Internal-Gravity Waves Observed During the August 21, 2017 Total Solar Eclipse by National Eclipse Radiosonde Campaign

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Internal gravity waves are oscillations of a fluid parcel about an equilibrium level generated by a buoyancy force when the stability of the fluid medium is disrupted. Such a disturbance occurs from the obstruction of solar irradiance during a solar eclipse and may generate a gravity wave that can be detected using radiosondes. In this study, surface and upper air measurements made from a series of radiosondes launched throughout the duration of the August 21, 2017 total solar eclipse over the US as part of the National Eclipse Ballooning Project are examined for eclipse-induced gravity-wave activity. Preliminary results of radiosonde wind data collected throughout the eclipse from multiple sites within the path of totality in Wyoming reveal the generation of waves with intrinsic angular frequencies in the range 3.3 – 4.2 x 10⁻² s⁻¹ at altitudes of approximately 19 km.

Nomenclature

\[ u = \text{Zonal wind ms}^{-1} \ (\text{from west is positive, from east is negative}) \]

\[ v = \text{Meridional wind ms}^{-1} \ (\text{from north is positive, from south is negative}) \]

\[ w = \text{Vertical ascent rate ms}^{-1} \ (\text{increasing is positive, decreasing is negative}) \]

\[ f = \text{Coriolis frequency s}^{-1} \]

\[ N = \text{Brunt-Väisälä frequency s}^{-1} \]

\[ \omega = \text{Intrinsic angular frequency x 10}^{-2} \text{ s}^{-1} \]

\[ \alpha = \text{Propagation angle of wave radians} \]

\[ x' = \text{Zonal wind displacement m} \]
\[ y' = \text{Meridional wind displacement m} \]
\[ z' = \text{Vertical displacement m} \]

I. Introduction

A total solar eclipse occurs when the Moon passes between the Earth and the Sun and casts a shadow onto the surface of the Earth. The first total solar eclipse to span the United States from coast to coast in nearly 100 years occurred on August 21, 2017 and presented a path of totality from Oregon to South Carolina. A nationwide campaign was organized by the Montana Space Grant Consortium (MSGC) to capture live images of the eclipse from the edge of space using large high altitude balloons. Fifty-five student lead teams from across the US launched a common camera payload developed by the Montana State University (MSU) Balloon Outreach, Research, Exploration, and Landscape Imaging System (BOREALIS) team from multiple locations within the path of totality. “The National Eclipse Ballooning Project” included atmospheric measurements by radiosondes from more than 10 teams along the path of totality. The campaign aimed to monitor the planetary boundary layer and detect effects generated within the Troposphere and Stratosphere at different times throughout the eclipse. The University of Montana (UM) BOREALIS team structured high altitude radiosonde soundings to span the duration of the eclipse in an effort to monitor the planetary boundary layer (PBL) and detect a gravity wave within the atmosphere directly attributable to the cooling region of the moon’s shadow during the total solar eclipse.

Internal gravity-wave perturbations in a gravitationally continuously stratified fluid when a source velocity exceeds the wave propagation speed are analogous to a ‘bow wave’ structured around the source [1]. During a solar eclipse, a gravity-wave system generated by the supersonic motion of the umbra through the atmosphere by analogy would propagate out from the center of the path of totality. The UM radiosonde team operated from three launch sites along the width of this region near Fort Laramie, Wyoming with students from UM, MSU, and Miles City Community College (MCC). This study works to identify and analyze a gravity-wave in the upper air radiosonde observations collected from each of these three launch sites.

II. Methodology

UM placed three launch sites across the width of the shadow of totality. Sites are designated as “North Edge” (42.752 N, 104.456 W), “Central” (42.277 N, 104.454 W), and “South Edge” (41.915 N, 104.382 W), and are located
in or near Lusk, Wyoming, Fort Laramie Wyoming, and Veteran Wyoming respectively. The shadow of totality spanned approximately 110 km (70 miles), making the separation between neighboring sites no more than 55 km. A total of 19 radiosondes were launched over the course of 48 hours between the 3 launch sites. On the day of the eclipse, each site launched four radiosondes in conjunction with each other at the times listed in Table 1. A complete list of radiosonde flight information is displayed in Table 2. Multiple radiosondes transmitting information within close proximity risks interference and erroneous data transmission. To avoid interference between multiple radiosondes aloft at one time, each radiosonde was assigned its own transmitting frequency during initialization, with a 200.0 kHz spacing between frequencies.

