5-2020

Waves Over McMurdo Station

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Abstract

Atmospheric gravity waves (GWs) are generated by gravity acting on weather systems effectively causing them to oscillate. These waves can then propagate upwards into the upper atmosphere, where they are observed as they pass through glowing layers of gas, called airglow, in the upper atmosphere at approximately 87 kilometers altitude. Using Physics and a little bit of chemistry we can observe the properties of these waves with special infrared cameras. Combining the data between images taken at the same time but with different filters, we can determine the temperature amplitudes of the waves, important for improving our understanding of their impact on the upper mesosphere, where they often break and deposit their momentum, like waves on a beach. This study uses data from Antarctica to identify GW events for detailed analysis and includes an in-depth look into one spectacular event that happened on the night of the third of August over McMurdo Station (77.5º S) during mid-winter in Antarctica.

Introduction

Gravity waves are perturbations in the atmosphere's temperature, density, and wind field which are not directly observable parameters. This has made them difficult to study in the past, but recent advancements using the Advanced Mesospheric Temperature Mapper (AMTM), developed at USU (Pautet, et al. 2014) have enabled collection and study of airglow data from which the brightness and temperature signatures on these waves can be determined, even in the presence of aurora. Other important improvements on the analysis front have been made, such as an algorithm to find key wave parameters developed by Matsuda et al. 2014. In this study I was given the task of "cleaning" and analyzing image data obtained from McMurdo Station Antarctica in the winter season of 2018. In addition I used my computer skills to bring a fresh perspective to the code and was able to help refactor it to (a). run more efficiently and (b.) be more understandable and user friendly, important for future users. Using this improved code, I made a detailed analysis of the temporal evolution of two spectacular interacting GW events, helping quantify their interactions for the first time.

Theory

GWs are characterized by several parameters; temperature, horizontal wavelength, and phase speed (hence the period). The AMTM, pictured in Figure 1, measures these properties and also allows us to determine the temperature amplitudes in the OH airglow layer (at approximately 87 kilometers altitude). A Fourier transform (spectral analysis) of "cleaned" AMTM intensity and temperature maps then allows us to calculate the wavelength and phase speeds, from which we can estimate the power and direction of the GWs.

Figure 1. The AMTM in Antarctica.

Airglow

Airglow is a naturally occuring phenomena involving chemical reactions in the upper atmosphere between minor species of hydrogen and ozone, creating hydroxyl in an excited state. As GWs propagate through this layer, they are observed as perturbations in the temperature and pressure of the emissive layer, creating a capability to remotely image the waves. The energy that GWs carry up to the upper atmosphere can also be deposited if the waves break during their passage through the emission layer. A green, visible airglow layer is pictured in Figure 2. The infrared OH layer occurs at a similar altitude, but is not visible to this camera.

