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Assessment of Gravity Wave Momentum Flux Measurement Capabilities by Meteor Radars Having Different Transmitter Power and Antenna Configurations

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Abstract

Measurement capabilities of five meteor radars are assessed and compared to determine how well radars having different transmitted power and antenna configurations perform in defining mean winds, tidal amplitudes, and gravity wave (GW) momentum fluxes. The five radars include two new-generation meteor radars on Tierra del Fuego, Argentina (53.8°S) and on King George Island in the Antarctic (62.1°S) and conventional meteor radars at Socorro, New Mexico (34.1°N, 106.9°W), Bear Lake Observatory, Utah (~41.9°N, 111.4°W), and Yellowknife, Canada (62.5°N, 114.3°W). Our assessment employs observed meteor distributions for June of 2009, 2010, or 2011 for each radar and a set of seven test motion fields including various superpositions of mean winds, constant diurnal tides, constant and variable semidiurnal tides, and superposed GWs having various amplitudes, scales, periods, directions of propagation, momentum fluxes, and intermittencies. Radars having higher power and/or antenna patterns yielding higher meteor counts at small zenith angles perform well in defining monthly and daily mean winds, tidal amplitudes, and GW momentum fluxes, though with expected larger uncertainties in the daily estimates. Conventional radars having lower power and a single transmitting antenna are able to describe monthly mean winds and tidal amplitudes reasonably well, especially at altitudes having the highest meteor counts. They also provide qualitative estimates of GW momentum fluxes at the altitudes having the highest meteor counts; however, these estimates are subject to uncertainties of ~20 to 50% and uncertainties rapidly become excessive at higher and lower altitudes. Estimates of all quantities degrade somewhat for more complex motion fields.

Introduction

Gravity waves (GWs) play significant roles in atmospheric dynamics, chemistry, microphysics, and plasma processes extending from Earth's surface into the thermosphere and ionosphere. At lower altitudes, GWs contribute to boundary layer and mesoscale structures, organize convection, induce turbulence and mixing of relevance to weather prediction and aircraft at flight altitudes. In the middle stratosphere, GWs induce polar stratospheric clouds that contribute to ozone destruction. Throughout the atmosphere, but especially at higher altitudes, GWs systematically influence the large-scale circulation and thermal structure via energy and momentum transport and deposition. These influences are typically slow and systematic at lower altitudes, but may be local and strong accompanying severe events. In the mesosphere and lower thermosphere (MLT), GWs lead to closure of the mesospheric jets, large departures from radiative equilibrium, strong turbulence and mixing of heat, momentum, and constituents, and significant interactions with, and influences on, tides and planetary waves. GWs are expected to have similar, but still largely unknown, effects higher in the thermosphere and ionosphere. Indeed, the vertical transport of horizontal momentum by GWs, and its deposition accompanying GW dissipation, account for the major influences of these motions on the mean and large-scale atmospheric circulation, structure, and variability. Reviews of these various dynamics emphasizing the higher altitudes are provided by *Hines* [1960], *Lighthill* [1978], *McIntyre* [1989], *Hocke and Schlegel* [1996], *Nappo* [2002], *Fritts and Alexander* [2003], *Kim et al*. [2003], *Fritts et al*. [2006a], and *Fritts and Lund* [2011]. The various responses to momentum transport by GWs noted above make this a key quantity in understanding and modeling atmospheric structure at all altitudes. Consequently, significant efforts have addressed these dynamics employing theoretical, modeling, and

73 observational methods, typically focusing on the higher altitudes where the effects of these 74 dynamics are most pronounced [*Fritts and Alexander,* 2003]. Further quantification of these 75 dynamics throughout the atmosphere also remain a major research need, given the important of 76 their proper parameterization for weather and climate forecasting [*Kim et al*., 2003]. 77 Prior to new meteor radar capabilities, direct measurements of GW momentum fluxes 78 have only been possible with Doppler radars or lidars having symmetric, relatively narrow, off79 zenith coplanar beam pairs [*Vincent and Reid*, 1983; *Reid and Vincent* 1987; *Fritts and Vincent*, 80 1987; *Fukao et al.*, 1988; *Reid et al*., 1988; *Fritts and Yuan*, 1989; *Fritts et al*., 1990, 1992, 81 2006b; Fritts and Janches, 2008; Sato, 1990, 1993, 1994; *Tsuda et al*., 1990; *Wang and Fritts*, 82 1990, 1991; *Hitchman et al*., 1992; *Nakamura et al*., 1993; *Murayama et al*., 1994; *Murphy and* 83 *Vincent*, 1993, 1998; *Acott et al*., 2009] or via *in situ* measurements by aircraft at lower altitudes 84 or chaff measurements in the MLT [*e.g., Lilly and Kennedy,* 1973*; Lilly et al.,* 1982; *Brown,* 85 1983; *Meyer et al.,* 1989; *Nastrom and Fritts*, 1992; *Smith et al*., 2008]. Indirect methods have 86 nevertheless contributed to quantification of, or constraints on, momentum fluxes employing 87 airglow [*e.g., Swenson et al*., 1999; *Fritts et al*., 2002; *Espy et al*., 2004, 2006], balloon [*e.g.,* 88 *Hertzog and Vial*, 2001; *Hertzog et al*., 2008], and satellite measurements [e.*g., Ern et al*., 2004]. 89 These various measurements have revealed a variety of responses, including systematic seasonal90 mean momentum fluxes accounting for large-scale forcing at lower and higher altitudes, 91 responses to specific sources and source regions, episodic and strong forcing accompanying 92 GWs that are transient and localized, but achieve large amplitudes, and significant filtering and 93 interactions with larger-scale mean, tidal, and planetary wave (PW) motions. 94 Ideally, routine momentum flux measurements would provide continuous sensitivity to 95 the magnitudes that are dynamically important and also capture the temporal variations

96 accompanying strong, but transient, events that may nevertheless contribute significantly to 97 hourly, daily, monthly, and seasonal means. Improved understanding and parameterization of 98 GW influences also impose a need for such measurements at a range of locations spanning 99 representative source regions for GWs and the environments in which they propagate. 100 Unfortunately, those systems that do (or did) have such measurement capabilities are very 101 limited, their costs are very high (typically ~$1 to 10M, with several much more costly), very 102 few measure continuously, and only two (to our knowledge), sodium resonance lidars at the 103 Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR) at 69.3°N in Norway 104 and the Andes Lidar Observatory (ALO) at 30°S in Chile, are even at the edges of regions of 105 identified high seasonal GW activity extending into the stratosphere and MLT. So there are 106 considerable motivations for exploring other measurement techniques that may offer the 107 potential to significantly expand such measurements with much cheaper systems. Such systems 108 should also have the potential for continuous measurements; optical systems, whether active 109 (lidar) or passive (airglow, FPI, etc.) cannot provide full diurnal and annual measurements, 110 independent of weather, suggesting that only radar measurements are likely to address this need. 111 The Southern Argentina Agile MEteor Radar (SAAMER) [*Fritts et al*., 2010a, hereafter 112 *F10a*] was specifically designed to add a potential for GW momentum flux measurements to the 113 conventional meteor radar capabilities for mean, tidal, and PW measurements for the reasons 114 noted above. This was accomplished by devising a radar beam pattern that yielded a majority of 115 meteors at zenith angles <50° and employing high power to achieve as high a meteor rate as 116 possible at these angles. SAAMER was installed at Rio Grande on Tierra del Fuego, Argentina 117 (53.8°S, 67.7°W) and became operational in May 2008. SAAMER momentum flux measurement 118 capabilities were evaluated using observed meteor distributions for September 2008, a series of

