Introduction to Research
August 24, 2016

Research Projects and Student Opportunities in Lu Group

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Learn about our Earth!

Earth in the solar system

- What are the fundamental physical processes on the Earth driving its dynamics and chemistry?
- What is the link from the lower to upper atmosphere, and to the space?
- How does the solar activity affect the Earth? What impacts does the evolution of the solar system have on the Earth in the long-term?
- How accurate can models predict climate change? How timely can models predict solar storms? Will and how the models can mitigate potential hazardous effects?

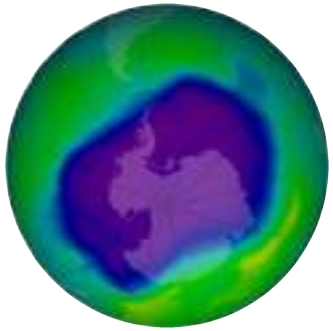
Motivations

- **More understanding about the fundamental processes on the Earth help us understand the whole universe and navigate safely across space.**

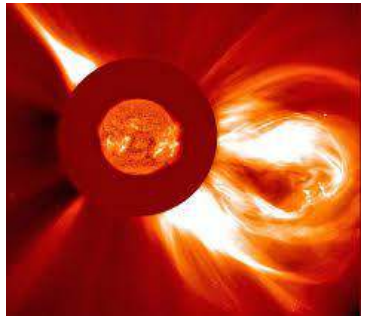
- **More knowledge about our planet help predict and prevent natural and human-caused hazards.**

Hurricane

Ozone Hole



Space Storm



- **Knowing more about the Earth help identify other habitable planets.**

In 5 billion years, the Sun will start helium-burning process and turn into a red giant star. When it expands, the outer layer will reach the Earth.

My Current Active Projects

My own research interests:

1) **Atmospheric Wave Dynamics and Coupling**
2) **Magnetosphere-Ionosphere-Thermosphere Coupling and Space weather**

1. **NSF (PI):** ***Exploration of lower-atmosphere wave forcing, vertical wave coupling and their impacts on the ionosphere and thermosphere variability using WAM, lidar and ISR***

   (10 Journal Papers, 5 Conference Papers, >20 Conference Presentations)

2. **NSF (Co-I):** ***Characterizing Gravity Waves and their Effects on the Antarctic Ozone Layer***

3. **NASA (PI):** ***Signatures of Energy Dissipation in the Magnetosphere-Ionosphere-Thermosphere Coupled System***

Three Important Waves

- Gravity wave (GW)

Period: minutes to hours

Scale: 10 km — A few thousand km

- Tides

Period: Subharmonics of a solar day

Planetary scale

- Planetary wave (PW)

Period: several days or stationary

Planetary scale

Why Waves?

A gravity wave roll over Tama, Iowa
Iowa Environmental Mesonet Webcam.

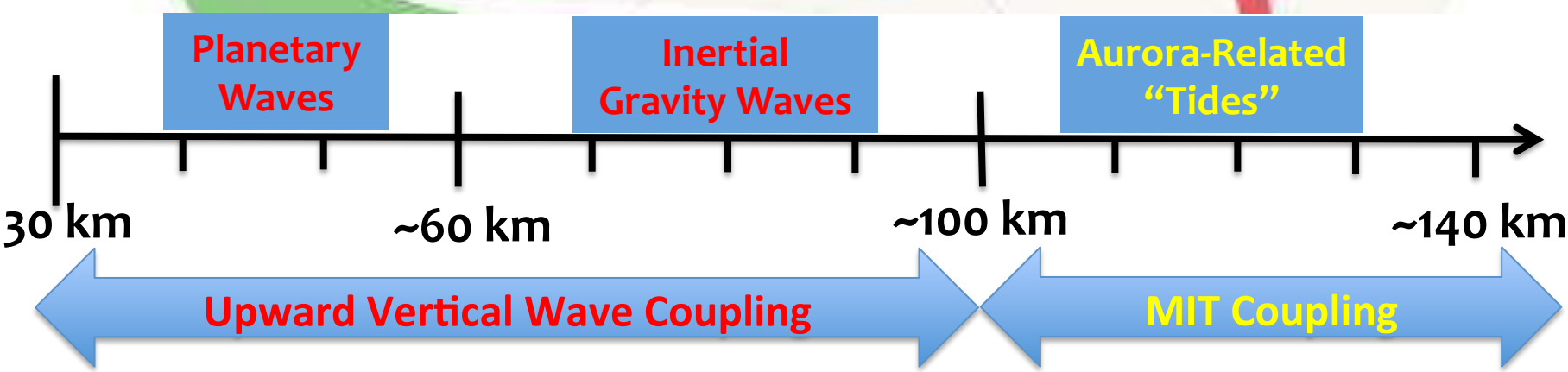
Simulation by high-resolution WACCM

- **In the middle and upper atmosphere, waves are ubiquitous and dominant.**
- **They transport momentum and energy, control the mean status and variability.**
- **They are the message carrier between lower-atmosphere weather and space weather.**
- **They are closely related to remarkable atmospheric phenomena such as thunderstorms, sudden stratospheric warming, Antarctic ozone hole, and etc.**

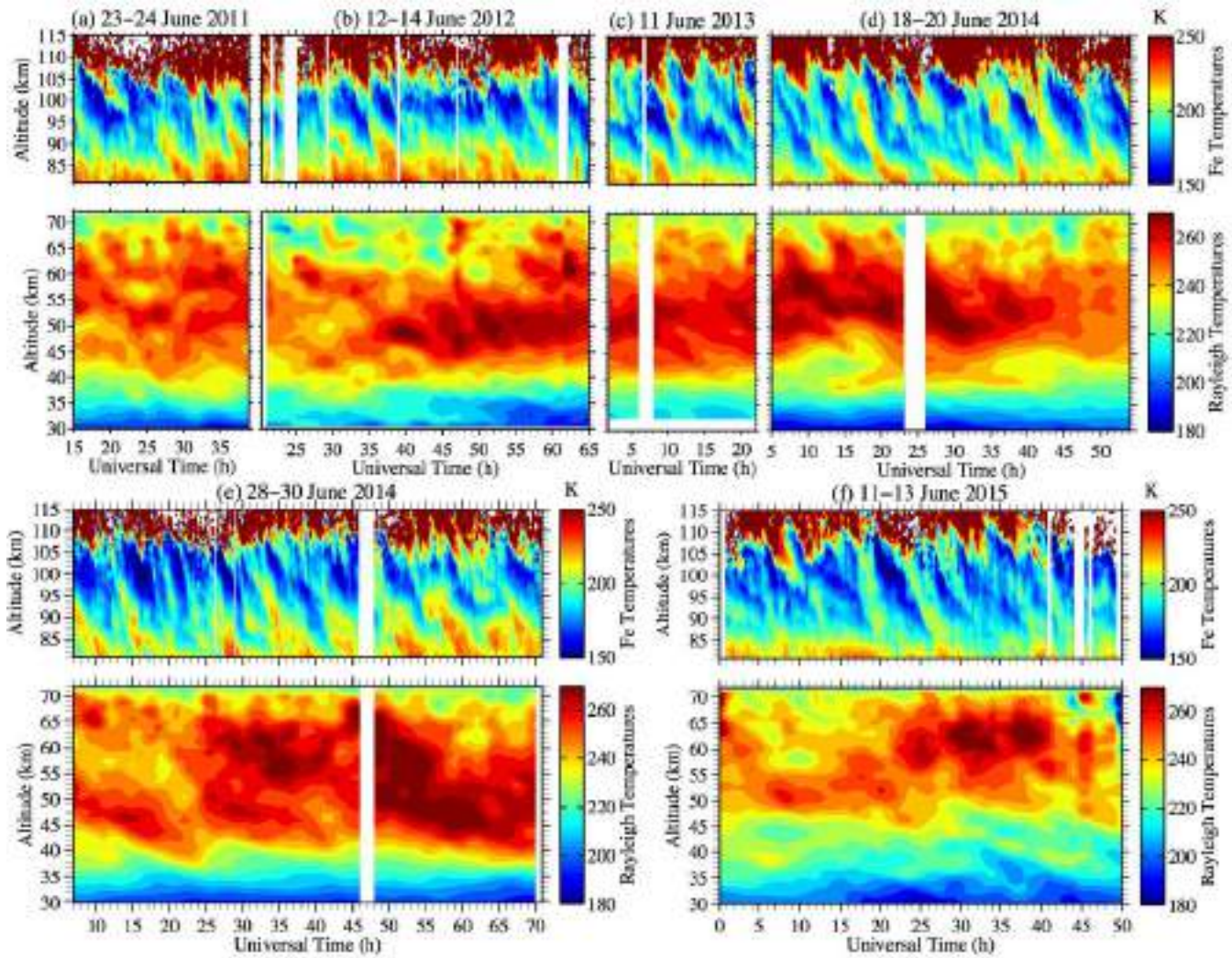
What have we learned from Project 1?

P1: ***Exploration of lower-atmosphere wave forcing, vertical wave coupling and their impacts on the ionosphere and thermosphere variability using WAM, lidar and ISR***

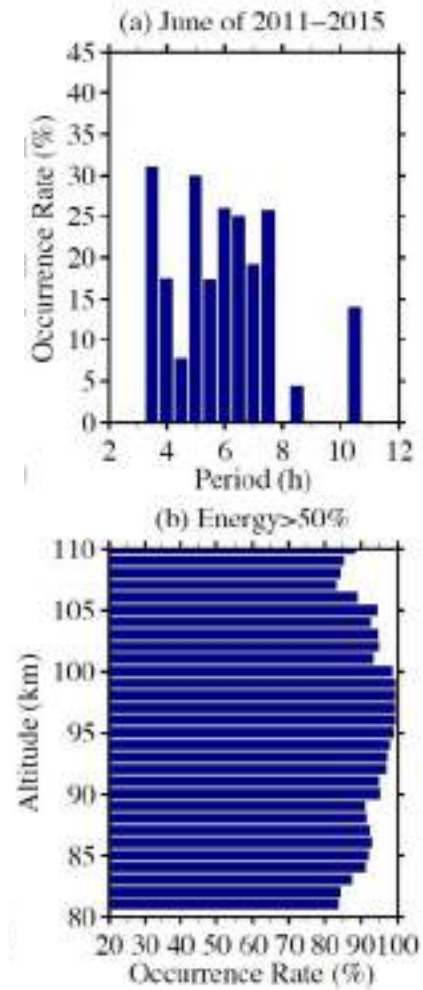
Atmospheric waves are playing a relay game in the Antarctic



Lidar Temperatures at McMurdo (78S), Antarctica



3-10 h Persistent IGWs



MLT (above 70 km): Inertial-Gravity Waves

Stratosphere (30-60 km): Planetary Waves

Chen et al., JGR, 2013, 2016

What questions have left from Project 1?

Two mysteries:

1) What are the sources for the persistent and strong IGWs?

Tools: Lidar Observation+ Ray-tracing model + General circulation models (GCMs)

2) How do PWs survive their critical level filtering and exist in the lower thermosphere (up to 110 km)?

Tools: PW model+ GCMs+Satellite/Lidar Observation

Student Opportunity 1

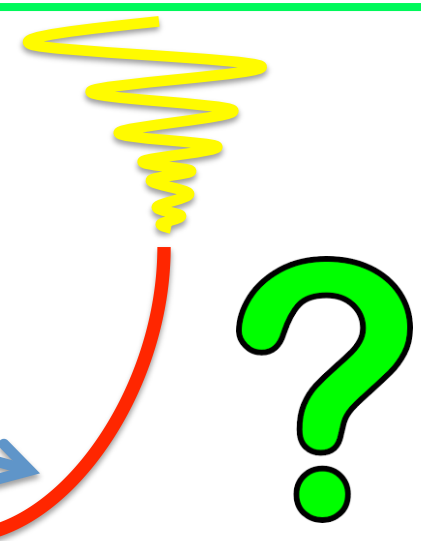
Ray Tracing Model: Search for Wave Source

Wave1 (k_0, l_0, m_0) Detected at (x_0, y_0, z_0)

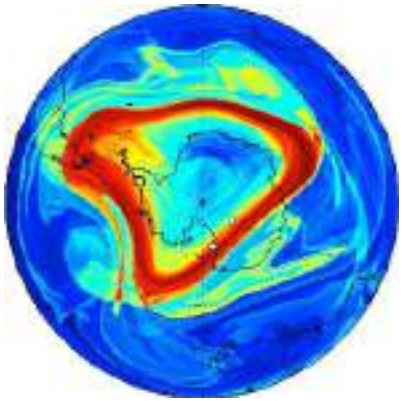
Background Winds (U, V)

Group Velocity (Cx, Cy, Cz)

