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Interactive Comment

Interactive comment on "Small-scale gravity waves in ER-2 MMS/MTP wind and temperature measurements during CRYSTAL-FACE" *by* L. Wang et al.

L. Wang et al.

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Major Comments

1. **Page 11380 L9-14**

   As far as we know, the CRYSTAL-FACE campaign was the first time when both ER2 MMS and MTP data were obtained on flights designed to sample the environment above convection. The STEP campaign in 1987 was an exception, but the height information for the MTP vertical scans has been lost (Bruce Gary, personal communication).

2. **Page 11381 L14**

   The ER-2 airspeed is 200 ms^{-1}, but its ground speed can vary giving differing horizonta resolutions, but by less than previously stated during CRYSTAL-FACE. 2 km will be the average horizontal sampling (now stated at L. 88-89). We use MTP data to estimate the vertical wavelength. The horizontal wavelength is determined from the 1-Hz sampled MMS data, so the horizontal sampling of MTP is not as important. In this study, we use the MTP temperatures only to derive GWs' vertical wavelengths. Other parameters, such as horizontal wavelengths, propagation directions, etc., are derived from the MMS winds and temperatures, which have a much better horizontal resolution ($\sim$ 0.2 km). We believe GWs with horizontal wavelengths of $\sim$ 10-20 km can be resolved using the MMS data.

   The vertical resolution of the MTP data has been improved since Denning et al. (1989) and it was $\sim$ 160 m at the flight level during CRYSTAL-FACE (Bruce Gary, personal communication). It is not $\sim$ 100 m as we stated in the original paper. We correct this mistake in the revised paper (L. 91).

3. **Page 11382 L5-11 and Page 11403 (Figure 3)**

   The vertical resolution of the MTP data is much better at the flight level than other altitudes, which explains why sloping phase is hard to observe at altitudes $>$ 2 km from the flight level. We remove Fig. 3 in the revised paper, as it contains little information relevant to what are actually done in this study. We use only the MTP temperatures and temperature gradients at the flight level to estimate GW vertical wavelengths in this analysis.

4. **Stokes Parameters and Cross Spectra: Pages 11385-11386**

   We agree with the reviewer that our new approach to estimate GW horizontal propagation directions is actually a variant of the Stokes parameter method and we acknowledge this in the revised paper (e.g., a relevant sentence in section

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6 is modified as follows in the revised paper: *"The horizontal propagation directions ϕ were estimated from MMS horizontal winds using a variant of the Stokes parameter method with the aid of the cross S-transform."* (L. 422-423). We also add the reference of Eckermann (1996) in the revised paper (L. 185-186).

We find that the values of δ generally cluster around 0° or 180°. There are also a few events with $|\delta|$ more or less close to 90°, but this is consistent with Fig. 10 (or Fig. 9 in the revised paper) which shows that there are also several relatively low frequency events. We think most readers are interested in the physical wave properties rather than intermediate quantities like δ, hence we do not show δ in the paper. Nevertheless, we add the following sentence in the revised paper: *"Furthermore, as mentioned before, more linearly polarized GWs have δ close to 0 or π. Indeed, we found that the values of δ generally cluster around 0 or π (not shown), being consistent with these waves having high $\hat{\omega}$."* (L. 235-237).

As suggested by the reviewer, we include the following simplified discussions on how to resolve the 180° ambiguity of ϕ' using the temperature information in the revised paper: *"Note that very high intrinsic frequency GWs are more linearly polarized, thus their δ are close to 0 or π. Eqn. (9) is then reduced to*

$$\Phi_T - \Phi_u = \pm\frac{\pi}{2} \tag{1}$$

ϕ is either ϕ' or $(\phi' + \pi)$ depending on the phase difference between T and u. Such a simplified relation is consistent with Eqn. (A10) in the appendix, which is equivalent to the GW polarization relation for a linearly polarized GW. " (L. 211-217).

There are typos in Eqns. (12) and (13) in the manuscript (we thank the reviewer for calling this error to our attention). They should have been

$$F_{px} = \frac{1}{2}\overline{\rho}\left(1 - f^2/\hat{\omega}^2\right)\tilde{u}\tilde{w}\cos\left(\Phi_w - \Phi_u\right) \tag{2}$$

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$$F_{py} = \frac{1}{2}\overline{\rho}\left(1 - f^2/\hat{\omega}^2\right)\tilde{v}\tilde{w}\cos\left(\Phi_w - \Phi_v\right) \tag{3}$$

We correct this mistake in the revised paper (L. 258-259).

