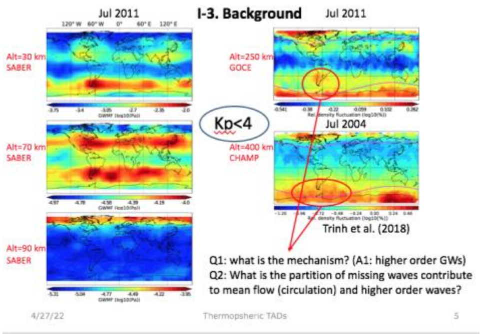
900 words, 8 min, 10 slides

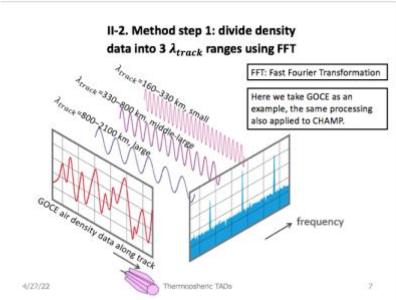
Good morning everyone! My name is Shuang Xu from Hampton university. Today I would like to share something about thermospheric GWs observed in GOCE. I also want to acknowledge my advisors Dr. Yue, Dr. Vadas and Dr. Russell. And also thank Dr. Heale for hosting this session.

Here is the outline of my presentation today. The first part is some background or motivation. The second part is based on our latest publication. The 3rd part will be what we are working at. The 4th part will be summary and the direction for our future works.

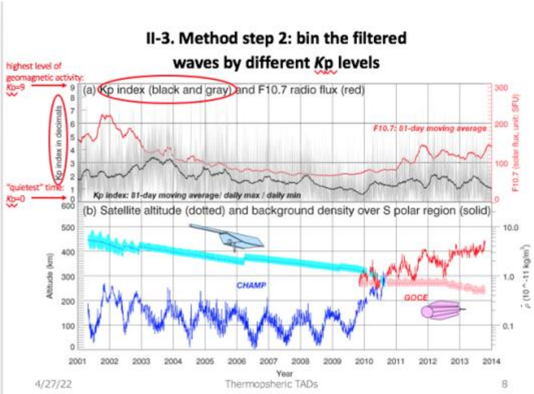


Our motivation can be summarized by Trinh et al 2018 paper about GW hotspots at different altitude and season. In this figure, it clearly shows the missing gravity waves at around 90 km altitude. You can see over Southern Andes there is a huge and well known hot spot, and then it disappears at around 90 km, and then reappear at altitude of 250 km and 400 km.

We knew that one contribution of the missing gravity waves in middle atmosphere is the residual circulations, but also we clearly see that one more very possible contribution of the missing gravity waves is the hotspot in thermosphere. So, the questions are: what is the mechanism that causes the variabilities in thermosphere, and an even more difficult question: What is the partition of missing waves contribute to mean flow (circulation) and higher order waves respectively?

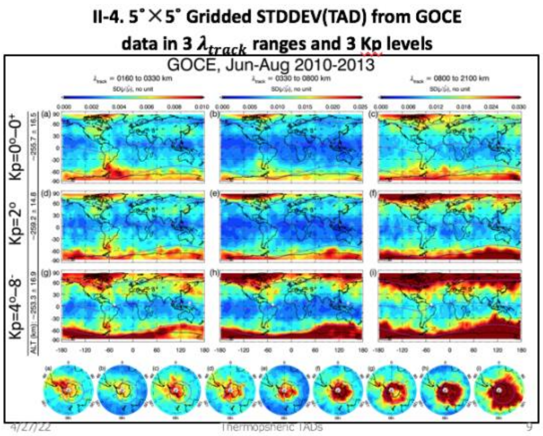


To answer this question, we use GOCE data to study the thermospheric variability. GOCE measures the thermospheric density data and cross-track wind at around 270 km altitude. In-situ measurements. Firstly, we apply FFT analysis to decompose the satellite data. We sort all the components with different wavelengths into 3 λ_track ranges. The λ_track here means the horizontal wavelength along satellite track.

