3000 words, 25 min, () 18 slides

(0-0’30’’)

Good afternoon everyone! My name is Shuang Xu. Today I would like to present you “Thermospheric gravity waves observed by GOCE satellites during geomagnetic quiet times”. My advisors are Dr. Yue, Dr. Vadas and Dr. Russell. The contents of this presentation are some studies we have done and where we are at right now.

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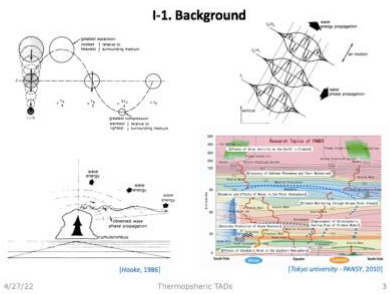
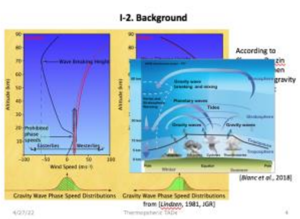
Here is the outline of my presentation today. The first part is some background, including the motivation of this study. The second part and the third part are based on our 2 published papers. The 4th part will be some progress we are working right now, the direction in the future and summary.



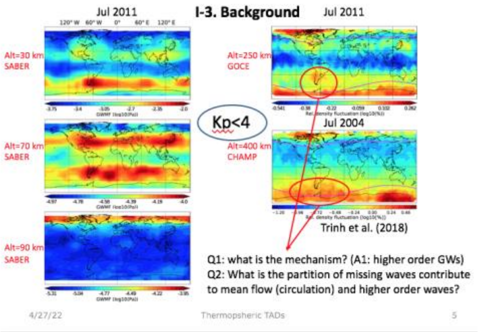
My research in the past several years are about atmospheric gravity waves. **The density decreases along altitude in stratified atmosphere.** After an air parcel experienced a sudden displacement vertically from its original position, the composition of gravity and buoyancy become the restoration force, and then the oscillation called “atmospheric gravity waves” would radiate away from the air parcel.

Although t some gravity waves are sourced from upper atmosphere, for example, from Auroral or plasma instabilities, **the eventual source of most atmospheric gravity waves are from the troposphere.** As shown in the slides here, a strong updraft, or a strong wind climb over a mountain range, or Kelvin-Helmholtz instabilities near jet stream, all of them can generate gravity waves. **The upward propagating gravity waves would break and then deposit momentum and energy to the background and cause changes in temperature and density.** They are one of the most important processes relate to energy coupling and material transfer in atmosphere.



An outstanding example of the influence of gravity wave is that gravity wave is a driver to circulation in middle and upper atmosphere. In 1961, Rossby and his student Charney found that in winter and summer, the zonal wind in middle latitude regions are symmetric with the equator in the lower atmosphere -- both are westerlies; but in the middle and upper atmosphere, the zonal wind in winter hemispheres and summer hemisphere are different. According to Charney-Drazin criterion, when phase speed of gravity wave is close to the wind speed, the gravity waves cannot propagate anymore. Therefore, the breaking altitude of gravity waves in Southern and Northern hemisphere are very different.

Wave breaking and hence momentum deposition produce body forces that drive large scale residual circulations. In the winter stratosphere -approximately 20 to 60 km - planetary wave breaking drives a residual circulation from the equator to the winter pole, while in the mesosphere, gravity wave breaking and dissipation drives a circulation from the summer to winter pole. [Andrews et al. 1987] [Vincent, 2015] The pole-to-pole circulation is the reason of a colder summer polar mesosphere and a warmer winter polar mesosphere.



The paper of Trinh et al in 2018 clearly shows the missing gravity waves at around 90 km altitude. One of the largest quiet time wintertime gravity wave hot spots in the lower to middle atmosphere is over the southern Andes. However, this hot spot disappears in the MLT region. You can see over here for safe from SABER data, there's a huge hot spot over the Southern Andes, and then it disappears at around 90 km altitude. Then again in the altitude of satellite GOCE and CHAMP at altitude of 250 km and 400 km this hotspot reappears.

