A Rossby Wave Bridge from the Tropical Atlantic to West Antarctica

A Physical Explanation of the Antarctic Paradox and the Rapid Peninsula Warming

Xichen Li; David Holland; Edwin Gerber; Changhyun Yoo

Acknowledgements: David Bromwich; Steve Price; Ryan Fogt

Scripps Institution of Oceanography / Courant Institute of Mathematics
OUTLINE

- Background of this Study
  - Recently observed climate changes around Antarctica
  - Potential linkages of these changes to the Tropical Oceans

- Atmospheric Bridge between Atlantic and Austral Circulation
  - Analysis and model study of the Atlantic-Antarctica teleconnection
  - Physical Mechanisms and Rossby Wave Dynamics

- The Impacts on the Sea Ice, Surface Temperature, Land Ice
  - Atlantic warming helps to explain Antarctic Paradox
  - and Peninsula warming / Impacts from different tropical oceans

- Conclusions and Future Research Plan
I. BACKGROUND

Recent Climate Change over Antarctica

A Teleconnection between Atlantic and Antarctica

- Vaughan et al. 2003
- D. Bromwich et al. 2012

Surface Temperature Changes: Marie Byrd Land


Xichen Li, SIO – UCSD, CIMS - NYU
I. BACKGROUND

Recent Climate Change over Antarctica

• Vaughan et al. 2003
• Yuan 2001, 2004
• D. Bromwich et al. 2012
• Stammerjohn 2008

Sea Ice Redistribution: Response to ABSL

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Recent Climate Changes over Antarctica

I. BACKGROUND

• **Rapid Regional Warming**  
  (10 times of GHG warming)

• **Sea Ice Redistribution**  
  (Extension and Redistribution)
Recent Climate Changes over Antarctica

1. BACKGROUND

- **Rapid Regional Warming** (10 times of GHG warming)

- **Sea Ice Redistribution** (Extension and Redistribution)

- **Accelerated Land Ice Melting**

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Recent Climate Changes over Antarctica

• **Rapid Regional Warming**  
  (10 times of GHG warming)

• **Sea Ice Redistribution**  
  (Extension and Redistribution)

• **Accelerated Land Ice Melting**

• **Change of Radiative Forcing can hardly explain all of these changes**
Recent Climate Changes over Antarctica

I. BACKGROUND

- **Rapid Regional Warming**  
  (10 times of GHG warming)

- **Sea Ice Redistribution**  
  (Extension and Redistribution)

- **Accelerated Land Ice Melting**

- **Change of Radiative Forcing can hardly explain all of these changes**

- **Oceanic / Atmospheric Circulation Change and Variability**

  A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Atmospheric Circulation Variability: ABSL

I. BACKGROUND

Recent Climate Change over Antarctica

• Vaughan et al. 2003
• D. Bromwich et al. 2012
• Yuan, Martinson 2001, 2004
• Stammerjohn. 2008
• Fogt et al. 2012

A Teleconnection between Atlantic and Antarctica

Figure 2. Map displaying the ABSL region (45°–75°S, 180°–60°W) and encompassed Ross, Amundsen, and Bellingshausen Seas.
I. BACKGROUND

Teleconnections: Tropical Anomaly Generates Rossby Wave

- **Karoly, Hoskins** 1981, 1989
I. BACKGROUND

Teleconnections: ENSO Interacts with SAM and PSA

- Bromwich 2002
- Fogt 2006

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO - UCSD, CIMS - NYU
I. BACKGROUND

Teleconnections: Potential Effect from Central Pacific Warming

• Karoly, Hoskins 1981, 1989
• Bromwich 2002
• Ding et al. 2011, 2012

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
The Focus of the Research Question

• *Previous Studies Focused on The Pacific – Antarctic Teleconnection*

  *Largely due to ENSO dominating the Interannual Variability*
I. BACKGROUND

The Focus of the Research Question

• Previous Studies Focused on The Pacific – Antarctic Teleconnection
  Largely due to ENSO dominating the Interannual Variability

• On Decadal time scale, the Atlantic Multi-decadal Oscillation is a Leading Mode of Global SST Variability
I. BACKGROUND

The Focus of the Research Question

• Previous Studies Focused on The Pacific – Antarctic Teleconnection
  Largely due to ENSO dominating the Interannual Variability

• On Decadal time scale, the Atlantic Multi-decadal Oscillation is a Leading Mode of Global SST Variability

• A Question Arises Naturally:

  The Role of Atlantic Ocean
  In the Tropical – Antarctic Teleconnection.
OUTLINE

- **Background of this Study**
  - Recently observed climate changes around Antarctica
  - Potential linkages of these changes to the Tropical Oceans

- **Atmospheric Bridge between Atlantic and Austral Circulation**
  - Analysis and model study of the Atlantic-Antarctica teleconnection
  - Physical Mechanisms and Rossby Wave Dynamics

