Response to Anonymous Referee #1

We thank Anonymous Referee #1 for his/her thorough and insightful comments, which are very helpful in our further revision of the manuscript. We have made every effort to address all the concerns raised. Our point-by-point response is given below.

This study presents some detailed observations and complex spectral/wavelet analysis of research aircraft measurements of gravity waves. The waves were observed during START08 and represent a unique dataset to study gravity waves associated with jets. The paper is well structured and provides new insight by quantifying the observed waves – it should be published in ACP. However, I feel that a little extra analysis could make this study more useful, both for quantifying the mesoscale signals and for understanding the wave generation. I suggest the authors consider these extra analyses, which shouldn't be too onerous, in their revised manuscript.

1. Spectral analysis (Figs. 4 and 5).

The authors claim that the spectra reproduce the -5/3 slope, which they do in many cases. However, because of the inherent properties of the spectra this slope is not entirely obvious in many cases, mostly because of the change in slope with scale. I suggest that the authors also complete spectra of kinetic energy (which includes horizontal and vertical velocities), which should show a -5/3 slope extending over more decades (especially in Fig. 5).

Per reviewer's recommendation, we will revise Figure 4 and Figure 5 using Figure R1.01 and Figure R1.02 given in this response below. The composite spectra of kinetic energy can be found in Figure R1.02e. The following sentence will be added in the revision around line 10 on page 4736.

"Even though the kinetic energy spectra (Fig. 5e) may show a -5/3 slope that covers a larger range, the -3 slope over small scale in KE is still evident. "

I can't determine the units of the spectra that are labelled as 'variance' but I assume they are in m^2/s^2 for the velocity components. It would be advantageous to plot the energy density (units of m^3/s^2) instead, which would allow direct comparisons to the cited studies (e.g., Nastrom and Gage 1985, Skamarock 2004).

Strictly speaking, the variance for the velocity components in the current study is " $m^2 s^{-2} \times unit of(N) / unit of(k^*)$**". Here, the unitof() give the unit of the variable inside the bracket; wavenumber k^* is equal to** $\dfrac{N\Delta x}{\lambda}$**; N is the number of points of data in the flight segments; Δx is the spatial resolution of the flight data; λ is the across-track wavelength.**

40   **In order to use the same unit as those in Nastrom and Gage (1985), all we need to do**
41 **is simply multiply the current value by Δx. After the modification, the unit will be "**
42 $unit of (\Delta x) \times m^2 s^{-2} \times unit of (N) / unit of (k^*) = m^3 s^{-2}$ **", which is consistent with Nastrom and**
43 **Gage (1985; their Figure 3). Since Δx is constant ($\Delta x = 250m$), there shouldn't be any**
44 **change in the spectra slope.**

45   **Please check the units in the titles of Figure R1.01 and Figure R1.02, which will be**
46 **replacing the original Figure 4 and Figure 5.**

47
48 *2. Inferences about propagation direction*
49
50 *I think the manuscript would benefit from enhanced discussion about what can be inferred about*
51 *horizontal propagation direction and how the superposition of gravity waves propagating in*
52 *opposing directions can complicate the analysis. In particular, around line 20 on p 4739, there is*
53 *discussion of cospectra varying sign. For example as shown in Fig. 7 (leg J3), the cospectra of w*
54 *and p suggest upward propagating waves (almost exclusively). Thus, the variations in sign of the*
55 *cospectra of u and w imply that this track is sampling waves propagating in both the forward*
56 *and backward direction. As argued by the authors (p4740 line ~5) this highlights a difficulty in*
57 *interpreting the waves observed by aircraft, but it does tell us something useful about the wave*
58 *field nonetheless.*
59
60   **As suggested, the following sentence will be added in the manuscript around line 21**
61 **on page 4739.**

62   **"The variations in the sign of vertical transports of horizontal momentum fluxes**
63 **imply that this flight segment is sampling waves propagating in both forward and**
64 **backward direction, assuming the vertical energy transports are generally upward."**

65
66 *For such legs it would be useful to obtain estimates of the net momentum flux. The analysis*
67 *presented could readily separate the averages into positive and negative components, which*
68 *should give a good indication of the dominance of which particular propagation direction as a*
69 *function of scale.*
70
71   **The results of net momentum fluxes are shown in Figure R1.03-R1.05, which**
72 **calculate the cospectrum of $\overline{u'w'}$, $\overline{v'w'}$, and $\overline{w'p_c'}$ based on Fourier transform,**
73 **respectively. For the scale below ~32 km, both positive values and negative values are**
74 **important in $\overline{u'w'}$ and $\overline{v'w'}$, while positive $\overline{w'p_c'}$ appears to be more continuous than**
75 **negative $\overline{w'p_c'}$. For the scale above ~32 km, negative $\overline{u'w'}$ (positive $\overline{w'p_c'}$) appears to be**
76 **generally more continuous than positive $\overline{u'w'}$ (negative $\overline{w'p_c'}$), while the dominant signs in**
77 **$\overline{v'w'}$ are generally inconclusive.**

78

79　*Similarly, in section 5 – the authors provide detailed analysis of specific example of waves and*
80　*their scales. From this analysis they should be able to infer the (intrinsic) propagation direction*
81　*for each case considered, based on the sign of the cospectra of u and w, and the vertical*
82　*propagation direction. This could be used to comment on the direction of propagation of the*
83　*waves away from any key synoptic features presented in Fig. 2, and whether there is broad*
84　*consistency between these sampled waves and those seen in WRF.*
85

86　　　　**Figure R1.06 in this document demonstrates the comparison between aircraft**
87　**measurements and high-resolution WRF simulations. Preliminary analysis shows that**
88　**WRF successfully captures the variations in wind, potential temperature, and pressure,**
89　**especially for segment J1, J2, J3, and M1. Probably due to upscale error growth with**
90　**relatively long-time integration for segment M2, there is indeed a ~150-km distance**
91　**between the observed V maximum location (at location ~400 km in M2) and the simulated**
92　**one (at location ~550 km in M2). Also, the observed V maximum is larger than the**
93　**simulated one (~60 m/s versus ~50 m/s). With that being said, the forecast error is within a**
94　**reasonable range, and the aircraft did manage to obtain the data within the jet exit region.**

95　　　　**However, it is beyond to the scope of the current study to investigate the**
96　**consistencies and differences between aircraft measurements and WRF. WRF simulations**
97　**and dynamics of the gravity waves will be examined in a separate study. In particular,**
98　**based on the high-resolution simulations, we will investigate the sensitivity of wave**
99　**response to the mean flow speed, wind direction, wind shear, and altitude, as suggested in**
100　**the above comments.**

101
102　*Minor comments:*
103
104　*1. p. 4727 line 15. Suggest changing to: "dominated by signals with sampled periods.." to be*
105　*clear that this isn't the wave period.*
106
107　　　　**This sentence will be modified in the revision.**

108
109　*2. p. 4730 line 19. I don't think this claim to be the 'first' is entirely correct. It may be the first*
110　*such flight to actually aim to find the mesoscale gravity waves from jet/fronts, but previous*
111　*studies/flights have measured them and analyzed them (e.g., Shapiro and Kennedy 1975; Koch et*
112　*al. 2005).*
113
114　　　　**The sentence in line 19 on page 4730 will be modified as below.**

115　　　　**"The second flight (RF02), which occurred on 21–22 April 2008, was dedicated, to**
116　**our knowledge for the first time, to probing mesoscale gravity waves associated with a**
117　**strong upper-tropospheric jet-front system, even though some previous studies may have**
118　**already measured or analyzed them (e.g., Shapiro and Kennedy 1975; Koch et al. 2005)"**

119
120　*3. To be clear: Do the authors ascertain that the small-scale signals represented in the data are*
121　*entirely fictitious? Or is it that these signals do exist, but the sampling errors (associated with*

122 *the violation of the assumptions about pressure) are very large making the spectral estimates*
123 *unreliable?*
124
125   **With limited observations and accuracy, we cannot ascertain that the small-scale**
126 **signals are entirely fictitious. The current study attempts to argue that small-scale pressure**
127 **could be problematic, and that the small-scale signals may be hard to understand/verify**
128 **using linear theory for propagating monochromatic gravity waves. However, it remains**
129 **possible, though unlikely, some of the small scale variations may be due to nonlinear**
130 **dynamics, shear instability, and/or turbulence that are physical. The below sentences will**
131 **be added to around line 4 on page 4746.**

132   **"The current study mainly attempts to verify fluctuations with the use of linear**
133 **theory for monochromatic gravity waves. Therefore, in addition to the measurement error,**
134 **the possibilities that those fluctuations may be due to other physical phenomena (e.g.,**
135 **nonlinear dynamics, shear instability and/or turbulence) cannot be completely ruled out."**
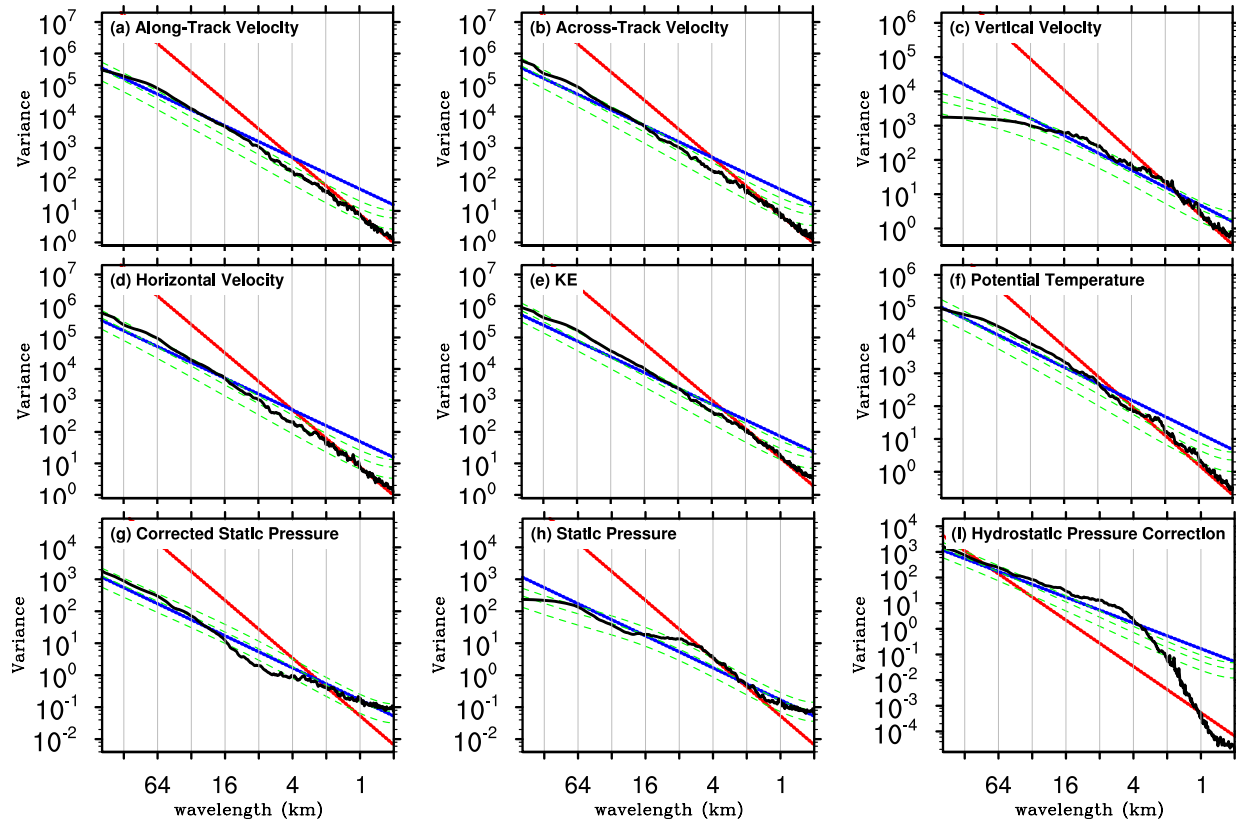
136

