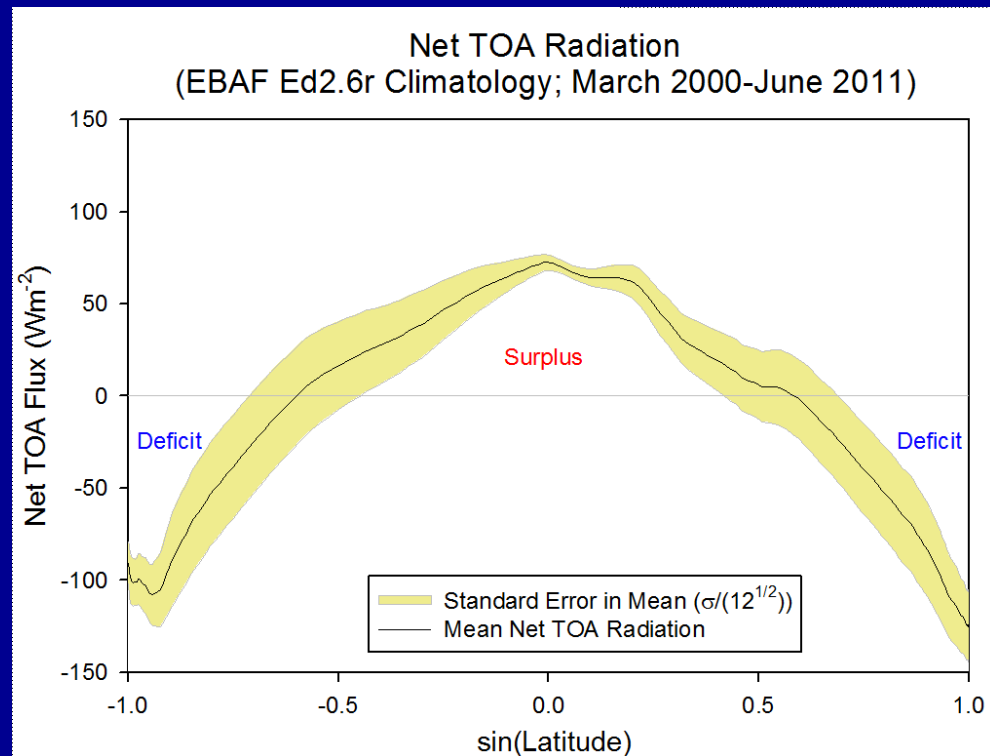
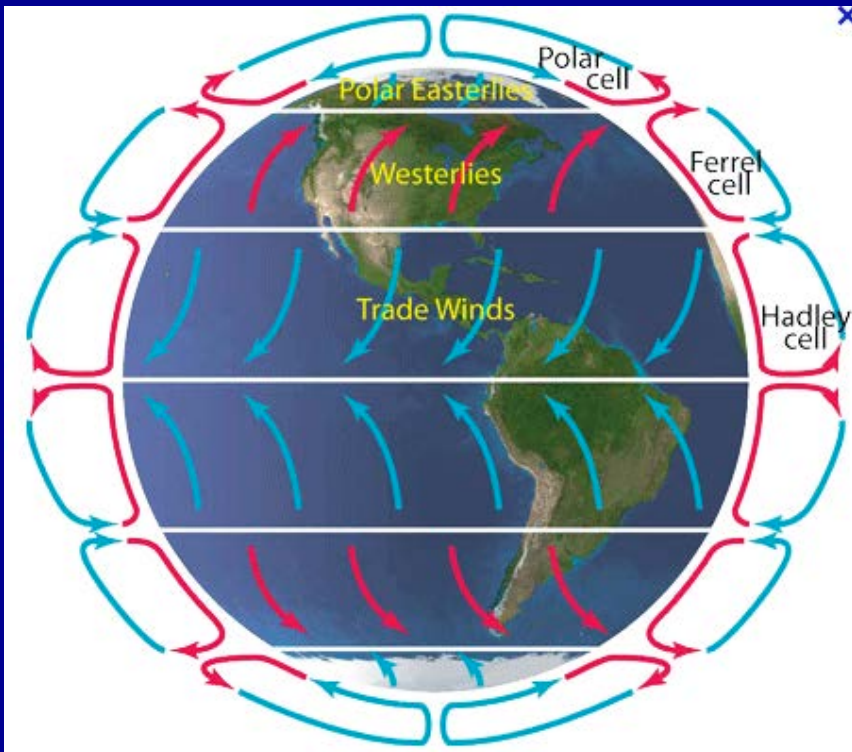


# Cloud Radiative Response to Intensification of Hadley Circulation

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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.
- How has the strength of the Hadley circulation change during the past decade?
- How did clouds and radiation respond to the circulation changes?



## Data Used

- ERA-Interim V component (+ve North) of wind at 37 pressure levels:  
1000, 975, 950, 925, 900, 875, 850, 825, 800, 775, 750, 700, 650, 600,  
550, 500, 450, 400, 350, 300, 250, 225, 200, 175, 150, 125, 100, 70, 50,  
30, 20, 10, 7, 5, 3, 2, 1 hPa.
- ERA-Interim TOA Fluxes (Synoptic Monthly Mean product).
- CERES EBAF Ed2.6r TOA radiation (March 2000-June 2011).
- SSF1deg-lite Ed2.6 cloud properties (March 2000-June 2011).

## 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 ( $\Psi$ ) 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

$\theta$ =Latitude

$g$ =Acceleration due to gravity

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

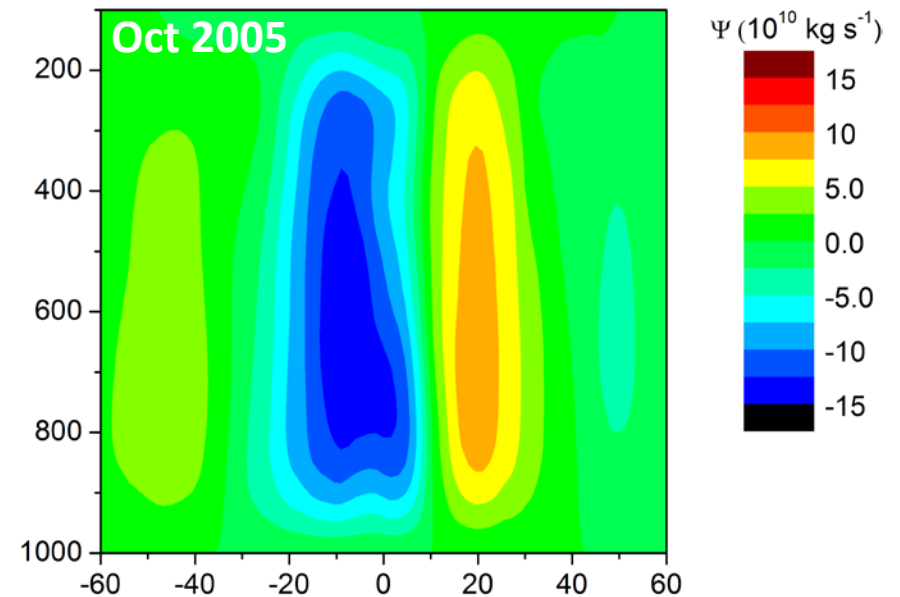
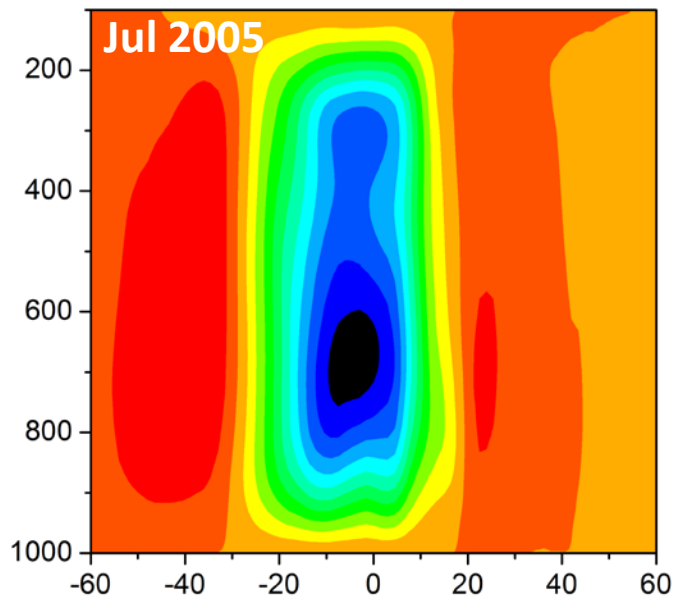
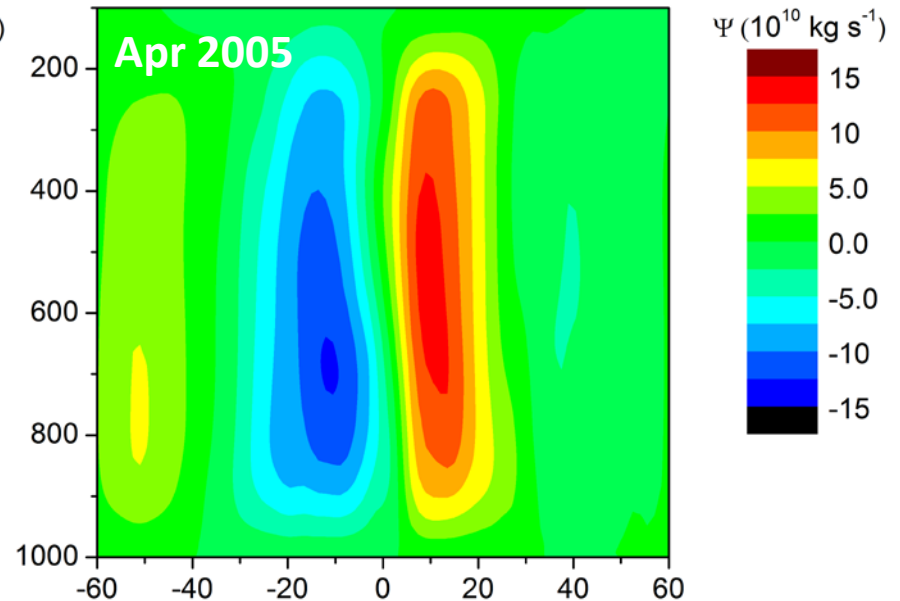
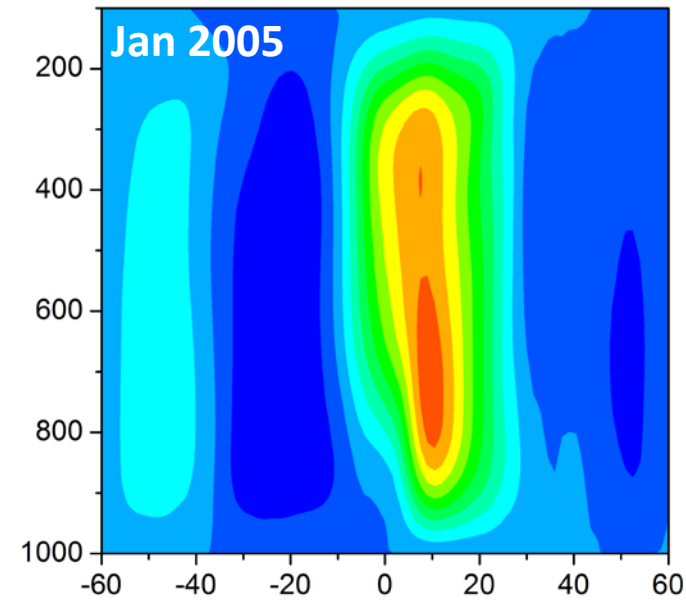
- Vertical velocity proportional to latitudinal gradient in stream function :

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



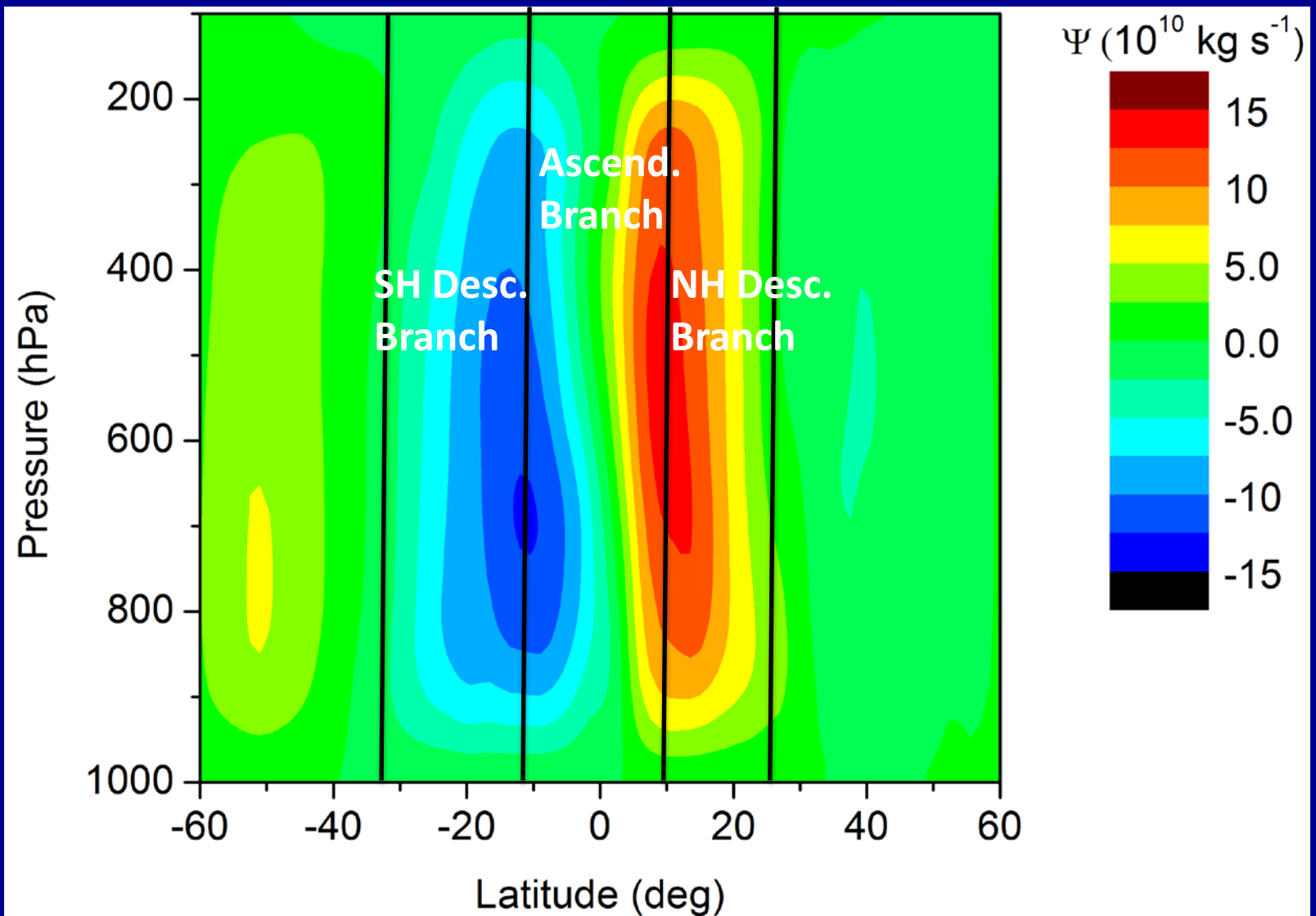
# Zonal Mean Mass Streamfunction ( $\Psi$ ) by Season

