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 " $m^2 s^{-2} \times unitof(N) / unitof(k^*)$ ". Here, the unitof() give the unit of the variable inside the bracket; wavenumber k^* is equal to $\frac{N\Delta x}{\lambda}$; 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.

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

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

2. Inferences about propagation direction

I think the manuscript would benefit from enhanced discussion about what can be inferred about horizontal propagation direction and how the superposition of gravity waves propagating in opposing directions can complicate the analysis. In particular, around line 20 on p 4739, there is discussion of cospectra varying sign. For example as shown in Fig. 7 (leg J3), the cospectra of w and p suggest upward propagating waves (almost exclusively). Thus, the variations in sign of the cospectra of u and w imply that this track is sampling waves propagating in both the forward and backward direction. As argued by the authors (p4740 line ~5) this highlights a difficulty in interpreting the waves observed by aircraft, but it does tell us something useful about the wave field nonetheless.

As suggested, the following sentence will be added in the manuscript around line 21 on page 4739.

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

For such legs it would be useful to obtain estimates of the net momentum flux. The analysis presented could readily separate the averages into positive and negative components, which should give a good indication of the dominance of which particular propagation direction as a function of scale.

The results of net momentum fluxes are shown in Figure R1.03-R1.05, which calculate the cospectrum of $\overline{u'w'}$, $\overline{v'w'}$, and $\overline{w'p_c'}$ based on Fourier transform, respectively. For the scale below ~32 km, both positive values and negative values are important in $\overline{u'w'}$ and $\overline{v'w'}$, while positive $\overline{w'p_c'}$ appears to be more continuous than negative $\overline{w'p_c'}$. For the scale above ~32 km, negative $\overline{u'w'}$ (positive $\overline{w'p_c'}$) appears to be generally more continuous than positive $\overline{u'w'}$ (negative $\overline{w'p_c'}$), while the dominant signs in $\overline{v'w'}$ are generally inconclusive.

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

Figure R1.06 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.

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

Minor comments:

1. p. 4727 line 15. Suggest changing to: "dominated by signals with sampled periods.." to be clear that this isn't the wave period.

This sentence will be modified in the revision.

2. p. 4730 line 19. I don't think this claim to be the 'first' is entirely correct. It may be the first such flight to actually aim to find the mesoscale gravity waves from jet/fronts, but previous studies/flights have measured them and analyzed them (e.g., Shapiro and Kennedy 1975; Koch et al. 2005).

The sentence in line 19 on page 4730 will be modified as below.

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

3. To be clear: Do the authors ascertain that the small-scale signals represented in the data are entirely fictitious? Or is it that these signals do exist, but the sampling errors (associated with *the violation of the assumptions about pressure) are very large making the spectral estimates unreliable?*

With limited observations and accuracy, we cannot ascertain that the small-scale signals are entirely fictitious. The current study attempts to argue that small-scale pressure could be problematic, and that the small-scale signals may be hard to understand/verify using linear theory for propagating monochromatic gravity waves. However, it remains possible, though unlikely, some of the small scale variations may be due to nonlinear dynamics, shear instability, and/or turbulence that are physical. The below sentences will be added to around line 4 on page 4746.

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

References

Koch, S. E., Jamison, B. D., Lu, C. G., Smith, T. L., Tollerud, E. I., Girz, C., Wang, N., Lane, T. P., Shapiro, M. A., Parrish, D. D., and Cooper, O. R.: Turbulence and gravity waves within an upper-level front, J. Atmos. Sci., 62, 3885–3908, 2005.

Nastrom, G. D., and K. S. Gage, 1985: A Climatology of Atmospheric Wavenumber Spectra of Wind and Temperature Observed by Commercial Aircraft. J. Atmos. Sci., 42, 950–960.

