Cloud-Radiation Response to Large-Scale Circulation Variability

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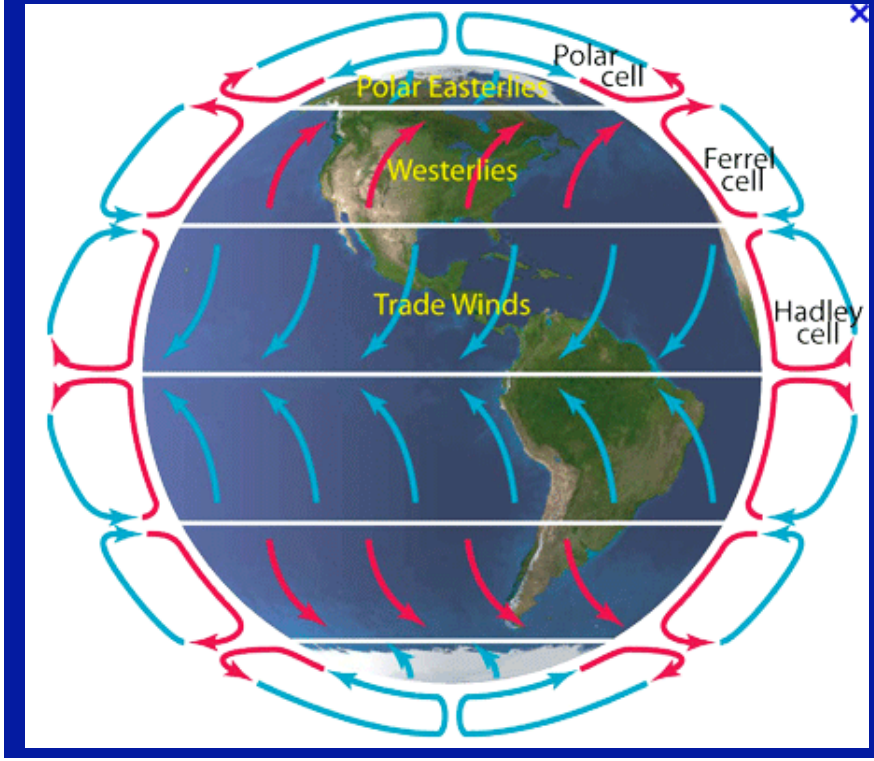
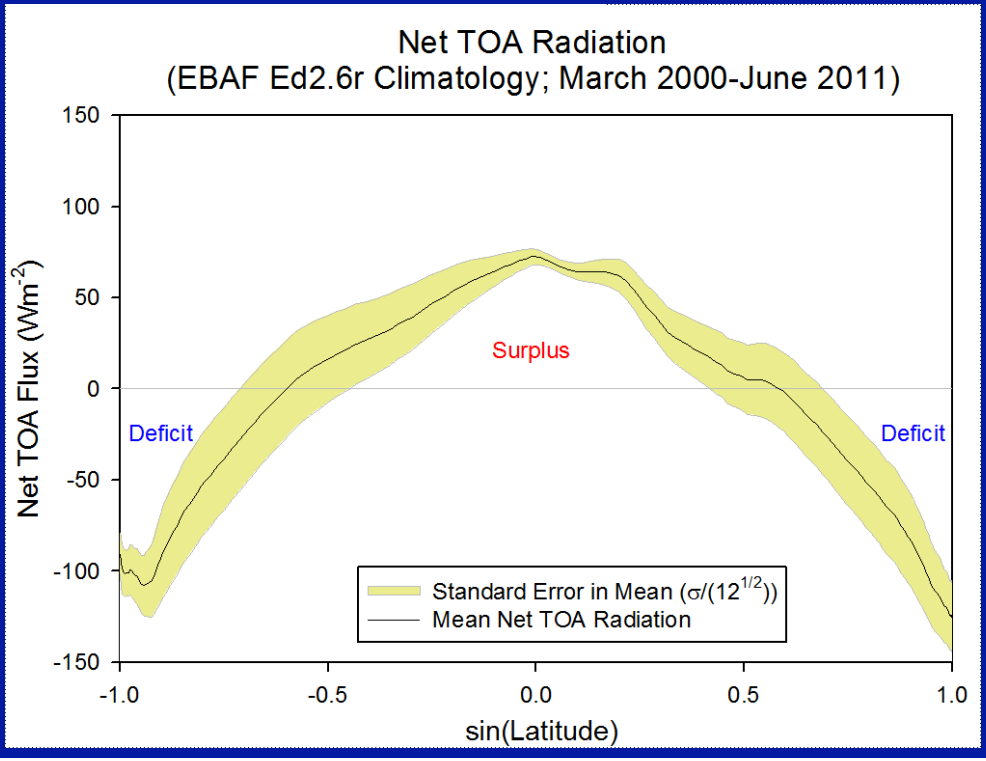
Introduction

- Hadley Circulation: Zonally symmetric meridional circulation with ascending motion over ITCZ and descending motion over subtropical high pressure belt.
- Driven by meridional differential radiative heating. Expected to weaken and expand under global warming.
- How variable is the Hadley circulation?
- How do clouds and radiation co-vary with Hadley circulation strength?





Data Used

- V component (+ve North) of wind:

1) ERA-Interim monthly means at 240 × 121 × 37 (longitude × latitude × plevel)
2) MERRA IAU 3d assimilated state on pressure. 288 × 144 × 42 (longitude × latitude × plevel)
3) NCEP Climate Forecast System Reanalysis (CFSR) Monthly Products. 720 × 360 × 37 (longitude × latitude × plevel)

- CERES EBAF Ed2.6r TOA and SFC radiation (March 2000-November 2011).
- Woods Hole Oceanographic Institution Objectively Analyzed Air-Sea Fluxes (OAFlux) product (LH, SH).

Hadley Cell Strength and Stream Function Gradient

- Strength of the mean meridional overturning of mass for 0°-30°N for northern branch and 0°-30°S for southern branch.
- Determine Stokes stream function (Ψ) from zonal mean meridional velocity (Oort and Yienger, 1996):

$$\Psi = \frac{2\pi R cos\theta}{g} \int_0^p \bar{v} dp$$

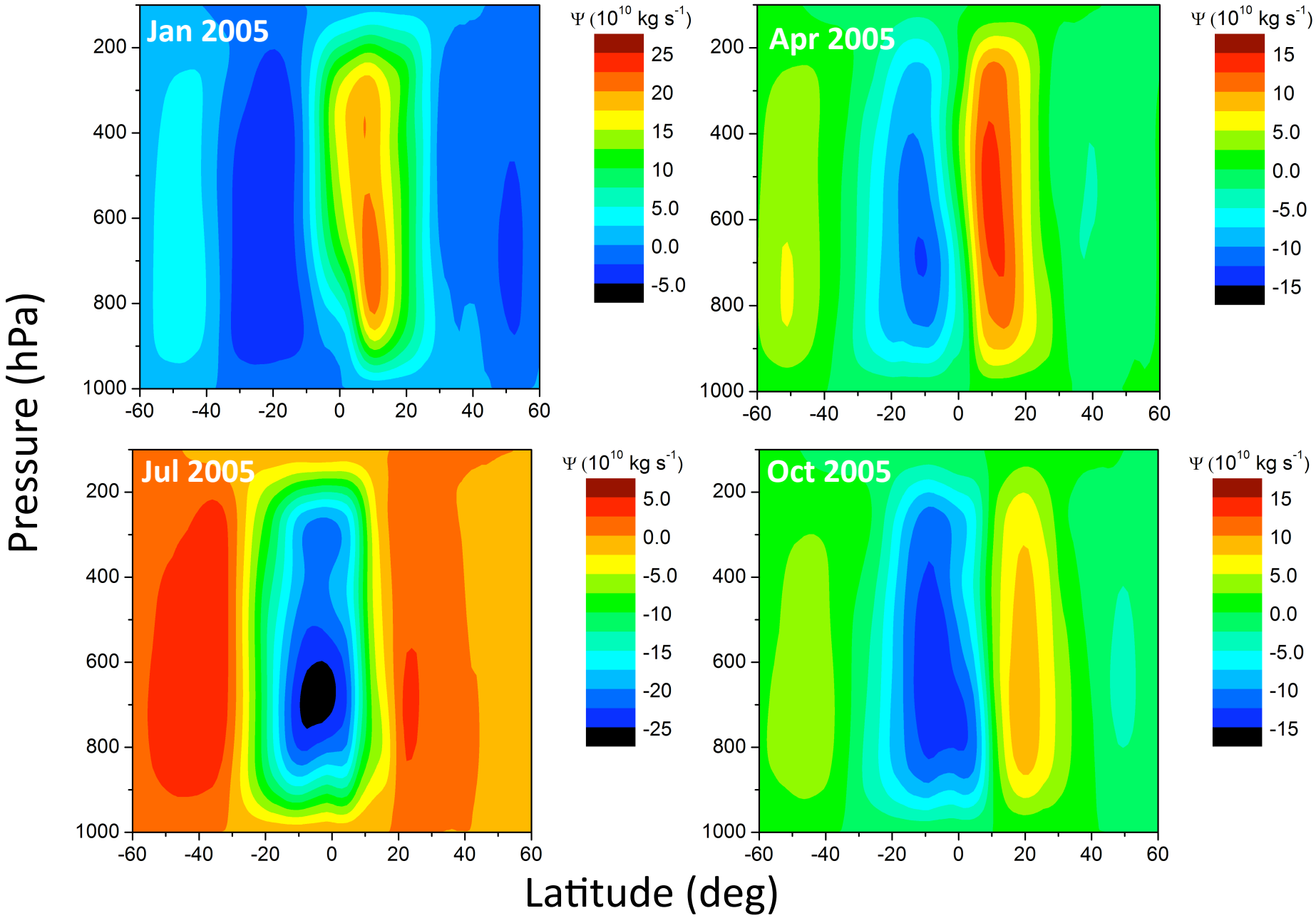
$\bar{v}$ = zonal mean meridional velocity
p=pressure
R=Radius of Earth
θ=Latitude
g=Acceleration due to gravity

- Determine Ψ_{max} for 0°-30°N and Ψ_{min} for 0°-30°S to determine strength of NH and SH branches of Hadley Cell, respectively.