Pressure (hPa)

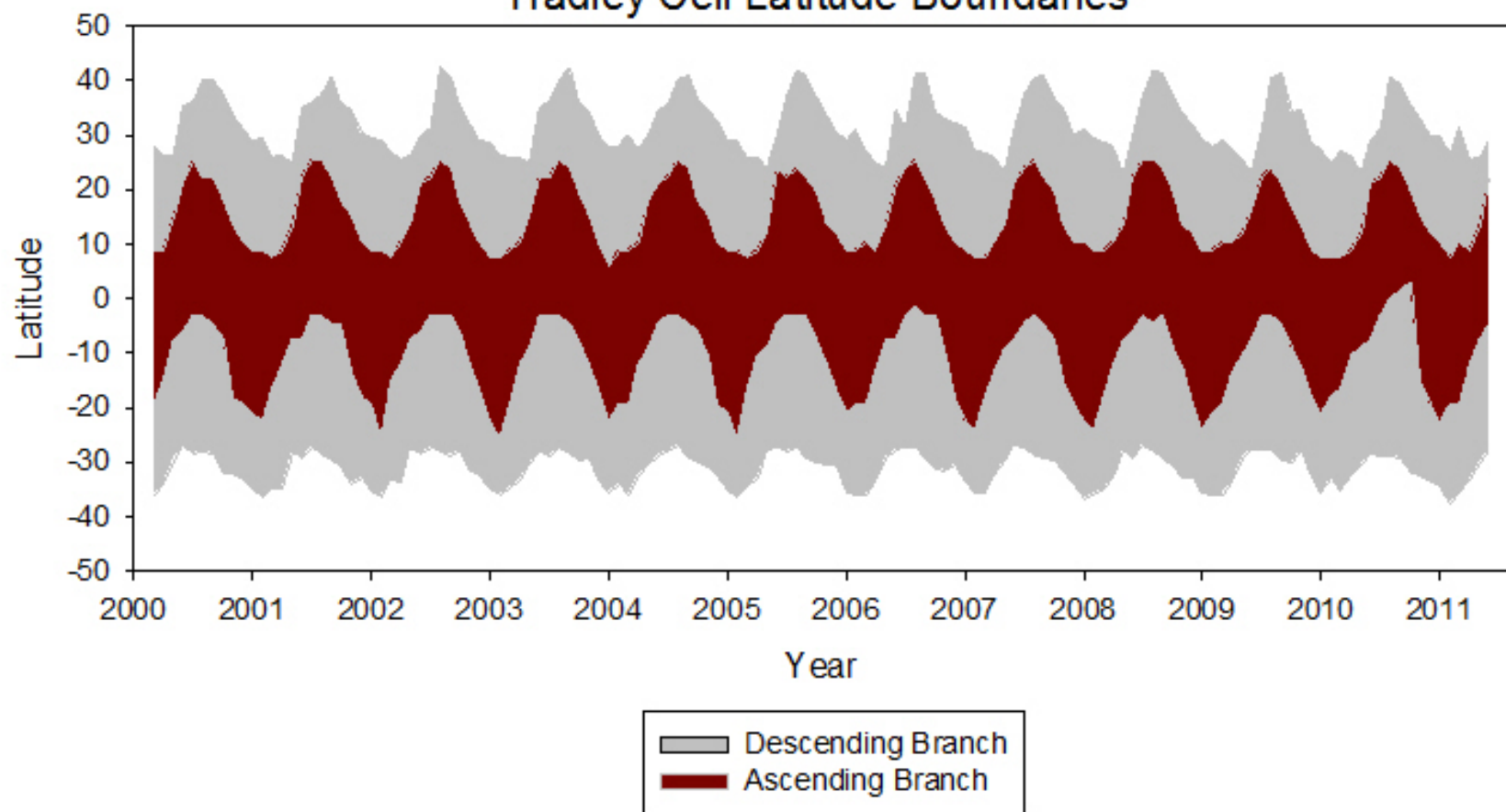


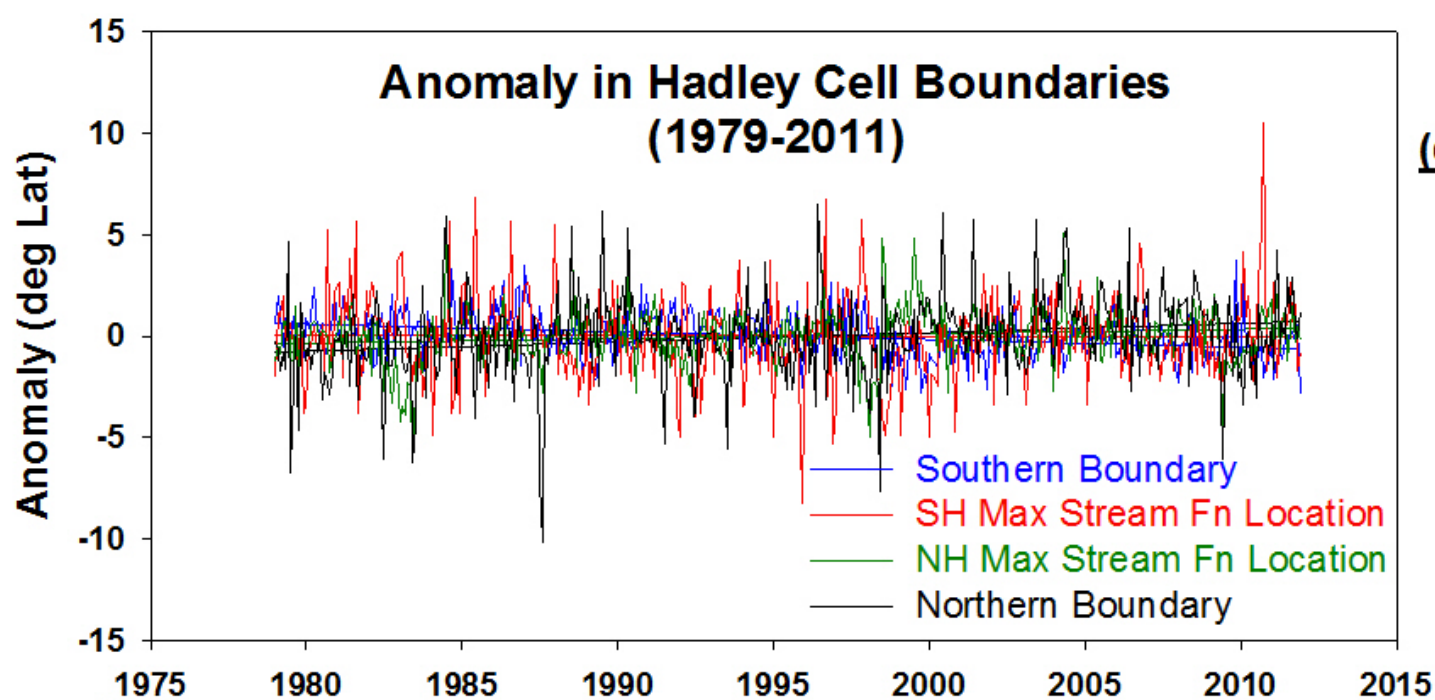
Latitude (deg)

# Defining Branches of Hadley Cell



## Hadley Cell Latitude Boundaries





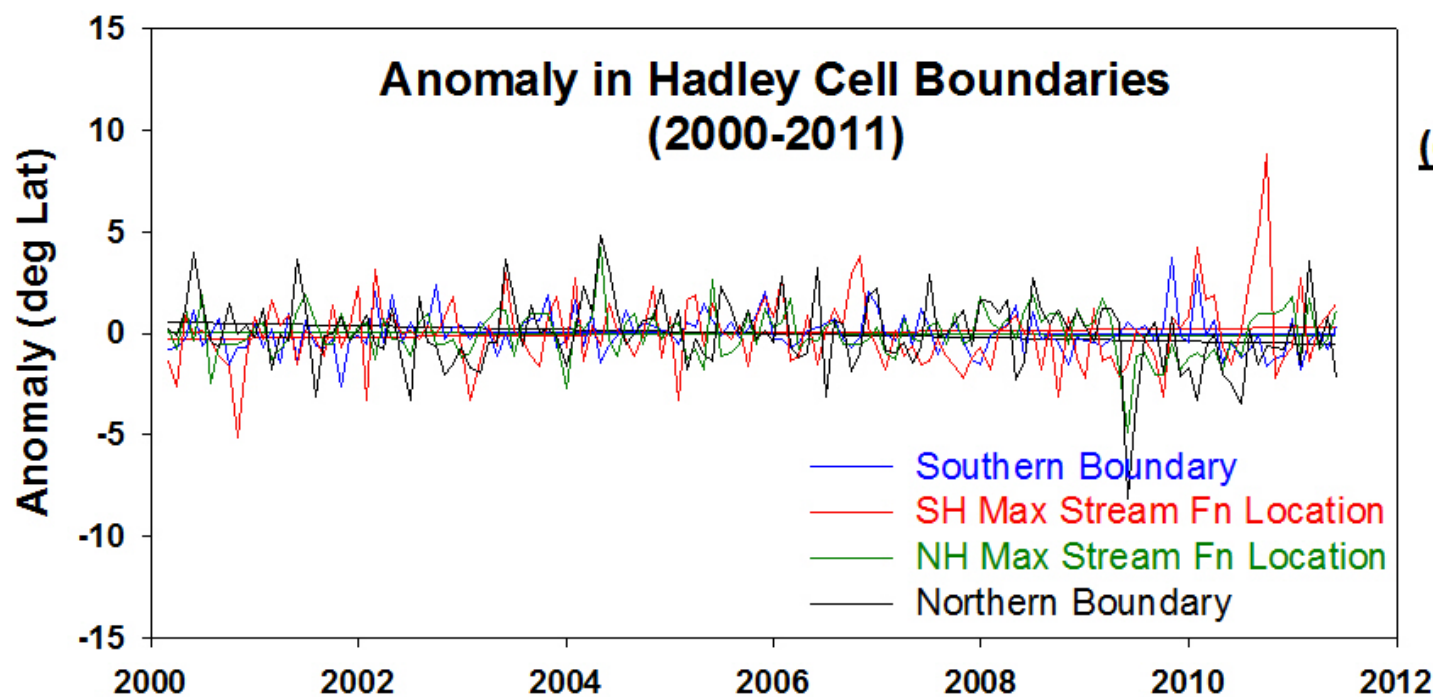
**Slope  
(deg per decade)**

**$-0.36 \pm 0.14$**

**$-0.013 \pm 0.26$**

**$0.22 \pm 0.21$**

**$0.46 \pm 0.26$**



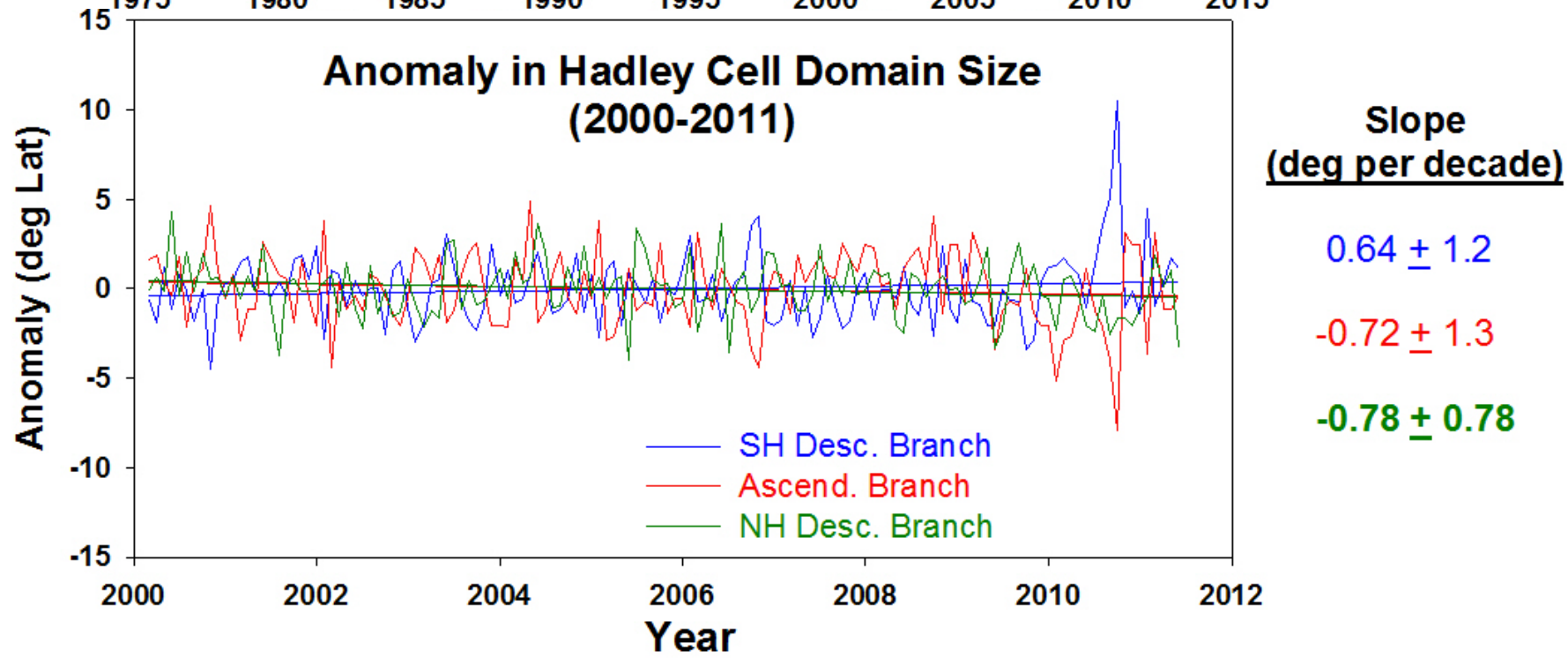
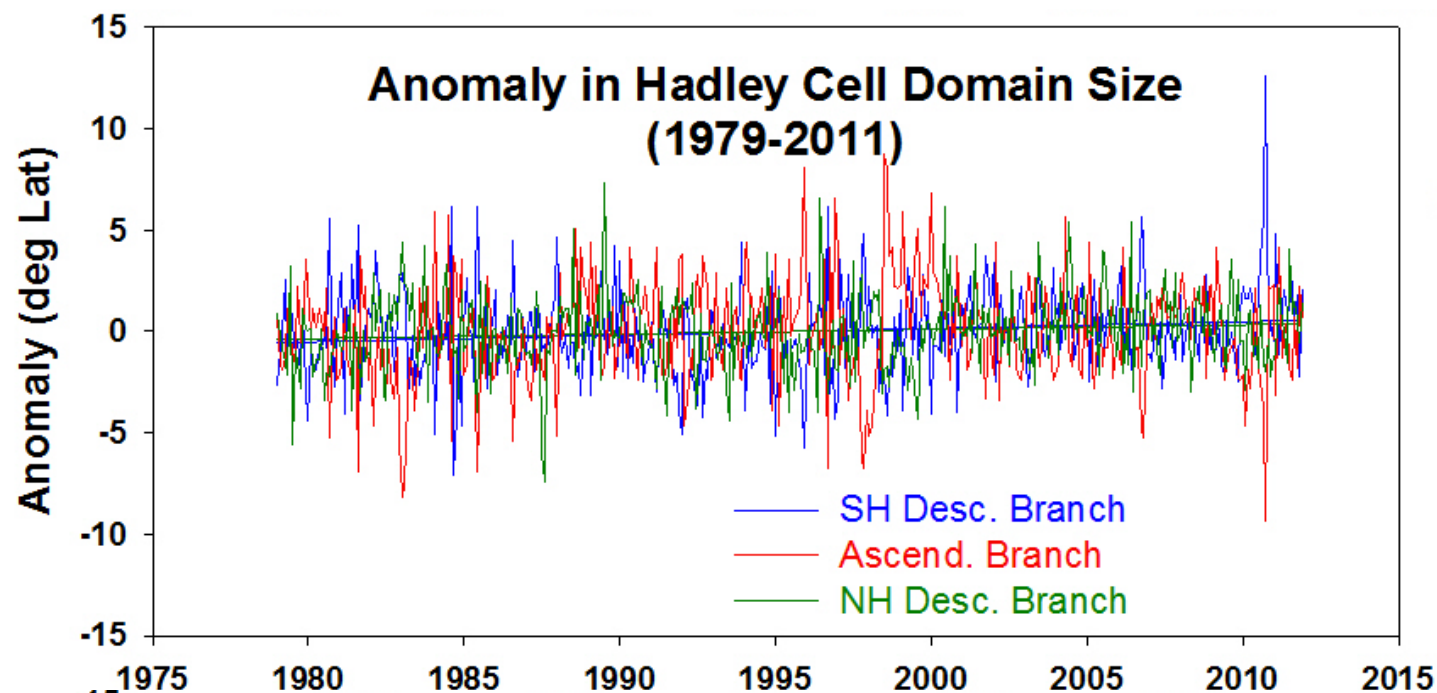
**Slope  
(deg per decade)**

