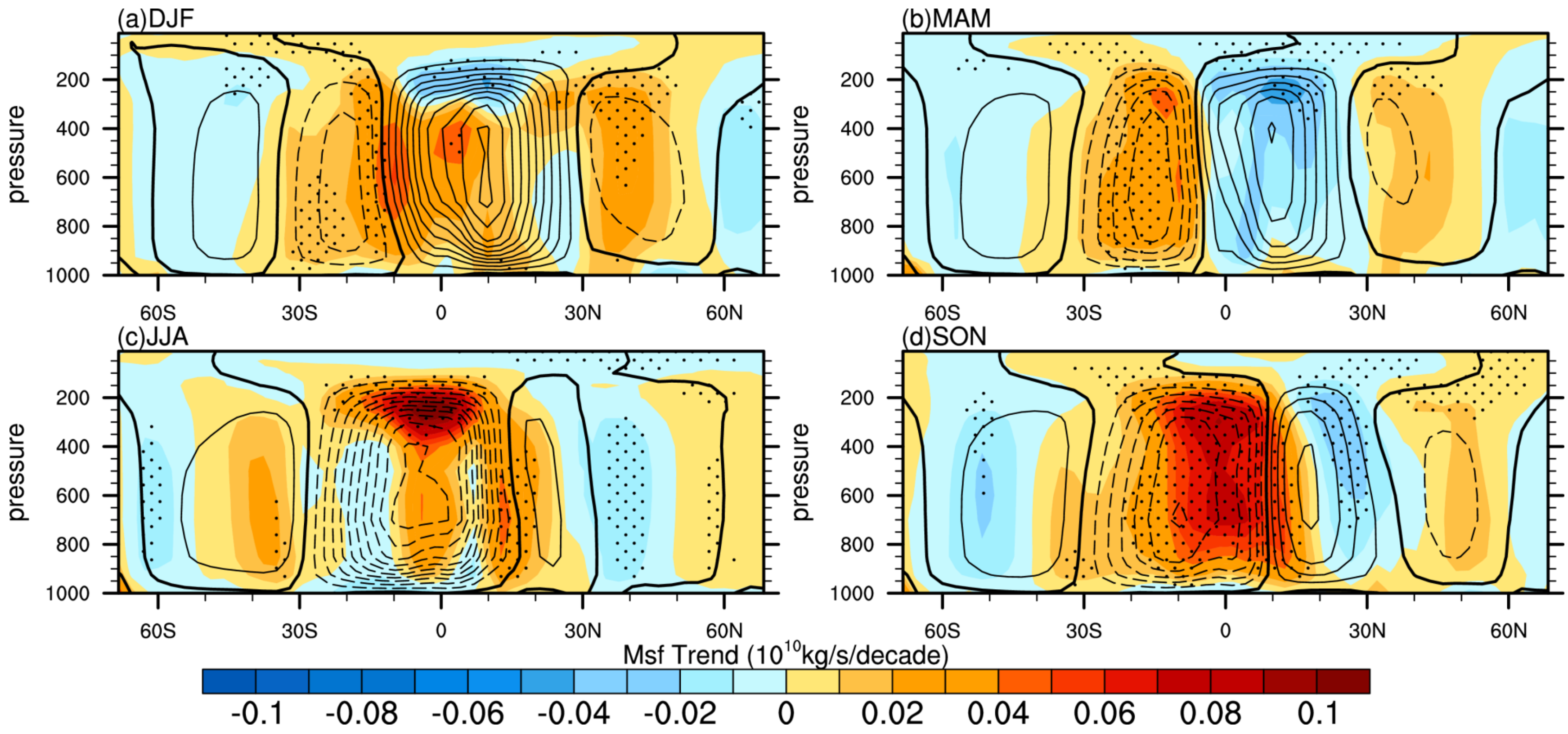
Anthropogenic aerosol forcing

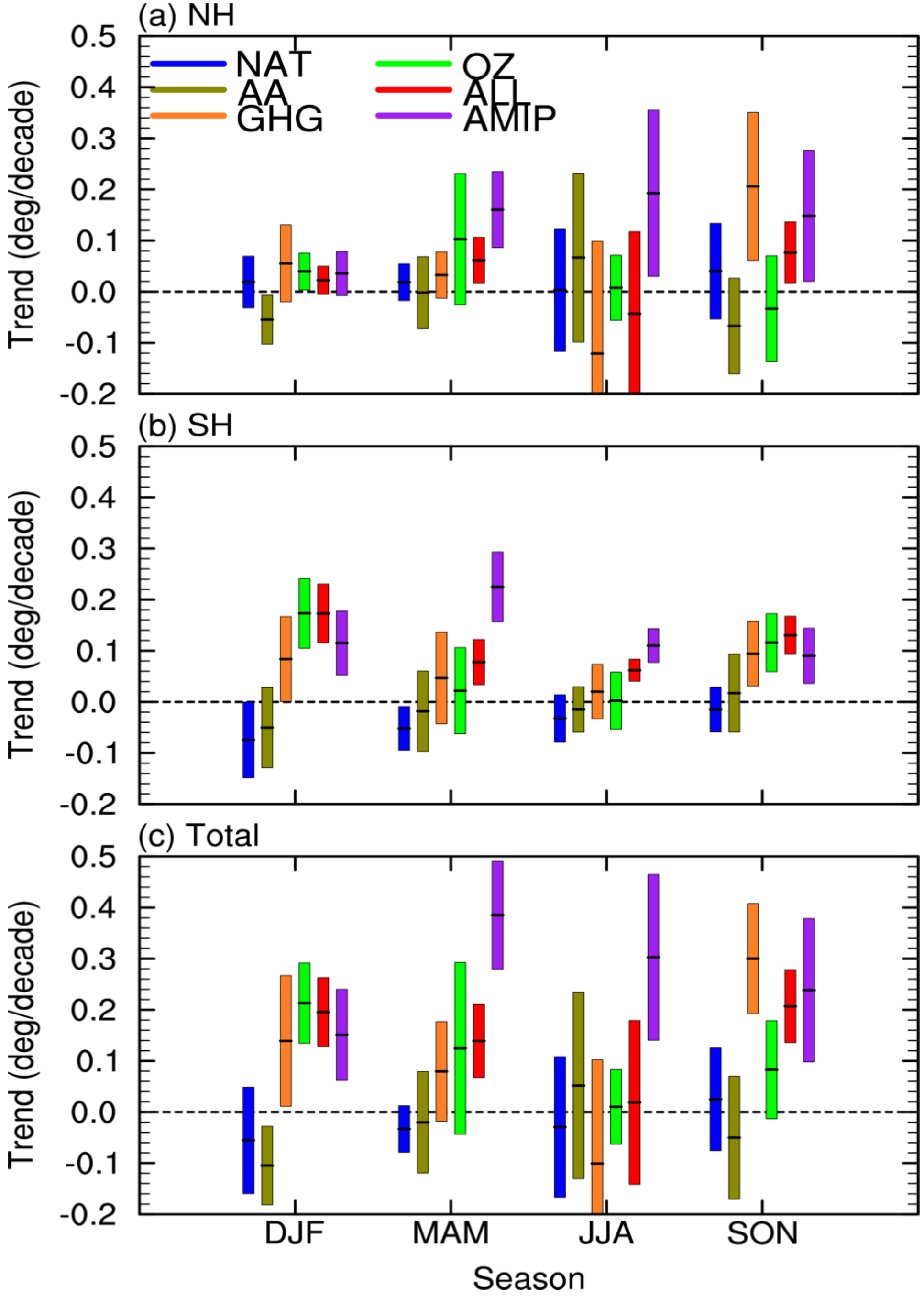


Tao et al. (2016, Climate Dynamics)