137

138 **References**

139
140 Koch, S. E., Jamison, B. D., Lu, C. G., Smith, T. L., Tollerud, E. I., Girz, C., Wang, N., Lane, T.
141   P., Shapiro, M. A., Parrish, D. D., and Cooper, O. R.: Turbulence and gravity waves within
142   an upper-level front, J. Atmos. Sci., 62, 3885–3908, 2005.
143 Nastrom, G. D., and K. S. Gage, 1985: A Climatology of Atmospheric Wavenumber Spectra of
144   Wind and Temperature Observed by Commercial Aircraft. J. Atmos. Sci., 42, 950–960.
145 Shapiro, M. A., and P. J. Kennedy, 1975: Aircraft Measurements of Wave Motions within
146   Frontal Zone Systems. Mon. Wea. Rev., 103, 1050–1054. doi:
147   http://dx.doi.org/10.1175/1520-0493(1975)103<1050:AMOWMW>2.0.CO;2
148 Skamarock, W. C., 2004: Evaluating Mesoscale NWP Models Using Kinetic Energy Spectra.
149   Mon. Wea. Rev., 132, 3019–3032.
150
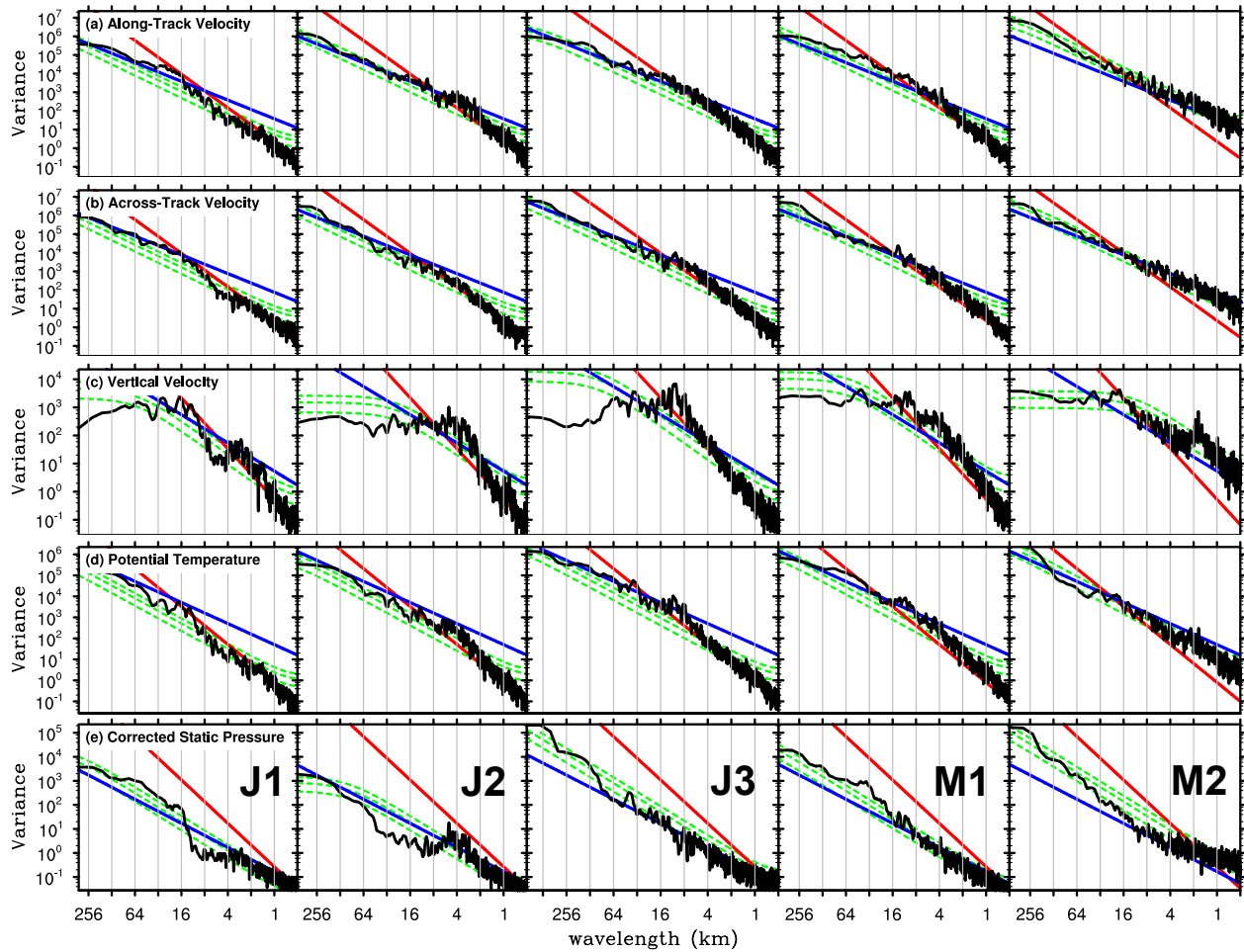
Figure R1.01 The spectrum (black line) of GV flight-level aircraft measurement during 5 selected segments (from left to right: J1, J2, J3, M1 and M2) of RF02 in START08: (a) along-track velocity component (unit: $m^2 s^{-2} \bullet m$), (b) across-track velocity component (unit: $m^2 s^{-2} \bullet m$), (c) vertical velocity component (unit: $m^2 s^{-2} \bullet m$), (d) potential temperature (unit: $K^2 \bullet m$), and (e) corrected static pressure (unit: $hPa^2 \bullet m$). Green lines show the theoretical Markov spectrum and the 5% and 95% confidence curves using the lag 1 autocorrelation. The blue (red) reference lines have slopes of -5/3 (-3).
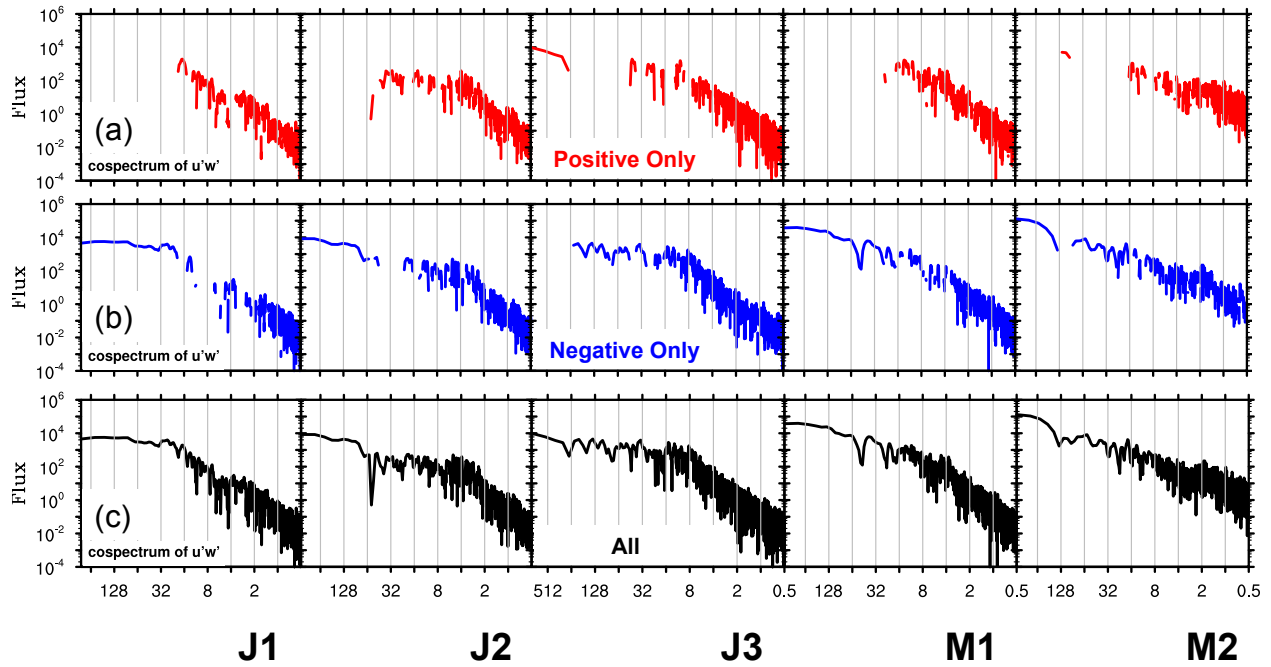
Figure R1.02 Composite spectrum (black line) of GV flight-level aircraft measurement averaging over all 68 segments in START08 (colored lines in Fig. 1): (a) along-track velocity component (unit: $m^2 s^{-2} \bullet m$), (b) across-track velocity component (unit: $m^2 s^{-2} \bullet m$), (c) vertical velocity component (unit: $m^2 s^{-2} \bullet m$), (d) horizontal velocity component (unit: $m^2 s^{-2} \bullet m$), (e) KE, (f) potential temperature (unit: $K^2 \bullet m$), (g) corrected static pressure (unit: $hPa^2 \bullet m$), (h) static pressure (unit: $hPa^2 \bullet m$), and (i) hydrostatic pressure correction (unit: $hPa^2 \bullet m$). Green lines show the composite curves of the theoretical Markov spectrum and the 5% and 95% confidence curves using the lag 1 autocorrelation. The blue (red) reference lines have slopes of -5/3 (-3). The subplot (e) KE is the sum of (a)-(c).
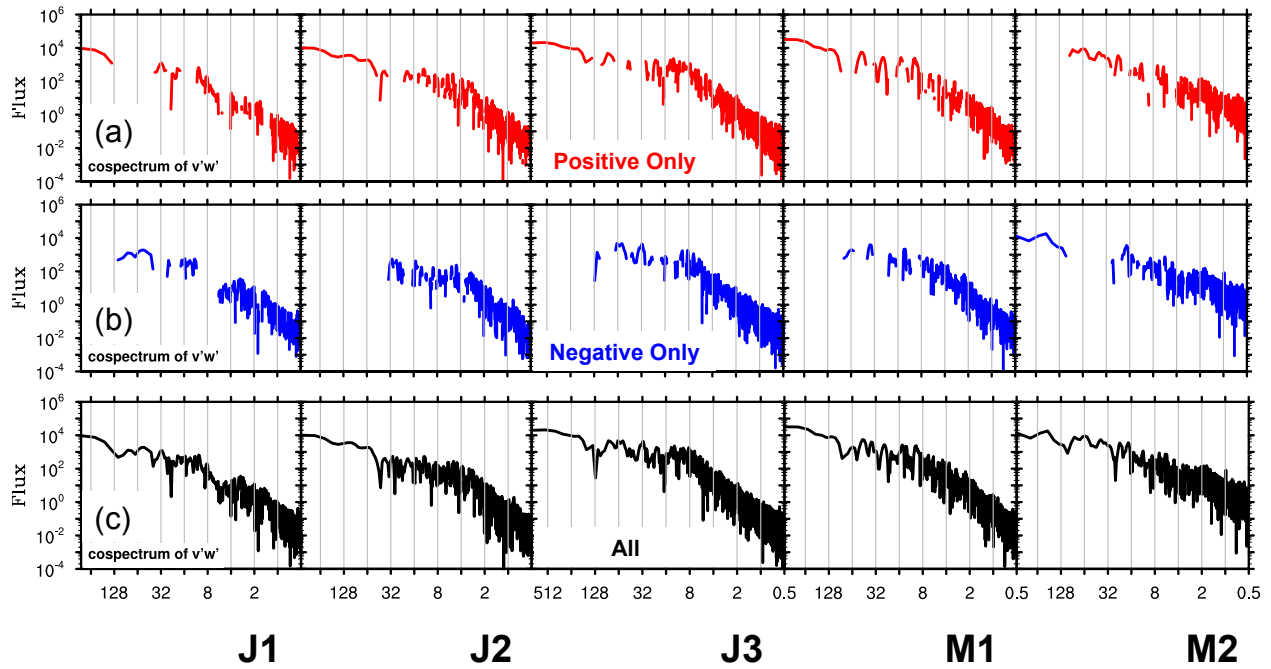
Figure R1.03 The cospectrum of along-track velocity component u and vertical velocity component w. (a) The absolute value of the positive only component. (b) The absolute value of the negative only component. (c) The absolute value of both positive and negative components.

Figure R1.04 The cospectrum of across-track velocity component v and vertical velocity component w. (a) The absolute value of the positive only component. (b) The absolute value of the negative only component. (c) The absolute value of both positive and negative components.

Figure R1.05 The cospectrum of vertical velocity component w and corrected static pressure p_c. (a) The absolute value of the positive only component. (b) The absolute value of the negative only component. (c) The absolute value of both positive and negative components.
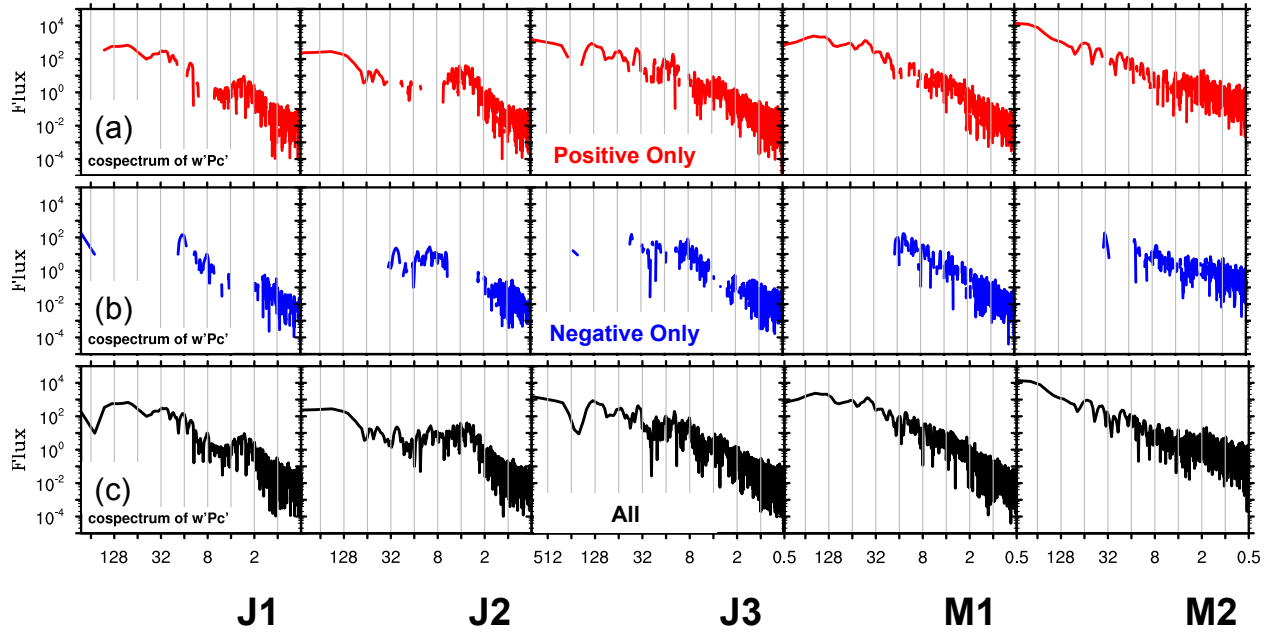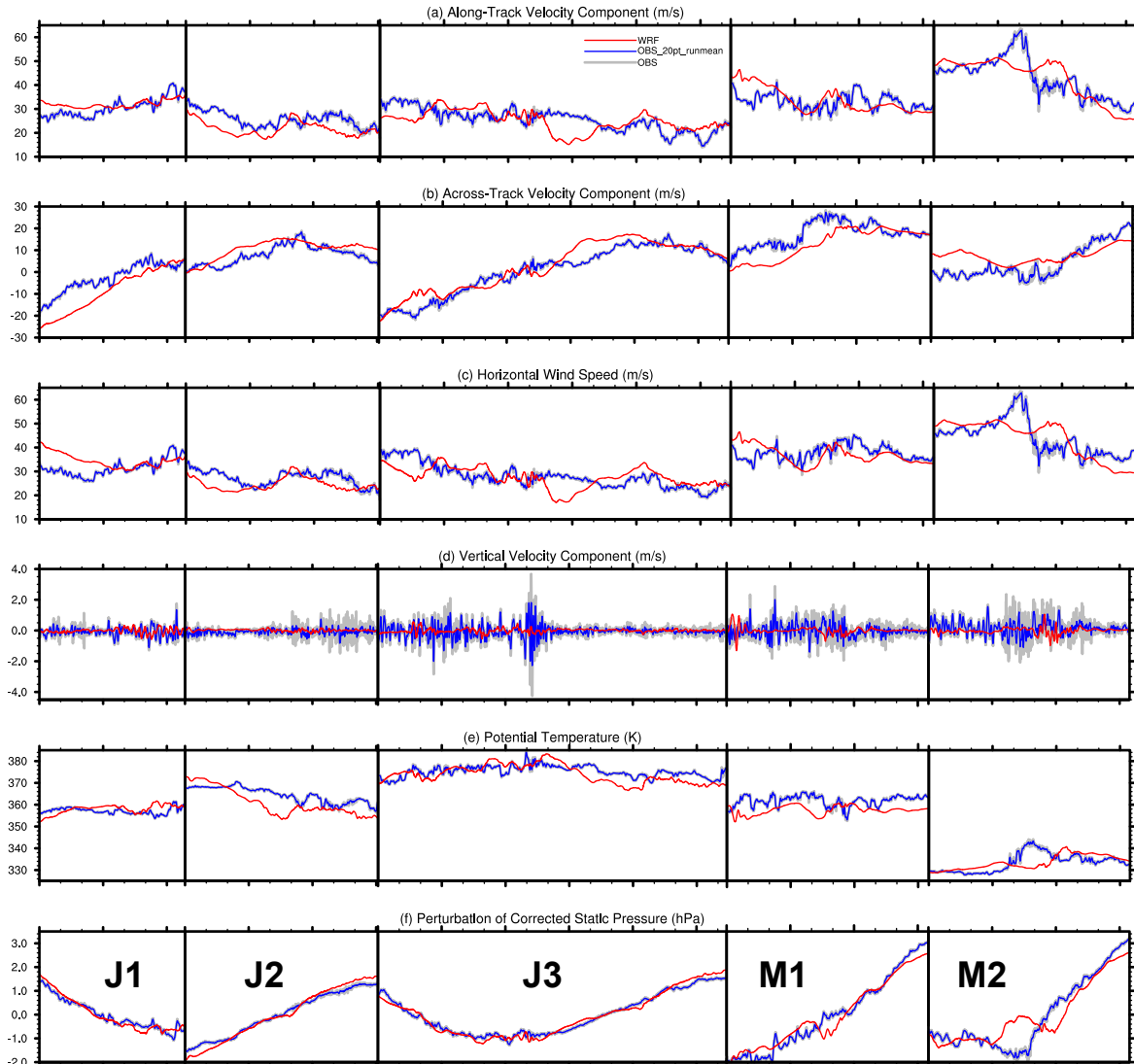
Figure R1.06 Comparision between GV flight-level aircraft measurements and WRF simulations during 5 selected segments (from left to right: J1, J2, J3, M1 and M2) of RF02 in START08: (a) along-track velcotiy component (m/s), (b) across-track velocity component (m/s), (c) horizontal wind speed (m/s), (d) vertical velocity component (m/s), (e) potential temperature (K), and perturbation of corrected static pressure (hPa). The grey lines represent the flight measurements with 250-m resolution, the blue lines represents 20-point running mean of the grey lines, and red lines represents the WRF simulations derived from D4 (1.67-km horizontal resolution) with 10-minute time interval. The series in segment J3 and M2 are reversed to facilitate the comparison with J1+J2 and M1, respectively. The distance between minor tick marks in x axis is 100 km. The perturbations in (f) are defined as the differences between the original data and their mean from their corresponding segments.