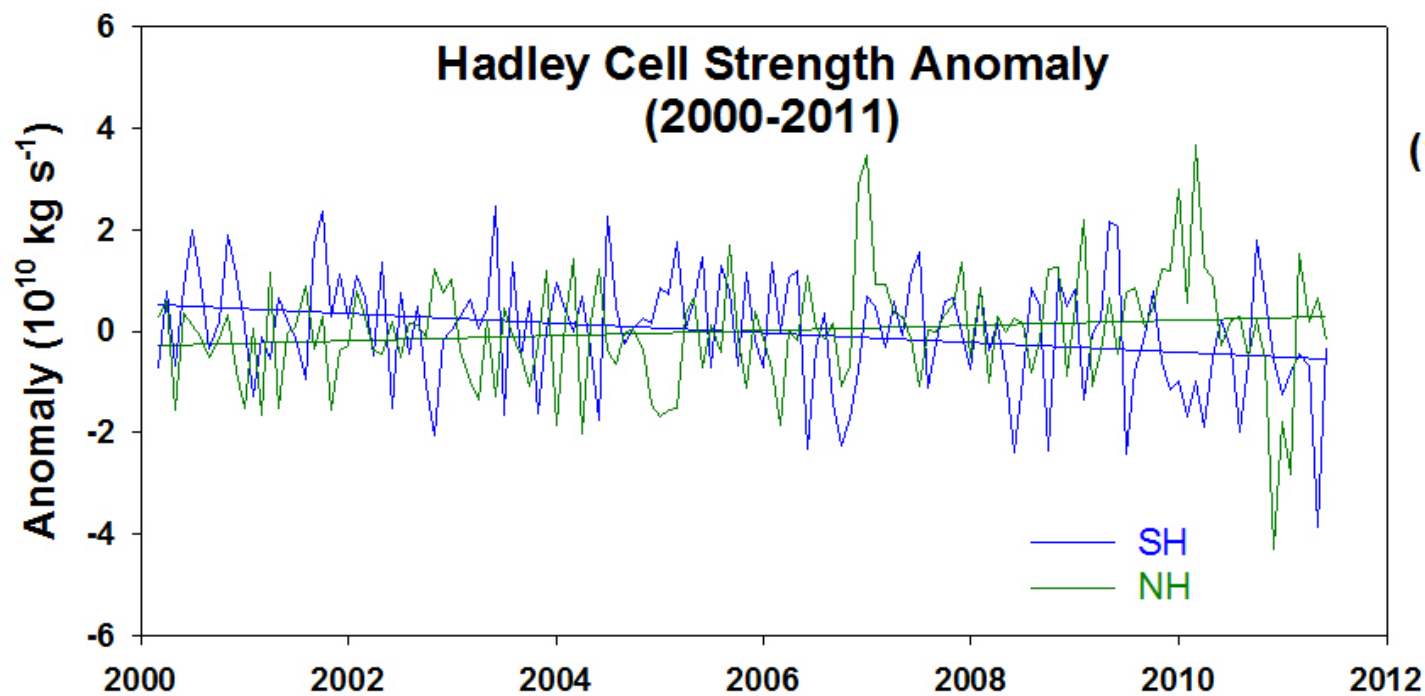
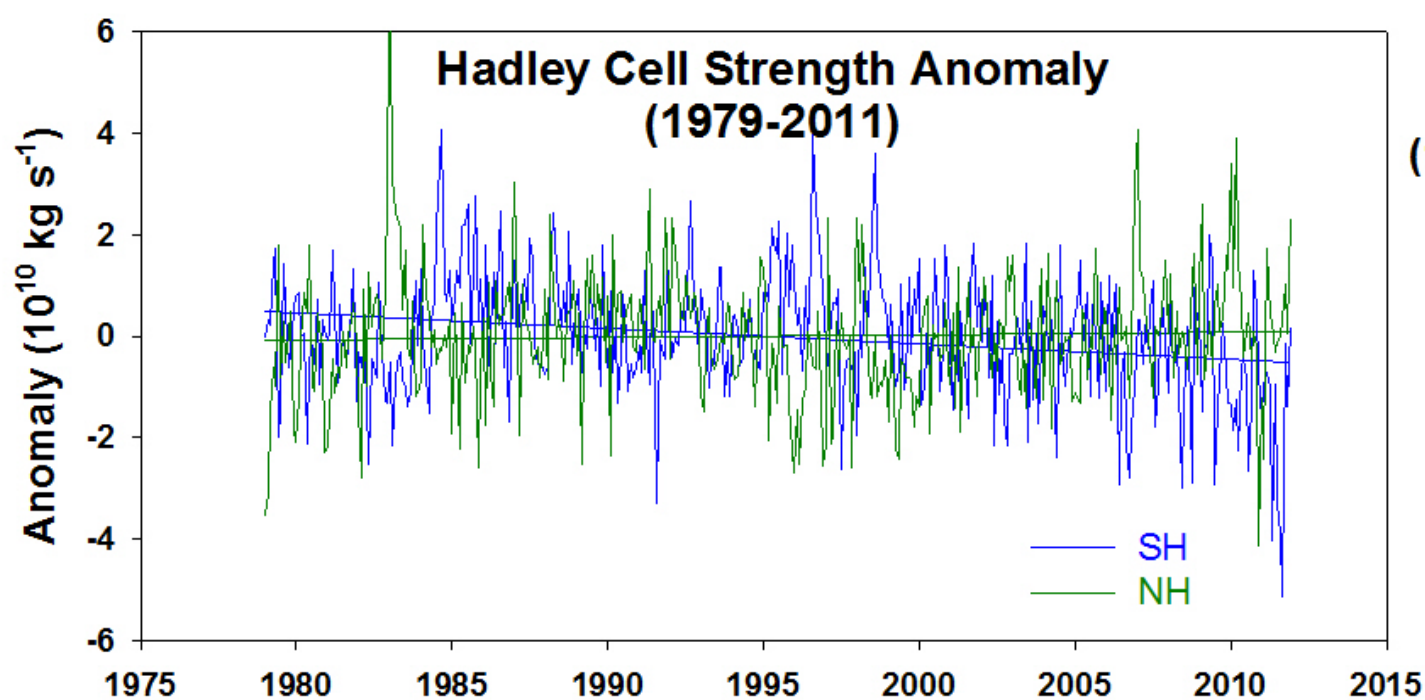
**$-0.066 \pm 0.50$**

**$0.57 \pm 1.1$**

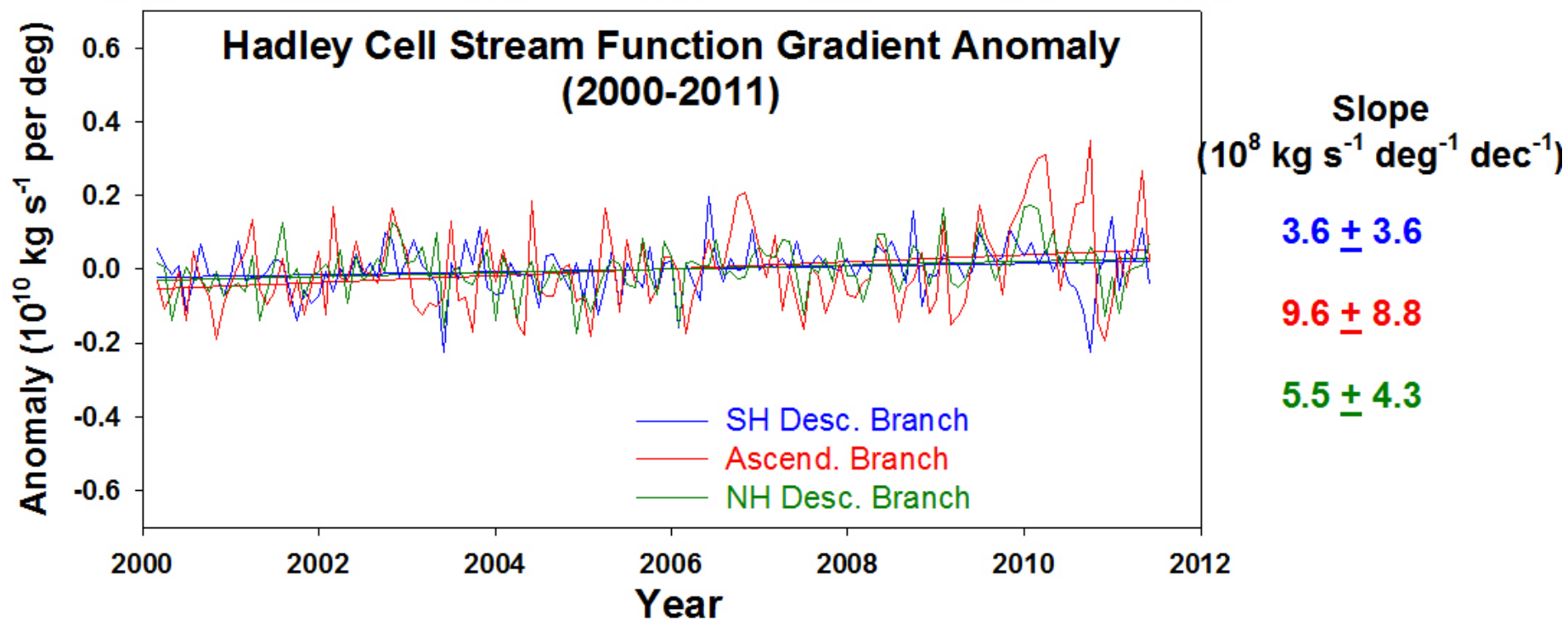
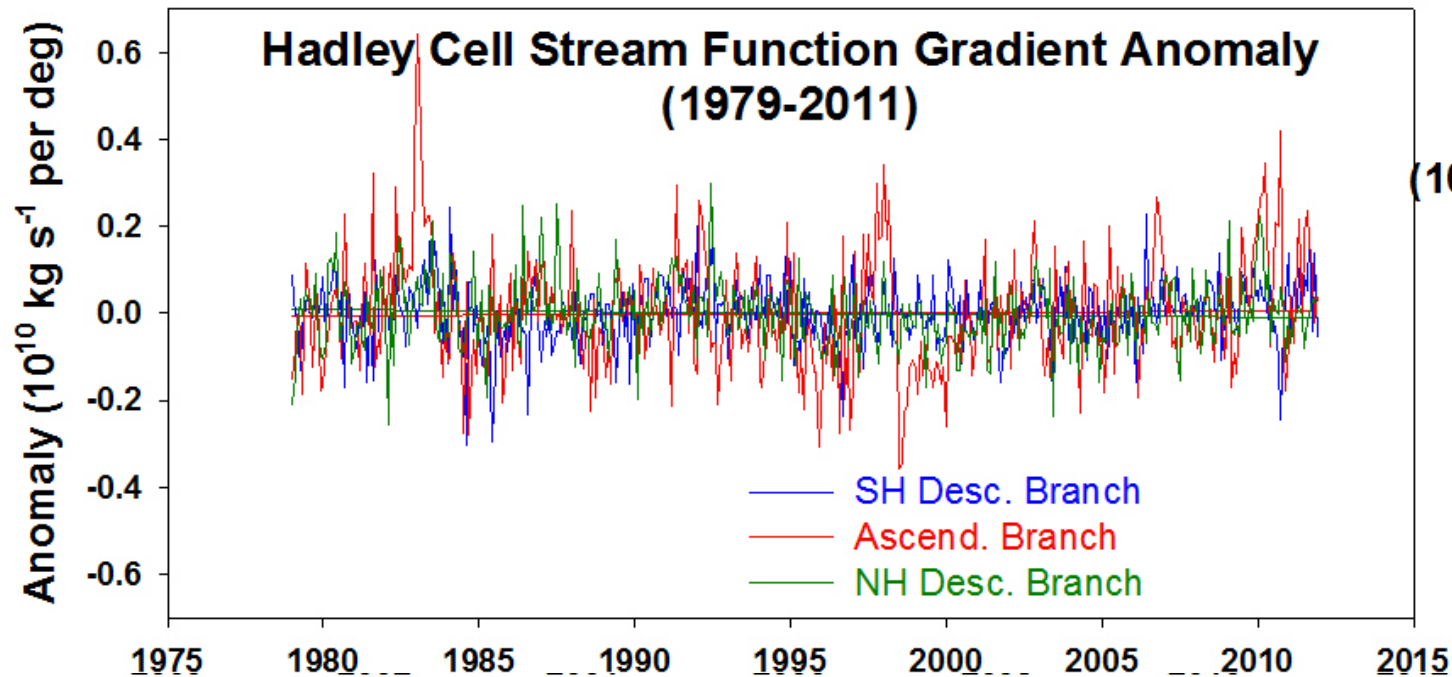
**$-0.15 \pm 0.72$**