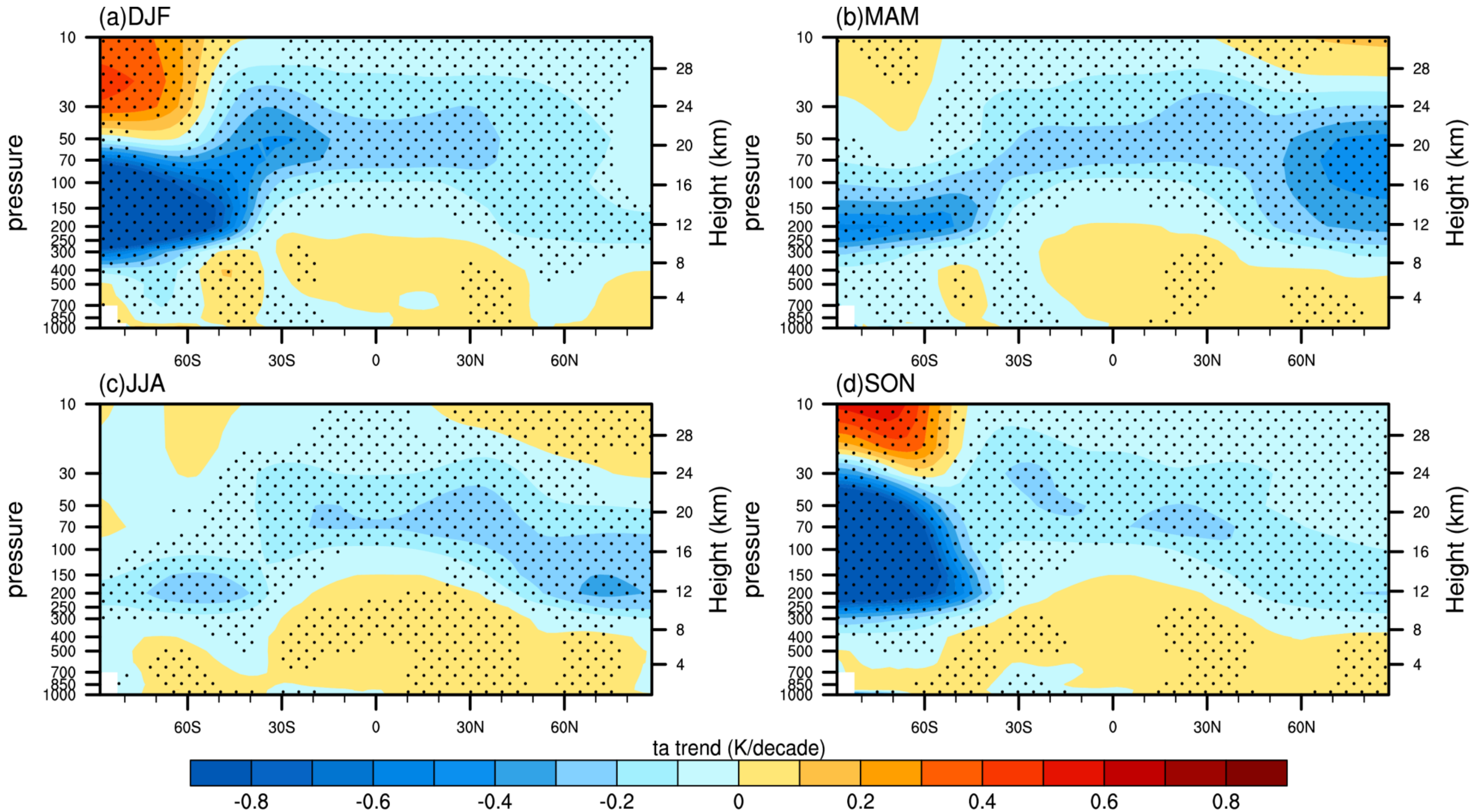
Mass streamfunction trend

(Anthropogenic aerosol forcing, 1950-2005)




(a) NH
NAT
AA
GHG
OZ
ALL
AMIP
Trend (deg/decade)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
(b) SH
(c) Total
DJF
MAM
JJA
SON
Season