Shapiro, M. A., and P. J. Kennedy, 1975: Aircraft Measurements of Wave Motions within Frontal Zone Systems. Mon. Wea. Rev., 103, 1050–1054. doi: http://dx.doi.org/10.1175/1520-0493(1975)103<1050:AMOWMW>2.0.CO;2

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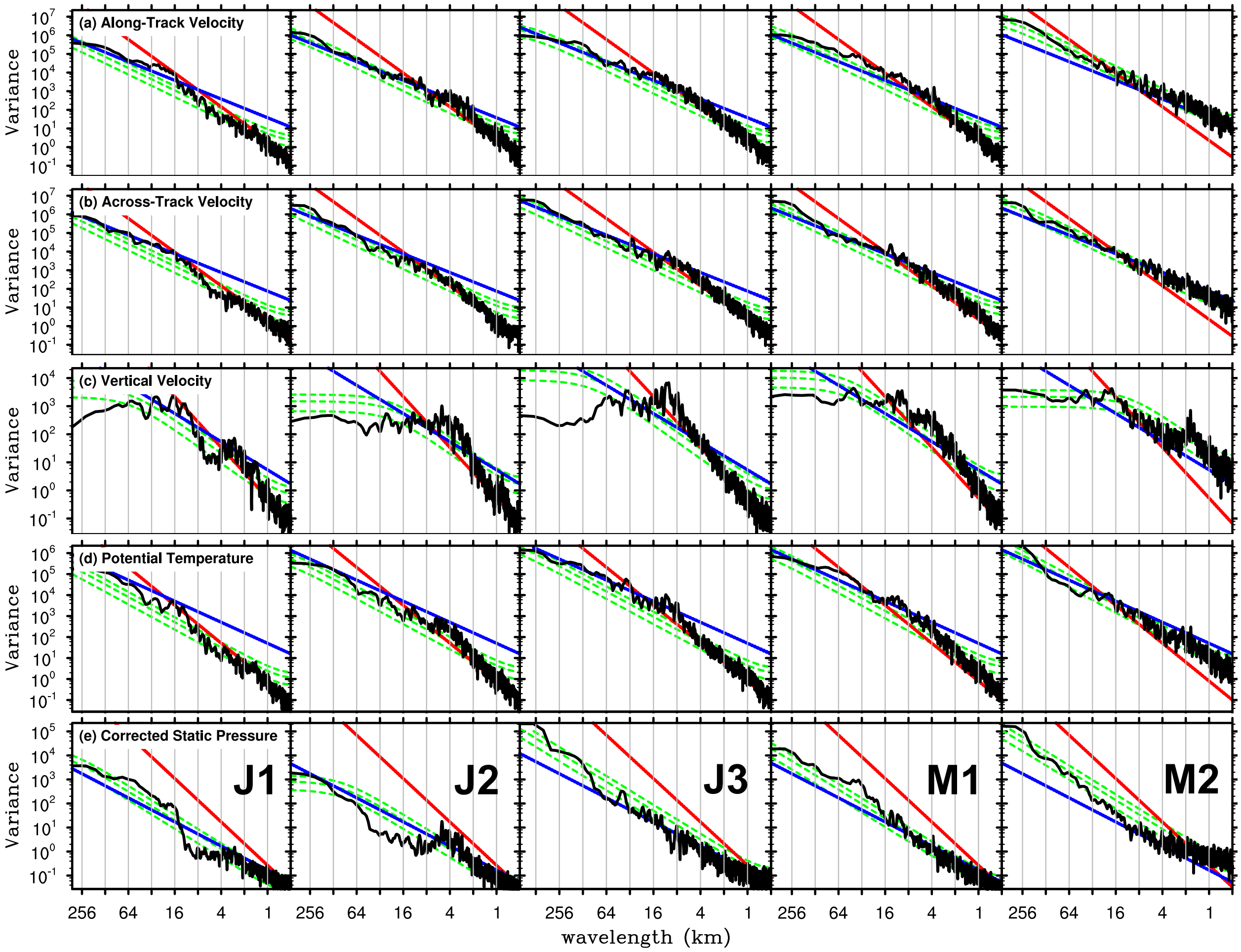

Figure R1.01 The spectrum (black line) of GV flight-level aircraft measurement during 5 selected segments (from left to right: J1, J2, J3, M1 and M2) of RF02 in START08: (a) along-track velocity component (unit: $m^2s^{-2} \bullet m$), (b) across-track velocity component (unit: $m^2s^{-2} \bullet m$), (c) vertical velocity component (unit: $m^2s^{-2} \bullet m$), (d) 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).