As I mentioned in the last slides, we knew that one contribution of the missing gravity waves in middle atmosphere is the residual circulations, but also we clearly see that another very possible contribution of the missing gravity waves is the hotspot in thermosphere. So the questions are: what is the mechanism of that caused the variabilities in thermosphere.

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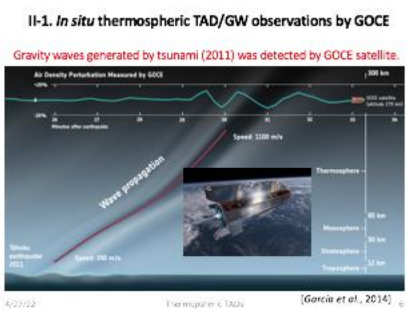
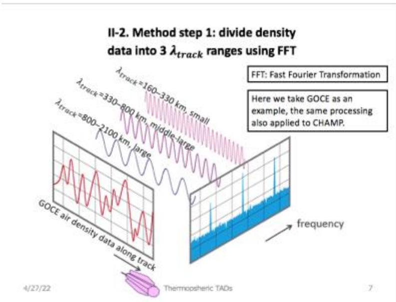
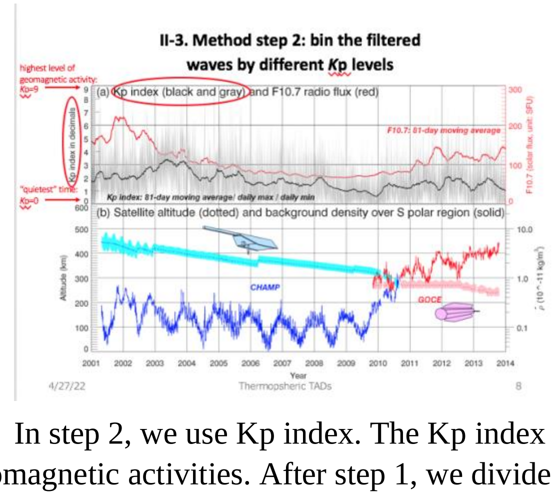


To answer this question, use GOCE data to study the thermospheric variability.

Although there are many indirect ways to observe TADs, the observation quality - such as accuracy and resolution - are usually low. The best way to observe those disturbances is by flying within them. GOCE and CHAMP were two of several satellite missions flew through thermosphere. GOCE and CHAMP carried highly accurate accelerometers, so they can derive air drag force and air density of its surroundings along satellite track. For example, in 2011, the GOCE observed density perturbation with amplitude more than 10%. Those perturbation are gravity waves caused by Tohoku tsunami, directly propagated from sea surface to thermosphere. Due to method limitation, it is impossible to retrieve the wind vectors, but we can still get the wind components that are perpendicular to the satellite orbit. In this presentation all the methods that applies to GOCE data actually also applies to CHAMP data.

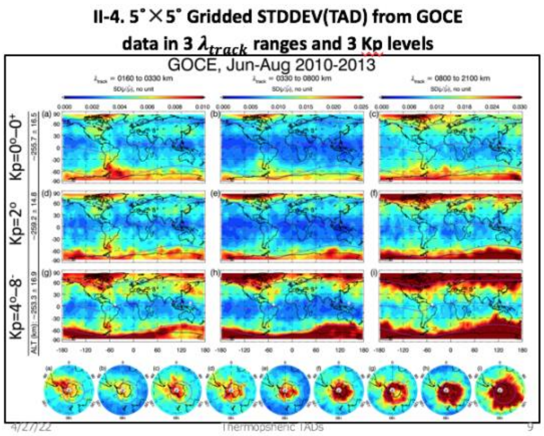


So, in our study, we process the GOCE and CHAMP air density perturbations, in a way similar to what people have done to find the waves caused by Tsunami. We process all of the GOCE density observation and get the climatological results. Firstly, we apply FFT analysis to decompose the satellite data. We sort all the components into 3 λ _track ranges. The λ _track here means the horizontal wavelength along satellite track.



In step 2, we use Kp index. The Kp index quantifies the level of overall global geomagnetic activities. After step 1, we divide the density perturbations into 3 λ _track ranges by FFT. In step 2, since Kp index and density along track data are both time-dependent, we classify the 3 groups of density perturbations components by their corresponding Kp levels.