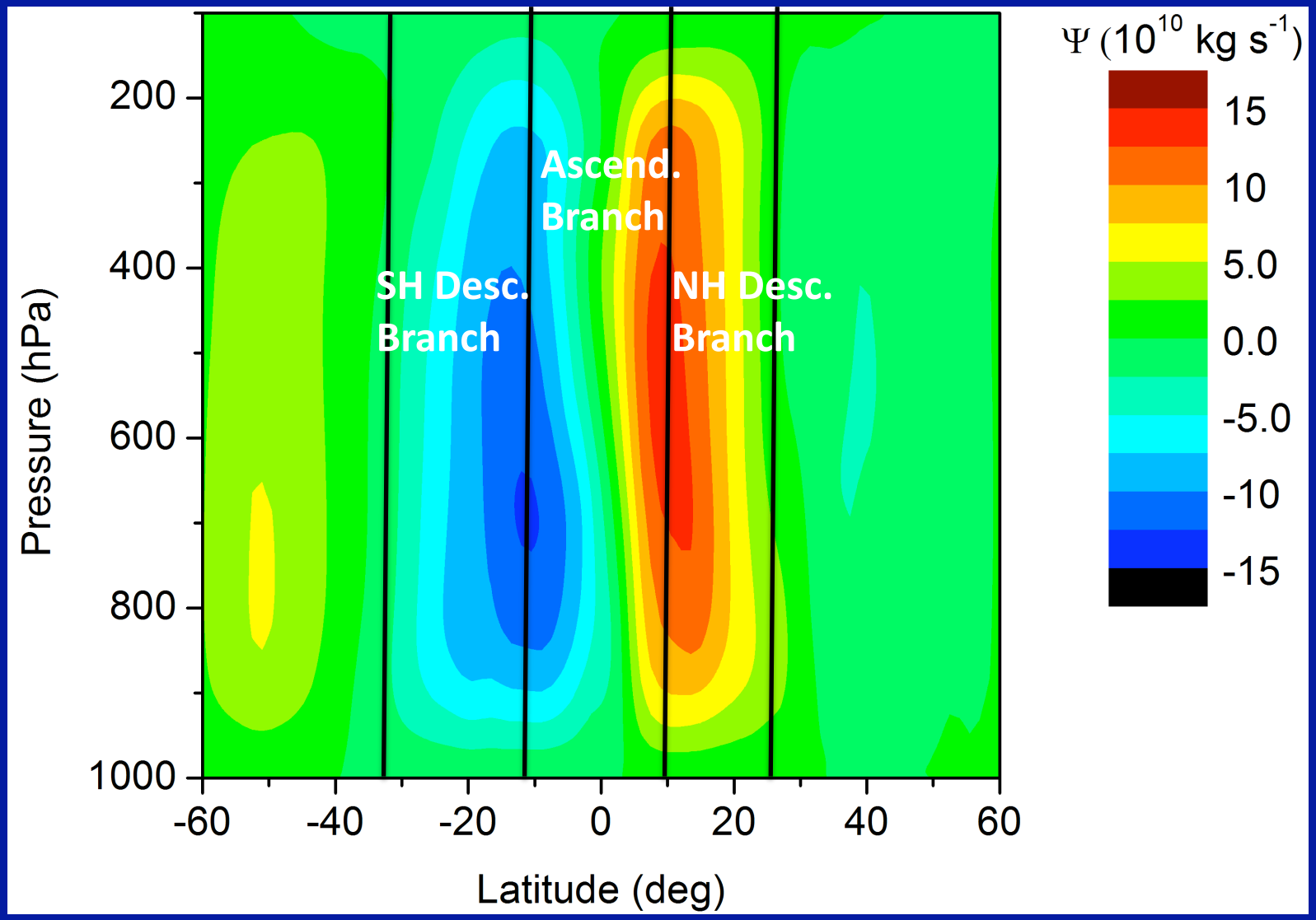
- Vertical velocity proportional to latitudinal gradient in stream function :

$$\bar{\omega} = -\frac{g}{2\pi R^2 cos\theta}\left(\frac{\partial \Psi}{\partial \theta}\right)$$

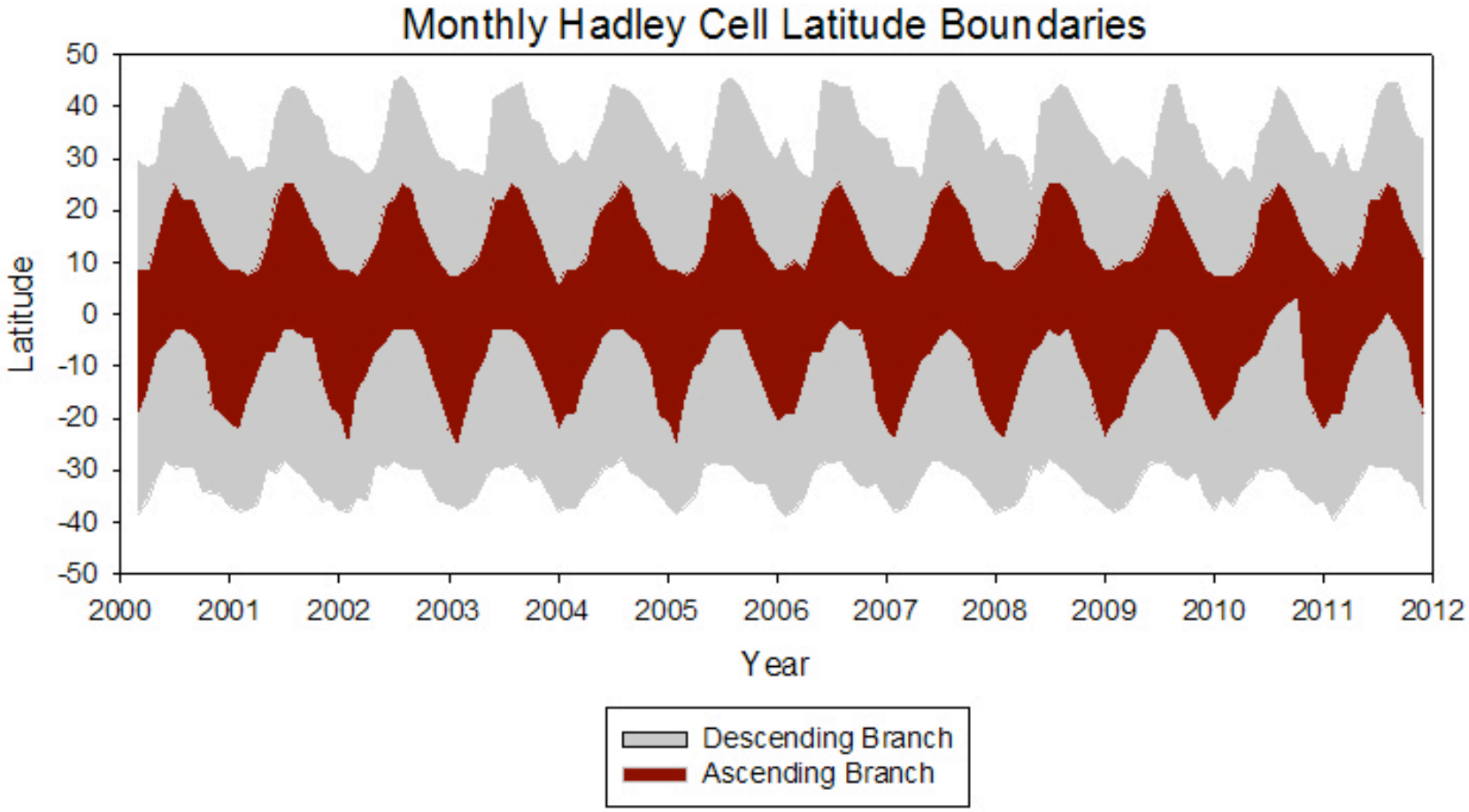
Zonal Mean Mass Streamfunction (Ψ) by Season