- **The Impacts on the Sea Ice and the Surface Temperature**
  - Atlantic warming helps to explain Antarctic Paradox
  - and Peninsula warming / Impacts from different tropical oceans

- **Conclusions and Future Research Plan**

---

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
II. ATMOSPHERIC TELECONNECTION

Atlantic Multidecadal Oscillation (AMO)

A. Centennial

B. Multi-decadal

C. AMO: Spatial Pattern

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Overview of Part II

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
II. ATMOSPHERIC TELECONNECTION

Overview of Part II

- **Relationship**
  - Regression
  - *Maximized Covariance Analysis (MCA)*

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Overview of Part II

- Relationship
  - Regression
  - Maximized Covariance Analysis (MCA)

- Causality
  - Comprehensive Atmospheric Model (CAM)

- Mechanism
  - Idealized Model (GFDL dynamical core)

A Teleconnection between Atlantic and Antarctica
II. ATMOSPHERIC TELECONNECTION

Overview of Part II

- **Relationship**
  - Regression
  - Maximized Covariance Analysis (MCA)

- **Causality**
  - Comprehensive Atmospheric Model (CAM)

- **Mechanism**
  - Idealized Model (GFDL dynamical core)

- **Physical Dynamics**
  - Theoretical Rossby Wave Model (Karoly Rossby Wave Model)

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
II. ATMOSPHERIC TELECONNECTION

Regression Analysis

Against Atlantic SST

- Austral Winter
  (June – July – August)

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
II. ATMOSPHERIC TELECONNECTION

Regression Analysis

A Teleconnection between Atlantic and Antarctica

Austral Winter
(June – July – August)

Against Atlantic SST

Xichen Li, SIO – UCSD, CIMS - NYU
Regression Analysis: Verification using ERA-interim data

II. ATMOSPHERIC TELECONNECTION

Data Analysis: Regression

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
II. ATMOSPHERIC TELECONNECTION

CAM4 Simulation & Regression for All Seasons

JJA

SON

DJF

MAM

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
II. ATMOSPHERIC TELECONNECTION

CAM4 Simulation & Regression for All Seasons

- JJA
- DJF
- SON
- MAM

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO - UCSD, CIMS - NYU
II. ATMOSPHERIC TELECONNECTION

CAM4 Simulation & Regression for All Seasons

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
II. ATMOSPHERIC TELECONNECTION

GFDL Dry-Dynamical-Core: An Idealized Model

- **Numerical Solver of the Primitive Equation**
  - *Isolated* from any parameterization processes
  - **Spectral** dynamical core
  - With a horizontal resolution of ~3 degree

- **Driven by Climatological Background State**
  - From the **ERA-interim** Reanalysis

- **Initial Condition Simulation**
  - The model is **Neutralized** with an external forcing
  - An external perturbation is introduced in the **Initial condition**
  - Model response is considered as the **Evolution** of the impact of this initial perturbation

- A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Rossby wave trains simulated by GFDL dynamical core: JJA

- GFDL initial condition simulations show clear Rossby Wave Trains
- Transport to Amundsen Sea within two weeks
- A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Rossby wave trains simulated by GFDL dynamical core: Seasonality

II. ATMOSPHERIC TELECONNECTION

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
II. ATMOSPHERIC TELECONNECTION

CAM4 Simulation & Regression for All Seasons

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Theoretical Stationary Rossby Wave Model

- Dispersion relation of Rossby wave
  \[ \omega = Uk - \frac{\beta_* k}{K^2} \]
- For stationary wave, \( \omega \) is 0.
  \[ K^2 = l^2 + k^2 = \frac{\beta_*}{U} \]
- Where
  \[ \beta_* = \beta - U_{yy} \]
Theoretical Stationary Rossby Wave Model

- Dispersion relation of Rossby wave
  \[ \omega = Uk - \frac{\beta_* k}{K^2} \]
- For stationary wave, \( \omega \) is 0.
  \[ K^2 = l^2 + k^2 = \frac{\beta_*}{U} \]
- Where
  \[ \beta_* = \beta - U_{yy} \]
- We can derive the group velocity at each location
  \[ c_{gx} = \frac{2 \beta_* k^2}{K^4} \quad c_{gy} = \frac{2 \beta_* kl}{K^4} \quad \frac{c_{gy}}{c_{gx}} = \frac{l}{k} \]

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
II. ATMOSPHERIC TELECONNECTION