Table 1 Launch times for site #1-3 on August 21, 2017

<table>
<thead>
<tr>
<th></th>
<th>5 min Before 1st Contact</th>
<th>40 min Before Totality</th>
<th>5 min Before Totality</th>
<th>30 min After Totality</th>
</tr>
</thead>
<tbody>
<tr>
<td>South</td>
<td>S1_30 min</td>
<td>S1_20 min</td>
<td>S1_Burst</td>
<td>S1_Burst</td>
</tr>
<tr>
<td>North</td>
<td>S2_30 min</td>
<td>S2_20 min</td>
<td>S2_Burst</td>
<td>S2_Burst</td>
</tr>
<tr>
<td>Central</td>
<td>S3_30 min</td>
<td>S3_20 min</td>
<td>S3_Burst</td>
<td>S3_Burst</td>
</tr>
</tbody>
</table>

Fig. 1: Map of UM launch sites in respect to the path of totality in Wyoming.

A. Surface

Conditions were measured at the surface of each radiosonde launch site. Center site near Fort Laramie recorded surface conditions using a Lufft WS502-UMB smart weather sensor and pyranometer beginning ~50 hours prior to eclipse totality and ending approximately 24 hours after eclipse 4th contact. Figure 2 shows a 14 hour period of raw surface wind speed and temperature measurements compared to solar radiation between 06:00 and 20:00 MST on
August 21, 2017. North edge and south edge sites in Lusk and near Veteran, respectively, recorded surface conditions using Kestrel 4500 and 5000 Pocket Weather Trackers. Error between Lufft and kestrel is small. Kestrels were calibrated and mounted on a tripod that placed them at the same altitude as the radiosondes during initialization. Kestrels were allowed to rotate freely with wind direction by attaching a wind vane to the mount. Kestrel data was continuously logged beginning ~ 3 hours prior to eclipse totality and ending approximately 2 hours after eclipse totality. Lufft and Kestrel measurements were used for surface values required by radiosonde software during radiosonde initialization as well as to verify that a radiosonde’s output was within desired specifications: < ±5 mb for pressure, < ±2 C for temperature, and < ±10 % for relative humidity before each launch.

B. Aloft

Upper air measurements were taken using GrawMet DFM-09 radiosondes suspended by 350 g or 1,000 g Kaymont latex high altitude weather balloons. The radiosonde is equipped with a temperature sensor designed to perform with resolution 0.1°C and accuracy of ±< 0.2 °C up to 40 km and code-correlated global positioning system (GPS) receiver. The GrawMet software then uses the corresponding temperature and GPS readings to calculate pressure, relative humidity, wind speed, wind direction, altitude, and vertical rise rate. Each sounding gives high temporal resolution (δt = 2 second) vertical profiles of the parameters listed above. The balloons were filled with helium to achieve an average rise rate of 5 m/s for adequate air flow over sensors on the radiosonde. The fill value was dependent on balloon mass, payload mass, surface temperature, and surface pressure.
UM launched radiosondes with a specific procedure and construction for adequate quality control. After initialization, a radiosonde is allowed to hang approximately 3 feet off the ground and within 5 feet of the Kestrel or Lufft surface weather station at least 15 minutes to fully acclimate to the surrounding conditions. The radiosonde is then attached to the weather balloon using 50 lb test string along with a parachute and a de-reeler containing ~29 meters of additional string. The top of the parachute is attached to the neck of the balloon with ~0.75 m of string. The de-reeler is attached to the bottom of the parachute with ~ 6.0 inches of string and, lastly, the radiosonde is secured to the end of the string within the de-reeler. When the balloon is released and ascends into the atmosphere, the de-reeler slowly unwinds to create more than 30 meters of space between balloon and radiosonde to avoid wake affects from the balloon. GrawMet software corrects for pendulum effects experienced by the radiosonde shortly after release.