Wave(k, l, m) Detected at (x, y, z) at former step



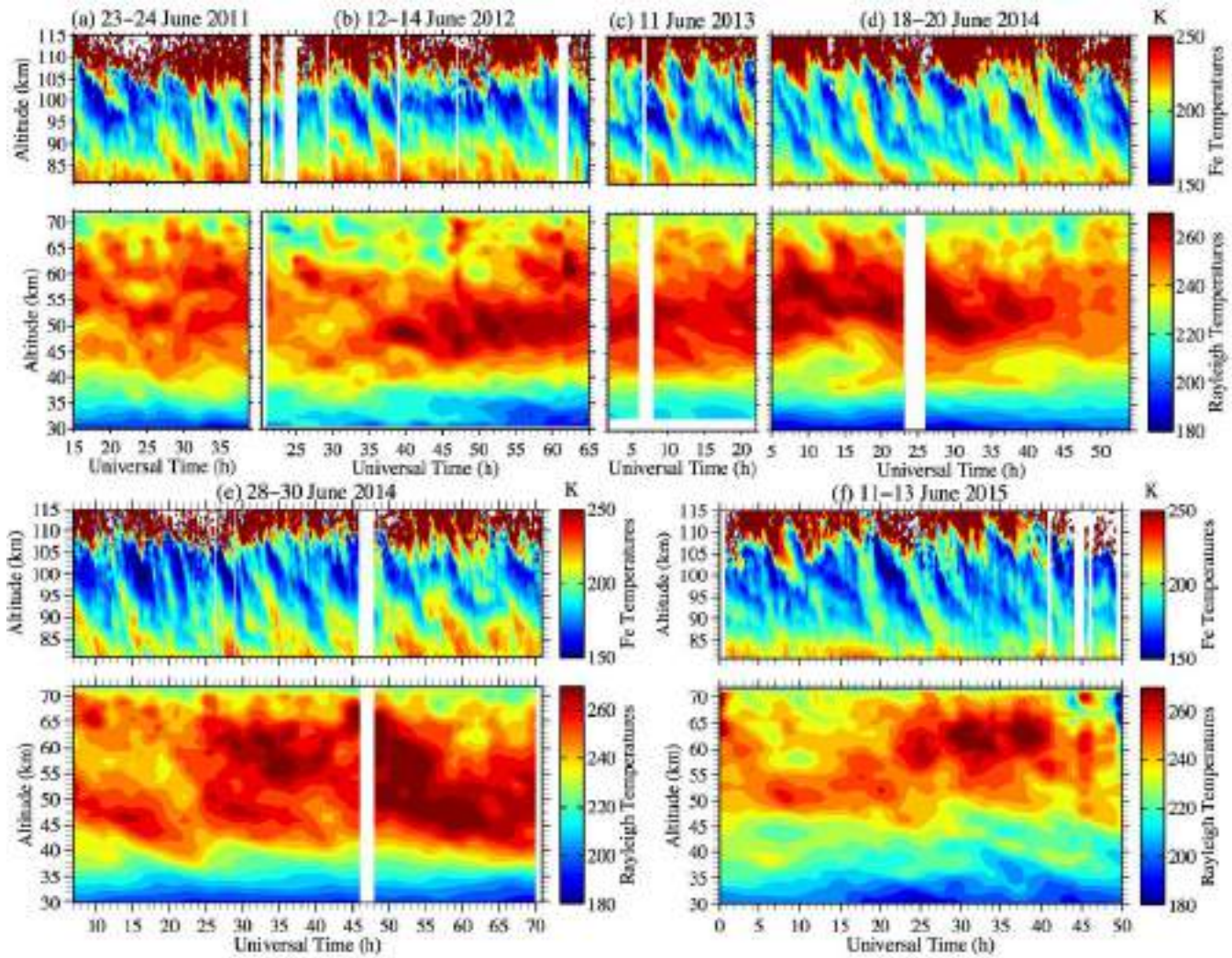
Polar Vortex Instability?



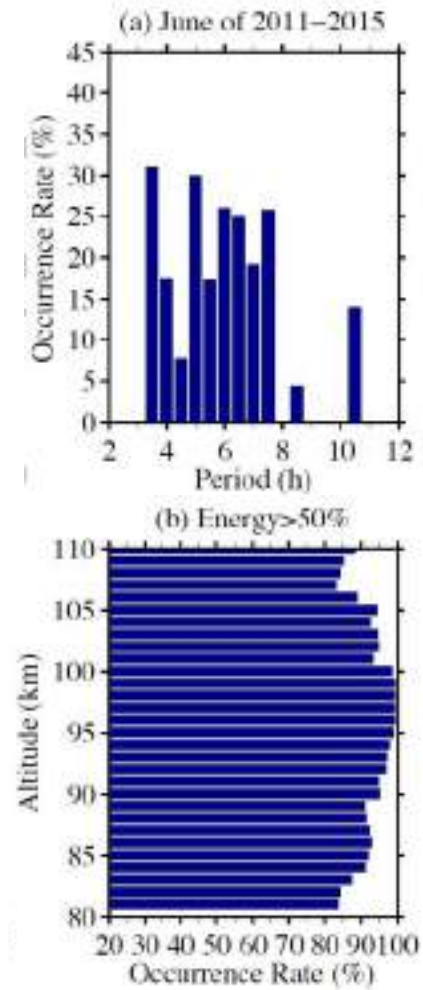
Topography+ Secondary Waves?

Resonant Vibration of Ross Ice Shelf?

Lidar Temperatures at McMurdo (78S), Antarctica



3-10 h Persistent IGWs

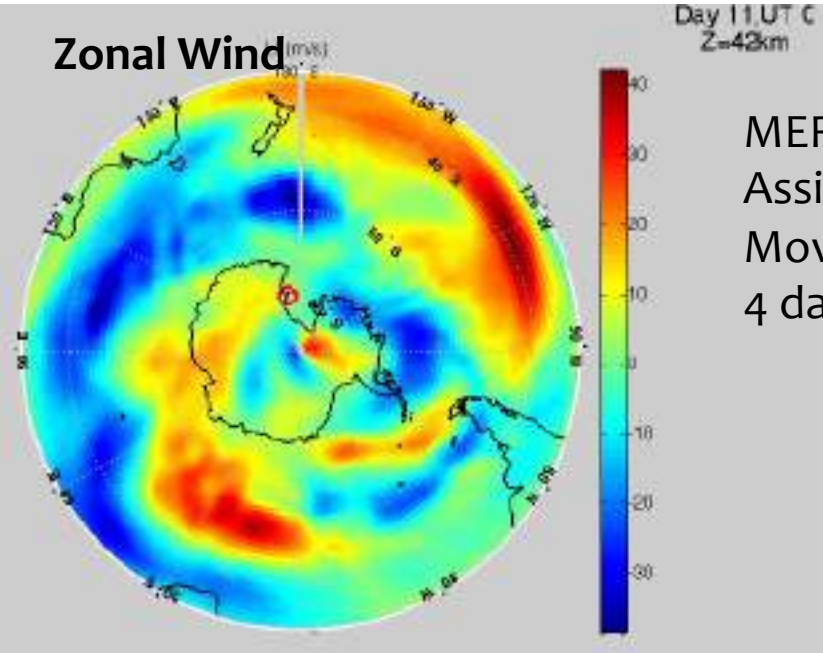


MLT (above 70 km): Inertial-Gravity Waves

Stratosphere (30-60 km): Planetary Waves

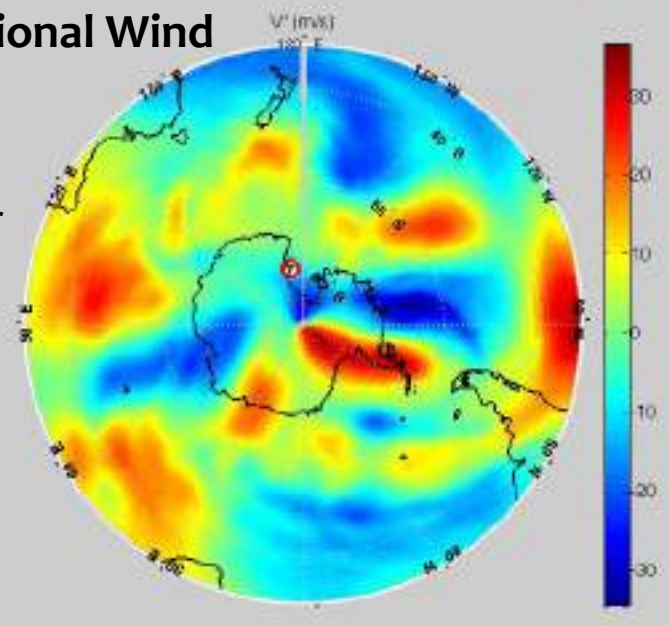
Chen et al., JGR, 2013, 2016

Zonal Wind



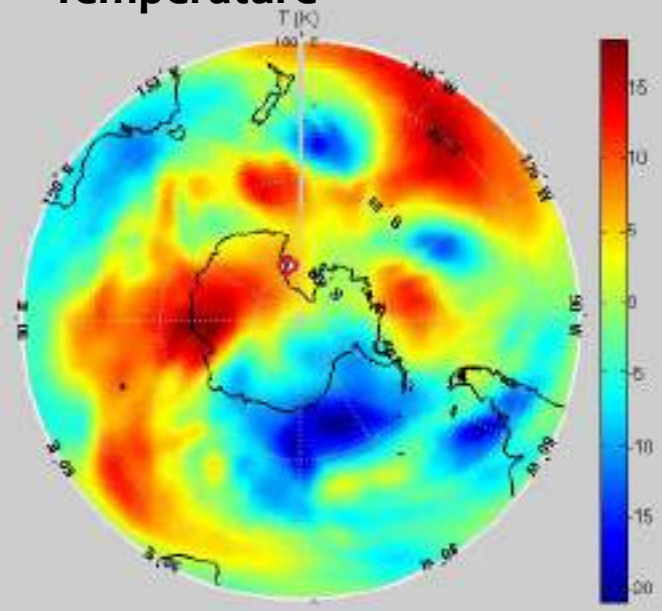
MERRA Assimilation Movie lasts for 4 days

Meridional Wind

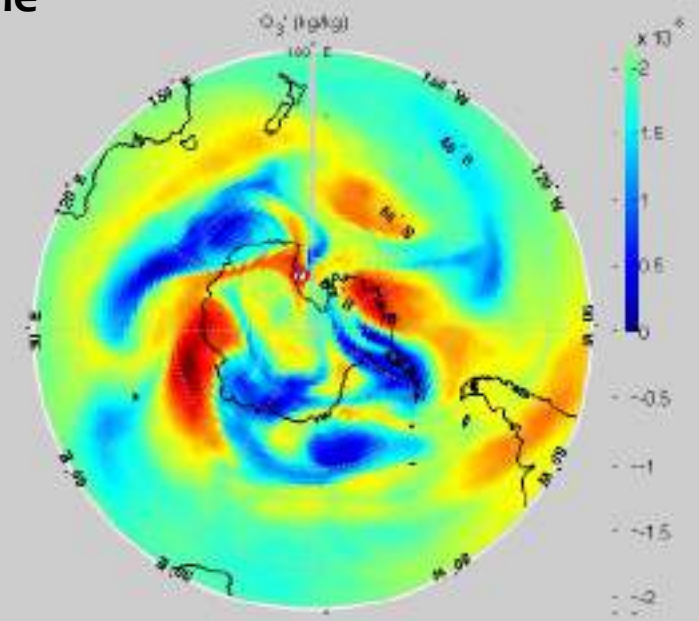


Planetary Waves Drive Polar Temperature, Winds and Ozone Variability

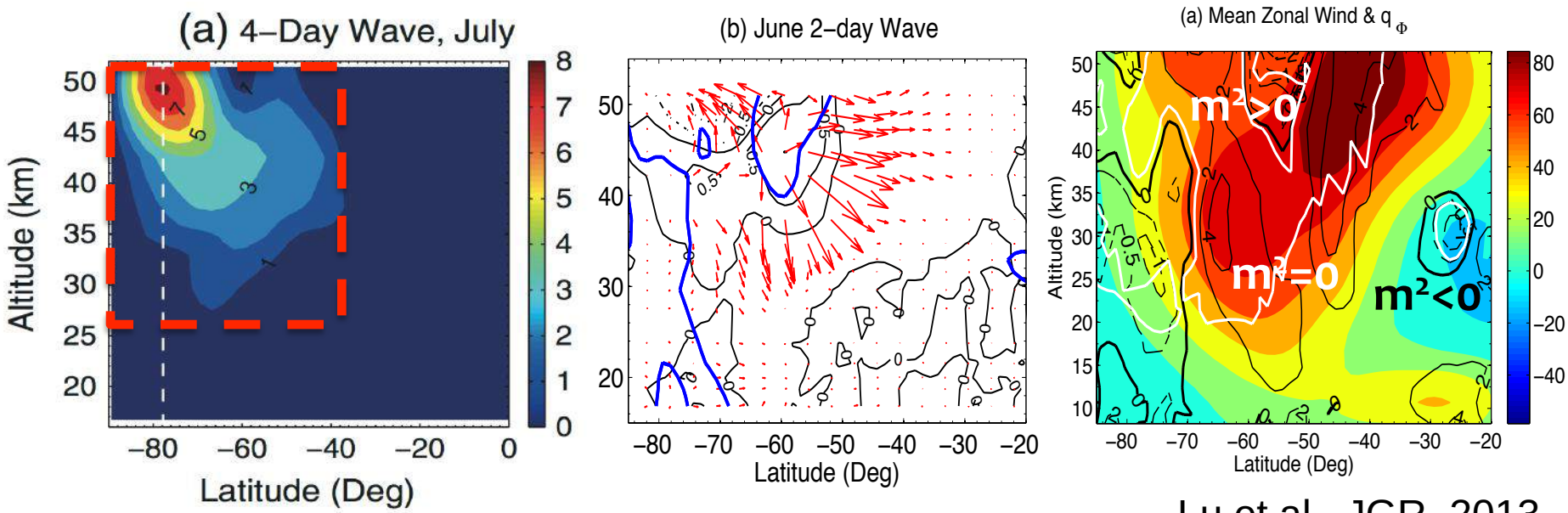
Temperature



Ozone



What have we learned about polar PWs?



