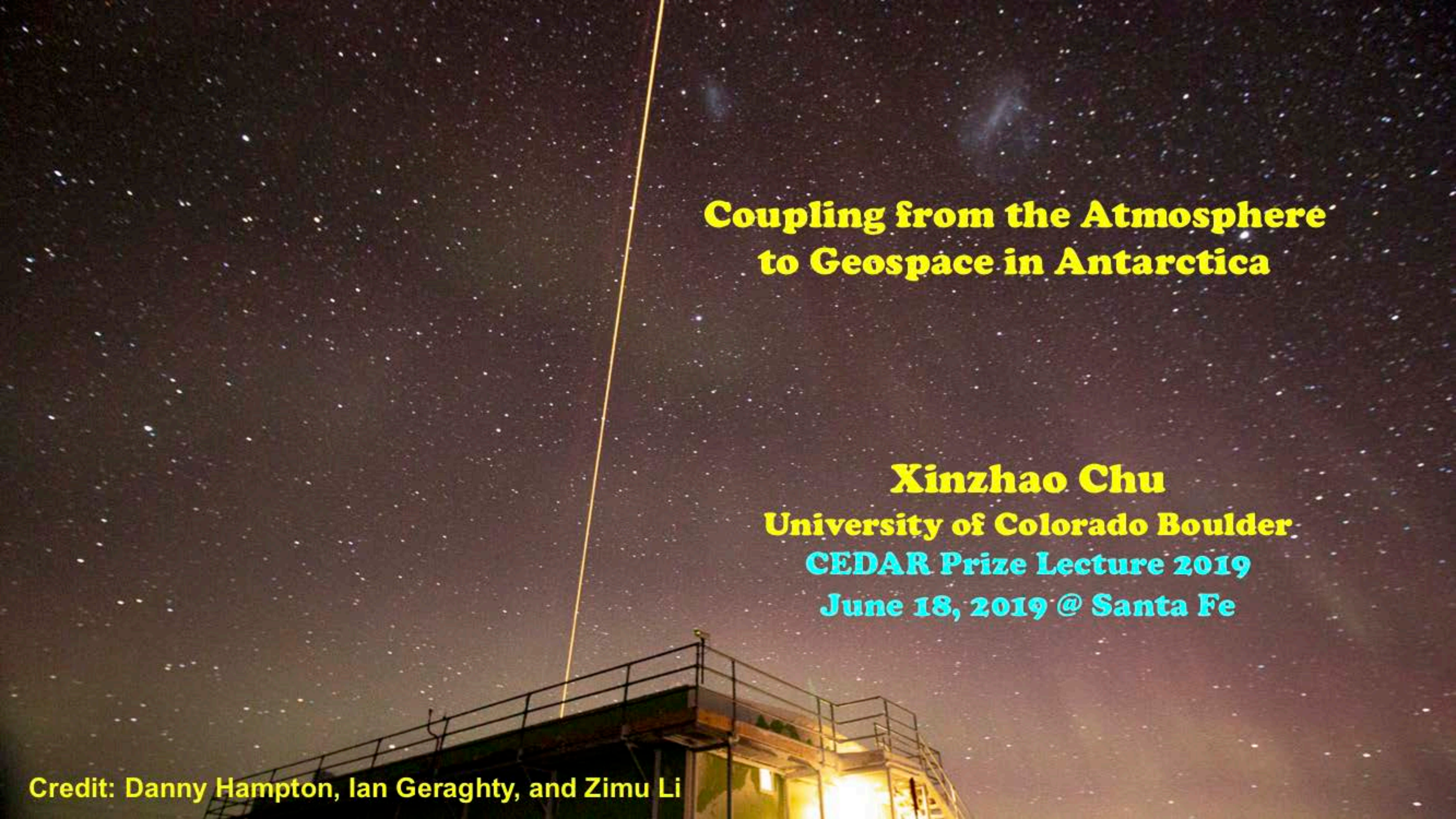


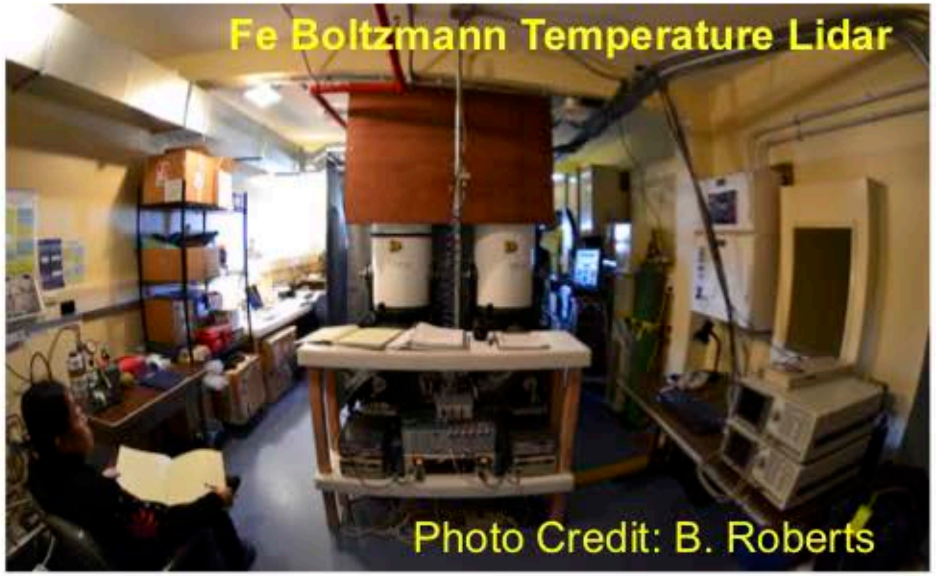
Coupling from the Atmosphere to Geospace in Antarctica

Xinzhao Chu
University of Colorado Boulder

CEDAR Prize Lecture 2019
June 18, 2019 @ Santa Fe

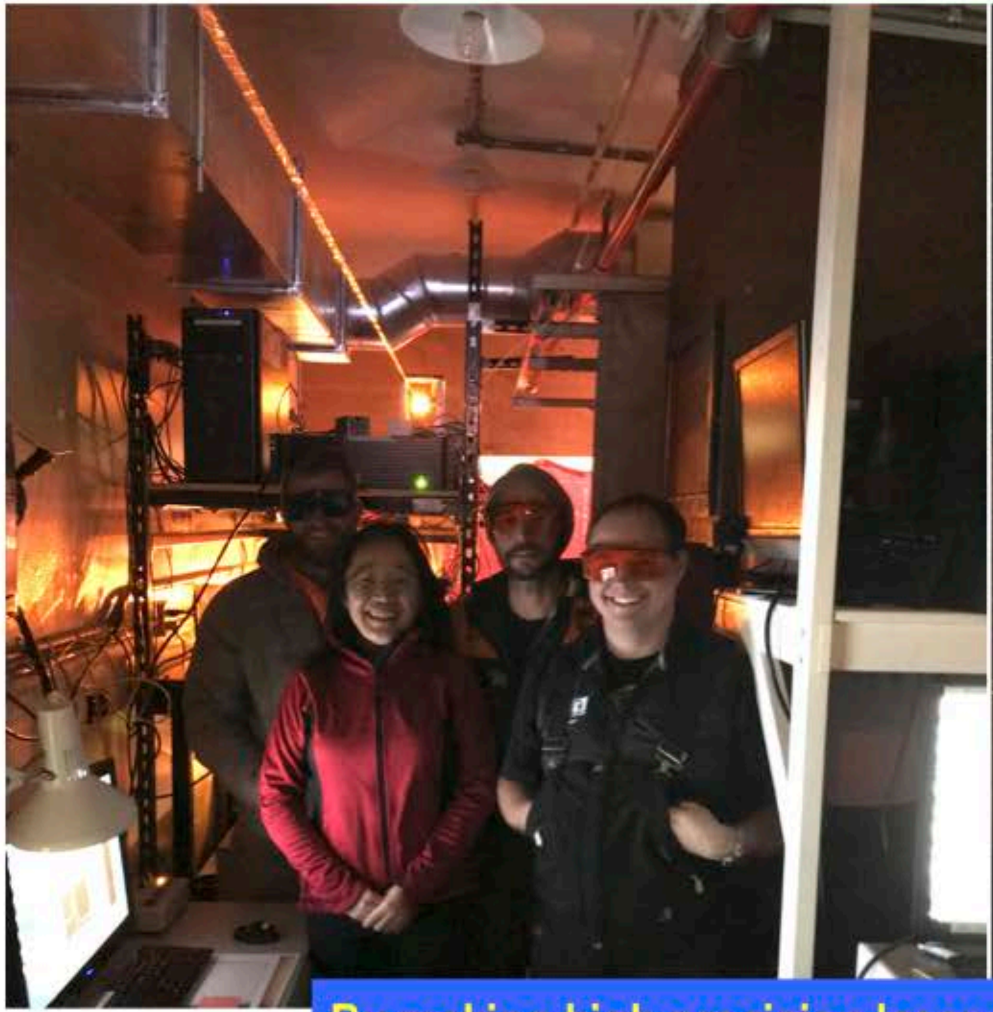
Credit: Danny Hampton, Ian Geraghty, and Zimu Li

McMurdo Fe Lidar Observations Since Dec. 2010



McMurdo lidar projects supported by NSF grants OPP-0839091, 1246405, and 1443726

STAR Na Doppler Lidar Added in Jan 2018

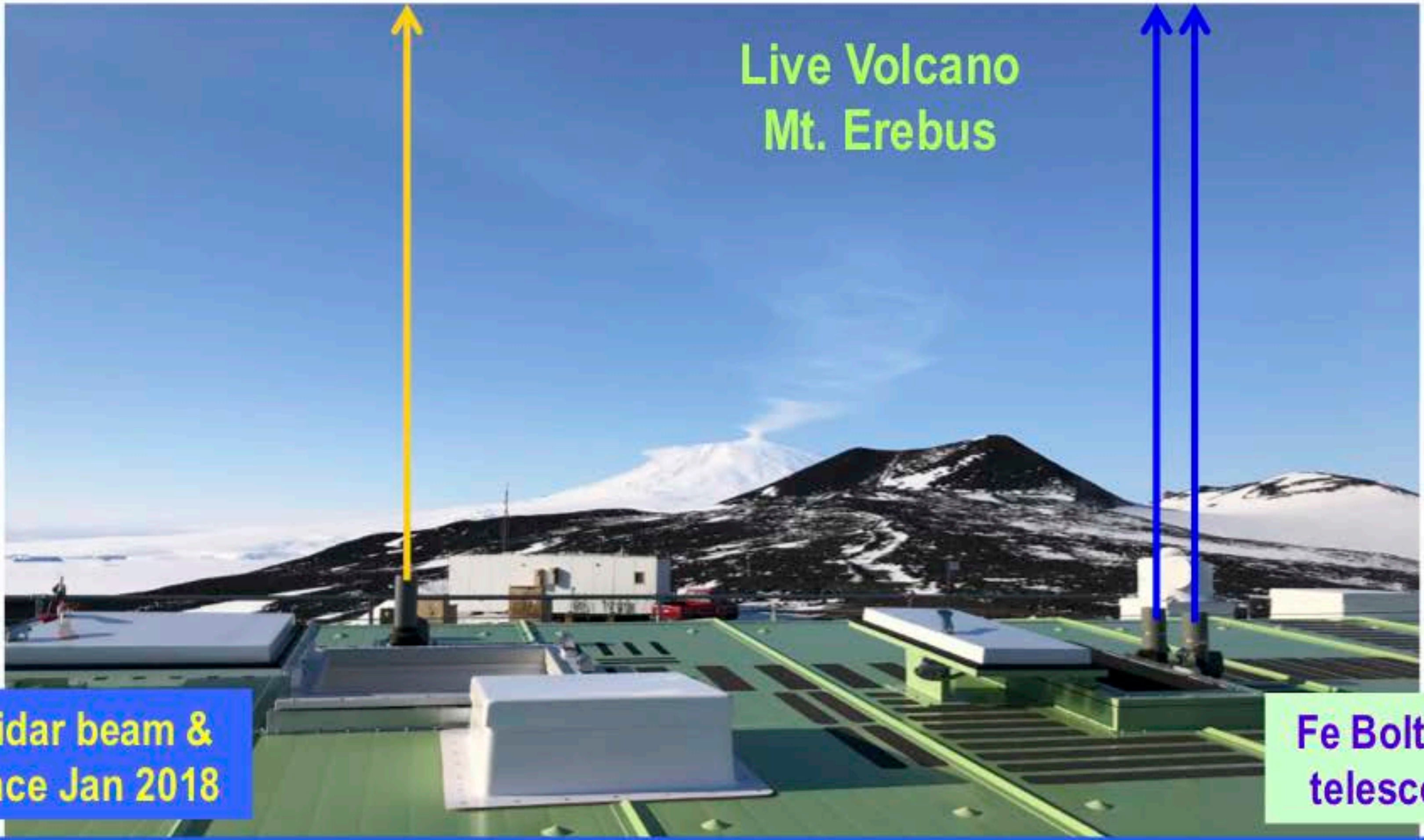


Credit: Danny Hampton, Ian Geraghty, and Zimu Li

By making high-precision laser spectroscopy in space, the neutral temperature, line of sight wind, and Na density are measured simultaneously via detecting the Doppler broadening and bulk Doppler shift of Na D_2 absorption line.

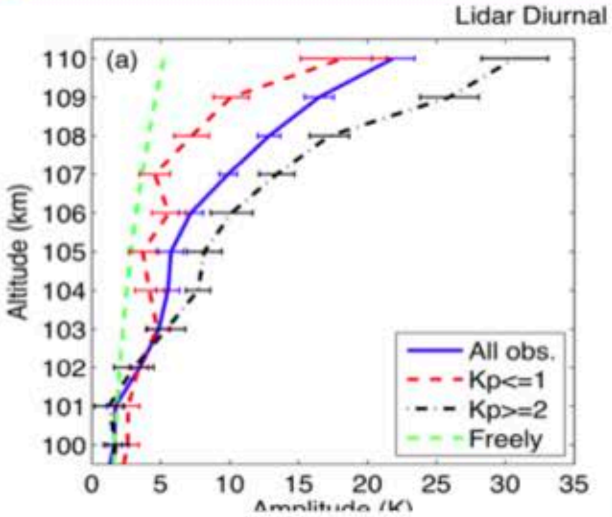
McMurdo lidar projects supported by NSF grants OPP-0839091, 1246405, and 1443726

Simultaneous & Common-Volume Observations with Na Doppler and Fe Boltzmann Lidars at McMurdo



Arrival Heights Lidar Observatory on Ross Island, Antarctica
Shooting laser beams at 589, 374 and 372 nm to probe Na and Fe metals, & profile temperatures, vertical winds, and various waves, etc.

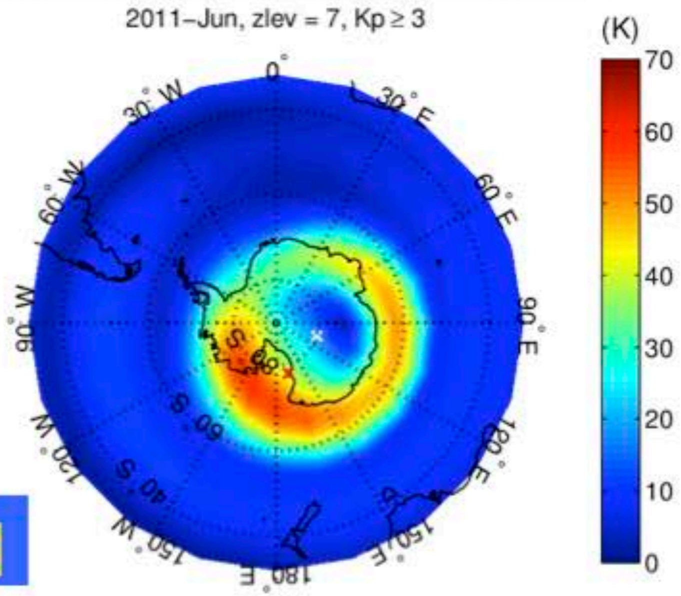
Lidar Discovery of Aurora Effect on Fast Amplitude Growth of Temperature Tides in the Thermosphere (Uniqueness of McMurdo: By the Edge of Polar Cap)

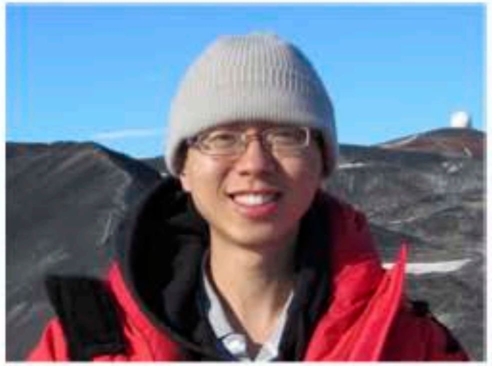


Hall-ion-drag induced adiabatic heating/cooling is responsible, tested by CTIPe model

Dr. Fuller-Rowell and Dr. Art Richmond

[Fong et al., GRL, 2015]

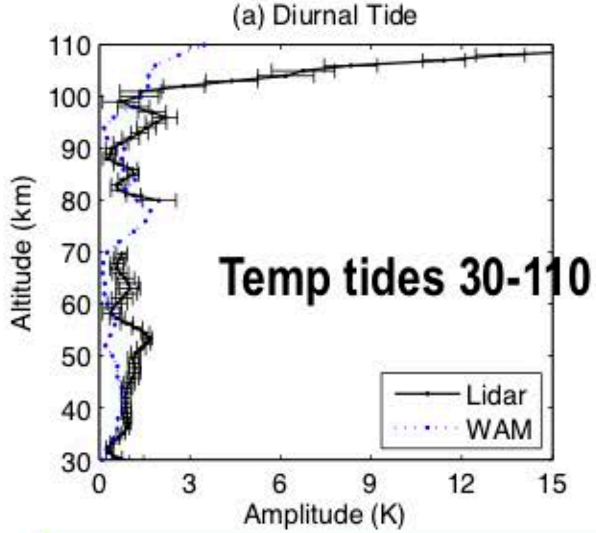




Dr. Weichun Fong

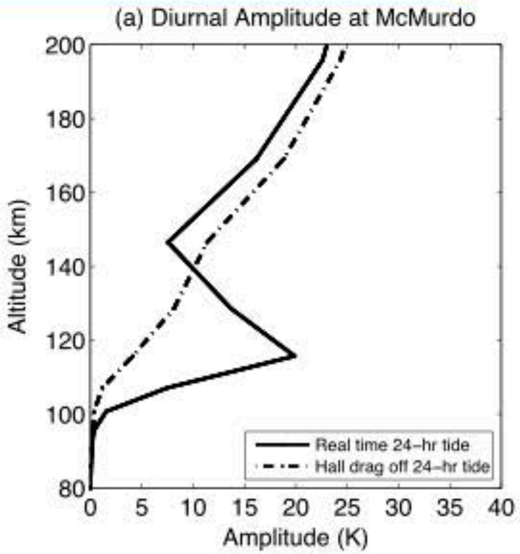
Winter-over 2013

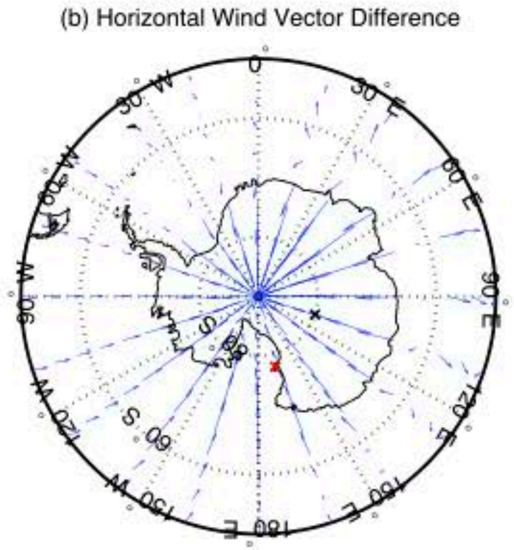
First Place Prize 2015 CEDAR Students Poster Competition