119 test motion fields including prescribed mean winds, diurnal and semidiurnal tide winds, and 120 GWs having various spatial and temporal scales [*Fritts et al*., 2010b, hereafter *F10b*], and the 121 analysis procedure suggested by *Hocking* [2005] employing a "full-field" fit to the various 122 winds, variances, and covariances characterizing the superposed mean winds, tides, and GWs. 123 These suggested that for real wind fields having similar composition and character to the test 124 fields, SAAMER should be expected to provide very good definition of the mean and tidal winds 125 and reasonably good definition of GW momentum fluxes where meteor count rates are sufficient. 126 The apparent success of SAAMER in measuring GW momentum fluxes in addition to 127 mean, tidal, and PW winds was the motivation for a SAAMER clone, the Drake Antarctic Agile 128 MEteor Radar (DrAAMER) that was installed at the Brazilian Antarctic Comandante Ferraz 129 Base (62.1°S, 58.7°W) in March 2010. Comparisons of the mean and tidal winds and the GW 130 momentum fluxes measured by SAAMER and DrAAMER by *Fritts et al.* [2011, hereafter *F11*] 131 demonstrated close correspondence between mean and tidal winds at the two sites, as well as 132 significant similarities between the inferred GW momentum fluxes between years and sites from 133 April to June of 2010 and 2011. This agreement suggested significant confidence in the GW 134 momentum flux measurement potential for both radars, given the tests performed with SAAMER 135 data. Nevertheless, we believe it is important to subject DrAAMER to the same tests applied to 136 SAAMER. We also believe that applications of these tests to additional meteor radars having 137 different characteristics (particularly power and beam configuration) may help us identify what 138 radar capabilities are required to achieve GW momentum flux measurements that are sufficiently 139 accurate to be valuable to the community. For example, the *Hocking* [2005] analysis method was 140 tested with meteor radar data from Socorro, NM and Resolute Bay, Canada and judged to 141 provide reasonable two-month estimates (though without validation). Other meteor radars have

142 also been employed for GW variance, momentum flux, and tidal modulation studies and suggest 143 that more radars may provide enhanced measurement capabilities with testing and suitable 144 analysis techniques [Kumar et al., 2007; Antonita et al., 2008; Clemesha et al., 2009; Mitchell 145 and Beldon, 2009; Placke et al., 2011]. A related study by *Vincent et al*. [2010] employed a 146 Monte Carlo analysis of measurement capabilities assuming a conventional meteor radar beam 147 pattern and expected radial velocity and angle-of-arrival uncertainties and concluded that 148 accurate momentum flux estimates with such systems would likely require long averages. 149 Our goals in this paper are to evaluate SAAMER and DrAAMER GW momentum flux 150 measurement capabilities relative to several other conventional meteor radars in order to 151 determine 1) what radar parameters are required to enable such measurements, 2) whether other 152 radars can also provide credible GW momentum flux measurements in their current 153 configurations, or 3) whether system upgrades are needed to enable these capabilities. The other 154 radars employed for this assessment are at Socorro (SRO), New Mexico (34.1°N, 106.9°W), Bear 155 Lake Observatory (BL), Utah (~41.9°N, 111.4°W), and Yellowknife (YKF), Canada (62.5°N, 156 114.3°W) (see *Hocking*, 2005, and *Hocking and Kishore Kumar*, 2011, respectively, for more 157 detailed descriptions of the SRO and YKF radars). To address these goals, our paper is structured 158 as follows. Section 2 provides a summary of the characteristics of the radars employed for this 159 assessment and the analysis methods used to evaluate the performance of each. Test motion 160 fields, which include mean winds, diurnal and semidiurnal tides, and/or GWs having various 161 characteristics are described in Section 3. The performance of the five radars for the various tests 162 employing real spatial and temporal sampling for each is described in Section 4. Section 5 163 summarizes our findings and discusses measurement accuracies relative to other assessments. 164 Our conclusions are presented in Section 6.

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Characteristics of Radars Employed for this Study

We employ five different meteor radars for our assessment of GW momentum flux measurement capabilities in this study. Two of these were specifically designed intending to provide this capability (*i.e.*, SAAMER and DrAAMER); the other three are conventional meteor radars having lower peak power and a single transmitting antenna that had not anticipated such measurements (*i.e.*, the SKiYMET meteor radars previously installed at Socorro, NM, Bear Lake Observatory, UT, and Yellowknife, Canada; see Table 1). The relative locations of the five radars and the meteor distributions for each are shown for one day during the month in Figure 1. Meteor distributions in altitude, by day throughout the month considered, and by hour throughout a composite day for each radar are shown for comparison in Figure 2. The meteor distributions in Figure 1 all exhibit nulls in the polar diagrams that arise from excluding meteors at range increments corresponding to the pulse repetition frequency (PRF) in order to exclude contamination due to ground clutter. SAAMER and DrAAMER use a smaller PRF, and thus have these nulls at larger spacing. The statistics in Figure 2 include meteors at zenith angles from 15 to 60° for all radars. As expected, meteor counts are significantly larger for the radars having higher power, and higher at smaller zenith angles for SAAMER and DrAAMER than for the radars with single-antenna TX systems. They also vary significantly throughout the month, especially at SAAMER and DrAAMER, and exhibit large diurnal variations at all radars. The GW momentum flux measurement potential of SAAMER was previously evaluated for a number of test fields by *F10b*. Comparisons of SAAMER and DrAAMER measurements for April, May, and June of 2010 and 2011 were presented by *F11*, and suggested that DrAAMER momentum flux estimates provided a consistent picture of GW momentum fluxes accompanying strong GW sources over the Drake Passage, but did not evaluate the DrAAMER

188 momentum flux measurement capability directly. An initial application of the method employed 189 here was also used by *Hocking* [2005] to estimate two-monthly GW momentum fluxes by 190 SkiYMET meteor radars at Socorro, NM and Resolute Bay, Canada. These estimates were seen 191 to be roughly consistent with expected values, but were not evaluated in detail. However, a 192 systematic evaluation of the relative momentum flux measurement potential of these various 193 radars with specific test fields has not been performed. This is the goal here, and the 194 characteristics of the five radars are described for comparison in Table 1. We employ meteor 195 distributions obtained during June 2011 for KGI and TdF, June 2010 for SRO and BL, and June 196 2009 for YKF, for which meteor counts tend to be larger at northern than at southern latitudes. 197 **3 Specification of Test Motion Fields** 198 We showed in *F10b* that the SAAMER beam pattern and meteor counts enable relatively 199 high-precision measurements of mean winds and tides over fairly short intervals, and that GW 200 momentum fluxes can be estimated with reasonable accuracies where meteor counts are high, 201 even when the large- and small-scale motion field is variable on multiple time scales. The first 202 measurements over DrAAMER and comparisons with those over SAAMER by *F11* suggest that 203 the same can likely be said for DrAAMER. Here we repeat the tests previously applied to 204 SAAMER for DrAAMER and the three conventional meteor radars at Socorro, MN, Bear Lake 205 Observatory, UT, and Yellowknife, Canada in order to evaluate DrAAMER capabilities more 206 completely and determine whether, and under what conditions, useful GW momentum flux 207 measurements may also be possible with the other convenional meteor radars. 208 Following *F10b*, we employ real meteor spatial and temporal distributions observed by 209 SAAMER, DrAAMER, and the three other meteor radars during various months to evaluate the 210 measurement capabilities of each. Radial velocities at each meteor location and time for each