We replace “coherence” with *“correspondence”* throughout the revised paper to avoid the possible confusion with the precise mathematical meaning of “coherence” (L. 163, 165, and 418).

5. **Reverse Ray Tracing: Page 11389**

   The original wording on describing the ray-tracing algorithm is inaccurate and misleading. The relevant sentences are modified as follows in the revised paper : *“The reverse ray-tracing was terminated when any of the following condi tions was met: the tracing time reached 3 hours, the ray reached the ground, or the wave was approaching its critical level (where $\hat{\omega} \to f$) or turning point (where $\hat{\omega} \to N$).”* (L. 290-293).

   We never allow the ray-tracing to violate the $f^2 < \hat{\omega}^2 < N^2$ li mits. We used the time-varying NCEP data as the background fields. Since the te mporal resolution of the NCEP data is 6 hours and we only ray-traced each ray f or up to 3 hours, we assumed that the ground-based frequency was constant durin g the ray-tracing.

6. **Vertically Trapped Stratospheric GWs or Critical Levels?: Pages 11391-11392**

   We speculate in the paper that those were likely trapped waves because they had high intrinsic frequencies and short horizontal wavelengths. The trapping mechanism is high $\hat{\omega}$ reflection. The uncertainty in our calculations does not warrant further detailed analysis of wave trapping.

   The relevant sentence is modified as follows in the revised paper: *“Most of the wave events identified in this study were found to have short horizontal wavelengths and high intrinsic frequencies, as mentioned in section 3. Such waves*

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are prone to be trapped in the atmosphere via high $\hat{\omega}$ reflection (Isler et al., 1997; Swenson et al., 2000; Marks and Eckermann, 1995), and the trapped waves carry no net vertical flux of horizontal momentum." (L. 337-341).

We add the following sentence in the revised paper: *" The uncertainty in our calculations, however, does not warrant further detailed analysis of wave trapping."* (L. 357-358).

Minor Comments

- **Page 11378**

  L2: The relevant sentence in the abstract is modified as *"The vertical temperature gradient was used to determine the vertical wavelengths of the events."* (L. 10-11).

  L8: modified accordingly

  L13-14: modified accordingly (L. 14-16)

  L24: We replace "cooling rates" with *"local wave-induced cooling rate"* in the revised paper. For more detailed discussion on the usage of the terminology, please refer to our reply to the comment "Page 11392, L20".

- **Page 11379**

  L2: modified accordingly

  L10: modified accordingly

  L13: modified accordingly

  L14: modified accordingly

  L27-28: modified accordingly (P. 2, Para. 2)

- **Page 11380**

  L1: modified accordingly

  L1-2: modified accordingly

  L2: modified accordingly (L. 52)

  L8: Bregman et al. (2002) examine mid-latitude cirrus clouds and their effects on the stratospheric chemistry at similar latitudes. Of more relevance to our study are subtropical-tropical cirrus clouds, which can influence the polar stratospheric chemistry indirectly by affecting the stratospheric humidity through the Brewer-Dobson circulation (Solomon, 1999). For the revised paper, we will use Solomon (1999) instead of Solomon et al. (1986) as the reference (L. 58).

  L9: modified accordingly (L. 59-60)

  L14: modified accordingly (P. 3, Para. 1)

  L20-21: modified accordingly (L. 68-69)

  L26: modified accordingly

  L26-27: modified accordingly (L. 74-75)

- **Page 11381**

  L1: modified accordingly (L. 75-76)

  L5: We capitalize *"Meteorological Measurement System"* the first time when we mention it in the revised paper.

  L7: We capitalize *"Microwave Temperature Profiler"* the first time when we mention it in the revised paper.