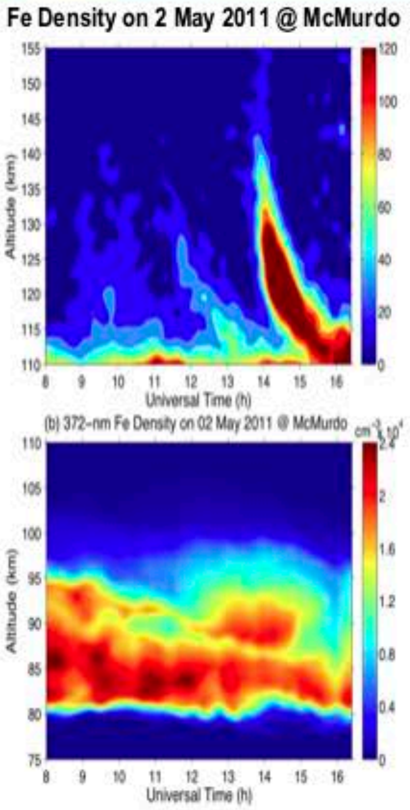
Temp tides 30-110 km

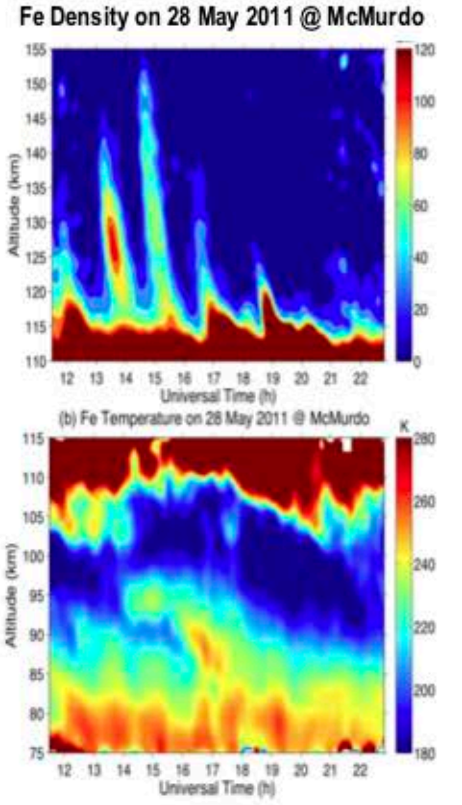
[Fong et al., JGR, 2014]

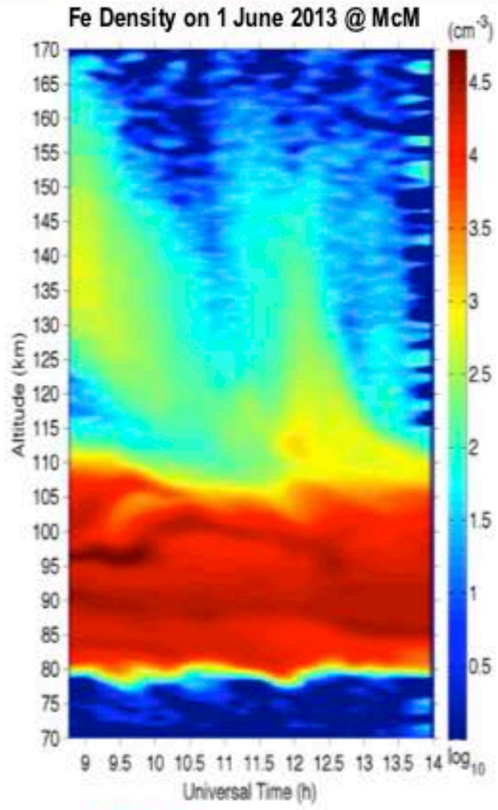


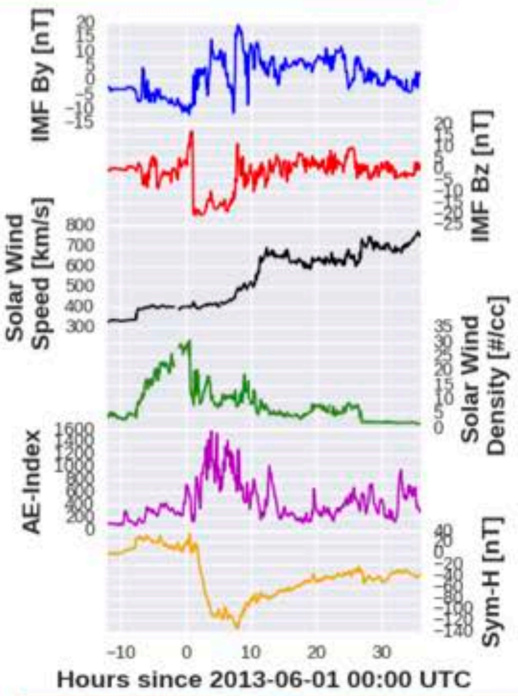


Lidar-Discovered Thermosphere-Ionosphere Fe Layers (TIFe) Correlated to Solar and Geomagnetic Storms





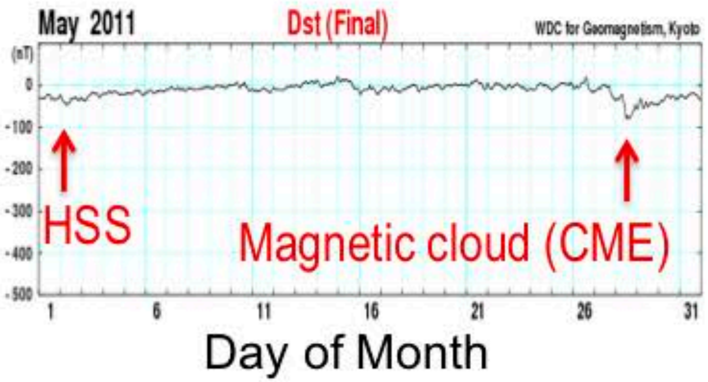


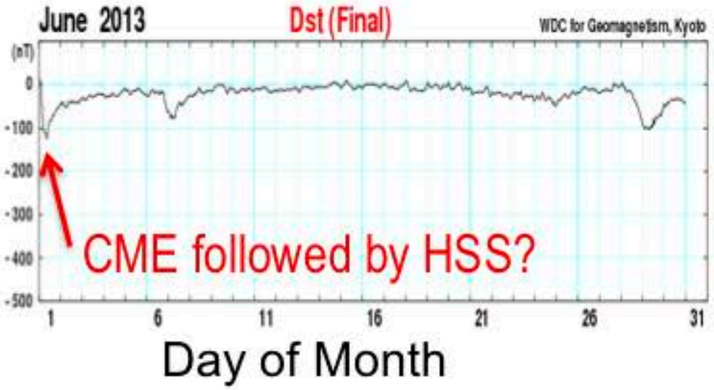


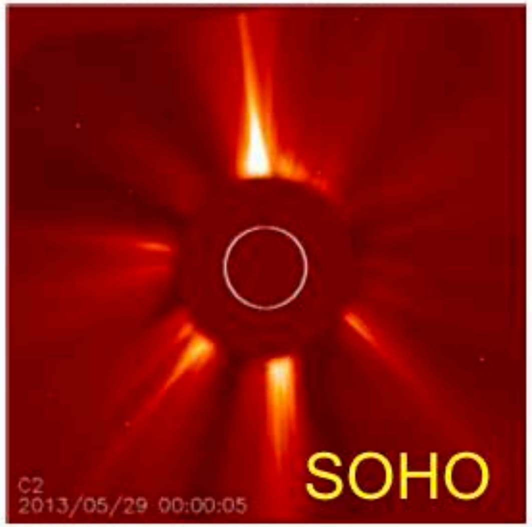
Dr. Zhibin Yu

Winter-over 2011

First Place Prize 2013 CEDAR Students Poster Competition



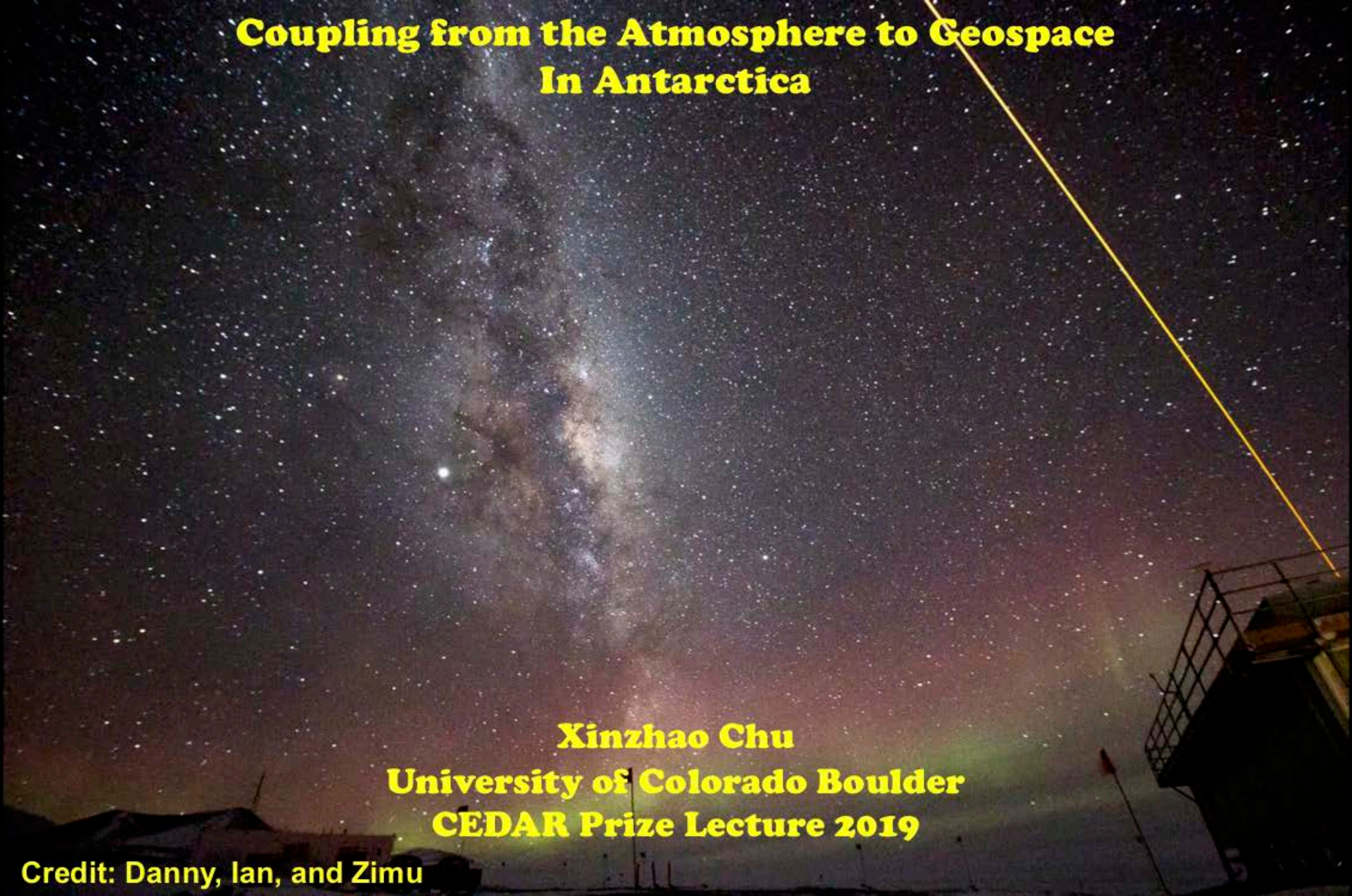




Courtesy of
Dr. Delores Knipp
&
Dr. Zhonghua Xu

Coupling from the Atmosphere to Geospace In Antarctica

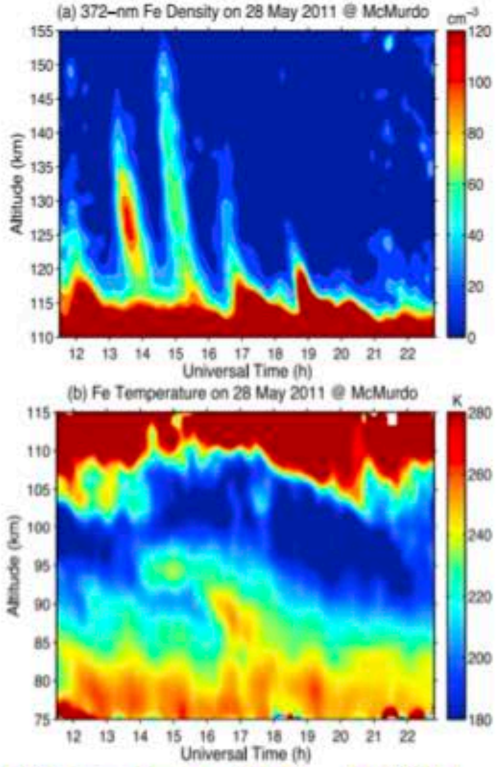
Xinzhao Chu
University of Colorado Boulder
CEDAR Prize Lecture 2019



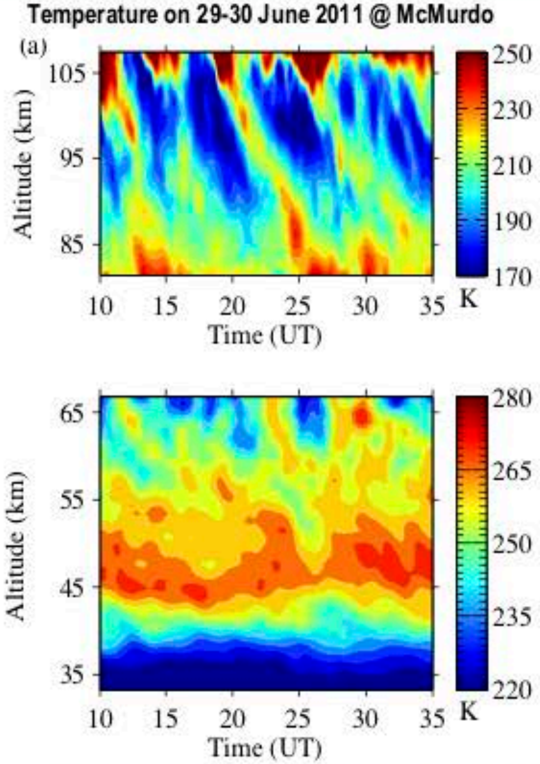
Credit: Danny, Ian, and Zimu

Arrival Heights is a Hotspot of Gravity Waves

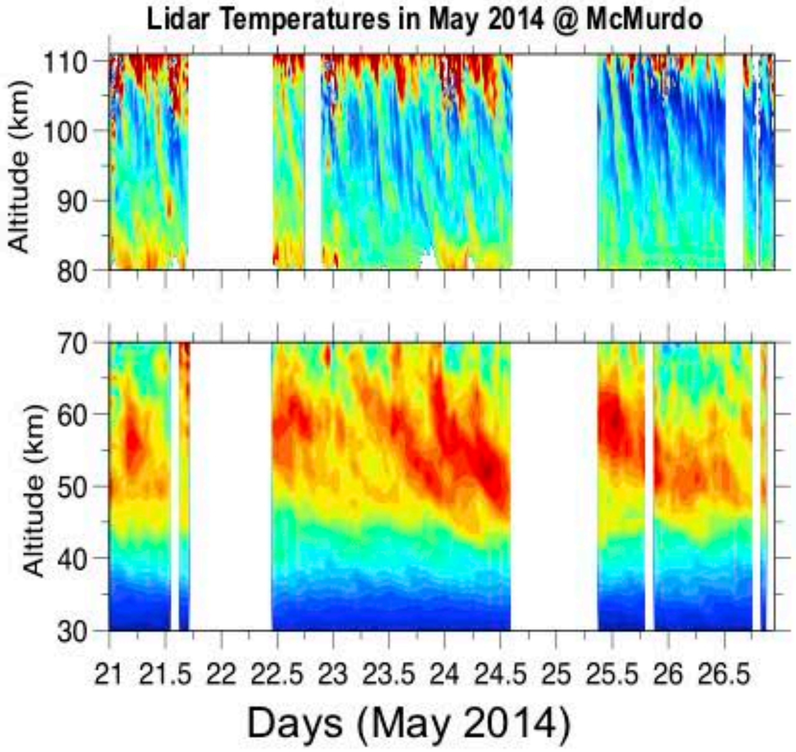
Dr. Cao Chen



[Chu et al., GRL, 2011]



[Chen et al., JGR, 2013]



[Lu et al., GRL, 2017]

Dr. Xian Lu

1.5-h GWs in TIFe layer

+

1.5-h GWs in Fe temp

+

3-10 h GWs in Fe temp

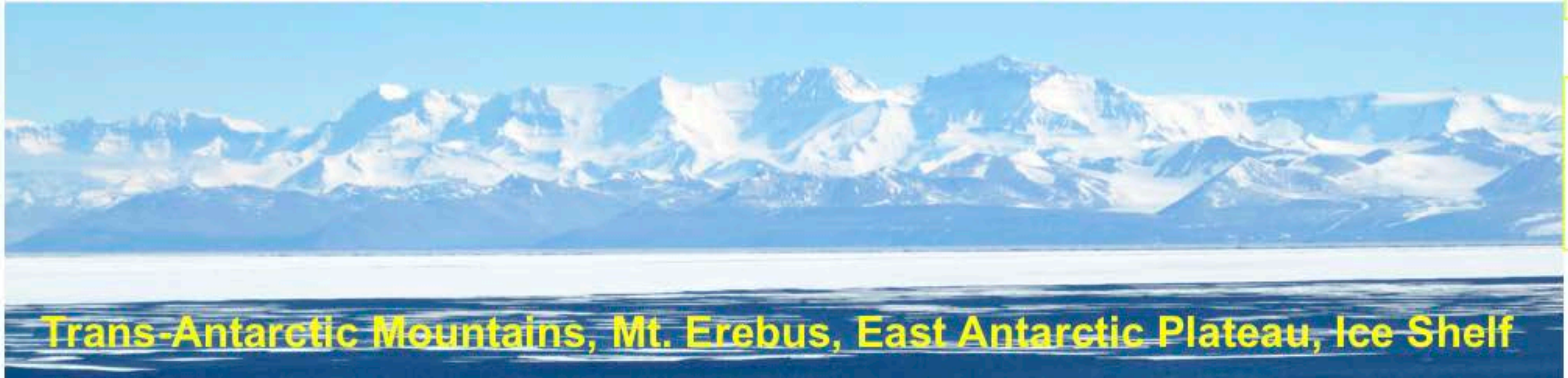
PWs in Fe Temp

+

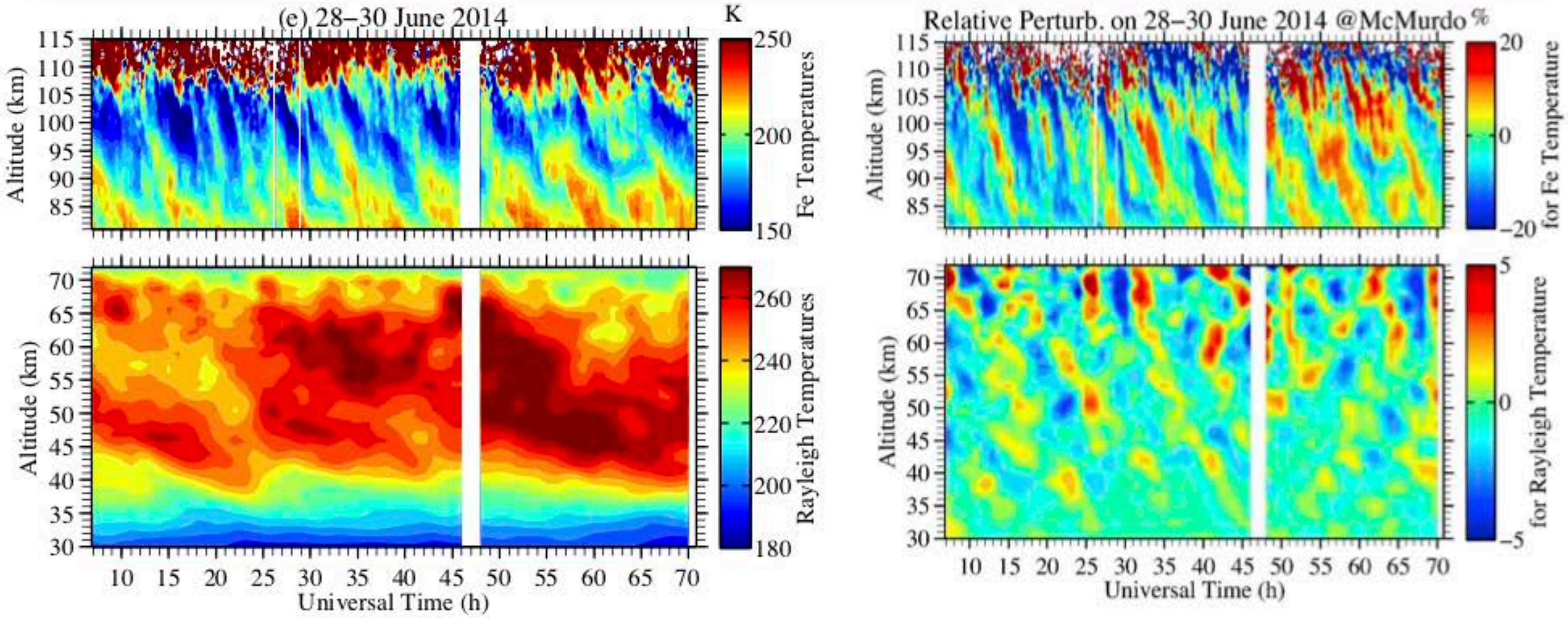
PWs in Rayleigh temp

+

GWs in Rayleigh temp



Lidar Discovery of Persistent Gravity Waves with Inertial τ of 3–10 h and λ_z of 20–30 km