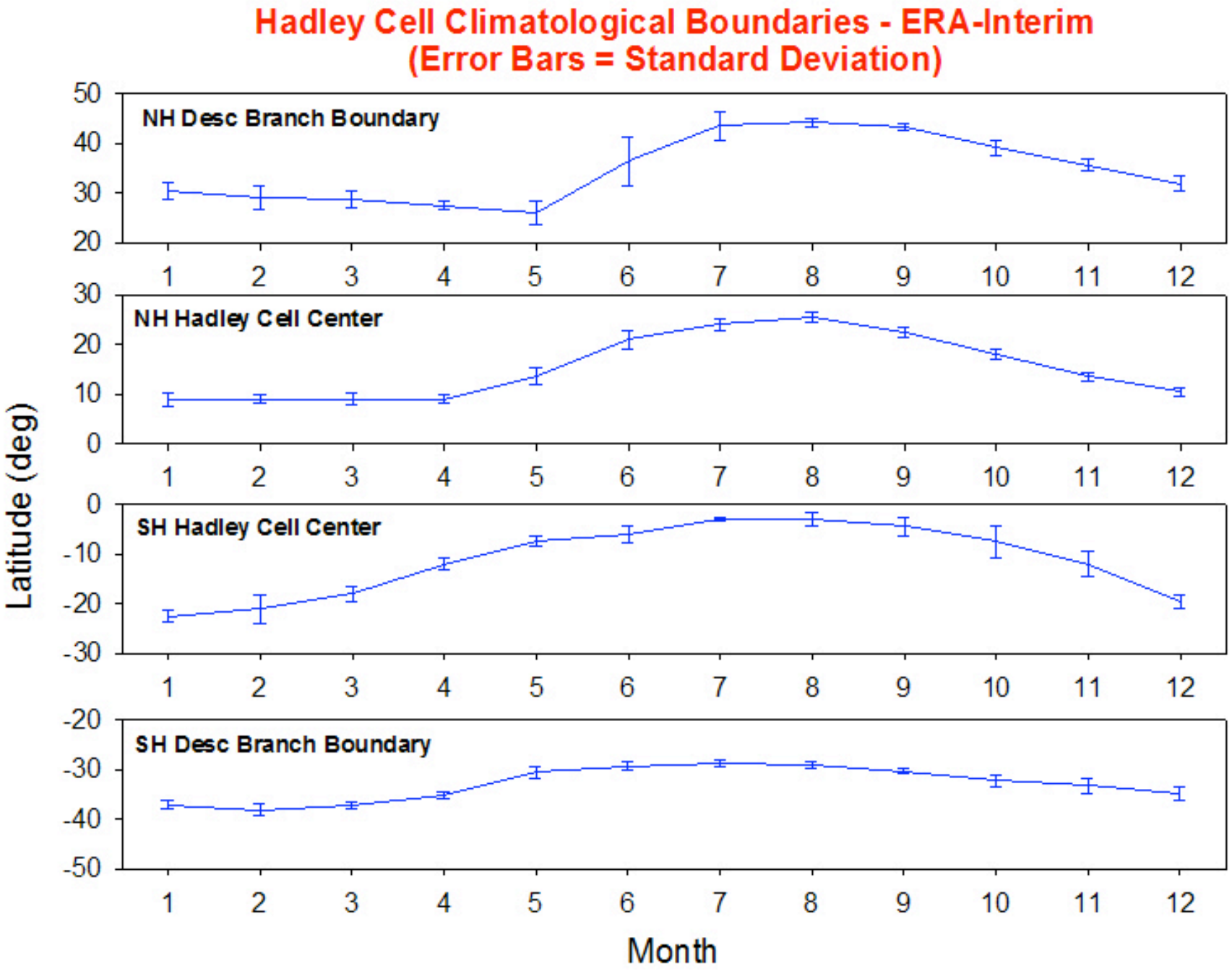


Analysis Domains: 3 Branches of Hadley Ciculation

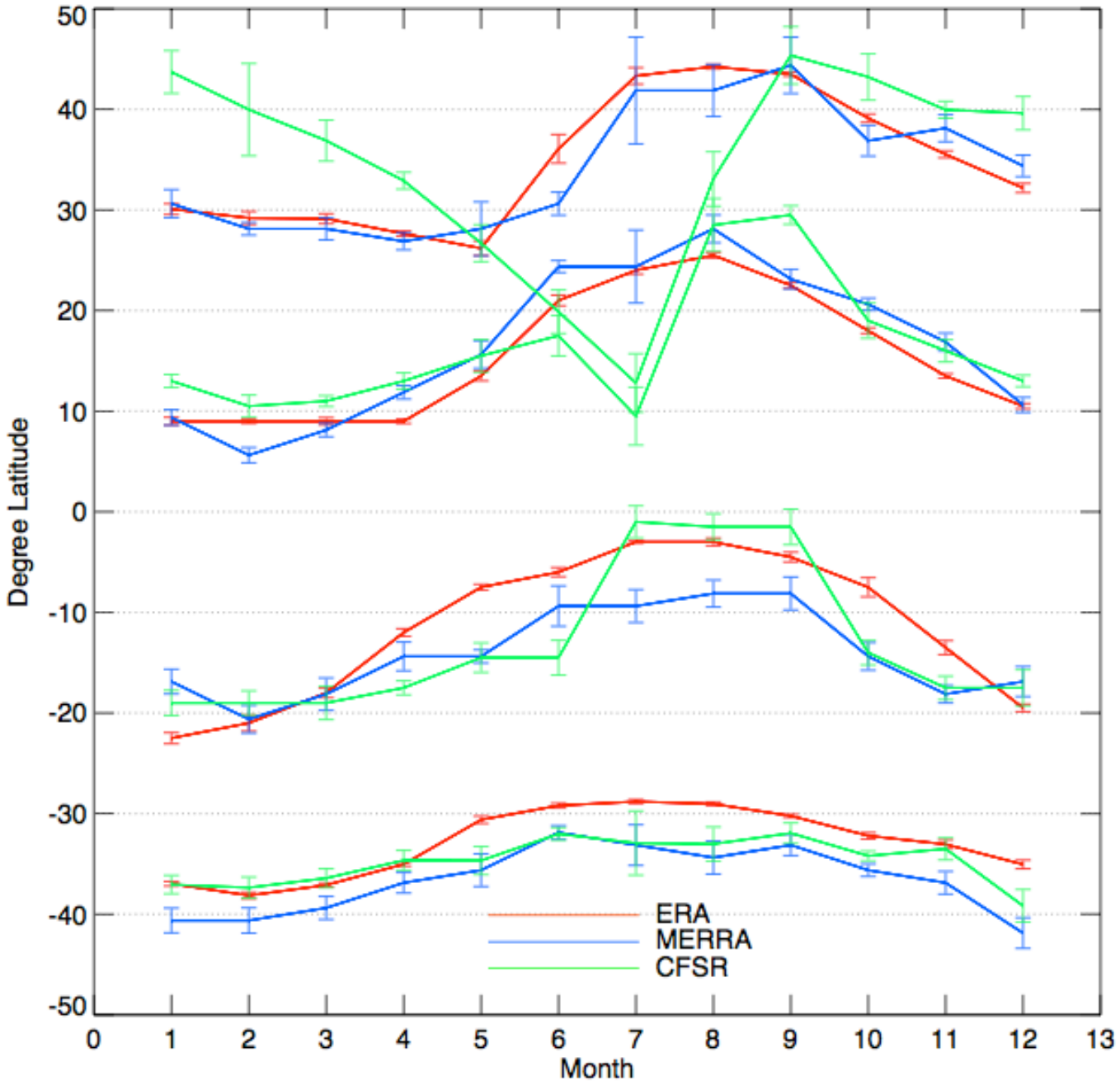


- Stratify CERES observations according to location of 3 branches of Hadley Circulation.
- The averaging domains change with season (follow large-scale circulation).

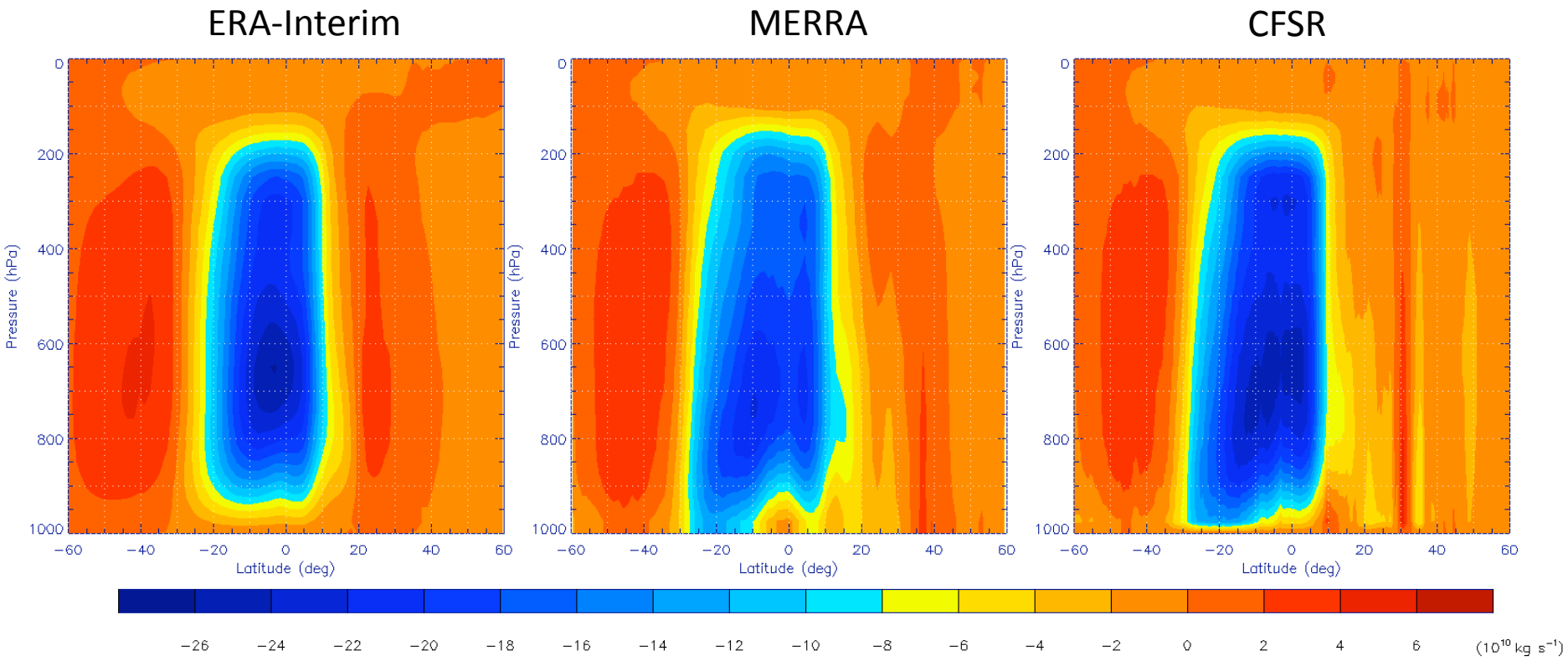

Monthly Hadley Cell Latitude Boundaries
Latitude
50
40
30
20
10
0
-10
-20
-30
-40
-50
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Year
Descending Branch
Ascending Branch


Hadley Cell Climatological Boundaries - ERA-Interim
(Error Bars = Standard Deviation)
NH Desc Branch Boundary
NH Hadley Cell Center
SH Hadley Cell Center
SH Desc Branch Boundary
Latitude (deg)
Month
50
40
30
20
10
0
-10
-20
-30
-40
-50
1
2
3
4
5
6
7
8
9
10
11
12