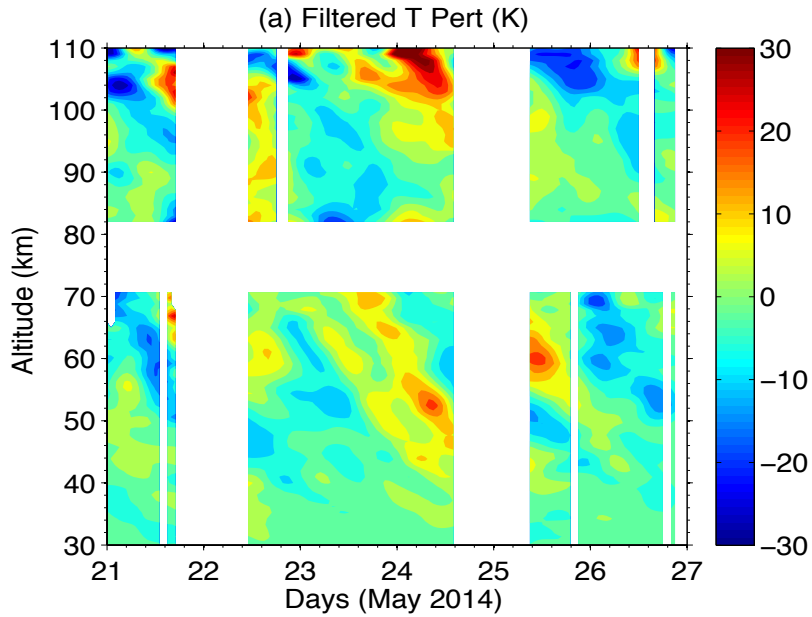
Lu et al., JGR, 2013

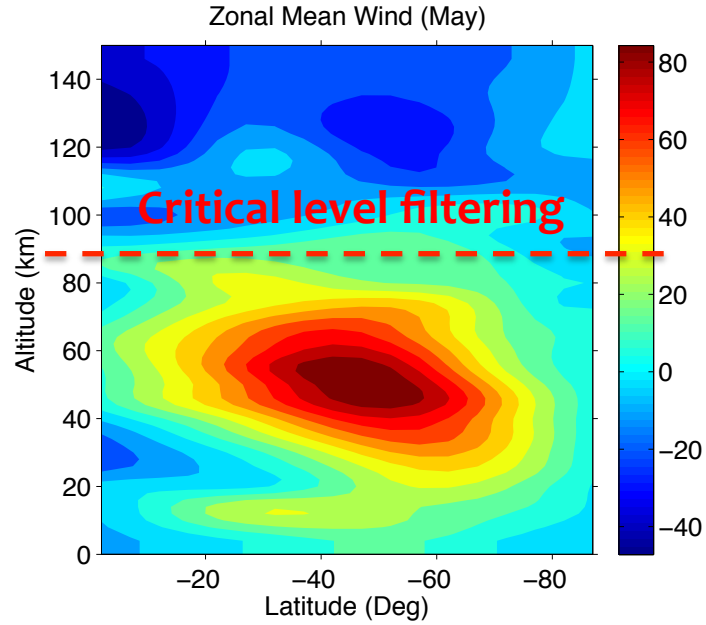
- Eastward traveling planetary waves with respective to grounds are dominant in the stratosphere.

- Wave source: Large wind shears of polar vortex cause instability.

- Refractive index becomes imaginary preventing wave propagation.

Mystery: how PWs reach upper atmosphere?

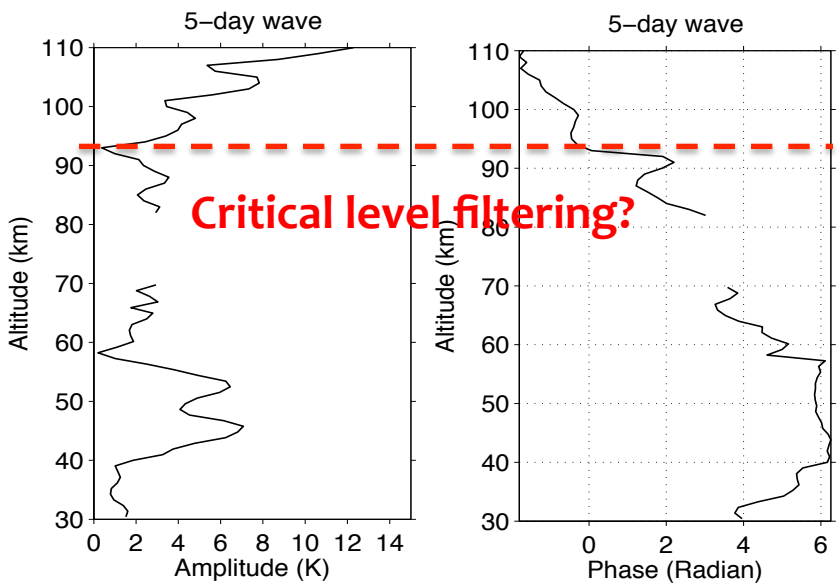


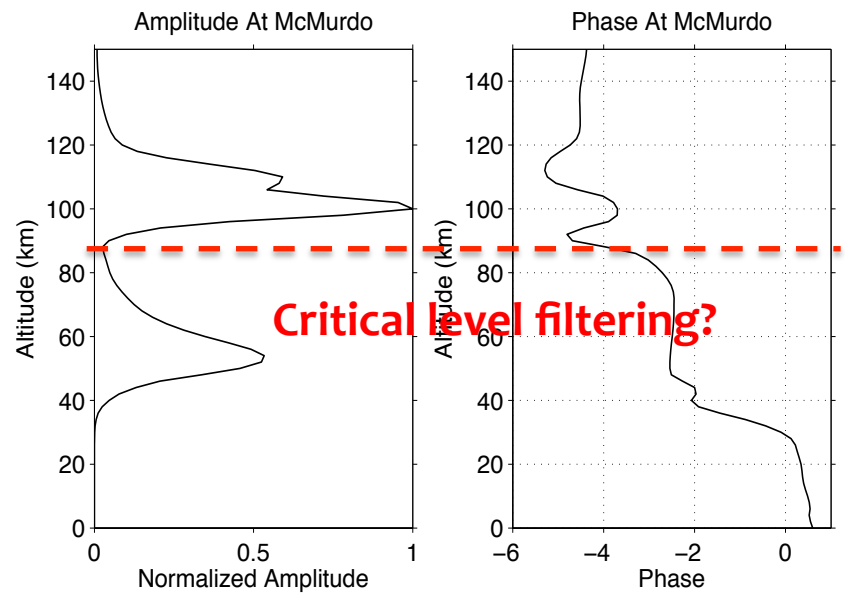


Lu et al., 2016b

Lidar

PW Model





Numerical Equations to Study PWs

We start from the vorticity equation of the QG model [*Hartmann*, 1979]:

$$\left(\frac{\partial}{\partial t}+\frac{\bar{u}}{a\cos\phi}\right)\left[\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{\sin^2\phi}\frac{\partial\Phi'}{\partial\phi}\right)+\frac{1}{\sin^2\phi\cos^2\phi}\frac{\partial^2\Phi'}{\partial\lambda^2}+(2\Omega a)^2\frac{1}{\rho}\frac{\partial}{\partial z}\left(\frac{\rho}{N^2}\frac{\partial\Phi'}{\partial z}\right)\right]+$$

$$\frac{1}{\cos\phi\sin^2\phi}\frac{\partial\bar{q}}{\partial\phi}\frac{\partial\Phi'}{\partial\lambda}=-(2\Omega a)^2\frac{1}{\rho}\frac{\partial}{\partial z}\left(\frac{\alpha\rho}{N^2}\frac{\partial\Phi'}{\partial z}\right)$$

$\Phi'=\psi(\phi,z,t)\exp(z/2H+im\lambda)$ is geopotential having a wave form along longitude λ.

$$\frac{\partial\bar{q}}{\partial\phi}=2\Omega\cos\phi-\frac{\partial}{\partial\phi}\left[\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\bar{u}\cos\phi}{a}\right)\right]-(2\Omega\sin\phi)^2\frac{a}{\rho}\frac{\partial}{\partial z}\left(\frac{\rho}{N^2}\frac{\partial\bar{u}}{\partial z}\right)$$ is vorticity gradient.

ϕ is latitude and α is newton cooling coefficient.

$$\left(\frac{\partial}{\partial t}+im\bar{\omega}\right)L(\psi)+\frac{im}{\cos\phi\,\sin^2\phi}\frac{\partial\bar{q}}{\partial\phi}\psi=-n^2K(\psi),$$

$$K(\psi)=\frac{\alpha}{N^2}\frac{\partial^2\psi}{\partial z^2}+\left(\frac{1}{N^2}\frac{\partial\alpha}{\partial z}+\alpha\frac{\partial N^{-2}}{\partial z}\right)\frac{\partial\psi}{\partial z}+\frac{1}{2H}\left(\frac{1}{N^2}\frac{\partial\alpha}{\partial z}+\alpha\frac{\partial N^{-2}}{\partial z}-\frac{\alpha}{2HN^2}\right)\psi.$$

$$L(\psi)=\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{\sin^2\phi}\frac{\partial\psi}{\partial\phi}\right)-\frac{m^2}{\sin^2\phi\,\cos^2\phi}\psi+\frac{n^2}{N^2}\left[\frac{\partial^2\psi}{\partial z^2}+N^2\frac{\partial N^{-2}}{\partial z}\left(\frac{\partial\psi}{\partial z}+\frac{\psi}{2H}-\frac{\psi}{4H^2}\right)\right],$$

Because it is a wave form along longitude, it becomes a 3-D problem as a function of latitude, altitude and time.

Numerical Scheme

Forward Time Difference:

$$\frac{\partial \psi}{\partial t} = \frac{\psi_{i,j}^{n+1} - \psi_{i,j}^{n}}{\Delta t}$$

$$\Delta t = 1.5h$$

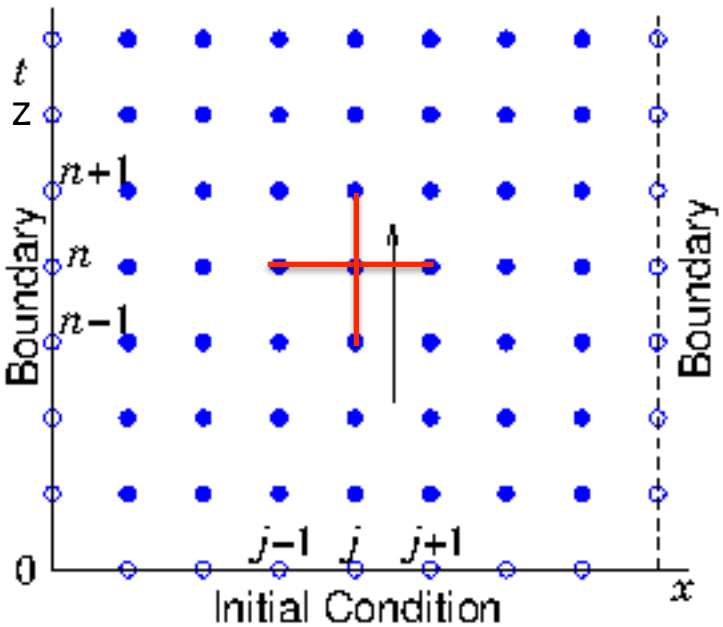
$$\Delta z = 2km$$

$$\Delta \phi = 5^\circ$$

Space Difference second order differential equation

$$\frac{\partial^2 \psi^n}{\partial z^2} = \frac{\psi_{i,j+1}^{n} - 2\psi_{i,j}^{n} + \psi_{i,j-1}^{n}}{\Delta z^2}$$

Grid Points



Matrix Method

$$\begin{bmatrix}
A_{1,1}^{1} & A_{2,1}^{1} & 0 & \cdots & 0 & A_{1,2}^{1} & 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\
A_{1,1}^{2} & A_{2,1}^{2} & A_{3,1}^{2} & 0 & \cdots & 0 & A_{2,2}^{2} & 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\
0 & A_{2,1}^{3} & A_{3,1}^{3} & A_{4,1}^{3} & 0 & \cdots & 0 & A_{3,2}^{3} & 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\
\vdots & 0 & A_{3,1}^{4} & A_{4,1}^{4} & A_{5,1}^{4} & 0 & \cdots & 0 & A_{4,2}^{4} & 0 & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\
\vdots & & 0 & & & & & & & & & & & & & \vdots \\
\vdots & & & 0 & & & & & & & & & & & & \vdots \\
\vdots & & & & 0 & & & & & & & & & & & \vdots \\
\vdots & & & & & 0 & & & & & & & & & & \vdots \\
\vdots & & & & & & 0 & & & & & & & & & \vdots \\
\vdots & & & & & & & 0 & & & & & & & & \vdots \\
\vdots & & & & & & & & 0 & & & & & & & \vdots \\
\vdots & & & & & & & & & 0 & & & & & & \vdots \\
\vdots & & & & & & & & & & 0 & & & & & \vdots \\
\vdots & & & & & & & & & & & 0 & & & & \vdots \\
\vdots & & & & & & & & & & & & & & & \vdots \\
0 & & & & & & & & & & & & & & A_{n*m,n*m}^{n*m} & A_{n*m,n*m}^{n*m}
\end{bmatrix}
\begin{bmatrix}
\psi_{1,1} \\ \psi_{2,1} \\ \psi_{3,1} \\ \vdots \\ \psi_{n,1} \\ \psi_{1,2} \\ \psi_{2,2} \\ \psi_{3,2} \\ \vdots \\ \psi_{n,2} \\ \vdots \\ \psi_{1,m} \\ \psi_{2,m} \\ \psi_{3,m} \\ \vdots \\ \psi_{n,m}
\end{bmatrix}
=
\begin{bmatrix}
B_{1,1} \\ B_{2,1} \\ B_{3,1} \\ \vdots \\ B_{n,1} \\ B_{1,2} \\ B_{2,2} \\ B_{3,2} \\ \vdots \\ B_{n,2} \\ \vdots \\ B_{1,m} \\ B_{2,m} \\ B_{3,m} \\ \vdots \\ B_{n,m}
\end{bmatrix}$$