Response to Anonymous Referee #2

We thank Anonymous Referee #2 for his/her thorough and insightful comments, which are very helpful in our further revision of the manuscript. We have made every effort to address all the concerns raised. Our point-by-point response is given below.

This manuscript presents an analysis of aircraft measurements of mesoscale gravity waves associated with topography and the upper tropospheric jet region. Fourier and wavelet spectra are investigated, and wavelet cross-correlations are compared to theoretical values for gravity waves. Overall, the results of these comparisons are mixed: some mesoscale features are consistent with gravity waves, but others show inconsistencies that are attributed to measurement errors and flight track fluctuations.

Overall, this is a well written manuscript and a detailed, careful analysis of the START08 data. There are a few issues that the authors gloss over, which I think could be better explored (see below), but generally I have only suggestions for minor revisions.

1. The discussion of spectral slopes from Fig. 4 is superficial and should be better connected to the literature. Reference curves with slopes of -3 and -5/3 are shown, presumably for comparison with the Nastrom-Gage spectrum. But Nastrom & Gage found spectral slopes of -3 only at scales larger than those considered here! The spectra in Fig. 4 are all inside the -5/3 part of the Nastrom-Gage spectrum, so it is not clear why the -3 reference is included. Overall, the u/v/theta spectra seem to be similar to -5/3 at "larger" scales (256 down to ~16 km), as expected, but are steeper (maybe -3) at smaller scales. It would be interesting to explore the reason for the steepening at small scales. In fact, this small-scale steepening has been noted before (Bacmeister et al., 1996), which should be discussed.

Per this review comment, we will add more discussions of the spectral slopes and make more connections to the literature in the revision. More specifically, there are two main reasons why the -3 power law (red lines in Figure 4 and 5) is included in the current study. First, theoretically speaking, the -3 power law is expected for quasigeostrophic turbulence theory (e.g., Charney, 1971). Second, observationally speaking, the small-scale steepening (slopes of around -3 instead of -5/3) in some cases has been verified in the observational aircraft measurements (e.g., u, v, θ in J1, J2, J3, and M1 as indicated in Figure 4), even though the exact range of the small-scale steepening (slopes of around -3) may be sensitive to the selection of smoothing method or tapering method. It is worth noting that the spectral slope in M2 for u, v, and θ generally follows -5/3 (even at small scales), and that the spectral slope in M1 for u, v, and θ tends to follow -3 at small scales. Even though we are still investigating the physical reason for the above-mentioned slope behavior differences between M1 and M2, one possibility highlighted in the current manuscript is that the differences may be due to the changing background flow (please check the discussion from line 9 in page 4735 to line 2 in 4736).

44 *2. Section 5 compares the cross-correlations with gravity wave theory for a few different cases.*
45 *Discrepancies are found for some cases, especially at small scales, and this is attributed to*
46 *measurement error or flight track fluctuations. But there seems to be another possible*
47 *explanation: maybe these fluctuations are just not gravity waves. Could these fluctuations be due*
48 *to other phenomena, such as shear instabilities, stratified turbulence, etc? This possibility should*
49 *at least be discussed, and ruled out if possible, if not explored in detail.*
50
51 **The below sentences will be added around line 4 on page 4746.**

52 **"The current study mainly attempts to verify fluctuations with the use of linear**
53 **theory for monochromatic gravity waves. Therefore, in addition to the measurement error,**
54 **the possibilities that those fluctuations may be due to other physical phenomena (e.g.,**
55 **nonlinear dynamics, shear instability and/or turbulence) cannot be completely ruled out."**

56
57 *Minor comments:*
58
59 *1. Fig. 2 caption: what is the "mesoscale component" of horizontal divergence? Presumably this*
60 *is just the filtered divergence (not "component"), but how and over what scales?*
61
62 **As stated in the last sentence of Figure 2 caption, "*A band-pass filter is applied to***
63 ***extract signals with wavelength from 50 to 500km for horizontal divergence.*"**

64
65 *2. Some figures are too small and difficult to read. For example, Fig. 4, has 25 panels! I had to*
66 *zoom 400% to look at this. I suggest breaking this figure into multiple figures, or being more*
67 *selective about what to show.*
68
69 **The current manuscript attempts to generalize the characteristics and compare the**
70 **differences among five selected segments in RF02. We believe that it is better to achieve this**
71 **purpose by presenting an ensemble of results in one plot. In revision for Figure 4, we will**
72 **try to make the black lines in front of all the other lines in order to make the plots much**
73 **easier to read.**

74 **Per reviewer's recommendation, and also per suggestion of another reviewer, we**
75 **will revise Figure 4 and Figure 5 using Figure R2.01 and Figure R2.02 given in this**
76 **response below.**

77
78 *3. How are power spectra computed? Are time series windowed (what kind?) or made periodic*
79 *in some other way?*
80
81 **The power spectra in Figure 4, including their significant tests, are computed with**
82 **the function provided by the NCAR Command Language (NCL), and the description of the**
83 **function can be found in the below link.**

84 ***http://www.ncl.ucar.edu/Document/Functions/Built-in/specx_anal.shtml***

85   **First, the series mean and least squares linear trend are removed (i.e., iopt = 1 in the**
86   **above function). Second, perform the smoothing by averaging 7 periodogram estimates**
87   **(i.e., jave=7 in the above function). Third, 10% of the series is tapered (i.e., pct=0.10 in the**
88   **above function).**

89   **The below sentences will be added around line 6 on page 4734.**

90   **"The calculations of the spectra are performed with the "specx_anal" function in**
91   **the NCAR Command Language (NCL). Several steps are done before the calculations.**
92   **Firstly, the series mean and least squares linear trend are removed. Secondly, perform the**
93   **smoothing by averaging 7 periodogram estimates. Thirdly, 10% of the series are tapered."**

94
95   *4. In the discussion of the spectral slopes: instead of saying things like "consistent with -5/3"*
96   *etc, why not actually measure and report the slopes with a least squares fit?*
97
98   **We thank the reviewer for the suggestion. However, the current manuscript mainly**
99   **shows that -5/3 and -3 are the representative spectral slopes to be compared with. Yes, one**
100   **could estimate the slope with a least-squares fit with a running window (e.g., the examples**
101   **in Figure R2.03 and Figure R2.04 given in this response below), but the estimation will be**
102   **quite sensitive to the width of the running window and the rather arbitrarily chosen**
103   **transition wavelength (not shown). We believe showing the reference slopes of -5/3 and -3 is**
104   **adequate to justify our statement and will not change the final conclusion in the**
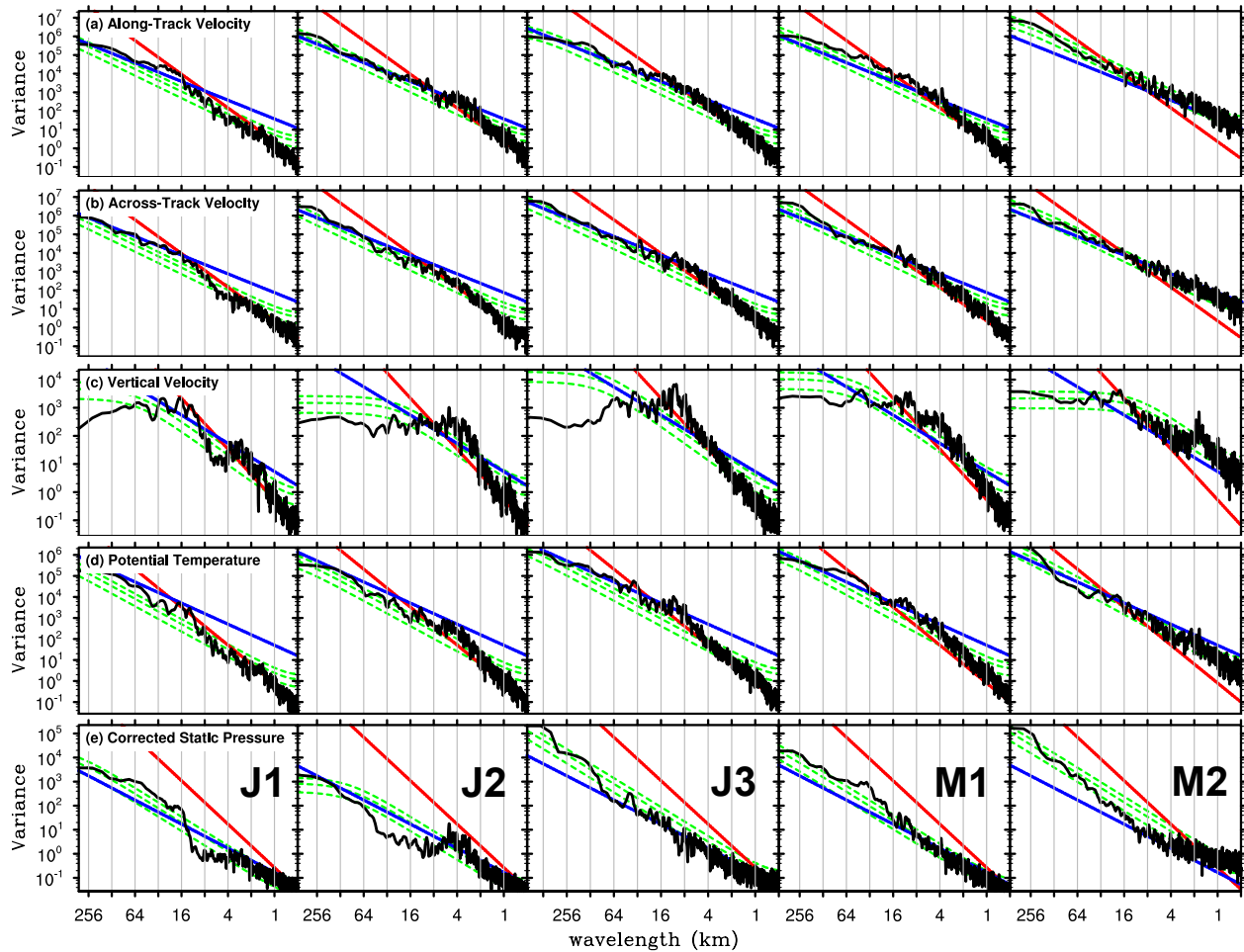105   **manuscript. Nevertheless, we revise the phrase to be "grossly *consistent with -5/3" and***
106   *alike.*

107

108

References

Charney, J. G.: Geostrophic turbulence, J. Atmos. Sci., 28, 1087–1095, 1971.
Nastrom, G. D. and Gage, K. S.: A climatology of atmospheric wavenumber spectra of wind and temperature observed by commercial aircraft, J. Atmos. Sci., 42, 950–960, 1985.

Figure R2.01 The spectrum (black line) of GV flight-level aircraft measurement during 5 selected segments (from left to right: J1, J2, J3, M1 and M2) of RF02 in START08: (a) along-track velocity component (unit: $m^2 s^{-2} \bullet m$), (b) across-track velocity component (unit: $m^2 s^{-2} \bullet m$), (c) vertical velocity component (unit: $m^2 s^{-2} \bullet m$), (d) potential temperature (unit: $K^2 \bullet m$), and (e) corrected static pressure (unit: $hPa^2 \bullet m$). Green lines show the theoretical Markov spectrum and the 5% and 95% confidence curves using the lag 1 autocorrelation. The blue (red) reference lines have slopes of -5/3 (-3).

124

Figure R2.02 Composite spectrum (black line) of GV flight-level aircraft measurement averaging over all 68 segments in START08 (colored lines in Fig. 1): (a) along-track velocity component (unit: $m^2 s^{-2} \bullet m$), (b) across-track velocity component (unit: $m^2 s^{-2} \bullet m$), (c) vertical velocity component (unit: $m^2 s^{-2} \bullet m$), (d) horizontal velocity component (unit: $m^2 s^{-2} \bullet m$), (e) KE, (f) potential temperature (unit: $K^2 \bullet m$), (g) corrected static pressure (unit: $hPa^2 \bullet m$), (h) static pressure (unit: $hPa^2 \bullet m$), and (i) hydrostatic pressure correction (unit: $hPa^2 \bullet m$). Green lines show the composite curves of the theoretical Markov spectrum and the 5% and 95% confidence curves using the lag 1 autocorrelation. The blue (red) reference lines have slopes of -5/3 (-3). The subplot (e) KE is the sum of (a)-(c).
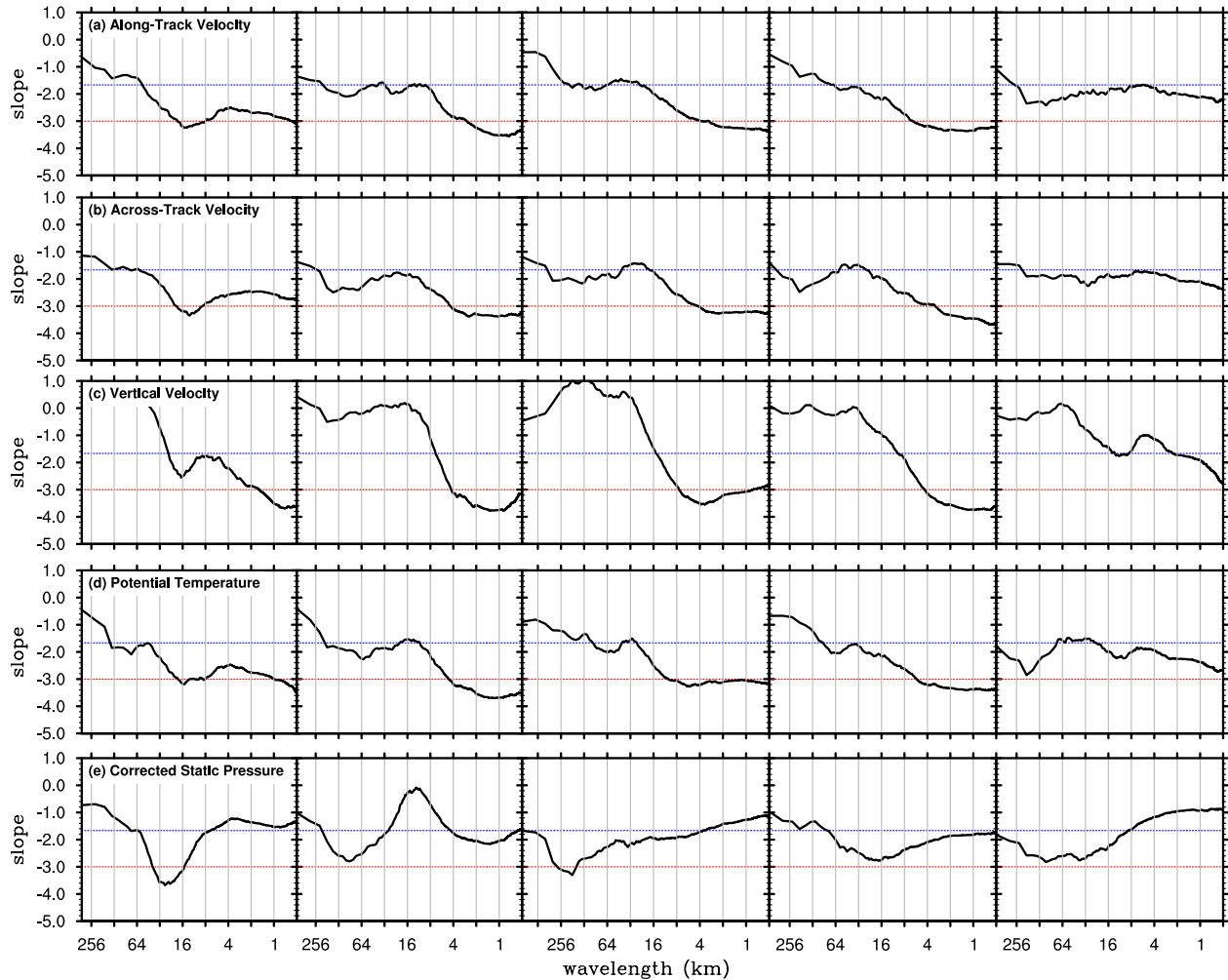
134

Figure R2.03 An example of the spectral slopes based on the results in Figure R2.01. The slopes are calculated with the linear regression coefficient between the log base 10 of the wavenumber and the log base 10 of the spectral power. A running window is used over the entire spectrum. The left boundary of the window is the maximum between wavenumber 1 and one quarter of the local wavenumber. The right boundary of the window is the minimum between maximum wavenumber (e.g., half of the total grid points) and four times the local wavenumber.