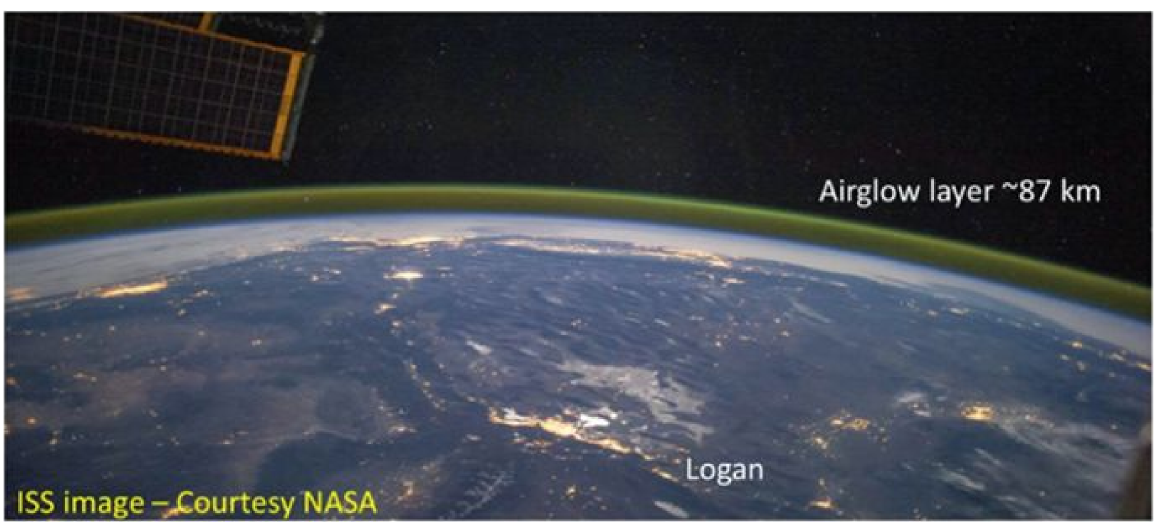


Figure 2. An image of the airglow layer taken from the International Space Station.

Method

The USU Advanced Mesospheric Temperature Mapper (AMTM) at McMurdo station captures images of airglow in the night sky over Antarctica. In these pictures we can see GWs, as perturbations in the airglow emissions brightness and rotational temperature, which is a good proxy for atmospheric temperature at the airglow level.

Data Collection

The AMTM filters out all other wavelengths besides those associated with the hydroxyl reaction; this allows us to take the ratio of the amounts of light we see to calculate the rotational temperature in the airglow layer. The AMTM does this by taking three pictures sequentially approximately every forty seconds. These pictures are denoted as Background, $P_1(2)$, and $P_1(4)$. These image data are then analyzed, as in Figure 3, to produce a brightness and temperature map.

First, the background is subtracted from both $P_1(2)$, and $P_1(4)$ photos to clear them of stars and noise. Second, the ratio between each pixel of the two images is calculated to find the temperature by the algorithm developed by Matsuda et al. 2014. Finally the image is calibrated and scaled to match standard geographic coordinates, with North being up and East being right.

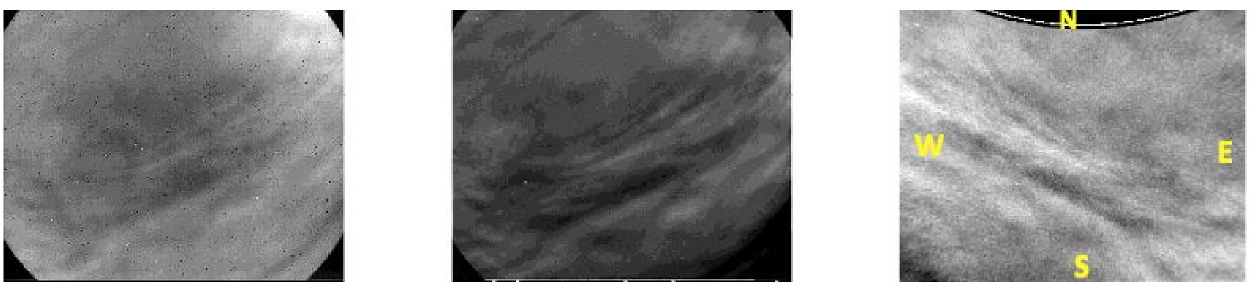


Figure 3. From left to right: a raw $P_1(4)$ image, the same image with the background subtracted, and finally the result of comparing the image to its corresponding $P_1(2)$ image and its calibration and unwrapping.

Data Cleaning

The part of the research I was initially most involved in was vetting the data for anomalies that would influence our data analysis. To do this I would use a program written and developed by the Atmospheric Imaging Lab at USU to view an entire nights worth of data. There were three types of anomalies that interfered with our data: aurora, clouds, and moon glare.

Aurora was the type of anomaly I saw the least. Since aurora's movements are easily seen by the human eye, they move extremely rapidly, at the pace of several km per second, as compared with the airglow, which typically moves at about a hundred meters per second or less. These aurora were very rare, and I only saw a small handful over the entire summer. The few times they did show up only lasted for a several minutes or less, so we were pretty confident that the analysis would not be skewed heavily by including them.