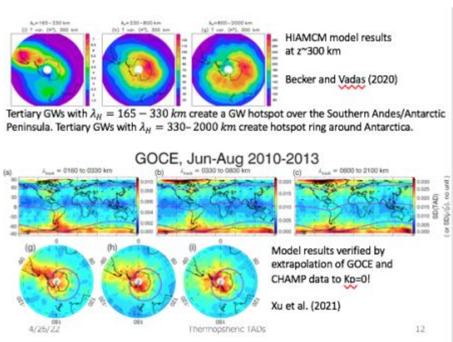
By the way, all the processing steps aforementioned for GOCE density data was applied to CHAMP data as well.



After step 1 and step 2, we gridded those filtered waves in 5 by 5 degree longitude-latitude bins, and calculate the standard deviation of data in each bin. The result here shows the distribution of STDDEV of TADs at 3 Kp levels and all the 3 λ_track ranges. In subfigure (a) at upper left panel and lower left panel (which is south polar view map), we can see that **for small- scale TADs when Kp is near 0, the hotspots over Southern Andes are clearly seen**. In subfigure (b) and (c), for middle and large-scale TADs when Kp is near 0, some hotspots are still over Southern Andes region, although they are weaker and more diffusive comparing to subfigure (a).

Well, for a long time, scientists assumed (but not fully confirmed) that the TAD hotspots over Southern Andes and Antarctic Peninsula during "quiet time" are mainly caused by the remnant of geomagnetic activities. However, in this figure, we see that this hotspot is actually more obvious when Kp is lower, which strongly suggest that those waves are mainly sourced from lower atmosphere instead of geomagnetic activities in upper atmosphere.

One more conclusion we can make is for numerical models. Since in conventional global circulation models, gravity waves are parameterized and launched in the troposphere or stratosphere, and the hot spot GWs over the Southern Andes in the quiet-time winter thermosphere cannot be successfully derived by those conventional GCM model, we also suggest that those TADs are likely secondary or tertiary (or higher-order) gravity waves.



As shown here, the HIAMCM simulation shows GW hotspot distribution in thermosphere (z=300 km), which is similar to the GOCE observation. We can see that for small scale waves the hotspot is right over Southern Andes but for larger scale waves the hotspot move to Antarctica. According to the Becker and Vadas 2020 paper, the HIAMCM is the only GCM that is able to model the temporally-dependent deposition of momentum, and it is the only simulation that generate this GW hotspot in quiet time, so we strongly suggest that in order to simulate the real thermosphere, the GCM should either take the multi-step GW generation mechanism into account, or change the current way of GW parameterization radically.

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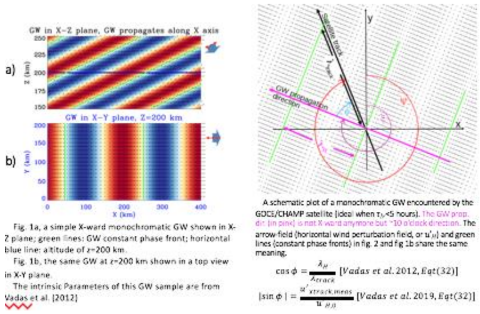
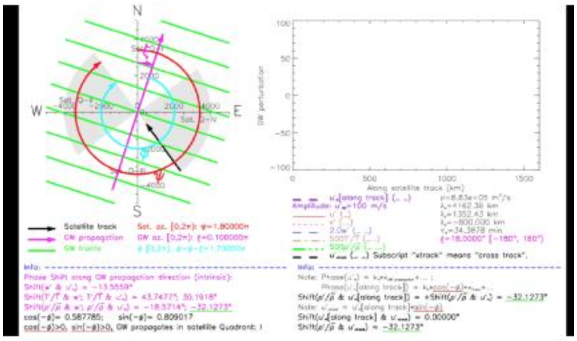