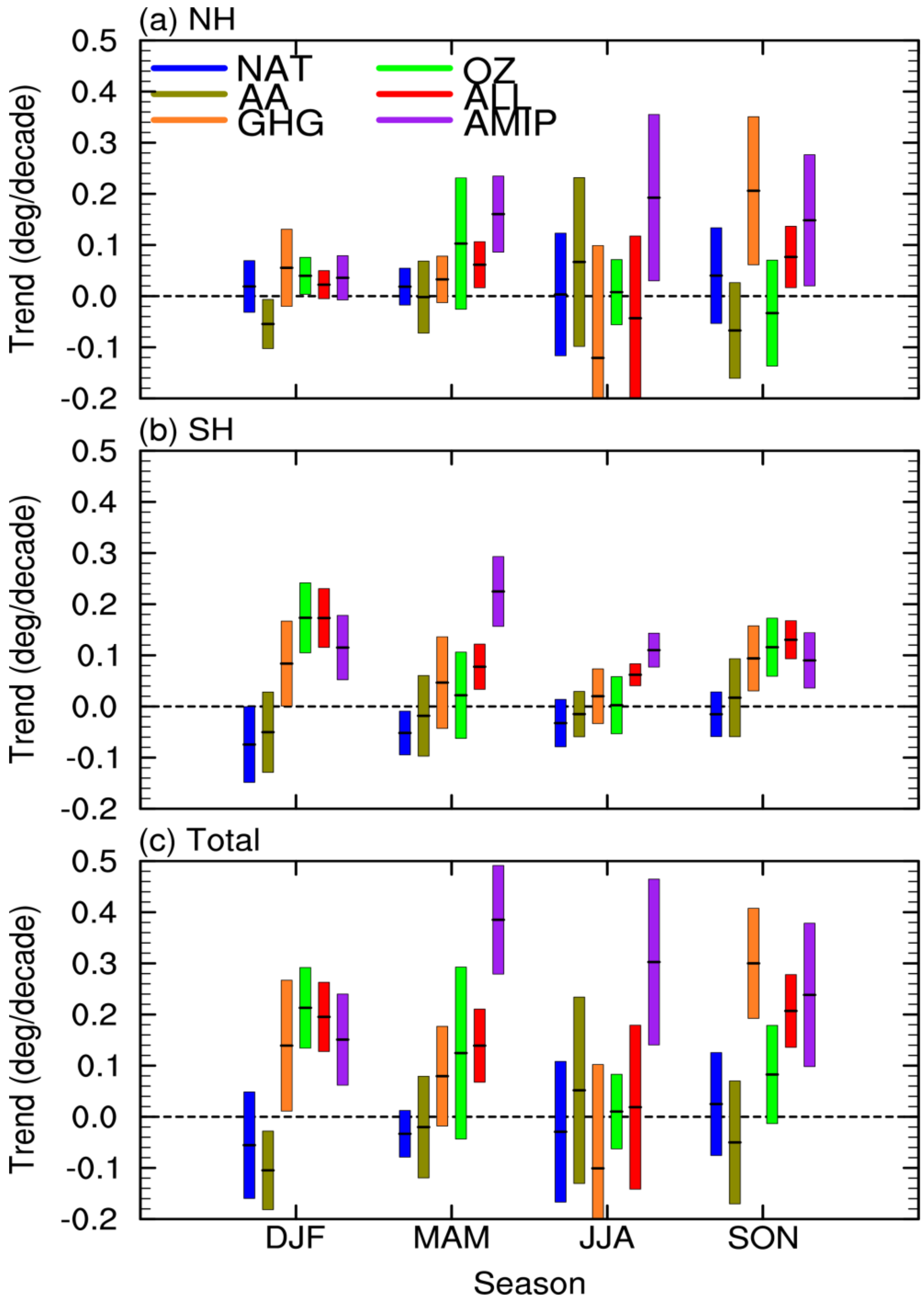
Temperature trends (Ozone-only, 1970-2005, CMIP5)



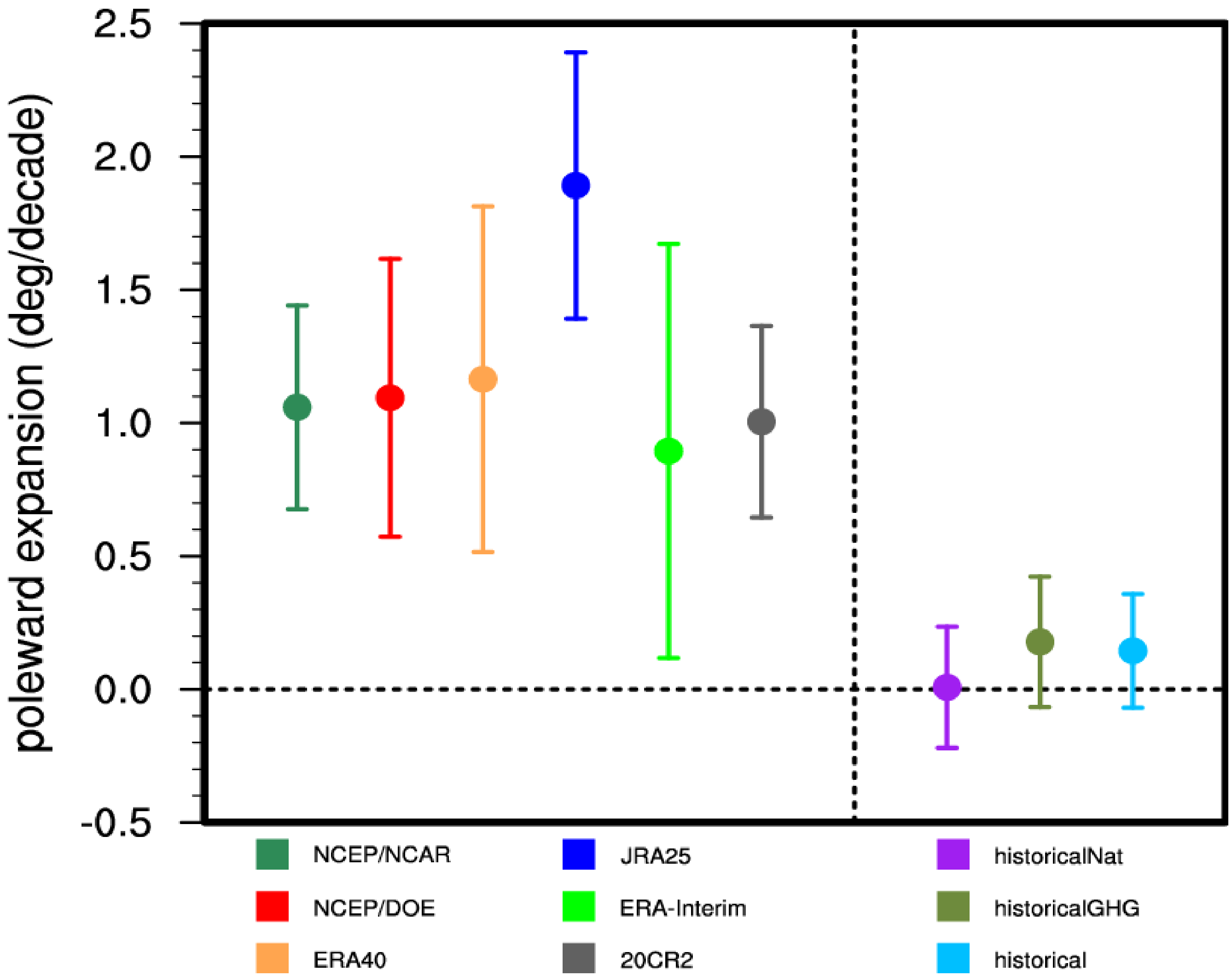
Tao, Hu and Liu (2015, Climate Dynamics)

各种人为辐射强迫的作用

Tao, Hu and Liu (2015, Climate Dynamics)