$$A : [n \times m] \times [n \times m]$$

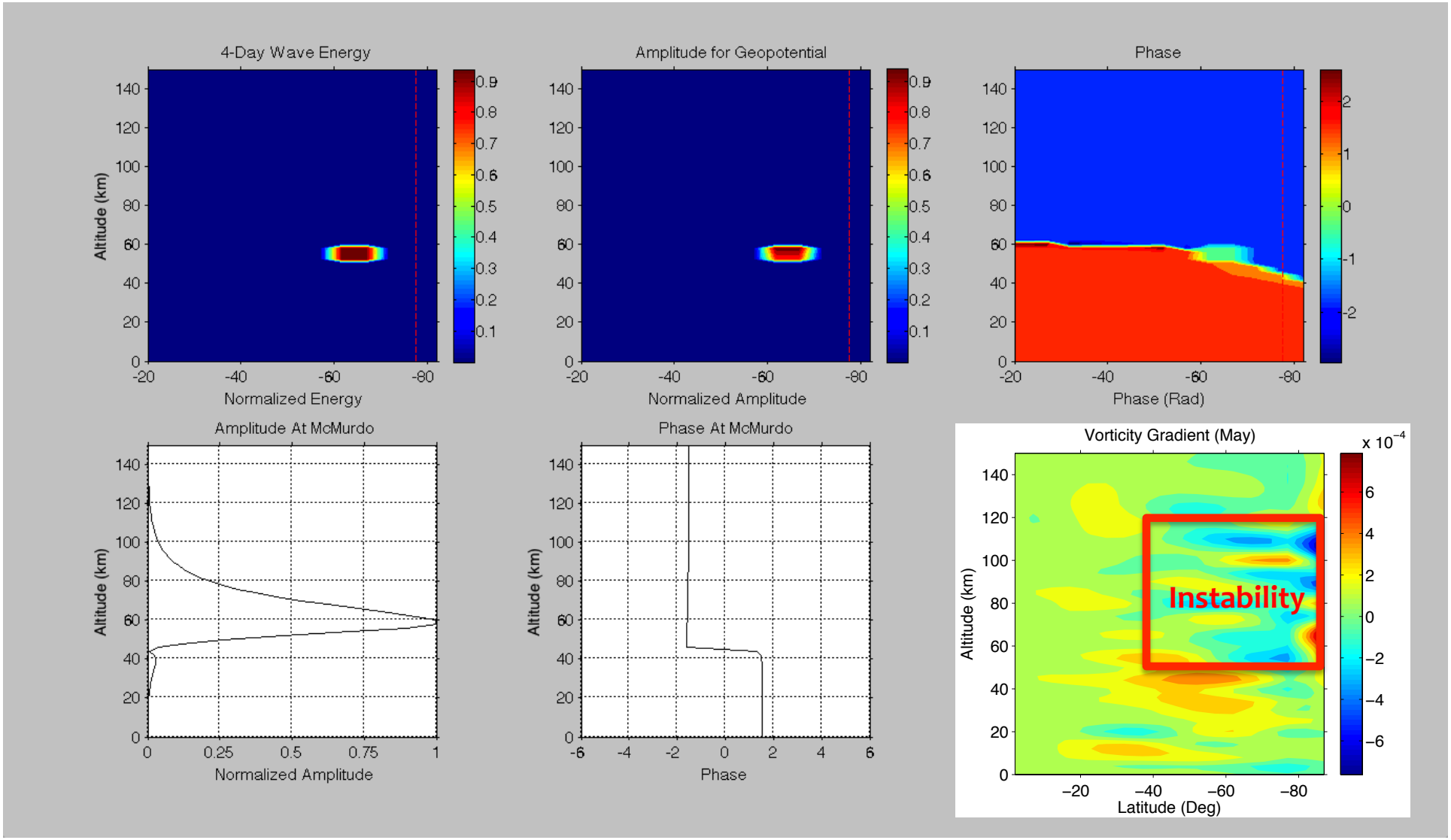
$$\psi : [n \times m] \times 1$$

$$B : [n \times m] \times 1$$

$$A = A(\psi^n, \Delta t, \Delta z)$$

$$B = B(\psi^n, \Delta t, \Delta z)$$

Simulation of PW Generation & Coupling



Wave Source: Instability of the Mean Winds

Lu et al., CEDAR, 2015

Potential Mechanisms?

- A QG model confirms the wave generation mechanism in the stratosphere and produces first-order wave structure.
- It doesn't give clear explanation for the existence of the waves in the upper atmosphere.

1. **Direct vertical propagation?**

2. **Mirror mechanism: PWs modulate GW activity in the lower atmosphere which propagate and project the PW signatures in the upper atmosphere?**

3. **In-situ instability in the upper atmosphere enhances the PWs?**

Next step: Implement GW effects

We start from the vorticity equation of the QG model [*Hartmann*, 1979]:

$$\left(\frac{\partial}{\partial t}+\frac{\bar{u}}{a\cos\phi}\right)\left[\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{\sin^2\phi}\frac{\partial\Phi'}{\partial\phi}\right)+\frac{1}{\sin^2\phi\cos^2\phi}\frac{\partial^2\Phi'}{\partial\lambda^2}+(2\Omega a)^2\frac{1}{\rho}\frac{\partial}{\partial z}\left(\frac{\rho}{N^2}\frac{\partial\Phi'}{\partial z}\right)\right]+$$

$$\frac{1}{\cos\phi\sin^2\phi}\frac{\partial\bar{q}}{\partial\phi}\frac{\partial\Phi'}{\partial\lambda}=-(2\Omega a)^2\frac{1}{\rho}\frac{\partial}{\partial z}\left(\frac{\alpha\rho}{N^2}\frac{\partial\Phi'}{\partial z}\right)$$

+ Gravity Wave Effects
+ More Realistic Mean winds

$\Phi'=\psi(\phi,z,t)\exp(z/2H+im\lambda)$ is geopotential having a wave form along longitude λ.

$$\frac{\partial\bar{q}}{\partial\phi}=2\Omega\cos\phi-\frac{\partial}{\partial\phi}\left[\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\bar{u}\cos\phi}{a}\right)\right]-(2\Omega\sin\phi)^2\frac{a}{\rho}\frac{\partial}{\partial z}\left(\frac{\rho}{N^2}\frac{\partial\bar{u}}{\partial z}\right)$$ is vorticity gradient.

ϕ is latitude and α is newton cooling coefficient.

$$\left(\frac{\partial}{\partial t}+im\bar{\omega}\right)L(\psi)+\frac{im}{\cos\phi\,\sin^2\phi}\frac{\partial\bar{q}}{\partial\phi}\psi=-n^2K(\psi),$$

$$K(\psi)=\frac{\alpha}{N^2}\frac{\partial^2\psi}{\partial z^2}+\left(\frac{1}{N^2}\frac{\partial\alpha}{\partial z}+\alpha\frac{\partial N^{-2}}{\partial z}\right)\frac{\partial\psi}{\partial z}+\frac{1}{2H}\left(\frac{1}{N^2}\frac{\partial\alpha}{\partial z}+\alpha\frac{\partial N^{-2}}{\partial z}-\frac{\alpha}{2HN^2}\right)\psi.$$

$$L(\psi)=\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{\sin^2\phi}\frac{\partial\psi}{\partial\phi}\right)-\frac{m^2}{\sin^2\phi\,\cos^2\phi}\psi+\frac{n^2}{N^2}\left[\frac{\partial^2\psi}{\partial z^2}+N^2\frac{\partial N^{-2}}{\partial z}\left(\frac{\partial\psi}{\partial z}+\frac{\psi}{2H}-\frac{\psi}{4H^2}\right)\right],$$

Because it is a wave form along longitude, it becomes a 3-D problem as a function of latitude, altitude and time.

Student Opportunity II

- Implement gravity wave effects or parameterization into the planetary wave model.
- Implement different background winds from GCMs with data assimilation (e.g. SD-WACCM) into the PW model.
- Study the vertical coupling process of planetary waves and their interactions with the mean and gravity waves.

2. NSF (Co-I): *Characterizing Gravity Waves and their Effects on the Antarctic Ozone Layer*

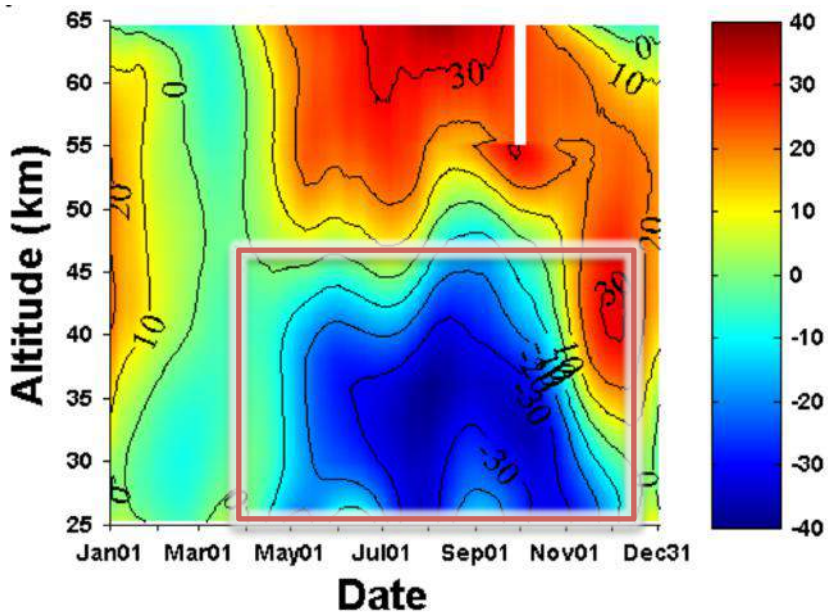
Long-lasting "Cold-Pole" Problem

Temperature → Polar Stratospheric Clouds → Ozone Depletion
→ hinders the accurate prediction of ozone formation and concentration.

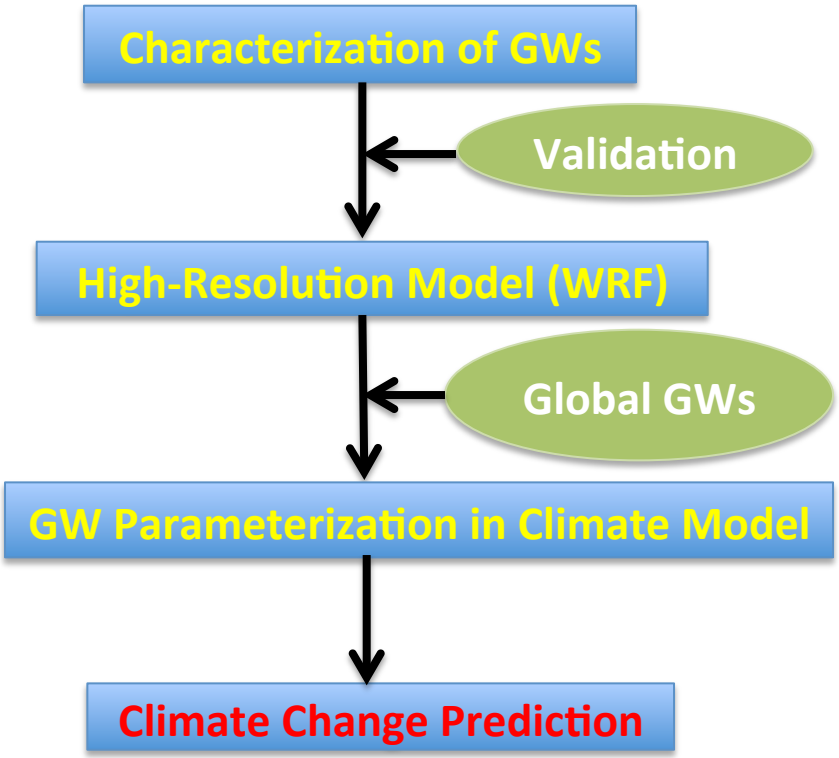
Ozone simulation significantly affect predictions of climate change, which are critical to assess the future inhabitability of the Earth.

One candidate for Cold Pole Problem: missing wave drag in the models.