Clouds were much more common and interfered with the airglow image measurements much more. Clouds primarily occur in the troposphere, between our ground based AMTM and the airglow layer that it views. Clouds consist of many tiny water droplets that scatter the light that passes through them, including the light our AMTM uses to make temperature maps. The first clue that clouds are obscuring the view of the airglow layer is the disappearance of the stars. On a clear night stars are visible rotating in a fixed pattern across the sky. When clouds block the view, the light from the star is scattered and the star seems to "disappear" (See Figure 6). The second clue is found on the temperature maps. Wave activity, initially visible on the temperature maps, quickly turns into a "randomized mess" as clouds enter the field of view. Any data that was found to have clouds was excluded from this analysis. In this endeavor I did have an initial amount of help from Dr. Dominique Pautet, who had already marked down the most cloudy nights that had excessive clouds so that I could focus on more sporadically clear nights. This enabled maximum usage of the data.

The third type of anomaly was also the most common in the data I cleaned: moon glare. This was caused by the light from the moon reflecting off of the interior of the observing dome. We did not have the opportunity to know how much this would affect the analysis, so we chose to omit it from our data analysis process. Note: moonlit data were identified and documented for possible future analysis. More research in this area is needed to investigate the magnitude of the moonlit effect on the determination of the GW parameters using the spectral analysis program.

Data Analysis

Code is a stepping stone between the language humans use and the binary of computers. It is well written when both humans and computers can understand its purpose and execution. The original code worked well, but required knowledge of its operations to be well understood. A major part of the work I did for my research project was to refactor this code; a process I did in three steps.

First was understanding the code myself. I made a list of all of the variables in the code to help me keep track of what was being done and where. Having this list would help immensely as it would allow me to define the purpose of each variable, which would help me rename them when the time came. This would be the second step; taking the purpose of each variable and putting it in the name. Alongside this step we added in various comments to explain what was happening as it happened.

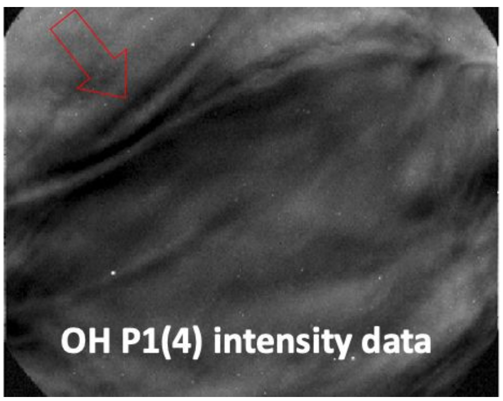
Once this was done, I introduced some structural changes. To understand these, it is important to know a basic overview of how the Matsuda code worked. This function has three parts: input validation, exit conditions, and the loop. Originally both the input validation and exit conditions would run on every step of the loop. The first structural change was to do the input validation and look for exit conditions at the beginning of the function without needing to do it again in the loop. This improved the run time for the function by eliminating redundant actions.

When this code was developed, it required a person to put in the hard-coded path to the files and also the hard-coded path to where the results should save to. The second structural change I made was to make these two paths into parameters of what was now a function so that a third, more general program could call it. This allowed a separate program to run the data analysis on every night without needing anyone to babysit it. A copy of this top level program was then made and modified to run code to make easily viewable videos of special events.

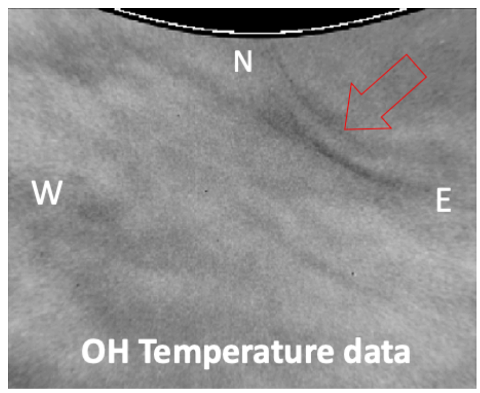
Results

Sixty four nights of data were analyzed with GW events detected on almost all of them, of which strong and interesting GW events were identified on twenty occasions. A visual analysis of one extremely special event, from August 3, 2018 is pictured below, in four phases.