211 radar and each month assessed are specified by each of seven test velocity fields. Each test field 212 includes superposed mean, tidal, and/or GW velocity fields with constant and/or spatially- and 213 temporally-variable tidal and GW amplitudes that are intended to be representative of the scales, 214 amplitudes, and momentum fluxes in the MLT over SAAMER and DrAAMER. Mean, tidal, and 215 GW parameters defining these motion fields for each case are listed in Table 2. The test fields 216 are those employed by *F10b*, range from highly idealized and stationary to spatially and 217 temporally modulated at large and small scales, and have the following components: 218 $U(x,y,z,t) = U_M + U_D(z,t) \sin(2\pi t/T_D) + U_{SD}(z,t) \sin(2\pi t/T_{SD})$ 219 $+ U_{GW1}(x,y,z,t) \sin(k_1x + l_1y + m_1z - 2\pi t/T_{GW1})$ 220 $+ U_{GW2}(x,y,z,t) \sin(k_2x + l_2y + m_2z - 2\pi t/T_{GW2})$ 221 $+ U_{GW3}(x,y,z,t) \sin(k_3x + m_3z)$ (1) 222 $V(x.y.z,t) = V_M - V_D(z,t) \cos(2\pi t/T_D) - V_{SD}(z,t) \cos(2\pi t/T_{SD})$ 223 $+ V_{GW1}(x,y,z,t) \sin(k_1x + l_1y + m_1z - 2\pi t/T_{GW1})$ 224 $+ V_{GW2}(x,y,z,t) \sin(k_2x + l_2y + m_2z - 2\pi t/T_{GW2})$ 225 $+ V_{GW4}(x,y,z,t) \sin(l_4y + m_4z)$ (2) 226 $W(x,y,z,t) = W_{GW1}(x,y,z,t) \sin(k_1x + m_1z - 2\pi t/T_{GW1})$ 227 $+ W_{GW2}(x,y,z,t) \sin(k_2x + l_2y + m_2z - 2\pi t/T_{GW2})$ 228 $+ W_{GW3}(x,y,z,t) \sin(k_3x + m_3z)$ 229 $+ W_{GW4}(x,y,z,t) \sin(l_4y + m_4z)$ (3)

230 Note that we employ the same test cases defined by F10b, but these Eqs. (1-3) correct several 231 typos appearing in the equations presented in *F10b*. 232 Each test field includes some or all of the following components: 233 a. zonal and meridional mean winds, U_M and V_M, 234 b. diurnal and semidiurnal tides having zonal and meridional amplitudes of (U_D, V_D) 235 and (U_{SD}, V_{SD}) assumed to rotate counterclockwise with time (assuming a southern 236 hemisphere location), and which may have either constant or varying amplitudes with 237 increasing altitude, 238 c. traveling GWs having amplitudes (U_{GW}, V_{GW}, W_{GW}), zonal, meridional, or oblique 239 propagation, spatial and temporal variability, correlated horizontal and vertical 240 motions, and constant or variable momentum fluxes, and 241 d. stationary mountain waves (MWs) having zonal and meridional propagation, only 242 spatial variability, correlated horizontal and vertical motions, and constant 243 momentum fluxes. 244 In each case, the test field amplitudes were chosen to correspond roughly to measured 245 values over SAAMER and DrAAMER on TdF and KGI, which include large semidiurnal tides 246 and GW momentum fluxes [*F10a, F10b, F11*]. Large semidiurnal tide amplitudes at these sites 247 are consistent with expectations of the most recent version of the Global-Scale Wave Model 248 (GSWM-09) [*Zhang et al*., 2010a, b, *F11*]. Large GW momentum fluxes are suggested by the 249 major global hotspot of GW activity in the stratosphere and lower mesosphere centered over the 250 Southern Andes, Drake Passage, and Antarctic Peninsula [*F10a*, and references therein]. 251 **4 Evaluation of Radar Measurement Capabilities**

We describe here the performance of each of the five radars for the seven test cases described above. Mean winds, diurnal and semidiurnal tidal amplitudes, and GWs having prescribed spatial and/or temporal variability and momentum fluxes propagating zonally, meridionally, or at other azimuths are defined by Eqs. (1-3) for the seven cases listed in Table 2. Specified and recovered (*i.e.*, the velocity fields inferred from our S-transform tidal fits and the Hocking statistical analysis) profiles of the mean winds, diurnal and semidiurnal tides, and GWs momentum fluxes, and their daily and composite-day hourly variability, where appropriate, are discussed separately for each case below.

b.1. Case 1

Specified fields, and those recovered using observed meteor distributions in space and time for each radar for June 2009, 2010, or 2011 as described above, are shown as monthly means for Case 1 in Figure 3. In this case, tides have only temporal variations and GWs have only horizontal variations, with 50 and 100 km wavelengths in the zonal and meridional motions, respectively (see Table 2). As seen in Figure 3, agreement between specified and recovered fields is highly variable among the five radars. As might be expected based on meteor counts, mean winds and diurnal and semidiurnal tide amplitudes are recovered quite well at KGI, TdF, and BL. Mean winds and diurnal tide amplitudes are recovered within a few percent at each of these sites, with slightly greater uncertainties at BL than at the other two. Semidiurnal tide amplitudes are systematically less than specified at all three sites, but only by ~2-3% at TdF and BL, and by ~5% at KGI. Mean winds and tidal amplitudes exhibit similar tendencies and accuracies at SRO and YKF at the central altitudes, but increasing errors at the lowest and highest altitudes where meteor counts are small.

275 GW momentum flux estimates at KGI, TdF, and SRO are likewise accurate within ~10%, 276 except at KGI and TdF below 79.5 km. In contrast, SRO and YKF exhibit errors of ~20% or 277 larger at intermediate altitudes, again with larger errors where meteor counts are small. 278 ***b.2. Case 2*** 279 Case 2 includes no mean winds or tides and only a zonal stationary GW with prescribed 280 horizontal and vertical phase variations with wavelengths of 50 and 15 km (not physical, but 281 simple, see Table 2). Referring to Figure 4, we see that, as in Case 1, the recovered mean and 282 tidal motions are quite accurate at KGI, TdF, and BL, typically within ~2 ms^{-1} or better, except 283 for the tidal amplitudes at BL above ~92 km. Estimates at SRO and YKF are slightly less 284 accurate, within ~5 ms^{-1}, but nevertheless quite reasonable, except at the highest and lowest 285 altitudes, especially at YKF. 286 Unlike Case 1, all the radars except YKF provided accurate estimates of GW momentum 287 fluxes in this case, with the largest departures of only ~5 m^2s^{-2} at the highest and lowest altitudes 288 shown. However, meteor counts at YKF were apparently too small to yield adequate statistics, 289 except at the central altitudes having the highest meteor counts, from 82.5 to 88.5 km. The 290 significant differences in the accuracies of the GW momentum fluxes at all sites and in the mean 291 wind and tidal amplitudes between Cases 1 and 2 suggest a strong influence of large and variable 292 winds on the quantification of GW momentum fluxes, even for persistent and well-defined GWs. 293 These influences will be quantified further below and discussed in some detail in Section 5. 294 ***b.3. Case 3*** 295 Case 3 considers a motion field varying from that of Case 2 only in having two 296 orthogonal GWs, each of which has no phase variation in altitude or time and with the GW 297 propagating in the zonal plane having a large vertical velocity of 10 ms^{-1} (again not physical, but