Reflection and Blocking of Rossby Wave Trains

- When $\beta$ is too small or $U_{yy}$ is too large, $\beta* = \beta - U_{yy}$ becomes small,

$$K = \sqrt{\frac{\beta*}{U}} \sim k$$

$$\frac{c_{gy}}{c_{gx}} = \frac{l}{k} \sim 0$$

Rossby Wave will be reflected
II. ATMOSPHERIC TELECONNECTION

Reflection and Blocking of Rossby Wave Trains

- When $\beta$ is too small or $U_{yy}$ is too large, $\beta_* = \beta - U_{yy}$ becomes small,
  \[
  K = \sqrt{\frac{\beta_*}{U}} \sim k \quad \frac{c_{gy}}{c_{gx}} = \frac{l}{k} \sim 0
  \]

  Rossby Wave will be reflected

- When $U$ is negative, $K = \sqrt{\frac{\beta_*}{U}}$ becomes imaginary
  Stationary Rossby Wave can no longer propagate and is blocked by the trade wind

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
II. ATMOSPHERIC TELECONNECTION

Theoretical Models & Rossby Wave Dynamics

Stationary Wave in Hoskins – Karoly Model

Rossby Wave is reflected several times and propagates along the southern edge of the Sub-tropical Jet

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Seasonality of the Stationary Wave Trains

A Teleconnection between Atlantic and Antarctica

K = 2
K = 3
K = 4
Atlantic – Antarctic Teleconnection

- Atlantic – Antarctic Teleconnection:
  Tropical Atlantic Warming Dramatically Enhances the SAM and Deepens the Amundsen Sea Low
Atlantic – Antarctic Teleconnection

- **Atlantic – Antarctic Teleconnection**:
  *Tropical Atlantic Warming Dramatically Enhances the SAM and Deepens the Amundsen Sea Low*

- **Seasonality of the Teleconnection**:
  *Pronounced in All Seasons Except Austral Summer (DJF)*
Atlantic – Antarctic Teleconnection

- **Atlantic – Antarctic Teleconnection**:
  
  *Tropical Atlantic Warming Dramatically Enhances the SAM and Deepens the Amundsen Sea Low*

- **Seasonality of the Teleconnection**:
  
  *Pronounced in All Seasons Except Austral Summer (DJF)*

- **Mechanisms**:
  
  *Stationary Rossby Wave Trains*
Atlantic – Antarctic Teleconnection

- **Atlantic – Antarctic Teleconnection**:
  *Tropical Atlantic Warming Dramatically Enhances the SAM and Deepens the Amundsen Sea Low*

- **Seasonality of the Teleconnection**:
  *Pronounced in All Seasons Except Austral Summer (DJF)*

- **Mechanisms**:
  *Stationary Rossby Wave Trains*

- **Dynamics**:
  *Critically Depends on the Background Flow, in Particular, the Sub-Tropical Jet*
OUTLINE

- **Background of this Study**
  - Recently observed climate changes around Antarctica
  - Potential linkages of these changes to the Tropical Oceans

- **Atmospheric Bridge between Atlantic and Austral Circulation**
  - Analysis and model study of the Atlantic-Antarctica teleconnection
  - Physical Mechanisms and Rossby Wave Dynamics

- **The Impacts on the Sea Ice and the Surface Temperature**
  - Atlantic warming helps to explain Antarctic Paradox
  - and Peninsula warming / Linearity from different tropical oceans

- **Conclusions and Future Research Plan**
III. SEA ICE and AIR TEMPERATURE

Air Temperature Response to Tropical Atlantic Warming

Linear Regression

Observed Trend

Numerical Simulation

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Air Temperature

Response to Tropical Atlantic Warming

III. SEA ICE and AIR TEMPERATURE

SAT Change

Linear Regression

Observed Trend

Numerical Simulation

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
III. SEA ICE and AIR TEMPERATURE

Sea Ice Response to Tropical Atlantic Warming

A Teleconnection between Atlantic and Antarctica

Linear Regression

Observed Trend

Numerical Simulation
III. SEA ICE and AIR TEMPERATURE

Sea Ice Response to Tropical Atlantic Warming

A Teleconnection between Atlantic and Antarctica

Linear Regression

Observed Trend

Numerical Simulation

Xichen Li, SIO - UCSD, CIMS - NYU
III. SEA ICE and AIR TEMPERATURE

Mechanism

Regression and simulation well reproduce the trend of SIC and SAT

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
III. SEA ICE and AIR TEMPERATURE

Mechanism

Regression and simulation well reproduce the trend of SIC and SAT

Mechanism: Mechanical Forcing & Thermal Advection

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Mechanism

Regression and simulation well reproduce the trend of SIC and SAT

Mechanism: Mechanical Forcing & Thermal Advection

Marie Byrd Land warming is not well explained by this mechanism

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
III. SEA ICE and AIR TEMPERATURE

Potential Impact on Land Ice

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Potential Impact on Land Ice

- **Zwally et al.** 2002

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Potential Impact on Land Ice