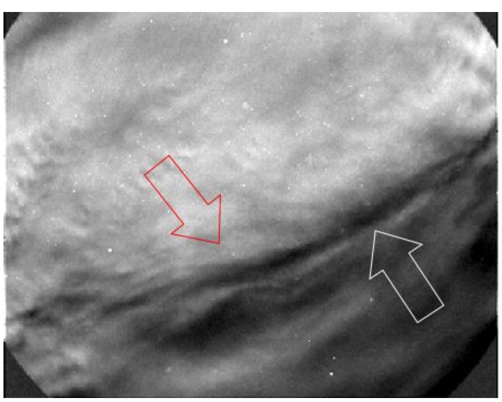
Figure 4. Compendium of $P_1(4)$ brightness on the left and Temperature maps on the right.



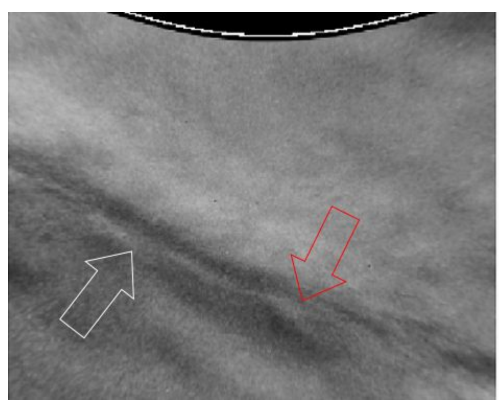
13:34 UT



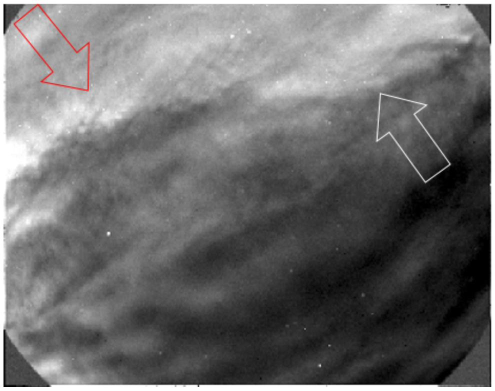
Phase 1: a GW front, shown with a red arrow, enters the field of view from the North East.



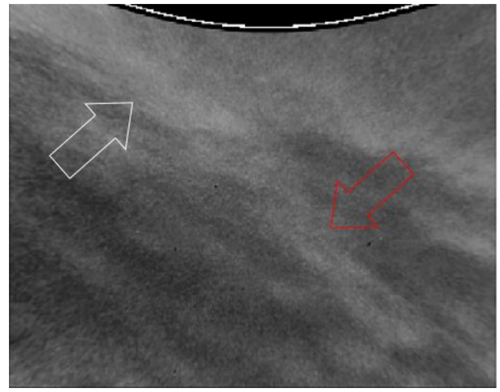
14:02 UT



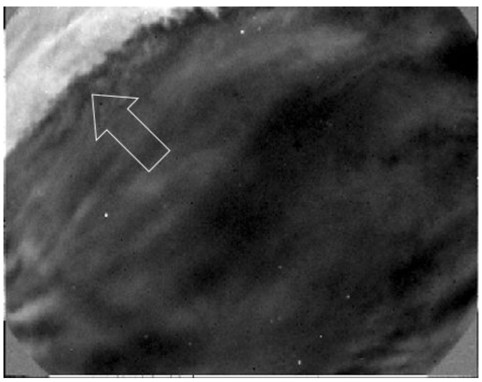
Phase 2: a second GW, shown with a white arrow, enters the field of view from the South West.



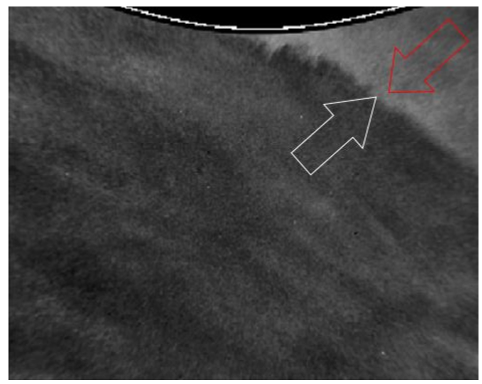
14:30 UT



Phase 3: the two waves interact, showing a strong increase in brightness.