143
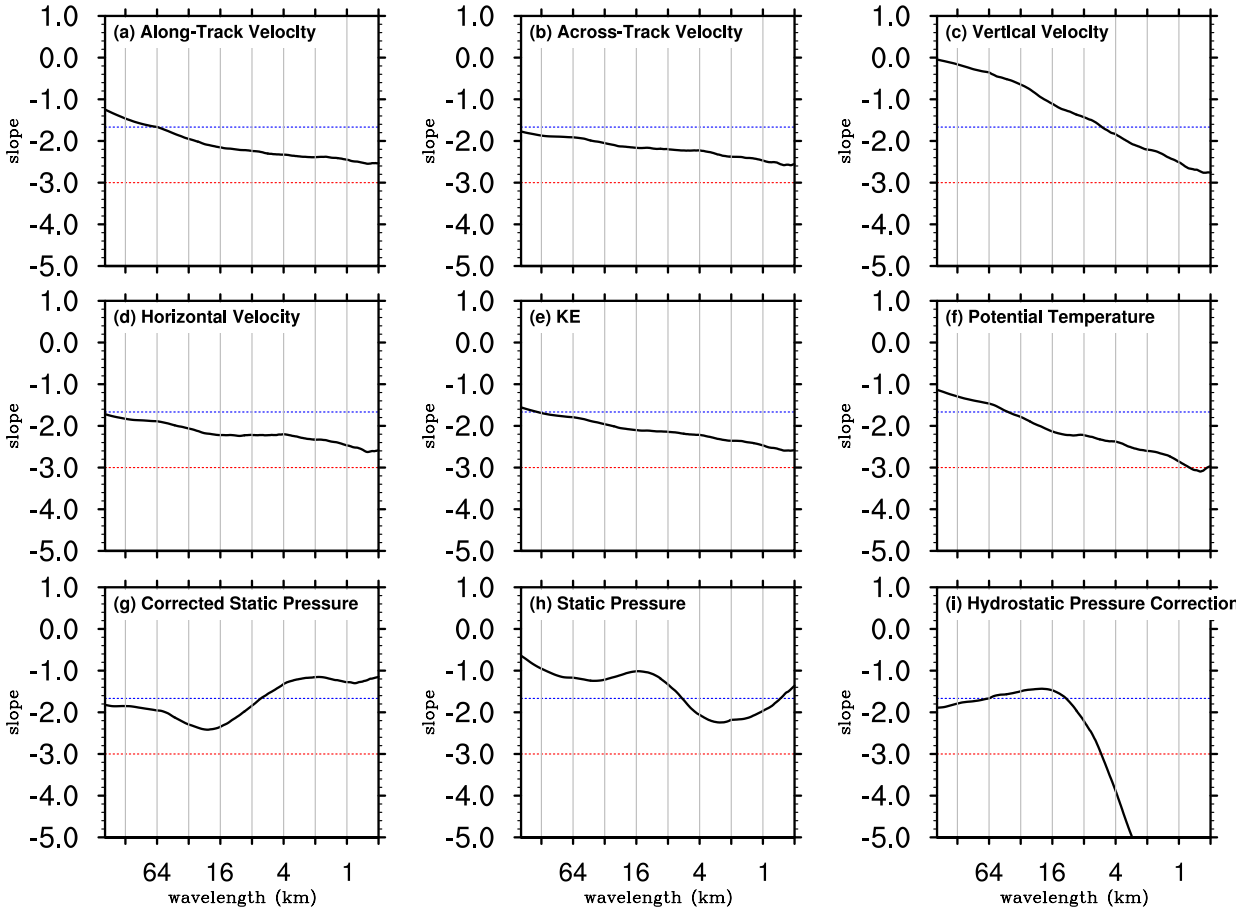
Figure R2.04 Same as Figure R2.03, but the calculations are based on the results in Figure R2.02.

Response to Anonymous Referee #3

We thank Anonymous Referee #3 for his/her detailed comments, which are very helpful in our further revision of the manuscript. We have made every effort to address all the concerns raised. Our point-by-point response is given below.

This is a study of mesoscale gravity waves observed during the START08 field experiment. The authors carefully identified gravity waves (GWs) from aircraft measures, and estimated gravity wave characteristics using spectral and wavelet analyses. The manuscript shows that spectra of horizontal winds and temperature follow the -5/3 power law. Overall, this is a well-constructed manuscript. I have a few minor comments. I recommend accept this manuscript after minor revision.

Comments:

1. Line 15, Page 4727: Signals with periods of ~20-~60 s. This is mentioned in the abstract and conclusion, but I cannot really see how this is estimated in the main text.

"*The periods of ~20-~60s*" in the abstract refers to the sample period, instead of the gravity wave period. The typical flight speed is approximately 250 m/s. Therefore, "*The periods of ~20-~60s*" in the abstract also corresponds to ~5-~15 km.

In the abstract (around line 16, page 4727), one note will be added as below.

"…are dominated by signals with periods of around 20–60 s and wavelengths of around 5–15 km (assuming that the typical flight speed is approximately 250 m/s). "

Similar revision will be made in the conclusion (around line 24, page 4745).

2. Line 1-2, Page 4734: u and θ change drastically near the high terrain (100-200 km west) associated with enhanced variance of w. This appears to suggest that this disturbance is associated with topography.

The below sentence will be added around line 4 on 4734.

"The enhanced variances of vertical motion, accompanied by the changes in horizontal wind and potential temperature, may be associated with topography for both M1 and M2 segments, even though the role of jet cannot be completely ruled out. "

33

3. 2nd paragraph of Page 4736: It is remarkable to see a power law can emerge from a very limited number of aircraft measurements. It appears to me that the composite spectra horizontal velocities (panels a, b, c ofFig. 5) and potential temperature (panel e of Fig. 5) show a slope somewhere between -5/3 and -3 for the considered wavenumber range by eye.

38

Below the scale of ~4-~16 km, there appears to be a noticeable departure from -5/3 for the composite spectra horizontal velocities and potential temperature. However, above the scale of ~4-~16 km, the above-mentioned spectra generally follow the -5/3 power law.

The updated version of Figure 5 is shown in Figure R3.01 in this document.

43

4. Line 7 of page 4735: The logic of this sentence is confusing. Continuity equation is always satisfied regardless of the scale of the motion, so it is difficult to use it to explain why power of w is much smaller at subsynptic scale.

47

Based on the scale analysis of continuity equation, the power of both horizontal divergence and vertical motion should be very small at larger scale (e.g., above the order of ~100 km). Mass may not be conserved if there is strong updraft or downdraft at large scale. Therefore, we expect that vertical motion have difficulties in demonstrating much stronger power toward larger scale. Similar results can be found in Bei and Zhang (2014) based on idealized moist baroclinic waves simulations.

54

5. Line 6 of Page 4742: rotation could also alter the dispersion relation, hence the phase relation between different variables. It is helpful to state clearly what types of GW dispersion relationship is used in this study. Is it non-hydrostatic GWs, or inertiagravity waves?

58
Earth rotation is considered in the current study. Please check the second paragraph (line 6-17) of page 4741. Based on the phase relationship between u and v, we have attempted to verify whether the waves in this particular example are influenced by earth rotation or not.

63

64

65 **References**

66
67 Bei, N., and F. Zhang, 2014: Mesoscale Predictability of Moist Baroclinic Waves: Variable and
68   Scale Dependent Error Growth. Advances in Atmospheric Sciences, 995-1008. doi:
69   10.1007/s00376-014-3191-7.
70
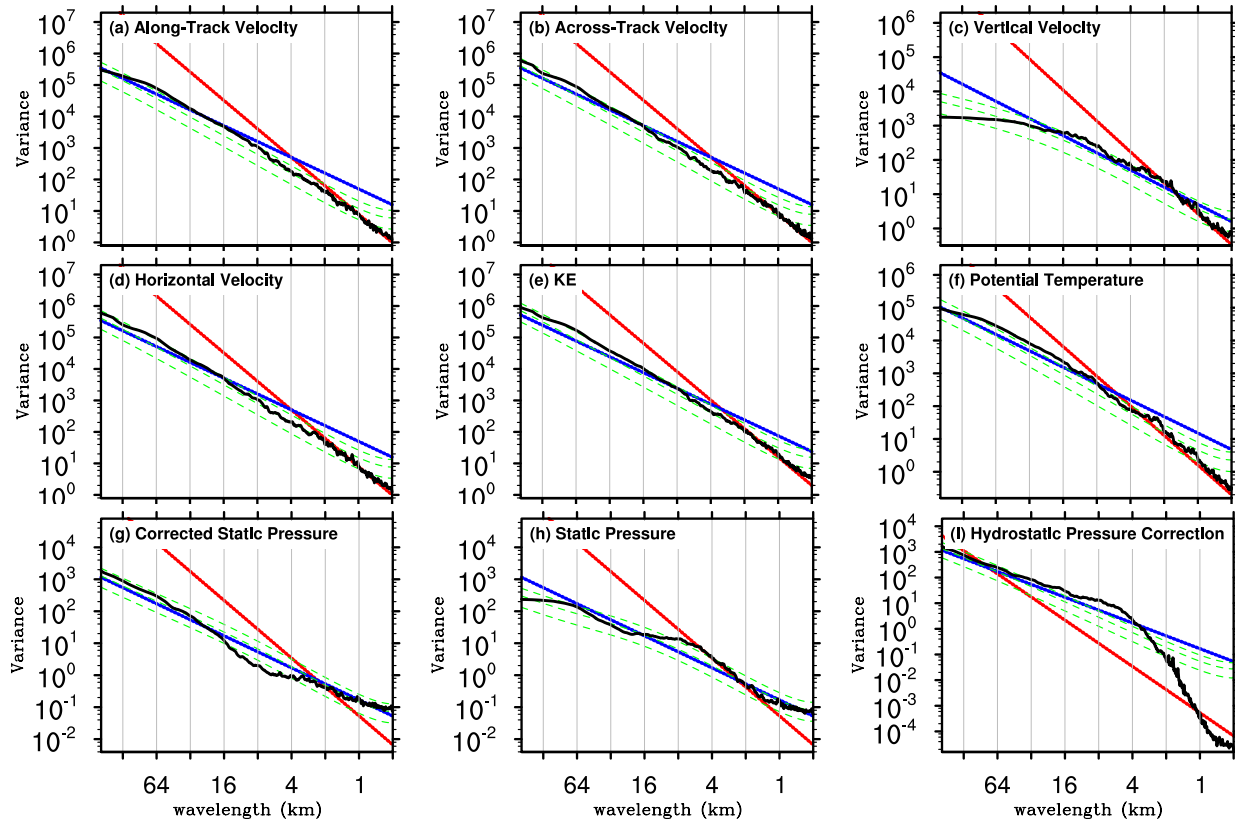
Figure R3.01 Composite spectrum (black line) of GV flight-level aircraft measurement averaging over all 68 segments in START08 (colored lines in Fig. 1): (a) along-track velocity component (unit: $m^2 s^{-2} \bullet m$), (b) across-track velocity component (unit: $m^2 s^{-2} \bullet m$), (c) vertical velocity component (unit: $m^2 s^{-2} \bullet m$), (d) horizontal velocity component (unit: $m^2 s^{-2} \bullet m$), (e) KE, (f) potential temperature (unit: $K^2 \bullet m$), (g) corrected static pressure (unit: $hPa^2 \bullet m$), (h) static pressure (unit: $hPa^2 \bullet m$), and (i) hydrostatic pressure correction (unit: $hPa^2 \bullet m$). Green lines show the composite curves of the theoretical Markov spectrum and the 5% and 95% confidence curves using the lag 1 autocorrelation. The blue (red) reference lines have slopes of -5/3 (-3). The subplot (e) KE is the sum of (a)-(c).

4

Response to Anonymous Referee #4

We thank Anonymous Referee #4 for his/her thorough and insightful comments, which are very helpful in our further revision of the manuscript. We have made every effort to address all the concerns raised. Our point-by-point response is given below.

The paper describes aircraft measurements that have been collected in the upper troposphere and lower stratosphere over the continental United States, and analyzes the gravity waves present in these measurements. One research flight of the START08 campaign was dedicated to gravity waves in the Upper Troposphere and Lower Stratosphere. This is, a priori, the first aircraft research flight dedicated to this theme. It is of interest to describe and document it. The paper shows: - that multiple events of gravity waves occured along the flight track, - both orographic and non-orographic waves are captured, - the analysis using wavelets allows to identify wave packets, but there are difficulties; part of the high frequency signal corresponds to measurement noise.

Overall, the paper leaves the impression that the analysis, even with a wealth of highresolution measurements, is difficult. Although much analysis is discussed with care, the paper leaves the reader somewhat unsatisfied. The description of the flights and the results of the spectral analysis of the measurements are valuable and of interest. Perhaps the paper in its present form contains too much information, in particular in the figures, and the reader may have difficulty in clearly singling out essential messages. I recommend publication after some revision to improve the focus of the study.

Major points

1. Many of the figures are difficult to read because they cover too much information. As an example, figure 4 contains 25 panels, each containing 6 curves... This needs to be reduced if information is to be retained from this figure. For instance, is it necessary to distinguish along and across-track spectra? They seem very similar, and unless one fears that the measurements are introducing a bias, I do not see any physical reason not to combine these into a wind speed and plot spectra for the wind speed. Whereas spectra of u_h, w, and potential temperature are common, I do not know of expectations for the spectra of static pressure. I believe one could do without this row of plots. Finally, do all the five legs of the flight really need to be plotted separately, or could some be combined or omitted?

Similarly: - figure 2 could contain less maps (e.g. 1800, 1950, 2210 and 0020UTC) - figure 5 could contain less panels (e.g. c, d, e) - figures 6 and 7 could contain less panels (e.g. horizontal velocity, w, theta for figure 6) - in each of the four figures 8, 9, 10 and 11: several curves are repeated many times, to display phase relationships (e.g. w is plotted 6 times among 9 panels!). This is excessive, there are other ways to present such information (e.g. profiles in a single plot, displaced in the vertical so as not to overlap, and with vertical lines indicating extrema (or zeros) of one reference signal...

The current manuscript attempts to generalize the characteristics and compare the differences among five selected segments in RF02. We believe that it is better to achieve this purpose by presenting an ensemble of results in one plot. In revision for Figure 4, we will try to make the black lines in front of all the other lines in order to make the plots much easier to read.

The updated Figure 4 and Figure 5 are presented as Figure R4.01 and Figure R4.02 in the current document.

In one of the earlier version of the manuscript for Zhang et al. (2015), we have tried to plot all the variables into one plot for Figure 8-10. Even though the results look readable for mesoscale examples, the plots actually look very messy for the short-scale examples. This is one of the reasons why we attempt to verify the phase relationship one by one, and to investigate the propagating characteristics from different aspects in each subplot for Figure 8-10.

2. While the figures provide too much information, it is sometimes difficult to find certain quantitative informations on the gravity waves. For example on p4733, line 27 onward: what are the largest amplitudes mentionned in the text? p4745: line 18: similarly, what are the amplitudes?

The below note will be added around line 28 on page 4733.

"The largest amplitude of w (magnitude of above 2 m/s) is during the middle portion of segment J3 (location 680-780 km) on the lee slopes of the Rocky Mountains (also see the discussion in section 5.2 on Figure 11). "

The below note will be added around line 19 on page 4745.