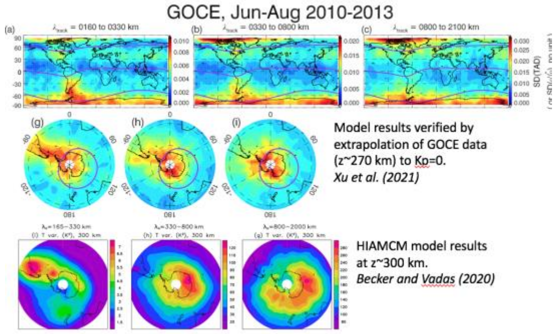


In step 2, we use Kp index during satellite’ s lifetime. Since Kp index and density along track data are both time-dependent, we can also classify the aforementioned GOCE density perturbation by their corresponding Kp levels.

BTW, all the processing steps aforementioned for GOCE density data was applied to CHAMP data as well. So we can also derive the GW hotspots at altitude of about 400 km.



After step 1 and step 2, we calculate the standard deviation of filtered wave in each 5 by 5 degree bin. The result here shows the distribution of STDDEV of TADs at 3 Kp levels and all of the 3 λ_track ranges. Although we found many interesting things when Kp is high, e.g., there is a clear aurora oval fingerprints in subfigure (g), but let’s just focus on the GW distribution by extrapolation these results to quiet time state with Kp=0.



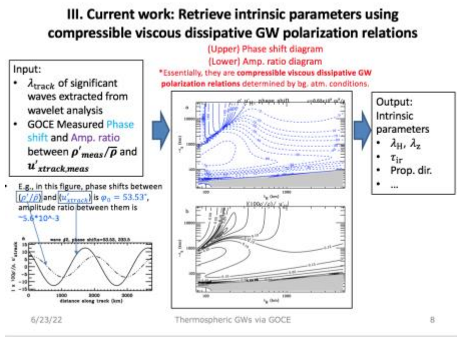
Tertiary GWs with $\lambda_H = 165 - 330$ km create a GW hotspot over the Southern Andes/Antarctic Peninsula. Tertiary GWs with $\lambda_H = 330$– 2000 km create hotspot around Antarctica continent.

In subfigure (a) at upper left panel, we can see that for small- scale TADs when Kp is near 0, the hotspot over Southern Andes is 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).

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 Southern Andes 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. As a comparison shown in the lowest panel, the HIAMCM simulation shows GW hotspot distribution in thermosphere (z=300 km). That is similar to the GOCE observation in many ways. 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.

By the way, our 2021 paper also includes the climatology results from CHAMP data, so please check out this 2021 paper if you are interested in.



OK, there are also some limitations with our method in that paper that we need to improve. For example, from the beginning to the end so far, we are analyzing waves with certain different λ_track ranges, ot horizontal wavelength λ_H. To solve that problem, firstly we have to replace FFT with wavelet.

Secondly, since the GOCE and CHAMP only provide the cross-track wind perturbation, not full wind vector perturbation, we have to find our own way to restore the possible full wind vectors and other intrinsic characteristics. The method we are using here is the GW dissipative dispersion and polarization relations originally proposed by Sharon in her 2013 paper. To be honest, we have a lot of results after this step but I have no time prepare them in slides in an organized way.

Anyway, this theory is very intricate but powerful, I’ m still thinking about how to introduce it intuitively. But fortunately, we have Sharon here in-person, so if you are interested in this part, please reach out to her or to me.

I’ll stop here with summary for you, and welcome if you have any questions or comments.

Shuang

Hi Sharon and Jia,

I have a question regarding the energy budget after gravity waves dissipate in the MLT region. As shown in Figure 2 of Trinh et al. [2018] and Figure 2 of Liu et al. [2019], GWs dissipate before or during reaching the mesopause (~90 km) in the mid-latitude region of the winter hemisphere. In the mesosphere, those gravity wave breaking and dissipation drive a circulation from the summer pole to the winter pole (i.e., the circulation that causes the summer polar mesosphere colder and the winter polar mesosphere warmer). So, here is my statement about the energy budget and hope you can confirm if my understanding is correct: After GW breaking and dissipation, (1) part of the deposited energy contributes to the drag on the mean flow and causes the meridional circulation aforementioned, while (2) the other part of the energy contributes to higher-order waves which can be shown in the thermospheric hotspots. Right now, we are trying to investigate the importance of process (2) over the thermosphere. Am I right?

Jia

Yes. But what is the partition of waves deposited to the mean

wind and that excite higher order waves? Do we know?