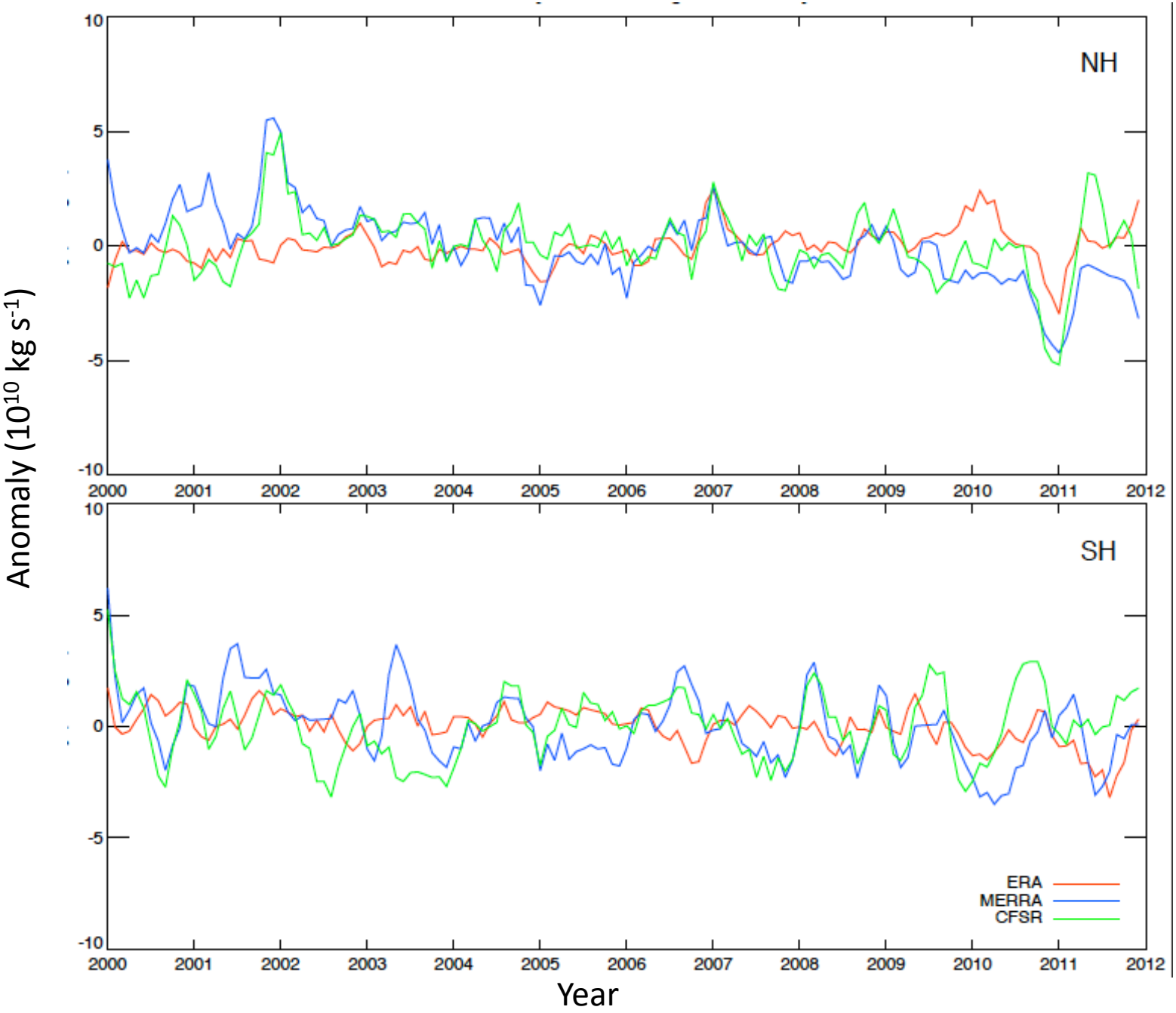
Hadley Cell Boundary Comparison: ERA-Interim, MERRA, CFSR



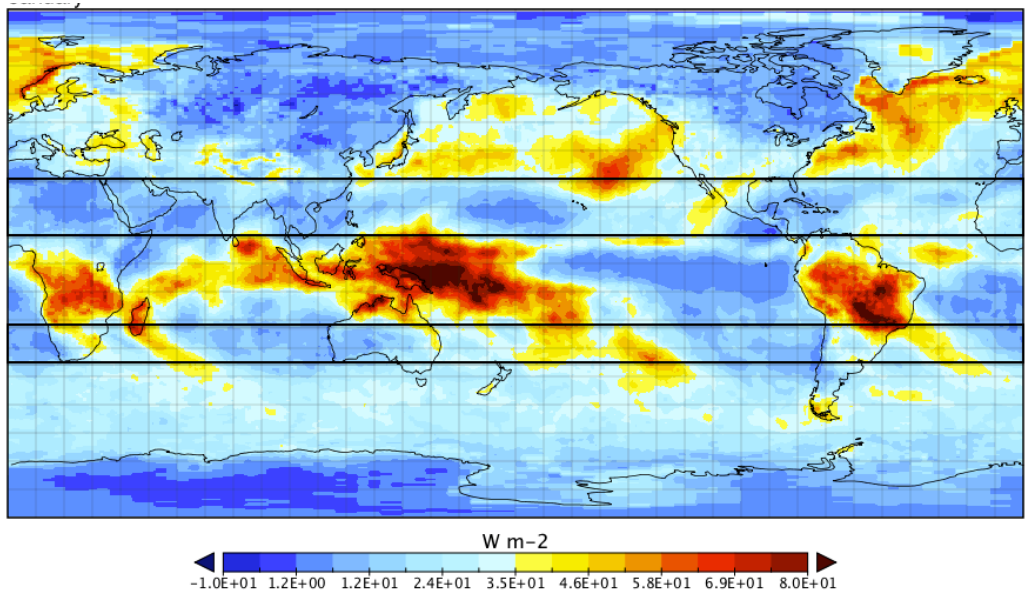
Climatological July Stream Function (10^{10} kg s^{-1})



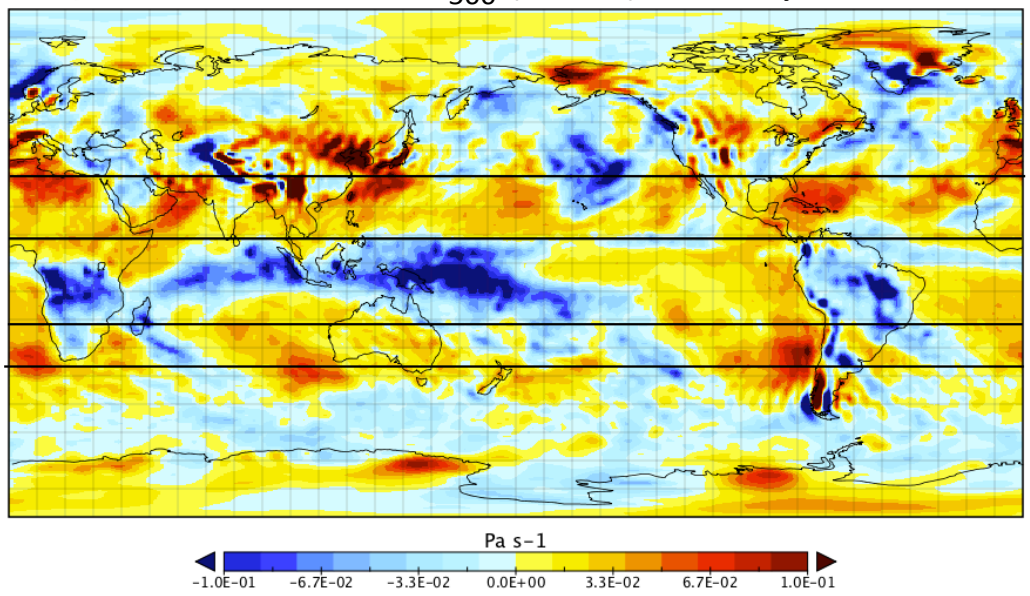
Anomaly in Hadley Strength: ERA-Interim, MERRA, CFSRA



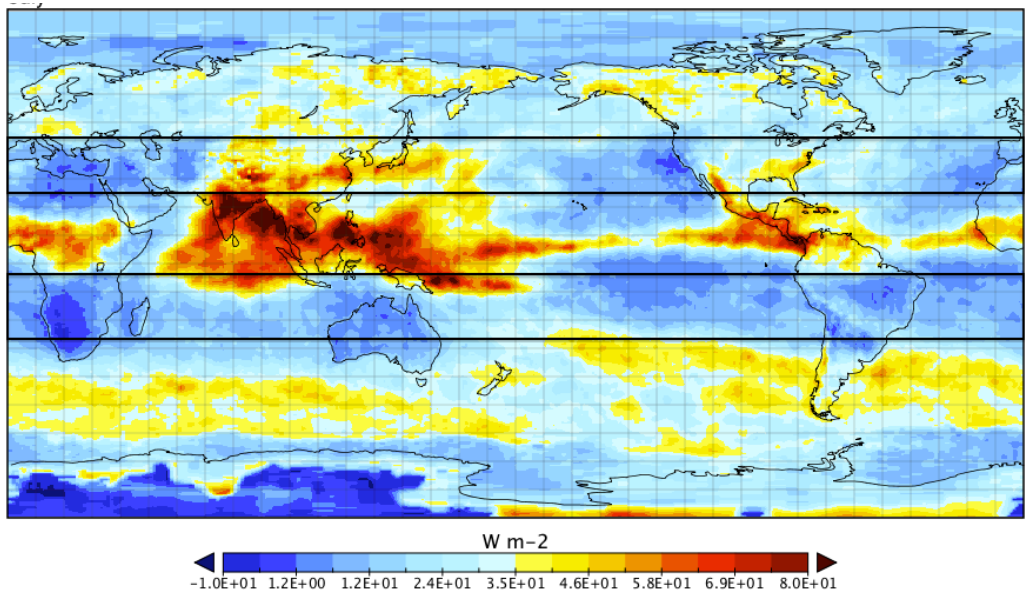
TOA LW Cloud Radiative Effect (Wm^{-2}) January 2005