**Table 2 Flight information from all radiosondes launched in Wyoming by UM BOREALIS.**

<table>
<thead>
<tr>
<th>Aug. 20, 2017</th>
<th>Launch time w.r.t eclipse</th>
<th>ID</th>
<th>Launch</th>
<th>Terminate</th>
<th>Max Altitude ASL, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 g</td>
<td>T/C2</td>
<td>N1</td>
<td>11:47 am</td>
<td>Burst</td>
<td>24,166</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S1</td>
<td>11:45:51 am</td>
<td></td>
<td>24,755</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C1</td>
<td>11:45:08 am</td>
<td></td>
<td>26,681</td>
</tr>
<tr>
<td></td>
<td>18 hours before T</td>
<td>C2</td>
<td>05:49:08 pm</td>
<td></td>
<td>26,181</td>
</tr>
<tr>
<td></td>
<td>12 hours before T</td>
<td>C3</td>
<td>11:46:04 pm</td>
<td></td>
<td>27,560</td>
</tr>
<tr>
<td>Aug. 21, 2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>350 g</td>
<td>6 hours before T</td>
<td>C4</td>
<td>05:46:04 am</td>
<td>Burst</td>
<td>25,106</td>
</tr>
<tr>
<td></td>
<td>5 min before C1</td>
<td>N2</td>
<td>10:18:57 am</td>
<td>~ 30 min</td>
<td>11,395</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S2</td>
<td>10:18:12 am</td>
<td></td>
<td>9,684</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C5</td>
<td>10:19:04 am</td>
<td></td>
<td>9,111</td>
</tr>
<tr>
<td></td>
<td>40 min before T/C2</td>
<td>N3</td>
<td>11:06:01 am</td>
<td>~ 20 min</td>
<td>7,561</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S3</td>
<td>11:05:44 am</td>
<td>~ 50 min</td>
<td>16,570</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C6</td>
<td>11:06:05 am</td>
<td>~ 20 min</td>
<td>7,083</td>
</tr>
<tr>
<td>1000 g</td>
<td>5 min before T/C2</td>
<td>N4</td>
<td>11:40:56 am</td>
<td>Burst</td>
<td>31,682</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S4</td>
<td>11:40:56 am</td>
<td></td>
<td>32,435</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C7</td>
<td>11:41:08 am</td>
<td>~ 25 min</td>
<td>9,490</td>
</tr>
<tr>
<td></td>
<td>30 min after T/C2</td>
<td>N5</td>
<td>12:16:55 pm</td>
<td>Burst</td>
<td>34,528</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S5</td>
<td>12:18:28 pm</td>
<td></td>
<td>32,241</td>
</tr>
</tbody>
</table>
Radiosonde profiles N2, N3, S2, C5, and C6 were terminated before totality and before reaching the stratosphere. For these reasons, analysis of these profiles will be left for planetary boundary layer studies around the eclipse and will not be presented here.

C. Analysis

Two methods of data analysis are applied to each radiosonde sounding. To first extract wave signal from the soundings, a filtering method presented by Scavuzzo [3] is applied to the horizontal and vertical raw wind profiles to isolate waves with intrinsic frequencies greater than the Coriolis frequency $f$ but less than the Brunt-Väisälä frequency $N$. The moving parcel method described by Marlton [2] is then applied to the filtered data to quantify wave frequency, amplitude and wavelength of the dominant wave signal. The angle of the winds with altitude are examined to reveal energy dissipation and propagation direction. Before applying any filters to the radiosonde data, a linear spline is applied to transform the irregularly spaced vertical profiles of temperature, pressure and wind into regular ones with resolution $\delta z = 10$ m. The filtering process works by first applying a low-pass filter that suppresses frequencies smaller $f$. A second low pass filter that suppresses frequencies smaller than the approximate upper bound of $N$ is applied to the resulting signal from the first filter. The complete filtered wave signal is obtained as the difference between the two filtered signals. Values of $N$ below 50 km are on the order of $10^{-2}$ s$^{-1}$. $N$ was calculated for each sounding from the thermodynamic variables measured by the radiosonde over a 250 m height window, Marlton [2]. The value of $f$ varies slightly between each launch site due to their different latitudes. Due to drift experienced by the radiosonde during flight, the value of $f$ experienced at the north edge site, south edge site, and center is averaged to be $9.87 \times 10^{-5}$ s$^{-1}$, $9.74 \times 10^{-5}$ s$^{-1}$ and $9.81 \times 10^{-5}$ s$^{-1}$, respectively.

Gravity waves are transverse; meaning the restoring buoyancy force is always transverse to their propagation. The phase of the wave is a function of height, and the exact intrinsic angular frequency $\omega$ of the gravity wave can be calculated using:

$$\omega^2 = f^2 \left( \sin \alpha \right)^2 + N^2 \left( \cos \alpha \right)^2$$

(1)
where $\alpha$ is the propagation angle of the wave, also known as the angle that the wave number vector makes with the horizontal plane. This equation is commonly referred to as the wave dispersion relation. In terms of the three-dimensional displacements of an air parcel, $\alpha$ is defined as:

$$
\alpha = \tan^{-1} \left( \frac{\sqrt{x'^2 + y'^2}}{|z'|} \right).
$$

(2)

To calculate the displacements, a second-order polynomial was fitted to the filtered $u$, $v$, and $w$ wind components from each profile to calculate background velocities. The background and filtered velocities are then integrated to generate mean and filtered displacements. The mean displacements are then subtracted from the filtered displacements to calculate the perturbations $x'$, $y'$, and $z'$. These displacements yield frequency and wavelength of the wave signal.