298 simple). Results displayed in Figure 5 show that mean motions, tidal amplitudes, and GW 299 momentum fluxes are again described well with the meteor distributions for KGI, TdF, and BL, 300 and the mean motions and GW momentum fluxes are described reasonably at SRO and at YKF, 301 but with increasing errors in momentum fluxes at the higher altitudes. However, tidal amplitudes 302 now exhibit larger errors at SRO and YKF than seen in Case 2, with these motions reasonably 303 defined at ~85 to 92 km at YKF and in the zonal component at SRO, but poorly defined at lower 304 and higher altitudes at both these sites and even at central altitudes in the meridional components 305 at SRO. This cannot be a result of insufficient sampling of the mean and tidal motions, as they 306 are all zero. Instead, the cause appears to be the larger GW vertical velocities that are not 307 sufficiently averaged in defining large-scale (horizontal) winds, despite the validity of the 308 momentum flux estimates for stationary GWs at these sites (see further discussion in Section 5). 309 ***b.4. Case 4*** 310 We now consider a more complex superposition of mean, tidal, and GW fields given by 311 the sum of the mean and tidal motions in Case 1 and both stationary and propagating GWs in 312 both the zonal and meridional planes (see Table 2). This case differs from the previous cases in 313 that both zonal and meridional GW momentum fluxes now have contributions from stationary 314 and propagating GWs having different spatial structures (with horizontal wavelengths of 30, 40, 315 50, and 100 km). Case 4 also includes both large semidiurnal tide amplitudes and GW vertical 316 velocities that were suggested above to contribute to errors in the estimates of mean and tidal 317 amplitudes and GW momentum fluxes. Depending on the phases of the four GWs, vertical 318 motions may be ~15 ms^{-1} or larger in this case. 319 Results displayed in Figure 6 show that errors in estimates of the mean winds and tidal 320 amplitudes are comparable (and small) for Cases 1 and 4 at KGI, TdF, and BL. Semidiurnal tide

321 amplitudes are very slightly underestimated, with the largest errors of ~5% at KGI (note the 322 different scales in the third columns of Figures 3 and 6). As seen in Case 1, mean wind and tidal 323 amplitude estimates at SRO and YKF for Case 4 are also reasonable at central altitudes, but 324 exhibit greater errors at lower and/or higher altitudes and at central altitudes in the meridional 325 diurnal tide amplitudes. 326 Turning now to GW momentum flux estimates for Case 4, we see that these are very 327 good at KGI, TdF, and BL, with comparable errors (~a few $m^2 s^{-2}$) except at the highest and 328 lowest altitudes where they are somewhat larger. Similar estimates are also obtained at SRO and 329 YKF at central altitudes (with errors for Case 4 of ~10 $m^2 s^{-2}$ or less), with much larger errors 330 occurring at lower and higher altitudes. Apparently, mean winds and large tidal amplitudes do 331 not prevent accurate estimates of GW momentum fluxes when meteor counts are sufficiently 332 high and GWs are sufficiently sustained (whether stationary or propagating) to enable sampling 333 of all phases throughout the month. Large GW amplitudes (especially vertical velocities), 334 however, do cause errors in estimates of means winds and tidal amplitudes where meteor counts 335 are not sufficiently high. 336 ***b.5. Case 5*** 337 Case 5 explores a superposition of larger mean winds, a larger, but constant, diurnal tide, 338 a semidiurnal tide that exhibits both a 10-day amplitude modulation and amplitude growth with 339 altitude, and four superposed GWs. The latter include 1) stationary GWs having zonal and 340 meridional orientations, constant amplitudes and momentum fluxes, and horizontal wavelengths 341 of 30 and 40 km and 2) propagating GWs having zonal and meridional orientations, horizontal 342 wavelengths of 50 and 100 km, respectively, and amplitude (and momentum flux) modulation 343 by, and anti-correlations with, the semidiurnal tide amplitudes.

Results for Case 5 are displayed in four formats. Figure 7 shows monthly mean profiles of mean winds, tidal amplitudes, and GW momentum fluxes as discussed for Cases 1 to 4 above. Figure 8 displays daily estimates of mean winds and diurnal tide amplitudes throughout the month in the presence of variable semidiurnal tide and GW amplitudes. Figure 9 compares daily estimates of semidiurnal tide amplitudes with the specified variations. Hourly estimates of GW momentum fluxes throughout the composite day are compared with the specified variations in Figure 10. Results shown in Figure 7 reveal mean wind estimates (first column) that are very accurate at all radars (within ~1 ms^{-1} except at the lowest and highest altitudes at SRO and YKF). Diurnal tide amplitude estimates (second column) are likewise very good at TdF, nearly as good at KGI and BL (within ~1 to 2 ms^{-1}), and reasonable at central altitudes at YKF (within ~2 ms^{-1}). Somewhat larger errors (~5 ms^{-1}) are again seen in the meridional diurnal amplitude at SRO. Mean semidiurnal tide amplitude estimates (third column) are seen to be very precise at TdF and BL, to exhibit slight underestimates at KGI, and to have comparable errors about the specified mean amplitudes at SRO. Larger errors are seen at YKF (as large as ~5-10 ms^{-1}), but the amplitude growth with altitude is still captured at the central altitudes. Daily mean wind and diurnal tide amplitude estimates shown for Case 5 in Figure 8 are most accurate at TdF and BL (with RMS uncertainties of ~1 ms^{-1} or less) and somewhat less accurate at KGI (with RMS uncertainties of ~2 ms^{-1}), except at the lowest altitude at KGI and the lowest and highest altitudes at BL where meteor counts are small. Daily mean estimates are considerably less accurate at SRO and YKF due to the significantly smaller meteor counts at all altitudes and the asymmetric meteor distributions seen in Figure 1. RMS errors of these estimates range from a few ms^{-1} for the zonal components at central altitudes at SRO to ~100% or greater

367 uncertainties at YKF that render the latter useless in defining day-to-day variability in these 368 quantities. 369 Estimates of semidiurnal tide zonal and meridional amplitudes for each day in Case 5 at 370 3-km altitude intervals are displayed in the left and right panels of Figure 9. These estimates are 371 seen to be in close agreement with the specified values (dashed lines) at all but the lowest 372 altitude at TdF and the lowest and highest altitudes for KGI and BL. Estimates at SRO and YKF, 373 in contrast, are reasonably accurate at the central four altitudes, apart from sporadic departures of 374 ~20 to 60 ms^{-1} at these altitudes, primarily at YKF and in the meridional component at SRO. 375 Hourly estimates of zonal and meridional GW momentum fluxes for the Case 5 376 composite day at 3-km altitude intervals are shown in the left and right panels of Figure 10. 377 These are seen to be close approximations to the specified values at TdF for all but the lowest 378 and highest altitudes, and even to follow the semidiurnal momentum flux modulations at these 379 altitudes, but with larger uncertainties. The results for KGI and BL are comparable and also very 380 good, but exhibit somewhat larger fluctuations about the specified values than seen at TdF at the 381 central four altitudes altitudes and increasing uncertainties at KGI at 76.5, 79.5, and 97.5 km and 382 at BL at 76.5, 94.5, and 97.5 km. Composite day hourly momentum flux estimates for SRO and 383 YKF are seen to occasionally follow the specified semidiurnal modulation at 85.5, 88.5, and 91.5 384 km, but with very large uncertainties. At higher and lower altitudes, these estimates exhibit very 385 large errors. 386 ***b.6. Case 6*** 387 We now compare the ability of the five radars to define mean and tidal motions and GW 388 momentum fluxes for the motion field defined by Case 6 in Table 2. This case includes mean and 389 tidal motions representative of higher latitudes and two transient GW packets having propagation 390 to the east and north and that occur randomly for 3 and 4 hr each day. The two GWs have zonal 391 and meridional propagation, daily mean momentum fluxes of 50 and 25 m^2s^{-2}, and periods of 20 392 and 30 min, respectively. Both also have horizontal and vertical phase variations with 393 wavelengths given in Table 2. Inferred monthly mean winds, tidal amplitudes, and GW 394 momentum fluxes obtained with each radar are shown in Figure 11. Hourly estimates of zonal 395 and meridional GW momentum fluxes for a Case 6 composite day at 3-km altitude intervals are 396 shown in the left and right panels of Figure 12. Note here that the composite day momentum flux 397 variations are different for each radar in each component. Case 6 differs from Cases 1 and 4 in 398 having 1) different, but comparable, mean

