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Growing Bores at the South Pole
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Abstract: Bores in the South Pole have been monitored for over ten years, and, until the year 2012, they were found to be relatively rare. Bores start with relatively large intensity and develop additional waves behind them depending on their movement and stability. The data from the South Pole was gathered from the US Admunsden-Scott South Pole station. A photo was taken every 30 seconds from the months of April to August with a wide-angled lens. The data was then processed and analyzed in multiple programs to determine wavelength, duration of event, relative velocity over time, and direction of propagation. Studies over the recent years of 2012-2016 have shown a total of 130 total bore events. The last 47 events are the subject for this paper, with additional data from previous reports.
Introduction:

Bores have been observed both in our atmosphere and in oceans and river outlets. Tidal bores act in response to the tide coming in and overcoming the current, as can be seen in Figure 1. Lord Rayleigh, a scientist observed effects of river bores from horseback, drew a diagram of these bores. As the tide pulls a wave, a pocket is formed underneath the cresting wave. This wave, also known as a tidal bore, creates additional waves behind it. This cresting wave is shown in Figure 2.

Atmospheric bores, or undular bores, are likewise created by pockets of air. These bores studied for this research are formed in the upper atmosphere through air pockets that vibrate due to gravity waves. Gravity waves, or more commonly known as acoustic gravity waves, form through the vertical movement of air. When an air pocket is moved by these gravity waves, it forms a bore: “It is now known that bands are caused by gravity waves originated from the lower atmosphere, and ripples are generated in situ by convective or dynamical instabilities” (Taylor 1). These ripples in the atmosphere are visible in the airglow of our atmosphere, as seen in Figure 3. This airglow is typically found ~85 to ~100 kilometers above the surface and is composed of OH and O$_2$ respectively.

Bores usually change slightly in temperature as they propagate. Each wave has a peak and trough, where the higher intensity wave-front is higher in temperature than its trough. This is because of the changes in air pressure. Because of this, atmospheric bores are sometimes confused with cold fronts, though there is no definitive research suggesting that bores change the overall temperature of the atmosphere (Davies, et al. 439). It is usually

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Figure 1: The tidal bore shows a leading wave with additional waves following. These waves are large enough that surfers ride these waves. Retrieved from Dickerson, S. (2016, August 8). Beachapedia. Retrieved April 17, 2017, from http://www.beachapedia.org/Tidal

Figure 2: A diagram drawn by Lord Rayleigh in response to his discovery of a tidal bore in 1908. The velocity, given by $u$ shows the velocity moving from left to right. $u'$ shows the velocity moving just right of the wave crest. $l$ represents the height of the wave before the crest, and $l'$ represents the height as the tide comes in. Retrieved from

Figure 3: An image of airglow taken from an orbiting satellite. The green rim around the Earth shows a rim of airglow, a layer of O$_2$ and OH with an altitude approximate to the mesosphere and lower thermosphere.
the result of a change in temperature that triggers a bore. In Australia, the presence of bores created a spike in the burning of brushfires. This peak occurred early in the morning, which accounts for another name of the phenomenon: Morning Glory (Davies, et al. 440). Atmospheric bores off a bay can be seen in Figure 4.

Since 1995 when Taylor et al. observed one of the first mesospheric bores during the Observations of the Hawaiian Airglow 1993 (ALOHA-93) campaign, bores have been sought after and analyzed. Few had been observed from that point, however, and they were considered to be rare.

Methods:

Before 2006, only one bore event had been witnessed in the South Pole. Since then, an observation location in the South Pole has been erected to view additional phenomena. Information from the Admudsen-Scott South Pole station observed the mesosphere and lower thermosphere (~80 – 100km), the highest layers of our atmosphere. The program used was an advanced mesospheric temperature mapper (AMTM) with a field of view (FOV) of 144km by 180km. Images were recorded every 30 seconds from mid-April through August 2012-2016. Christina Solorio analyzed data from 2012 – 2014. The rest was analyzed for this report. These winter months provided relative darkness for the atmospheric bore study.

Images were taken from the Bear Lake observatory as raw images and were then processed to remove much of the clutter and excess light around the image. Bores could be seen as waves moving across the field of view, forming additional waves behind, also known as trailing waves. The processed images were rotated according to a 360° Cartesian coordinate system, with 0° oriented straight up. The images were then un-warped to account for the wide angle of the lens.

Results:

Bores were detected through both the use of keograms and through watching the sequences of images through an image processor called Norway. The images were played as though through a long sequence, so this version of detecting events could detect individual bores and their paths across the sky. A single event image can be seen in Figure 5. Keograms were primarily used to determine the propagation of movement and direction. Keograms are extended images of single images. Each image taken every 30 seconds was condensed to a single line only a few pixels in diameter. These images were then spread throughout the length of the day. Bores could be seen as brighter lines in contrast to darker troughs, as in Figure 6. Temperature keograms showed the
difference in temperature of the crests of each bore to their troughs. A segment of a temperature keogram can be seen in Figure 7.