- **Zwally et al.** 2002
- **Bromirski et al.** 2010

A Teleconnection between Atlantic and Antarctica

Xichen Li, SIO – UCSD, CIMS - NYU
Summary: Atlantic Impacts on Antarctic Climate

- Atlantic – Antarctic Teleconnection Helps to Explain:
  
  **The Antarctic Ice Paradox**
  
  **The Sea Ice Redistribution**
  
  **The Rapid Peninsula Warming**
Summary: Atlantic Impacts on Antarctic Climate

- Atlantic – Antarctic Teleconnection Helps to Explain:
  - The Antarctic Ice Paradox
  - The Sea Ice Redistribution
  - The Rapid Peninsula Warming

- Further Contribute to
  - Land Ice Melting
  - Sea Level Rise
  - Deep Ocean Circulation
OUTLINE

- Background of this Study
  - Recently observed climate changes around Antarctica
  - Potential linkages of these changes to the Tropical Oceans

- Atmospheric Bridge between Atlantic and Austral Circulation
  - Analysis and model study of the Atlantic-Antarctica teleconnection
  - Physical Mechanisms and Rossby Wave Dynamics

- The Impacts on the Sea Ice and the Surface Temperature
  - Atlantic warming helps to explain Antarctic Paradox and Peninsula warming

- Conclusions and Future Research Plan
Recent Climate Changes over Antarctica

- **Atlantic – Antarctic Teleconnection**: SAM and ABSL

- **Impact on the Sea Ice and Surface Temperature**

- **Rossby Wave Depends on the Background Flow**: Seasonality

- **Linearity of Tropical Impacts on the Antarctic Circulation**
Recent Climate Changes over Antarctica

• **Atlantic – Antarctic Teleconnection**: SAM and ABSL
• *Impact on The Sea Ice and Surface Temperature*
• *Rossby Wave Depends on the Background Flow*: Seasonality
• *Linearity of Tropical Impacts on the Antarctic Circulation*
Recent Climate Changes over Antarctica

- **Atlantic – Antarctic Teleconnection**: SAM and ABSL
- **Impact on The Sea Ice and Surface Temperature**
- **Rossby Wave Depends on the Background Flow**: Seasonality
- **Linearity of Tropical Impacts on the Antarctic Circulation**
Recent Climate Changes over Antarctica

- Atlantic – Antarctic Teleconnection: SAM and ABSL
- Impact on The Sea Ice and Surface Temperature
- Rossby Wave Depends on the Background Flow: Seasonality
- Linearity of Tropical Impacts on the Antarctic Circulation
Discussion and Future Research Plan

• **Ocean – Ice – Air Interaction is not involved in Present Study, which require more observation and coupled model simulation**

• **Observations and estimations over Antarctica is inadequate/inaccurate, and could be Better Organized**
IV. CONCLUSION

Discussion and Future Research Plan

• *Ocean – Ice – Air Interaction is not involved in Present Study, which require more observation and coupled model simulation*

• *Observations and estimations over Antarctica is inadequate/inaccurate, and could be Better Organized*
Thanks 😊
Separate the Ocean Basins based on Observed SST Trend
III. LINEARITY OF DIFFERENT OCEANS

SST Trend as Model Forcing

A Teleconnection between Atlantic and Antarctica

Xichen Li, CIMS - NYU
A Teleconnection between Atlantic and Antarctica

Xichen Li, CIMS - NYU
III. LINEARITY OF DIFFERENT OCEANS

Linearity & Additive Property

A Teleconnection between Atlantic and Antarctica

Xichen Li, CIMS - NYU
III. LINEARITY OF DIFFERENT OCEANS

Linearity & Additive Property

A Teleconnection between Atlantic and Antarctica

Xichen Li, CIMS - NYU
III. LINEARITY OF DIFFERENT OCEANS

Linearity & Additive Property

A Teleconnection between Atlantic and Antarctica

Xichen Li, CIMS - NYU
A Teleconnection between Atlantic and Antarctica

Xichen Li, CIMS - NYU
III. LINEARITY OF DIFFERENT OCEANS

Linearity & Additive Property

A Teleconnection between Atlantic and Antarctica

Xichen Li, CIMS - NYU
Rossby Wave Source

A Teleconnection between Atlantic and Antarctica

Xichen Li, CIMS - NYU
Spatial Pattern Strongly Project on Southern Annular Mode (SAM)

- with spatial pattern correlation $> 0.8$
- A Teleconnection between Atlantic and Antarctica

Xichen Li, CIMS - NYU
Stationary Wave in Hoskins – Karoly model
Rossby Wave Trains

A Teleconnection between Atlantic and Antarctica

Xichen Li, CIMS - NYU
I. BACKGROUND

Recent Climate Change over Antarctica

ABSL trend

A Teleconnection between Atlantic and Antarctica