motions, 2) stochastic rather than uniform (and 399 stationary) GWs, and 3) vertical phase variations of the GWs. 400 Monthly estimates of mean winds and tidal amplitudes shown in the three left columns of 401 Figure 11 have accuracies and biases that are very similar to those seen previously in Cases 1 402 and 4. Mean wind and diurnal tide amplitude estimates are again very accurate at TdF and nearly 403 as accurate at KGI and BL. Somewhat greater uncertainties are observed at SRO and YKF, but 404 even these are not larger than ~2 ms^{-1} except at the lowest and highest altitudes. Semidiurnal tide 405 amplitude estimates are also nearly identical to those obtained in Cases 1 and 4. Amplitudes are 406 again under-estimated by ~5% at KGI, SRO, and YKF, and by ~2% at TdF and BL. The similar 407 accuracies achieved in these three cases suggest that the greater intermittency of the larger 408 amplitude GWs in Case 6 does not impact the ability of these radars to provide reasonably 409 accurate definitions of the monthly mean and tidal fields. 410 GW momentum flux estimates shown in the right column of Figure 11 are seen to be 411 relatively more accurate at KGI, TdF, and BL, where uncertainties are ~10% or less at central 412 altitudes, but approach 20% at KGI and BL at the lowest and/or highest altitudes. Momentum

flux estimates are also relatively accurate at SRO and YKF at the central 2 to 4 altitudes having the highest meteor counts, but exhibit large errors at lower and higher altitudes where meteor counts are low. Accuracies at KGI, TdF, and BL are comparable to those seen in Case 1 for which GW amplitudes and momentum fluxes are smaller. However, accuracies are not as good as seen in Case 4 where the zonal momentum flux is largely determined by the stationary, large amplitude GW contributing the majority of the momentum flux. Diurnal variability of the composite day zonal and meridional momentum fluxes for each radar shown in Figure 12 reinforce the statements above about the monthly mean profiles. The TdF and BL radars capture the specified momentum flux distributions extremely well, but with slightly greater uncertainties at TdF at the highest altitude, at TdF and BL at the lowest altitude, and a greater loss of sensitivity at the highest altitudes at BL. Momentum flux estimates at KGI are slightly less precise than either TdF or BL at central and lower altitudes, but are somewhat better than at BL at the higher altitudes. In contrast, momentum flux estimates at SRO and YKF are only accurate at the central ~4 and 2 altitudes, respectively, and are susceptible to very large uncertainties below and above. These results suggest that high meteor counts (and more uniform sampling of the motion field) are essential in defining momentum fluxes when GWs are variable and tides achieve large amplitudes. In order to assess whether momentum flux estimates are negatively influenced by large tidal amplitudes, we also performed the same mean, tidal, and GW momentum flux assessments for Case 6, but with zero mean winds and tidal amplitudes. This yielded 1) very accurate mean wind estimates (except at the lower altitudes at YKF), 2) diurnal and semidiurnal tide amplitude estimates of ~1 ms^{-1} at KGI, TdF, and BL and ~2 ms^{-1} at the central altitudes at SRO and YKF, and 3) momentum flux estimates comparable to or slightly more accurate than with the tides

436 present, with the greatest improvements at SRO. Hourly estimates for the composite day without 437 mean winds and tides are likewise of comparable accuracy to those for the full field specified for 438 in Case 6 in Table 2. 439 ***b.7. Case 7*** 440 Case 7 is very similar to Case 6, with the same mean and tidal winds, but including two 441 intermittent large-amplitude GWs having propagation to the NE and SE. The GW propagating to 442 the NE occurs for 2 hr twice daily at random times; that propagating to the SE occurs for 1 hr 3 443 times daily at random times. The GWs have periods of 20 and 15 min and both horizontal and 444 vertical phase variations. Amplitudes and wavelengths of each are listed in Table 2. Together, 445 they result in mean zonal and meridional momentum fluxes of 75 and -25 $m^2 s^{-2}$, respectively. 446 Inferred monthly mean winds, tidal amplitudes, and GW momentum fluxes obtained with each 447 radar for Case 7 are shown in Figure 13. Figure 14 shows hourly estimates of zonal and 448 meridional GW momentum fluxes for a Case 7 composite day at 3-km altitude intervals. 449 Monthly mean wind, tidal amplitude, and GW momentum flux estimates for Case 450 7 are very similar to those seen in Case 6 above. Mean wind and diurnal tide amplitude estimates 451 are very accurate at KGI, TdF, and BL but exhibit larger errors at SRO and YKF at the highest 452 and lowest altitudes, respectively. Semidiurnal tides are under-estimated by ~5% at KGI, SRO, 453 and YKF, and by ~2% at TdF and BL, as in Case 6. However, larger errors are seen at SRO and 454 YKF at the highest and lowest altitudes, respectively, as seen for the mean winds and diurnal tide 455 amplitudes. GW momentum flux estimates also exhibit comparable accuracies to those in Case 456 6, suggesting that GW packet duration does not have a strong influence on the ability to define 457 these quantities. Finally, as for Case 6, we also performed these assessments with mean winds 458 and tidal amplitudes specified to be zero. Similar to the results for Case 6, this yielded 1) 459 extremely accurate mean wind estimates (except at the lower altitudes at YKF), 2) diurnal and 460 semidiurnal tide amplitude estimates of ~1-2 ms^{-1} at KGI, TdF, and BL and ~2-5 ms^{-1} at the 461 central altitudes at SRO and YKF, and 3) momentum flux estimates comparable to or slightly 462 more accurate than with the tides present. As in Case 6, hourly estimates for the composite day 463 without mean winds and tides are of comparable accuracy to those for the full field specified for 464 in Case 7 in Table 2. 465 **5 Summary and Discussion** 466 We have assessed the relative measurement accuracies of meteor radars having similar 467 frequencies (32.55 to 36.9 MHz) but different antenna configurations, peak power, and sampling 468 modes. Our