Though Figure 5 does not show the consistent bands that Figures 6 and 7 do, it has a greater intensity. Figure 5 also shows a rare phenomenon: the bore appears to be breaking at its center. The greater intensity of a bore shows its greater potential for breaking. Because this image shows such great intensity between its crests and troughs, the bore is breaking rather quickly. Figures 5 and 6 show a much more consistent bore. It is traveling NW and creating multiple wavelets trailing behind. The lack of difference in intensity shown between the crests and troughs indicates that this event lasted much longer than the event on April 23, 2015.

The keogram segments for June 11, 2015, and April 23, 2015 show a much less consistent variation in waves. Figures 8 and 9 refer to April 23, 2015, and Figures 10 and 11 refer to June 11, 2015. Figures 8 and 9 show a burst of intensity moving NW early in the morning. The image for this occurred for an hour. The created wavelets seem to fade as the image progresses. The temperature shows little change except in the boundary between its emergence. Figures 10 and 11 show exceptional change in temperature from trough to crest. The images show that the bore tends to twist, moving from left to right. This twisting seems to be the reason for the bore to break in its center.
Figure 8: Keogram of bore dated April 23, 2015. The large changes in intensity show a definitive line between the bore and its additional wavelets. The trailing waves fade as the bore moves NW.

Figure 9: Keogram of temperature fluctuation of the bore on April 23, 2015.

Figure 10: Keogram of bore dated June 11, 2015. This bore shows a spiraling motion. It breaks very quickly, showing very few additional wavelets trailing. This bore is also moving NW.

Figure 11: Much larger changes in temperature show that this bore changed temperature with pressure.
The rate of bores per month for 2015 and 2016 is given in Graph 1. Bores are most common in the beginning and end of the winter season. Graph 2 displays the average time of day in the years 2015 and 2016 that events occurred. As seen, bores occur regularly in the morning from 00:00 – 06:00 hours. The bore events in the morning also show the greatest intensity. The others vary depending on the month.

The South Pole experiences such cold temperatures in the winter that snow cannot accumulate in the air. The air flowing in this region forms a vortex that prevents airflow moving in and out. Atmospheric wave events pass through the atmosphere but are destroyed at the edge of the vortex (Taylor). Waves are created inside the vortex, since no atmospheric events can penetrate it. This suggests that morning and evening events may be in response to temperature fluctuations, which, in turn, may be the causes for the change in pressure.

The overall data for the 48 events seen in 2015 and 2016 show a wide range of durations, periods, wavelengths, velocities, and direction of propagation. Table 1 gives the data of particularly excellent events that occurred in both 2015 and 2016. Table 2 shows an average for all bore events of these two years.

**Discussion:**

Initial hypotheses suggested that bore events would be rare phenomena which had only been observed near the Equator. This hypothesis also referred to the propagation and creation of waves in the atmosphere before a storm occurred. Changes in air pressure and temperatures suggest that bores would most often occur in the atmosphere over oceanic regions near land masses where convection currents heated and cooled the air. It has been suggested for years that oceans determine acoustic gravity wave propagation in the atmosphere. Recent studies have determined that the different frequencies emitted from the ocean do determine atmospheric anomalies (Godin 2015). This is reasonable to assume because large storms...
Table 1: Exceptional bore events for every winter month of 2015 and 2016. Most bore events occurred either the beginning or the end of the season. Possible reasons could be that frigid air does not provide enough temperature fluctuation. Also, pressure fluctuations may account for independence on warmer air.

<table>
<thead>
<tr>
<th>Date of Event</th>
<th>Wavelength (km)</th>
<th>Velocity (m/s)</th>
<th>Period (min)</th>
<th>Duration of Event (min)</th>
<th>Direction of Propagation (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 23, 2015</td>
<td>21.77 ± 2.05</td>
<td>42.99</td>
<td>8.44</td>
<td>69:42</td>
<td>287.10 ± 6.52</td>
</tr>
<tr>
<td>May 4, 2015</td>
<td>33.91 ± 2.54</td>
<td>45.90</td>
<td>12.31</td>
<td>227:00</td>
<td>246.34 ± 5.00</td>
</tr>
<tr>
<td>June 11, 2015</td>
<td>29.61 ± 1.96</td>
<td>32.00</td>
<td>15.42</td>
<td>65:12</td>
<td>332.13 ± 4.35</td>
</tr>
<tr>
<td>July 26, 2015</td>
<td>76.46 ± 10.96</td>
<td>4.05</td>
<td>302.31</td>
<td>52:15</td>
<td>97.13 ± 11.42</td>
</tr>
<tr>
<td>August 16, 2015</td>
<td>31.39 ± 2.00</td>
<td>48.66</td>
<td>10.75</td>
<td>97:46</td>
<td>237.00 ± 4.00</td>
</tr>
<tr>
<td>April 26, 2016</td>
<td>64.24 ± 8.54</td>
<td>51.24</td>
<td>20.90</td>
<td>126:51</td>
<td>192.53 ± 9.95</td>
</tr>
<tr>
<td>May 25, 2016</td>
<td>23.84 ± 1.28</td>
<td>33.84</td>
<td>11.74</td>
<td>102:15</td>
<td>229.90 ± 3.45</td>
</tr>
<tr>
<td>June 5, 2016</td>
<td>74.03 ± 11.12</td>
<td>64.55</td>
<td>9.11</td>
<td>105:06</td>
<td>180.00 ± 11.31</td>
</tr>
<tr>
<td>July 29, 2016</td>
<td>21.32 ± 1.03</td>
<td>73.89</td>
<td>4.81</td>
<td>88:46</td>
<td>120.26 ± 3.06</td>
</tr>
<tr>
<td>August 22, 2016</td>
<td>20.25 ± 1.91</td>
<td>66.14</td>
<td>7.37</td>
<td>70:49</td>
<td>20.23 ± 4.26</td>
</tr>
</tbody>
</table>