Dr. Cao Chen

Winter-over 2014

First Place Prize 2012 CEDAR Students Poster Competition

[Chen et al., JGR, 2016]

Persistent, large-amplitudes, dominant in the MLT (T' ~ ±20–30 K)

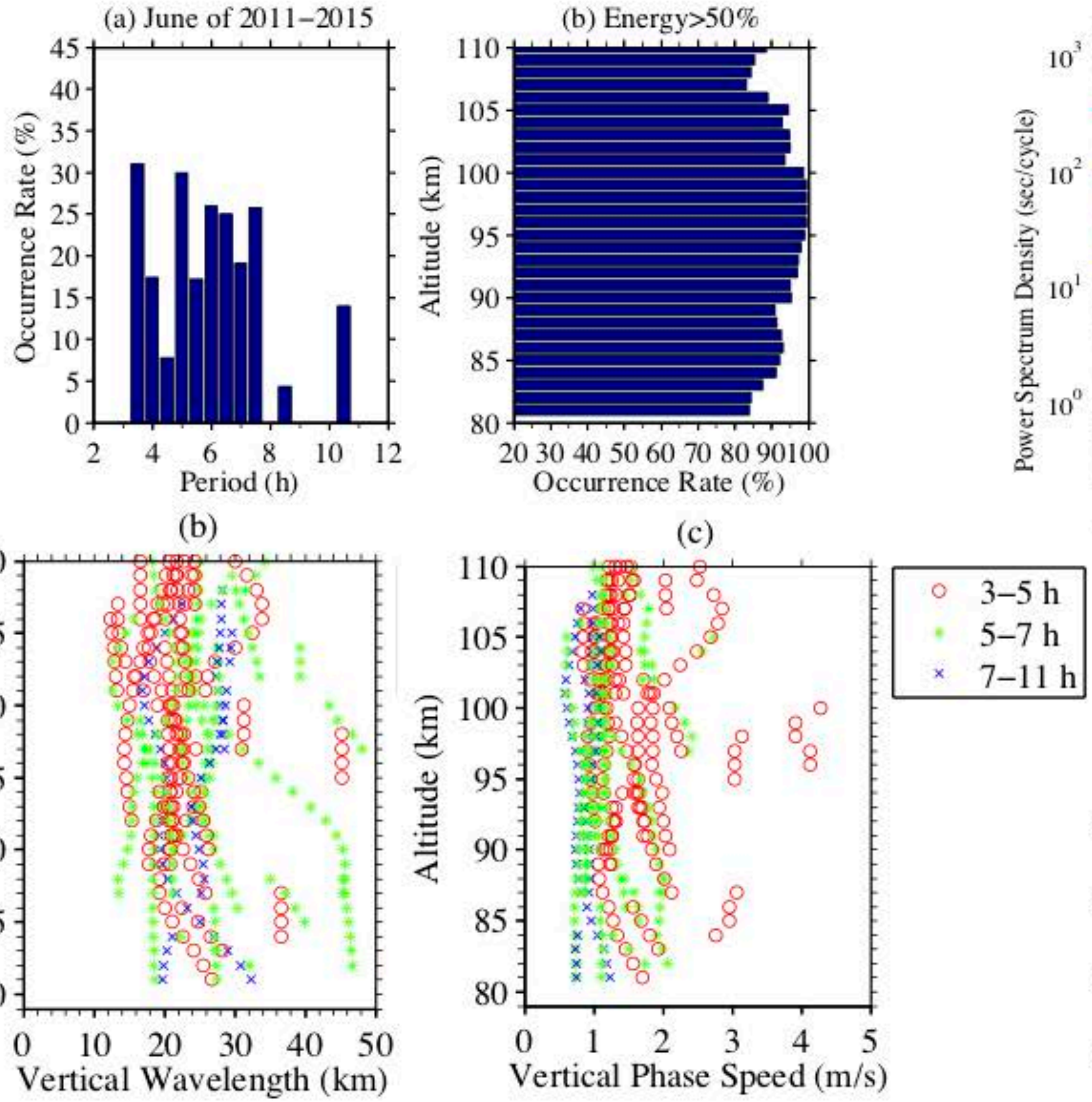
No pause during nearly 3-day observation!!!

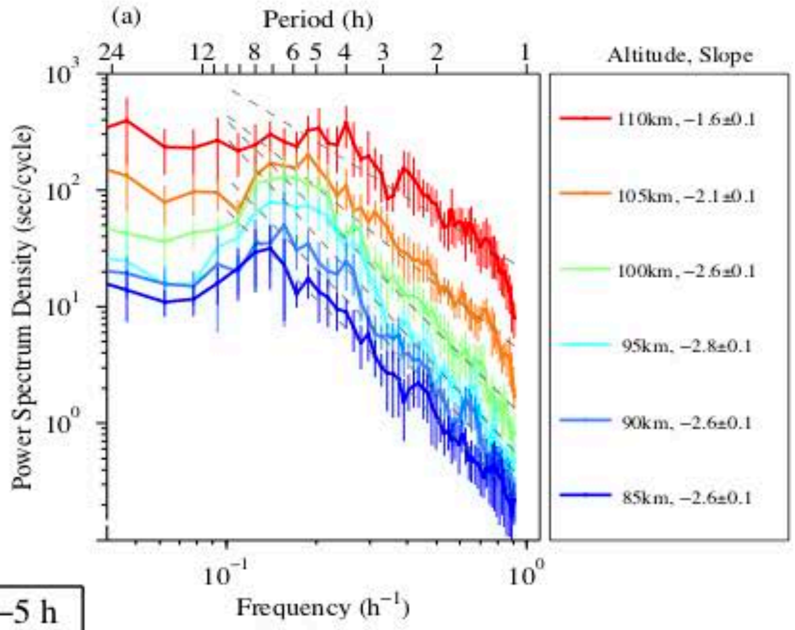
Occurring on every lidar run; as a group, these waves are perpetual

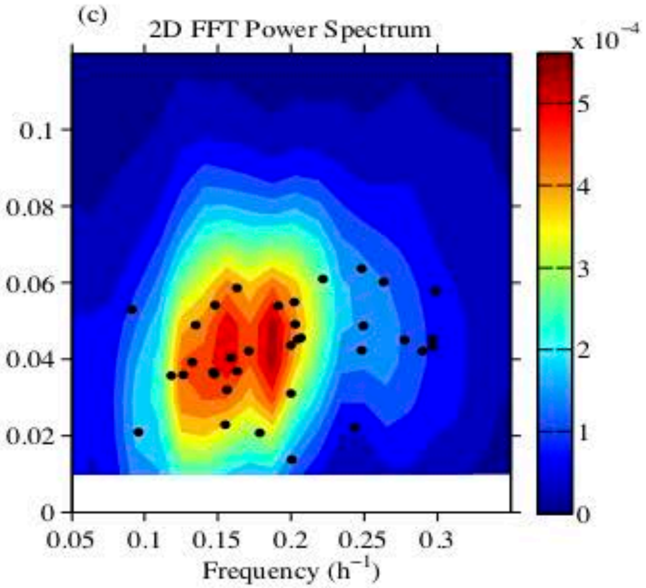
What wave sources could be so persistent???

Non-tidal periods, non-fixed phases, phase traced down to the stratosphere

MLT Persistent Gravity Waves in June 2011-2015





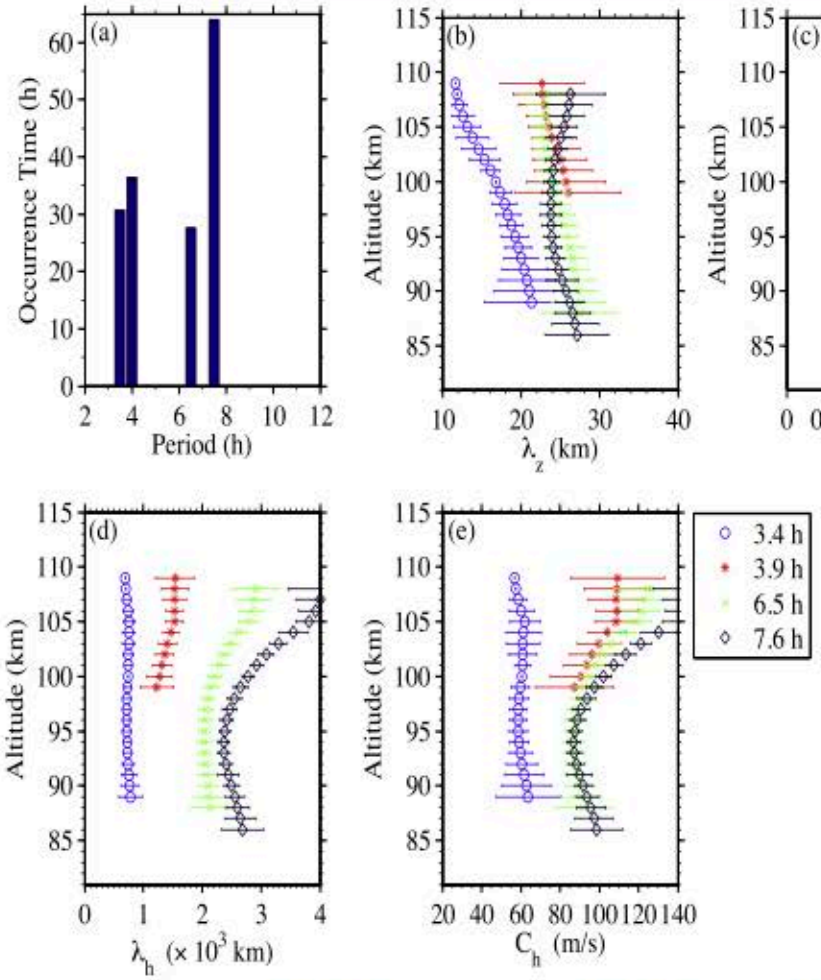


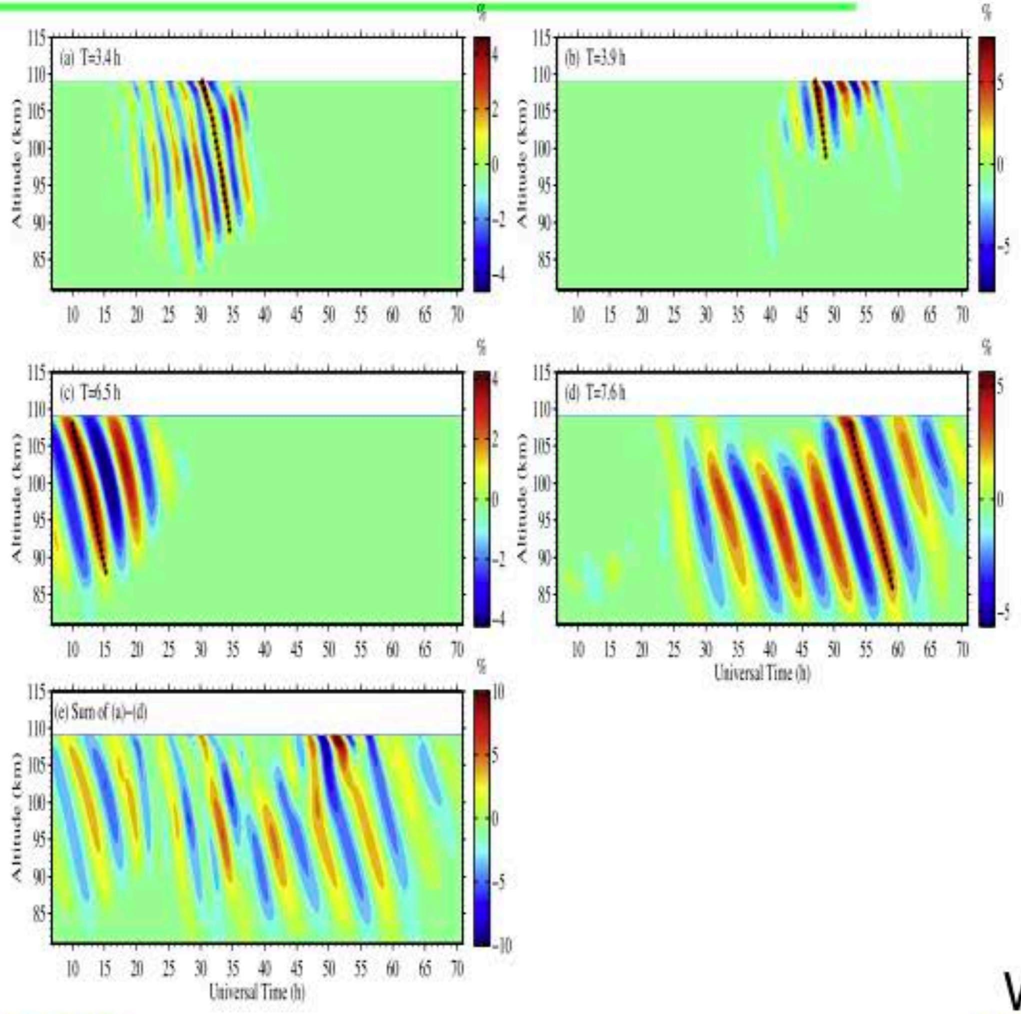
[Chen et al., JGR, 2016]

Freq-spectral slopes -2.7 below 100 km, gradually become shallower -1.6 at 110 km

Persistent waves aren't tidal waves, aren't atmos. normal modes, unlikely wave-wave interactions, but gravity waves!

Wave Recognition Based on 2D Wavelet for Characterization of Persistent Gravity Waves





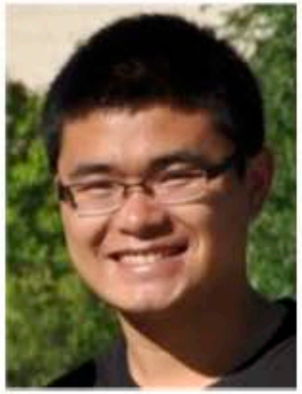
Dr. Cao Chen
Winter-over 2014

Ian Geraghty
Winter-over 2019
Undergrad Honorable Mention 2017

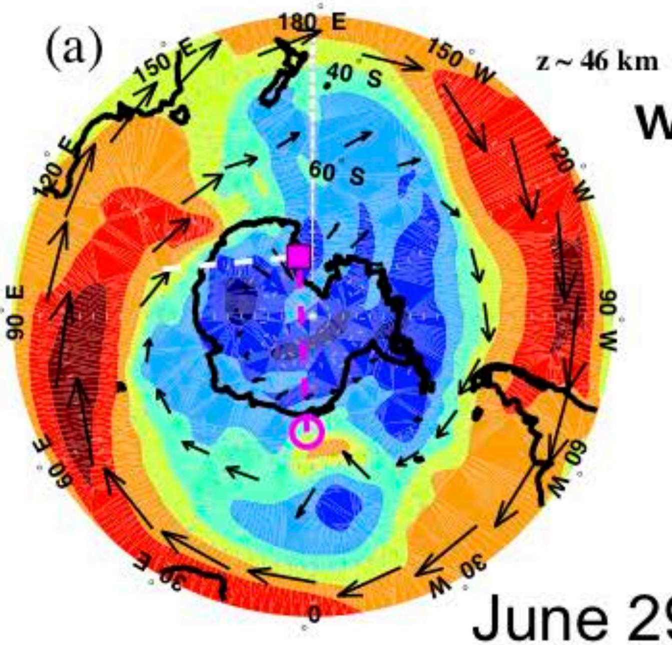
[Chen and Chu, JASTP, 2017] $\lambda_H \approx 800 - 4000\ km$

What wave sources could be so persistent???

Sources of the MLT Persistent Waves ??? Traced Back to the Stratosphere

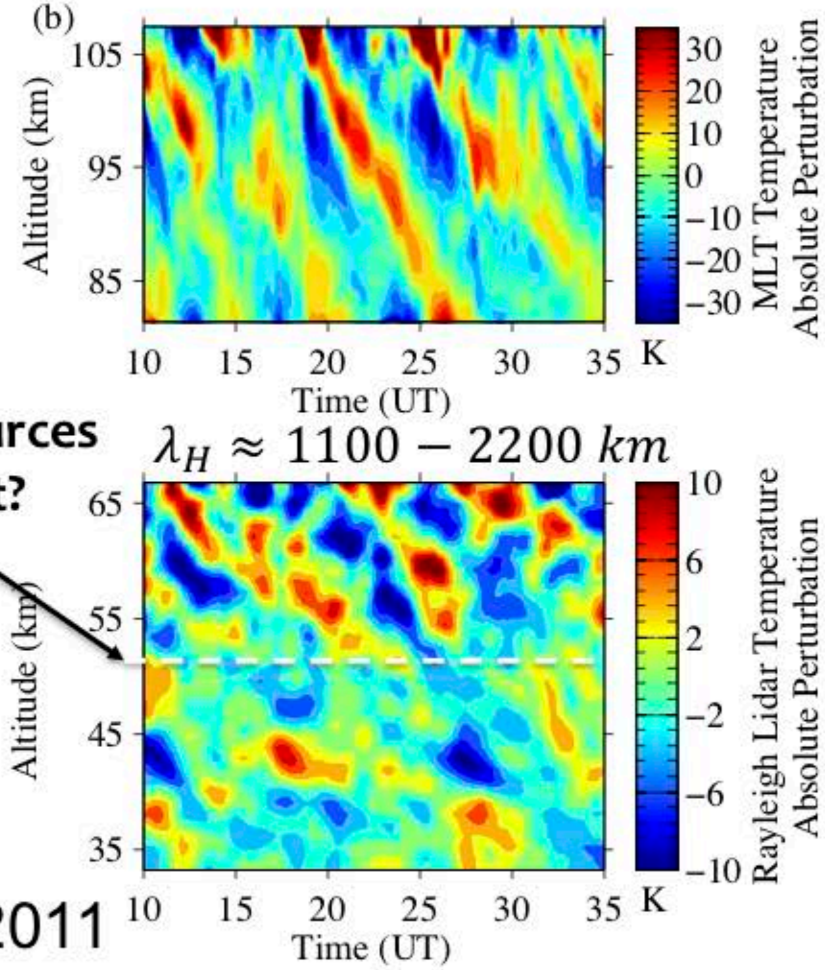


With Scott Base MF radar wind data, we can derive where the waves come from in case studies.