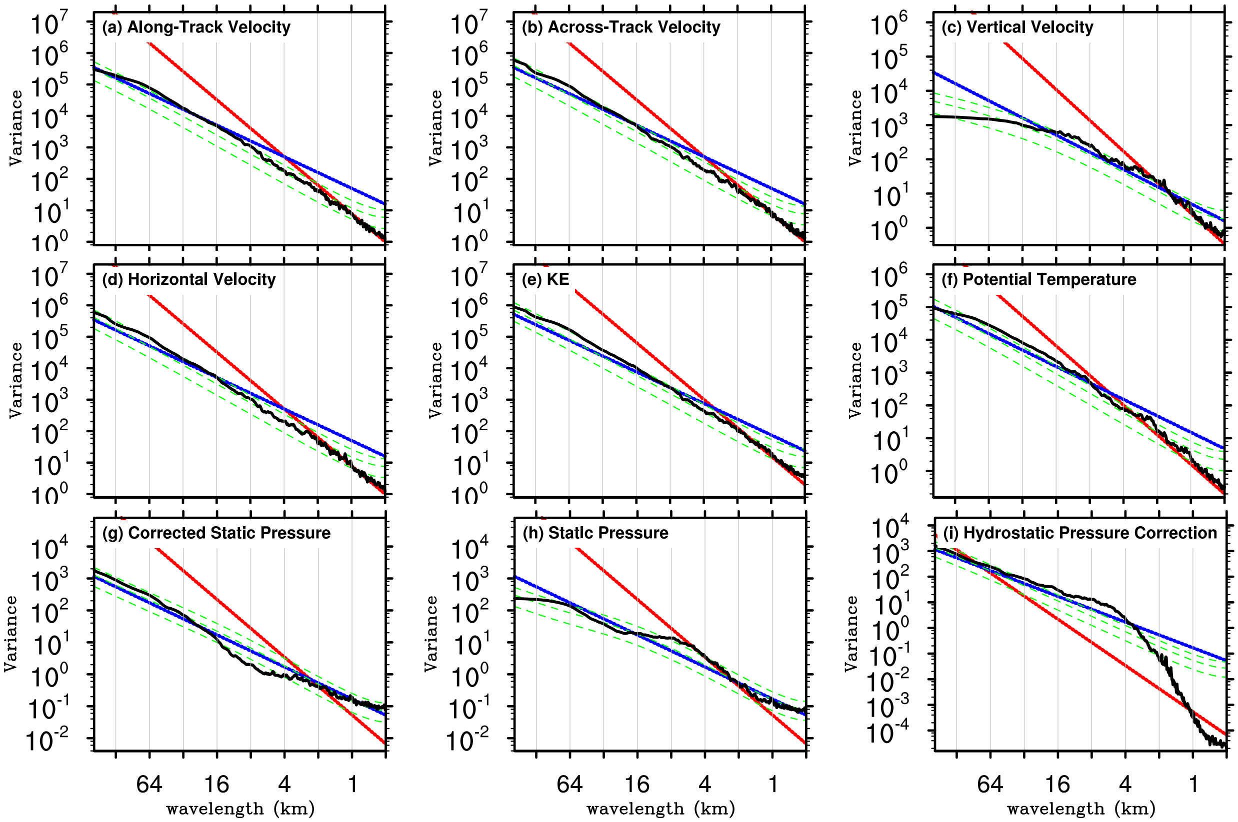

Figure R1.02 Composite spectrum (black line) of GV flight-level aircraft measurement averaging over all 68 segments in START08 (colored lines in Fig. 1): (a) along-track velocity component (unit: $m^2 s^{-2} \bullet m$), (b) across-track velocity component (unit: $m^2 s^{-2} \bullet m$), (c) vertical 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).