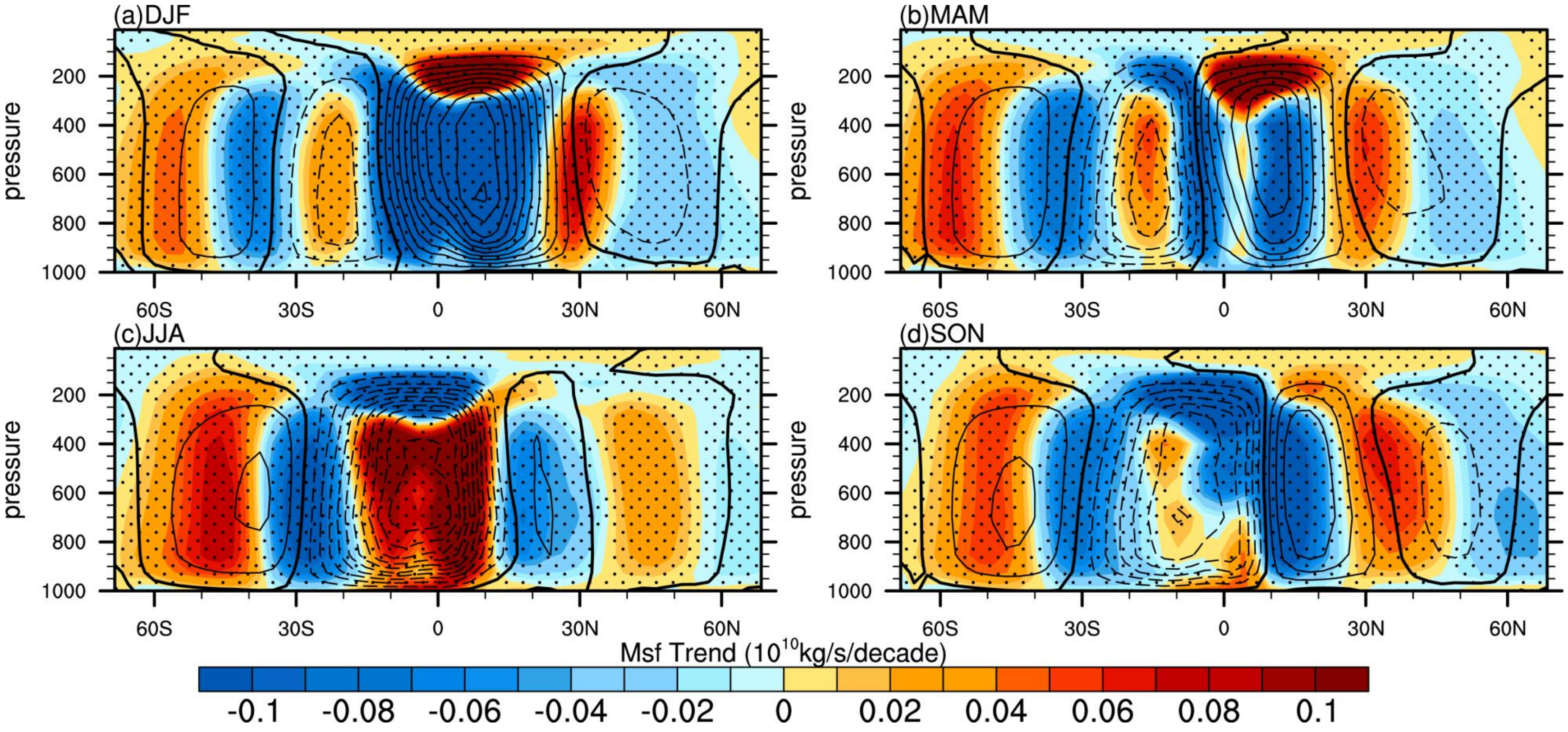


Observed HC widening is much weaker than Simulations



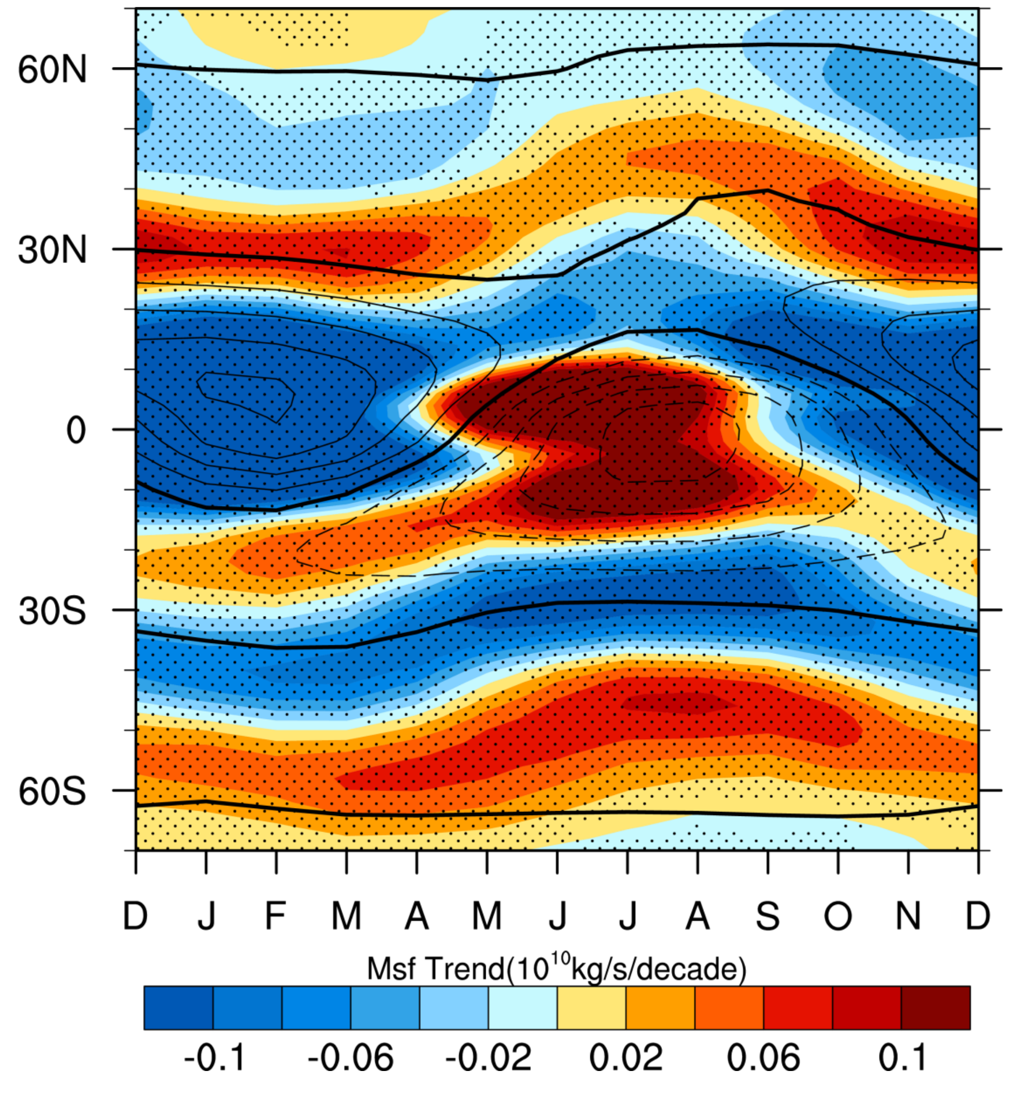
Hu et al. (2013, AAS, AR5)

Mass streamfunction trend
(RCP8.5, 2005-2100)