Wave Sources Height?

$\lambda_H \approx 1100 - 2200\ km$

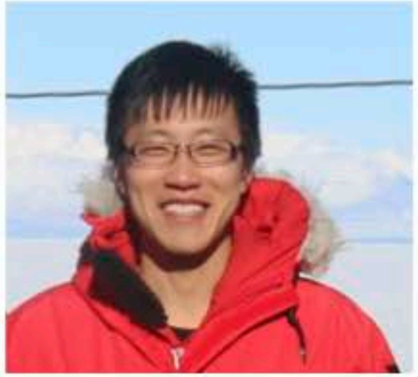


June 29-30, 2011

Dr. Adrian McDonald

This is the first time inertia-gravity waves (IGWs) observed in the Antarctic MLT by lidar and radar together. [Chen et al., JGR, 2013]

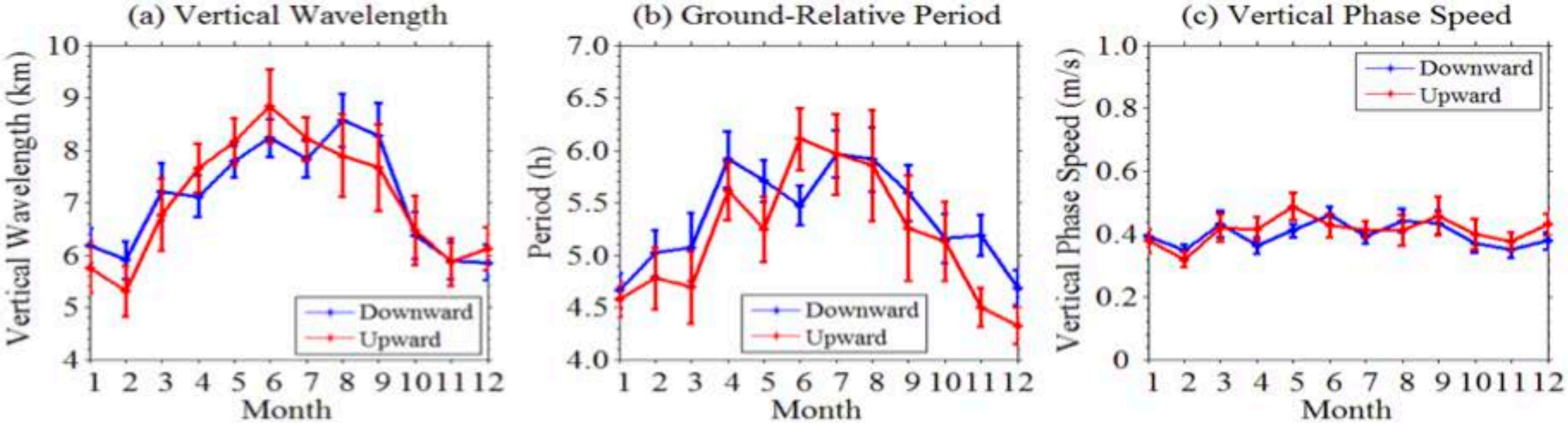
Statistical Characterization of Dominant Gravity Waves in the Stratosphere (30-50 km)



Dr. Jian Zhao
Winter-over 2015

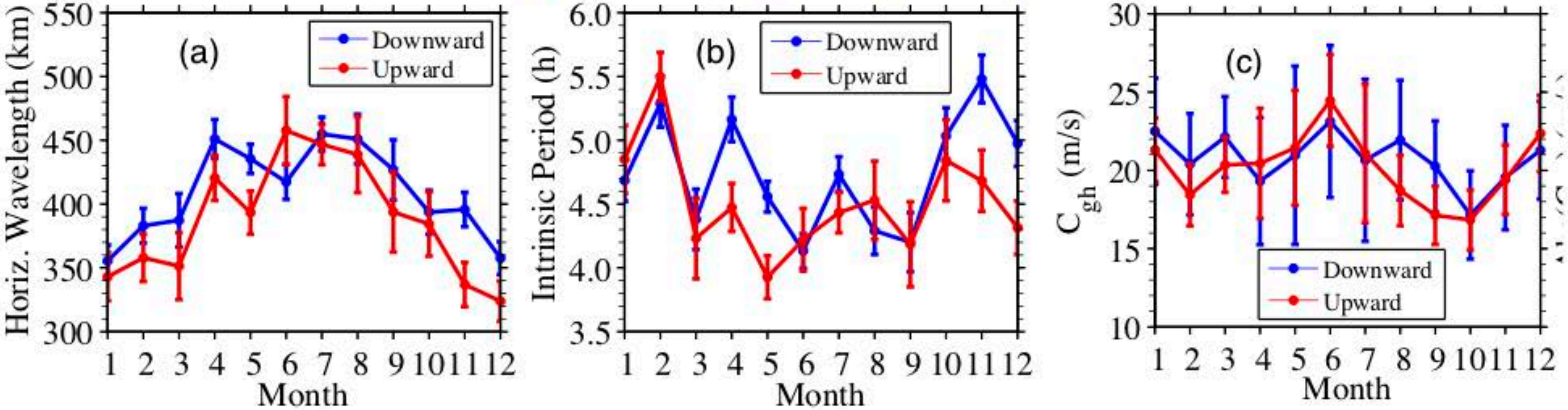
Dr. Chihoko Yamashita

First Place Prize 2011 CEDAR Students Poster Competition



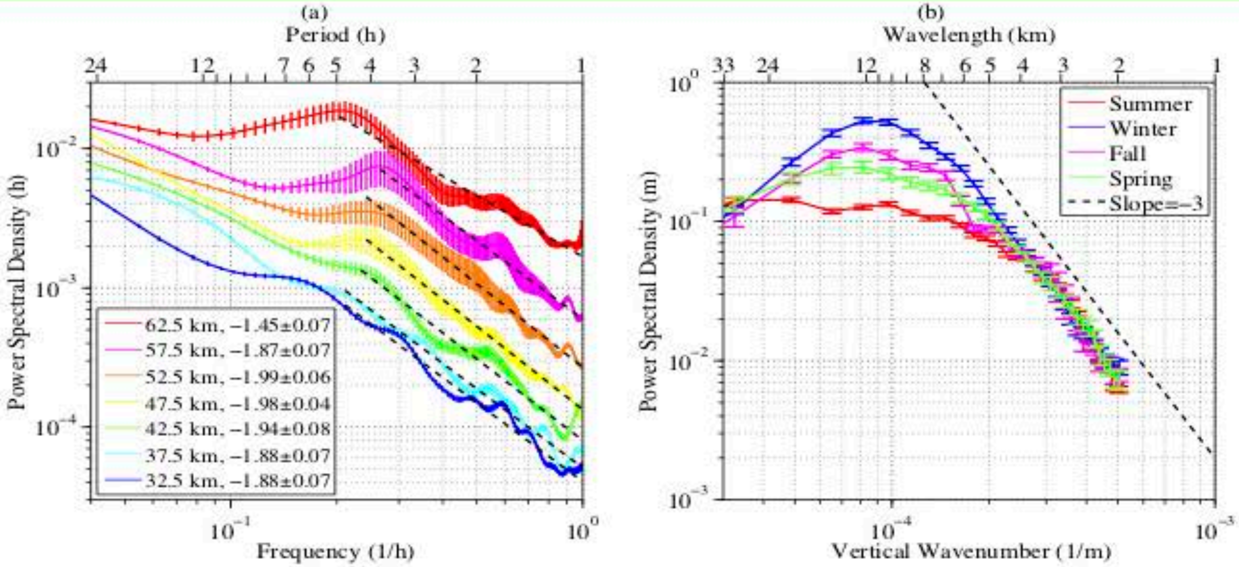
$\lambda_H \approx 400\ km$

[Zhao et al., JGR, 2017]

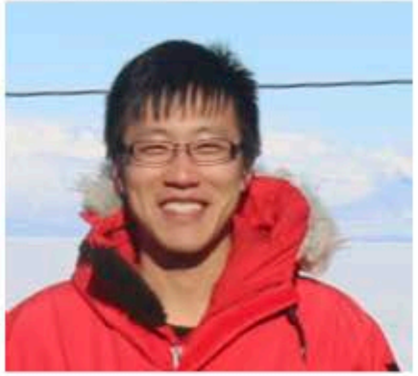


Dominant GWs in the stratosphere are different from the MLT persistent waves

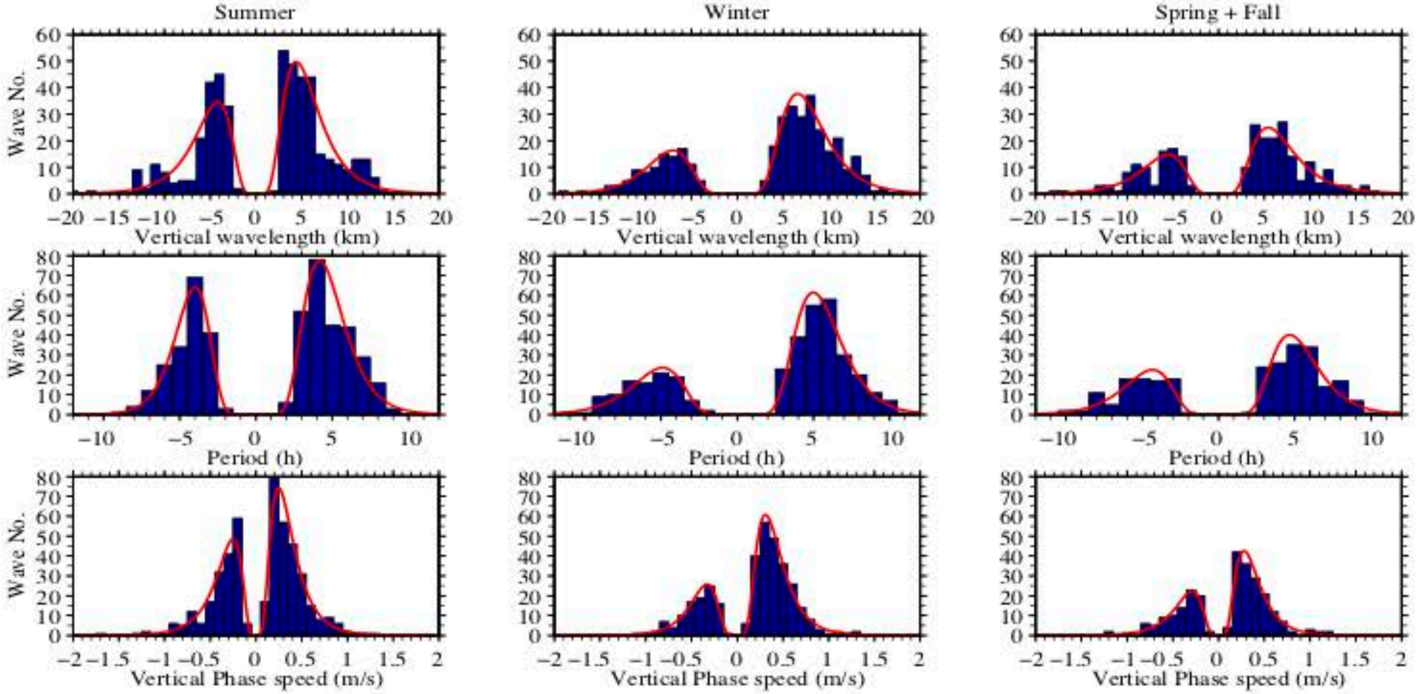
Stratospheric Gravity Wave Spectra & Characteristics



Frequency-spectra
Seasonal m-spectra
[Zhao et al., JGR, 2017]



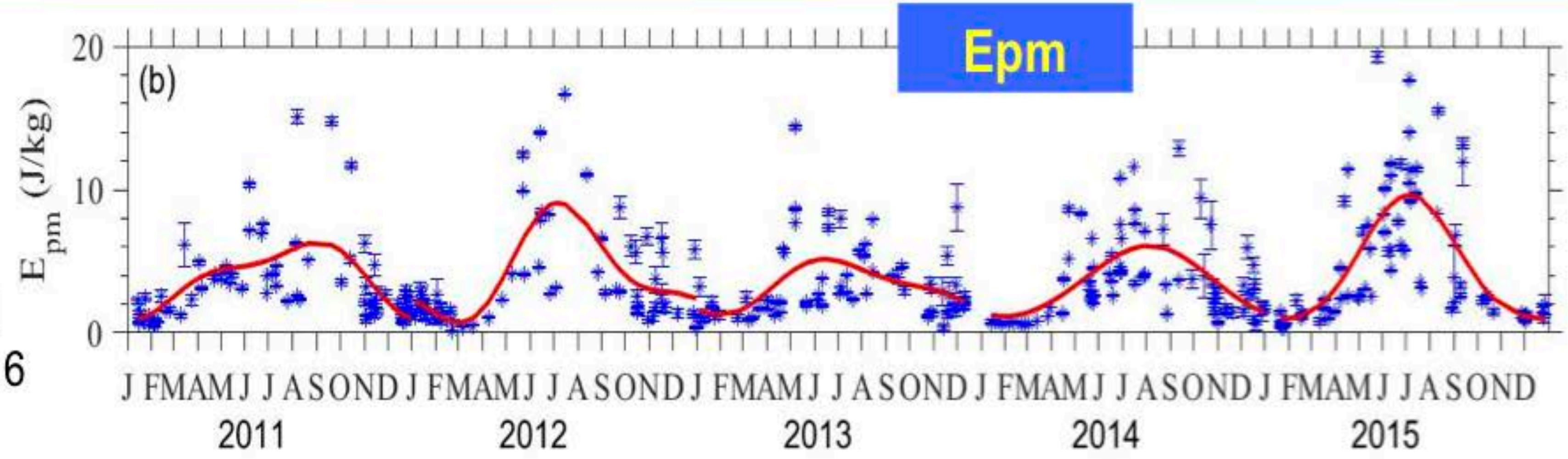
Dr. Jian Zhao
Winter-over 2015

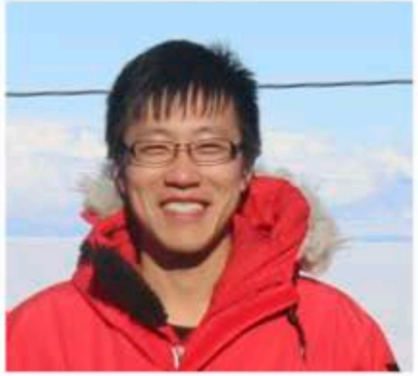


Lognormal distributions of vertical wavelength, period, and vertical phase speed
[Zhao et al., JGR, 2017]

Stratospheric Gravity Waves are Intriguing

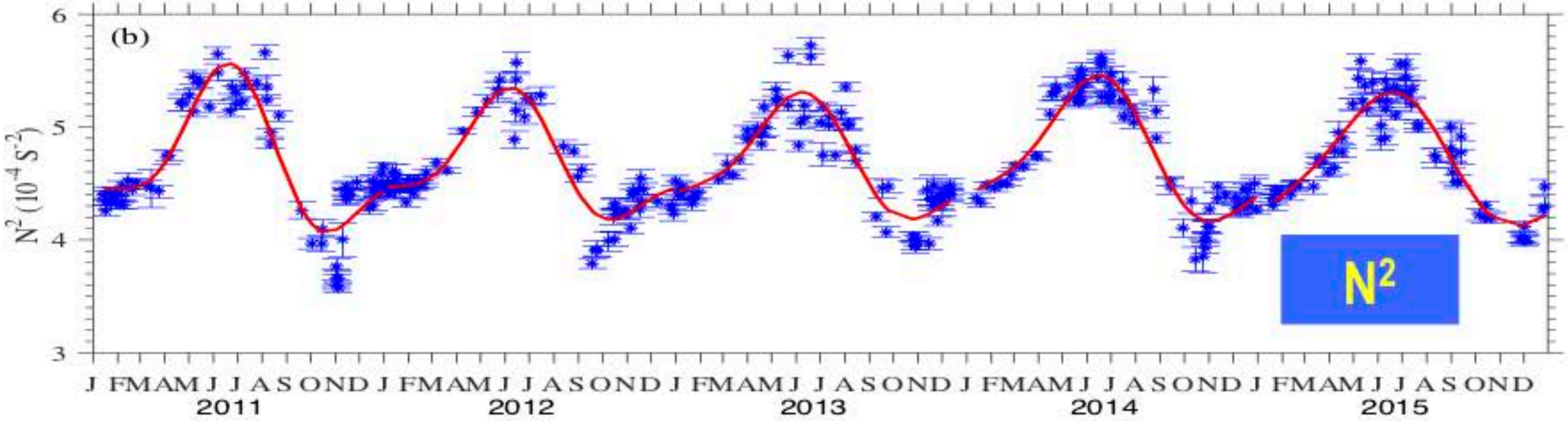
Dr. Xian Lu
Summer 2015-2016





Dr. Jian Zhao
Winter-over 2015

GW potential energy density (30-50 km) over 5 years [Chu et al., JGR, 2018]



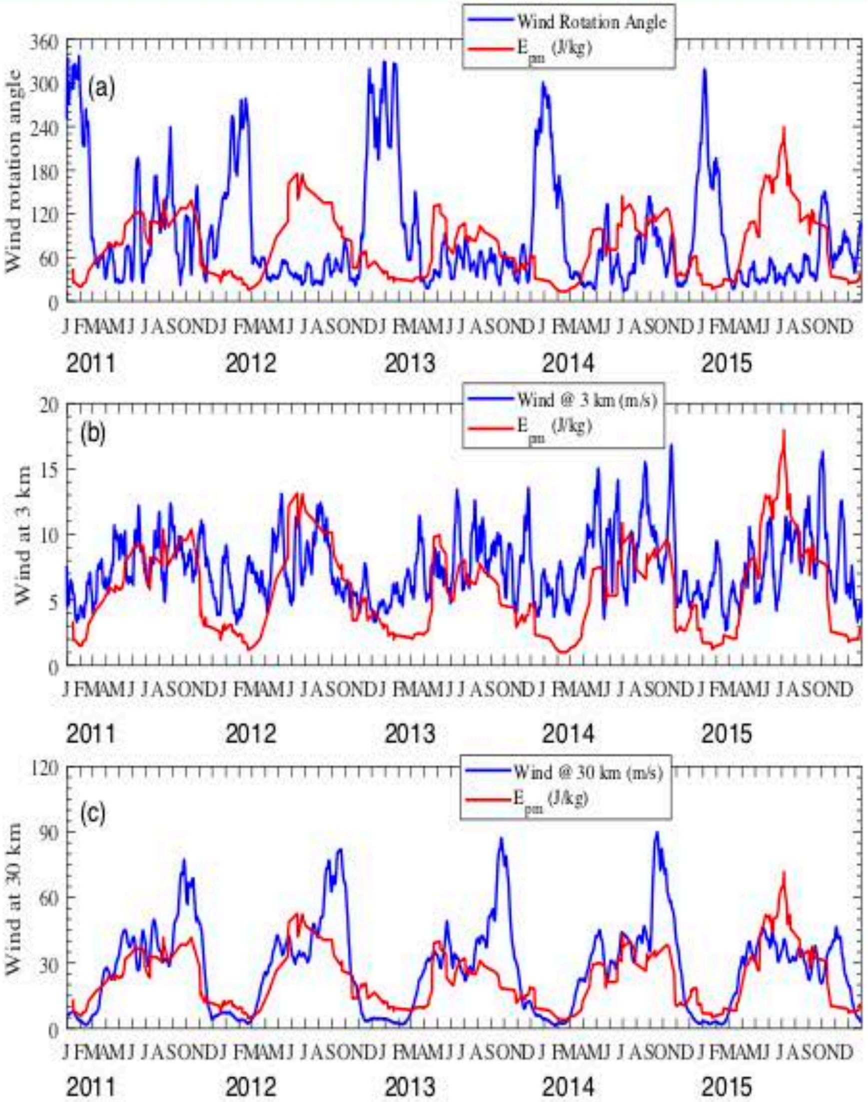
Epm and N^2 exhibit seasonal patterns with summer minima & winter maxima