"…it is found that there are clear signals of significant mesoscale variations with wavelengths ranging from 50 to500 km in almost every segment of the 8 h flight (order ranging from 0.01 m/s to 1.0 m/s in vertical motion), which took place mostly in the lower stratosphere."

3. WRF simulations are used in Figure 2 to exhibit the flow configuration, but the comparison between the simulated GW and the observed ones is hardly discussed.

Figure R4.03 in this document demonstrates the comparison between aircraft measurements and high-resolution WRF simulations. Preliminary analysis shows that WRF successfully captures the variations in wind, potential temperature, and pressure, especially for segment J1, J2, J3, and M1. Probably due to upscale error growth with relatively long-time integration for segment M2, there is indeed a ~150-km distance between the observed V maximum location (at location ~400 km in M2) and the simulated one (at location ~550 km in M2). Also, the observed V maximum is larger than the simulated one (~60 m/s versus ~50 m/s). With that being said, the forecast error is within a reasonable range, and the aircraft did manage to obtain the data within the jet exit region.

86   **However, it is beyond to the scope of the current study to investigate the**
87   **consistencies and differences between aircraft measurements and WRF. WRF simulations**
88   **and dynamics of the gravity waves will be examined in a separate study. In particular,**
89   **based on the high-resolution simulations, we will investigate the sensitivity of wave**
90   **response to the mean flow speed, wind direction, wind shear, and altitude, as suggested in**
91   **the above comments.**

92

93

94   **References**

95

96   Zhang, F., J. Wei, M. Zhang, K.B. Bowman, L.L. Pan, E. Atlas, and S.C. Wofsy, 2015: Aircraft
97   measurements of gravity waves in the upper troposphere and lower stratosphere during the
98   START08 Field Experiment, Atmos. Chem. Phys. Discuss., 15, 4725-4766,
99   doi:10.5194/acpd-15-4725-2015.

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101
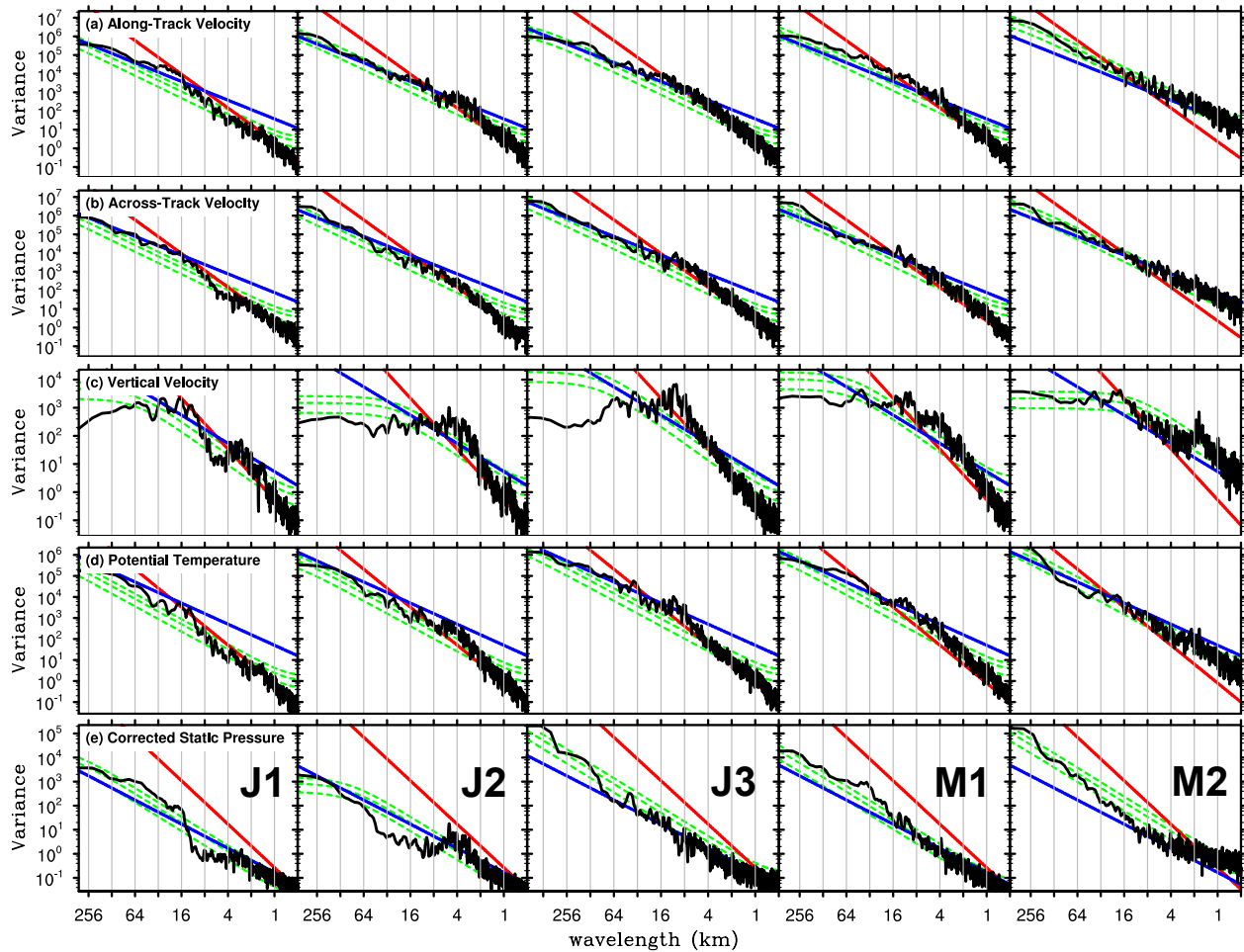
Figure R4.01 The spectrum (black line) of GV flight-level aircraft measurement during 5 selected segments (from left to right: J1, J2, J3, M1 and M2) of RF02 in START08: (a) along-track velocity component (unit: $m^2 s^{-2} \bullet m$), (b) across-track velocity component (unit: $m^2 s^{-2} \bullet m$), (c) vertical velocity component (unit: $m^2 s^{-2} \bullet m$), (d) potential temperature (unit: $K^2 \bullet m$), and (e) corrected static pressure (unit: $hPa^2 \bullet m$). Green lines show the theoretical Markov spectrum and the 5% and 95% confidence curves using the lag 1 autocorrelation. The blue (red) reference lines have slopes of -5/3 (-3).

5

Figure R4.02 Composite spectrum (black line) of GV flight-level aircraft measurement averaging over all 68 segments in START08 (colored lines in Fig. 1): (a) along-track velocity component (unit: $m^2s^{-2} \bullet m$), (b) across-track velocity component (unit: $m^2s^{-2} \bullet m$), (c) vertical velocity component (unit: $m^2s^{-2} \bullet m$), (d) horizontal velocity component (unit: $m^2s^{-2} \bullet m$), (e) KE, (f) potential temperature (unit: $K^2 \bullet m$), (g) corrected static pressure (unit: $hPa^2 \bullet m$), (h) static pressure (unit: $hPa^2 \bullet m$), and (i) hydrostatic pressure correction (unit: $hPa^2 \bullet m$). Green lines show the composite curves of the theoretical Markov spectrum and the 5% and 95% confidence curves using the lag 1 autocorrelation. The blue (red) reference lines have slopes of -5/3 (-3). The subplot (e) KE is the sum of (a)-(c).

Figure R4.03 Comparision between GV flight-level aircraft measurements and WRF simulations during 5 selected segments (from left to right: J1, J2, J3, M1 and M2) of RF02 in START08: (a) along-track velcotiy component (m/s), (b) across-track velocity component (m/s), (c) horizontal wind speed (m/s), (d) vertical velocity component (m/s), (e) potential temperature (K), and perturbation of corrected static pressure (hPa). The grey lines represent the flight measurements with 250-m resolution, the blue lines represents 20-point running mean of the grey lines, and red lines represents the WRF simulations derived from D4 (1.67-km horizontal resolution) with 10-minute time interval. The series in segment J3 and M2 are reversed to facilitate the comparison with J1+J2 and M1, respectively. The distance between minor tick marks in x axis is 100 km. The perturbations in (f) are defined as the differences between the original data and their mean from their corresponding segments.

1   **Aircraft Measurements of Gravity Waves in the Upper Troposphere and Lower**

2   **Stratosphere during the START08 Field Experiment**

3

4   Fuqing Zhang[1*], Junhong Wei[1], Meng Zhang[1], Kenneth P. Bowman[2], Laura L. Pan[3], Elliot

5   Atlas[4], and Steve C. Wofsy[5]

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26   **Abstract**

27   This study analyzes *in-situ* airborne measurements from the 2008 Stratosphere-Troposphere

28   Analyses of Regional Transport (START08) experiment to characterize gravity waves in the

29   extratropical upper troposphere and lower stratosphere (ExUTLS) region. The focus is on the

30   second research flight (RF02), which took place on 21-22 April 2008. This was the first airborne

31   mission dedicated to probing gravity waves associated with strong upper-tropospheric jet-front

32   systems. Based on spectral and wavelet analyses of the *in-situ* observations, along with a

33   diagnosis of the polarization relationships, clear signals of mesoscale variations with

34   wavelengths ~50-500 km are found in almost every segment of the 8-hr flight, which took place

35   mostly in the lower stratosphere. The aircraft sampled a wide range of background conditions

36   including the region near the jet core, the jet exit and over the Rocky Mountains. In contrast to

37   the long wavelength mesoscale variations, smaller-scale wavelike oscillations below 50 km are

38   found to be quite transient. In particular, aircraft measurements of several flight segments are

39   dominated by signals with sampled periods of ~20-~60 seconds and wavelengths of ~5-~15 km

40   (assuming that the typical flight speed is approximately 250 m/s). We speculate that at least part

41   of these nearly-periodic high-frequency signals are a result of intrinsic observational errors in the

42   aircraft measurements or small-scale flight-altitude fluctuations that are difficult to fully

43   characterize. Despite the presence of possibly spurious wave oscillations in several flight

44   segments, the power spectra of horizontal winds and temperature averaged over the analyzed

45   START08 flight segments generally follow the -5/3 power law.

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1. Introduction

One of the challenges to understanding the extratropical upper troposphere and lower stratosphere (ExUTLS) is that dynamical processes with a wide range of scales occur in the region. Gravity waves, in particular, are known to play a significant role in determining the structure and composition of the ExUTLS. Tropopause jets and fronts are significant sources of gravity waves (O'Sullivan and Dunkerton 1995; Reeder and Griffins 1996; Zhang 2004; Wang and Zhang 2007; Mirzaei et al. 2014; Wei and Zhang 2014, 2015), along with surface topography (Smith 1980) and moist convection (Lane et al. 2001). Gravity waves above the jet may be responsible for double or multiple tropopauses (Yamanaka et al. 1996; Pavelin et al. 2001) and may contribute to layered ozone or PV structures (Bertin et al. 2001). Also, strong horizontal and vertical shear in the layer and the discontinuity in static stability at the tropopause provide a favorable environment to reflect, capture, break and dissipate gravity waves generated in the lower troposphere, such as those produced by surface fronts (Plougonven and Snyder 2007). Gravity wave breaking and wave-induced turbulence (e.g., Koch et al. 2005) can contribute significantly to mixing of trace gases in the ExUTLS, thereby affecting chemical composition (Vaughan and Worthington, 2000). Also, convectively-generated gravity waves may extend the impact of moist convection far above cloud tops through wave-induced mixing and transport (Lane et al. 2004).

In particular, mesoscale gravity waves with horizontal wavelength of ~50-~500 km are known to occur in the vicinity of unbalanced upper-tropospheric jet streaks and on the cold-air side of surface frontal boundaries (Uccellini and Koch 1987; Plougonven and Zhang 2014). This phenomenon has been identified repeatedly in both observational studies (Uccellini and Koch 1987; Schneider 1990; Fritts and Nastrom 1992; Ramamurthy et al. 1993; Bosart et al. 1998;

72 Koppel et al. 2000; Rauber et al. 2001; Plougonven et al. 2003) and numerical investigations of

73 the observed cases (Powers and Reed 1993; Pokrandt et al. 1996; Kaplan et al. 1997; Zhang and

74 Koch 2000; Zhang et al. 2001, 2003; Koch et al. 2001, 2005; Lane et al. 2004). In addition,

75 idealized simulations of dry baroclinic jet-front systems in a high-resolution mesoscale model

76 have been performed to investigate the generation of mesoscale gravity waves (Zhang 2004), the

77 sensitivity of mesoscale gravity waves to the baroclinicity of jet-front systems (Wang and Zhang

78 2007), and the source of gravity waves with multiple horizontal scales (Lin and Zhang 2008).

79 Most recently, Wei and Zhang (2014, 2015) studied the characteristics and potential source

80 mechanisms of mesoscale gravity waves in moist baroclinic jet-front systems with varying

81 degree of convective instability.

82   Advances in space technology provide the means to observe gravity waves in detail.

83 Recent studies have demonstrated that satellites such as Microwave Limb Sounder (MLS) and

84 Advanced Microwave Sounding Unit-A (AMSU-A) offer quantitative information of gravity

85 waves in the middle atmosphere (Alexander and Rosenlof 2003; Wu and Zhang 2004; Zhang et

86 al. 2013). In addition to satellite measurements, gravity waves are also observed by surface

87 observations (Einaudi et al. 1989; Grivet-Talocia et al. 1999; Koppel et al. 2000), high-resolution

88 radionsonde networks (Vincent and Alexander 2000; Wang and Geller 2003; Zhang and Yi

89 2007; Gong and Geller 2010), radars (Vaughan and Worthington 2000, 2007), and super-

90 pressure balloons (Hertzog and Vial 2001).

91   Among the abovementioned observational tools, aircraft have also been widely used as

92 *in-situ* measurements of gravity waves. Probably since Radok (1954), which was one of the first

93 observations of mountain waves with aircraft, past aircraft field campaigns have mainly focused

94 on terrain-induced gravity waves (Radok 1954; Vergeiner and Lilly 1970; Lilly and Kennedy

95   1973; Smith 1976; Karacostas and Marwitz 1980; Brown 1983; Moustaoui et al. 1999;

96   Leutbecher and Volkert 2000; Poulos et al. 2002; Dornbrack et al. 2002; Doyle et al. 2002;

97   Smith et al. 2008). The recent Terrain-Induced Rotor Experiment (T-REX) in March-April 2006

98   (Grubišić et al. 2008) was the first full research project to use the National Science Foundation

99   (NSF) – National Center for Atmospheric Research (NCAR) Gulfstream V (GV) (Laursen et al.

100 2006), which has better Global Positioning System (GPS) accuracy than the previous versions.

101 The National Aeronautics and Space Administration (NASA) high-altitude ER-2 research

102 aircraft was also employed during the recent Cirrus Regional Study of Tropical Anvils and

103 Cirrus Layers Florida Area Cirrus Experiment (CRYSTAL-FACE) (Jensen et al. 2004), which

104 conducted research flights in the vicinity of sub-tropical and tropical deep convection to study

105 the effects of convectively generated gravity waves (Wang et al. 2006). However, systematic *in-*

106 *situ* measurements of mesoscale gravity waves, especially those associated with upper-

107 tropospheric jet-front systems in the ExUTLS are very scarce. Relevant work includes Nastrom

108 and Fritts (1992) and Fritts and Nastrom (1992), who used commercial aircraft measurements to

109 infer the different sources of gravity waves (convections, front, topography, and jet streaks).

110 They found that mesoscale variances of horizontal wind and temperature were large at the jet-

111 front vicinity regions. However, little is known quantitatively about the generation mechanisms,

112 propagation and characteristics of gravity waves associated with the tropospheric jet streaks.

113 This is due in part to the fact that gravity waves are transient in nature and hard to resolve with

114 regular observing networks (Zhang et al. 2004).