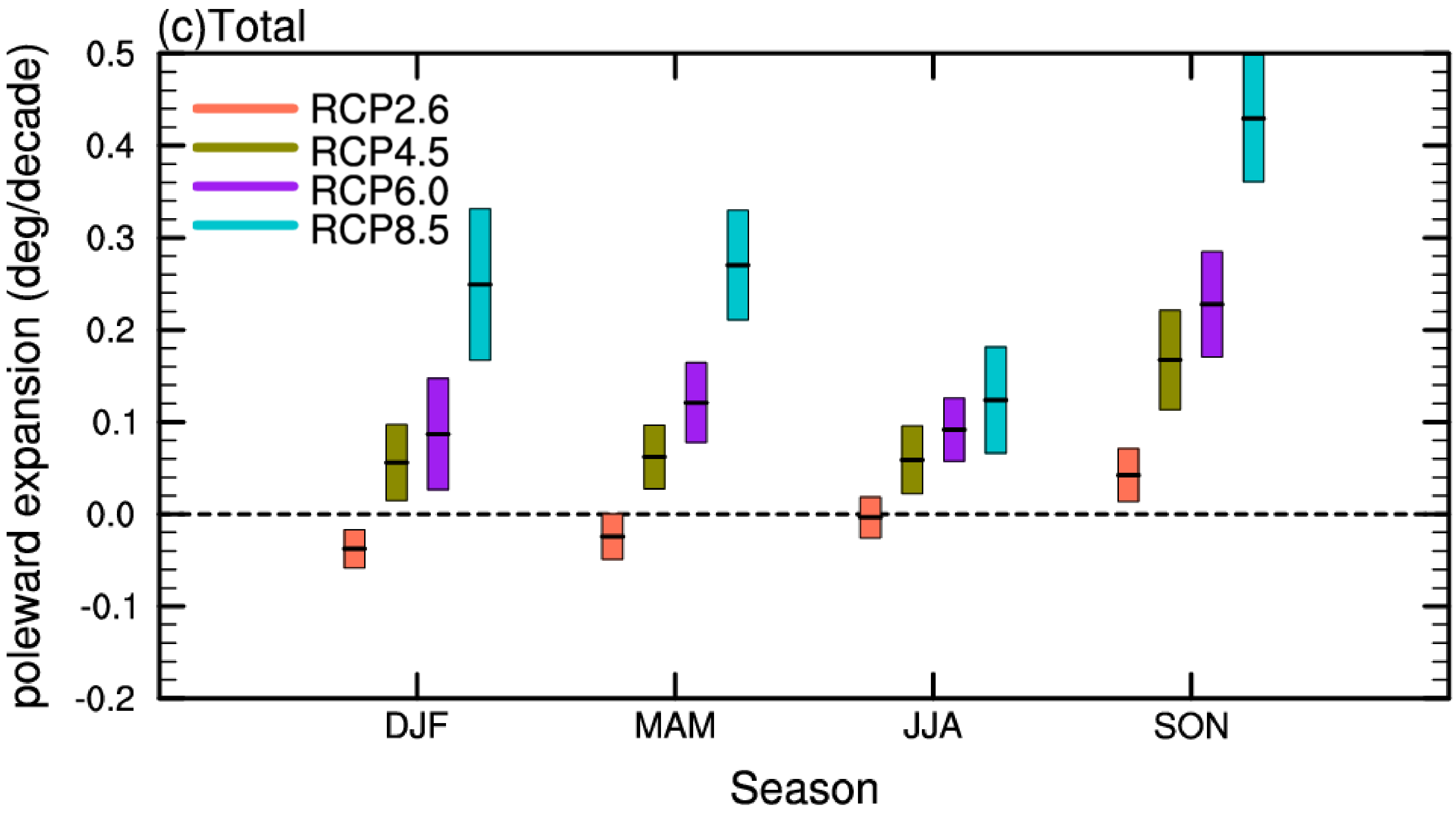


Mass streamfunction trend

(RCP8.5, 2005-2100)



21st century projection



Hu et al. (2013, AAS)

Summary

1. It took more 200 years from the first observation to the theory.
2. The widening trend is common in all datasets, while the strength trends are not consistent.
3. All forcing and GHG forcing → HC widening, but weakening.
4. Ozone depletion → HC widening and strengthening.
5. Anthropogenic aerosols → no significant HC changes.
6. 21st century, HC widening and weakening.

Questions or homework

1. All forcing and GHG forcing: why is the trend in SON the largest?
2. Ozone forcing: why is HC strengthened (SH cell)?
3. NH cell: is static stability more important (Lu et al., 2007)?
4. SH cell: is eddy poleward shift more important (Chen et al., 2009)?
5. Why does anthropogenic aerosol forcing have no significant effects?
6. SST: depending on the time period?
7. The zonal-mean Hadley circulation and regional monsoon, circulation,
8. Strength vs. width

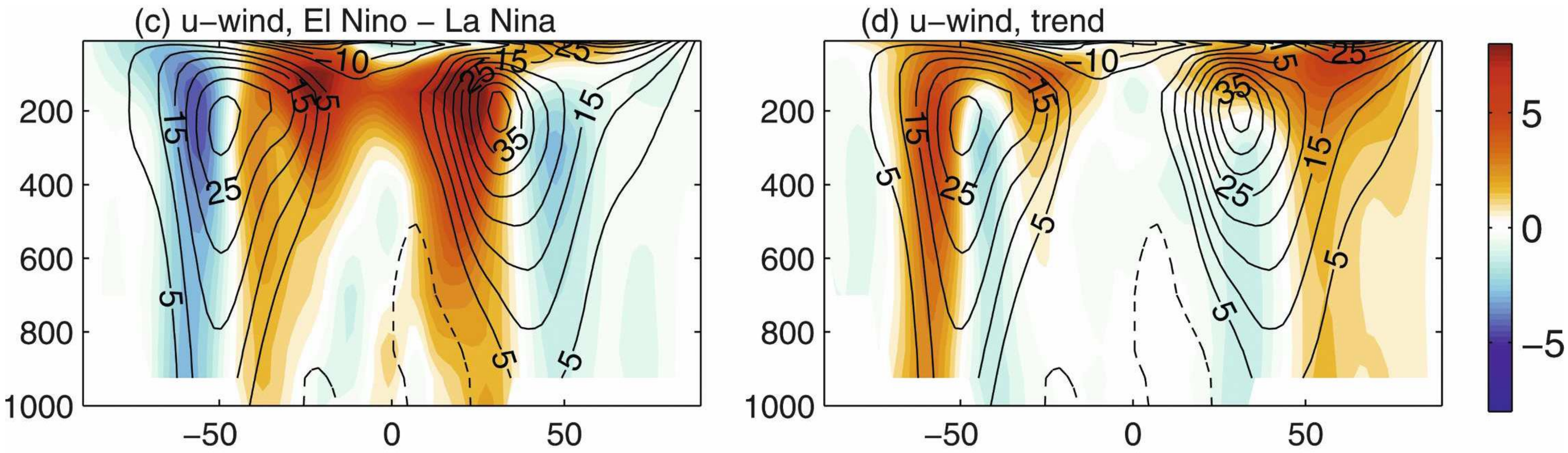
Strength vs. width

$$\frac{\partial \overline{u}}{\partial t} - f\overline{v} = -\frac{\partial\left(\overline{u'v'}\right)}{\partial y}$$

$$\frac{\partial \overline{u}}{\partial t} = 0, \Rightarrow f\overline{v} = \frac{\partial\left(\overline{u'v'}\right)}{\partial y}$$

$$\overline{v} = \frac{1}{f}\frac{\partial\left(\overline{u'v'}\right)}{\partial y}$$