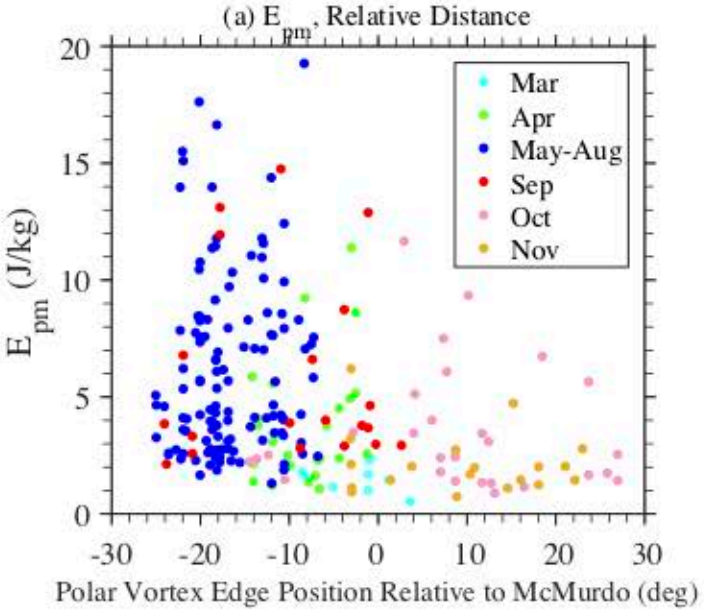
Driving Factors for Epm Seasonal Variations

Critical level filtering

Near surface wind

Stratospheric wind at 30 km





Dr. Lynn Harvey

Polar Vortex

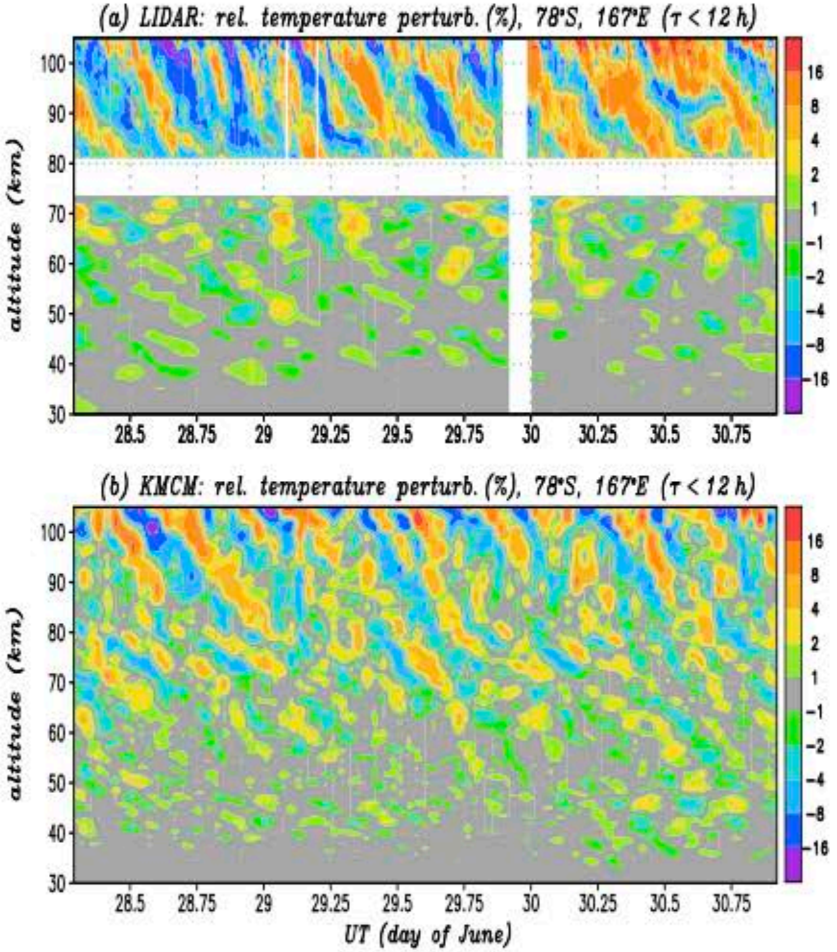
Stratospheric Epm vs. Critical Level Filtering and Wave Sources [Chu et al., JGR, 2018]

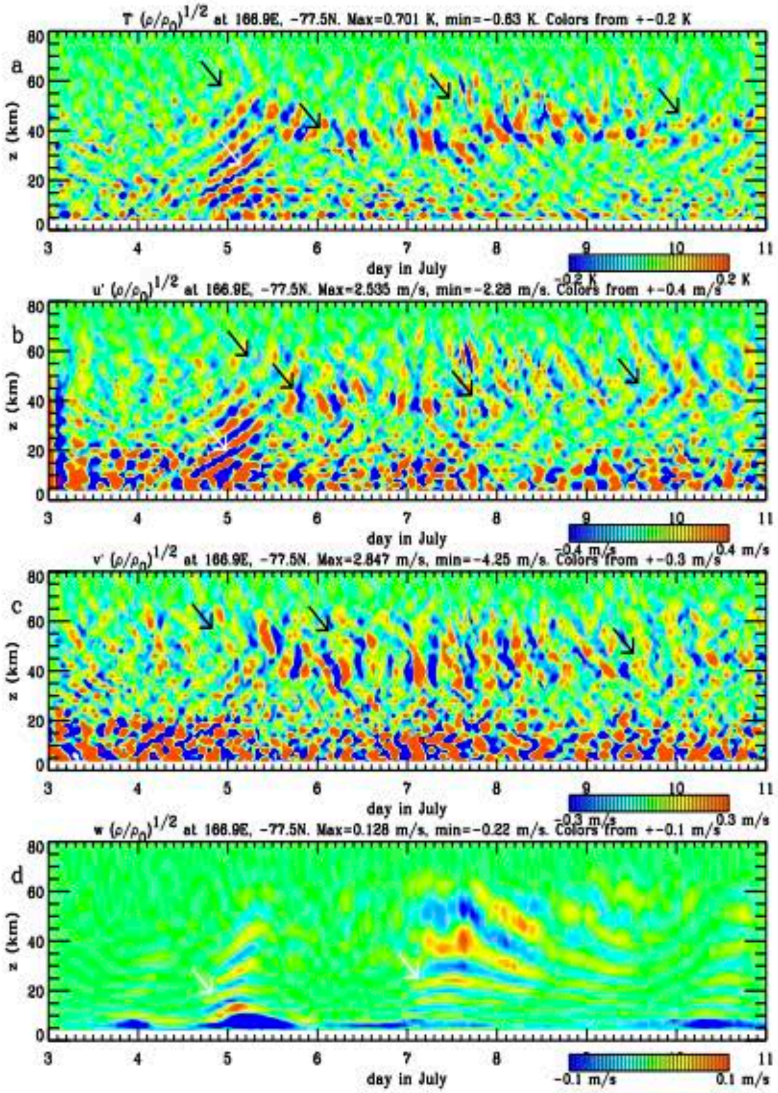
Stratospheric Epm vs. Polar Vortex Location [Chu et al., JGR, 2018]

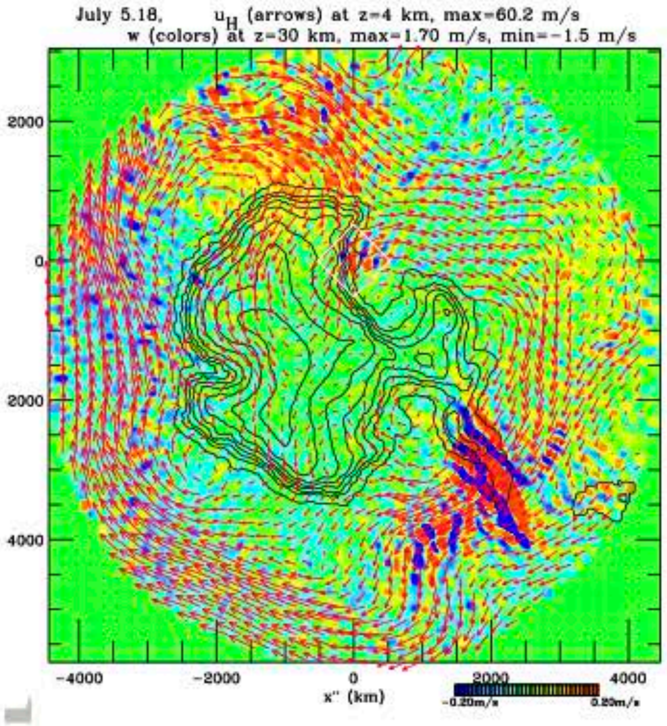
Lidar Discoveries Inspired Theoreticians and Modelers to Search for the Wave Sources (Vadas and Becker)

Dr. Sharon Vadas
Dr. Erich Becker

GW-resolved KMCM



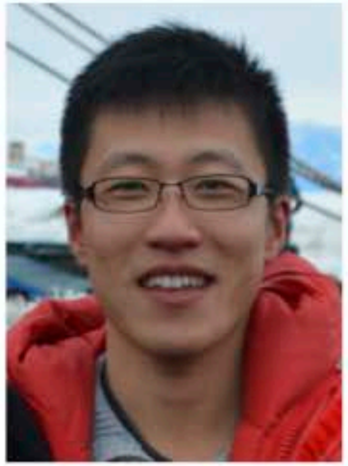




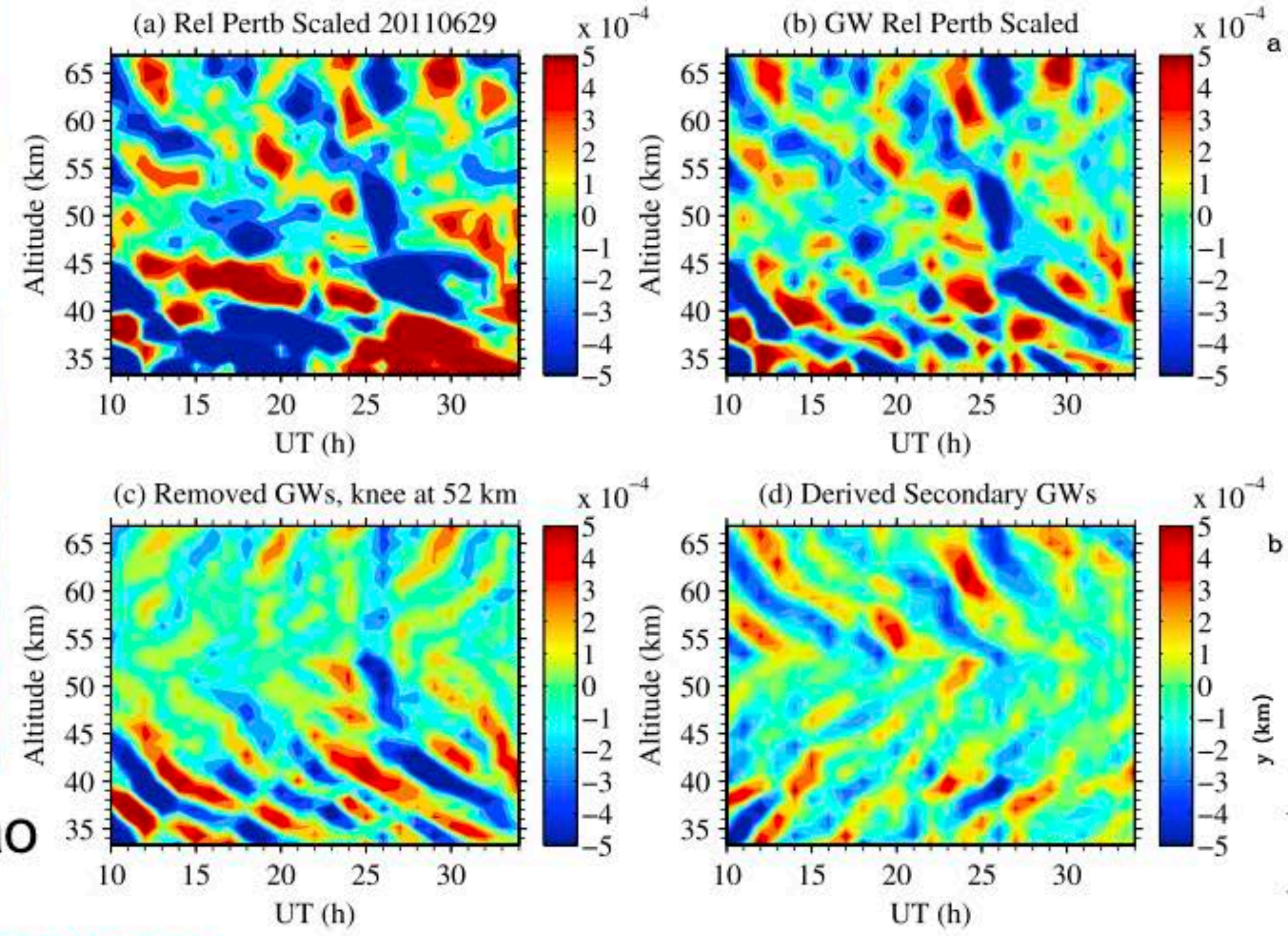
[Becker and Vadas, JGR, 2018; Vadas and Becker, JGR, 2018]

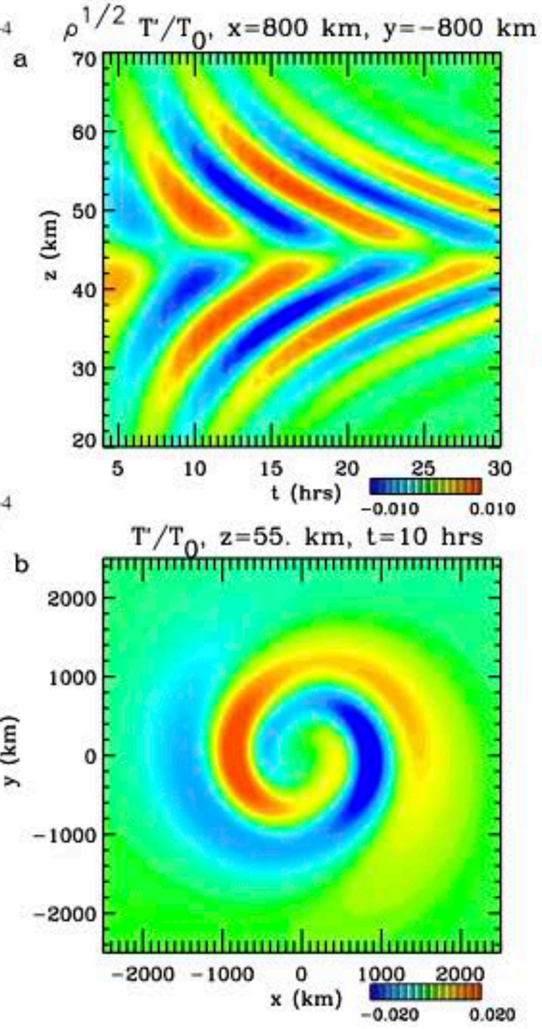
Secondary Gravity Wave Generation by Localized, Intermittent Body Force

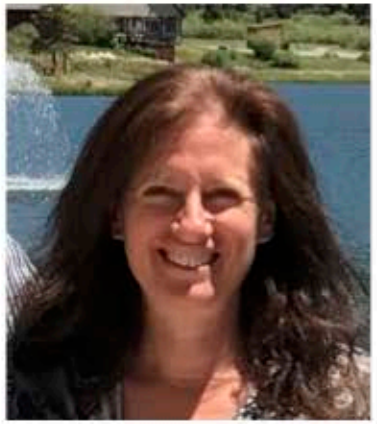
Dr. Becker



Dr. Jian Zhao







Dr. Vadas

Theory

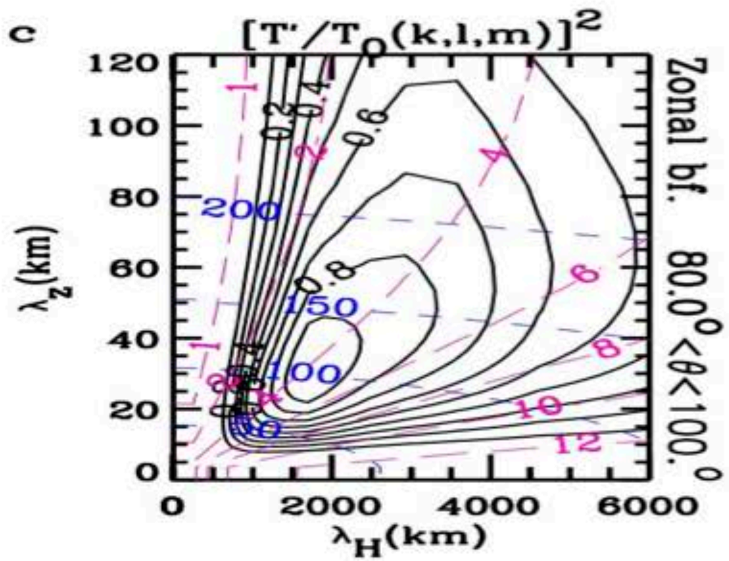
Observations

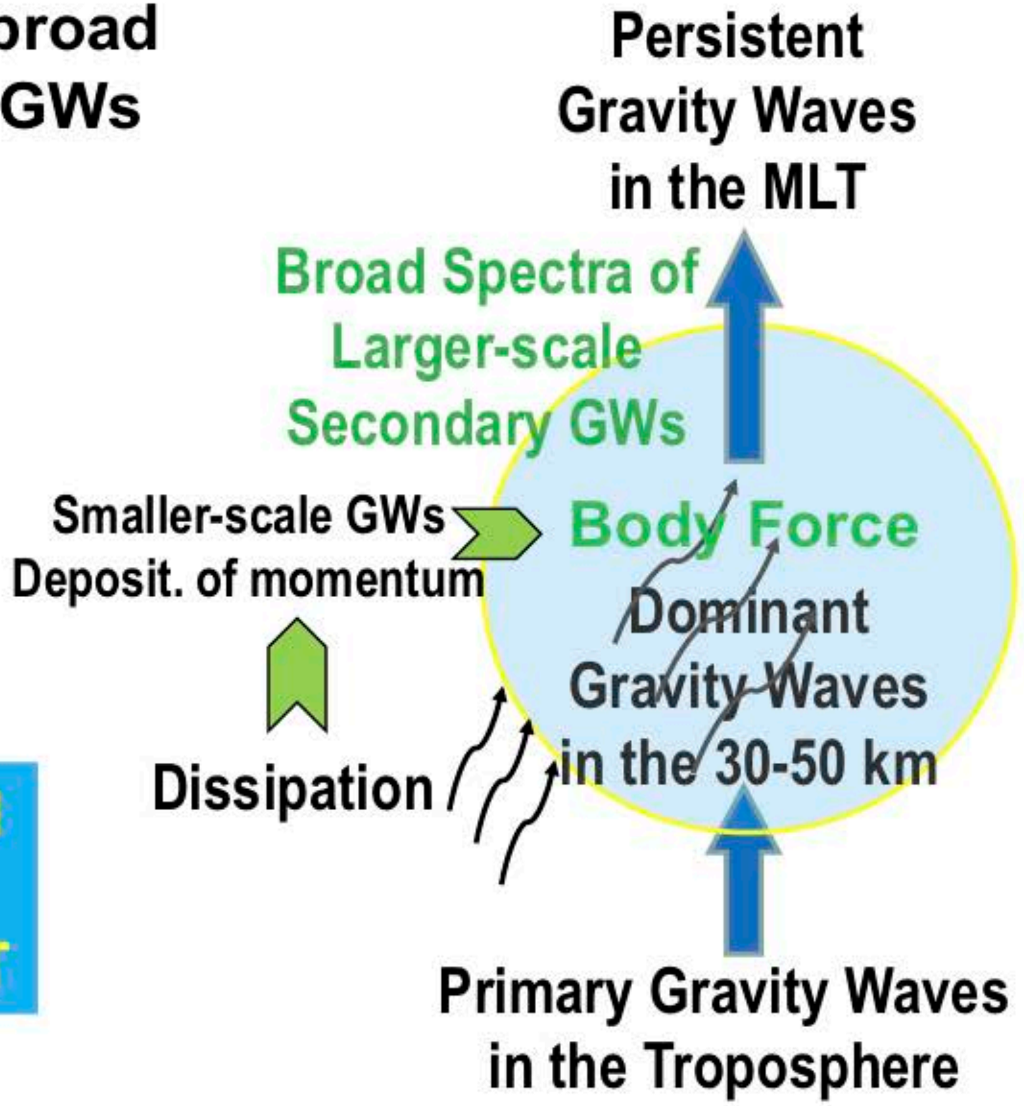
June 29-30, 2011 @ McMurdo

[Vadas, Zhao, Chu, and Becker, JGR, 2018]

A New Picture of Antarctic Gravity Waves in Our Papers

Body force generates a broad spectrum of secondary GWs





Mainly secondary gravity waves; but still some GWs coming from below?