115   The recent Stratosphere-Troposphere Analyses of Regional Transport 2008 (START08)

116 experiment was conducted to examine the chemical structure of the ExUTLS in relation to

117 dynamical processes spanning a range of scales (Pan et al. 2010). In particular, one specific goal

4

118   of START08 was to observe the properties of gravity waves generated by multiple sources,

119   including jets, fronts, and topography. During the START08 field campaign, a total of 18

120   research flight (RF) missions were carried out during April-June 2008 from the NCAR aviation

121   facility in Broomfield, Colorado (also see the online field catalog of the 18 RFs at

122   http://catalog.eol.ucar.edu/start_08/missions/missions.html). The second flight (RF02), which

123   occurred on 21-22 April 2008, was dedicated, to our knowledge for the first time, to probing

124   mesoscale gravity waves associated with a strong upper-tropospheric jet-front system, even

125   though some previous studies may have recognized the presence of these waves (e.g., Shapiro

126   and Kennedy 1975; Koch et al. 2005). Although only one flight specifically targeted gravity

127   waves, many of the other flights during START08 obtained high-quality observations of gravity

128   waves in the ExUTLS under a wide range of meteorological conditions. This study is an analysis

129   of the gravity wave observations from the START08 mission.

130   A brief description of the experimental design for RF02 and its corresponding

131   meososcale simulation are presented in section 2, followed in section 3 by a review of the flight-

132   level measurements. Section 4 investigates the localized wave variance with wavelet analysis

133   and examines the polarization relationship based on cospectrum/quadraspectrum analysis.

134   Several examples of wave-like variances are shown and discussed in section 5. Section 6

135   contains a summary.

136

137   **2. Experimental design**

138   The GV research aircraft is ideally suited for investigating gravity waves in the ExUTLS

139   region. The flight ceiling of the aircraft is about 14 km with the START08 payload, which

140   enables sampling the vertical structure of the ExUTLS. With a typical flight speed of ~250 m/s at

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142 cruise altitude, the flight duration of ~8 hours for a single flight enables the GV to sample a large

143 geographic area with high-resolution (1-Hz) *in-situ* observations. A total of 68 flight segments

144 (color lines in Fig. 1) during the START08 are selected for analysis (also see Fig. 2 in Pan et al.

145 2010 for GV ground tracks of the 18 RFs). Each of these flight segments is longer than 200 km

146 and has near-constant flight-level static pressure and a relatively straight path. This will largely

147 eliminate spurious wave variance due to rapid changes in direction or altitude. In particular, the

148 RF02 mission was conducted over the central United States (38.87-51.10°N, 94.00-109.95°W) to

149 study the gravity wave excitation from a jet-front system and topography in the ExUTLS (Fig. 2

150 and Table 1). It started at 17:53 UTC on 21 April 2008 and finished at 02:54 UTC on 22 April

151 2008. This ~8-hour flight covered a total horizontal distance of ~6700 km, mostly in the lower

152 stratosphere. Five flight segments (thick blue lines in Fig. 1; thick blue lines in Fig. 2b-Fig. 2f;

153 details in section 3) in RF02 are used here. For most of the 5 flight segments, the aircraft flew at

154 an altitude of ~12.5 km (red lines in Fig. 3d; Table 1) and at a speed of ~250 ms^{-1} (Table 1).

155   The Weather Research and Forecast (WRF) model (Skamarock et al. 2005) was used for

156 flight-planning forecasts. Real-time forecasts used WRF version 2.2.1 and were run with 45-km

157 and 15-km grid spacing for single deterministic forecasts (D1 and D2 in Fig. 1) and 45-km grid

158 spacing for ensemble prediction (D1 only). The model was initialized with a 30-member

159 mesoscale ensemble-based multi-physics data assimilation system (Zhang et al. 2006; Meng and

160 Zhang 2008a,b) and assimilated standard radiosonde observations. The real-time WRF forecasts

161 were archived at the START08 field catalog (http://catalog.eol.ucar.edu/cgi-

162 bin/start08/model/index). The flight track of RF02 was assigned to fly across the jet exit region

163 and gravity wave active area predicted by the real-time forecasts (also see Fig. 11 in Pan et al.

164 2010 for the real-time mesoscale forecast of gravity waves). Higher-resolution post-mission

165   WRF simulations with 5-km and 1.67-km grid spacing (D3 and D4 in Fig. 1) were also

166   conducted to examine the role of small-scale dynamical processes (e.g., convection and gravity

167   waves), which will be briefly reported in section 3. Nevertheless, an in-depth investigation of the

168   gravity wave dynamics based on the high-resolution post-mission WRF simulations is beyond

169   the scope of the current study, and will be reported elsewhere.

170

171   **3. Overview of the flight-level measurements**

172   Figure 2 depicts the track design of the entire flight and five flight segments during RF02,

173   along with the horizontal wind speed and the smoothed horizontal divergence near the flight

174   level simulated by the high-resolution post-mission WRF simulations valid at different

175   representative times of each five segments. Three flight segments pass mainly along an upper-

176   tropospheric jet streak. These are labeled J1, J2, and J3 and are displayed in Fig. 2b, 2c, and 2d,

177   respectively. Two other flight segments cross the mountains and high plains of Colorado and

178   Kansas. These are labeled M1 and M2 and are displayed in Fig. 2e and 2f, respectively. Flight

179   segment J3 is the longest during RF02. That segment includes flight through or above: the jet

180   core (gray shading in Fig. 2), a jet over high mountains (see the terrain map in Fig. 1), the exit

181   region of the jet, and a surface cold front (not shown). The other two segments, J1 and J2, were

182   intended to be a single segment, but an altitude change was necessary due to air traffic control.

183   Guided by the WRF model forecasts (e.g., Fig. 11 in Pan et al. 2010), this GV flight

184   mission sampled WRF-predicted gravity waves with different potential sources including

185   imbalance of jet streak and orographic forcing. Figure 3 shows the along-track horizontal

186   velocity component (u), across-track horizontal velocity component (v), horizontal wind speed

187   (V; $V = \sqrt{u^2 + v^2}$), vertical velocity component (w), potential temperature (θ), corrected static

188   pressure (p_c), static pressure (p_s), hydrostatic pressure correction (p_h) derived from the airborne

189   *in-situ* measurements as well as flight height, and terrain along each of the five flight segments.

190   To facilitate spectral and wavelet analyses of these measurements, each variable from the 1-Hz

191   aircraft measurement along the flight segment is linearly interpolated into 250-m spatial series

192   with fixed resolution in distance. The right-hand rule is used to determine the relationships

193   among the positive along-track directions, the positive across-track directions, and the positive

194   vertical directions. For segments J1, J2, and J3, the positive along-track (across-track) directions

195   are all approximately toward the northeast (northwest). For segments M1 and M2, the positive

196   along-track (across-track) directions are both approximately toward the east (north). The

197   corrected static pressure p_c is calculated using the formula of Smith et al. (2008, their equation

198   12):

199
$$p_c = p_s + p_h = p_s + \bar{\rho}g(z - z_{ref}) \quad (1)$$

200   where z is the GPS altitude, z_{ref} is the average altitude of flight segment and $\bar{\rho}$ is the average

201   density of flight segment. Corrected static pressure p_c from equation 1 is to correct the measured

202   static pressure p_s to a common height level (i.e., z_{ref}) based on the assumption of local

203   hydrostatic balance. Smith et al. (2008) suggests that the contribution of p_s to p_c is much smaller

204   than p_h, because it is assumed that the aircraft almost flies on an isobaric surface.

205   Consistent with what was predicted by the real time WRF forecast guidance (as shown in

206   Fig.11 of Pan et al. 2010) as well as simulated by the high-resolution post-mission WRF

207   simulations (in particular the horizontal divergence as potential signals of gravity waves as

208   shown in Fig. 2), the GV *in-situ* measurements of different atmospheric variables suggest there

209   are prevalent gravity wave activities along almost every leg of the 8-hr flight, most notably in the

210   vertical motion field. The largest amplitude of w (over 2 m/s) is during the middle portion of

8

211 segment J3 (location 680-780 km) on the lee slopes of the Rocky Mountains (also see the

212 discussion in section 5.2). The high terrain and the lee slopes also have the enhanced vertical

213 motions for both segment M1 and segment M2. Though not as large in amplitude, enhanced

214 fluctuations of vertical motions are also observed in the northern end of segment J3, which is in

215 the exit region of the upper-level jet streak and above the surface front. The enhanced variances

216 of vertical motion, accompanied by the changes in horizontal wind and potential temperature,

217 may be associated with topography for both M1 and M2 segments, even though the role of jet

218 cannot be isolated.

219　　　Power spectra of five selected aircraft measurement variables are given in Fig. 4 for each

220 of the five flight segments during RF02. The calculations of the spectra are performed with the

221 "specx_anal" function in the NCAR Command Language (NCL). Several steps are done before

222 the calculations. Firstly, the mean and least squares linear trend in each of the series are

223 removed. Secondly, smoothing by averaging 7 periodogram estimates is performed. Thirdly,

224 10% of the series are tapered. For segment J1, u, v, θ and p_c have several significant spectral

225 peaks for wavelengths ranging from 16-128 km (mesoscales). The statistically significant

226 spectral peaks in w are more for smaller scales, one at 2-4 km, and the other at 8-32 km. The

227 spectral characteristics for segment J2 are mostly the same as J1 except for much less power at

228 longer wavelengths (16-128 km) and only one peak at smaller scales (2-8 km). For segment J3,

229 both u and θ have statistically significant spectral peaks at mesoscales (~50 and 128 km) and at

230 smaller scales (8-16 km), the later (not the former) of which is also very pronounced for the w

231 spectrum. No significant spectral peak is found for the corrected static pressure p_c for segment

232 J3, except at 512 km, which is likely a reflection of the sub-synoptic scale pressure patterns at

233 the flight level (Fig. 2d). For segment M1, there is a significant mesoscale spectral peak at

9

236   around 32-64 km for u, θ and p_c, while smaller-scale variations from 4-16 km are also

237   significant for nearly all variables except for p_c. There are almost no significant spectral peaks

238   for all 5 variables for segment M2 except for around 2 km for w.

239   Past studies from both aircraft observations (e.g., Nastrom and Gage 1985; Bacmeister et

240   al. 1996; Lindborg 1999) and numerical simulations (e.g., Skamorcok 2004; Waite and Snyder

241   2013) have revealed/verified the existence of an approximate -5/3 power law that is expected for

242   the direct energy cascade in isotropic three-dimensional turbulence (e.g., Kolmogorov 1941) and

243   the inverse cascade in two dimensions (e.g., Kraichnan 1967), as well as an approximate -3

244   power law that is expected for quasigeostrophic turbulence theory (e.g., Charney 1971). The

245   spectral slopes of different variables derived from the flight-level measurements from START08

246   are thus examined here in detail. Overall in segment J3, the spectrum slope for θ (the third

247   column in Fig. 4d) is remarkably similar to those for u (the third column in Fig. 4a) and v (the

248   third column in Fig. 4b), except that there appears to be a deviation from both -3 and -5/3 power

249   laws for scales of ~8-~16 km. The spectral slope of w (the third column in Fig. 4c) is also similar

250   to that of θ (the third column in Fig. 4d) for all scales below 32 km, including the above-

251   mentioned deviation. However, for scale larger than ~32 km, the slope of w (the third column in

252   Fig. 4c) quickly dropped to almost zero, which is consistent with the continuity equation for

253   near-balanced non-divergent large-scale motions.

254   There are also similarities and differences in spectral slopes among different flight

255   segments depicted in Fig. 4. For example, the above-mentioned spectral shapes of u and v from

256   segment J3 are similar to those from segment J2 (i.e., the second and third columns in Fig. 4a

257   and Fig 4b). Such consistent signals probably result from sampling under similar large-scale

258   background flow at similar flight altitude with almost identical topography, especially between

10

259   the adjacent flight segments J1+J2 and J3. Despite the overall resemblance among the flight

260   segments of RF02, there are some unique characteristics in the power spectral distributions for

261   individual segments. For segments M1 and M2, for example, (i.e., the fourth column versus the

262   fifth column in Fig. 4), the slopes of u and v during segment M1 are approximately consistent

263   with a -3 power law for the scale of ~0.5-~8 km, while those during segment M2 follows a -5/3

264   power law instead. This is probably associated with the fact that segment M2 successfully

265   captures a rapid decrease in u (from ~65 m/s to ~40 m/s) while segment M1 has no such a

266   dramatic reduction in u (the fourth column in Fig. 3a versus the fifth column in Fig. 3a). Note

267   that the aircraft during segment M1 flew away from the jet core region, as the jet was still

268   moving eastward to the downhill side of the topography. In contrast, the aircraft during segment

269   M2 flew directly toward the approaching jet core at a lower flight level than segment M1 (the

270   fourth column in Fig. 3d versus the fifth column in Fig. 3d), and the observed decline of u (i.e., a

271   potential jet exit region) is located roughly on the downhill side of the topography (the fifth

272   column in Fig. 3d). This suggests that the spectral slopes for the aircraft measurements can, in

273   fact, be extremely sensitive to changes in the background flow, even though sampling takes place

274   in the same area only a few hours apart.

275   Figure 5 shows composite spectra for eight selected variables averaged over 68 flight

276   segments. Unsurprisingly, the composite spectra are much smoother due to averaging. For u

277   (Fig. 5a), v (Fig. 5b), and horizontal wind speed V (Fig. 5d), the slope of the power spectra are

278   consistent with a -5/3 power law for scales above ~8-~16 km. For w (Fig. 5c), its spectral slope

279   is generally consistent with -3 power laws for the scale of ~0.5-~2 km but is nearly zero for

280   scales over 32 km, while the slopes in between (~2-~32 km) appear to follow an approximate -

281   5/3 power law, with a statistically significant spectral peak at ~8-16 km. Even though the kinetic

11

285   energy spectra (Fig. 5e) may show a -5/3 slope that covers a larger range, the -3 slope over small

286   scale in KE is still evident. For θ (Fig. 5f) at scales between ~0.5 km and ~2 km, its slope also

287   obeys a -3 power law. For θ (Fig. 5f) at the scale greater than ~8-~16 km, the slope of power

288   spectrum tends to have a -5/3 slope, which is similar to u (Fig. 5a), v (Fig. 5b), and V (Fig. 5d)

289   for the same scales. For all the three pressure-related variables (i.e., p_c in Fig. 5g, p_s in Fig. 5h,

290   p_h in Fig. 5i), their slopes generally fall around a -5/3 power law, except for scales less than ~4

291   km in p_h (Fig. 5i). However, it is noteworthy that there is a sudden concavity (convexity) in p_c

292   (p_s or p_h) for scales between ~4 km and ~16 km (also see the discussion in section 5.3).

293

294   **4. Wavelet analysis**

295   *4.1 Single-variable wavelet analysis*

296   Standard spectral analysis methods characterize the variance as a function of wavelength

297   for an entire data record (flight segment), but do not indicate where variance of a particular

298   wavelength is located within the data record. We use wavelet analysis to complement the

299   spectral analysis in section 3 to study the variance as a function of wavelength within the five

300   flight segments from RF02. A Morlet wavelet function is employed in this study (e.g., Torrence

301   and Compo 1998; Zhang et al. 2001; Woods and Smith 2010). This is a continuous wavelet

302   transform that uses non-orthogonal complex wavelet functions comprising a plane wave

303   modulated by a Gaussian function (e.g., equation 1 in Torrence and Compo 1998):

304    $$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2} \quad (2)$$

305   where ω_0 is the dimensionless wave number and η is the dimensionless distance. Here ω_0 is set

306   to 6 to satisfy the admissibility condition (Farge 1992). The continuous wavelet transform, used

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314   to extract localized spectral information, is defined as the convolution of the series of interest x

315   with the complex conjugate of the wavelet (e.g., equation 2 in Torrence and Compo 1998)

316    $$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \psi^* \left[\frac{(n'-n)\Delta x}{s} \right] \quad (3)$$

317   where * is the complex conjugate, n is the localized position index, s is the wavelet scale, and

318   Δx is the resolution of the data (0.25 km in this case). The cone of influence (COI) shows the

319   region of the wavelet spectrum where the edge errors cannot be ignored. Computation of the

320   wavelet spectrum and edge error is performed with the wavelet function of equation 3 (Torrence

321   and Compo 1998) in NCL.