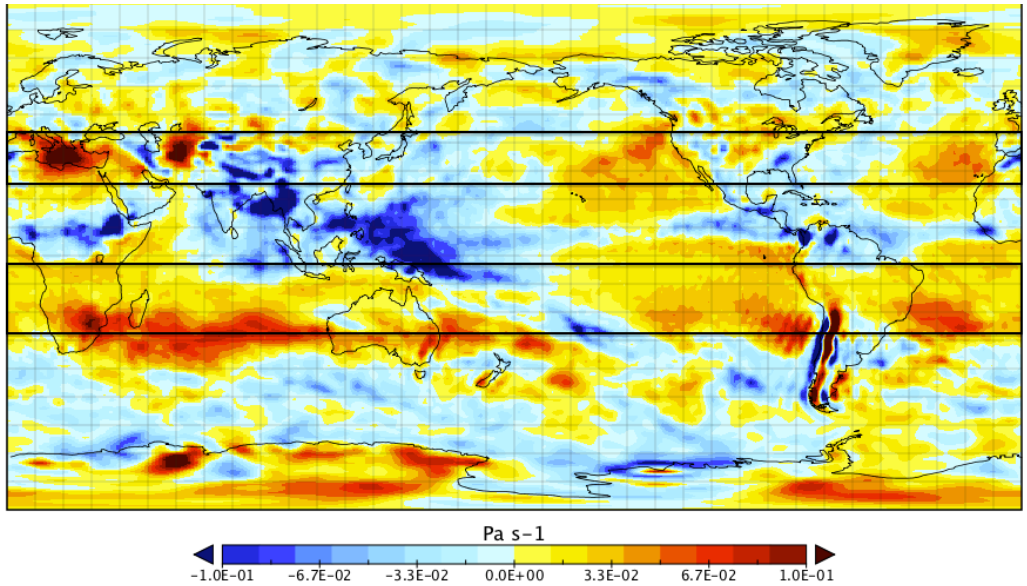
ω_{500} (Wm^{-2}) January 2005

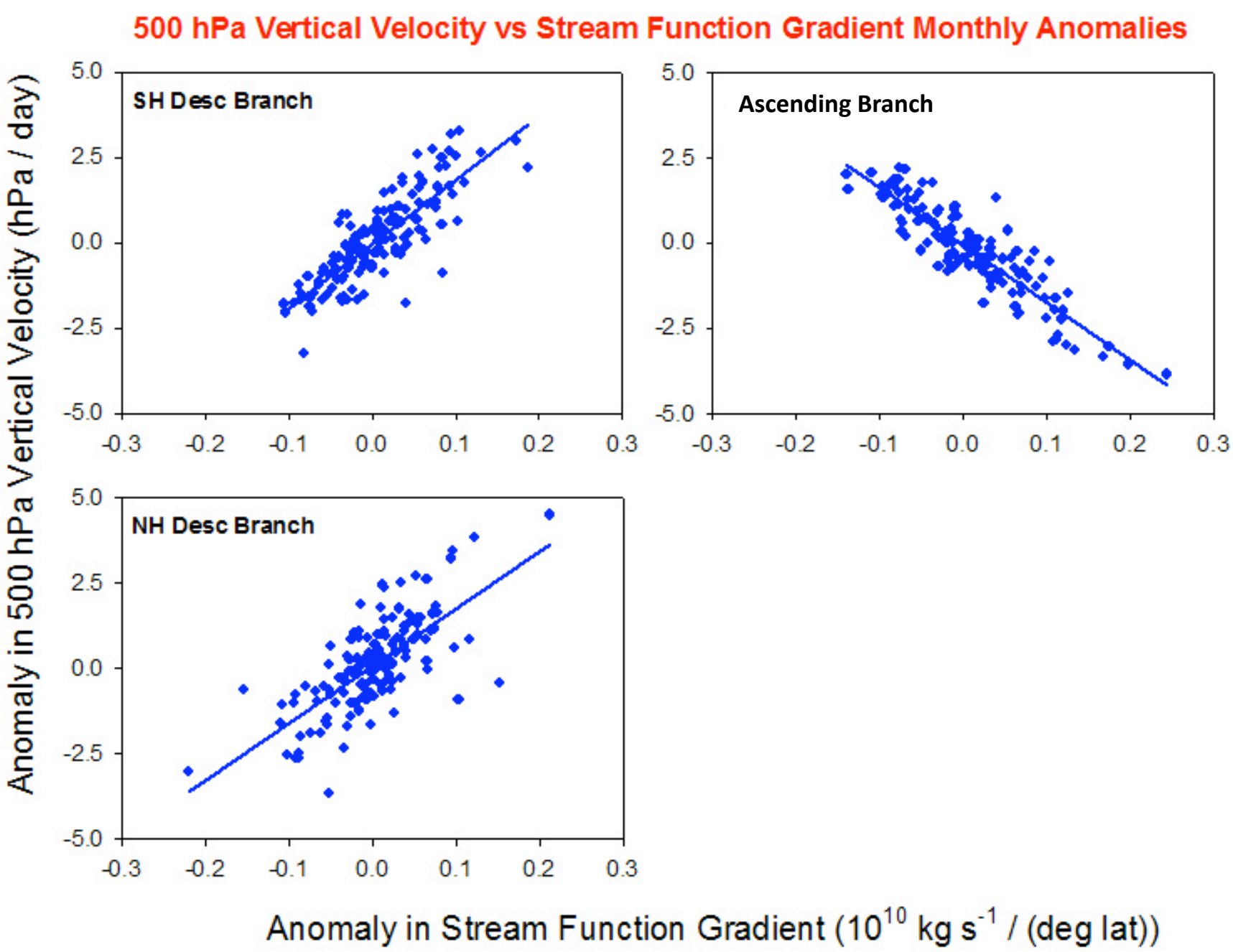


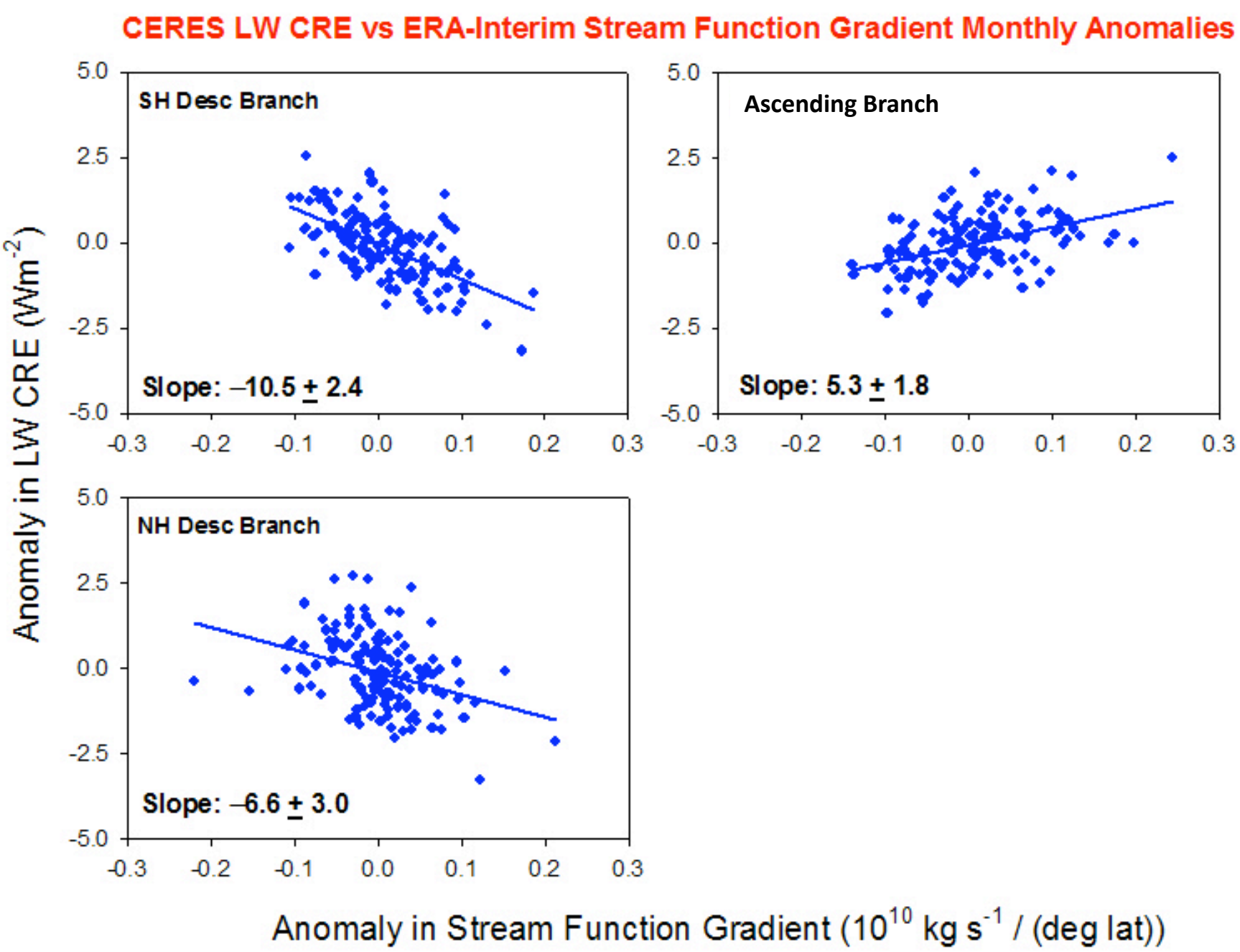
TOA LW Cloud Radiative Effect (Wm^{-2}) July 2005