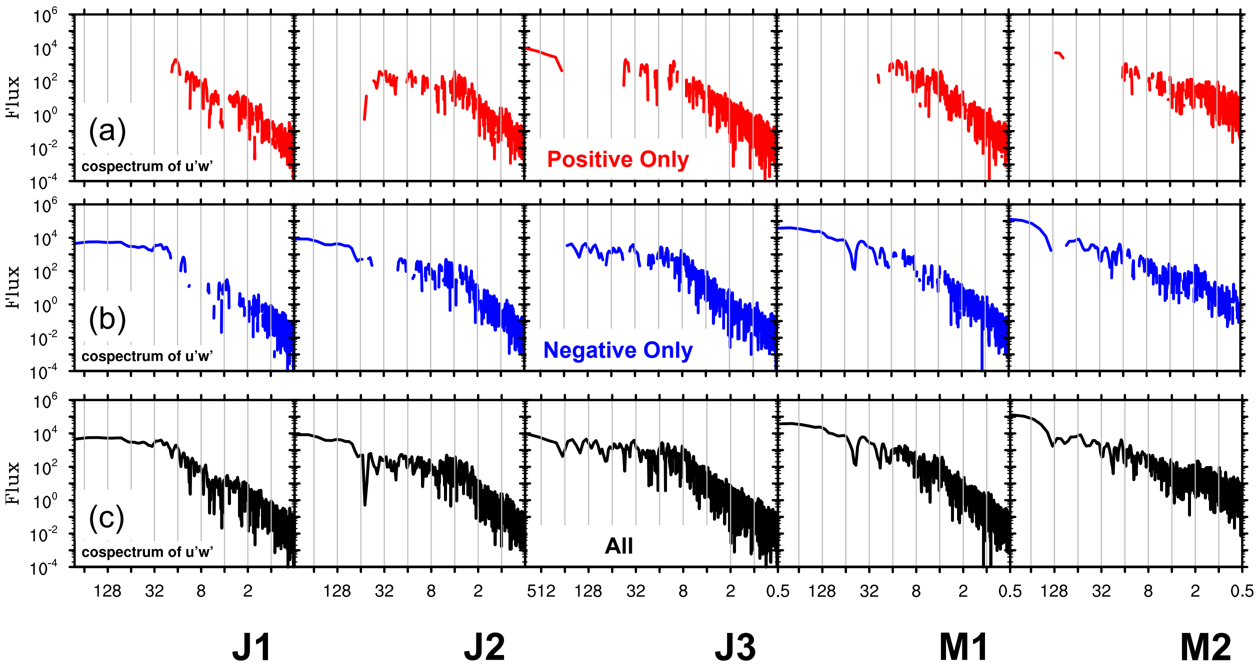

Figure R1.03 The cospectrum of along-track velocity component u and vertical velocity component w. (a) The absolute value of the positive only component. (b) The absolute value of the negative only component. (c) The absolute value of both positive and negative components.