### III. Observations

Maximum eclipse at occurred at 17:46:18 UTC at center site with only seconds difference between maximum eclipse experienced at north and south edge sites. Each radiosonde sounding provides high temporal resolution ($\delta t = 2$ second) vertical profiles. The first set of radiosondes were launched 24 hours prior to totality at each site and allowed to enter the stratosphere. Figure 3 displays unfiltered $u$, $v$ and temperature within the troposphere from these soundings. A shift in wind direction seen at roughly 2 km at each site corresponds to a temperature inversion at this

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**Fig. 3:** Unfiltered $u$ (solid), $v$ (dashed), and temperature [C] (dotted) data from south (left), north (right), and center (center) launched 24 hours prior to eclipse totality.
altitude, marking a PBL. A predominantly south-westerly wind is present in each sounding with peak amplitude centered around 14 km. This amplitude is nearly 10 m/s greater than wind speeds recorded 4 km above and below and nearly 20 m/s greater than wind recorded near the surface and above 18 km. This are typical characteristics of mid-latitude soundings due to the presence of the ferrel westerly cell. The vertical profiles collected every 6 hours beginning 24 hours prior to eclipse totality from the center site also display these characteristics. Oscillations above 18 km in u and v reveal a 180° counter-clockwise rotation of the winds occurring over a distance of 6 km in the daytime while rotations diminish to no more than 45° counter-clockwise at night.

The profiles of horizontal wind and vertical ascent speed collected within 24 hours of eclipse totality were filtered to isolate a pre-eclipse wave signal. Figure 4 displays the filtered wind profiles from each site launched 24 hours prior to eclipse totality. Each profile shows an amplitude spike in winds from the west around 2 km and phase opposition between the wind components u and v. An area of consistent phase opposition between u and v exists in filtered center wind profiles C1–C4 from 5 to 7 km. Above the ferrel westerly cell and into the stratosphere, larger amplitude peaks of u and v are seen to be roughly half cycle out of phase at 18 km, shifting to one quarter out of phase with increasing altitude and eventually in phase around 20 km and 23 km corresponding to the peak seen in the raw profiles at this altitude and indicating decreasing intrinsic frequency with altitude.

![Fig. 4: Filtered u (solid) and v (dashed) from south (left), north (right), and center (center) launched 24 hours prior to eclipse totality.](image-url)
The frequency of the wave signal in filtered profiles S1, C1 and N1 are shown in figure 5. The lowest intrinsic angular frequencies are centered on altitudes of 2, 6, and 17 km. The higher frequencies concentrated around 10 km arise from the large perturbations calculated within the ferrel cell. Between 18 and 25 km, the intrinsic angular frequency approximately averages to $1 \times 10^{-2} \text{s}^{-1}$. Filtered profiles C2, C3, and C4 leading up to the eclipse display similar frequency patterns with additional local minimums in frequency centered around 19 and 21 km appearing at night. The profiles of radiosondes from the north and south edge sites that were allowed to ascend into the stratosphere post-totality (N4, N5, S4 and S5) are presented in figure 6. These radiosondes were launched with a 1,000 g latex balloon and reached heights not spanned before the eclipse. Therefore, comparisons for eclipse-generated wave-structures at altitudes greater than 27 km cannot be made. Post-totality, the amplitudes of the oscillations in u and v above 18 km have diminished by half. The large frequencies measured around 10 km 24 hour prior to totality have reduced by nearly 2/3. A wave signal with dominant intrinsic angular frequency of $~4.2 \times 10^{-2} \text{s}^{-1}$ is first detected in N5 at 19.5 km approximately 50 minutes after totality. This wave signal is again present at altitude ~ 19 km and ~30 minutes later with slightly lower frequency of $~3.6 \times 10^{-2} \text{s}^{-1}$ in S5, $~3.3 \times 10^{-2} \text{s}^{-1}$ in N5. These frequencies correspond to vertical wavelengths of ~ 20 m at this altitude. Further analysis involves the confirmation that this frequency and wavelength is within reasonable bounds to be generated by the obstruction of solar irradiance experienced during the eclipse and that similar signatures are not present 24 hours following eclipse totality in C9.

![Fig. 5: Filtered intrinsic angular frequency from a) S1, b) C1, and c) N1.](image-url)
Fig. 6: Filtered $u$ (solid) and $v$ (dashed) from a) S4, b) N4 and c) S5, d) N5.

Fig. 7: Filtered intrinsic angular frequency from a) S4, b) N4, c) S5, and d) N5.
References