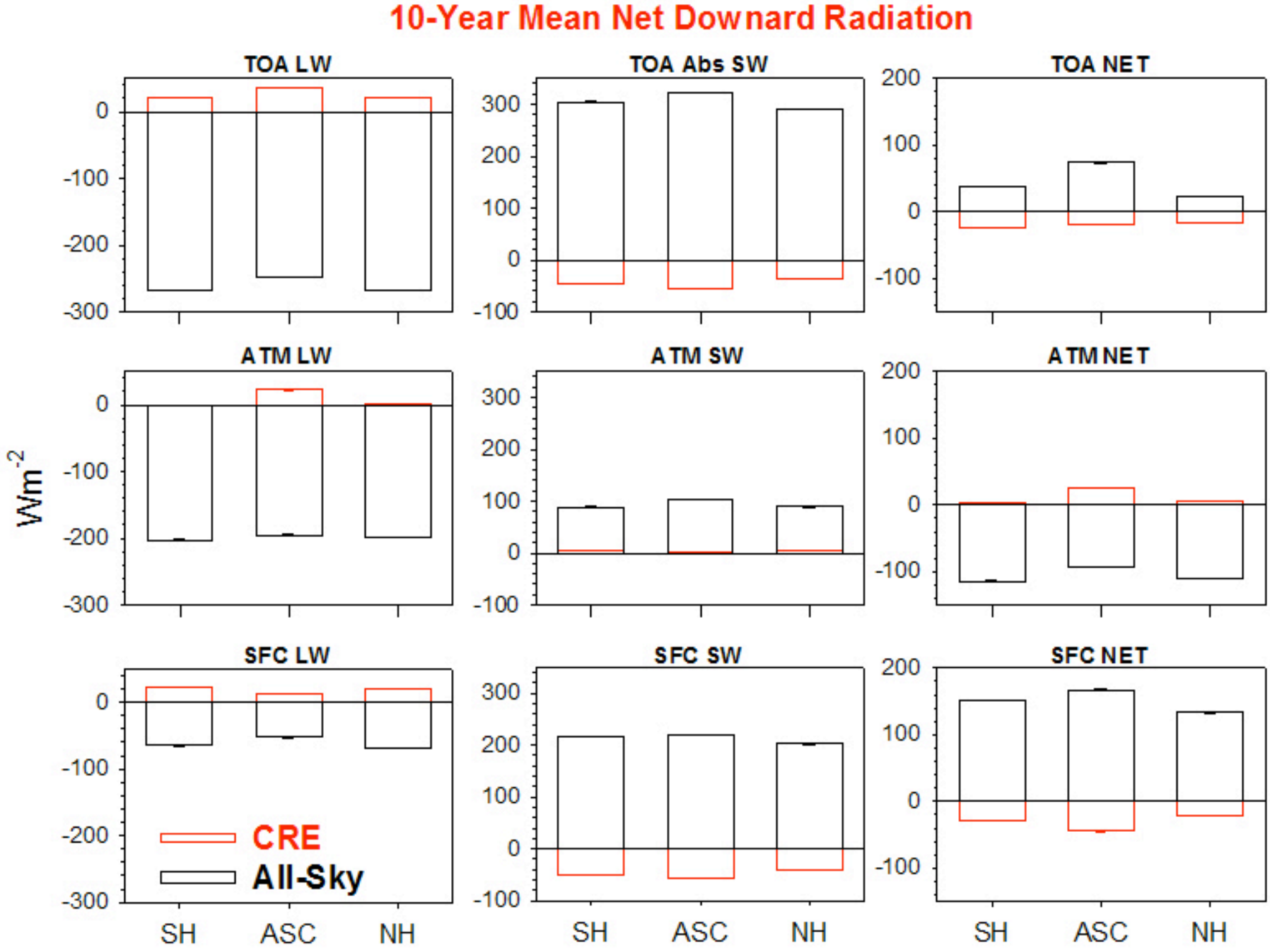


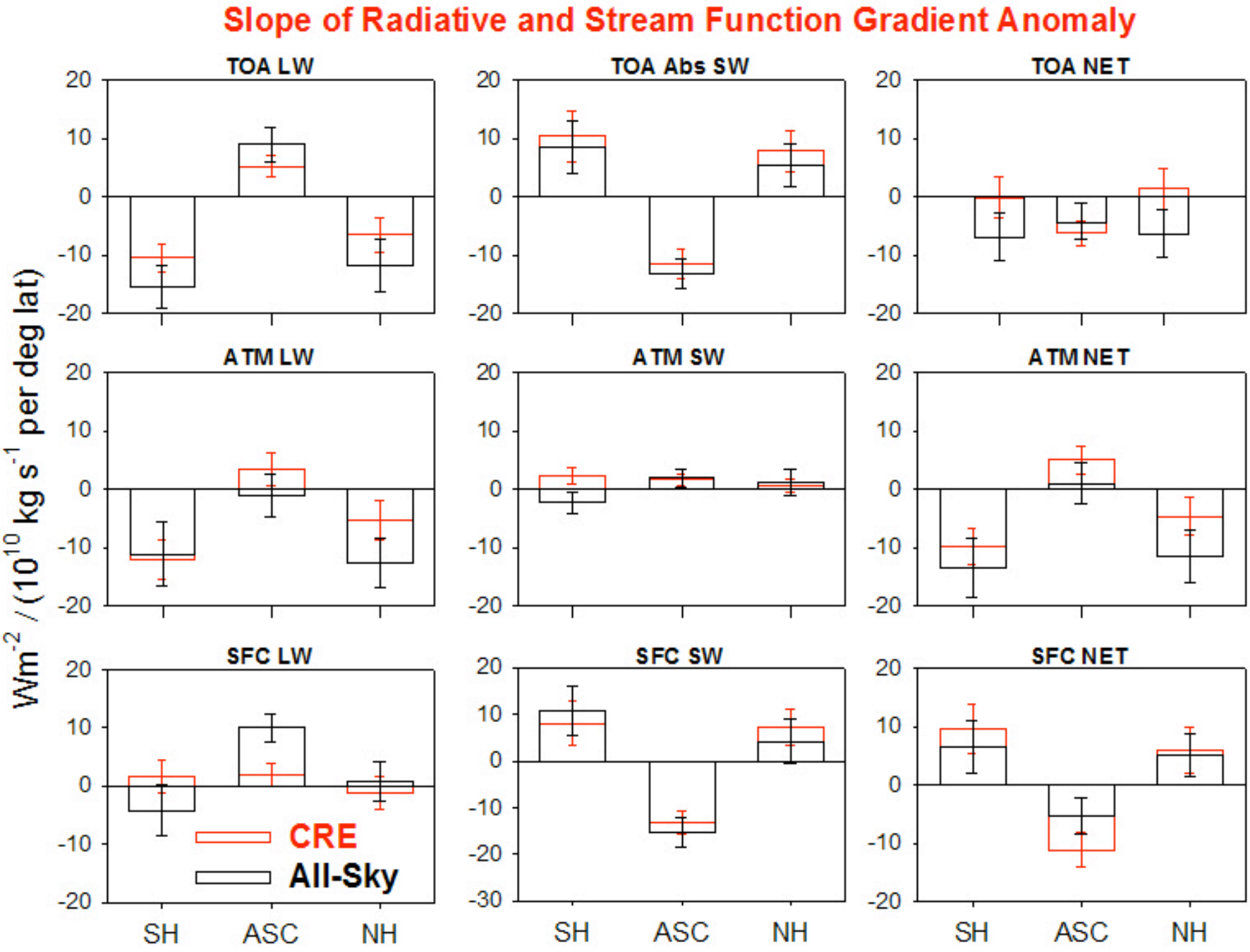
ω_{500} (Wm^{-2}) July 2005



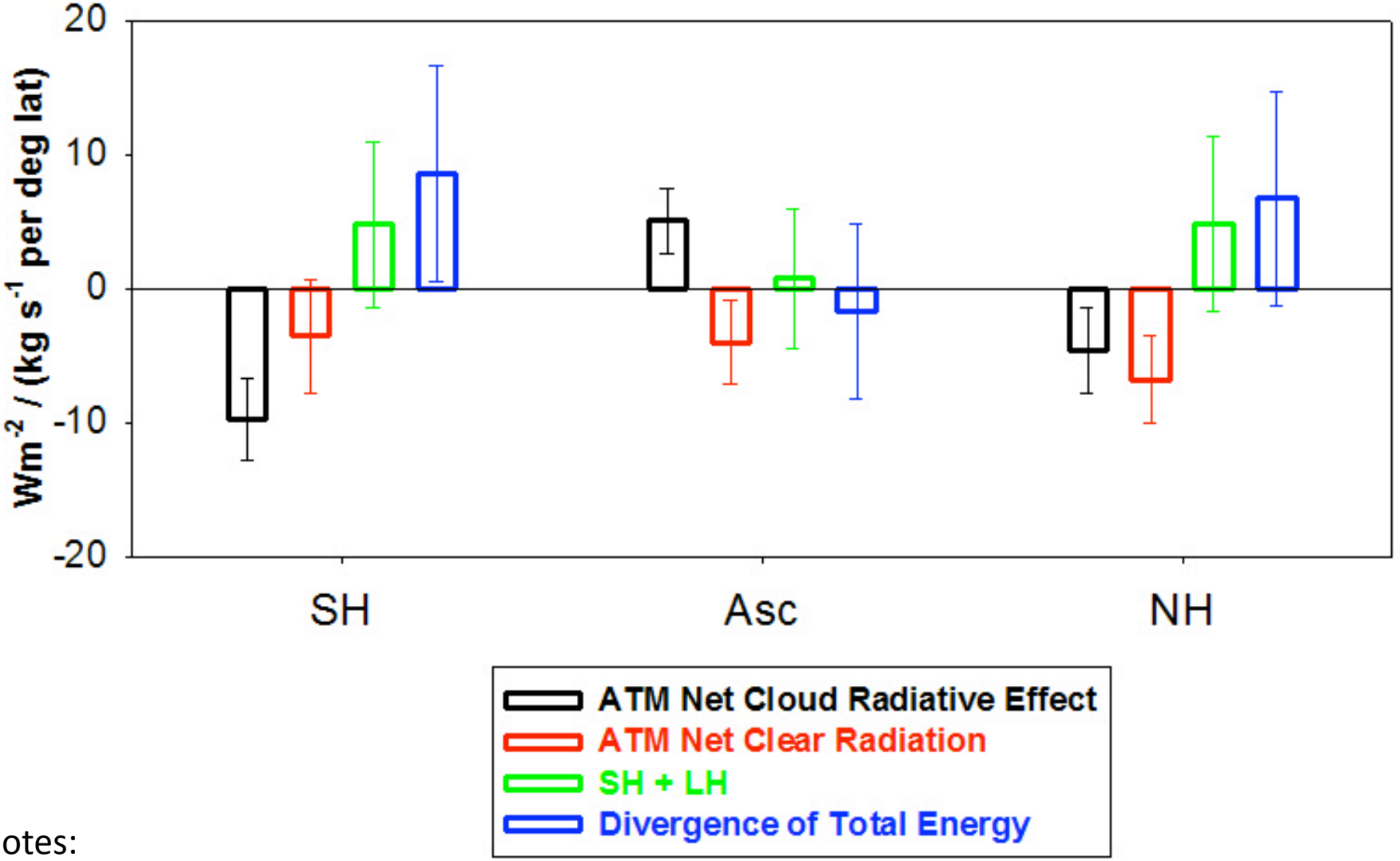

500 hPa Vertical Velocity vs Stream Function Gradient Monthly Anomalies
SH Desc Branch
Ascending Branch
NH Desc Branch
Anomaly in 500 hPa Vertical Velocity (hPa / day)
Anomaly in Stream Function Gradient (10^10 kg s^-1 / (deg lat))
5.0
2.5
0.0
-2.5
-5.0
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3