Because the South Pole experiences its winter months in a vortex, it was reasonable to assume that large bores with separations of roughly >15 km (Taylor 2007) would be scarce. However, since observations have begun in 2012, 130 bores have been found and documented. The average wavelength, velocity, period, duration of event, and direction of propagation, found in Table 2, shows that the relative data points are remarkably similar. There was a total of 48 events, 41 of which were large enough to be analyzed.

Table 2: Average and Range of Data seen in the South Pole of the years 2015 and 2016. The average shows a more accurate view of wavelength, velocity, period, and duration of event. Several outliers must be discounted for more accurate results.

<table>
<thead>
<tr>
<th>Range</th>
<th>Wavelength (km)</th>
<th>Velocity (m/s)</th>
<th>Period (min)</th>
<th>Duration of Event (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>42.25</td>
<td>46.66</td>
<td>29.73</td>
<td>85.57</td>
</tr>
<tr>
<td>Range</td>
<td>7.11 – 92.50</td>
<td>5.01 – 81.03</td>
<td>4.11 – 32.41</td>
<td>18:33 – 277:00</td>
</tr>
</tbody>
</table>

Table 1: Exceptional bore events for every winter month of 2015 and 2016. Most bore events occurred either the beginning or the end of the season. Possible reasons could be that frigid air does not provide enough temperature fluctuation. Also, pressure fluctuations may account for independence on warmer air.

originating in the ocean and bays show variation in cloud formations. Increased surveillance images of the sky during hurricanes, though hard to obtain, should show events in the sky similar to atmospheric bores. This must suggest that atmospheric bores experience changes in air pressure and temperatures inside the vortex event. The South Pole’s average temperatures reach as low as -80° F. Because of this extreme cold, it is suggested that the warmest times of the winter may show the greatest amount of bores.

Table 2: Average and Range of Data seen in the South Pole of the years 2015 and 2016. The average shows a more accurate view of wavelength, velocity, period, and duration of event. Several outliers must be discounted for more accurate results.
There is sufficient error in the average wavelength to assume that there is significant variation. Though the most common entries averaged from 40km to 60km, the variation should be consistent with the time of year. The longest wavelengths tend to be early in the morning; these wavelengths also tend to break early, showing much more intensity and far fewer trailing waves. The range of velocities are also extremely wide. This may be due to the variation in the waves as they propagate in a bore event. A wave may experience a change in rate of 20m/s over the course of an event from leading bore to the last trailing wave. This might suggest such a variation in velocity. There is also a significant difference in the range for the period. When calculating the results outliers such as 299.15 and 302.60 were discarded due to its inconsistency; this may have been because of the variation in velocity. Lower and fewer recorded velocities for a given event show a large discrepancy in period. Wavelengths also determine the length of a period, and inconsistent results of wavelengths and velocities give wide variations in the period. Finally, the duration of events showed the widest range. This may have been due to the difference in pressure and temperature in the atmosphere. Bores are created as acoustic gravity waves. Gravity waves vary the movement of waves in air. The longest bores were less intense and have continuous trailing waves. The shortest bores have great intensity in relation to their troughs. The most intense of these occurred in 2015. 2016 provided a rare double-bore event, one moving at a roughly 330° the next trailing at roughly 30°.

**Conclusion:**

Atmospheric bores appear to have little consistency in duration but have relatively accurate averages in wavelength, velocity, and period. Bores are much more common than originally believed. They have been found through this study to be much more consistently found in the warmer months of the winter. There have been multiple examples of rare events, including a bore moving in a helix, a bore so intensely bright that it burned itself out before trialing waves could be formed. And finally, a bore experienced a change in direction or created a new bore shortly after. Future studies in bore activities could allow us to determine weather anomalies and see how water affects atmospheric gravity waves.

**References:**