evaluation was performed with meteor distributions observed by five radars 469 extending from 62.1°S to 62.5°N obtained during June of 2009, 2010, or 2011 for which meteor 470 statistics tend to be better at northern than southern latitudes. Two of these radars, SAAMER on 471 Tierra del Fuego and DrAAMER on King George Island (53.8 and 62.1°S, respectively) were 472 specifically designed for enhanced measurement capabilities for large-scale motions and GW 473 momentum fluxes. This was accomplished in each case with an 8-Yagi transmitting array 474 directing power into 8 lobes centered at 35° zenith angles separated by 45° in azimuth. The other 475 three radars are conventional meteor radars at northern latitudes (see Figure 1). Our purpose was 476 to determine the relative abilities of different meteor radar configurations to recover specified 477 mean winds, diurnal and semidiurnal tide amplitudes, and GW momentum fluxes. 478 Seven test motion fields included various superpositions of constant mean winds, 479 constant and/or variable tidal amplitudes, and GWs having varying amplitudes, momentum 480 fluxes, scales, periods, propagation directions, and intermittencies. The test fields were sampled 481 according to the observed meteor distributions throughout the month for each radar assuming no 482 radial velocity, range, or angular uncertainties in the measurements. Only meteors at zenith 483 angles between 15 and 60° were used, due to the large altitude uncertainties accompanying ~1° 484 zenith angle uncertainties in angle-of-arrival estimates at larger zenith angles. The various fields 485 were estimated in 3-km altitude bins (centered from 76.5 to 94.5 km) using the method described 486 by *F10b*, in which mean winds and tidal amplitudes are determined by S-transform fits and 487 removed from each radial velocity distribution before application of the *Hocking* [2005] method. 488 For each case mean wind, tidal amplitude, and GW momentum flux profiles were determined for 489 monthly and/or daily intervals (as appropriate). Also estimated in cases having diurnal variations 490 in GW momentum fluxes were hourly profiles throughout a composite day. 491 Our evaluation of relative radar performance revealed the following: 492 1) measurement accuracies depend strongly on meteor counts and antenna beam patterns; 493 accuracies improve with higher meteor counts, smaller zenith angles, and more 494 symmetric beam patterns enabled by crossed antennas, 495 2) SAAMER (on TdF), having ~12,000 meteors/day between 15 and 60° zenith angles 496 (~120 meteors/hr in a 3-km altitude bin at ~90 km) performed best overall, yielding quite 497 accurate mean wind,

tidal amplitude, and GW momentum flux estimates for all test cases, 498 3) the BL meteor radar and DrAAMER (on KGI) performed comparably and very well, 499 despite DrAAMER having ~30% smaller meteor counts (~8,000 meteors/day compared 500 to ~12,000 total at BL, or ~80 and 120 meteors/hr in a 3-km altitude bin near the peak of 501 the meteor distribution); however, DrAAMER yielded a consistently larger under502 estimate of semidiurnal tide amplitudes (~5% rather than the ~2% seen at BL), and 503 4) the SRO and YKF meteor radars having 6 kW peak power and antenna with only one 504 polarization (having ~ 5,000 and 3,000 meteors/day, respectively, or 50 and 30 505 meteors/hr in 3 km) provided less accurate measurements and over more limited 506 altitudes; they nevertheless described monthly mean winds and tidal amplitudes 507 adequately, with the best results at central altitudes; monthly mean and hourly composite508 day GW momentum flux estimates were generally poor at lower and higher altitudes, but 509 reasonable at ~85 to 90 km. 510 More general conclusions obtained from inter-comparisons of our various cases include 511 the following: 512 5) momentum flux estimates are more accurate when tidal amplitudes are small (or zero) 513 and when GW amplitudes and momentum fluxes are large, 514 6) momentum flux estimates are not significantly impacted by complexity of the GW field, 515 including superposition, multiple scales and frequencies, and intermittency, 516 7) well configured radars (those having symmetric beam patterns (*e.g.,* crossed Yagis) 517 and/or more meteors at smaller zenith angles) capture daily and composite-day hourly 518 variability of total winds and GW MFs well at altitudes where meteor count are high, and 519 8) radars that have asymmetric beam patterns (crossed Yagis) and/or low meteor counts 520 (less than ~25 meteors/hr in 3 km) will likely exhibit significant biases in estimates of 521 daily mean winds and tidal amplitudes; they will likely also exhibit significant biases in 522 estimates of hourly composite-day GW momentum fluxes and variability of these fields 523 on longer time scales. 524 Our assessment of meteor radar performance above assumed no radial velocity, range, or 525 angle-of-arrival measurement uncertainties. Introducing such uncertainties would of course 526 degrade measurement accuracies to some degree in all cases. Here we assess the likely impacts

527 of such measurement uncertainties for the magnitudes of the mean, tidal, and GW motions and 528 momentum fluxes considered above. 529 If we assume that RMS radial velocity uncertainties are ~1 to 2 ms^{-1} (which is a 530 reasonable estimate for SAAMER), then these contributions to measured radial velocities are 531 significantly less than typical radial velocity magnitudes, given the mean winds and tidal and 532 GW amplitudes employed for our assessment. For meteors at the largest zenith angles, ~60°, 533 these uncertainties would contribute little to GW momentum flux assessments given their small 534 implied errors in vertical velocity contributions to radial velocity variance relative to the large 535 contributions by large horizontal velocities. These uncertainties at large zenith angles would also 536 contribute very small errors in estimates of mean and tidal motions, which are obtained by 537 averaging large horizontal motions rather than effectively differencing radial velocity variances 538 for GW momentum flux assessments. 539 At smaller zenith angles, there is a greater potential for influences of radial velocity 540 uncertainties, given that these angles provide greater sensitivity to the differential radial 541 velocities with azimuth that contribute to the momentum flux determination. The most sensitive 542 radars to such uncertainties will be those focusing transmitted power at small zenith angles, 543 specifically SAAMER and DrAAMER, both of which achieve maximum meteor counts at ~35° 544 zenith angles. 545 To assess qualitatively the impacts of radial velocity uncertainties on measurements of 546 GW momentum fluxes, we assume that all meteors occur at the 35° zenith angle of maximum 547 meteor counts for SAAMER and DrAAMER. We then evaluate the relative uncertainty of the 548 momentum flux assessment using the "dual-beam" analysis of *Vincent and Reid* [1983] for a GW

549 propagating zonally with superposed tidal winds and nominal radial velocity measurement 550 uncertainties. The east and west radial velocities are given by 551 $V_E = (u' + U_D + U_S)\sin\theta + w'\cos\theta \square \Delta v_E'$ (4) 552 and 553 $V_W = -(u' + U_D + U_S)\sin\theta + w'\cos\theta \square \Delta v_W'$ (5) 554 where u' and w' are the horizontal and vertical GW velocities, U_D and U_S are the zonal diurnal 555 and semidiurnal tidal motions (assuming negligible vertical tidal motions and no horizontal 556 phase variations), $\theta = 35^{\circ}$, $\Delta v_E'$ and $\Delta v_W'$ are the radial velocity uncertainties, and angle 557 brackets denote temporal averaging. Assuming all of the velocities in Eqs. (4) and (5) are 558 uncorrelated except for u' and w', which are in phase or antiphase, squaring, subtracting Eq. (5) 559 from Eq. (4), and rearranging, the measured momentum flux may be written as 560 $\langle u'w'\rangle_M = (V_E^2 - V_W^2 + \Delta v_E'^2 - \Delta v_W'^2)/2\sin(2\theta)$ (6) 561 $= \langle u'w'\rangle_T + (\Delta v_E'^2 - \Delta v_W'^2)/2\sin(2\theta)$ 562 where $\langle u'w'\rangle_T$ is the true GW zonal momentum flux for the specified motion field. The 563 fractional uncertainty in the measured momentum flux is then 564 $\Delta\langle u'w'\rangle/\langle u'w'\rangle_T = (\Delta v_E'^2 - \Delta v_W'^2)/[\langle u'w'\rangle_T\, 2\sin(2\theta)]$ (7) 565 Thus, fractional uncertainties are minimized if radial velocity uncertainty variances are small 566 relative to the true GW momentum flux, as $2\sin(2\theta) = 1.88$ for the zenith angle specified. The 567 largest magnitude of the numerator occurs if the radial velocity uncertainty variance is negligible 568 in one beam. But for the uncertainties assumed above, this is $\Delta v'^2 \sim 3\ m^2 s^{-2}$, with likely values 569 significantly smaller. By comparison, mean GW momentum fluxes in the MLT are typically ~10 570 $m^2 s^{-2}$, with peak values ~3 to 10 times larger, at most locations, with values over the Drake 571 Passage "hotspot" expected (and measured, see *F10b*) to be ~2 to 5 times larger. These values