322   Figure 6 contains the wavelet power spectra of five selected observed variables along the

323   five selected flight segments of RF02. Using the long segment J3 as an example again (third

324   column in Fig. 6), there is a substantial peak in the power of u (Fig. 6a) at wavelengths around

325   128-km between 400 and 700 km along the flight leg (also seen in p_c of Fig. 6e); ~100-km wave

326   power peaks at location 100-300 km; the wave power of wavelength from ~64 km to ~128 km

327   also peaks at location 1200-1400 km. The greatest similarity is between the spectra of w and θ

328   (Figs. 6c and d). For example, from location 100 km to 800 km during segment J3, local

329   maximum of power in w (the third column in Fig. 6c) resembles the one in θ (the third column

330   in Fig. 6d). In particular, three distinguished wave modes (~64 km, ~32 km, and ~10 km in

331   along-track wavelength) collocate at location 600-800 km (downstream of a localized hill around

332   600 km in the third column of Fig. 3d). Relatively persistent ~10-km waves in w are shown at

333   location 200-700 km, which corresponds to a similar peak in the spectral analysis of w in the

334   third column of Fig. 4c. Note that such ~10-km waves are also found in other flight segments in

335   RF02 (e.g., location 0-600 km during segment M1, the fourth column in Fig. 6c) and other

13

338 research flights in START08 (not shown). Interpretations of such small-scale localized wave

339 variances, as well as mesoscale localized wave variances, are discussed in section 5.

340

341 *4.2 Polarization relationships from cross-wavelet analysis*

342   Following Woods and Smith (2010), the phase relationship between two variables (e.g., u

343 and v, hereafter in short noted as $(u'v')_p$) can be determined from the cospectrum $(u'v')_c$ and

344 quadrature spectrum $(u'v')_q$, which are defined as (also see section 6c in Torrence and Compo

345 1998; equation 8 and appendix A in Woods and Smith 2010):

346 $$(u'v')_c = Re\{U_n(s_j)V_n^*(s_j)\} \quad (4)$$

347 $$(u'v')_q = Im\{U_n(s_j)V_n^*(s_j)\} \quad (5)$$

348 where U_n and V_n represent the wavelet transforms of u and v from equation 3, $U_n(s_j)V_n^*(s_j)$ is

349 the complex-valued cross-wavelet spectrum, while $Re\{\ \}$ and $Im\{\ \}$ represent the real and

350 imaginary parts of the variables inside the parentheses, respectively. Woods and Smith (2010)

351 focus on the energy flux by analyzing $(p_c'w')_c$ from equation 4 for vertically propagating waves

352 and $(p_c'w')_q$ from equation 5 for vertically trapped/ducted waves. In principle, $(p_c'w')_p$ should

353 be, theoretically speaking, associated with $(u'w')_p$ $((v'w')_p)$ (e.g., Eliassen and Palm 1960;

354 Lindzen 1990). This is particularly true for stationary mountain waves, which may be present for

355 RF02 given complex topography during each of the flight segments. However, in practice,

356 Woods and Smith (2010, their section 7) argued that the perturbation longitudinal velocity was

357 noisier than pressure in their study. In addition to equation 4 and equation 5, one can also define

358 the absolute coherence phase angle as $\frac{180}{\pi}\times arctan\left(\left|\frac{Im\{U_n(s_j)V_n^*(s_j)\}}{Re\{U_n(s_j)V_n^*(s_j)\}}\right|\right)$ (also see section 6d in

359 Torrence and Compo 1998).

14

360   The phase relations among multiple variables are examined to further explore whether the

361   enhanced variances from the spectral and wavelet analyses are vertically propagating gravity

362   waves. Figure 7 shows three selected examples of cospectrum analysis (i.e., $(u'w')_c$ in Fig. 7a,

363    $(v'w')_c$ in Fig. 7b, $(p_c'w')_c$ in Fig. 7c), one selected example of quadrature spectrum analysis

364   (i.e., $(\theta'w')_q$ in Fig. 7d), and one example of absolute coherence phase angle for $(\theta'w')_p$ (Fig.

365   7e). In the case of a single monochromatic internal gravity wave propagating vertically, for

366    $(u'w')_c$ (Fig. 7a), positive (negative) values indicate upward (downward) flux of along-track

367   momentum. For $(v'w')_c$ (Fig. 7b), positive (negative) values indicate upward (downward) flux

368   of across-track momentum. For $(p_c'w')_c$ (Fig. 7c), positive (negative) values indicate positive

369   (negative) vertical energy transport. For the quadrature spectrum of $(\theta'w')_q$ (Fig. 7d), values

370   should be nonzero while the absolute coherence phase angle of $(\theta'w')_p$ (Fig. 7e) should be close

371   to 90 degree.

372   We again take segment J3 as an example (the third column in Fig. 7): for the small-scale

373   component with along-track wavelength less than 50 km (horizontal solid line), enhanced but

374   incoherent variances are detected for location 100-500 km and for location 600-800 km, with

375   fluctuating positive and negative values for both $(u'w')_c$ (the third column in Fig. 7a) and

376    $(v'w')_c$ (the third column in Fig. 7b). The variations in the signs of vertical transports of

377   horizontal momentum fluxes imply that this flight segment is sampling waves propagating in

378   both forward and backward direction, assuming the vertical energy transports are generally

379   upward. Correspondingly, the absolute coherence phase angle for $(u'v')_p$ (not shown) also

380   alternates frequently between nearly 0 degree and nearly 90 degree. In particular, some of the

381   enhanced variances in the cospectra for along-track wavelengths from ~4 km to ~16 km, though

382   fluctuating in signs, are significant above the 95% confidence level.

15

383   For the mesoscale component with wavelengths from ~50 to ~100 km, remarkable

384   localized quadrature variance is found in $(\theta'w')_q$ (the third column in Fig. 7d) for location 500-

385   800 km, consistent with the wavelet analysis of w in the third column of Fig. 6c and θ in the

386   third column of Fig 6d. The absolute coherence phase angle for $(\theta'w')_p$ in Fig. 7e also

387   demonstrate that the cross-wavelet spectrum between θ and w is mostly dominated by their

388   quadrature spectrum (red color shading in Fig. 7e), though there are some exceptions (blue color

389   shading in Fig. 7e).

390   The similarities/discrepancies among different wavelet cospecta and quadrature spectra

391   examined in Fig. 7 demonstrate the difficulties in gravity wave identification and the

392   uncertainties in gravity wave characteristics estimation based solely on aircraft measurements.

393   In addition to cross-wavelet analysis, the signs of the net fluxes (e.g., $\overline{u'w'}$, $\overline{v'w'}$, and

394    $\overline{w'p_c'}$) at each wavelength can also be estimated by the cospectrum analysis based on Fourier

395   transform over the entire segment (not shown). Generally speaking, for the scale below ~32 km,

396   both positive values and negative values are important in $\overline{u'w'}$ and $\overline{v'w'}$, while positive $\overline{w'p_c'}$

397   appears to be more continuous than negative $\overline{w'p_c'}$. For the scale above ~32 km, negative $\overline{u'w'}$

398   (positive $\overline{w'p_c'}$) appears to be more continuous than positive $\overline{u'w'}$ (negative $\overline{w'p_c'}$), while there

399   is no dominant sign for $\overline{v'w'}$ one way or the other.

400

401 **5. Selected Wave-like Examples: signal of gravity waves or measurement noise?**

402   This section examines several examples of wave-like variations during segment J3 in

403   more detail. Bandpass-filtered values of selected variables are computed by synthesizing the

16

404 wavelet transform using wavelets with scales between j_1 and j_2 using (e.g., equation 29 in

405 Torrence and Compo 1998)

$$x_n' = \frac{\Delta j \Delta x^{1/2}}{C_\delta \psi_0(0)} \sum_{j=j_1}^{j_2} \frac{Re\{W_n(s_j)\}}{s_j^{1/2}} \quad (6)$$

407 where Δj is the scale resolution and C_δ is a reconstruction factor taken as 0.776 for Morlet

408 wavelet. The wavelet-based filter in equation 6 has the advantage in removing noise at each

409 wave number and isolating single events with a broad power spectrum or multiple events with

410 different wave number (Donoho and Johnstone 1994; Torrence and Compo 1998).

411   Nine pairs of variables, including $(u'w')_p$, $(v'w')_p$, $(u'v')_p$, $(p_c'u')_p$, $(p_c'v')_p$,

412 $(p_c'w')_p$, $(\theta'w')_p$, $(p_s'w')_p$, and $(p_h'w')_p$, are selected to examine whether the phase

413 relationship of the variations in the airborne measurements is consistent with the linear theory for

414 gravity waves. Generally speaking, the phase relation between two variables can be classified

415 into two major categories: 1) In-phase or out-of-phase relationships, in which one variable leads

416 or lags the other variable by approximately 0° or 180°; 2) Quadrature relationships, in which one

417 variable leads or lags the other by approximately 90°.

418   The phase relationships for linear gravity waves are determined by theory and their

419 propagation characteristics. Take $(u'w')_p$, $(v'w')_p$, and $(p_c'w')_p$ as examples, if they have an

420 in- or out-of-phase relationship, the waves are propagating in the vertical direction; if they have a

421 quadrature relationship, the waves do not propagate vertically and may be trapped or ducted.

422 Take $(u'v')_p$ as another example, if they have an in- or out-of-phase relationship, the waves may

423 be internal gravity waves whose intrinsic frequencies are much higher than the Coriolis

424 frequency; if they have a quadrature relationship, the waves may be inertio-gravity waves with

425 intrinsic frequencies close to the Coriolis frequency. For vertically propagating linear gravity

426 waves, $(\theta'w')_p$ should have a quadrature relationship. According to Smith et al. (2008), p_h'

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427 should dominate over p_s', if the aircraft almost flies on a constant pressure surface.

428 Consequently, $(p_h'w')_p$ should be almost identical to $(p_c'w')_p$.

429

430 *5.1 Examples of mesoscale wave variances*

431   Figure 8 demonstrates an example of potential mesoscale gravity waves selected based on

432 the wavelet analysis of u (Fig. 6a), w (Fig. 6c), θ (Fig. 6d), and p_c (Fig. 6e) for location 250-360

433 km in segment J3 (the exit region of northwesterly jet in Fig. 2d). The wave signals are further

434 highlighted by applying a wavelet-based filter (i.e., equation 6) to extract wavelike variations

435 with along-track wavelength between 100 and 120 km. Panels a, b, d, and e show out-of-phase

436 relationships for $(u'w')_p$, $(v'w')_p$, $(p_c'u')_p$, and $(p_c'v')_p$ respectively; while panels c, f, and i

437 show in-phase relationships for $(u'v')_p$, $(p_c'w')_p$, and $(p_h'w')_p$. Panels g and h show

438 quadrature relationships for $(\theta'w')_p$ and $(p_s'w')_p$. The observed phase relations shown in Fig. 8

439 are generally consistent with linear theory for propagating monochromatic gravity waves, as

440 indicated by the cospectrum/quadrature spectrum analysis in Fig. 7. These signals are likely to be

441 internal gravity waves (due to the in-phase relation of $(u'v')_p$ in Fig. 8c) with positive vertical

442 group velocity (due to their positive vertical energy flux, Fig. 8f).

443   In contrast, Figure 9 is an example of wave-like disturbances that lacks a clear,

444 propagating, linear-wave, phase relationship. This example is also selected based on the wavelet

445 analysis of segment J3 for u, v, and p_c (Figs. 6a, b, and e) for along-track wavelength near 128

446 km and location between 560 and 688 km along the segment. This segment lies above the

447 complex topography as depicted in the third column of Fig. 3d. According to Figs. 9a-9e,

448 $(u'w')_p$, $(u'v')_p$, and $(p_c'u')_p$ seem to have out-of-phase relationships, while $(v'w')_p$ and

449 $(p_c'v')_p$ have almost perfect in-phase relationships. These phase relationships appear to be

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450 reasonable and generally consistent with the linear theory. The near in-phase relationship

451 exhibited by $(\theta'w')_p$ (Fig. 9g), however, raises doubts about whether these variations are true

452 gravity waves, as this is not consistent with linear theory. If they are in fact gravity wave signals,

453 the discrepancy highlights the difficulties of extracting gravity wave perturbations from

454 observations. For example, the mesoscale variances may be contaminated by small-scale

455 variability of θ and w due to the coexistence of wave variances at different scales for this region

456 (see the wavelet analysis of w in Fig. 6c in and θ in Fig. 6d). Additionally, there are uncertainties

457 in extracting mesoscale gravity waves from a varying background flow (e.g., Zhang et al. 2004),

458 especially for u, v and θ. Note that θ and w have a very consistent quadrature relation from ~8

459 km to ~64 km for this region in their quadrature spectrum of Fig. 7d (also see Fig. 7e), but this

460 quadrature relation (the third column in Fig. 7d), including their corresponding wavelet spectrum

461 (the third column in Fig. 6c and Fig. 6d) is much weaker for wavelengths near 128 km for

462 location 560-688 km in segment J3.

463   Consistent with Smith et al. (2008), the amplitude of p_h' is much larger than the

464 amplitude of p_s' for both examples of mesoscale wave variances. Therefore, $(p_h'w')_p$ is almost

465 identical to $(p_c'w')_p$ for both cases (Fig. 8f versus Fig. 8i; Fig. 9f versus Fig. 9i). It appears that

466 the assumption of constant p_s flight height is valid for these two mesoscale examples.

467

468 *5.2 Examples of small-scale wavelike variations*

469   Figure 10 shows an example of short-scale wave-like disturbances that have a phase

470 relationship consistent with linear gravity wave theory based on the wavelet analysis in Fig. 6

471 with scales from 32 to 64 km located at 650 to 750 km during segment J3. In-phase relationships

472 are seen in the filtered signals of $(p_c'v')_p$ (Fig. 10e), while out-of-phase relationships are seen in

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473    $(u'v')_p$ and $(p_c'u')_p$ (Figs. 10c and d). Quadrature relationships can generally be seen in

474    $(u'w')_p$, $(v'w')_p$, $(p_c'w')_p$, and $(\theta'w')_p$ (Figs. 10a, b, f, and g). These small-scale waves have

475   no apparent vertical flux of horizontal momentum (Figs. 10a and b) and no vertical energy flux

476   (Fig. 10f), a key sign of vertically trapped gravity waves. Short-scale waves based on GV aircraft

477   measurements and/or numerical simulations are also discussed in Smith et al. (2008), Woods and

478   Smith (2010; 2011).

479   However, parts of the small-scale wave variations derived from the *in-situ* measurements,

480   especially for wavelengths from 5 to 15 km, may be difficult to classify as gravity waves. Figure

481   11 shows an example of short-scale wave variations in the aircraft measurements with along-

482   track wavelengths from 8 to 16 km for locations 680 to 780 km along segment J3. As depicted in

483   Fig. 11, $(u'w')_p$ (Fig. 11a) appears to have a quadrature relationship, even though this relative

484   phase varies, especially for locations from 710 to 730 km. Compared to $(u'w')_p$ (Fig. 11a),

485    $(v'w')_p$ and $(\theta'w')_p$ (Fig. 11b and g) have consistent quadrature relationships within this 100-

486   km distance. On the other hand, $(u'v')_p$ (Fig. 11c) varies significantly from one wavelength to

487   the next. The amplitude of w' in this example is extremely large (~2.5 m/s at its maximum) in

488   this selected example. In comparison, the amplitude of p_c' is rather small, and it is actually too

489   small to be noticed when using a wider bandpass window (not shown). Also, the quadrature

490   relationship in $(p_c'w')_p$ (Fig. 11f) is not as remarkable as those in $(u'w')_p$ and $(v'w')_p$ (Figs.