  L9: modified accordingly

  L10: The relevant sentence is modified as follows in the revised paper: *"The original sampling rate of the MMS was $\sim$ 10 Hz, but the 1 Hz version was used in this study as it had a better signal-to-noise ratio." (L. 84-86).*

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L24: modified accordingly (L. 97-99)

- **Page 11382**

  L1: modified accordingly (L. 103-104)

  L3: modified accordingly (L. 105-107)

  L7: modified accordingly

  L12-14: The relevant sentences are modified as follows in the revised paper: *"In the next section, we describe the procedure to identify GW events from the flight segments in a more quantitative way, and estimate GW parameters including wavelengths, horizontal propagation directions, and vertical fluxes of horizontal momentum for such events."* (L. 111-113).

  L24: We use ψ for the mother wavelet (L. 127) and Ψ for the CWT in the revised paper (L. 121-122).

- **Page 11383**

  L1: modified accordingly (L. 125-127)

  L4: We delete "and i is the imaginary unit" in the revised text.

  L15: We define w for MMS vertical velocity (L. 103-104) and use ψ for mother wavelet (L. 127) in the revised paper.

  L23: modified accordingly

  L24: The following text is added in the revised paper: *"Note that such wave amplitudes for u, v and T are much smaller than what are usually seen in inertia GWs typically resolved in radiosonde profiles (e.g., Wang and Geller, 2003). Such smaller values are consistent, via GW polarization relations, with the much higher intrinsic frequencies inferred for these GWs (which will be discussed in the next subsection). Also, note that the ER-2 aircraft flight paths were chosen*

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to avoid areas directly above deep rain events where the most vigorous GW motions might be present. Such a sampling bias in the aircraft data likely causes an underestimation of the actual GW amplitudes in the region." (L. 155-162).

- **Page 11384**

  L12: modified accordingly

  L17: modified accordingly

- **Page 11386**

  L14-15: Their units (radians per second) are clarified in the revised paper (L. 225, 227).

  L16: We show the value of N/f in the paper mainly to remind readers that the subtropical N/f is much larger than the mid-latitude one ($\sim$ 200), a value that most readers are more familiar with. For the two events, N/f calculated directly from the MTP data is $\sim$ 360, being larger than that from the NCAR/NCEP reanalysis (i.e., 319). We use the value calculated directly from the MTP data in the revised paper (L. 229).

  L17-22: The relevant sentence is changed as follows in the revised paper: *"We chose not to use this approach since we were mostly dealing with short horizontal scale and high intrinsic frequency waves which are more linearly polarized and thus they cannot be diagnosed for their ellipticities to infer intrinsic frequencies."* (L. 232-235).

  L19: modified accordingly

  L24-25: Since the vertical resolution of the MTP data is 160 m (see also the reply to major comment # 2), we do not think that the estimated λ_z is biased toward $\lambda_z \geq$ 4 km.

  L27: Yes, they are horizontal speeds. We add "horizontal" in the revised paper to make them clear to readers (L. 222).

- **Page 11387**

  L6: The term is modified as follows in the revised paper: *"GW induced background wind acceleration* $(\overline{X}, \overline{Y})$*"* (L. 247-248).

  L12: Yes, we agree that the $(1 - f^2/\hat{\omega}^2)$ factors can be deleted in Eqns.11-13 (Eqns. 13-15 in the revised paper) for most but not all the waves we observe. We retain the term for completeness. We keep the $1 \pm \hat{\omega}^2/N^2$ terms in the dispersion relation in this study.

- **Page 11388**

  L24: modified accordingly (L. 283-284.).

- **Page 11389**

  L2: We use k' in Eqn. (2) in the revised paper (L. 129-130).

  L12: The color of the flight track is made lighter in Fig. 8 (or Fig. 7 in the revised paper) to make it more distinct from the background dark gray color. The color of the reverse traced rays is changed to deep blue to make them more distinct. The blue 3-character markers are the NEXRAD site codes indicating where the radars are located (AMX: Miami, BYX: Key West) (the information is added to the figure caption). The image was downloaded from the NASA Langley Research Center NEXRAD radar image website (L. 296-297). The units of the NEXRAD image are provided in the revised paper (L. 301). The range of the image corresponded to the CRYSTAL-FACE site.

  L20: Please see the reply below.