14:50 UT



Phase 4: the two waves interact nonlinearly and exhibit strong breaking “surf-like” signatures, with a temperature decrease of about 20 K.

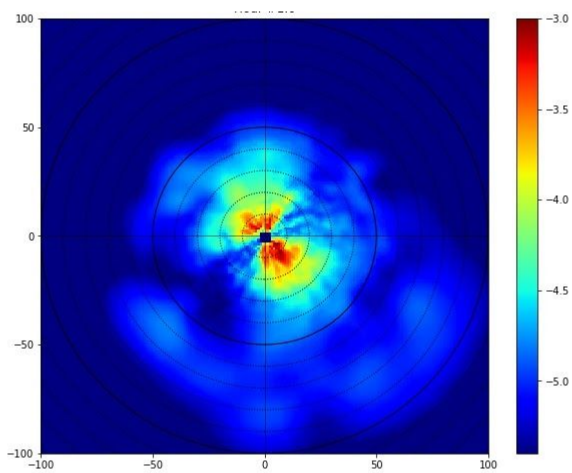
These pictures are interesting, but the action of the waves is much more distinguishable in a graphic interchange format (GIF). These files are available for viewing with the following QR codes or their corresponding URLs.

The $P_1$4 data in GIF. This leads to https://imgur.com/a/6P95nnt

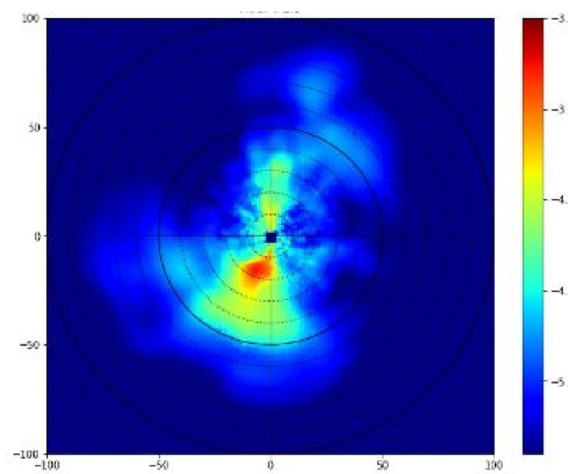
The Temperature Map data in GIF. This leads to https://m.imgur.com/a/Y6pBZwR.

This event shown in Figure 4 was discovered while I was cleaning the data. After all of that was done, the analysis yielded the following azimuthal power diagrams, shown in Figure 5 below:

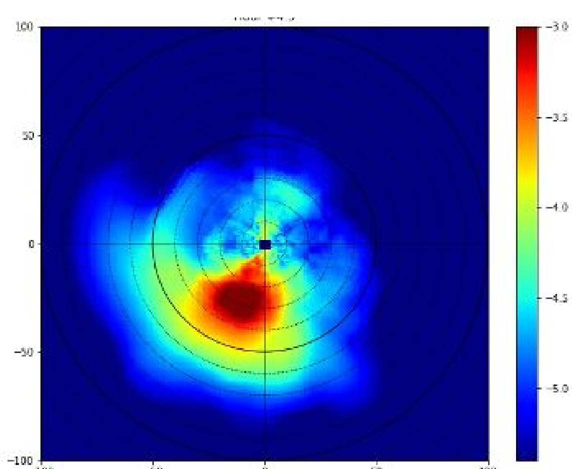
Figure 5. Time Series Analysis Showing GW interaction and dissipation. Each of these diagrams show the computed azimuthal power in the GWs for eight near sequential two hour blocks from the night of August 3, 2018, with a duration of approximately 16 hours. Of special interest is diagram 6, with its strong North East and South West directionality, evident in the event shown above (Figure 4), where the two wave events were interacting and breaking.