**$-0.93 \pm 1.1$**

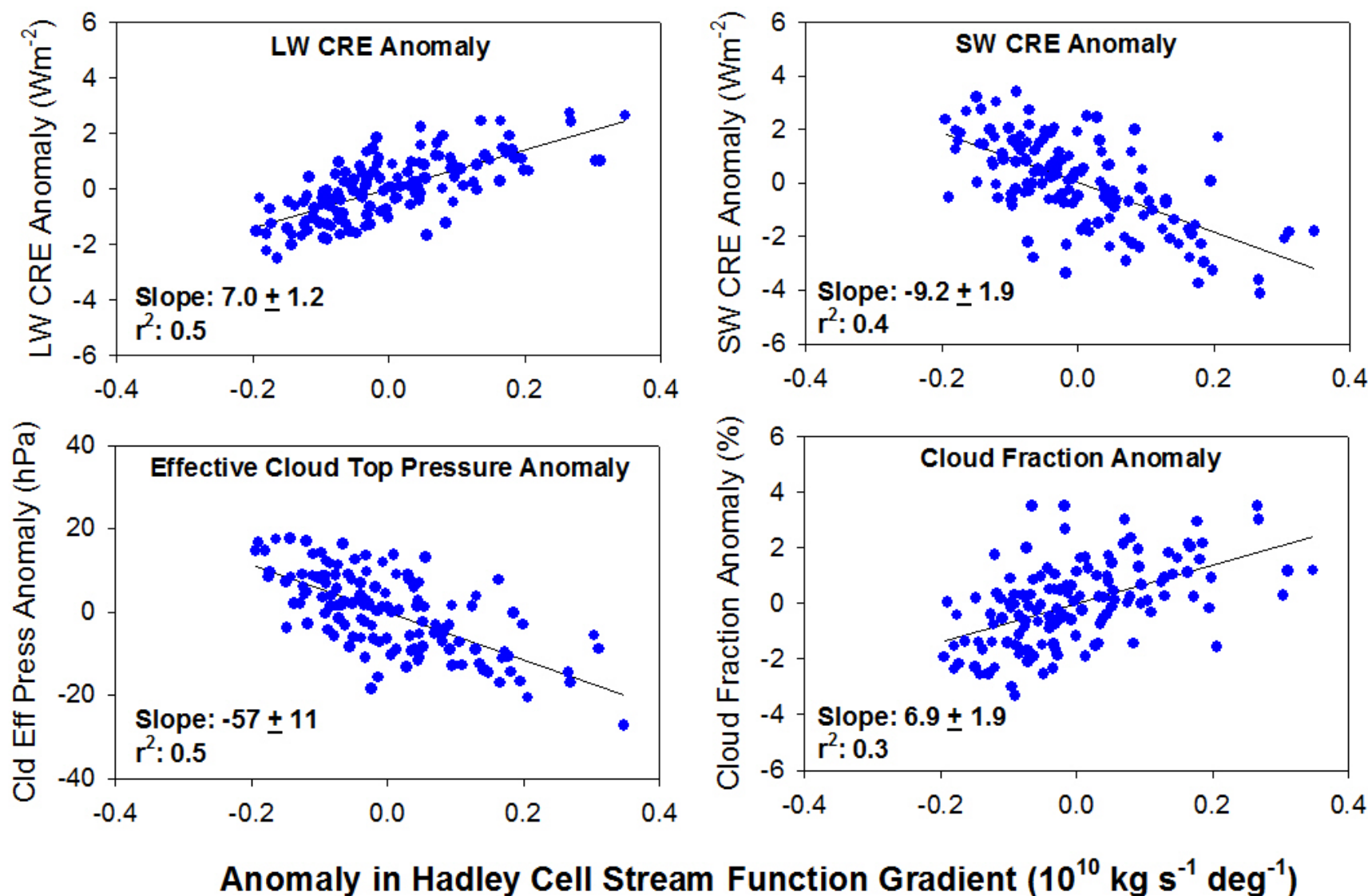






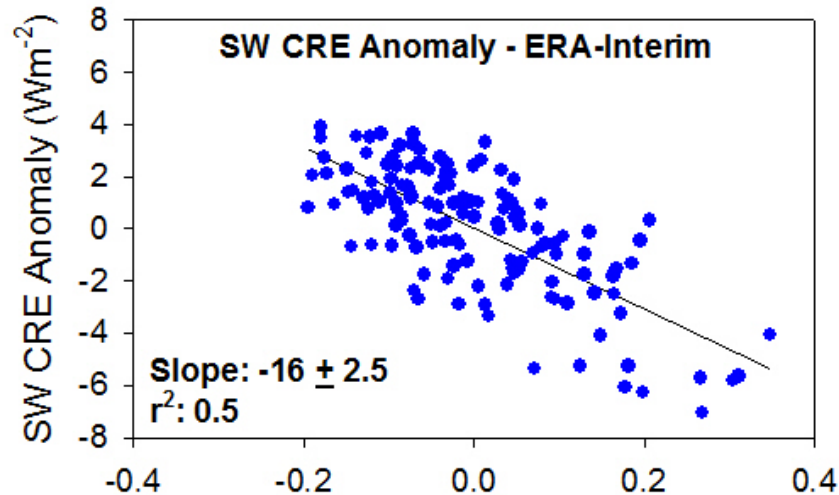
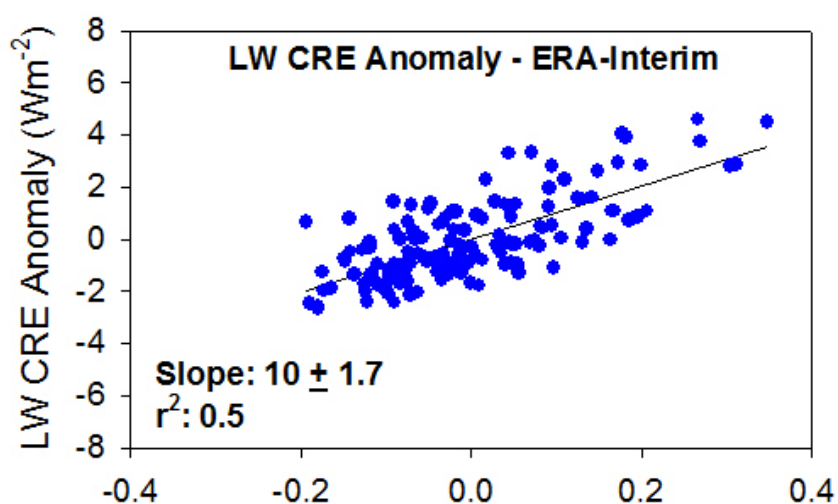
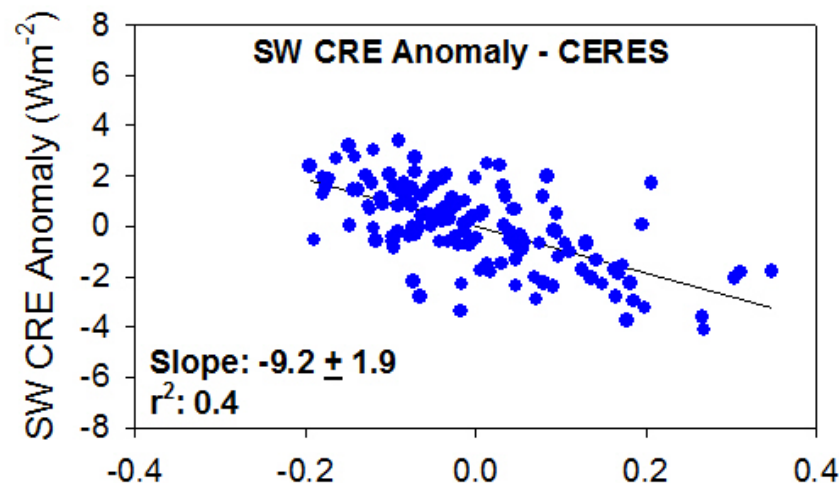
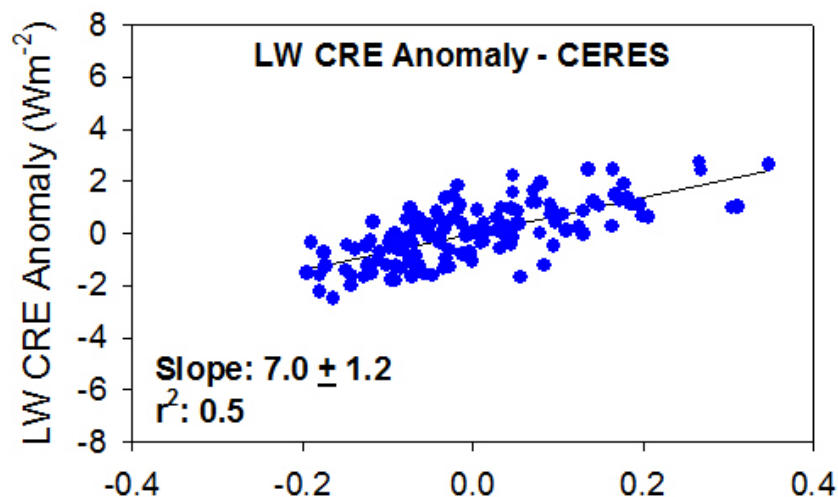


## Cloud Radiative Effect vs Hadley Cell Gradient Monthly Anomalies (Ascending Branch of Hadley Cell)



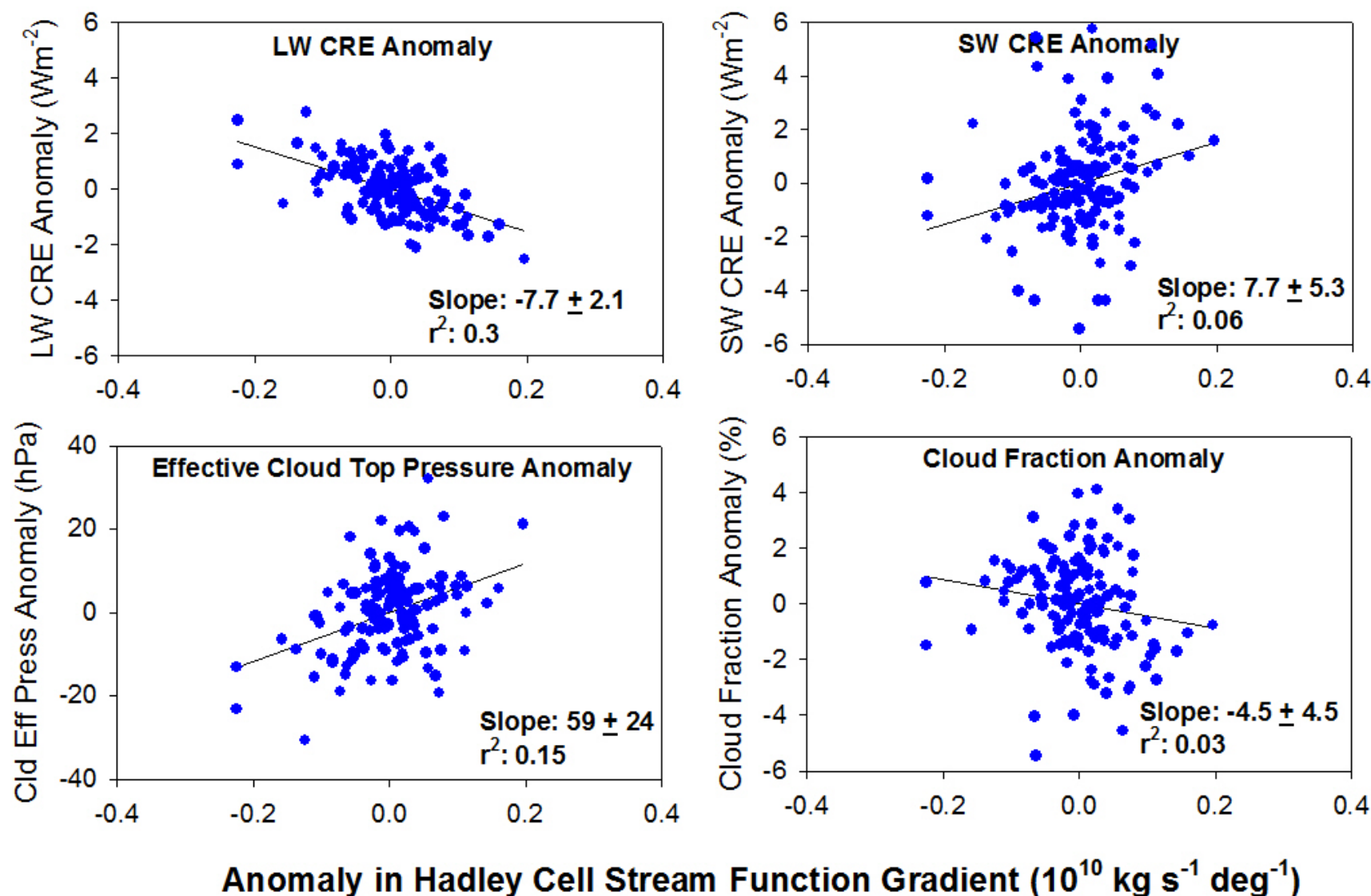


## Cloud Radiative Effect vs Hadley Cell Gradient Monthly Anomalies (Ascending Branch of Hadley Cell)

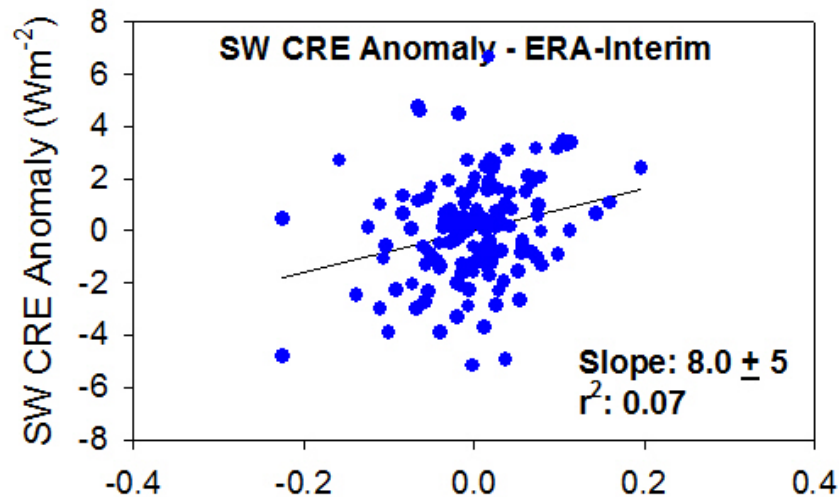
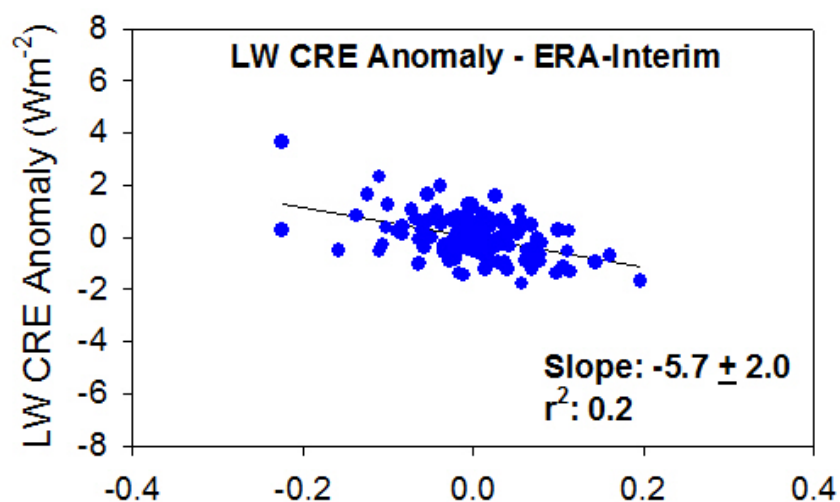
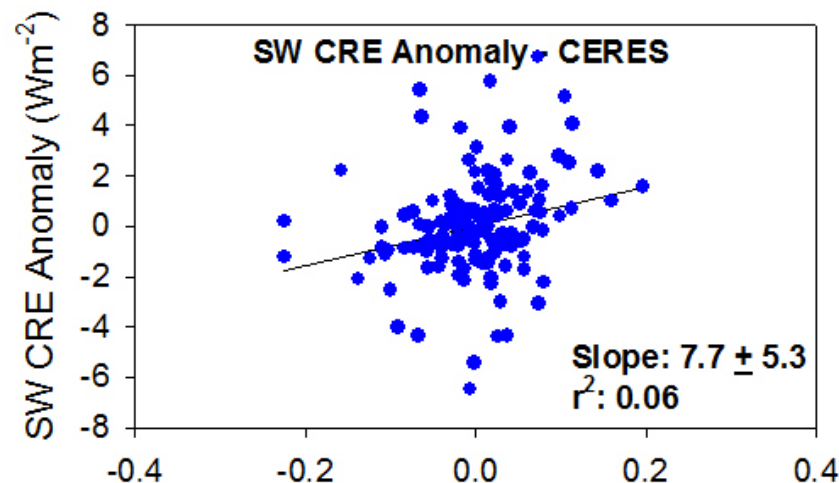
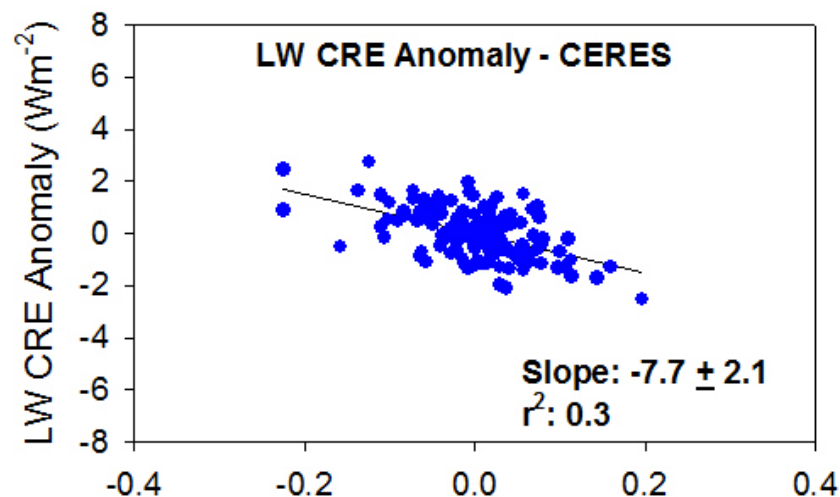