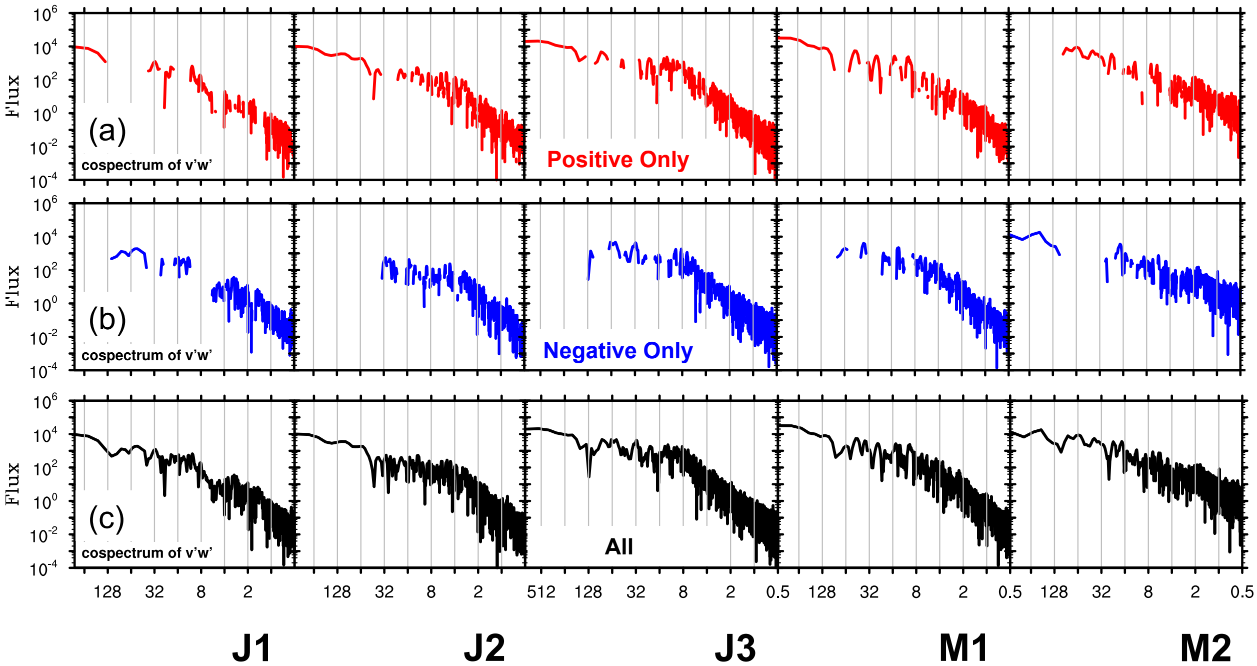

Figure R1.04 The cospectrum of across-track velocity component v and vertical velocity component w. (a) The absolute value of the positive only component. (b) The absolute value of the negative only component. (c) The absolute value of both positive and negative components.

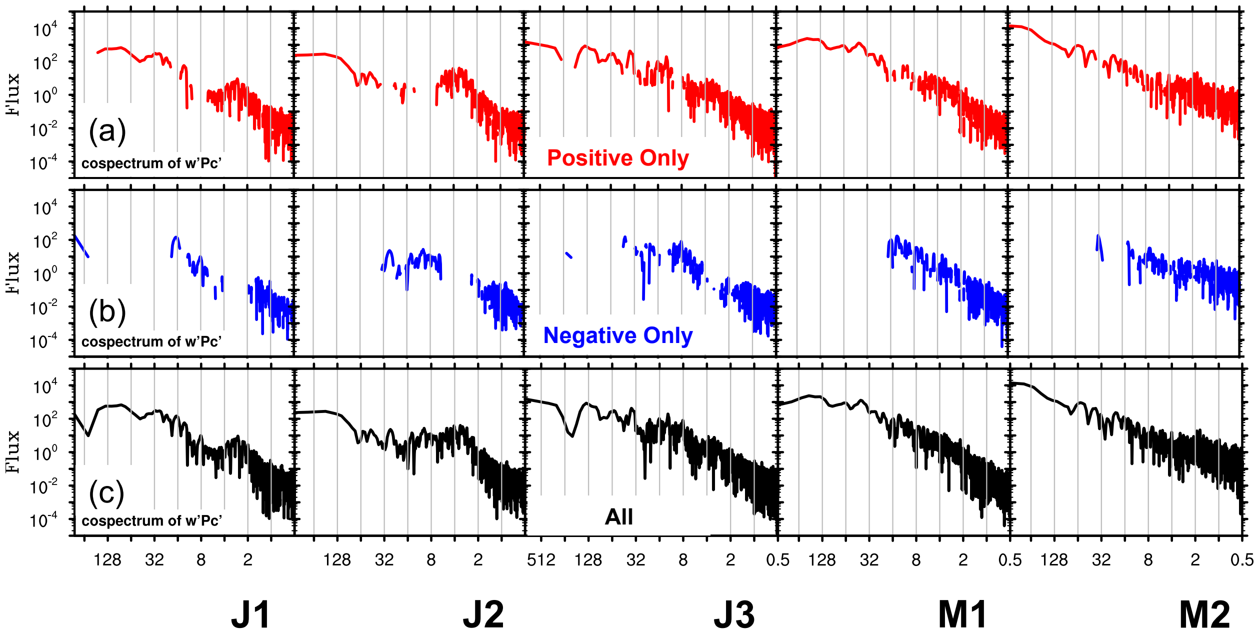

Figure R1.05 The cospectrum of vertical velocity component w and corrected static pressure p_c. (a) The absolute value of the positive only component. (b) The absolute value of the negative only component. (c) The absolute value of both positive and negative components.

