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

Collaboration between USAP and AntNZ

Lidar beams @ Arrival Heights

Fe Boltzmann Temperature Lidar

Aurora on 28 May 2011

Photo Credit: Zhibin Yu

McMurdo lidar projects supported by NSF grants OPP-0839091, 1246405, and 1443726
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 D₂ absorption line.

McMurdoo lidar projects supported by NSF grants OPP-0839091, 1246405, and 1443726
Simultaneous & Common-Volume Observations with Na Doppler and Fe Boltzmann Lidars at McMurdo

Live Volcano Mt. Erebus

Na Doppler lidar beam & telescope since Jan 2018

Fe Boltzmann lidar beams & telescopes since Dec 2010

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

May 2011  Dst (Final)  
HSS  Magnetic cloud (CME)  
Day of Month

June 2013  Dst (Final)  
CME followed by HSS?  
Day of Month

Courtesy of Dr. Delores Knipp & Dr. Zhonghua Xu
Coupling from the Atmosphere to Geospace in Antarctica

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Credit: Danny, Ian, and Zimu
Arrival Heights is a Hotspot of Gravity Waves

1.5-h GWs in TIFe layer
1.5-h GWs in Fe temp
3-10 h GWs in Fe temp

[Chu et al., GRL, 2011]
[Chen et al., JGR, 2013]
[Lu et al., GRL, 2017]

Trans-Antarctic Mountains, Mt. Erebus, East Antarctic Plateau, Ice Shelf
Lidar Discovery of Persistent Gravity Waves with Inertial $\tau$ of 3–10 h and $\lambda_z$ of 20–30 km

[Chen et al., JGR, 2016]

Persistent, large-amplitudes, dominant in the MLT ($T' \sim \pm 20–30$ 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

Dr. Cao Chen
Winter-over 2014
First Place Prize 2012
CEDAR Students Poster Competition
MLT Persistent Gravity Waves in June 2011-2015

Frequency-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!

[Chen et al., JGR, 2016]
Wave Recognition Based on 2D Wavelet for Characterization of Persistent Gravity Waves

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

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?

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)

\[ \lambda_H \approx 400 \text{ km} \]

[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]

Lognormal distributions of
vertical wavelength, period,
and vertical phase speed
[Zhao et al., JGR, 2017]
Stratospheric Gravity Waves are Intriguing

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
Driven Factors for Epm Seasonal Variations

Critical level filtering

Near surface wind

Stratospheric wind at 30 km

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)

GW-resolved KMCM

[Becker and Vadas, JGR, 2018; Vadas and Becker, JGR, 2018]
Secondary Gravity Wave Generation by Localized, Intermittent Body Force

(a) Rel Pertb Scaled 20110629
(b) GW Rel Pertb Scaled
(c) Removed GWs, knee at 52 km
(d) Derived Secondary GWs

Theory

Dr. Becker
Dr. Vadas
Dr. Jian Zhao
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

![Diagram showing body force and gravity waves]

- Persistent Gravity Waves in the MLT
- Broad Spectra of Larger-scale Secondary GWs
- Smaller-scale GWs Deposit of momentum
- Body Force Dominant Gravity Waves in the 30-50 km
- Primary Gravity Waves in the Troposphere

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

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

Broad spectra of SGWs excited
Dissipating shorter \( \lambda_z \) SGWs
Longer \( \lambda_z \) SGWs reach the MLT

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

[Vadas et al., JGR, 2018; Chu et al., JGR, 2018]
Scientific Merits of the New Understandings

(a) 372 nm Fe Density on 28–30 June 2014 @ McMurdo

(b) 374 nm Fe Density

(c) Absolute Temperature Perturbations

[Chen et al., JGR, 2016]

[Becker and Vadas, JGR, 2018]
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

Fe Density on 28 May 2011 @ McMurdo

Obs

(a) Fe⁺, E-Field+Horizontal+Vertical Winds

(b) Fe, E-Field+Horizontal+Vertical Winds

[Yu, PhD Dissertation, 2014]

Equator

Meteor Input

E

B

Particle Precipitation

Production I:

Fe⁺ + e⁻ → Fe + hv

Loss:

Fe + hv → Fe⁺ + e⁻
Fe + e⁻ → Fe⁺ + e⁻ + e⁻
Fe + NO⁺ → Fe⁺ + NO
Fe + O₂⁺ → Fe⁺ + O₂

Production II:

Fe⁺ + O₂ → FeO⁺ + O₂
FeO⁺ + e⁻ → Fe + O

[Chu and Yu, JGR, 2017]

N_e-

Southward Wind

Northward Wind

Diverged by E-field

Gravitational Force

Vertical Wind

Westward Wind

Converged by E-field

E

Energy Propagation

Horizontal Divergence

Gravity Waves

Meteoric Metals Main Deposition Region

Pole

Winter-over 2011

First Place Prize 2013

CEDAR Students Poster Competition

Dr. Zhibin Yu
Forming a Big Picture of Antarctic Gravity Waves

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?

[Zhao, PhD Dissertation, 2018]

[Vadas and Becker, JGR, 2019]
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 D₂ absorption line.
High-freq. waves
\[ \tau \sim 10-20 \text{ min} \]
Very obvious on \( W \)
Still visible on \( T \)

\[ \vec{T} \approx -\frac{iN^2}{g\omega} \vec{W} \]

Persistent waves
\[ \tau \sim 3-10 \text{ hr} \]
Dominate \( T \) variations
Still visible on \( W \)

Resolutions used
\[ \Delta t = 3 - 6 \text{ min} \]
\[ \Delta z = 0.5 - 1 \text{ km} \]

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

PMC Layers

Fe layer over 7 days

Vertical Winds
Surprising Results from ~9 Years of Lidar Data

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

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

Zimu Li
Winter-over 2019

Zhuoying Chen

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

[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

<table>
<thead>
<tr>
<th>Name</th>
<th>Degree</th>
<th>Year</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhibin Yu</td>
<td>PhD</td>
<td>2014</td>
<td>TiFe layers: lidar observations and numerical modeling</td>
</tr>
<tr>
<td>John A. Smith</td>
<td>PhD</td>
<td>2014</td>
<td>Na and Fe Doppler lidar development &amp; Mach-Zehnder Inter.</td>
</tr>
<tr>
<td>Weichun Fong</td>
<td>PhD</td>
<td>2015</td>
<td>Temp tides and aurora effects on temp, &amp; lidar development</td>
</tr>
<tr>
<td>Cao Chen</td>
<td>PhD</td>
<td>2016</td>
<td>Persistent gravity waves &amp; wave recognition methodology</td>
</tr>
<tr>
<td>Jian Zhao</td>
<td>PhD</td>
<td>2018</td>
<td>Gravity waves in the stratos. &amp; secondary GW generation</td>
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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
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Dr. Art Richmond
Dr. Jeff Forbes
Dr. Joe She
Lidar “Geeks” to Explore the Unknown

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National Science Foundation -- where discoveries begin

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