Anomaly in Hadley Cell Stream Function Gradient (10<sup>10</sup> kg s<sup>-1</sup> deg<sup>-1</sup>)

## Cloud Radiative Effect vs Hadley Cell Gradient Monthly Anomalies (SH Descending Branch of Hadley Cell)

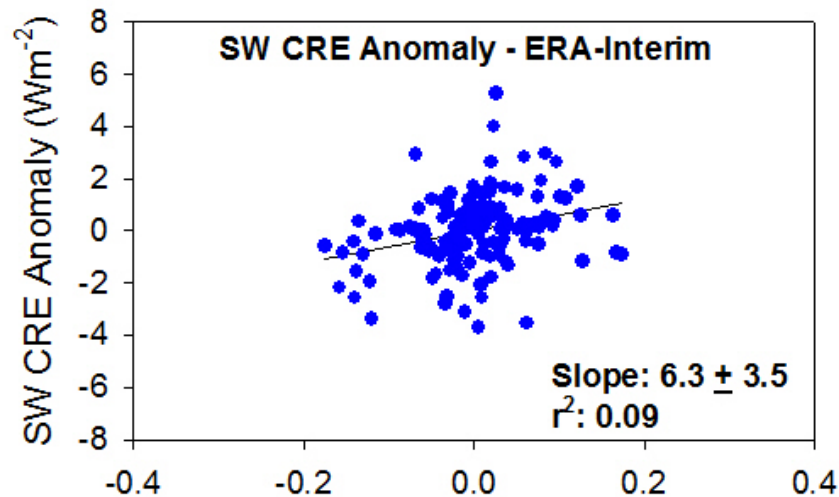
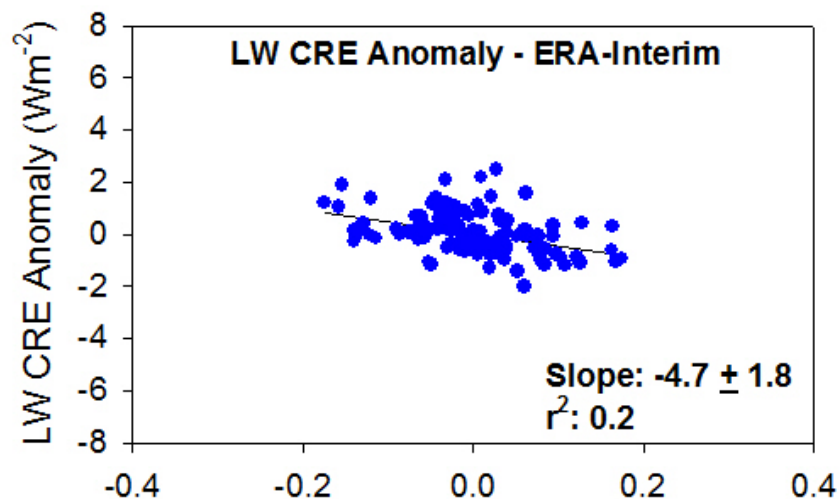
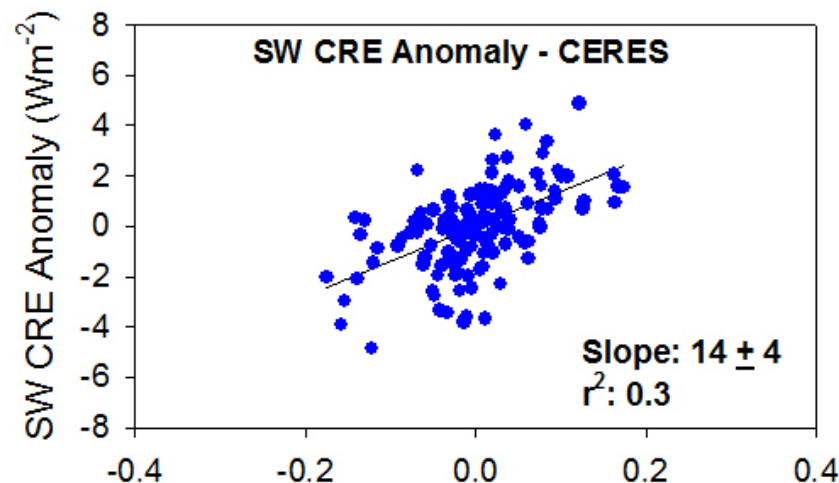
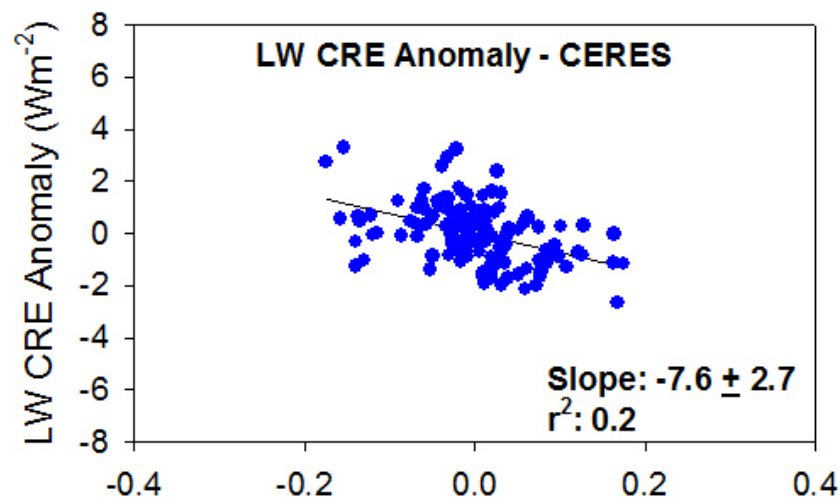


## Cloud Radiative Effect vs Hadley Cell Gradient Monthly Anomalies (SH Descending Branch of Hadley Cell)

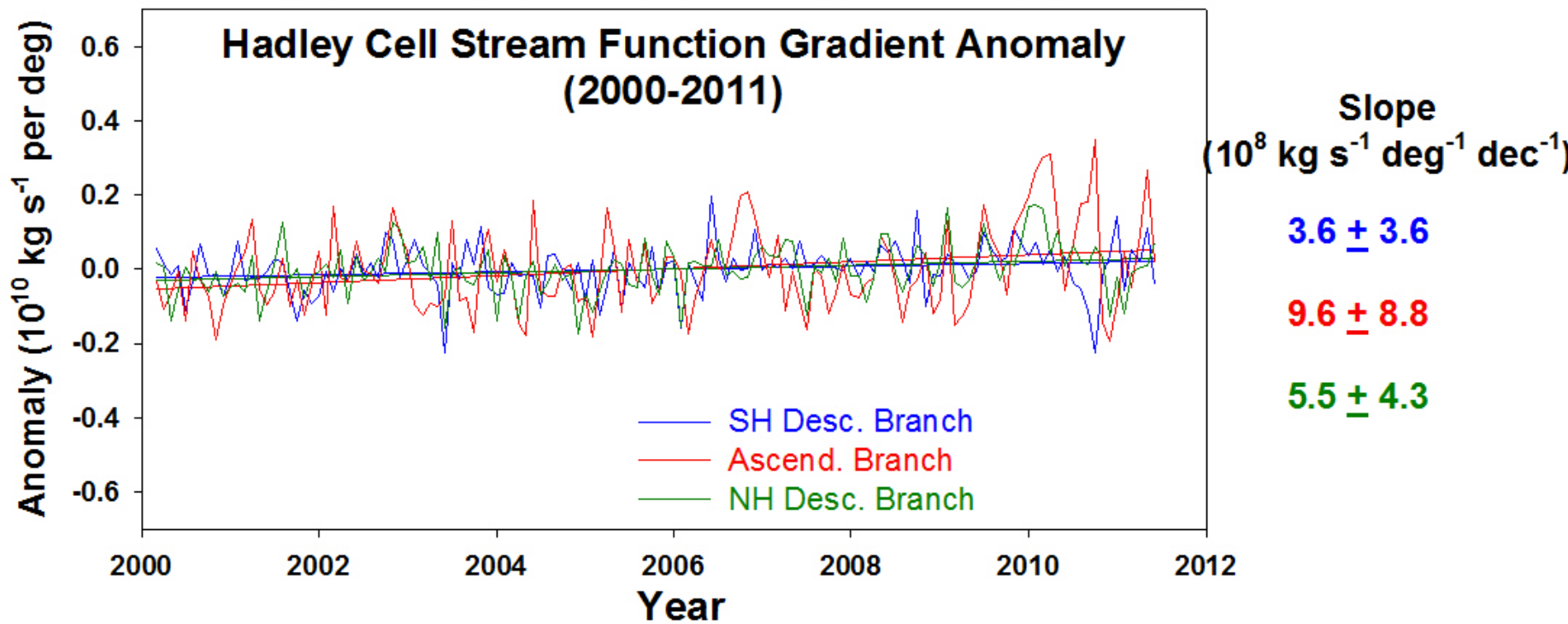


Anomaly in Hadley Cell Stream Function Gradient (10<sup>10</sup> kg s<sup>-1</sup> deg<sup>-1</sup>)

## Cloud Radiative Effect vs Hadley Cell Gradient Monthly Anomalies (NH Descending Branch of Hadley Cell)

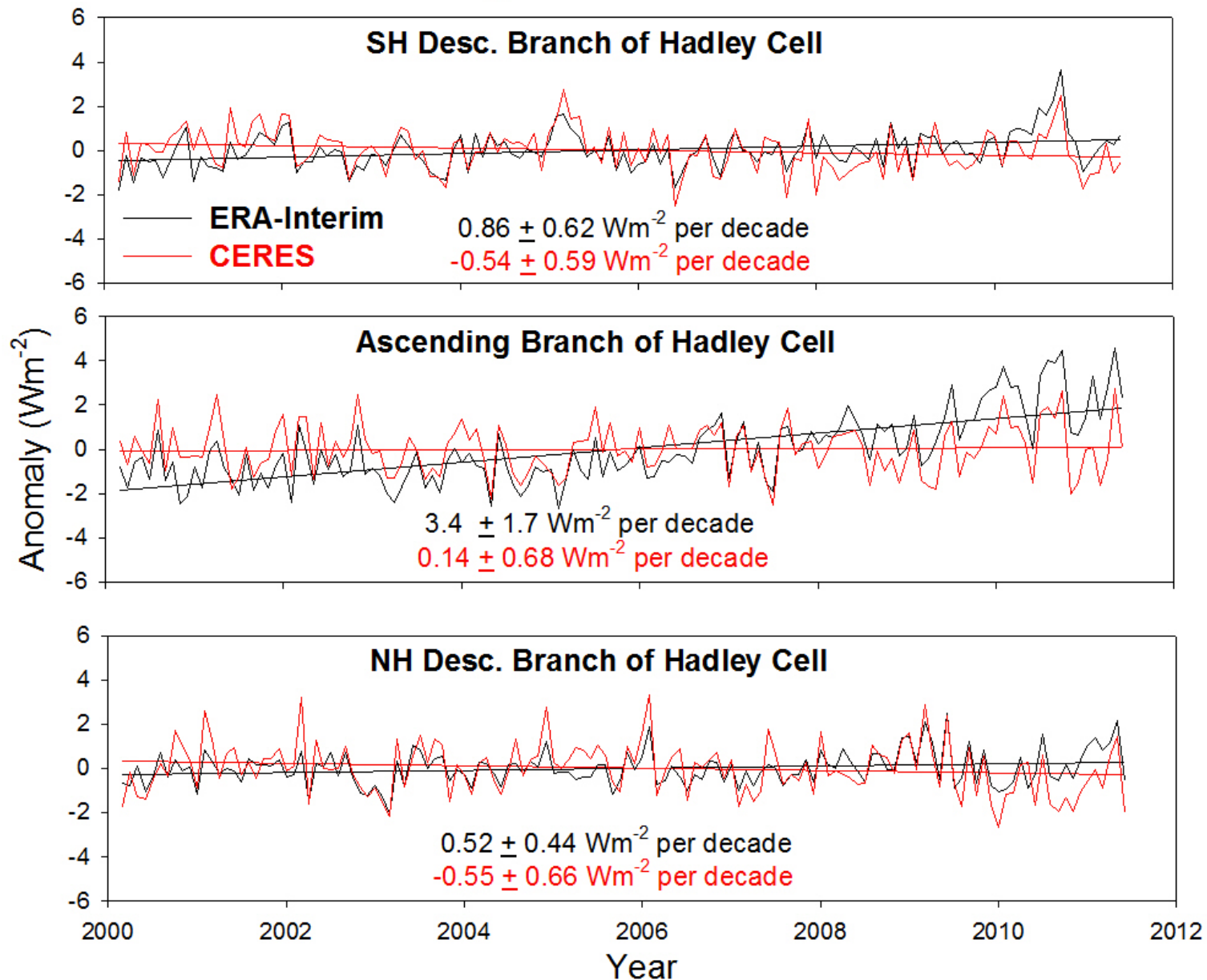


Anomaly in Hadley Cell Stream Function Gradient ( $10^{10} \text{ kg s}^{-1} \text{ deg}^{-1}$ )