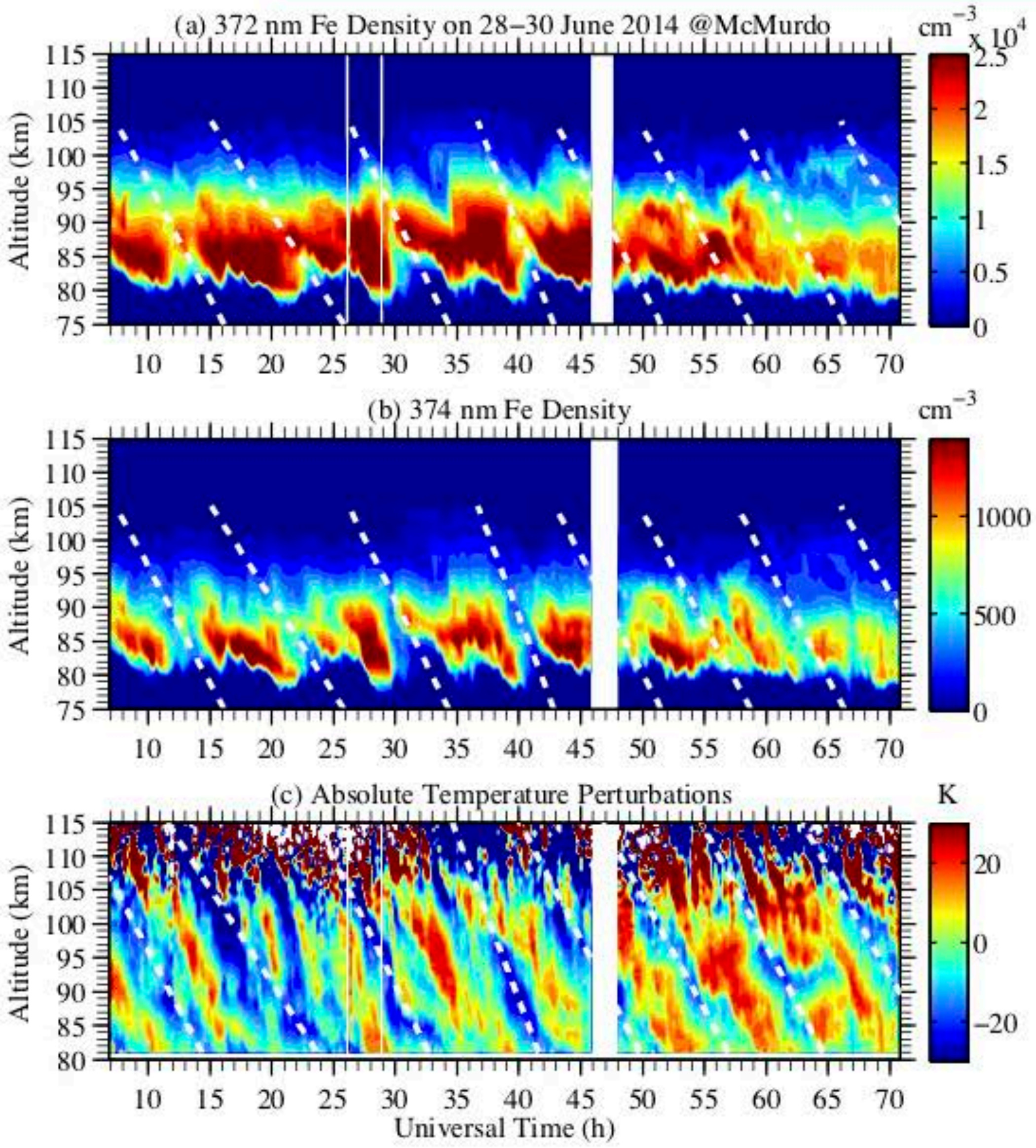
Shorter-period MWs, GWs by polar vortex Secondary GWs …

MWs various periods, IGWs by jet stream & Rossby wave break

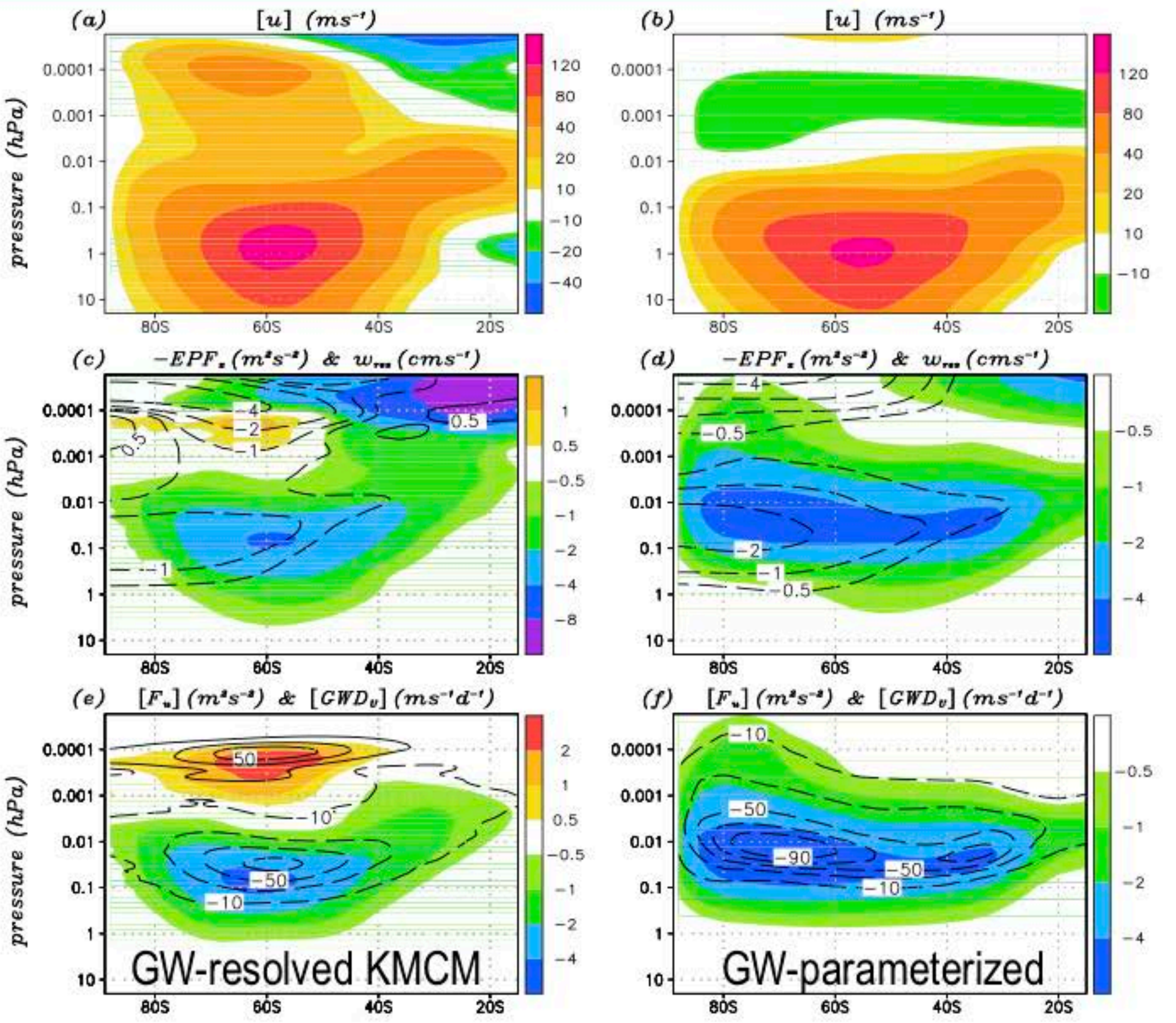
Broad spectra of SGWs excited
Dissipating shorter λ_z SGWs
Longer λ_z SGWs reach the MLT

[Vadas et al., JGR, 2018; Chu et al., JGR, 2018]

Scientific Merits of the New Understandings



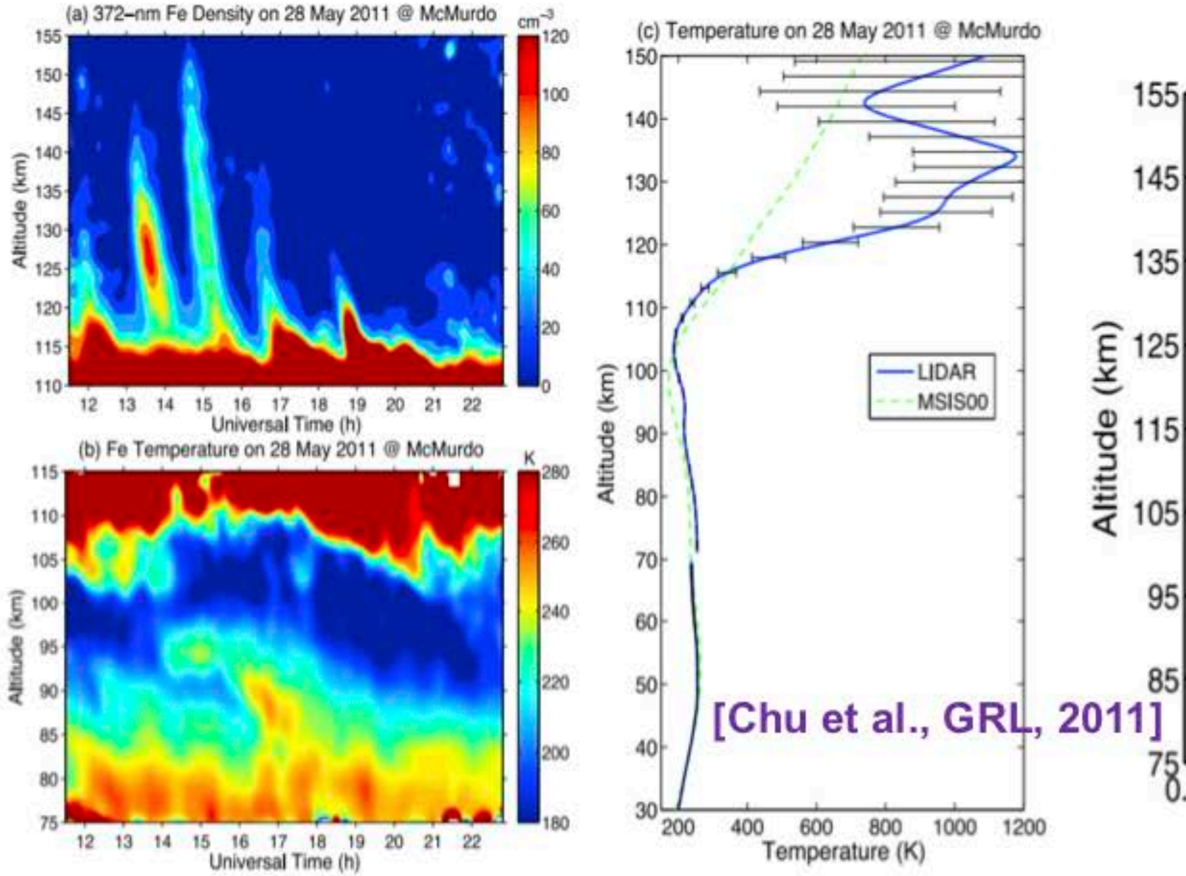
[Chen et al., JGR, 2016]

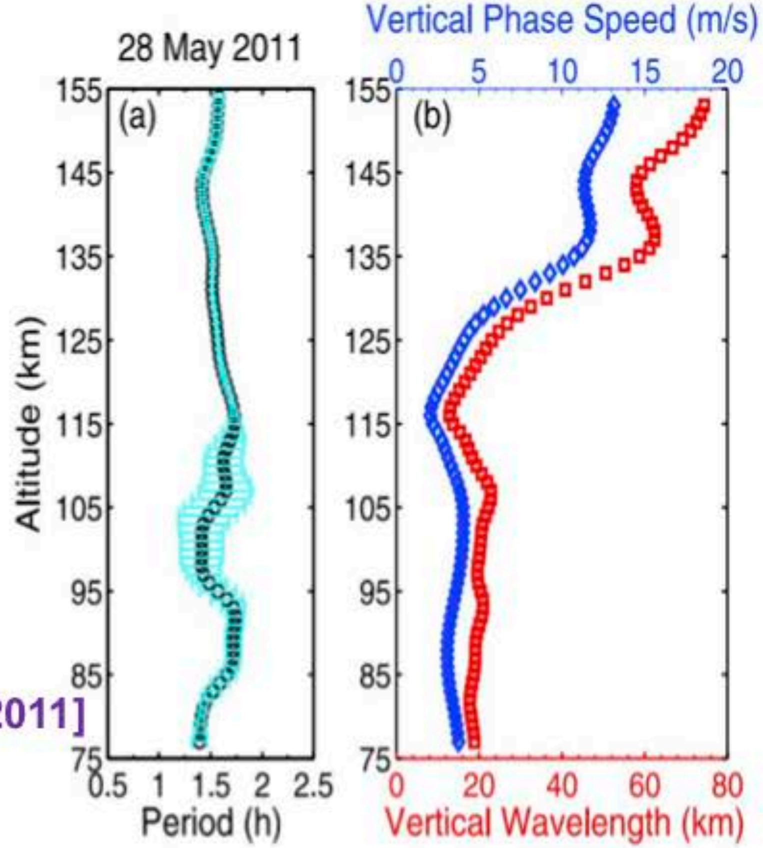


[Becker and Vadas, JGR, 2018]

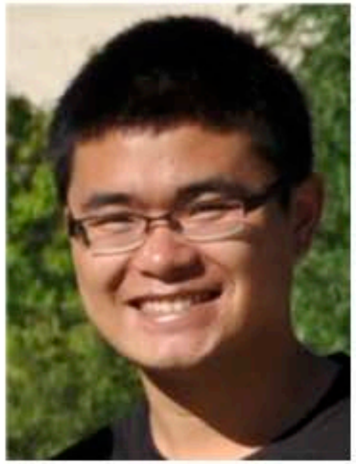
TIFe Layers Formed by Plasma-Neutral Coupling

Thermosphere-Ionosphere Fe (TIFe) layers [Chu et al., GRL, 2011]





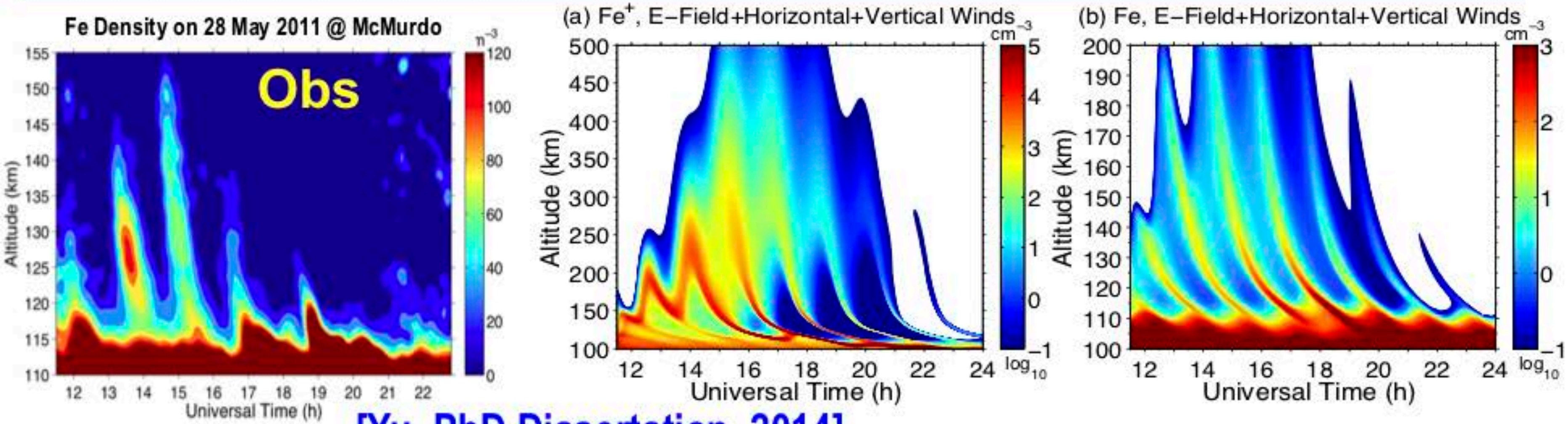
Dr. Zhibin Yu



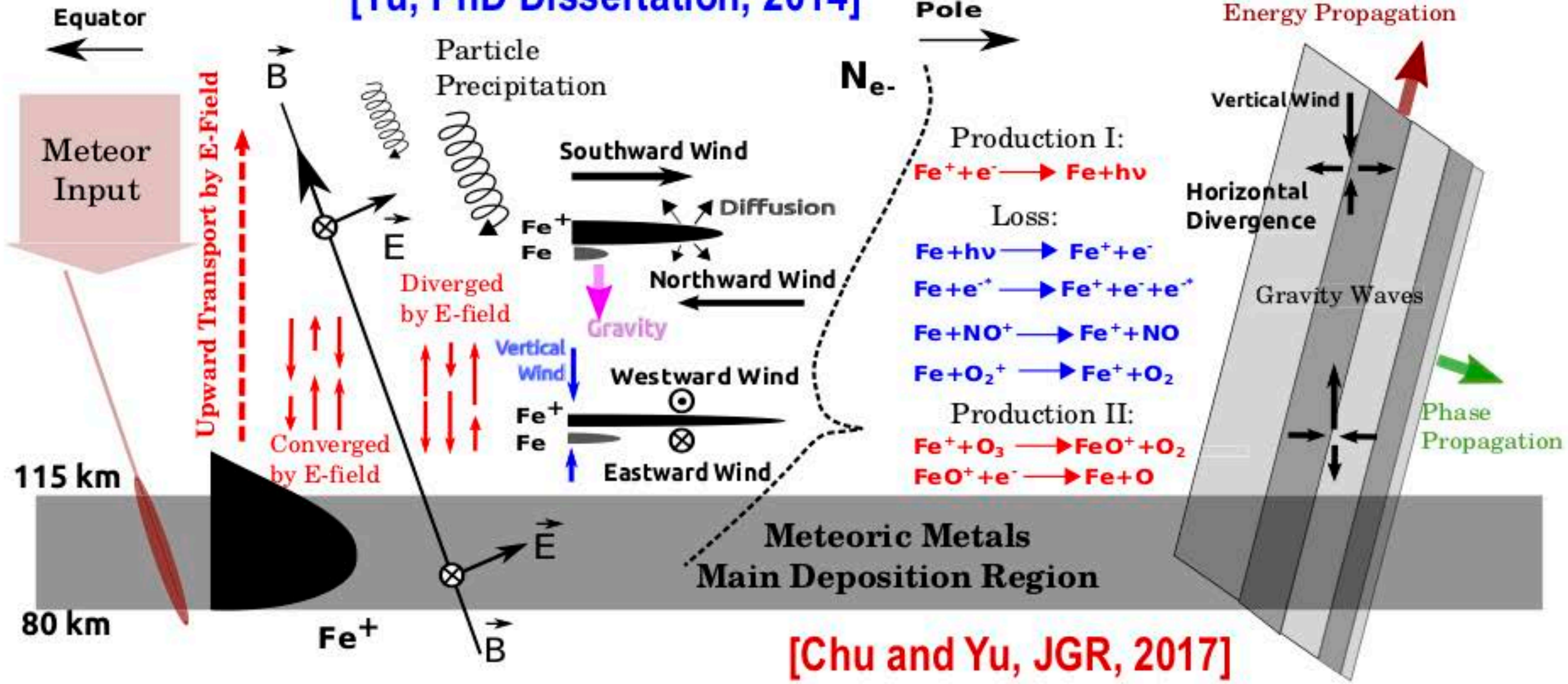
Dr. Cao Chen

This TIFe layer event on 28 May 2011 demonstrates complex gravity wave activity in Antarctica: 1) 3-10 hr inertial-period gravity waves dominate the temperature variations in the MLT; 2) ~1.5 hr fast gravity waves propagate from the MLT well into the thermosphere.