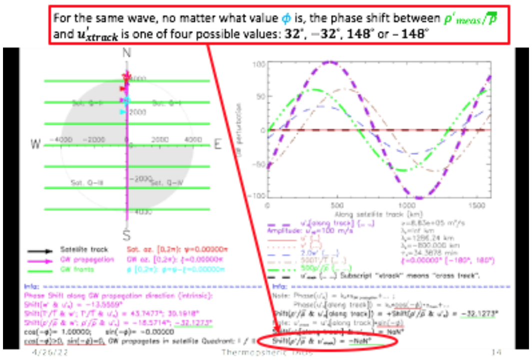
In the third part, I’m going to introduce a case study along a GOCE satellite orbit segment with track length of only about 4000 km long. It is a preliminary study about how we restore the complete parameters of a gravity waves based on very limited data from GOCE observations using the physics law of thermospheric gravity waves. This part might be very intricate but also very challenging.

So firstly, let me give you a qualitative picture about the characteristics of thermospheric gravity waves, and what a satellite would experience when it is passing through them. Alright, the left two panels show an ideal X-ward propagating monochromatic GW, it is shown in 2 viewing direction: Fig 1a is shown in X-Z plane. The green lines are GW constant density phase fronts, the horizontal blue line denotes the altitude of 200 km. Fig 1b is the same gravity wave shown in a horizontal profile in X-Y plane at the altitude of 200 km. The small arrows denote the wind perturbation field. The special part of Fig 1a is that if you look at the arrows carefully, you can see that they are not perfectly parallel to constant phase fronts, which means that there are some sort of phase shifts between horizontal wind perturbation u’ and vertical wind w’. Actually, there are **also** phase shifts between horizontal wind perturbation and density perturbation, that’s because you have to consider the effects caused by compressibility and viscosity determined by the background condition of thermosphere.

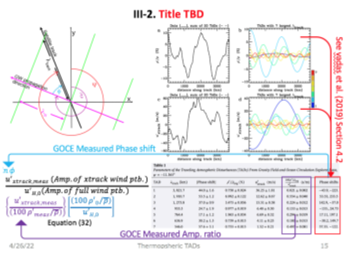
The panel on the right side shows a schematic plot of a monochromatic GW encountered by the GOCE/CHAMP satellite. The black arrows denote the horizontal vectors of wind perturbation. The observation of GOCE and CHAMP includes the local density change along their path derived from their accelerometers, which is good. But unfortunately, due to limitations in the observation method, the data provider can only retrieve the cross-track wind perturbation, which means the wind component of those vectors perpendicular to satellite orbit, NOT the full wind vectors. Therefore, we have to find our own ways to restore the possible full wind vectors and other characteristics using the GW dissipative dispersion and polarization relations.



In order to make this method more intuitively, I made this movie. Imagine there is an ideal monochromatic thermospheric GW occupies the whole space and GOCE satellite is marching towards ~11 o'clock. The right-hand side shows everything, including u', v', T'/T-bar, Rho'/Rho_bar, along satellite track. Note that GOCE can only observe **cross-track wind perturbation (the black dashed line)** and **density perturbation (the green dashed line)**. So using the GOCE satellite we can derive the phase shift between density and cross-track wind of this particular wave that is -32˚.

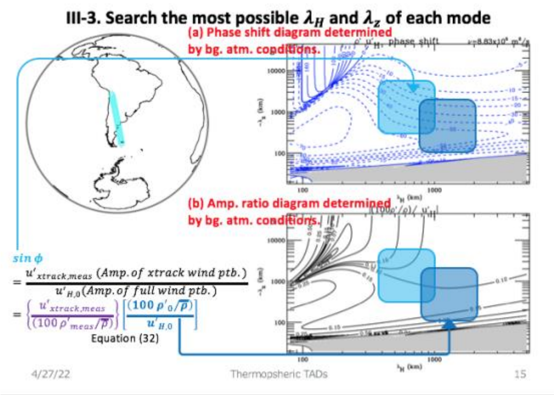


However, in the real world, the value of Phi – I mean the angle between the satellite track and gravity wave propagation direction – can be any value between 0 to 2*pi, which makes the observation extremely complicated. For example, the amplitude ratio between density and cross-track wind means nothing if we don't have the value of Phi. But there is still one thing we can hope, which is the only clue provided by the phase shift between density and cross-track wind perturbations. As shown in the movie, for this particular wave, no matter what value Phi is, the phase shift between density and cross-track wind has only four possibilities. This important clue makes it possible to restore the complete intrinsic characteristics of this gravity wave.