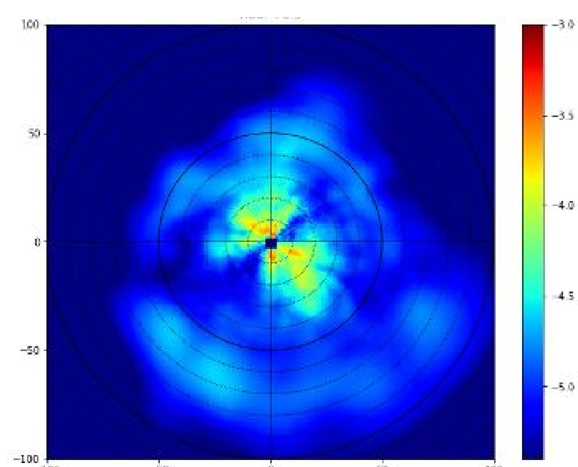
1. 3:45 to 5:45



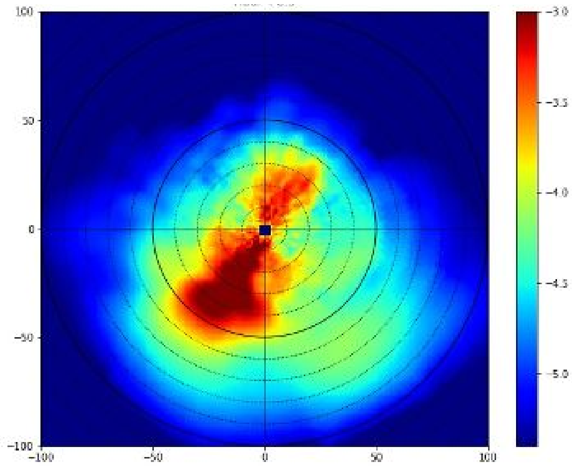
2. 5:15 to 7:15 UT



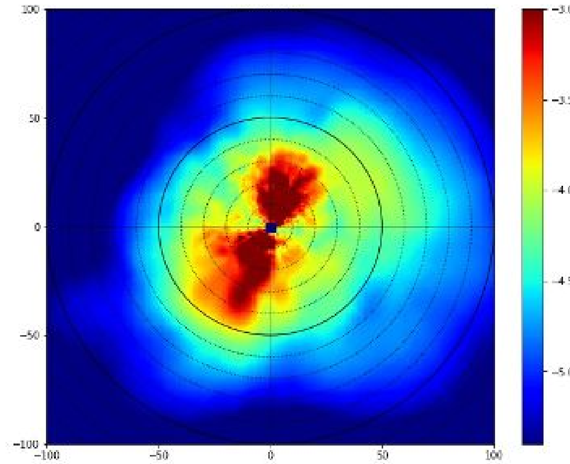
3. 7:15 to 9:15 UT



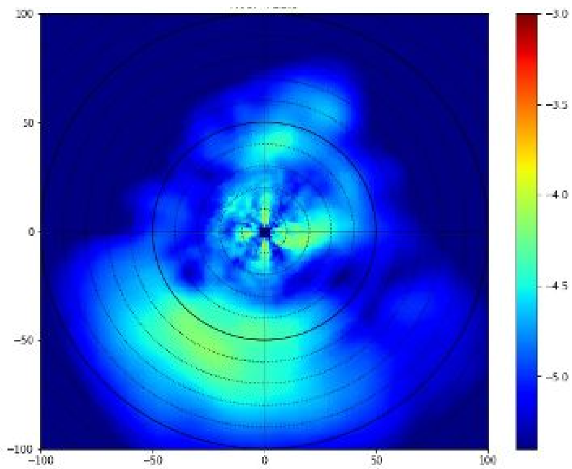
4. 9:15 to 11:15 UT



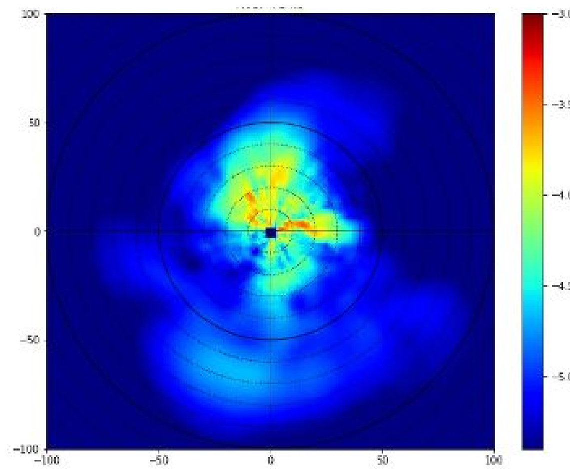
5. 11:15 to 13:15 UT



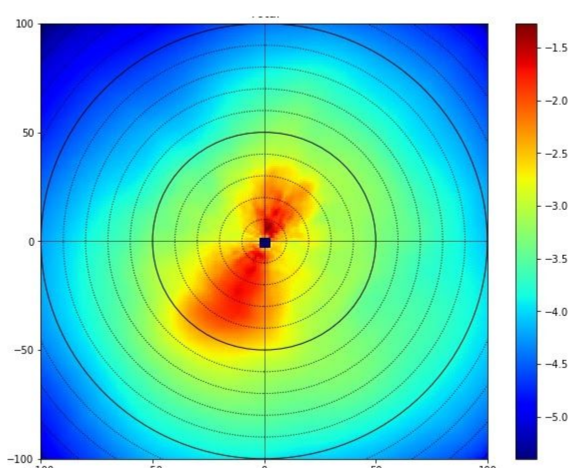
6. 13:15 to 15:15 UT



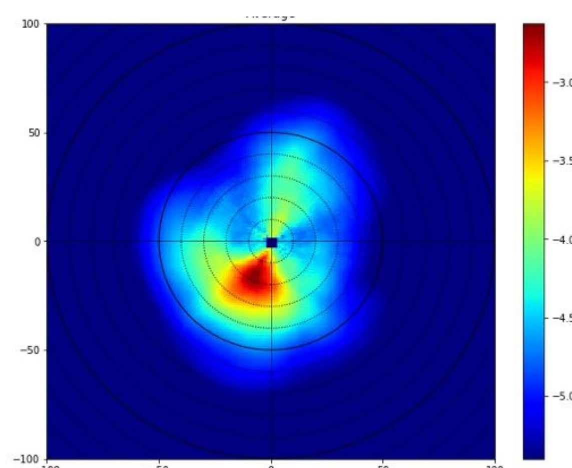
7. 15:15 to 17:15 UT



8. 17:15 to 19:15



9. Data totaled over the entire night



10. The average of the data from the entire night

Summary of the event

As the night starts, we see predominant wave motion towards the South West. These GWs became strongly reinforced around 11:30 UT. At the same time, a second set of waves entered the FOV, propagating in almost the opposite direction, to the North East. The event occurred from approximately 13:00 to 15:00 UT and exhibited large wave power in both directions- SW