  L26: Visual inspection of individual plots similar to Fig. 8 (or Fig. 7 in the revised paper) was applied to determine whether a given event can be traced to a convective source. If a line similar to the dashed red line in Fig. 8 crossed a region with base reflectivity larger than ~ 40 dBz, the event was considered to be traceable to a convective source. The relevant sentences are modified as follows in the revised paper: *"Visual inspection of Fig. 7 shows that the wave event was located over a convectively active region (with base reflectivity larger than* $\sim$ *40 dBz) in the troposphere one hour before it was observed in the lower stratosphere by the ER-2 aircraft, implying that the source of the event was likely the strong convection in the troposphere at* $\sim$ *(25.5°N, 81.3°W."* (L. 306-310). Also, the following sentence is added in the revised paper: *"We applied the same procedure to the rest of the events."* (L. 311).

- **Page 11390**

  L3: Yes, this means that a turning point occurred. The relevant sentences are modified as follows in the revised paper: *For those GW events which could not be traced back to convective sources in the troposphere, most had shorter* λ_h *and higher* $\hat{\omega}$ *at 20* km*, and the ray tracing gave turning points (*$\hat{\omega} \rightarrow N$*) somewhere between 13 and 20* km*.* (L. 317-319).

  L6-7: The relevant sentence is changed to *"The source to event direction was defined as the direction from the convective sources we identified to the mid-point of each event."* in the revised paper (L. 322-323).

  L9: modified accordingly

  L17: The relevant text is modified as follows: "The approximation in Eq. (16) follows from *"an approximation to the GW dispersion relation when* $f \ll \hat{\omega} \ll N$*.*" (L. 331-333).

  L22-23: modified accordingly (L. 337)

  L25: modified accordingly (L. 341)

- **Page 11391**

  L4-6: The vertical resolution of the MTP data is $\sim$ 160 m (see also the reply to major comment # 2), so we do not think that Fig. 10 (or Fig. 9 in the revised paper) is affected severely by the vertical resolution of the MTP data.

L24: The relevant sentences are changed as follows: *"As mentioned above, our results are distinct in that the GWs examined in this study were short horizontal scale and high intrinsic frequency GWs, whereas the previous radiosonde studies, as referenced here, focused on long horizontal scale and low intrinsic frequency inertio GWs."* (L. 362-365).

- **Page 11392**

  L14: modified accordingly

  L15: modified accordingly

  L20: We share the reviewer's concern about the wording used in the text. Nevertheless, we think it should be clear to ice cloud modelers if we change the wording of $\hat{\omega}\tilde{T}$ to the *"reversible cooling rate $\hat{\omega}\tilde{T}$"* throughout the revised text (L. 26-27, 389, and 450). To avoid any confusion, we will also change the wording in the figure caption of Fig. 11 (or Fig. 12 in the original paper) to *"The probability of observing a reversible cooling rate $\hat{\omega}\tilde{T}$ within a given range from the ER-2 aircraft during CRYSTAL-FACE. The red error bars are calculated based on the Poisson counting statistics. See text for further details."* in the revised paper.

  L23: We use *"with a certain reversible cooling rate $\hat{\omega}\tilde{T}$."* in the revised paper (L. 450).

  L28: We would like to have the use of our cooling rates in ice cloud models to ice cloud modelers, but would invite future collaboration on these issues.

- **Page 11393**

  L6: modified accordingly

  L20: modified accordingly

  L22: The relevant sentence is modified as follows: *"The horizontal propagation directions ϕ were estimated from MMS horizontal winds using a variant of the Stokes parameter method with the aid of the cross S-transform."* (L. 422-423).

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L28: The vertical resolution of the MTP data during CRYSTAL-FACE was $\sim$ 160 m.

- **Page 11394**

  L1: modified accordingly (L. 430)

  L4: modified accordingly (L. 433)

  L11: modified accordingly (L. 440)

  L22: We refer the term as "the reversible cooling rate that occurs during each wave cycle", the first time when it is used in the text (L. 389). We place $\hat{\omega}\tilde{T}$ along with each use of cooling rate afterwards.

- **Page 11401** We double the thickness of the Florida coastline and use lighter blue for the flight track in Fig. 1 in the revised paper.

- **Page 11406** The relevant figures (Figs. 4-6 and 11 in the revised paper) are modified to include the error bars based on the Poisson counting statistics as suggested by the reviewer.

- **Page 11412** modified accordingly

Interactive comment on Atmos. Chem. Phys. Discuss., 5, 11377, 2005.