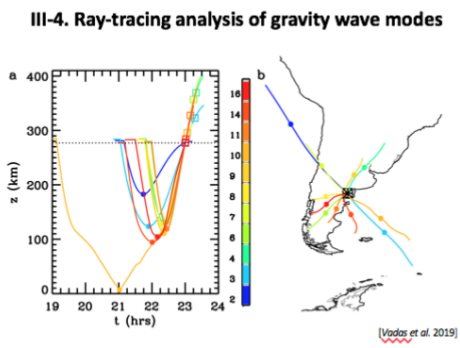


In this page and next page, I will briefly introduce how to restore GW characteristics. For the interest of time, I will skip a lot of details. You can go to the paper Vadas et al. (2019) for the theory details.

In the upper right 4 panels, subfigure a and c shows the GOCE observations of density and cross-track wind, By applying FFT decomposition, we can calculate the phase shifts between each density mode and cross-track wind mode with the same mode number. We can plug the phase shifts into the blue part of the equation and plug the amplitude ratios into the purple part of the equation.

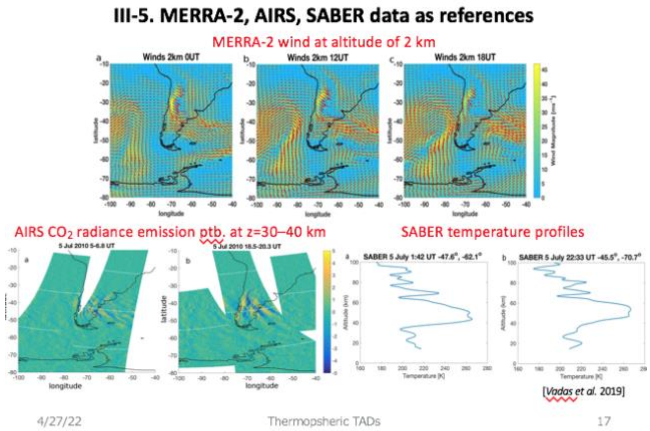


Then in the next step, we generate the diagram of **Phase shift** that is determined by the background atmosphere conditions, of which the inputs are background density, temperature, scale height, local time, etc. Also, we generate the diagram of **Amplitude ratio** that is determined by background atmosphere conditions. Note that the two diagrams shown here share the same dependent variables: horizontal wavelength λ_H and vertical wavelength λ_z. So the two diagrams work like two treasure maps. If we have the values and uncertainties of phase shift and amplitude ratio derived from the previous page, we can plot those uncertainties as two buffer zones in the diagrams. The overlap region denotes the maximum likelihood estimation of intrinsic characteristics λ_H and λ_z of the gravity wave that GOCE observed.



Finally, we apply the ray-tracing analysis to those resolved wave modes from **Phase shift diagram** and **amplitude ratio diagram**. After the inverse ray-tracing and calculating the history path of those wave modes, most of them have never been to altitude lower than 100 km, which means they must be higher order waves and they are generated above the mesosphere. The only wave mode here (wave #10) has possible source at earth surface, but we found that its phase speed relative to ground is close to sound speed, which is unacceptable characteristic of mountain waves.

Therefore, it must be generated by a moving source such as jet stream from a certain altitude in the middle in the atmosphere.



To further determine whether those waves are generated directly from troposphere over Southern Andes mountain ranges or indirectly from middle atmosphere, we also reference the wind field at the altitude of 2 km in MERRA-2, the stratospheric emission radiance perturbation from AIRS data, and SABER temperature profiles over this region. We can see that at 2 km high and in stratosphere, there are strong wave generation. While the SABER profiles show that the temperature perturbations reach their maximum at altitude of 70 km, which probably means that the waves start dissipation and breaking above 70 km.