491   11a and b), which appears to contradict the theoretical description of Eliassen and Palm (1960)

492   on energy and momentum fluxes (also see Lindzen 1990). In addition, it is worth mentioning that

493    $(p_s'w')_p$ and $(p_h'w')_p$ in Figs. 11h and i have almost perfect out-of-phase and in-phase

494   relationships, respectively.

20

495   In contradiction to Smith et al. (2008), the amplitude of p_h' in the above example of Fig.

496   11 is comparable with the amplitude of p_s' (Fig. 11h versus Fig. 11i). Surprisingly, $(p_c'w')_p$,

497    $(p_s'w')_p$, and $(p_h'w')_p$ are also very different from each other (compare Figs. 11f, h, and i). The

498   signals of p_s' and p_h' (Fig. 11h and i) are out-of-phase for wavelengths near 10 km and have

499   comparable amplitude, which leads to nearly no such wave variances in p_c' (Fig. 11d-11f) given

500   p_c' is the sum of p_s' and p_h'.

501

502   *5.3 Insight from spectral analysis of different pressure variables*

503   Figure 12a compares the power spectrum of three pressure-related variables (i.e.,

504   corrected static pressure p_c, static pressure p_s, hydrostatic pressure correction p_h; also see

505   equation 1). Using segment J3 as an example, for wavelengths greater than ~32 km, p_c is almost

506   identical to p_h; for wavelengths between ~32 km and ~4 km, the variances between p_s and p_h

507   are comparable, and the variances of p_c are noticeably smaller than those in p_s and p_h; for

508   wavelengths less than ~4 km, p_c is almost identical to p_s. Figure 12b shows the quantity

509    $\sqrt{\frac{spec(p_s)+spec(p_h)}{spec(p_c)}}$, where $spec(\ \ )$ indicates the power spectrum of the variable inside the

510   parentheses (e.g., Figs. 4-5). For segment J3, the square root of the ratio is close to 1.0 for the

511   wavelengths greater than ~32 km and less than ~4 km. At intermediate wavelengths, the square

512   root of the ratio reaches a maximum near 10 for wavelengths of ~10 km. This suggests that p_s'

513   and p_h' may tend to cancel each other at intermediate scales, which reduces the amplitude of p_c'

514   at these intermediate wavelengths (also see the example in Fig. 11) since p_c' is the sum of p_s'

515   and p_h'. Similar behaviors can be also observed in other segments, although the exact ranges of

516   the intermediate wavelengths may be different from case to case.

21

517   Figure 12 suggests that the assumption of constant p_s flight height may not be valid at all

518   scales, though it appears to be true for mesoscale waves. In consequence, $p_h{}'$ may not always

519   dominate over $p_s{}'$ as assumed in Smith et al. (2008). The spectral analysis and wavelet analysis

520   of p_s (not shown) demonstrate that p_s indeed has relatively large variances for the short-scale

521   range, and that p_s and w share some common characteristics (also see Fig. 3). Moreover, the

522   hydrostatic approximation, which is the underlying assumption for equation 1, may no longer be

523   valid for short scales.

524

525   **6. Concluding remarks and discussion**

526   One of the primary objectives of the recent START08 field experiment is to characterize

527   the sources and impacts of mesoscale waves with high-resolution flight-level aircraft

528   measurements and mesoscale models. The current study focuses on the second research flight

529   (RF02), which was the first airborne mission dedicated to probing gravity waves associated with

530   strong upper-tropospheric jet-front systems and high topography. Based on spectral and wavelet

531   analyses of the *in-situ* observations, along with a diagnosis of the polarization relationships, it is

532   found that there are clear signals of significant mesoscale variations with wavelengths ranging

533   from ~50 to ~500 km in almost every segment of the 8-hr flight (order ranging from 0.01 m/s to

534   1.0 m/s in vertical motion), which took place mostly in the lower stratosphere. The flow sampled

535   by the aircraft covers a wide range of background conditions including near the jet core, a jet

536   over the high mountains, and the exit region of the jet. In contrast, smaller-scale wavelike

537   oscillations below 50 km are found to be quite transient. In particular, aircraft measurements of

538   several flight segments are dominated by signals with sampled periods of ~20-~60 seconds and

539   wavelengths of ~5-~15 km (assuming that the typical flight speed is approximately 250 m/s).

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542   This study suggests that at least part of the nearly-periodic high-frequency signals might

543   be unphysical and a result of intrinsic observational errors in the aircraft measurements or small-

544   scale flight-altitude fluctuations that are difficult to account for. Such potentially contaminated

545   variations are often collocated with larger-scale wave signals, which in turn may lead to larger

546   uncertainties in the estimation of the wave characteristics. Part of the uncertainties may come

547   from the inability of the aircraft to maintain constant static pressure altitude in the presence of

548   small-scale turbulence. The current study mainly focuses on examining the fluctuations with the

549   use of linear theory for monochromatic gravity waves. Therefore, in addition to measurement

550   errors, the possibilities that those fluctuations may be due to other physical phenomena (e.g.,

551   nonlinear dynamics, shear instability and/or turbulence) cannot be completely ruled out.

552   Nevertheless, despite the presence of possibly spurious wave oscillations in different flight

553   segments, the power spectra of horizontal winds and temperature averaged over many START08

554   flight segments generally follow the -5/3 power law. The common characteristics and individual

555   features of the wave variances and spectrum slope behaviors appear to be generally consistent

556   with past studies on the spectral analysis of aircraft measurement, including Nastrom and Gage

557   (1985) using the Global Atmospheric Sampling Program (GASP) flight dataset, and Lindborg

558   (1999) using the Measurement of Ozone and Water Vapor by Airbus In-Service Aircraft

559   (MOZAIC) aircraft observations. Spectral behaviors of atmospheric variables have also been

560   studied by high-resolution non-hydrostatic mesoscale numerical weather prediction (NWP)

561   models (e.g., Skamarock 2004; Tan et al. 2004; Zhang et al. 2007; Waite and Snyder 2013; Bei

562   and Zhang 2014).

563   Although the real-time mesoscale analysis and prediction system gave a reasonable

564   forecast guidance on the region of potential gravity wave activities, it remains to be explored (1)

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566 how well the current generation of numerical weather models predicts the excitation of gravity

567 waves, (2) how often gravity waves break in the ExUTLS region, and (3) what evidence in tracer

568 measurements is shown for the contribution of gravity wave breaking to mixing. Future work

569 will also seek to examine the origin and dynamics of the gravity waves observed during RF02 of

570 START08 through a combination of observations and numerical modeling. This will help to

571 distinguish whether the sampled mesoscale and small-scale variances are gravity waves or

572 artifacts of the observing system.

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Figure Captions

803   **Figure 1.** The 68 Gulfstream V (GV) flight segments (colored lines) selected for wave analysis

804   during START08. The 18 colors represent 18 research flight (RF) missions. The thick blue lines

805   represent the second flight (RF02). The grey shadings give the terrain elevation map (shaded

806   every 250 m) over north America. The 4 black boxes are the model domain design for the second

807   research flight (RF02) during 21-22 April 2008, which are named D1-D4 from coarse to fine

808   domain with horizontal resolution as 45 km, 15 km, 5 km and 1.67 km, respectively. The field

809   catalog   of   the   18   RFs   are   available   online   (at

810   http://catalog.eol.ucar.edu/start_08/missions/missions.html). The GV ground tracks of the

811   18 RFs are also documented in Fig. 2 of Pan et al. (2010).

812

813   **Figure 2.** Simulated pressure at 9 km altitude (black contours; unit in hPa; $\Delta = 2hPa$),

814   horizontal wind speed at 9 km altitude (black shadings; unit in ms^{-1}; levels at 30, 40, 50, 60

815   ms^{-1}), and the mesoscale component of horizontal divergence at 12.5 km (blue contours,

816   positive; red contour, negative; contour levels at $\pm7.5, \pm15, \pm30, \pm60 \times 10^{-5}s^{-1}$) during RF02

817   in START08, with marked GV flight track (blue line) at selected time: (a) entire flight track at 21

818   April 18:00 UTC, (b) segment J1 at 21 April 19:10 UTC, (c) segment J2 at 21 April 19:50 UTC,

819   (d) segment J3 at 21 April 22:10 UTC, (e) segment M1 at 21 April 23:10 UTC, and (f) segment

820   M2 at 22 April 00:20 UTC. The triangle and circle marks represent the aircraft at the start time

821   of the segment and at selected time. The two-dimensional (2D) variables are based on D4 in Fig.

822   1. A band-pass filter is applied to extract signals with wavelength from 50 to 500 km for

823   horizontal divergence.

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825   **Figure 3.** GV flight-level aircraft measurements during 5 selected segments (from left to right:

826   J1, J2, J3, M1 and M2) of RF02 in START08: (a) along-track velocity component (red; unit in

827   ms^{-1}; left y axis), across-track velocity component (blue; unit in ms^{-1}; right y axis) and

828   horizontal velocity component (black; unit in ms^{-1}; left y axis), (b) vertical velocity component

829   (red; unit in ms^{-1}; left y axis) and potential temperature (blue; unit in K; right y axis), (c)

830   perturbation of hydrostatic pressure correction (red; unit in hPa; left y axis), static pressure

831   (blue; unit in hPa; right y axis) and corrected static pressure (black; unit in hPa; left y axis), and

832   (d) flight height (red; unit in km; left y axis) and terrain (blue; black shading below terrain; unit

833   in km; right y axis). The series in segment J3 and M2 are reversed to facilitate the comparison

834   with J1+J2 and M1, respectively. Therefore, the orientation of x axis is from west to east along

835   each flight segment. The distance between minor tick marks in x axis is 100 km. The

836   perturbations in (c) are defined as the differences between the original data and their mean from

837   their corresponding segments.

838

839   **Figure 4.** The spectrum (black line) of GV flight-level aircraft measurement during 5 selected

840   segments (from left to right: J1, J2, J3, M1 and M2) of RF02 in START08: (a) along-track

841   velocity component (unit: $m^2 s^{-2} \bullet m$), (b) across-track velocity component (unit: $m^2 s^{-2} \bullet m$), (c)

842   vertical velocity component (unit: $m^2 s^{-2} \bullet m$), (d) potential temperature (unit: $K^2 \bullet m$), and (e)

843   corrected static pressure (unit: $hPa^2 \bullet m$). Green lines show the theoretical Markov spectrum and

844   the 5% and 95% confidence curves using the lag 1 autocorrelation. The blue (red) reference lines

845   have slopes of -5/3 (-3).

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852 **Figure 5.** Composite spectrum (black line) of GV flight-level aircraft measurement averaging

853 over all 68 segments in START08 (colored lines in Fig. 1): (a) along-track velocity component

854 (unit: $m^2 s^{-2} \bullet m$), (b) across-track velocity component (unit: $m^2 s^{-2} \bullet m$), (c) vertical velocity

855 component (unit: $m^2 s^{-2} \bullet m$), (d) horizontal velocity component (unit: $m^2 s^{-2} \bullet m$), (f) potential

856 temperature (unit: $K^2 \bullet m$), (g) corrected static pressure (unit: $hPa^2 \bullet m$), (h) static pressure

857 (unit: $hPa^2 \bullet m$), and (i) hydrostatic pressure correction (unit: $hPa^2 \bullet m$). The subplot (e) kinetic

858 energy (unit: $m^2 s^{-2} \bullet m$) is the sum of (a)-(c). Green lines show the composite curves of the

859 theoretical Markov spectrum and the 5% and 95% confidence curves using the lag 1

860 autocorrelation. The blue (red) reference lines have slopes of -5/3 (-3).

861

862 **Figure 6.** Wavelet power spectrum of GV flight-level aircraft measurement during 5 selected

863 segments (from left to right: J1, J2, J3, M1 and M2) of RF02 in START08: (a) along-track

864 velocity component, (b) across-track velocity component, (c) vertical velocity component, (d)

865 potential temperature, and (e) corrected static pressure. Reference line (black line) shows the

866 cone of influence (COI), and the area outside COI is where edge error becomes important. Black

867 contour lines with dot shading represent 95% significance level based on a red noise background

868 (also see Torrence and Compo 1998; Woods and Smith 2010). The x axis is the same as in Fig.

869 3, including the reversal of segment J3 and M2.

870

871 **Figure 7.** The wavelet cospectrum of (a) $(u'w')_c$, (b) $(v'w')_c$, (c) $(p_c'w')_c$, (d) the quadrature

872 spectrum of $(\theta'w')_q$, and (e) the absolute coherence phase angle of $(\theta'w')_p$ for GV flight-level

873 aircraft measurement during 5 selected segments (from left to right: J1, J2, J3, M1 and M2) of

874 RF02 in START08. Reference line (black line) shows the cone of influence (COI), and the area

37

884 outside COI is where edge error becomes important. Black contour lines with dot shading

885 represent 95% significance level (also see Torrence and Compo 1998; Woods and Smith 2010).

886 The x axis is the same as in Fig. 3, including the reversal of segment J3 and M2. The horizontal

887 black line marks the scale of 50 km.

888

889 **Figure 8.** A relatively good/clean example of mesoscale variations during segment J3 (location

890 250-360 km): (a) along-track velocity component (red; unit in m/s) and vertical velocity

891 component (blue; unit in m/s), (b) across-track velocity component (red; unit in m/s) and vertical

892 velocity component (blue; unit in m/s), (c) along-track velocity component (red; unit in m/s) and

893 across-track velocity component (blue; unit in m/s), (d) corrected static pressure (red; unit in

894 hPa) and along-track velocity component (blue; unit in m/s), (e) corrected static pressure (red;

895 unit in hPa) and across-track velocity component (blue; unit in m/s), (f) corrected static pressure

896 (red; unit in hPa) and vertical velocity component (blue; unit in m/s), (g) potential temperature

897 (red; unit in K) and vertical velocity component (blue; unit in m/s), (h) static pressure (red; unit

898 in hPa) and vertical velocity component (blue; unit in m/s), and (i) hydrostatic pressure

899 correction (red; unit in hPa) and vertical velocity component (blue; unit in m/s). A wavelet-based

900 band-pass filter is applied to extract signals with wavelength from 100 to 120 km for all the

901 above flight variables.

902

903 **Figure 9.** Same as in Fig. 8, but for a relatively bad/noisy example of mesoscale variations

904 during segment J3 (location 560-688 km). The wavelet-based band-pass window is 118-138 km.

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906   **Figure 10.** Same as in Fig. 8, but for a relatively good/clean example of smaller-scale variations

907   during segment J3 (location 650-750 km). The wavelet-based band-pass window is 32-64 km.

908

909   **Figure 11.** Same as in Fig. 8, but for an example of smaller-scale variations during segment J3

910   (location 680-780 km). The wavelet-based band-pass window is 8-16 km.

911

912   **Figure 12.** (a) The spectrum of corrected static pressure (black), static pressure (blue), and

913   hydrostatic pressure correction (red) based on GV flight-level aircraft measurement during 5

914   selected segments (from left to right: J1, J2, J3, M1 and M2) of RF02 in START08. (b) The

915   spectrum of the square root ratio (see the text for its definition).

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918 **Table 1:** The aircraft statistic parameters of five selected flight segment in RF02 during the
919 START08 field campaign. Column 1-7 represent the name, the starting time (s), the ending time
920 (s), the averaged flight height (km), the averaged static pressure (hPa), the total distance (km),
921 and the averaged flight speed (m/s) of each selected flight segment.
922

Flight Segment	Start (s)	End (s)	Averaged Flight Height (km)	Averaged Static Pressure (hPa)	Distance (km)	Averaged Flight Speed (m/s)
J1	2450	5000	11.8	196.9	685.74	268.92
J2	5170	8620	12.5	178.7	908.53	263.34
J3	9120	16850	13.1	162.1	1641.93	212.41
M1	17100	20630	12.6	178.5	950.46	269.25
M2	21500	26430	11.0	227.6	946.90	192.07

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