(Model – Observation) @ South Pole

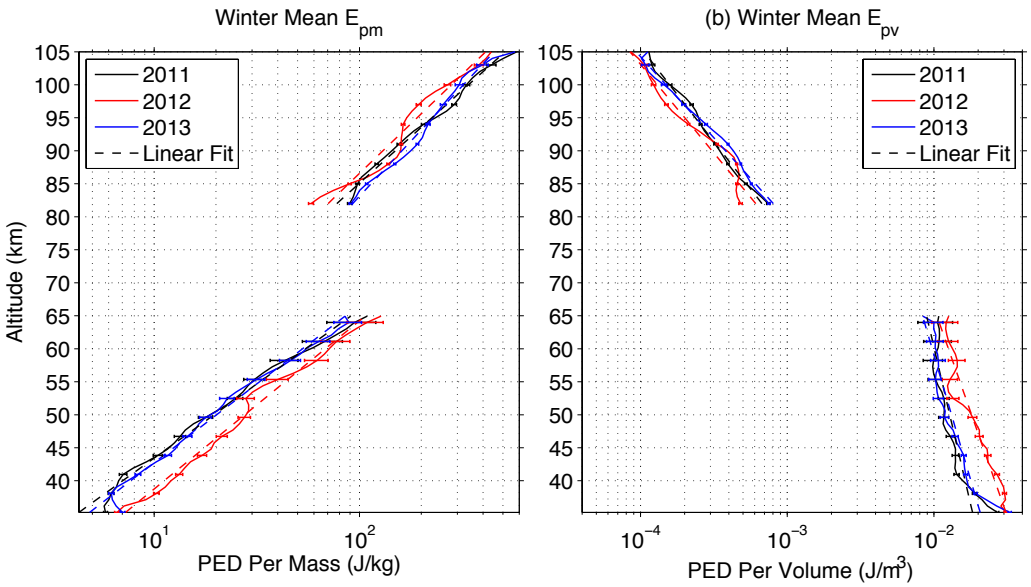


Tan et al., CEDAR, 2010



NSF-funded Project (Co-I): Characterizing Gravity Waves and their Effects on the Antarctic Ozone Layer

Gravity Wave Potential Energy Density



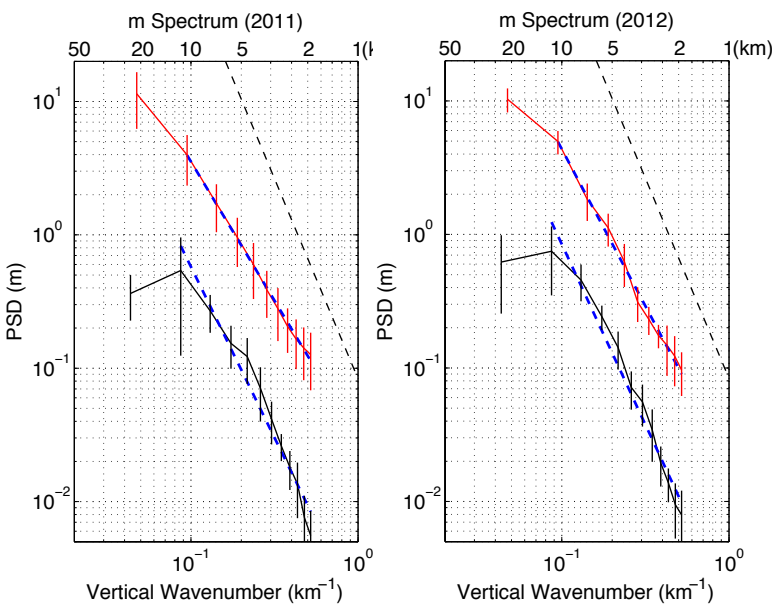
$$E_{pm}(z) = \frac{1}{2}\left(\frac{g}{N_0(z)}\right)^2 \overline{\left(\frac{T'(z)}{T_0(z)}\right)^2}$$

Growth Rate (Scale Height)

Region	Resolution	Vertical Filter	2011	2012	2013
Fe	(1 h, 1 km)	No	12.2±0.4*	13.0±0.8	14.5±0.6
		Yes*	14.2±1.0	13.0±1.0	15.6±1.0
	(0.25 h, 0.5 km)	No	11.8±0.3	13.1±0.6	12.2±0.3
		Yes	15.3±0.6	12.0±0.4	13.2±0.4
Rayleigh	(1 h, 1 km)	No	9.8±0.3	11.1±0.4	10.4±0.3
		Yes	12.2±0.3	13.6±0.5	12.8±0.4

Lu et al., JGR, 2015a

Gravity Wave Vertical Wavenumber Spectra



$$F(m_k) = \frac{\Delta z \left| f(m_k) \right|^2}{N} = \frac{\Delta z}{N} \left| \sum_{n=1}^{N} x(z_n) e^{-\frac{2\pi(n-1)(k-1)}{N} i} \right|^2$$

Altitudes	Resolution	2011	2012	2013
35–60 km	(1h, 1km)	-2.56±0.17*	-2.70±0.15	-2.47±0.18
81–105 km	(1h, 1km)	-2.08±0.03	-2.35±0.07	-2.26±0.04
	(0.25h, 1 km)	-1.98±0.03	-2.23±0.05	-2.10±0.04
	(1h, 0.5 km)	-2.18±0.05	-2.39±0.05	-2.33±0.04
	(0.25h, 0.5 km)	-1.99±0.05	-2.22±0.05	-2.15±0.05

PSD Slopes

Lu et al., JGR, 2015a

Student Opportunity III

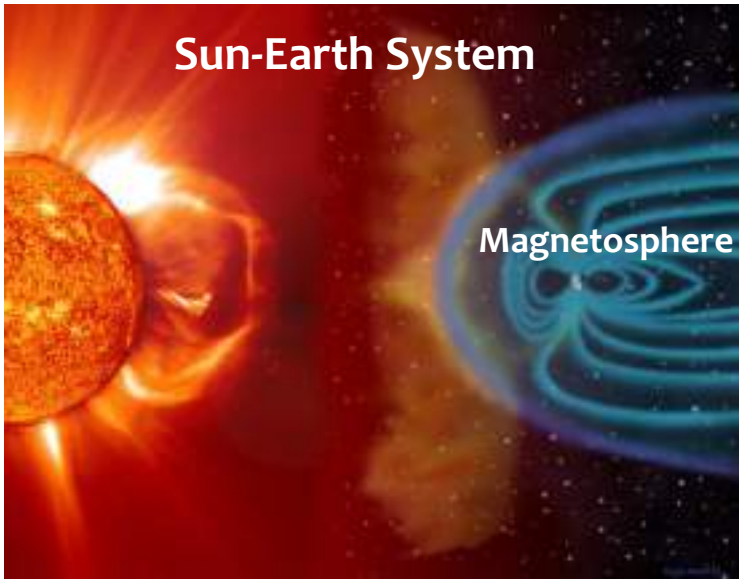
- Analyze the gravity wave characteristics and extend the database of their potential energy densities and vertical wavenumber spectra to 6 (2011-2016) years.

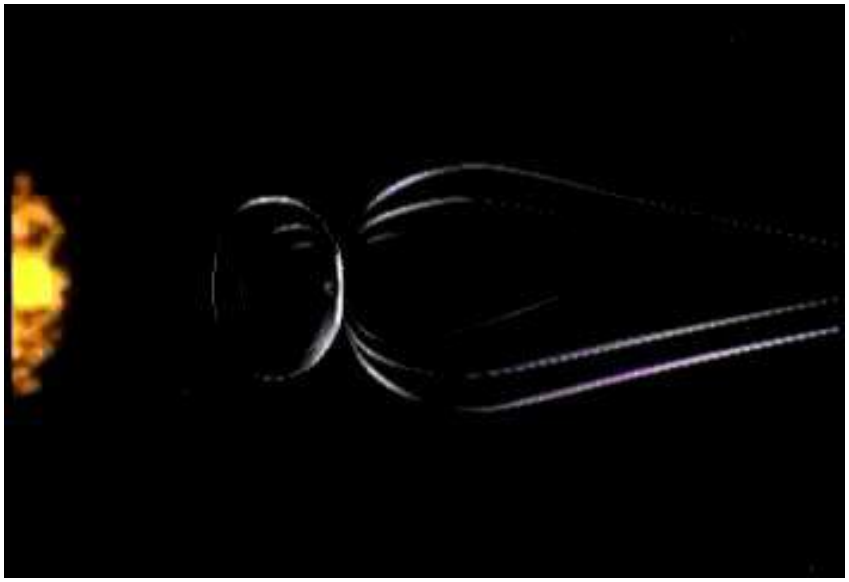
- Analyze the gravity wave characteristics using the same method in high-resolution model (WRF) and compare with the observations.

- Help the team to improve the gravity wave parameterization in the climate models.

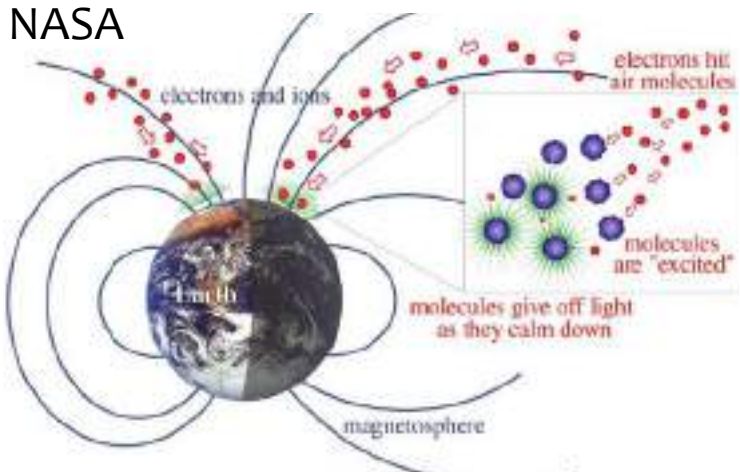
3. NASA (PI): *Signatures of Energy Dissipation in the Magnetosphere-Ionosphere-Thermosphere Coupled System*

Magnetosphere Energy Dissipation





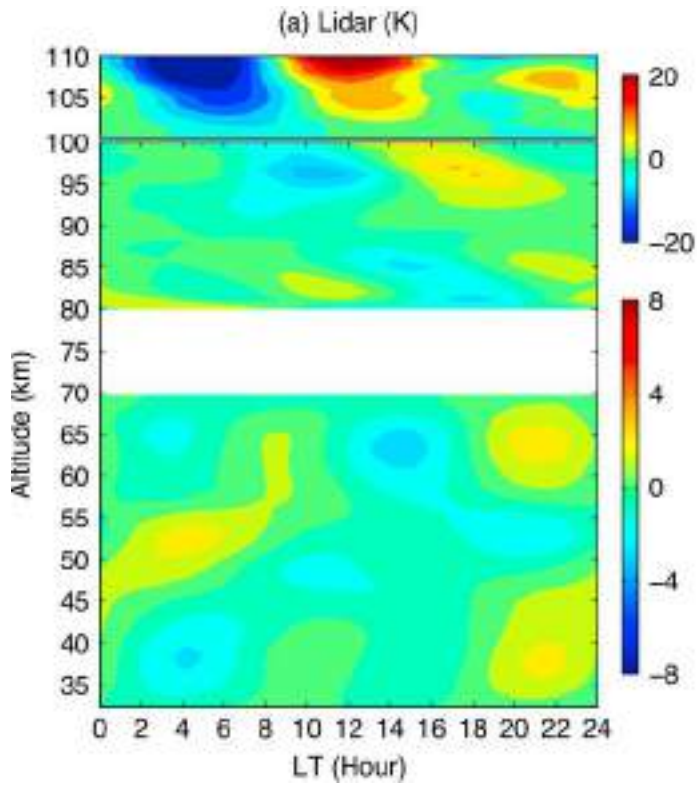
Credits: NASA



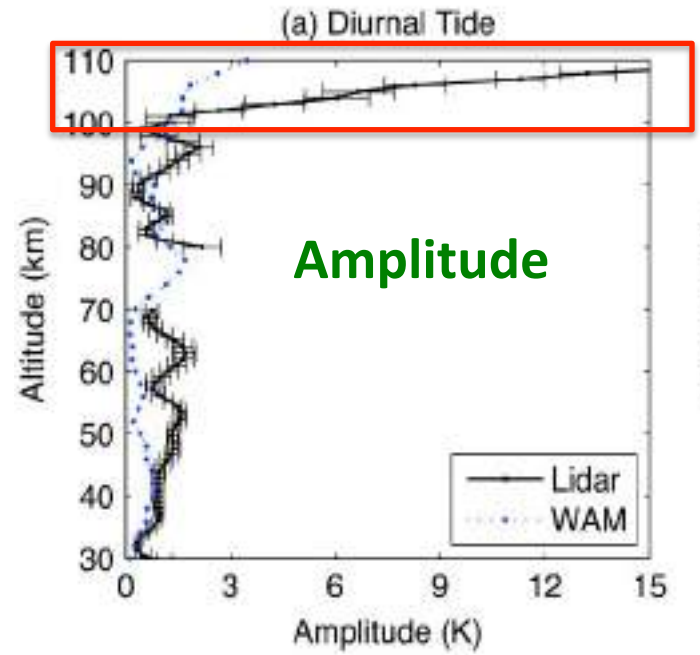
We see aurora because of the magnetosphere-ionosphere-thermosphere (MIT) coupling

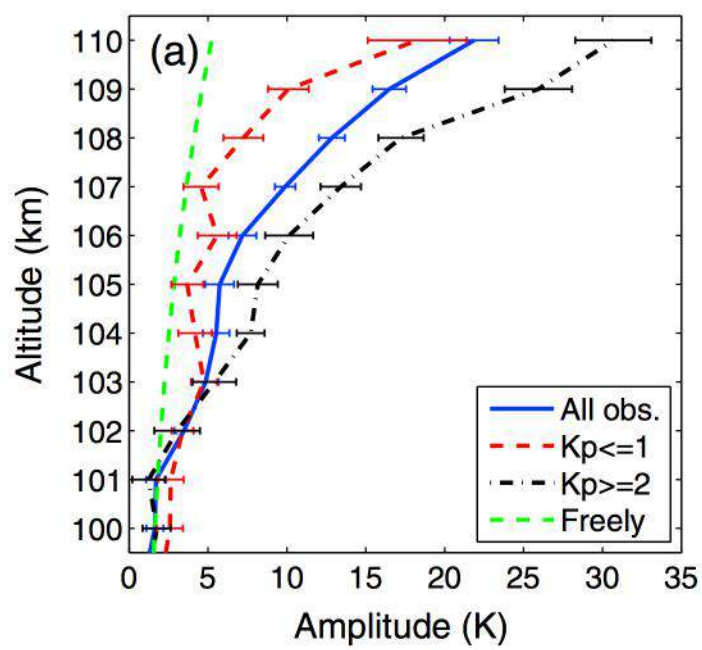
Wave III Atmospheric "Tides"