Shuang

I ask this because I'm thinking about how our GOCE/CHAMP study is related to other branches in Aeronomy, and the scientific merit of our GOCE/CHAMP study that can be contributed to atmospheric science. Thanks!

Jia

Can we answer some scientific questions using GOCE/CHAMP and HIAMCM? If so, would be contributions to space sciences.

What is the overall momentum flux/drag force to the thermosphere wind? Compared to other forcing, like pressure gradient force set up by solar heating.

Can we calculate momentum flux from GOCE wind/density data? If so, how is it compared to HIAMCM?

If the energy and momentum that transferred from the lower atmosphere to the thermosphere by GWs can be quantified, is it significant to the thermosphere mean field?

If higher order GWs are not considered, how different is the thermosphere state?

Just some food for thought.

Sharon

Hi Shuang, good questions. Jia's answers are good. I want to add from a theoretical perspective the following. GW breaking leads to momentum deposition over a localized region. IF that momentum is deposited infinitely slowly in time, then NO higher-order GWs are created but the mean state is still changed because of the momentum deposition. (So a breaking eastward (northward)-propagating GW packet creates an eastward (northward) wind locally in the region of the breaking.) This is what nearly all GCMS assume--that the momentum is deposited infinitely slowly so that no higher-order GWs are excited. However, the reality is that the momentum is deposited into the atmosphere over time scales of order the wave period (i.e., 1/4-2 times wave period). This changes everything. The momentum deposited is the same. The mean local wind change is the same. However, now higher-order GWs are excited because of the rapid deposition of momentum. So, in order to take this real effect into account, a GCM needs to be able to model the temporally-dependent deposition of momentum. The HIAMCM does do this, and is currently the only GCM which does so and which has verified the scales and amplitudes of the resulting higher-order GWs via comparison with different data sets.

The rough fluid dynamics is this. By momentum deposition, we mean that momentum is deposited into the fluid (i.e., air) over the time scale Chi (the duration of the local body force). This force causes the fluid to accelerate in the direction of the force over the localized spatial region of the force. If this acceleration is rapid, then the background fluid adjusts to this acceleration by radiating higher-order GWs in order to attain an un-accelerated state (which is what the fluid "wants"). after radiating the higher-order GWs, the fluid is happy to sit there "forever" with a local mean wind change from the acceleration. if the force is applied infinitely slowly, then the mean state can slow adjust to the momentum deposition without needing the radiate higher-order GWs to reach equilibrium.

The deposition of energy also excites higher-order GWs (Vadas and Fritts, 2001, Vadas, 2013). Same deal: if this deposition happens infinitely slowly, then NO higher-order GWs are excited. However, this is highly unrealistic, since the deposition will happen of order the wave period. In that case, higher-order GWs are excited. (this is how GWs are excited from joule heating of the lower thermosphere, for example).

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waves which can be shown in the thermospheric hotspots. Right now, we are trying to investigate the importance of process (2) over the thermosphere. >Am I right?

In wave breaking, there is momentum and energy deposition. Momentum deposition changes the background mean wind locally. Energy deposition causes changes in the temperature (Shuang: mean temperature I think? Or just temperature perturbation? No viscosity, no energy deposition, is that right?) which also changes the wind. It turns out that the effect of momentum deposition is usually more important than the effect of energy deposition. So, I would change "energy" to "momentum and energy" in your above. And yes, you are trying to understand the momentum and energy transfer from #2. Although the higher-order GWs have much smaller amplitudes initially (of order 10% of the primary breaking GWs), they grow exponentially with altitude and so become important within a few density scale heights above where the primary GWs broke. Then they can break too because now their amplitudes are too large, which deposits momentum and energy which then excites tertiary GWs. etc.

Shuang

Sharon, could you explain a little more about those 2 terms? My

understanding is that "energy deposition" refers to the conversion of the kinetic energy of gravity waves to the internal energy of its breaking local region. Is that right?

Sharon

Hi Shuang, for molecular viscosity, energy deposition is conversion of kinetic energy to heating. But for wave breaking, there is a cascade to turbulence, to smaller and smaller wave scales and vortical motions, eventually reaching the turbulence scale (cm or m down here). Then the energy is converted to heat. this is my understanding. Erich Becker is the expert.