Alright. Now, it seems like a perfect case study. We restored the intrinsic parameters of gravity waves using only the density and cross-track wind observations from the GOCE satellite. We also proved that nearly all of the wave modes in the observed perturbations are generated as higher order waves above the mesosphere.

However, the case study was very rudimentary.

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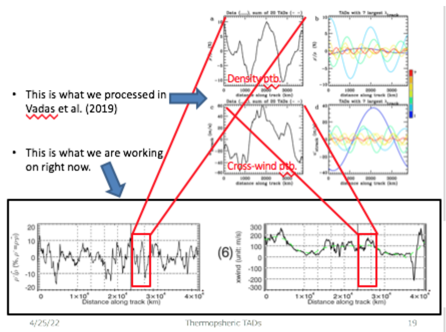
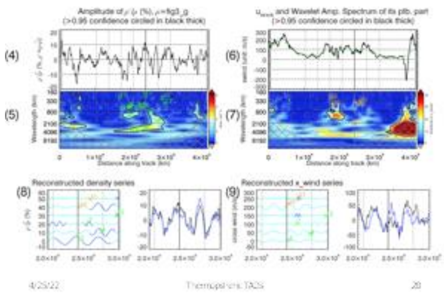


First, as shown in the upper part 4 subfigures, length of the track is so short, so we can assume that the modes decomposed by FFT analysis is reasonable throughout the track. Fourier methods assume a time/space invariance of wave properties, but more efforts are needed in the aspect of localization of these wave properties because, in reality, many waves are inherently **intermittent** and **localized**. It is especially true if we try to make the track length longer. For example, the lower panel shows the same relative density and cross-track wind but along the corresponding full circle orbit. We can see that the wave patterns are relatively high only in the middle part of the orbit when satellite is over high latitude region near south pole.



Therefore, the reasonable processing method is Wavelet analysis instead of FFT, because Wavelet analysis can evaluate the wave amplitude of at each location of data point. The second reason that pushed us to Wavelet analysis is: we underestimated GOCE observation noise when in the 2019 paper, but the good news is that now we can use red noise model or Markov process assumption to re-evaluate the signal to noise level independently. As shown here, the subfigure 4 and subfigure 6 are the full circle orbit data in the previous page. subfigure 5 and 7 are the Wavelet amplitude spectrum. The thick black contours show the confidence level at 95%, while green and orange crosses are waves identified higher than that level.

结束

(5’30’’-)

After step 1 and step 2, we gridded those filtered waves in 5 by 5 degree longitude-latitude bins, and calculate the standard deviation of data in each bin. The result here shows the distribution of STDDEV of TADs at 3 Kp levels and all the 3 λ_track ranges. In subfigure (a) at upper left panel and lower left panel (which is south polar view map), we can see that for small- scale TADs when Kp is near 0, the hotspots over Southern Andes are clearly seen. In subfigure (b) and (c), for middle and large-scale TADs when Kp is near 0, some hotspots are still over Southern Andes and Antarctic peninsula region, although they are weaker and more diffusive comparing to subfigure (a).

You may ask why we are exciting about this observation. Well, for a long time, scientists assumed (but not fully confirmed) that the TAD hotspots over Southern Andes and Antarctic Peninsula during “quiet time” are mainly caused by the remnant of geomagnetic activities. However, in this figure, we see that this hotspot is actually more obvious when Kp is lower, which strongly suggest that those waves are mainly sourced from lower atmosphere instead of geomagnetic activities in upper atmopshere.

One more conclusion we can make is for numerical models. Since in conventional global circulation models, gravity waves are parameterized and launched in the troposphere or stratosphere, and the hot spot GWs over the Southern Andes in the quiet-time winter thermosphere cannot be successfully derived by those conventional model, we also suggest that those TADs are likely secondary or tertiary (or higher-order) gravity waves.

18:38:00 (min 1 page 1-2)

Good afternoon everyone! My name is Shuang Xu. I'm a graduate student from Department of Atmospheric and Planetary Sciences. Here I would like to present you a brief introduction about thermospheric Traveling Atmospheric Disturbances observed by GOCE and CHAMP satellites.