Diurnal Composition at McMurdo



Fong, Lu, Chu et al., JGR, 2014

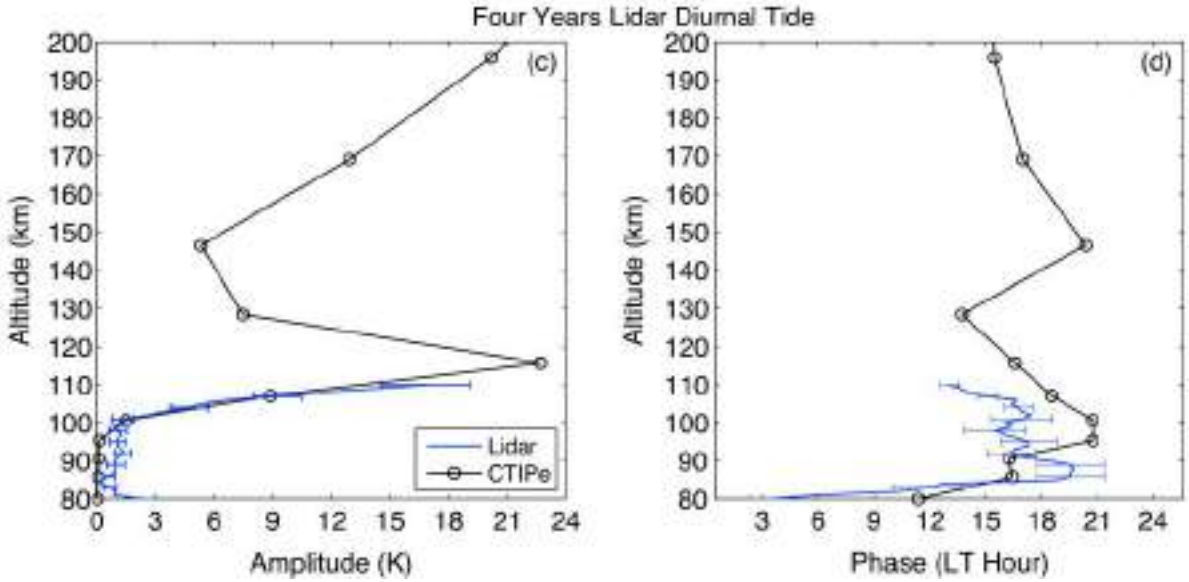


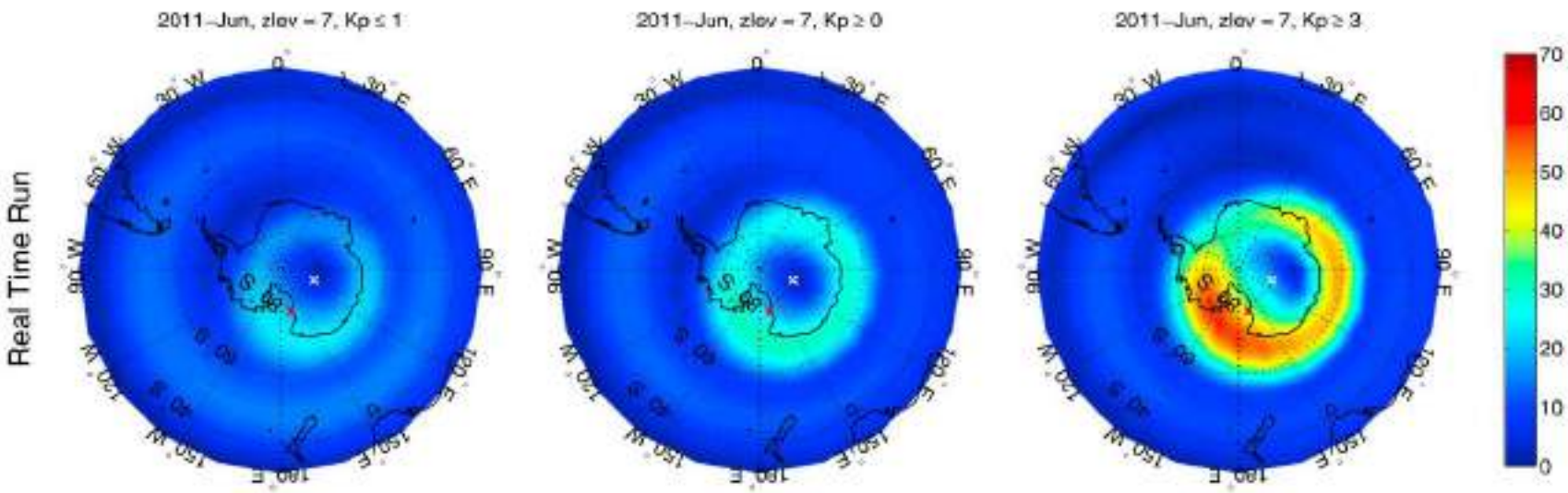


Super-exponential increases of tidal amplitudes and Kp dependence illustrate magnetic source for the "tide".

CTIPe model simulation of "Tides"

Coupled **T**hermosphere **I**onosphere **P**lasmasphere **E**lectrodynamics





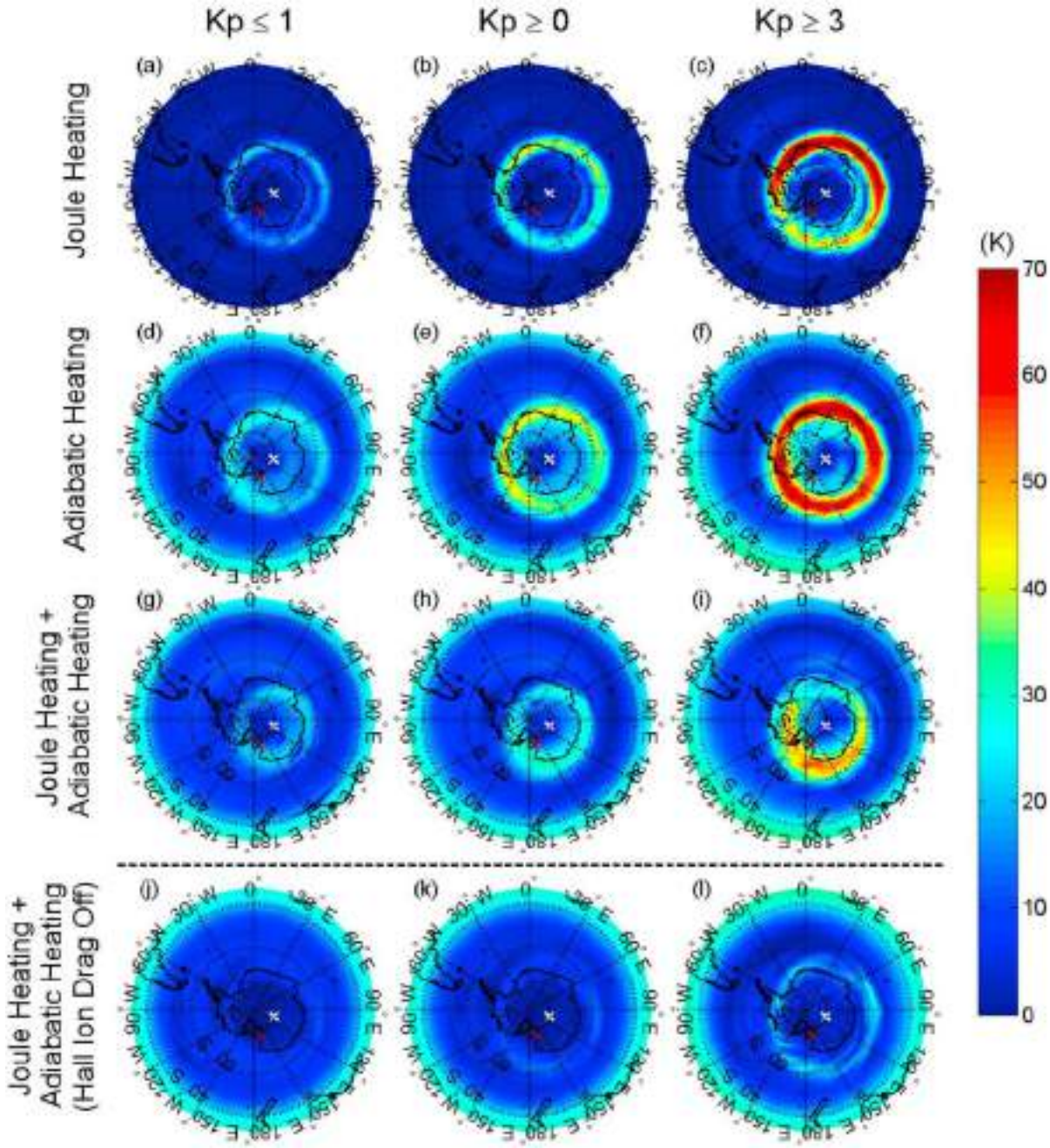
Fong, Chu, Lu et al., GRL, 2015

Joule Heating

Adiabatic Heating

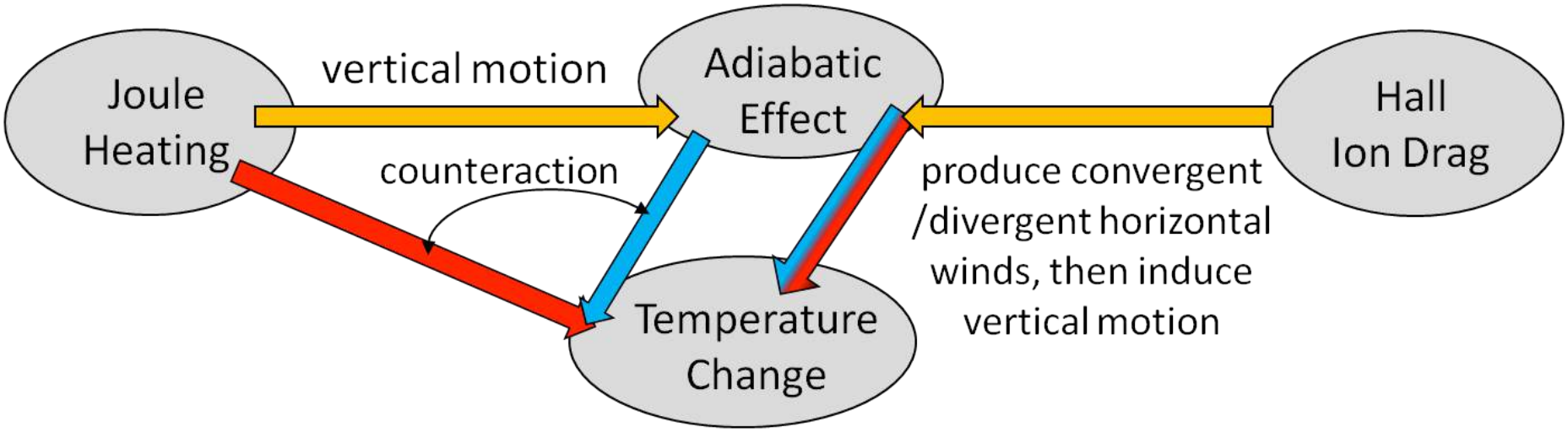
Joule+Adiabatic Heating

Joule+Adiabatic Heating Ion Drag Off



Fong, Chu, Lu et al., GRL, 2015

Conclusions for "Tidal" Source



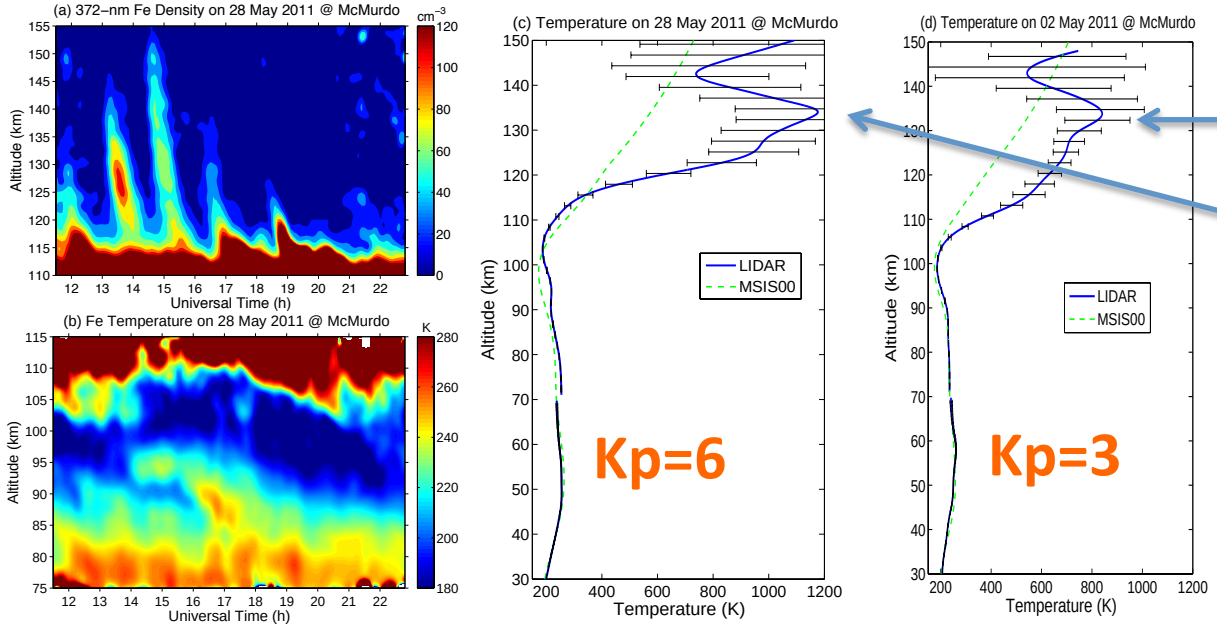
- Joule heating is a minor contributor due to the counteraction by Joule-heating-induced adiabatic cooling.