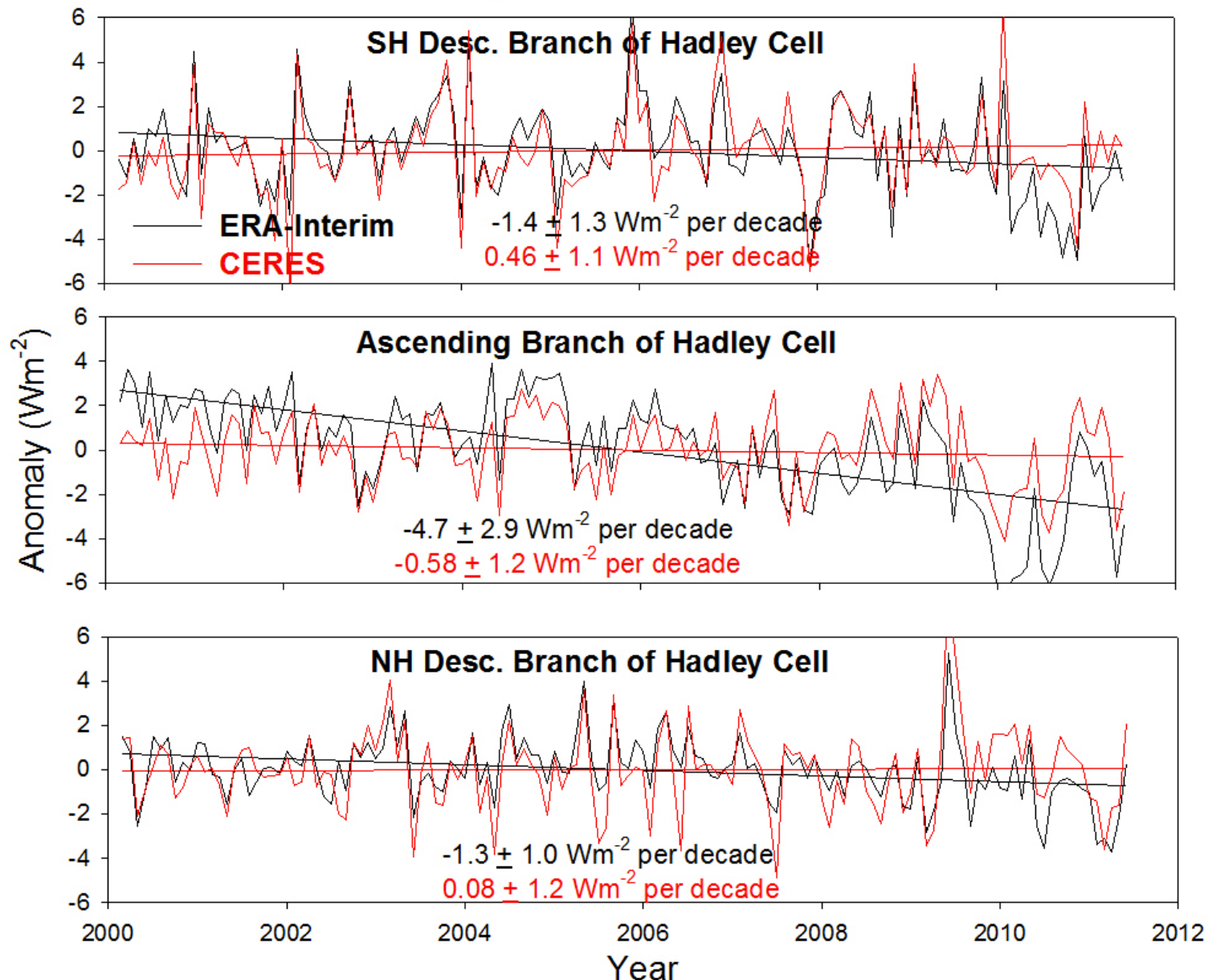


## Monthly Anomalies in LW CRE



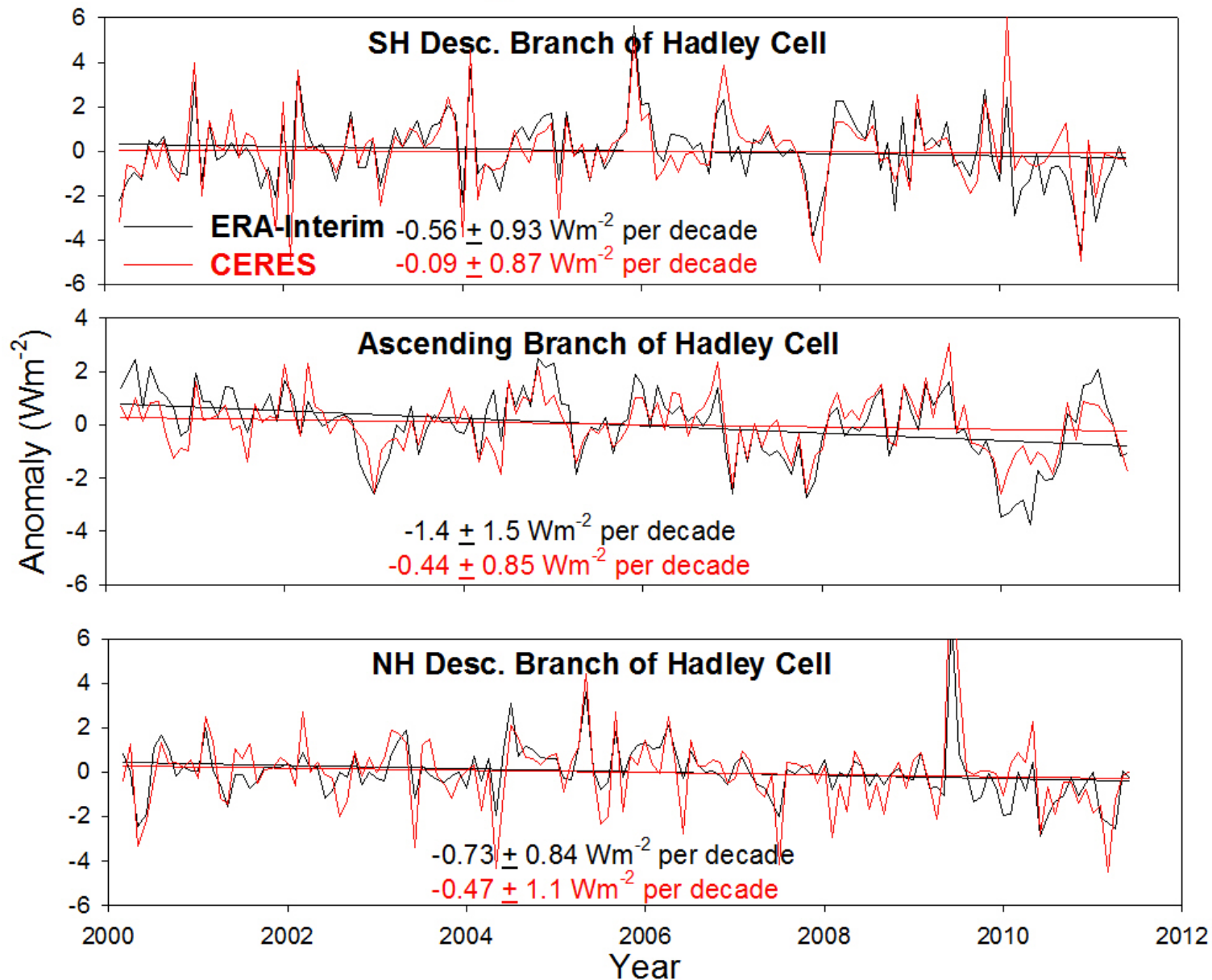
- Increase circulation strength: Weaker LW cloud effect in desc. branch for CERES, but opposite for ERA-Interim. Same sign in ascending branch but very different magnitudes.

## Monthly Anomalies in SW CRE



- Increase circulation strength: Weaker SW cooling by clouds in desc. branch for CERES, but opposite for ERA-Interim. Large difference in ascending branch.

## Monthly Anomalies in NET CRE



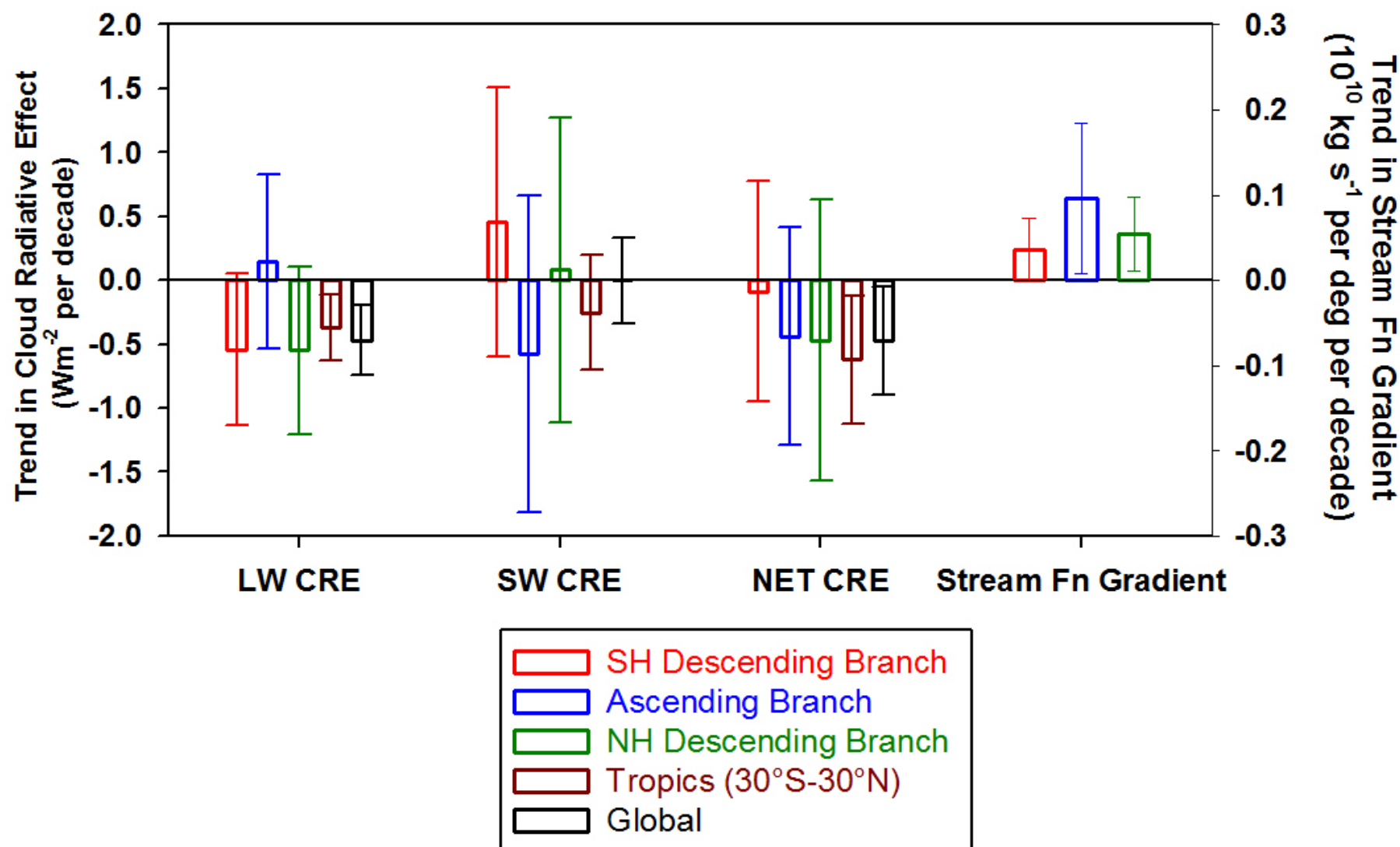
- Increase circulation strength: net cooling by clouds for CERES and ERA-Interim: SW CRE change dominates in ascending branch; LW CRE change dominates in descending branch.

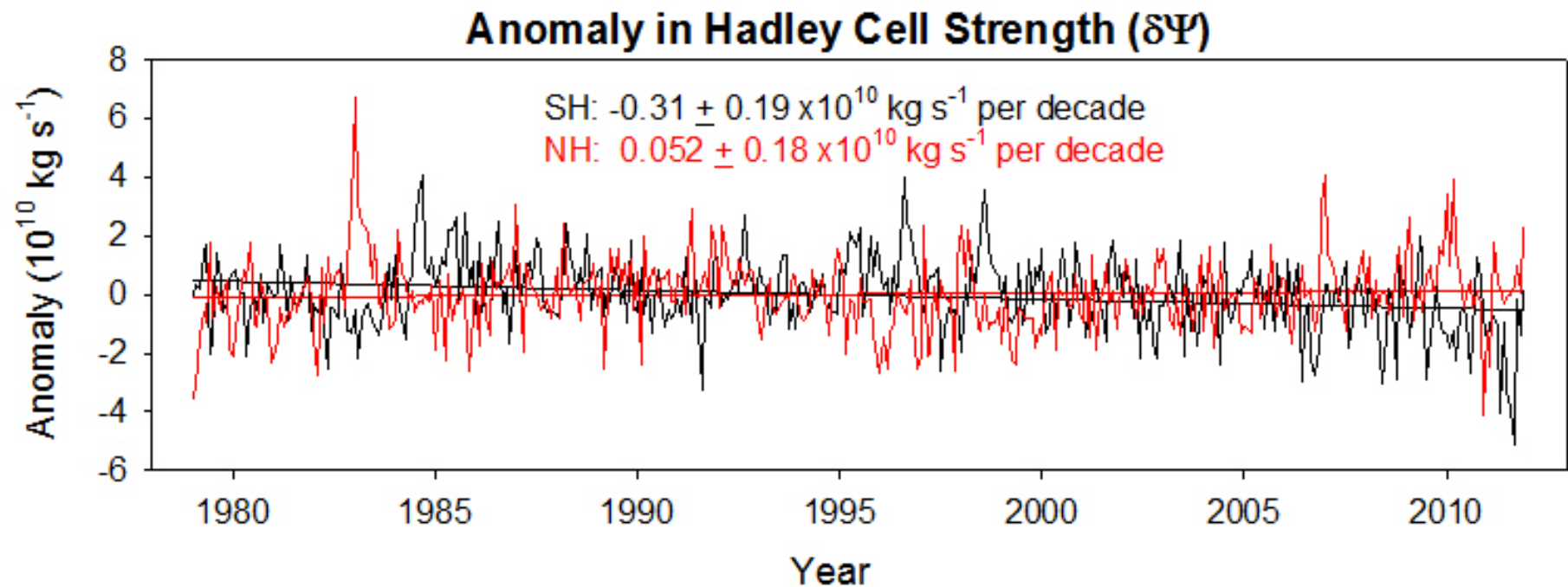
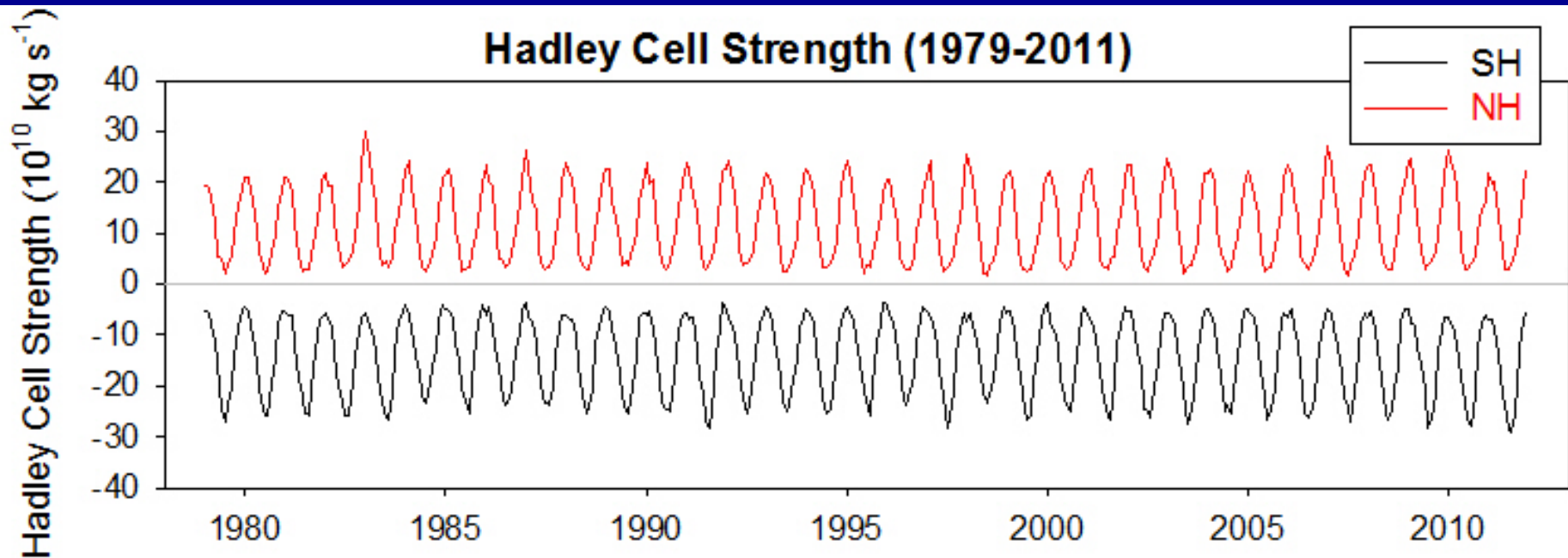