CERES LW CRE vs ERA-Interim Stream Function Gradient Monthly Anomalies
SH Desc Branch
Slope: –10.5 ± 2.4
Ascending Branch
Slope: 5.3 ± 1.8
NH Desc Branch
Slope: –6.6 ± 3.0
Anomaly in LW CRE (Wm-2)
Anomaly in Stream Function Gradient (10^10 kg s^-1 / (deg lat))
5.0
2.5
0.0
-2.5
-5.0
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3


10-Year Mean Net Downard Radiation
TOA LW
TOA Abs SW
TOA NET
ATM LW
ATM SW
ATM NET
SFC LW
SFC SW
SFC NET
Wm-2
CRE
All-Sky
SH
ASC
NH


Slope of Radiative and Stream Function Gradient Anomaly
TOA LW
TOA Abs SW
TOA NET
ATM LW
ATM SW
ATM NET
SFC LW
SFC SW
SFC NET
Wm-2 / (10^10 kg s-1 per deg lat)
CRE
All-Sky
SH
ASC
NH

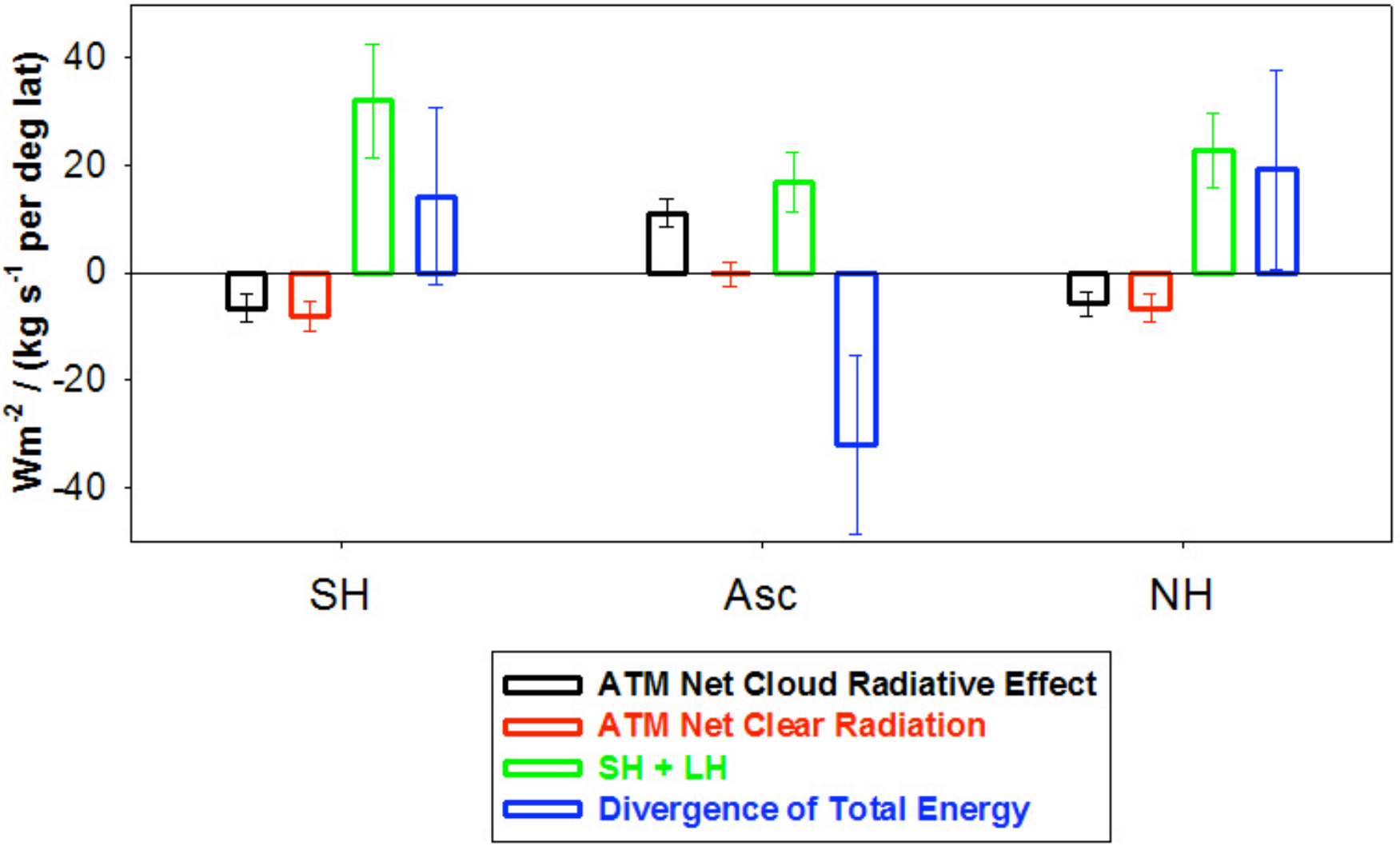
Within-Atmosphere Sensitivity to Variations in Stream Function Gradient



Notes:

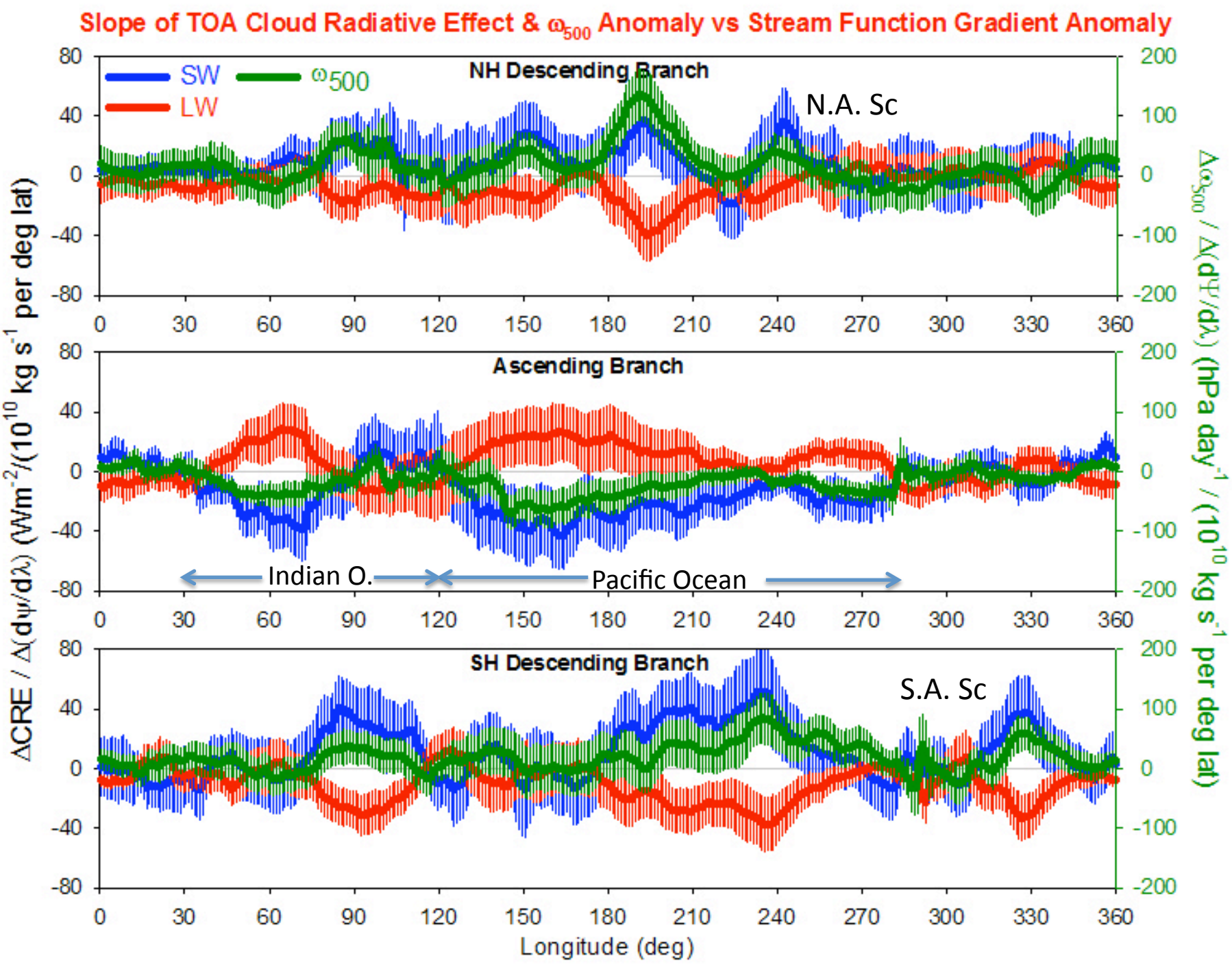
- ATM fluxes inferred from CERES EBAF (TOA & SFC)
- SH + LW determine from WHOI OAFlux product (ocean only)
- Divergence of total energy computed as residual: R_{CLR} + CRE + SH + LH – Div_E_T = 0