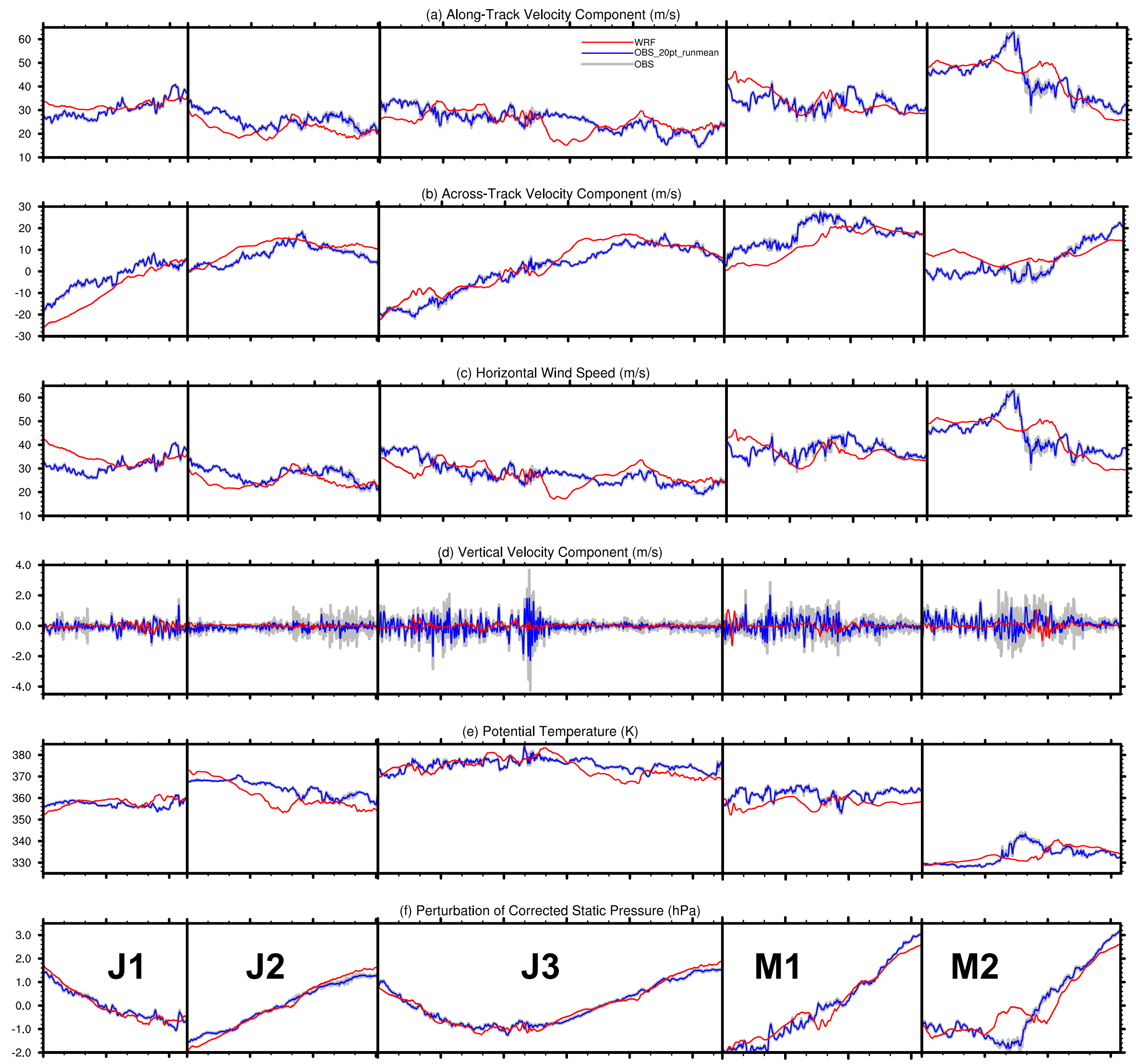

Figure R1.06 Comparision between GV flight-level aircraft measurements and WRF simulations during 5 selected segments (from left to right: J1, J2, J3, M1 and M2) of RF02 in START08: (a) along-track velcotiy component (m/s), (b) across-track velocity component (m/s), (c) horizontal wind speed (m/s), (d) 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.