Firstly, let me introduce you a little bit background about the atmosphere structure if you are not familiar with those layers. The thermosphere that we are interested in here, is more than 85 km from the ground surface. As shown here, this region is above the red dashed line. Most of ionosphere is in this region as well. Disturbances in ionosphere can endanger low orbit satellites, and shut down radio transmissions.

3900 (min 1 page 3-4)

For thermospheric Traveling Atmospheric Disturbances, most of them are atmospheric gravity waves, or AGWs. Sorry for one more term. I don't mean to confuse you but the nomenclature here has its own historical reason. I will explain after the presentation if we have time. Right now, let me go back to the gravity waves.

Just like ripples across water surface when a tossed stone disturbs the water surface, gravity waves are born when air masses are pushed up or down. In atmosphere, gravity waves are not excited by stone, but much more powerful things, such as a thunderstorm, or when strong wind climb over a mountain range. Just like the water surface waves, the restoration force is gravity, or buoyancy. That's why they got their name "Gravity waves". Please not to be confused with "Gravitational waves". They have nothing to do with buoyancy.

The figure here is showing gravity wave propagation in lower atmosphere, generated by a thunderstorm. The horizontal scale of their impacts, as you can see is about 2000 km, so it's quite regional in atmosphere.

By the time they reach the upper atmosphere, however, they can dominate atmospheric processes because the air density in upper atmosphere is extremely thin. The two movies here show two different wind field, one is at the earth surface and one is at 90 km high. See those waves propagating in the 2nd map. It is very clear that the effects of gravity waves can't be neglected in the upper atmosphere.

4100 (min 1)

Although there are many indirect ways to measure TADs, the data quality (such as accuracy and resolution) are usually low, because the air density there is so low and thermosphere is so far from the ground. The best way to observe them is by flying within them. GOCE is one of those several satellite missions flew through thermosphere. The satellite carried six highly accurate accelerometers, so they can derive air drag force and air density of its surroundings along satellite track. For example, in 2011, the GOCE observed density perturbation with amplitude more than 10%. Those waves are caused by Tohoku tsunami, directly propagate from sea surface to thermosphere.

So, in our study, we process the GOCE and CHAMP air density perturbations, in a way similar to what people did when they found the waves caused by Tohoku Tsunami. However, we are not satisfied with just a case study like that, we process all of the GOCE density observation and get the climatological results. Firstly, we apply Fast Fourier Transform analysis to decompose the satellite data. We sort the components into 3 λ_track ranges. The λ_track here means the horizontal wavelength along satellite track of density perturbation components.

In the second step of processing, we use Kp index. The Kp index quantifies the level of overall global geomagnetic activities. For example, the higher Kp index, the more Aurora activities we can see. Since Kp index and GOCE density data are both time-dependent variables, the perturbations derived from along track density data can be classified by their corresponding Kp levels. After we divide the density perturbations into 3 λ_track ranges by FFT, the second step is that we divide each group of results again by different Kp levels.

The altitude of GOCE satellite was about 270 km, the CHAMP satellite was another satellite also in the thermosphere, observing the density in the similar way but at a higher altitude, from 450 to 300 km.

we assign each GOCE density observation with a corresponding Kp index according the observation time.

There are many remote sensing methods to observe gravity waves in thermosphere. One of the very interesting method is using the GPS signals received on the ground. When thermospheric gravity waves are passing through the ionosphere, they leave signatures called TIDs, or traveling ionospheric disturbances. For example, as shown in the short movie, Hurricane Matthew, denoted by the black cross, is generating gravity waves propagating slowly outwards over Southeast coast. The observation is retrieved by thousands of GPS receivers over United States.

Both GOCE and CHAMP thermospheric in-situ density data are derived from accelerometers onboard (Doornbos, 2019). We use GOCE data in Jun–Aug 2010–2013 and CHAMP data in Jun– Aug 2004–2007.

• Kp index is also a time-dependent variable, so perturbations derived from along track density data and can be classified by their corresponding Kp levels.

• We bin the results in three λ"#$%& ranges: λ"#$%& =160–330 km, λ"#$%& =330–800 km, and λ"#$%&=800–2100 km. (λ"#$%& is along-track horizontal wavelength measured by GOCE or CHAMP)