- Adiabatic cooling/heating associated with Hall ion drag is the dominant source.

- Sum of total dynamical effects and Joule heating explains ~80% of temperature diurnal amplitude.

Mystery: T Inversion Layer (~130 km) During Storms

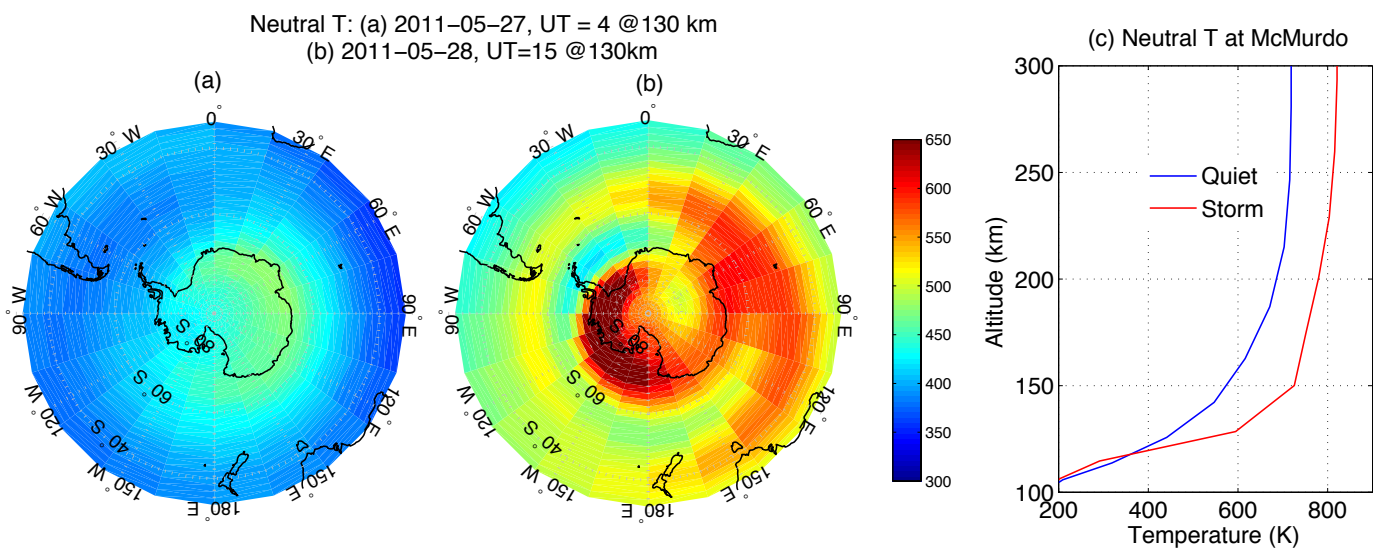
Discovery of Thermospheric Metal Layers at McMurdo



The T increase and inversion is missing in the IT model

[Chu et al., GRL, 2011]

CTIPe Model Simulation

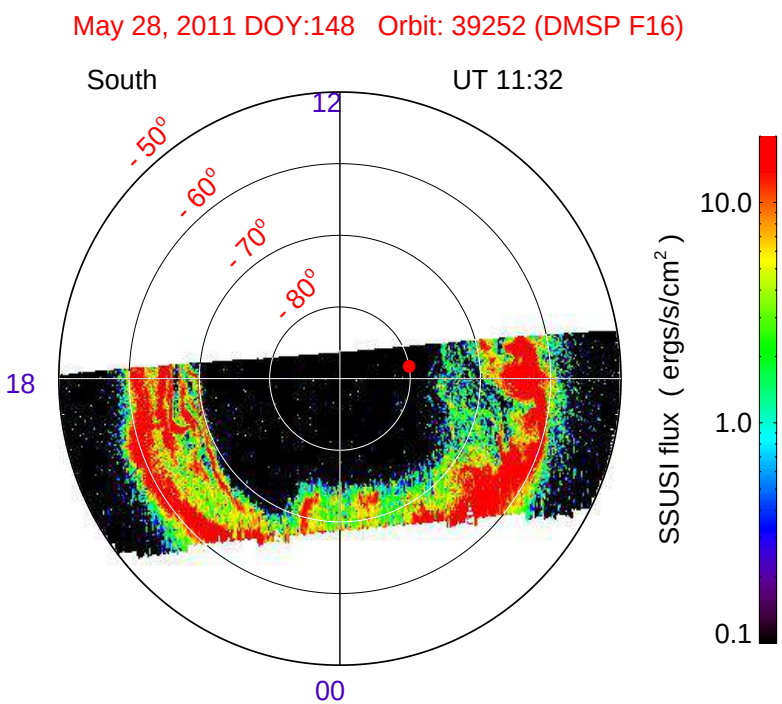


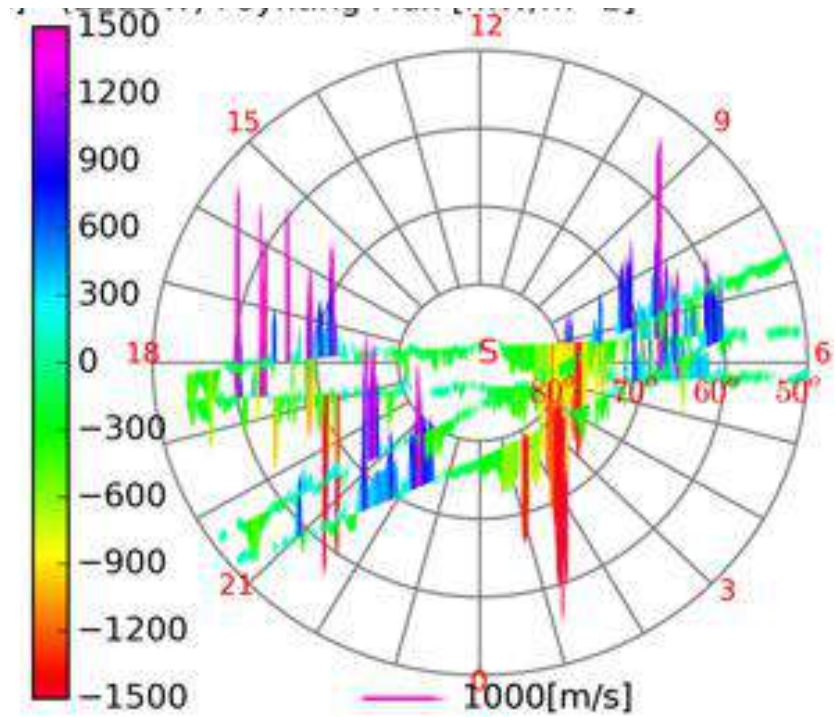
Local Effects!!!

Challenges for IT Models

Most Ionosphere-Thermosphere (IT) models are still driven by statistical auroral maps and convection fields which may underestimate the local structure of heating.

Energy Flux & Ion Drift by DMSP

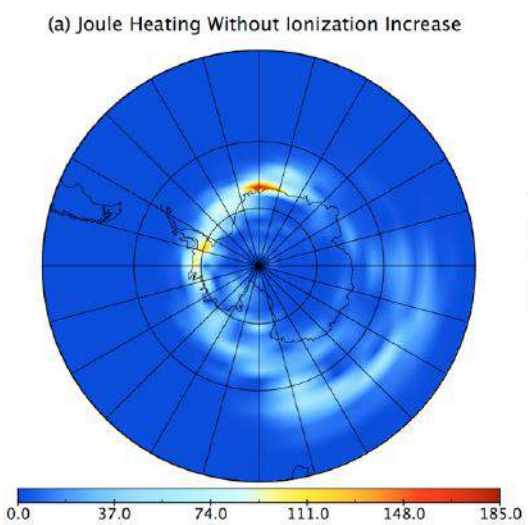


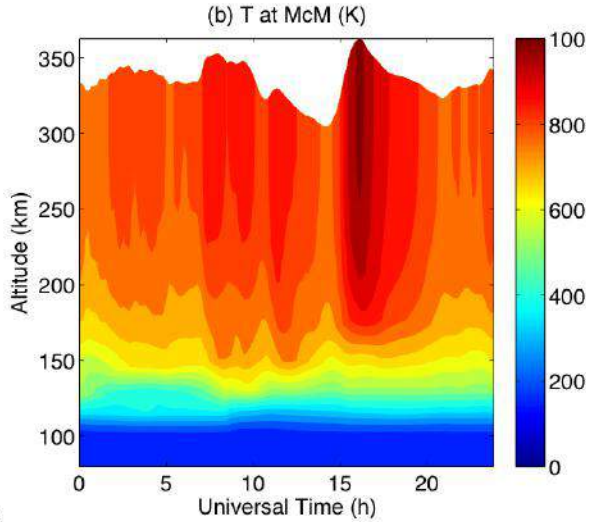


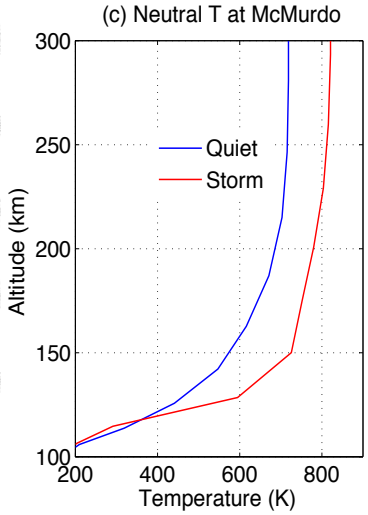
It is time to go beyond a global 'statistical' picture and use recent new observations to quantify how the magnetospheric energy is dissipated locally.