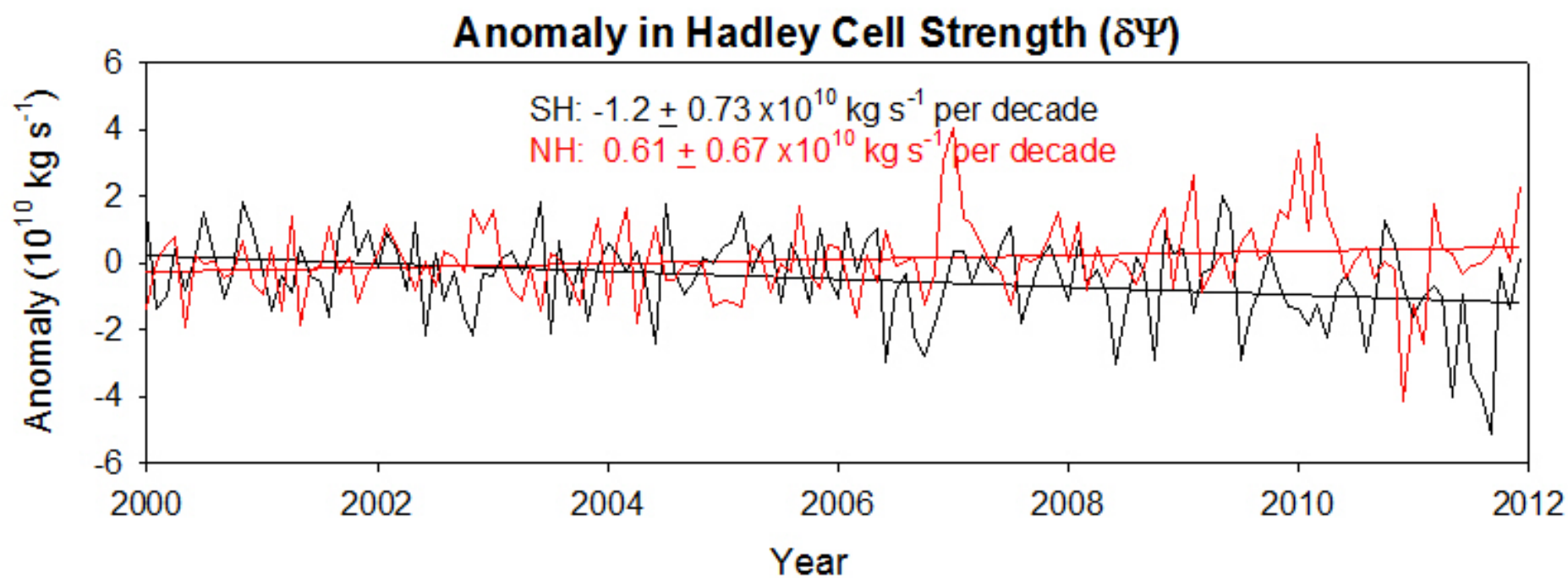
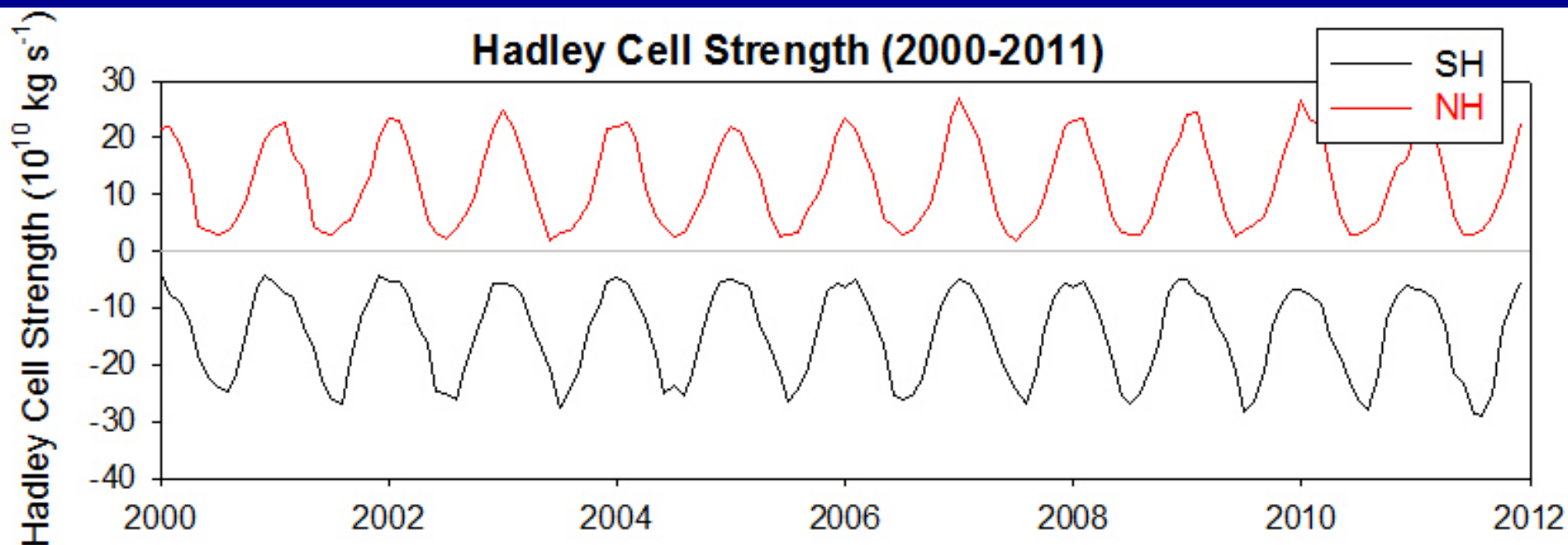
# Conclusions

- Past decade is associated with an increase in stream function gradient in all 3 branches of Hadley Cell.
  - => In SH Desc. Branch: Intensification of Hadley Cell strength.
  - ⇒ In NH Desc. & Asc. Branch: Intensification of Hadley Cell strength & contraction of Hadley circulation.
- Monthly anomalies in CERES clouds and radiation show expected sensitivity to variations in Hadley Cell stream function gradient.
  - ⇒ Best correlation in ascending branch and for LW CRE.
- In response to intensification in Hadley circulation for 2000-2011:
  - CERES shows increase in LW warming and SW cooling by clouds in ascending branches of Hadley circulation. Net cloud effect is cooling.
  - CERES shows reductions in LW warming and SW cooling by clouds in descending branches of Hadley circulation. Net cloud effect is cooling.
  - ERA-Interim CRE sign consistent with CERES in ascending branches but short-term trend is an order of magnitude larger than CERES.
  - ERA-Interim CRE short-term trend of opposite sign as CERES in descending branches of Hadley circulation.

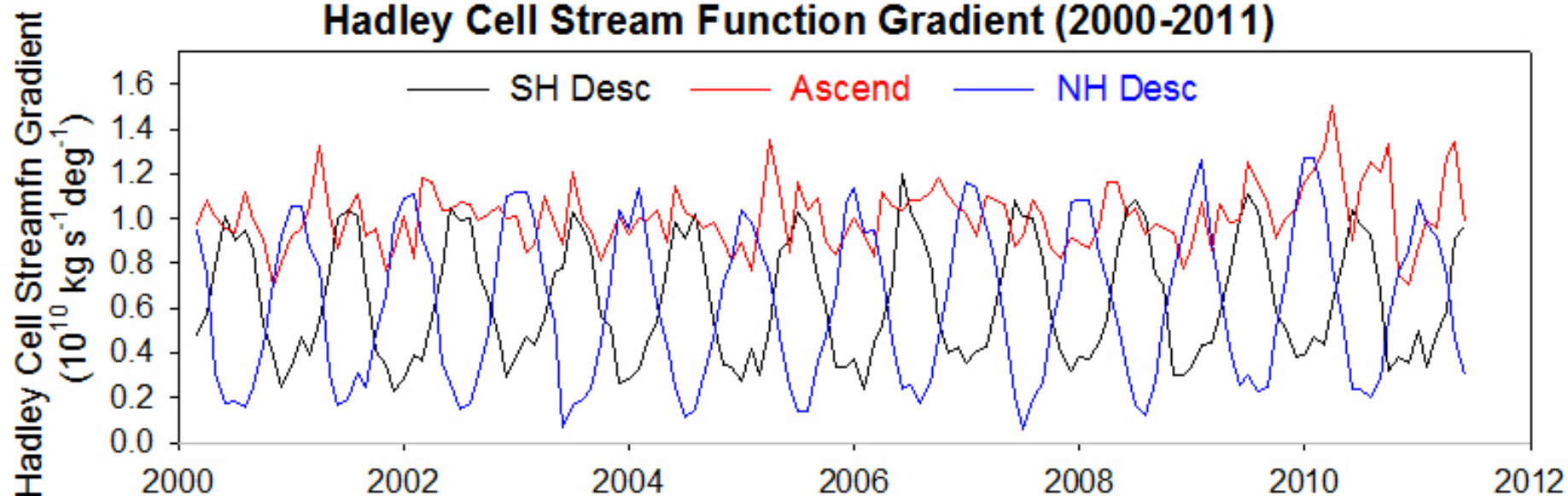
# Short-Term Trend in Cloud Radiative Effect & Stream Function Gradient (March 2000 - June 2011; CERES EBAF Ed2.6r)