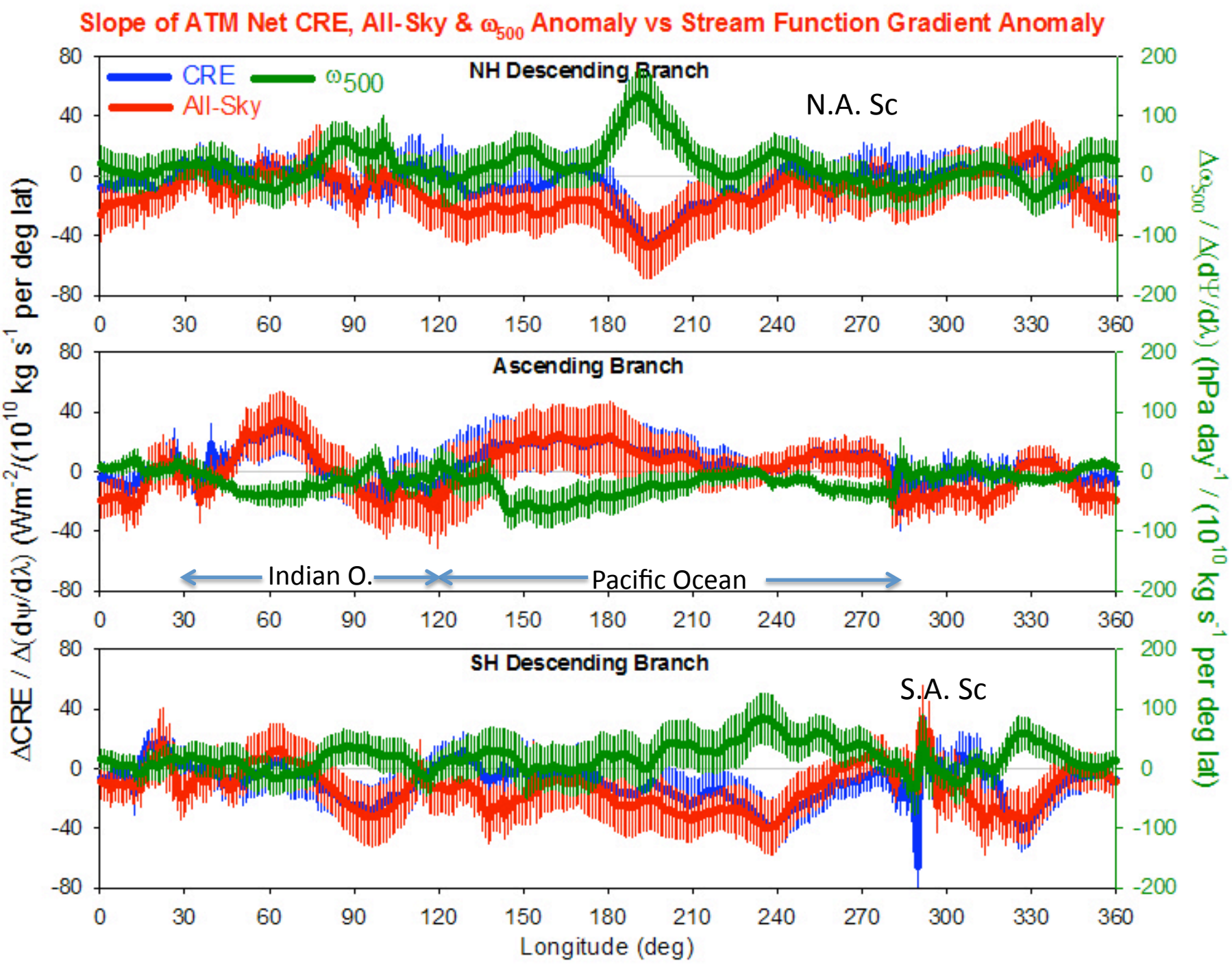
Within-Atmosphere Sensitivity to Variations in Stream Function Gradient (ERA-Interim)



Notes:

- All Terms : R_{CLR}, CRE, SH, LH and $-Div_E_T$ from ERA-Interim


Slope of TOA Cloud Radiative Effect & ω500 Anomaly vs Stream Function Gradient Anomaly
SW
LW
ω500
NH Descending Branch
N.A. Sc
Ascending Branch
Indian O.
Pacific Ocean
SH Descending Branch
S.A. Sc
ΔCRE / Δ(dψ/dλ) (Wm-2/(10^10 kg s-1 per deg lat)
Δω500 / Δ(dΨ/dλ) (hPa day-1 / (10^10 kg s-1 per deg lat)
Longitude (deg)


Slope of ATM Net CRE, All-Sky & ω500 Anomaly vs Stream Function Gradient Anomaly
CRE
ω500
All-Sky
NH Descending Branch
N.A. Sc
Ascending Branch
Indian O.
Pacific Ocean
SH Descending Branch
S.A. Sc
ΔCRE / Δ(dψ/dλ) (Wm-2/(10^10 kg s-1 per deg lat)
Δω500 / Δ(dΨ/dλ) (hPa day-1 / (10^10 kg s-1 per deg lat)
Longitude (deg)

Conclusions

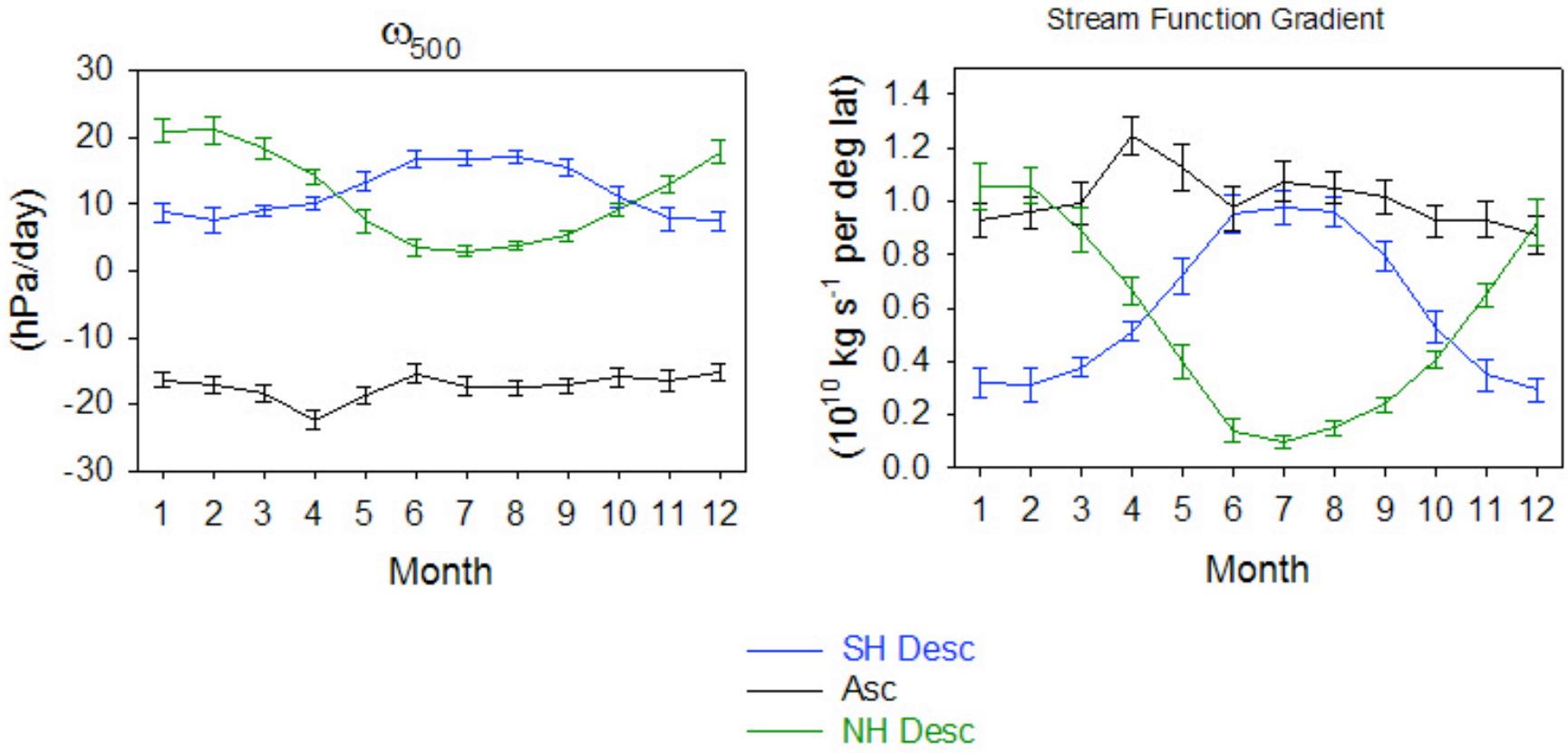
- CERES data sorted according to 3 “branches” of Hadley circulation:
  - Spatial patterns in CERES LW CRE consistent with ω_{500} in each branch.
  - Convection mainly confined to ascending branch, subsidence mainly confined to descending branches.
  - All 3 regions vary with season in a coherent manner.
  - Interannual variations in CERES radiation data show expected sensitivity to variations in stream function gradient in all 3 branches of Hadley cell.

- In response to intensification in Hadley circulation:
  - Increase in TOA & SFC LW radiative warming and SW cooling in ascending branches of Hadley circulation. Opposite is true in descending branches.
  - Net effect of radiation in ATM is to cool in descending branches. Small radiative impact in ascending branch due to opposing changes in clear and cloudy regions.
  - SH+LH and divergence of total energy compensate for radiative cooling in descending branches.

Conclusions

- Longitudinal dependence of radiation—stream function gradient anomaly regressions suggest strong cloud type dependence (likely trade cumulus in subsidence regions; high cloud in ascending region).

Future work:

- Use new CERES ISCCP D2 data product to identify cloud types that co-vary with circulation strength.
- Compare with climate models.

Climatological Mean Vertical Velocity and Stream Function Gradient
(Error Bars = Standard Deviation)