Strength vs. width



Lu et al. (2010, JC)

Chang, E. K. M., 1995: The influence of Hadley circulation intensity changes on extratropical climate in an idealized model. *J. Atmos. Sci.*, **52,** 2006–2024.

$$\frac{\cos\varphi}{\sin^2\varphi} = \frac{2\Omega a(U_2 - U_1)}{g(H_2 - H_1)(\theta_2 - \theta_1)/\Theta_0}$$

Philips (1954)

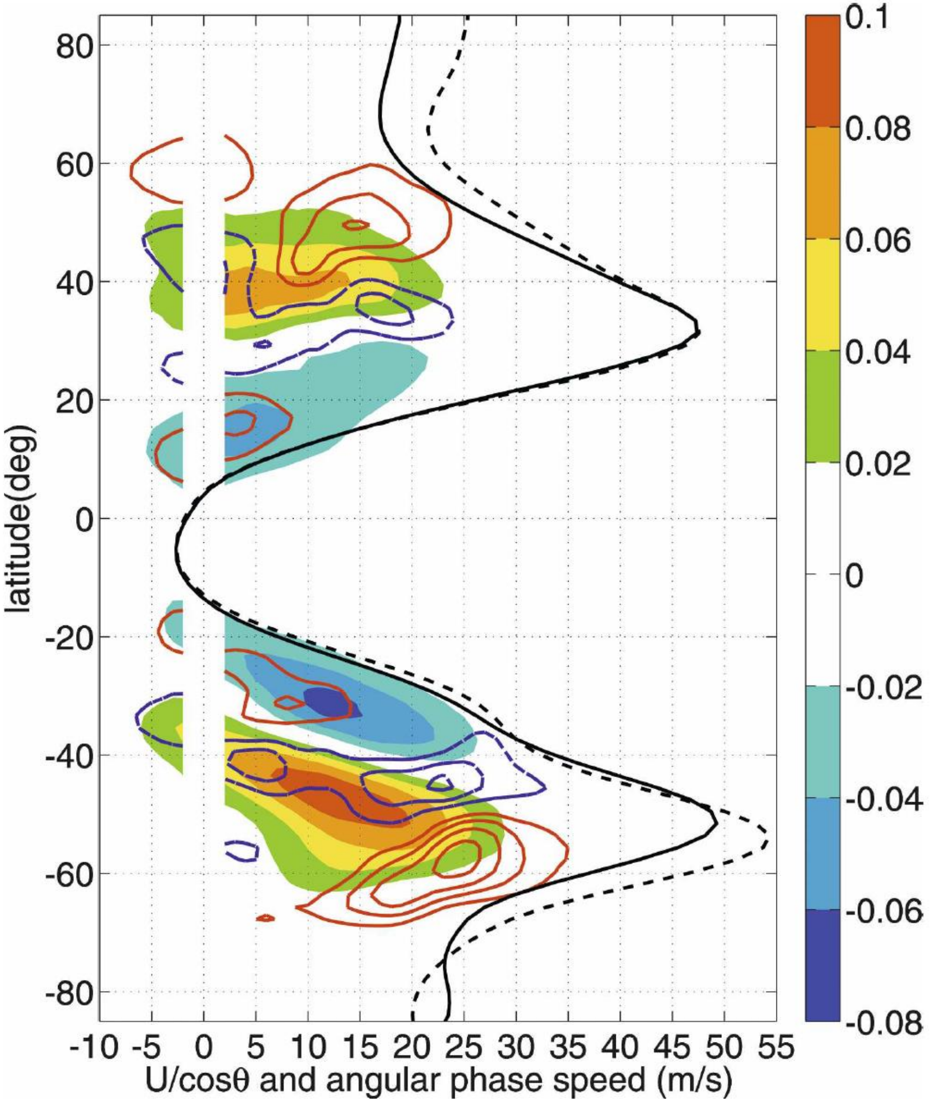
$$\Phi_H = \frac{f}{\beta}\frac{\Delta_y T}{\Delta_z T}$$

$\Delta_y T$： horizontal temperature gradient

$\Delta_z T$： vertical temperature gradient

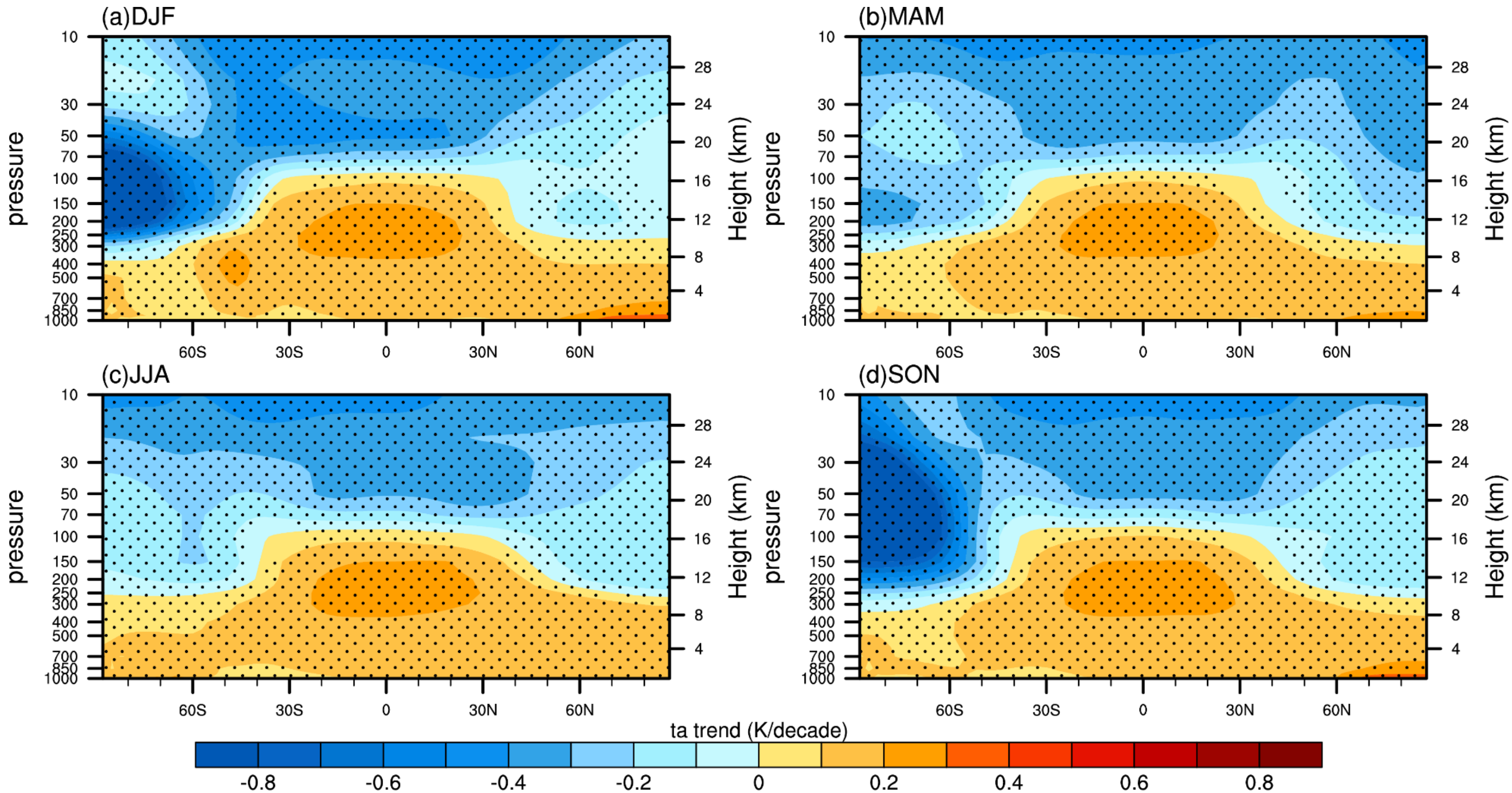
Korty and Schneider (2008)