TIFe Model Simulations and Overall Picture



[Yu, PhD Dissertation, 2014]



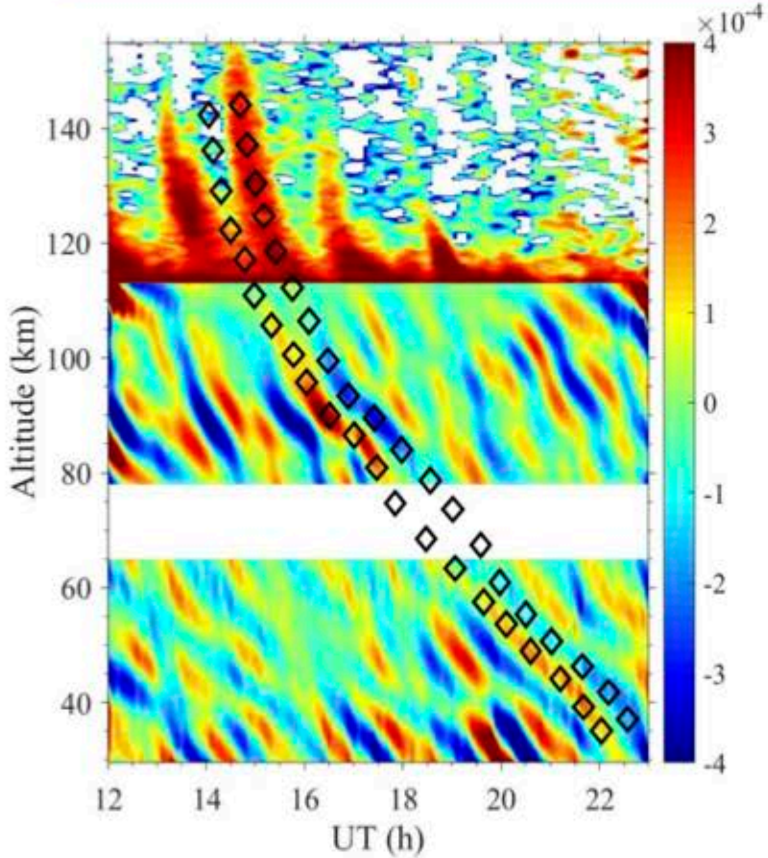
[Chu and Yu, JGR, 2017]

Dr. Zhibin Yu

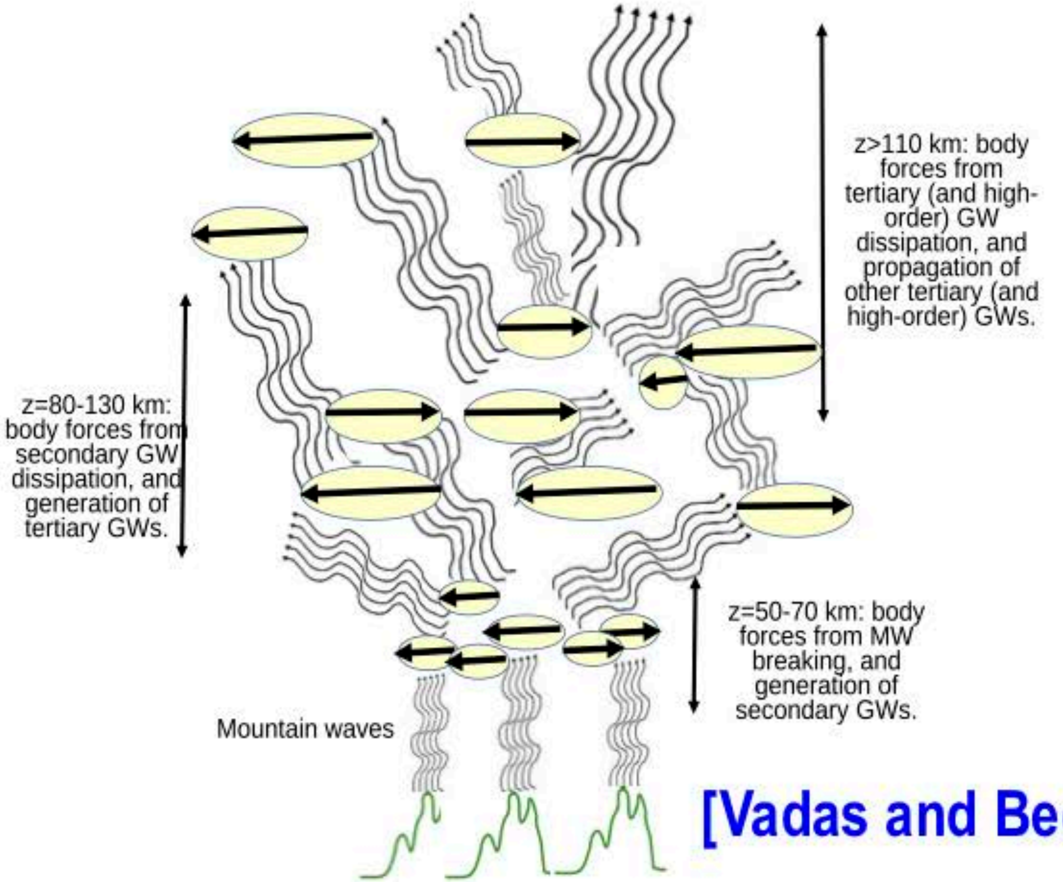
Winter-over 2011

First Place Prize 2013 CEDAR Students Poster Competition

Forming a Big Picture of Antarctic Gravity Waves



[Zhao, PhD Dissertation, 2018]

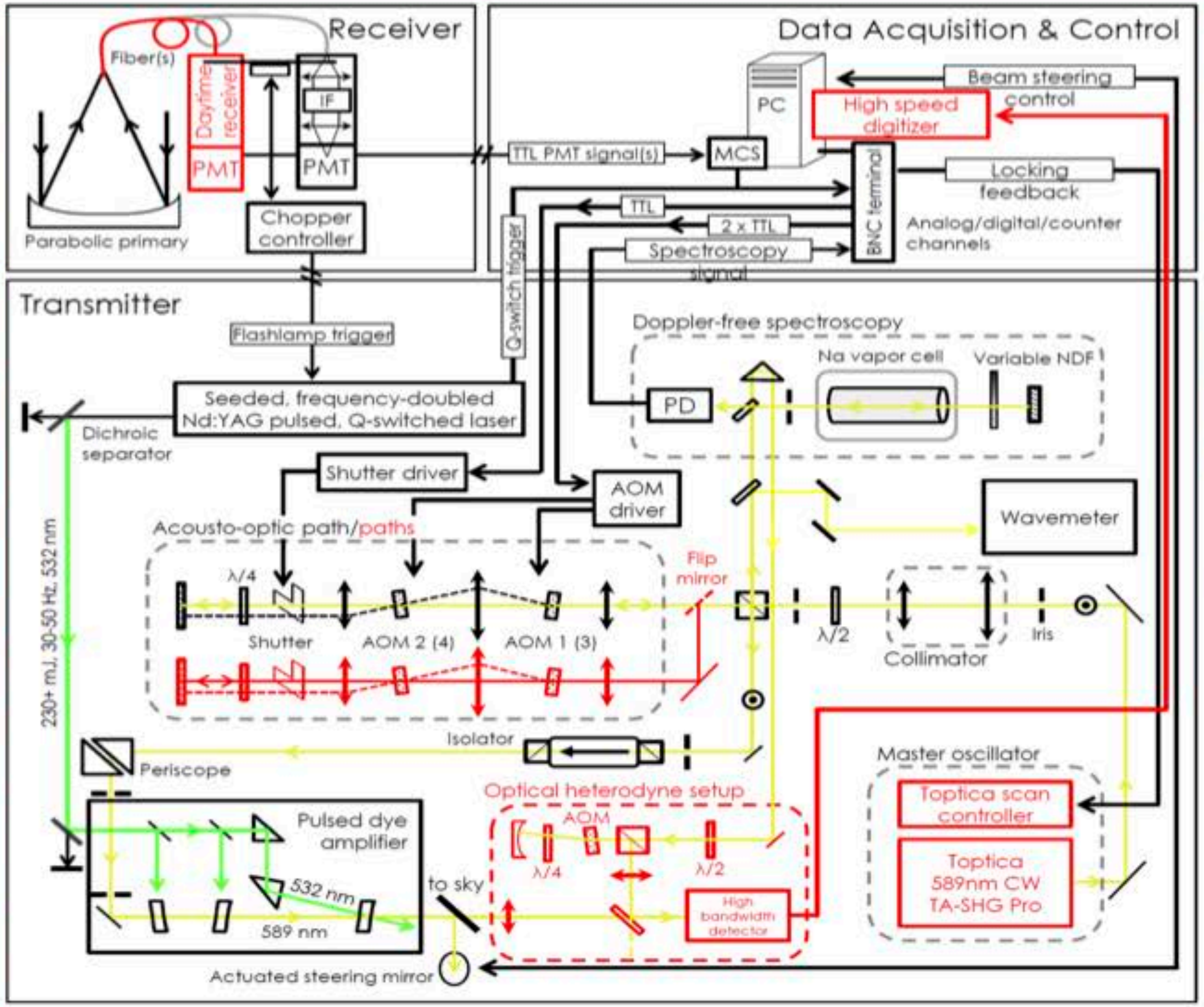


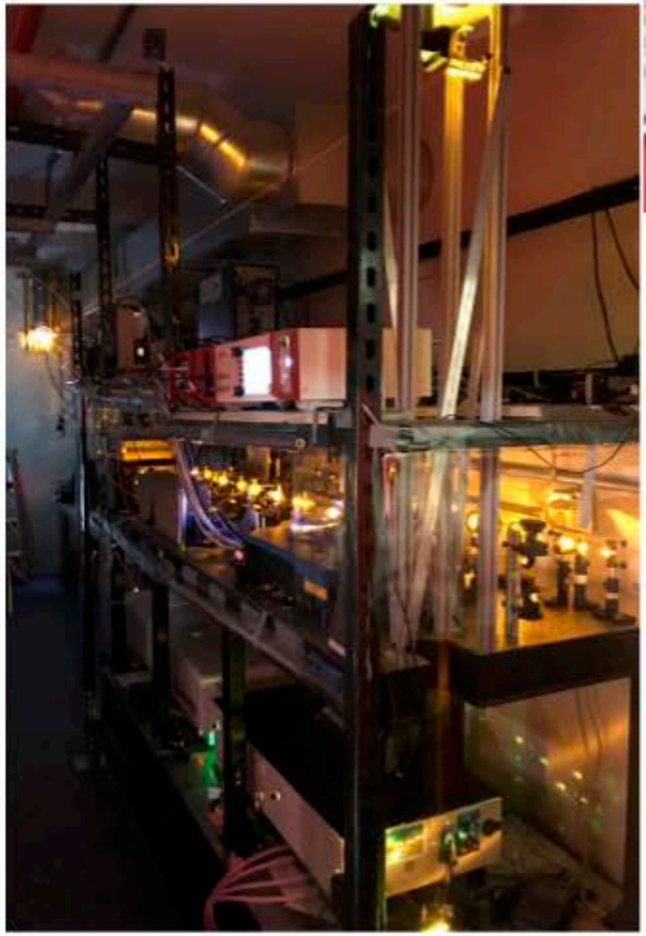
[Vadas and Becker, JGR, 2019]

A paradigm shift: Energy and momentum are transferred from lower atmosphere sources to the MLT via a complex multi-step coupling processes involving primary, secondary, and tertiary gravity waves.

Convection is absent from winter Antarctica. Is it possible to form a big picture of gravity wave coupling from near the surface to the thermosphere in Antarctica?

High-Resolution STAR Na Doppler Lidar

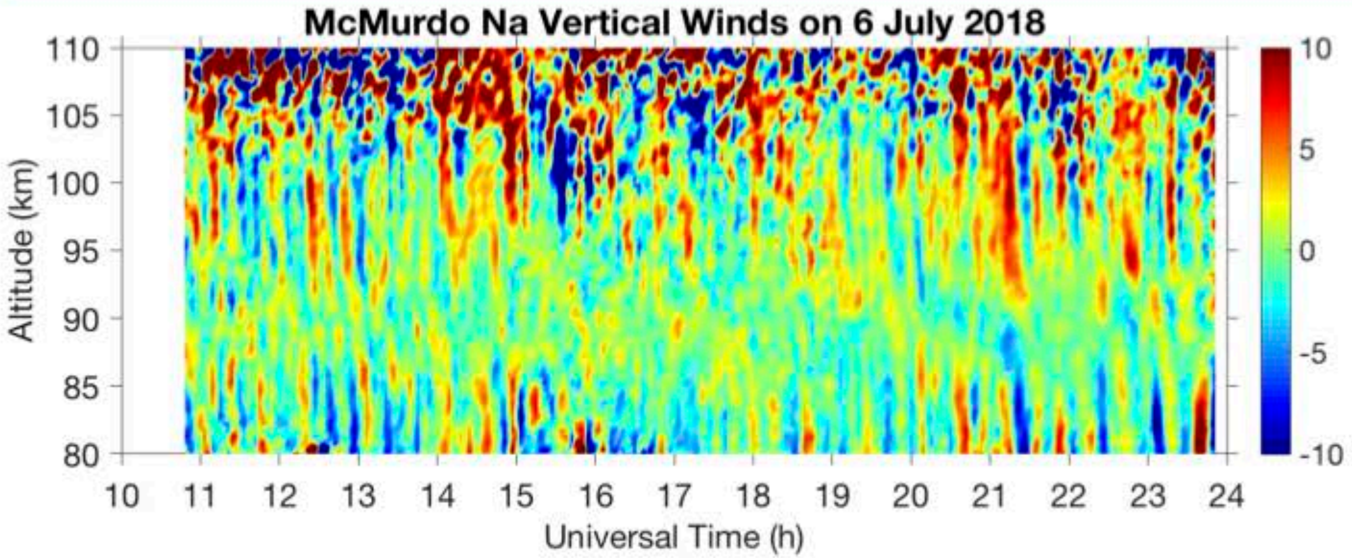




@ Arrival Heights

By making high-precision laser spectroscopy in space, the neutral temperature, line of sight wind, and Na density are measured simultaneously via detecting the Doppler broadening and bulk Doppler shift of Na D_2 absorption line.

High-Resolution Vertical Wind & Temp Obs.



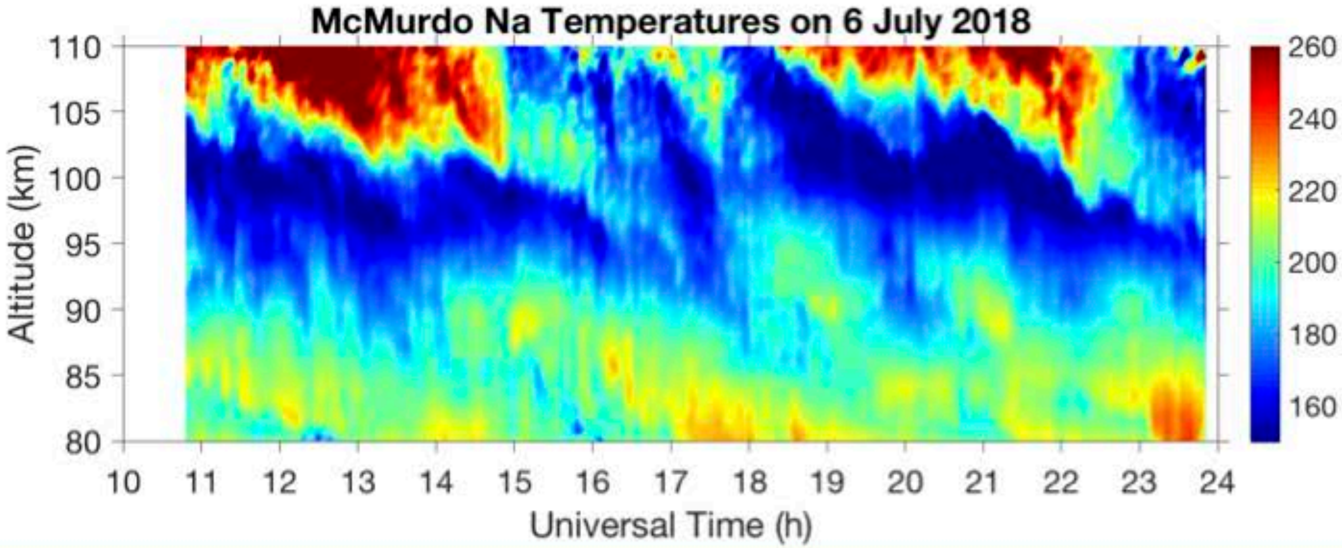
High-freq. waves

τ ~10-20 min

Very obvious on W

Still visible on T

$$\widetilde{T} \approx -\frac{iN^2}{g\hat{\omega}}\widetilde{w}$$



Persistent waves

τ ~3-10 hr

Dominate T variations

Still visible on W

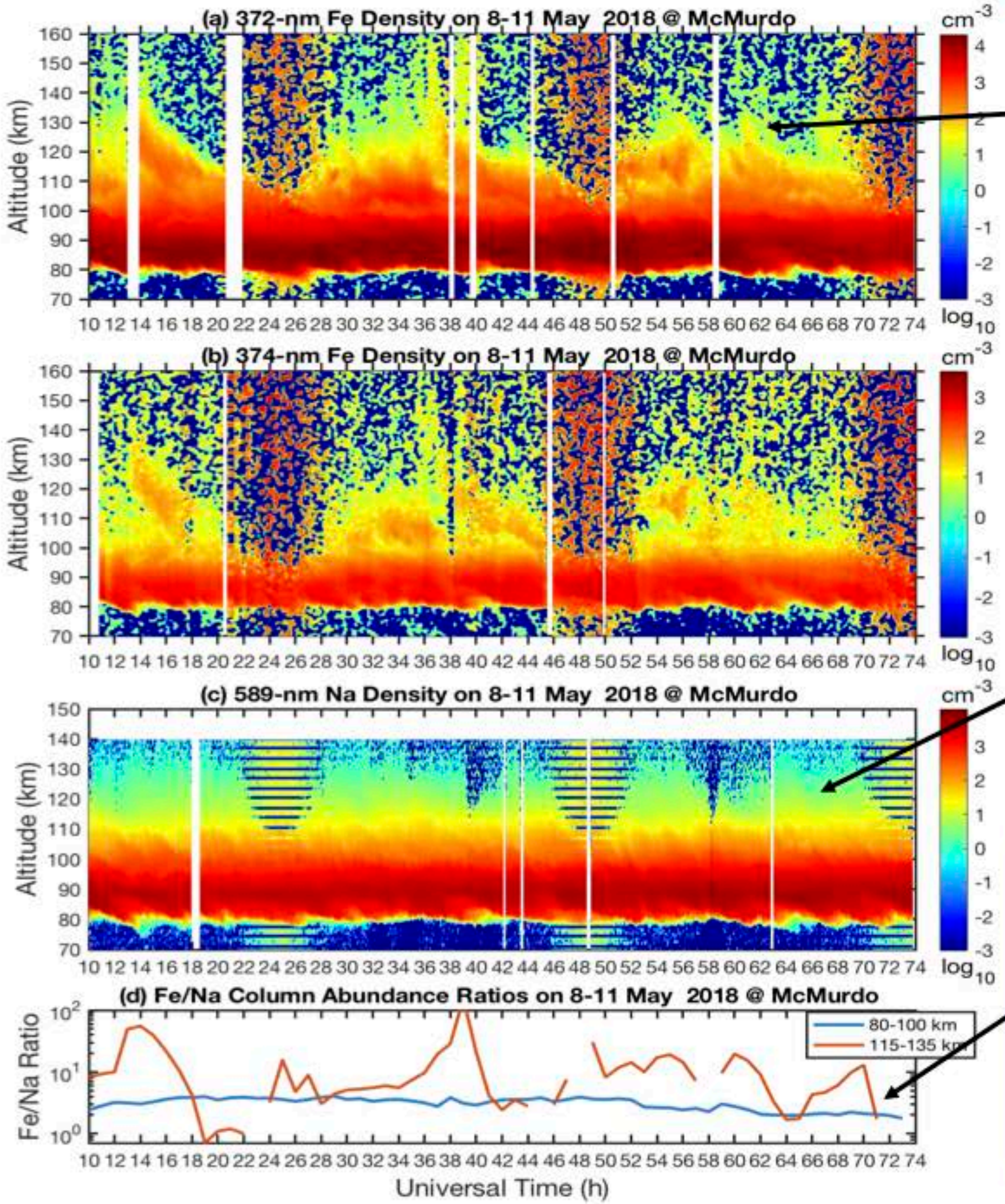
Resolutions used

Δt = 3 -- 6 min

Δz = 0.5 -- 1 km

High-frequency gravity waves are observed with Na lidar in Antarctica. Both secondary and tertiary gravity wave generation are possible.