572 suggest a maximum fractional uncertainty of the momentum flux due to radial velocity 573 uncertainties of ~15% at typical sites and ~5% in GW source hotspots. 574 We anticipate range uncertainties comparable to the range resolution of 2 km and angle575 of-arrival uncertainties of ~1° in zenith angle and ~1.5° in azimuth. These imply that altitude 576 uncertainties are defined by zenith angle uncertainties near zenith angles of ~60° and by range 577 uncertainties at smaller zenith angles. At all zenith angles, however, these values suggest altitude 578 uncertainties comparable to or smaller than our chosen 3-km altitude bin. Thus range and angle579 of-arrival uncertainties appear unlikely to significantly impact measurements of mean and tidal 580 winds having large vertical scales or GW momentum fluxes that rely most on radial velocities 581 occurring at smaller zenith angles. These results suggest that measurement uncertainties are 582 likely to contribute much less to momentum flux uncertainties than inadequate definition of the 583 mean, tidal, and GW fields due to low meteor counts arising due to low radar sensitivity or small 584 averaging intervals and/or range bins. 585 Several previous studies have assessed the potential for momentum flux measurement 586 uncertainties due to inadequate sampling of the motion field. *Kudeki and Franke* [1998] and 587 *Thorsen et al*. [2000] evaluated momentum flux measurements employing the "dual-beam" 588 technique and concluded that very long averaging intervals were required to achieve statistical 589 significance. *Kudeki and Franke* [1998] assumed the GW velocity fields to be defined by 590 Gaussian distributions with a net momentum flux equal to 1% of that assuming a single GW was 591 present and inferred a required integration time of 16 days. This assumption, however, is in 592 contradiction to the strong correlations among component velocities that often occur when one or 593 several large-amplitude GWs dominate the high-frequency motion field and the total momentum 594 flux, as is often observed. In such cases, the averaging time implied by the *Kudeki and Franke*

595 [1998] would decrease by 2 decades or more. Examples of dual-beam or multiple-beam 596 measurements employing MF, VHF, and UHF radars that provide clear evidence for significant 597 and variable GW momentum fluxes (magnitudes as large as ~70 $m^2 s^{-2}$) occurring on time scales 598 as short as a few hours or less include the following: 599 1) MLT measurements with the MF radar at Buckland Park, Australia showing clear diurnal 600 tide modulation of GW momentum fluxes with a modulation amplitude of ~30 $m^2 s^{-2}$ 601 [*Fritts and Vincent*, 1987], 602 2) MLT measurements with the SOUSY VHF radar at Andoya, Norway revealing 603 momentum fluxes (per unit density) of ~66 $m^2 s^{-2}$ over ~3 hours [*Reid et al*., 1988], 604 3) troposphere and stratosphere measurements using the MU VHF radar at Shigaraki, Japan 605 for multi-beam measurements of GW momentum fluxes over 6 days that exhibit clear 606 episodic enhancements as short as an hour simultaneously in multiple beams and 607 spanning multiple altitudes [*Fritts et al*., 1990], 608 4) MLT measurements employing the former VHF radar at Poker Flat, Alaska that revealed 609 clear anti-correlations between diurnal and semidiurnal tide winds and GW momentum 610 fluxes over 4 and 16 day intervals exhibiting stronger momentum flux modulations (~5 to 611 10 $m^2 s^{-2}$) accompanying larger tidal amplitudes [*Wang and Fritts*, 1991], 612 5) MLT measurements spanning two 10-day intervals with the Jicamarca VHF radar in Peru 613 that exhibit daily mean momentum fluxes of ~10 $m^2 s^{-2}$ and maxima of ~30 $m^2 s^{-2}$, with 614 hourly profiles exhibiting significant coherence in altitude and time and maximum 615 magnitudes of ~60 $m^2 s^{-2}$ [*Fritts et al*., 1992],

616 6) MLT measurements with the MF radar at Buckland Park, Australia exhibiting clear 617 diurnal modulation of GW momentum fluxes by a large-amplitude 2-day wave [*Murphy* 618 *and Vincent*, 1998], 619 7) MLT measurements employing the dual-beam Arecibo UHF radar that revealed variable 620 GW momentum fluxes often near zero, but exhibiting occasional maxima as large as ~50 621 $m^2 s^{-2}$, that were largely anti-correlated with the large-scale wind field [*Fritts et al*., 622 2006b], and 623 8) MLT measurements spanning ~8 hr employing the Arecibo UHF radar that revealed very 624 significant GW activity, but with momentum fluxes that were very small, suggesting 625 ducting [*Fritts and Janches*, 2008]. 626 A more recent study by *Vincent et al*. [2010] employed numerical simulations of test GW 627 fields with a statistical model of radial velocity and angle-of-arrival uncertainties to evaluate the 628 accuracy of meteor radar measurements of mean winds and GW velocity variances and 629 momentum fluxes as functions of the meteor rate within a 2-km range bin. These authors 630 concluded that mean winds could be determined with relatively few meteors, but that estimation 631 of GW variances, and especially momentum fluxes, with small uncertainties required 632 considerable averaging enabling large meteor counts. The meteor counts employed to assess 633 measurement capabilities in the study ranged from 10 to 200. 634 By comparison, our assessment above assumed a need for significant meteor counts, with 635 the typical averaging interval for definition of mean and tidal winds and GW momentum fluxes 636 being a month, but with mean wind and semidiurnal tide assessments also evaluated for one day 637 or for one hour of a composite day for the month (hence 24 or 30 hr of data). Employing real 638 meteor distributions observed during a test month for each of five radars (June of 2009, 2010, or

639 2011), these yielded meteor counts in a 3-km altitude bin at the peak of the meteor distribution 640 for the month of ~80,000 at TdF, ~70,000 at BL, ~40,000 at KGI, and ~25,000 at SRO and YKF. 641 Meteor counts at the upper and lower edges of these distributions varied by radar, but were 642 typically smaller by ~2 to 4 times. Daily and composite-day hourly assessments employed ~3 643 and 4% of these meteor counts, respectively. Thus, in all cases, our meteor counts for each radar 644 were significantly larger than those assessed by *Vincent et al*. [2010] near the peak of the meteor 645 distribution. 646 Assuming that accuracies vary as the signal-to-noise ratio (S/N) and thus as $N^{1/2}$, where N 647 is the meteor count, we can compare our inferred accuracies with those of *Vincent et al*. [2010]. 648 As noted above, the radars at BL, TdF, and KGI have peak monthly meteor counts of N ~40,000 649 to 80,000 in a 3-km altitude bin, with N ~10,000 to 25,000 at the edges of the distributions. 650 These imply reductions by factors of ~15 to 25 in the mean wind measurement errors at the 651 meteor distribution peak relative to the 5 ms^{-1} uncertainties displayed by *Vincent et al*. [2010] in 652 Table 1, with reductions by factors of ~10 at the highest and lowest altitudes. Inspection of the 653 monthly mean winds for the seven cases considered above suggests that our results are largely 654 consistent with that expectation. Similarly, we expect error reductions of ~4 and 2 in the center 655 and edge regions for daily mean winds, implying errors of ~1 to 3 ms^{-1}. These are largely 656 consistent with the daily mean winds inferred for our Case 5 test fields displayed in Figure 8. 657 Finally, meteor counts at SRO and YKF suggest monthly mean wind uncertainties smaller than 658 the ~5 ms^{-1} uncertainties of *Vincent et al*. [2010] by ~12 and 5 in the center and edge regions. In 659 these cases, our uncertainties seem to be comparable to, or somewhat larger than, those expected. 660 We note, however, that the antenna patterns implied by the meteor locations shown in Figure 1 661 suggest significant asymmetries that likely also contribute to measurement errors.