CTIPe Model with Enhanced Ionization Produces Observed Temperature Structure

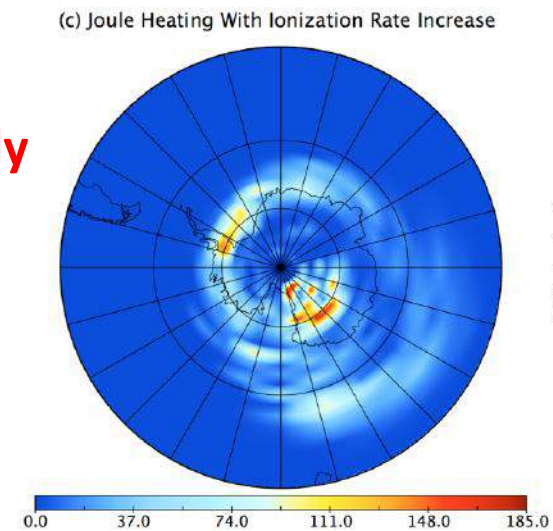
Without Enhanced Ionization

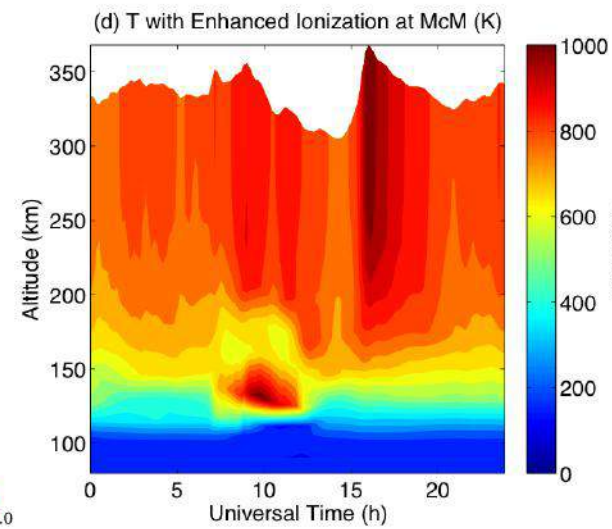


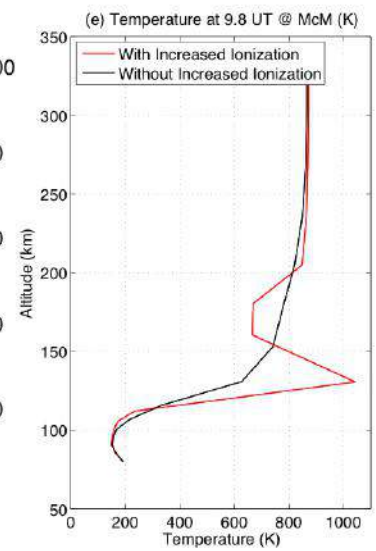




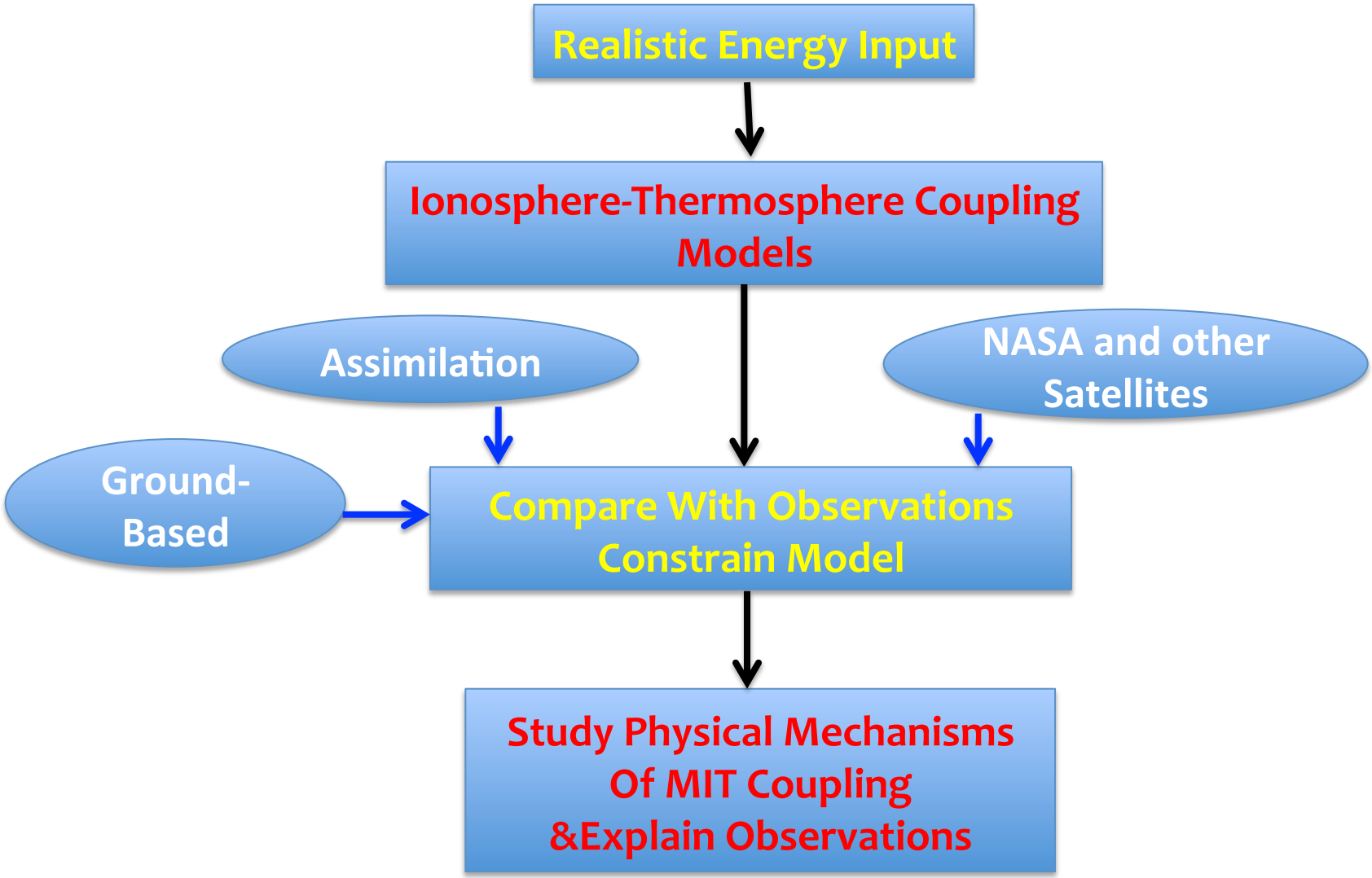
With locally Enhanced Ionization







Student Opportunity IV

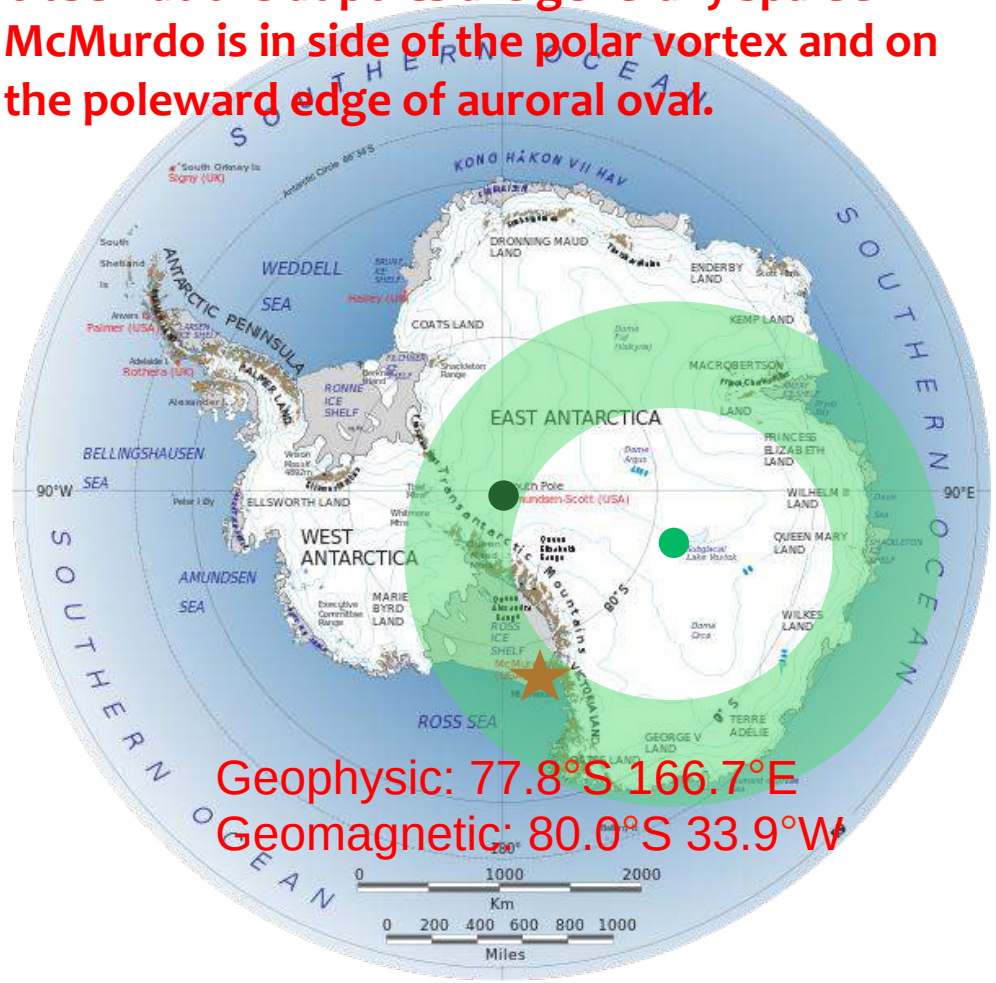


NASA-funded Project (PI): Signatures of Energy Dissipation in the Magnetosphere-Ionosphere-Thermosphere Coupled System

Student Opportunity to Develop Experimental Skills

McMurdo Lidar Campaign

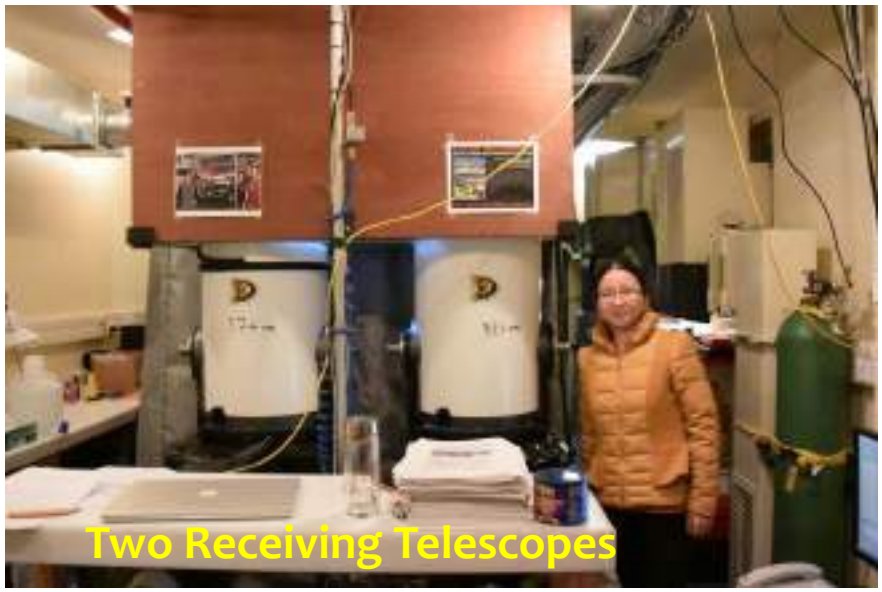
Observations at poles are generally sparse. McMurdo is in side of the polar vortex and on the poleward edge of auroral oval.

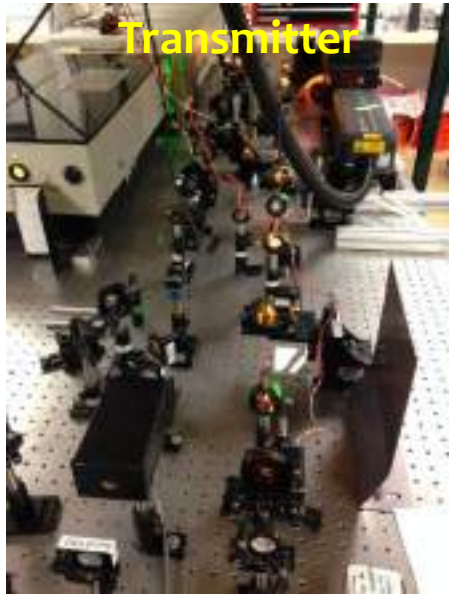


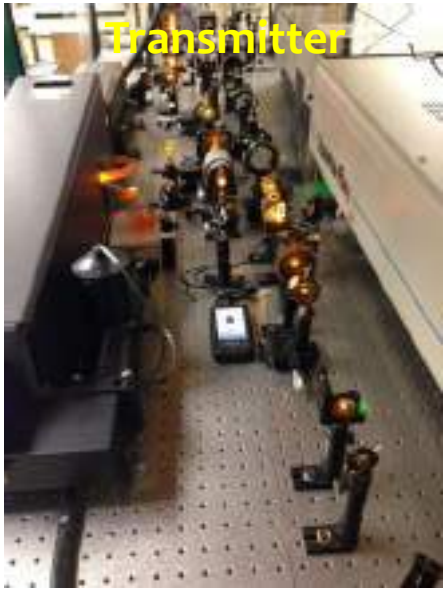
2015-2016 Summer

From L to R: Dr. Xinzhao Chu, Dr. Xian Lu, Ian Barry, Muzhou Lu

Working on Lidar in Antarctica and Boulder

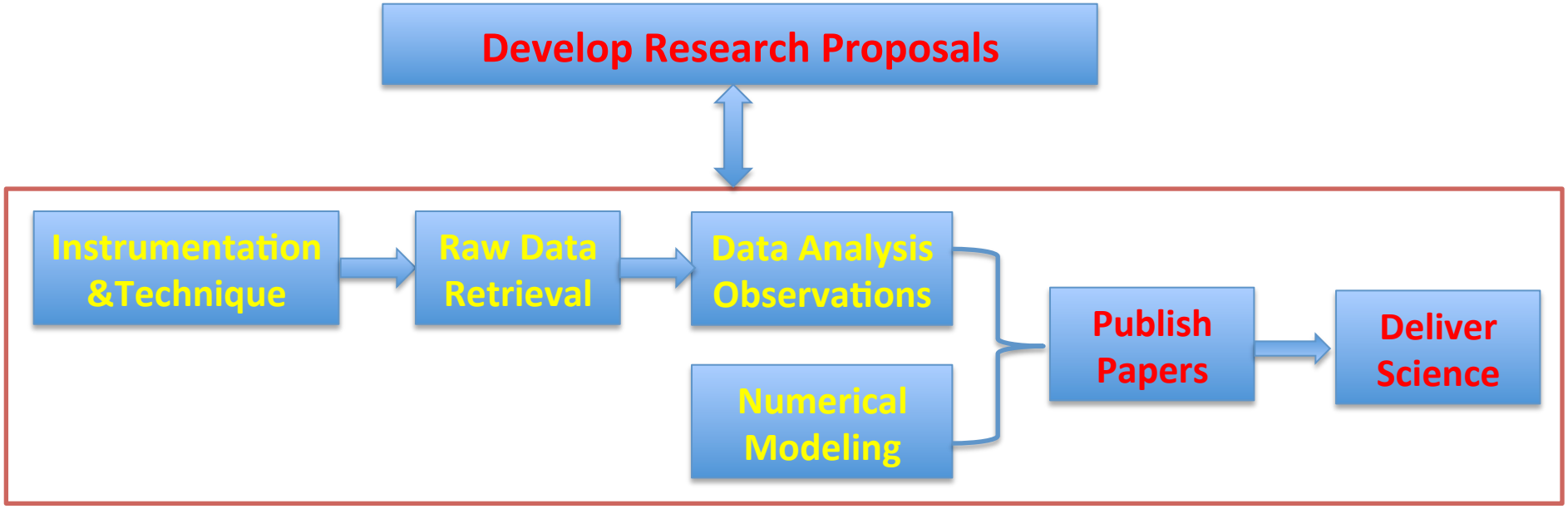






Whole Spectrum of Research Skills

- Develop a full spectrum of skills for atmospheric science study that can be also transformed for other disciplines and also be beneficial for your post-PhD lives.



In addition to the three current projects, more are expected, and you could be a part of the team to develop research proposals.

About Myself:

Reality

- Easy-going, encourage and inspire
- Extensive experiences of mentoring students
- Respect + Guidance
- Good mentor (help students to be successful)+ friend (be supportive)

Summary and Contact Information

- Xian Lu

102A Kinard Lab,

864-656-4204

xianl@clemson.edu

- Projects:

1) Data analysis (Ground-based+Satellite+Models)

2) Numerical modeling

WACCM (CESM), CTIPe, PW Model, GW ray-tracing model, WRF

First step: Relocate the models to Clemson Palmetto system

3) Technique learning (Lidar remote sensing)

- Collaborators: NCAR, NOAA, NASA,

University of Colorado Boulder, Virginia Tech, USU, UIUC, and etc.