Simultaneous TIFe and TINa Observations



8-11 May 2018

Very dynamical TIFe layers with high contrast plus some "regular" TIFe peaking around 6-7 UT

Stunning distinction TIFe vs. TINa Above 105 km

"Diffuse" distribution of TINa throughout night plus TINa layers at time similar to TIFe layers

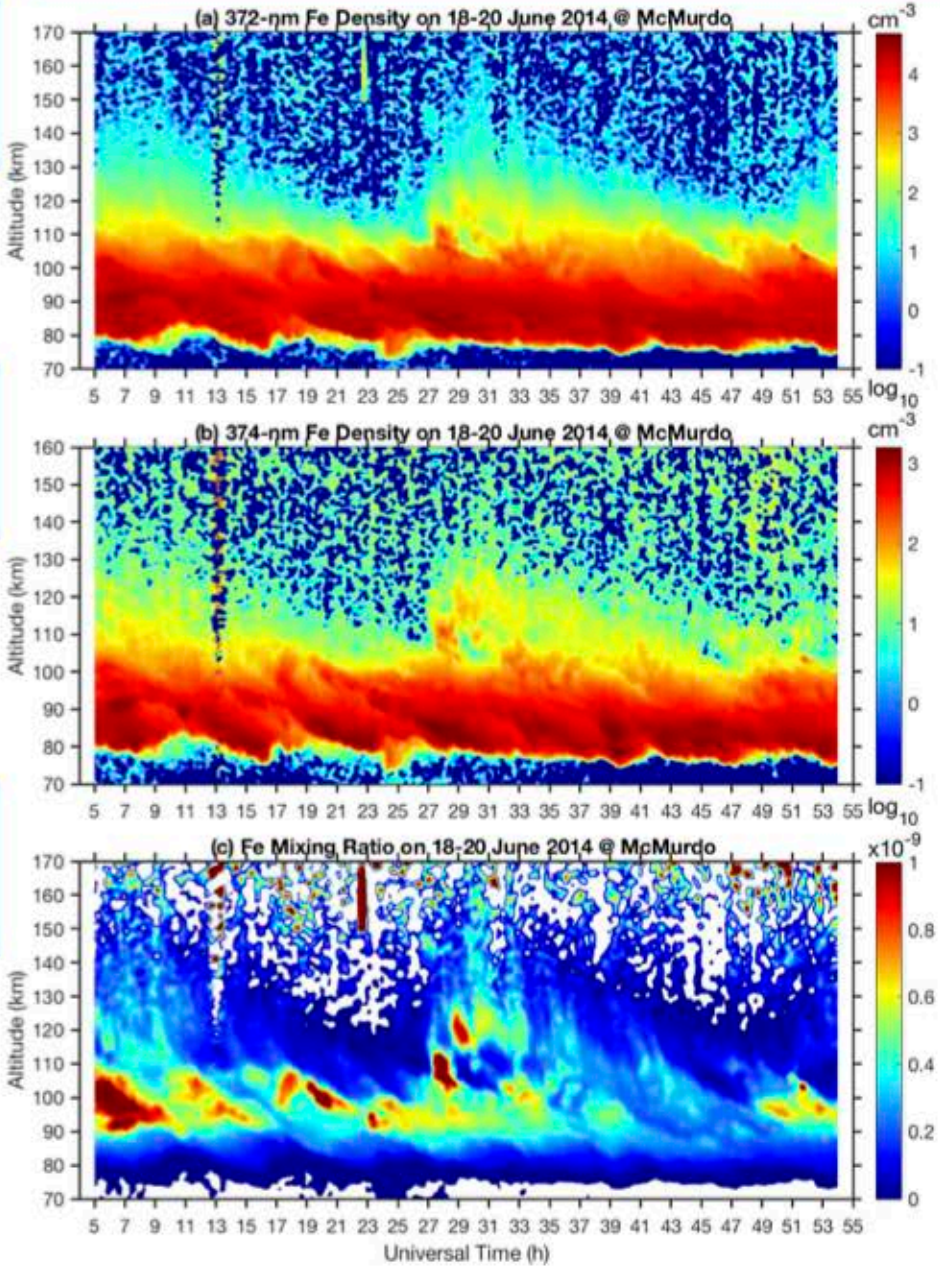
Mesospheric Fe/Na column abundance ratio is ~3, but the TIFe/TINa ratio varies significantly from <1 to ~55 or higher

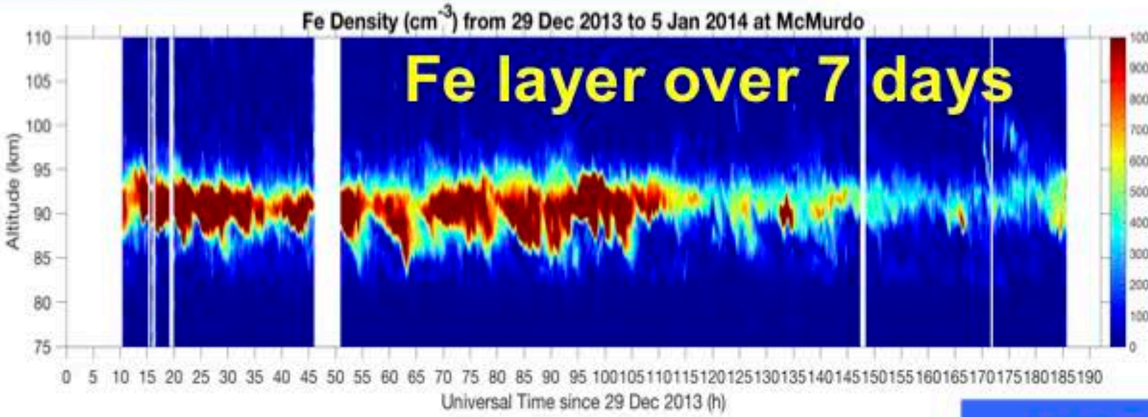
High Sensitivity to Detect Diurnal Cycles of TIFe, PMC & V. Winds

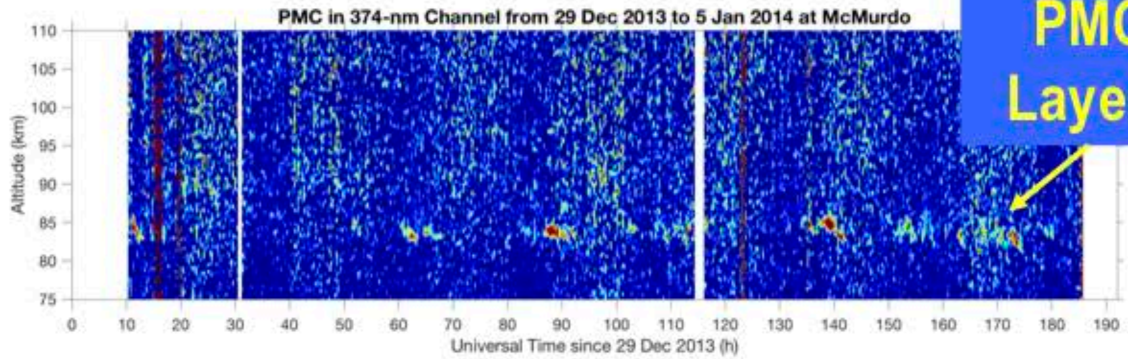
TIFe Layer 372 nm

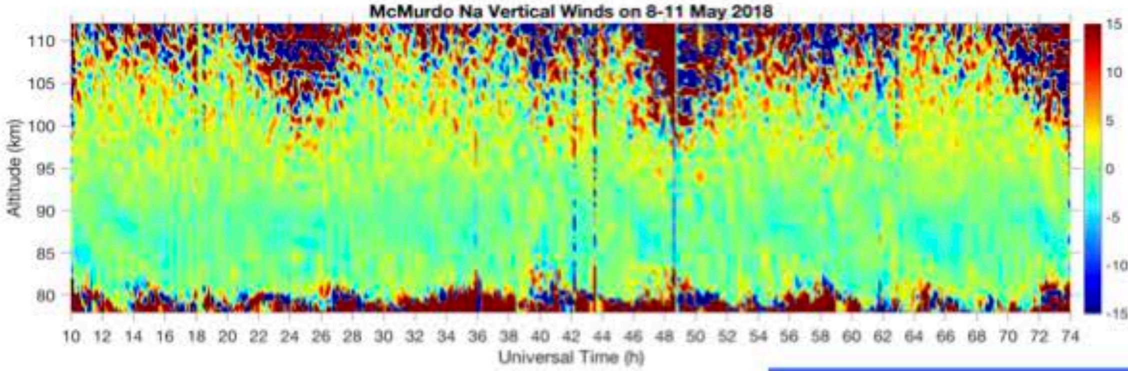
TIFe Layer 374 nm

Fe Mixing Ratio



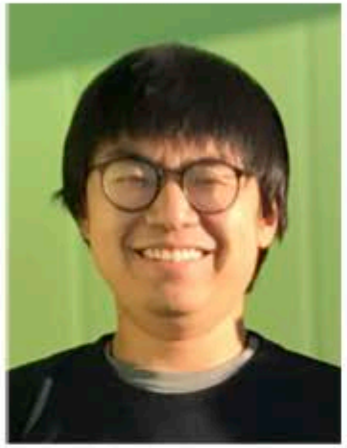






Vertical Winds

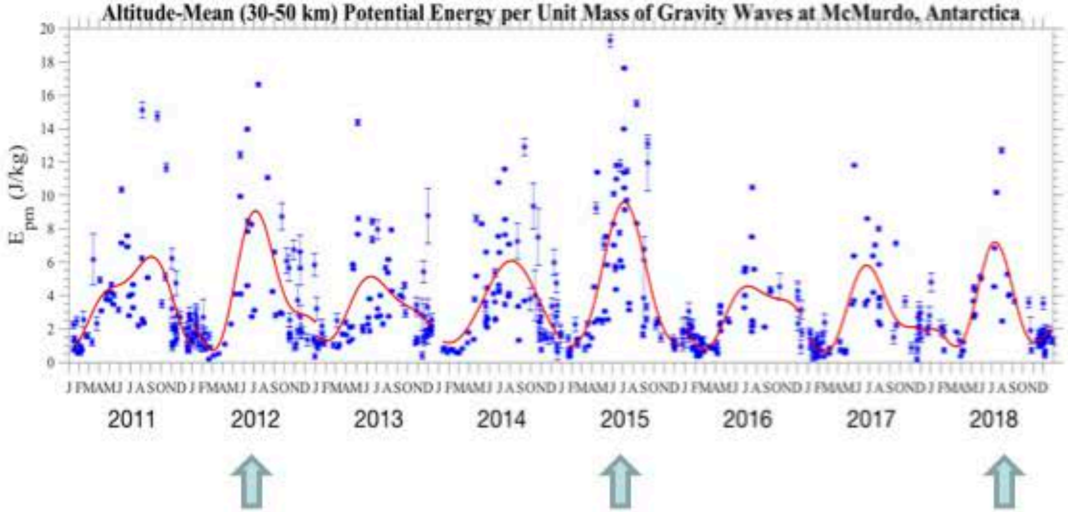
Surprising Results from ~9 Years of Lidar Data

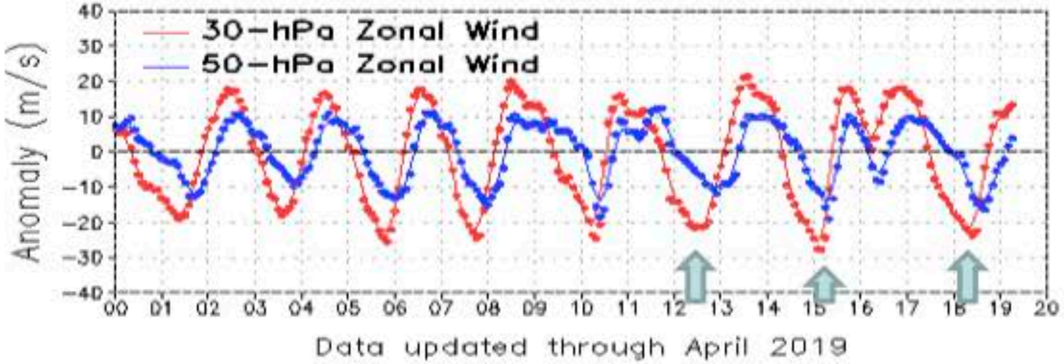


Zimu Li
Winter-over 2019

Zhuoying Chen

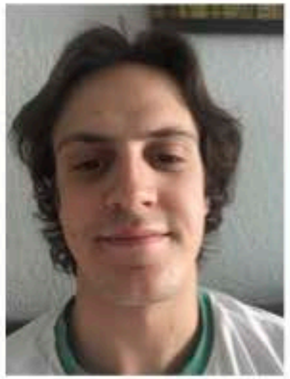
78°S Epm (30-50 km) versus Equatorial QBO Easterly Phase



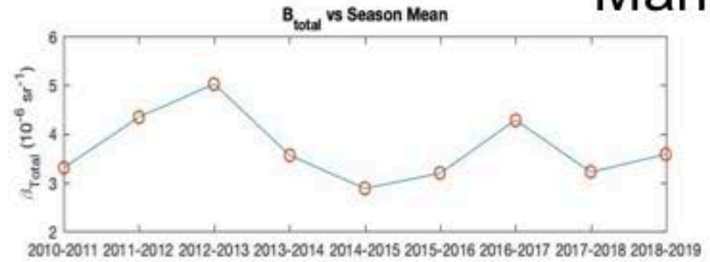


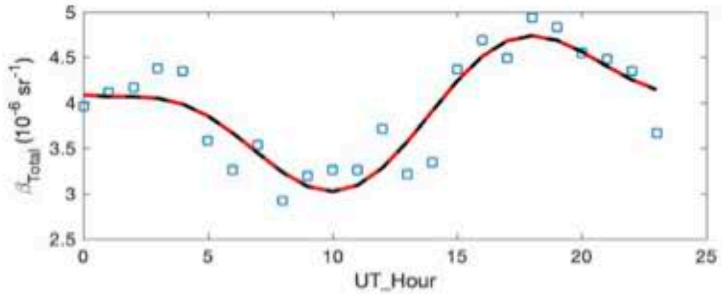
[Chen, Li, et al., CEDAR poster, 2019]

9 Years of PMC vs. solar cycle or lack of it ?



Manuel Lindo





PMC Diurnal

[Lindo et al., CEDAR poster, 2019]

Concluding Remarks and Outlook

1) Synthesis of McMurdo lidar observations, numerical modeling and GW theories leads to a new picture of gravity wave coupling from the lower atmosphere to the thermosphere via secondary GW generation and multi-step coupling concepts. → a paradigm shift?
2) Still many remaining questions, e.g., wave impacts on transport & circulation, high-freq gravity waves, tertiary waves, MWs, … questioning our own interpretations every day.
3) Lidar observations at McMurdo provide huge potentials to the CEDAR--GEM sciences ... What we have studied is just the tip of the iceberg, and many more are awaiting …

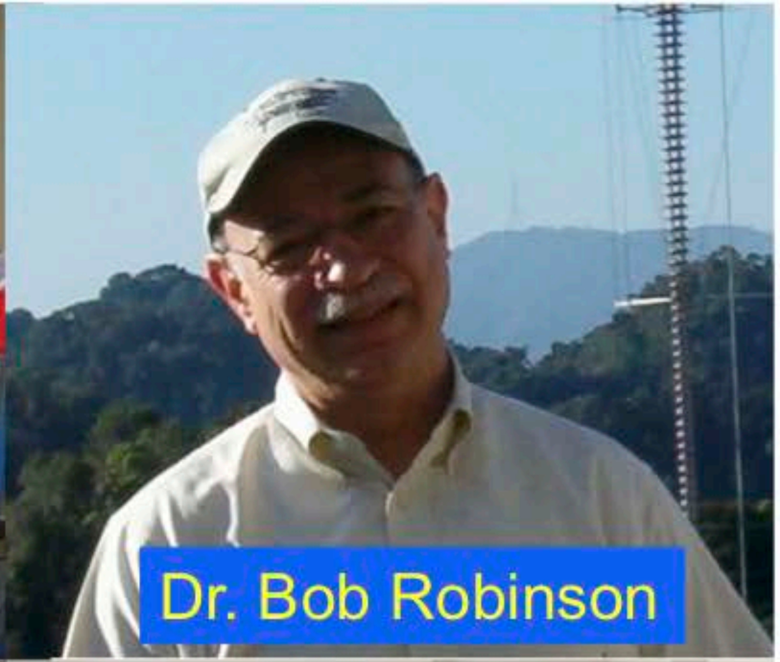
May we use the entire Antarctica as a natural laboratory to advance and test theories of gravity waves, TIMt layers, and A-I-M coupling, etc.?

Gratefully Acknowledge the Tremendous Contributions by Winter-Over Students, Summer Scientists, and Collaborators

Zhibin Yu	PhD	2014	TIFe layers: lidar observations and numerical modeling
John A. Smith	PhD	2014	Na and Fe Doppler lidar development & Mach-Zehnder Inter.
Weichun Fong	PhD	2015	Temp tides and aurora effects on temp, & lidar development
Cao Chen	PhD	2016	Persistent gravity waves & wave recognition methodology
Jian Zhao	PhD	2018	Gravity waves in the stratos. & secondary GW generation

Other winter-overs: Zimu Li, Ian Geraghty, Brendan Roberts, Ian Barry, Zhengyu Hua, D. Chang
Summer scientists: Wentao Huang, Xian Lu, Zhangjun Wang, Muzhou Lu, Mike Lotto
Collaborators: Sharon Vadas, Erich Becker, Chester S. Gardner, Art Richmond, Tim Fuller-Rowell, Lynn Harvey, Adrian McDonald, Mike Jones, John Plane, Jeff Forbes, Bob Robinson, R. Bishop, Zhonghua Xu, Delores Knipp, Hanli Liu, Qian Wu, Mike Taylor, Y. Zhao, D. Pautet, S. Palo, … …

Special Thanks to Great Mentors



Lidar "Geeks" to Explore the Unknown

National Science Foundation -- where discoveries begin

Do not follow where the path may lead.
Go instead where there is no path & leave a trail.