Trends in eddy-momentum fluxes at 250 hPa

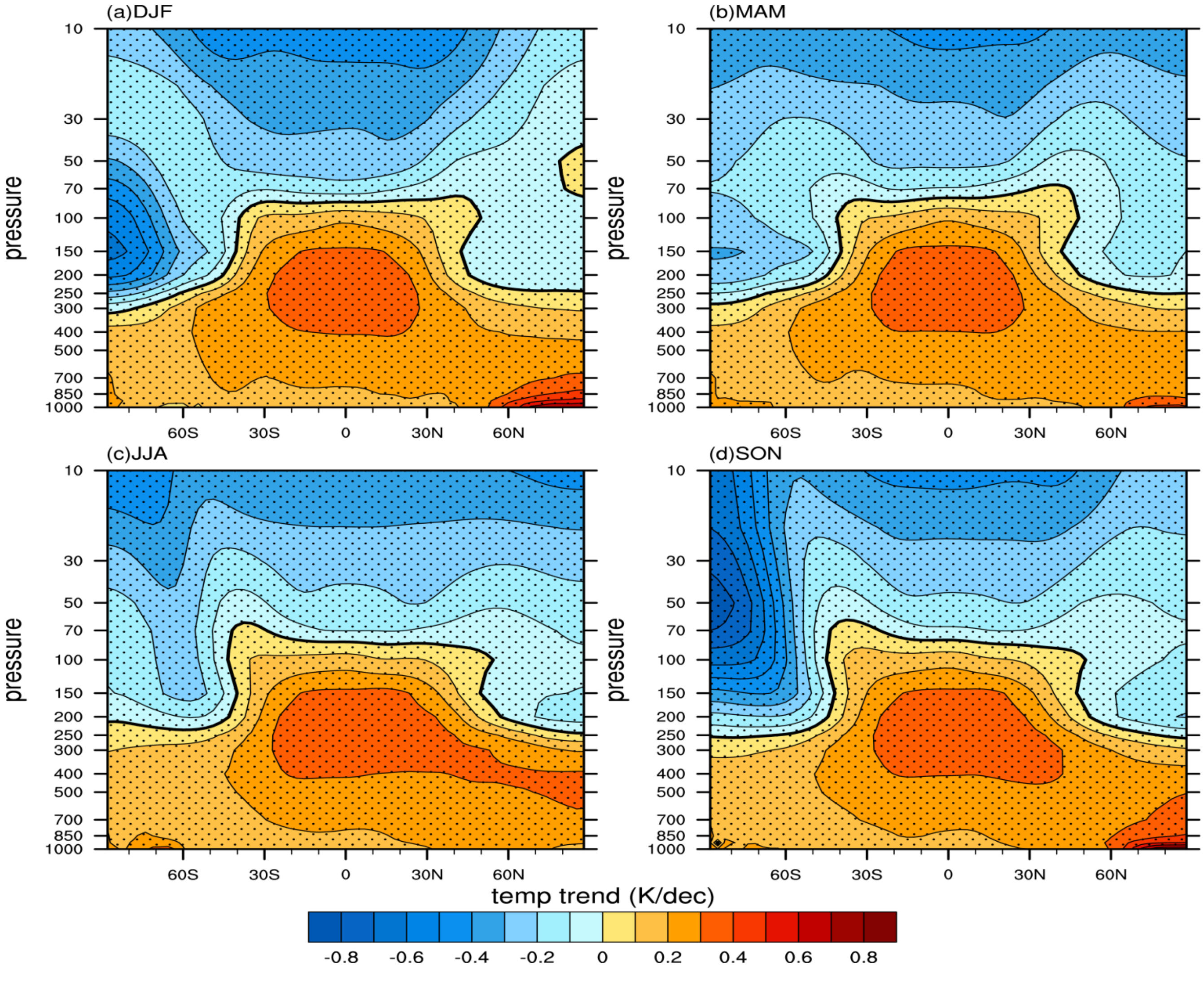


Lu et al., 2008

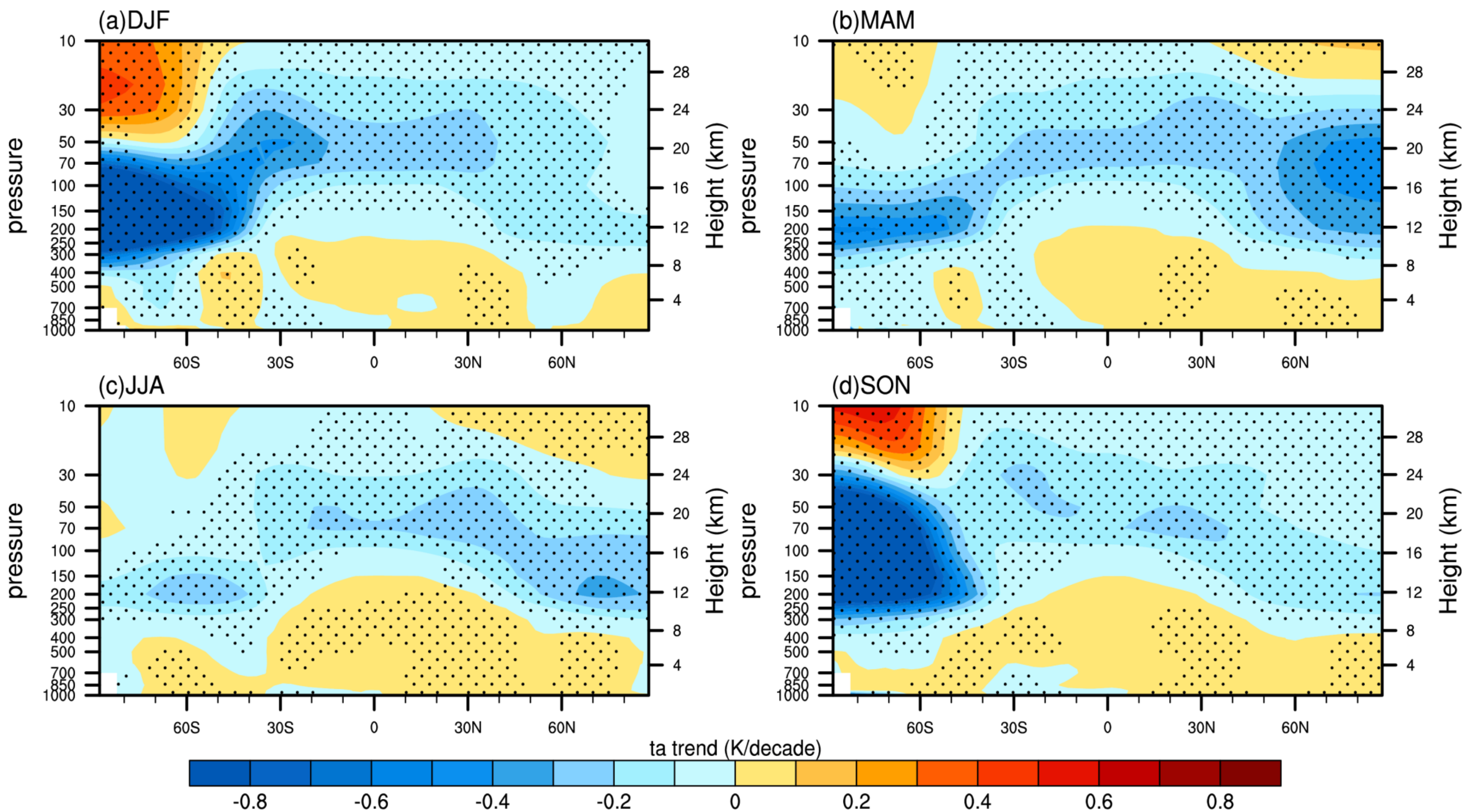
Temperature trends (All forcing, 1970-2005)



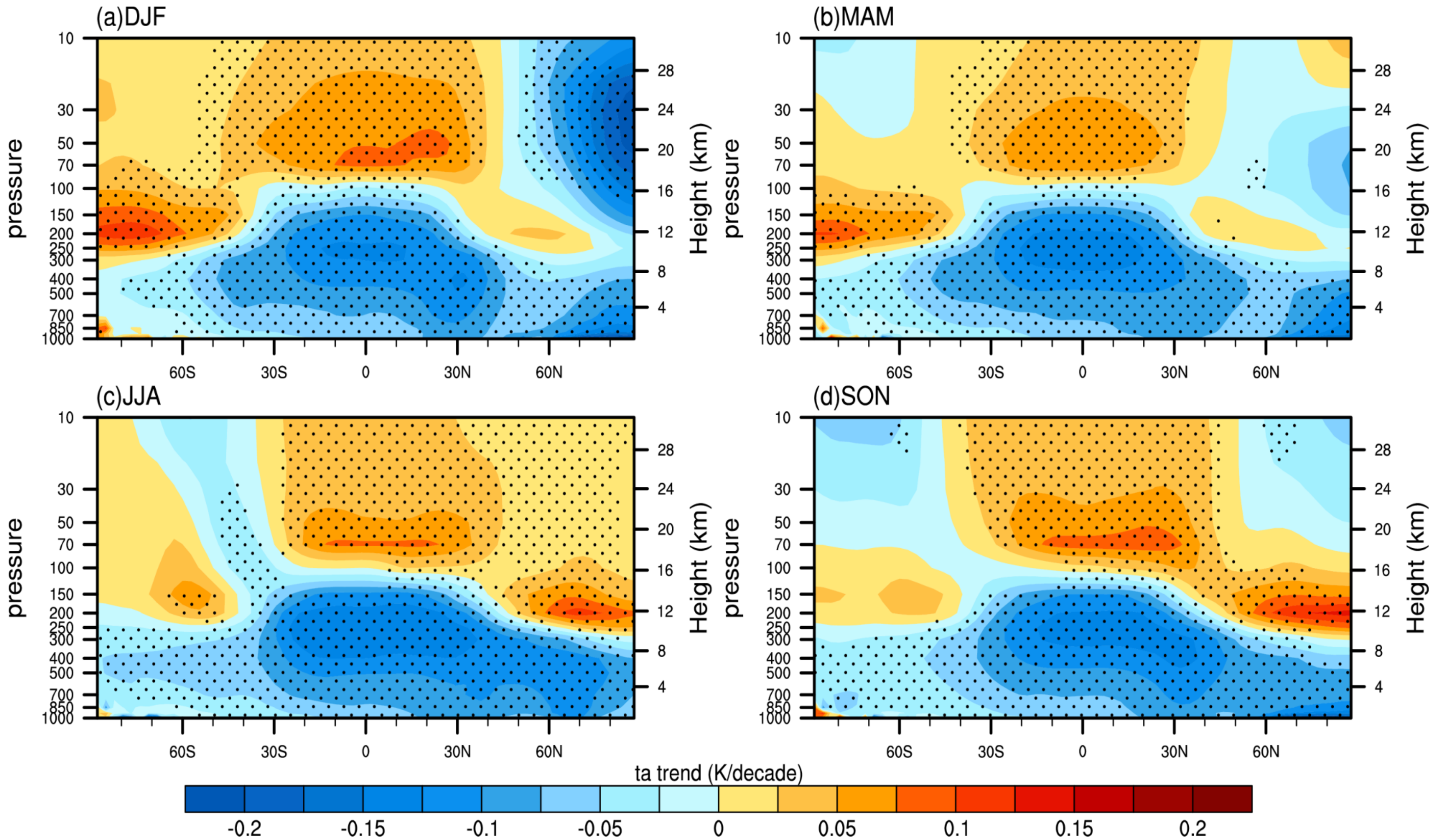
Temperature trends
(GHG-only, 1970-2005)



Temperature trends (Ozone-only, 1970-2005)



Temperature trends
(Anthropogenic forcing, 1970-2005)



Trends in zonal-mean zonal winds

(GHG forcing, 1950-2005)