and NE. Subsequently much weaker wave activity occurred predominantly towards the north for the rest of the night. Special attention should be paid to

Over 60 Antarctic nights were analyzed. This was by far the most impressive night!

Future Work

There are many areas for research into automation for this project that could vastly improve the speed and efficiency of our analysis. They fall into two familiar categories: Cloudy Nights and Moon Glare.

Figure 6. This $P_1(4)$ image taken at 9:29 UT on September 13, 2018. The lack of stars in this image is a clue that clouds are obscuring our view of the airglow layer.

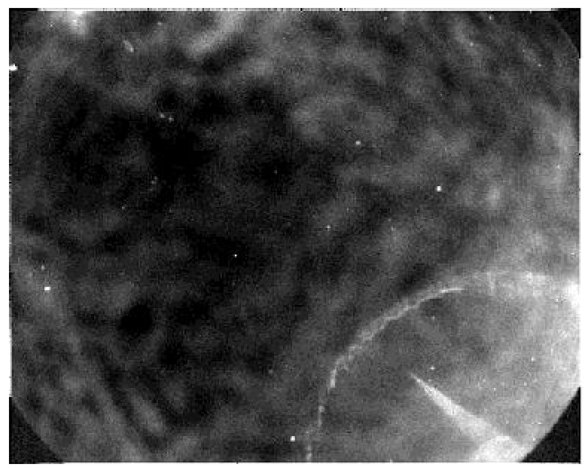


Figure 7. $P_1(4)$ image taken at 7:10 UT, August 22, 2018. Moon glare is shown on the bottom right of the image, appearing as a spike with a ring around it due to reflections off the dome. Note the patchy airglow structures and stars elsewhere in the image.