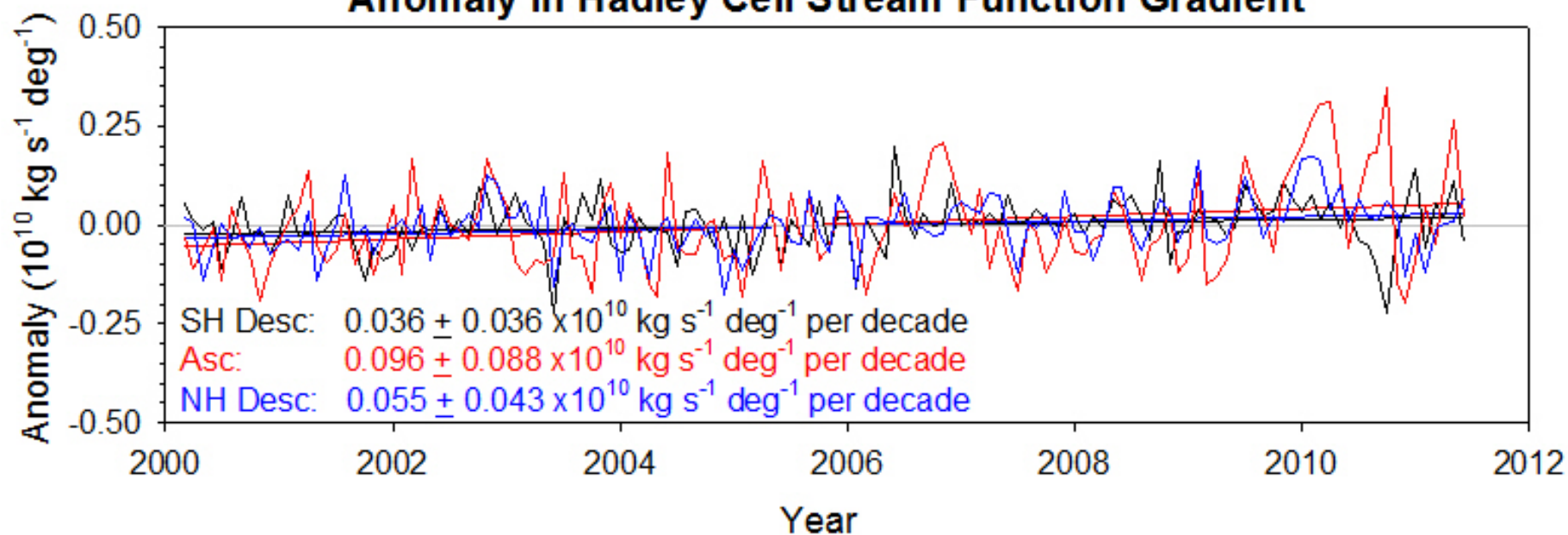




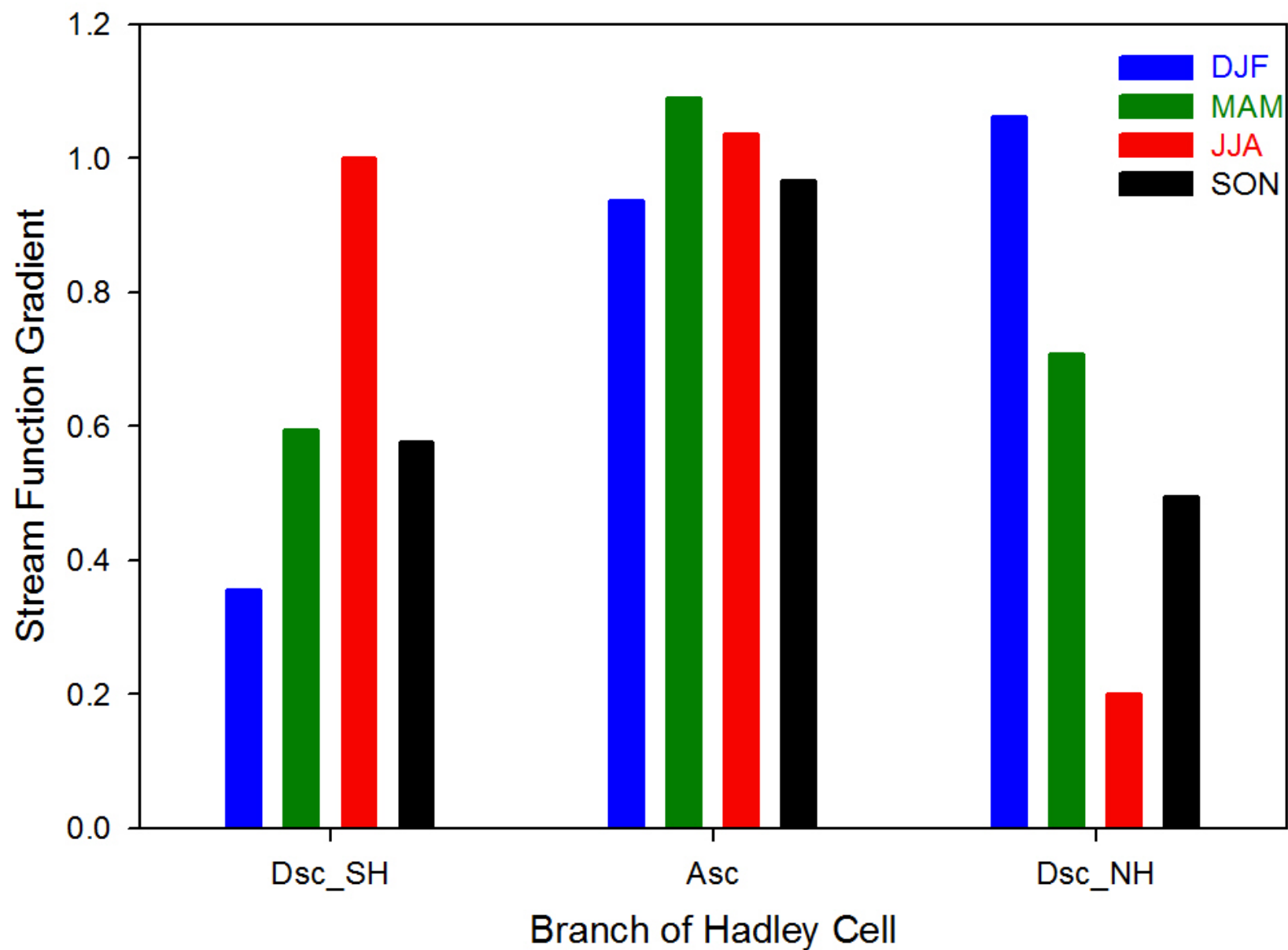
## Hadley Cell Stream Function Gradient (2000-2011)



## Anomaly in Hadley Cell Stream Function Gradient

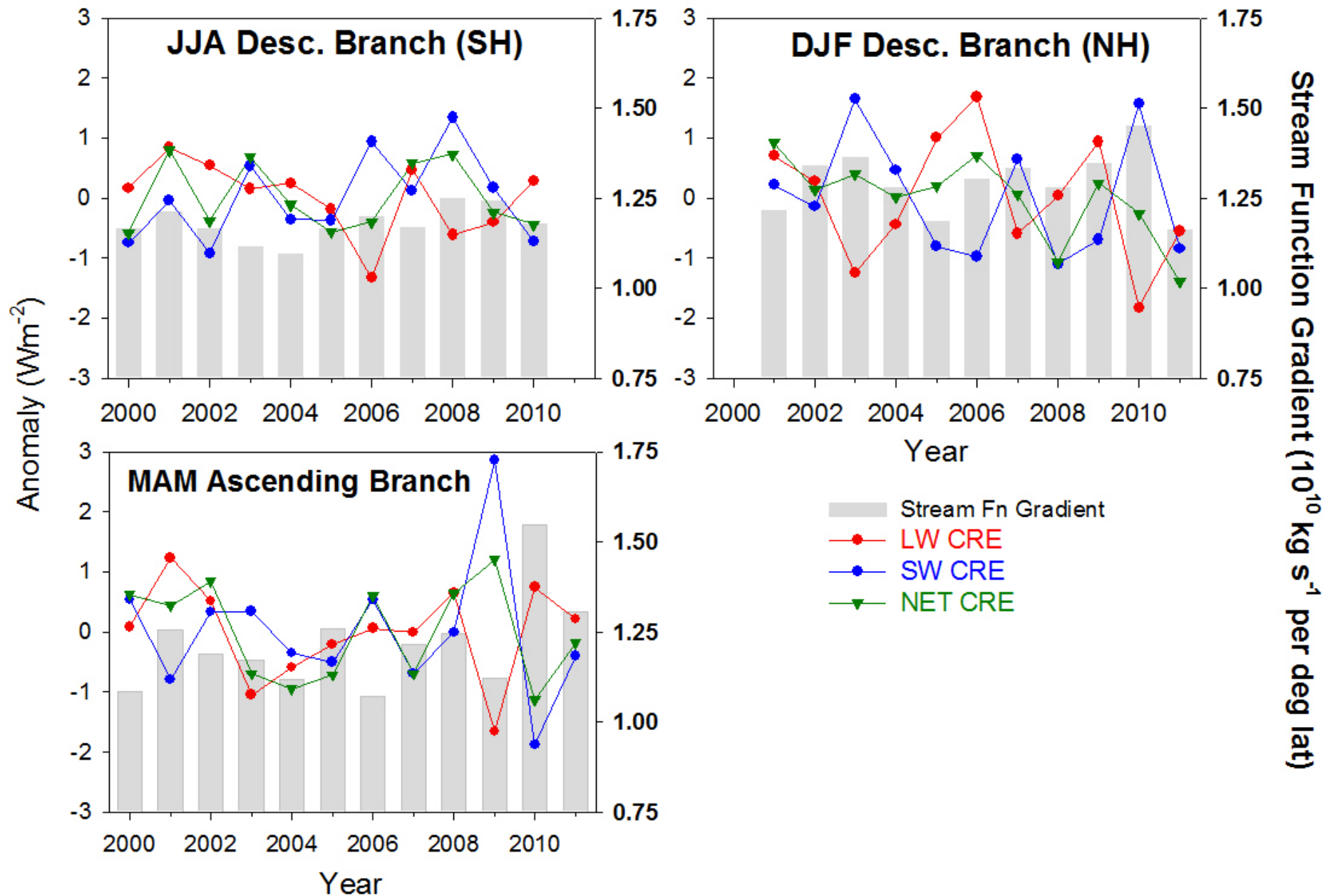


## Seasonal Dependence of Hadley Cell Stream Function Gradient

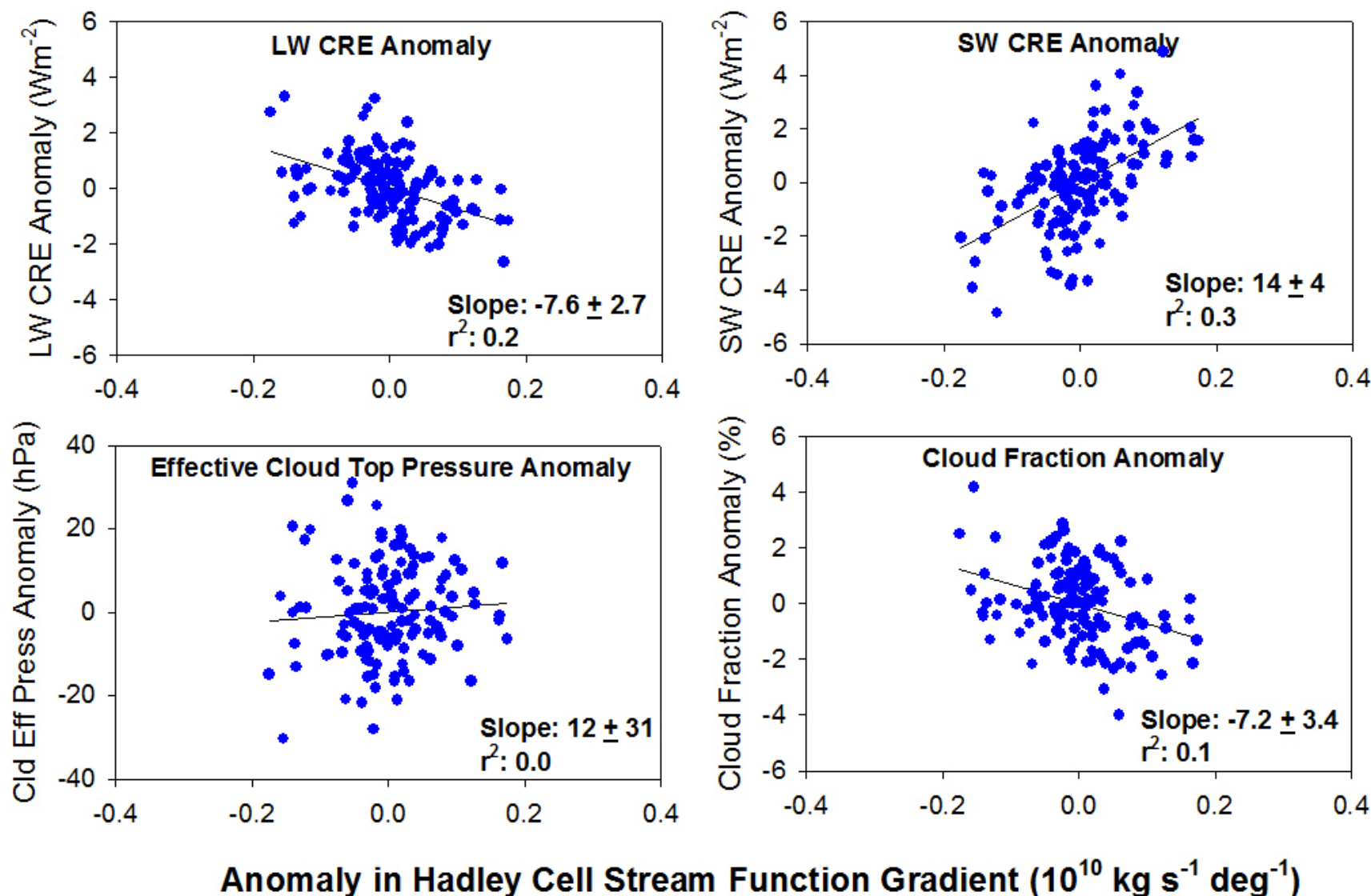




# Anomalies in Cloud Radiative Effect (For Season with Maximum Stream Fn Gradient)

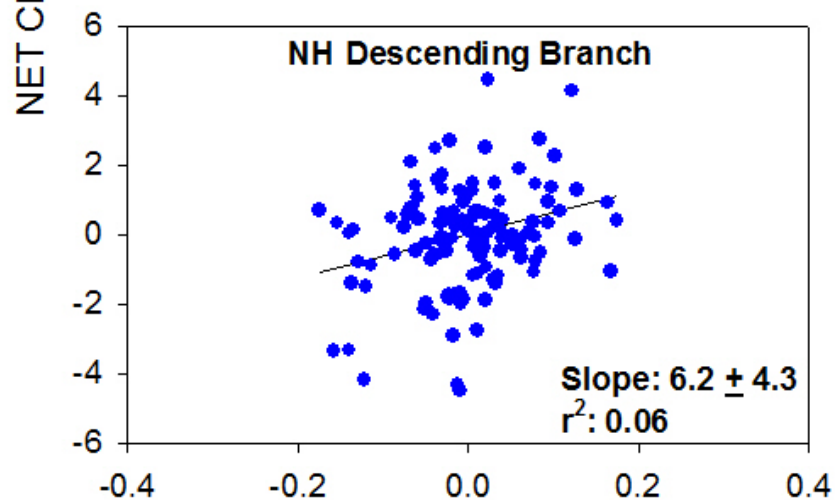
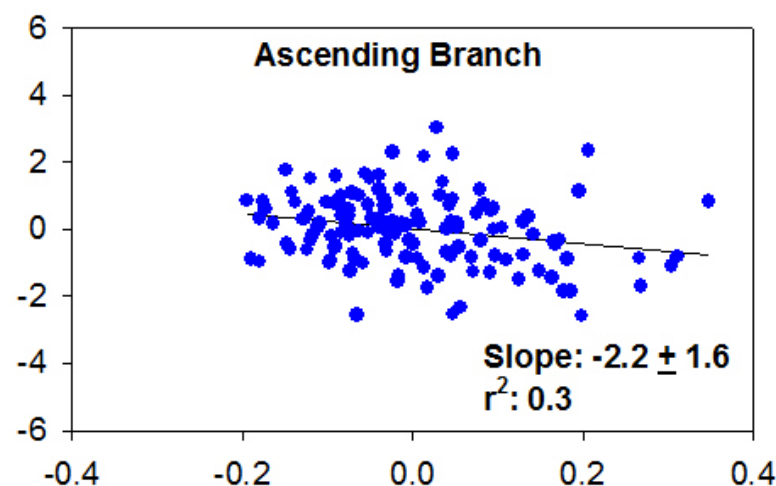
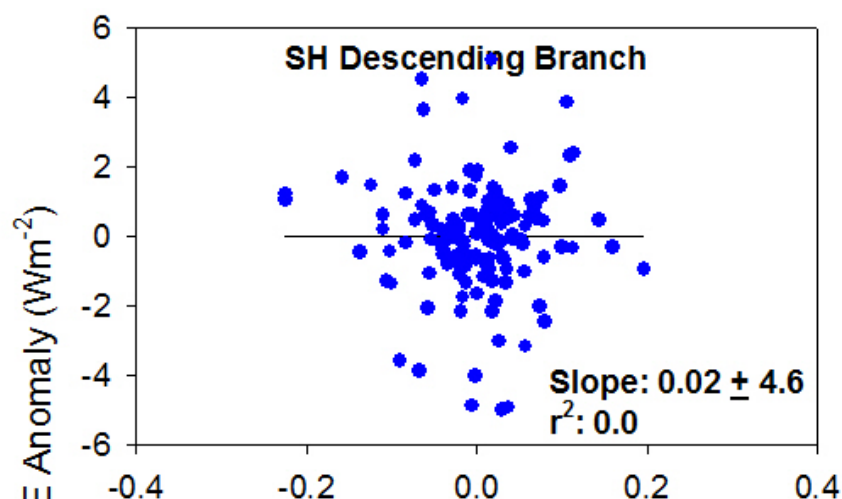


## Cloud Radiative Effect vs Hadley Cell Gradient Monthly Anomalies (NH Descending Branch of Hadley Cell)





## NET Cloud Radiative Effect vs Hadley Cell Gradient Monthly Anomalies



Anomaly in Hadley Cell Stream Function Gradient ( $10^{10} \text{ kg s}^{-1} \text{ deg}^{-1}$ )

## NET Cloud Radiative Effect vs Hadley Cell Gradient Monthly Anomalies (ERA-Interim)