1. **Cloudy Nights.**

Every pixel in a picture on a computer is merely the computer's way of representing a number. In our system, what we saw as a bright star was really just a really large number that the

AMTM used to denote a star. A program could be made to find these big numbers and track them; if their movement became erratic or they disappeared, it would be a very big hint that clouds were obscuring the view of the AMTM.

Another way we could detect clouds would be the randomness shown in the temperature maps. An average between a pixel and its neighbors in space and time could be calculated and compared to either some constant or a form of the standard deviation. This would be another clue towards knowing if clouds were there that wouldn't require a human to be looking at it.

The third way is the one I am least familiar with: machine learning. Just as I started to recognize the patterns after a month or two of looking at data, a computer could be trained to do much the same. Whether this would be faster or slower than implementing the two above methods is a question I leave up for debate.

2. **Moon Glare.**

Because our optical equipment uses glass, we must deal with the problem of when light reflects internally off the glass. Moon glare is interesting because of its predictability. It would start in about the same location every time and move along a similar path. It would also keep a rather consistent cone shape.

A moon glare filter could be developed to add on top of good data to obtain a control with a dependent variable. This would allow us to compare the two directly to see how much of a difference it would make.

Once we know how much of a difference it does or doesn't make, we can decide if we need to minimize it. Having given the matter a bit of thought, there are two ways I think we could deal with this:

A. **Statistical Method.**

The moon glare was usually a bright spot on the screen. If the pixels were arranged as a histogram, we might see two distributions; one centered on reasonable temperatures for the night, and another centered on the moon glare. If this is verified, the pixels with a value in the second distribution could be replaced with either an average of pixels outside the second distribution or a value that had roughly the same place in the main distribution as the pixel had in the second distribution.

B. **Astronomical Method.**

The moon exhibits phases as it orbits the earth. These phases are well known and that are easily calculated for any location on earth. In theory we could calculate when the moon would be shining on McMurdo station and use the relative position of the moon and the lens of the AMTM to choose an area to "black out" of our analysis. This calculation would be more difficult than the statistical method.

Summary

I have discovered that GWs can be a most interesting phenomena, which occur everywhere in the atmosphere, stretching from the ground to the upper reaches of the atmosphere, up to approximately 100 km. These waves are generated primarily by strong weather events in the troposphere, and they naturally grow in amplitude as they propagate upwards due to the decreasing atmospheric density. In the upper atmosphere these waves break, depositing their energy and momentum in the upper atmosphere, which is extraordinarily dynamic.

The remote sensing airglow imaging measurements that are the topic of my study have been used to identify and investigate GWs over McMurdo Station in Antarctica. It is one of the most remote stations in the world. Sitting in my dark room, watching waves dance over the Antarctic sky was most enjoyable and refreshing. I have discovered this fundamental capacity to learn about and measure waves in the furthest levels of our atmosphere using modern technology.

As we move into the future, our methods to improve these analyses will improve even beyond the code we were able to put together this year. When we do this, utilizing our best methods, even one night can yield amazing results, due to how dynamic the upper atmosphere can be. Future trans-continental air travel will use aircraft that will fly in the mesosphere, and knowledge and prediction of the effects of gravity waves on mesospheric weather will be as important as tropospheric weather forecasting is today.

Acknowledgments

My first acknowledgment is Brett Adair. While searching for a professor to do my research with, he pointed me in the direction of Kenneth Zia and Dr. Taylor. I would also like to thank Dominique Pautet and Yucheng Zhao for their role in helping me see my role in the team. Most of all I would like to thank Mike Taylor and Kenneth Zia. Ken was very helpful in getting me started with the data analysis and showing me the patterns to look for. He was always there to answer questions I had and explain what I was seeing. Professor Taylor was no less of a help. He advised me on the significance of GWs and was a real asset to help me edit both this paper and my SRS presentation.

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