Applying the same factors to our momentum flux estimates, we expect to see errors of 663 ~10 and 25% for the monthly means at the center and the edges of these distributions. Again, our 664 results are consistent with these expectations, though with variations that depend on the 665 complexity of our motions fields and the meteor distribution of each radar. Note, in particular, 666 that *Vincent et al*. [2010] did not include tidal winds in their assessment, but that variable tidal 667 winds can induce apparent mean winds and GW momentum fluxes if the meteor distribution is 668 not approximately uniform in space and time. Our results also are relatively more accurate for 669 cases having constant GW character throughout the month; they are less accurate for Cases 6 and 670 7 for which GWs are randomly distributed and likely more similar to the GW spectra specified 671 by *Vincent et al*. [2010]. We cannot assess the contributions of the assumed radial velocity and 672 angle-of-arrival uncertainties employed by *Vincent et al*. [2010] to the overall uncertainties 673 displayed in their Table 1. However, our own assessment of radial velocity uncertainties above 674 suggests that the majority of the measurement errors seen in our results can be attributed 675 primarily to the expected dependence on meteor counts. 676 677 **6 Conclusions** 678 Our assessment of meteor radar measurement capabilities presented in previous sections 679 has demonstrated both 680 1) clear capabilities for quantitative measurements of mean winds, tides, and GW 681 momentum fluxes by radars that achieve sufficiently high meteor counts and provide 682 sensitivity to radial velocities at sufficiently small zenith angles, and 683 2) strong dependence of these measurement capabilities on radar power, beam geometry and 684 sensitivity, and spatial and temporal meteor distributions.

685 Meteor radars that combine high power, high meteor counts at small zenith angles, and 686 symmetric beam patterns exhibit the smallest measurement errors. Those having low power, 687 acquiring a majority of meteor detections at large zenith angles, and/or experiencing beam or 688 meteor detection asymmetries exhibit much larger measurement uncertainties, thus either 689 requiring longer averaging intervals or precluding the more challenging measurements, 690 especially estimations of GW momentum fluxes. 691 Monthly mean winds can typically be measured to within 1 ms^{-1} over ~15 to 20 km, with 692 maximum accuracies between ~85 and 90 km, for radar frequencies near 35 MHz and having 693 higher power that conventional meteor radars. These radars can also provide daily mean winds 694 having accuracies of ~1 to 3 ms^{-1} where meteor counts are sufficient, even in the presence of 695 large tidal motions. Monthly mean diurnal and semidiurnal tide amplitudes are also recovered 696 very well by higher-power meteor radars, but typically with amplitude under-estimates of a few 697 %. Mean winds and tidal amplitudes are recovered much more accurately, however, by meteor 698 radars that achieve high meteor counts at small zenith angles compared to meteor radars 699 achieving the same meteor counts, but at larger zenith angles. 700 GW momentum flux estimates are challenging for meteor radars because of the large 701 number of meteors required to adequately resolve differences in radial velocity variances at 702 opposite azimuths. Nevertheless, accurate estimates over sufficiently long time scales (typically 703 averages over ~1 to 30 days) appear to be possible with sufficient meteor counts (~2,000 to 704 60,000 in an altitude bin). Accuracies are also enhanced with high meteor counts at small zenith 705 angles, given the greater sensitivity of these radial velocities to the correlations between 706 horizontal and vertical velocities within the GW field. Importantly, meteor radars appear to 707 measure momentum fluxes for stationary and propagating GWs, for complex GW 708 superpositions, and for GW fields exhibiting significant intermittency equally well on monthly 709 time scales. 710 **Acknowledgments**

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720 Acott, P., 2009: Mesospheric momentum flux studies over Fort Collins, CO, Ph.D. dissertation, 721 Colorado State University, 2009. 722 Antonita, T. M., G. Ramkumar, K. K. Kumar, and V. Deepa, 2008: Meteor wind radar 723 observations of gravity wave momentum fluxes and their forcing toward the Mesospheric 724 Semiannual Oscillation, J. Geophys. Res., 113, D10115, doi:10.1029/2007JD009089. 725 Clemesha, B. R., P. Batista, R. A. Buriti da Costa, and N. Schuch, 2009: Seasonal variations in 726 gravity wave activity at three locations in Brazil, Ann. Geophys., 27, 1059–1065. 727 Brown, P. R. A., 1983: Aircraft measurements of mountain waves and their associated 728 momentum flux over the British Isles, Q. J. Roy. Met. Soc., 109, 849-865. 729 Ern, M., P. Preusse, M. J. Alexander, and C. D. Warner, 2004: Absolute values of gravity wave 730 momentum flux derived from satellite data, J. Geophys. Res., 109, D20103,

731 doi:10.1029/2004JD004752. 732 Espy, P. J., R. E. Hibbins, G. R. Swenson, J. Tang, M. J. Taylor, D. M. Riggin, and D. C. Fritts, 733 2006: Regional variations of mesospheric gravity-wave momentum flux over Antarctica, 734 Ann. Geophys., 24, SRef-ID: 1432-0576/ag/2006-24-81, 81–88. 735 Espy, P. J., G. O. L. Jones, G. R. Swenson, and M. J. Taylor, 2004: Tidal modulation of the 736 gravity-wave momentum flux in the Antarctic mesosphere, Geophys. Res. Lett., 31, L11111, 737 doi:10.1029/2004GL019624. 738 Fritts, D. C., and M. J. Alexander, 2003:A review of gravity wave dynamics and effects in the middle 739 atmosphere, *Rev. Geophys*., **41**, doi:10.1029/2001RG000106. 740 Fritts, D. C., and D. Janches, 2008: Dual-beam measurements of gravity wave momentum fluxes 741 over Arecibo: Re-evaluation of wave structure, dynamics, and momentum fluxes, J. 742 Geophys. Res., 113, D05112, doi:10.1029/2007JD008896. 743 Fritts, D. C., D. Janches, and W. K. Hocking, 2010b: Southern Argentina agile meteor radar 744 (SAAMER): Initial assessment of gravity wave momentum fluxes, J. Geophys. Res., 115, 745 D19123, doi:10.1029/2010JD013891. 746 Fritts, D. C., D. Janches, H. Iimura, W. K. Hocking, and J. V. Bageston, and N. M. Pene, 2011: 747 Drake Antarctic Agile Meteor Radar (DrAAMER) First Results: Configuration and 748 Comparison of Mean and Tidal Wind and Gravity Wave Momentum Flux Measurements 749 with SAAMER, J. Geophys. Res., submitted. 750 Fritts, D. C., D. Janches, H. Iimura, W. K. Hocking, N. J. Mitchell, B. Fuller, B. Vandepeer, J. 751 Hormaechea, C. Brunini, and H. Levato, 2010a: Southern Argentina agile meteor radar 752 (SAAMER): System design and initial measurements of large-scale winds and tides, J. 753 Geophys. Res., 115, D18112, doi:10.1029/2010JD013850.

754 Fritts, D. C., D. Janches, D. M. Riggin, R. G. Stockwell, M. P. Sulzer, and S. Gonzalez, 2006b: 755 Gravity waves and momentum fluxes in the MLT using 430 MHz dual-beam measurements 756 at Arecibo: 2. Frequency spectra, momentum fluxes, and variability, J. Geophys. Res., 111, 757 D18108, doi:10.1029/2005JD006883. 758 Fritts, D. C., and T. Lund, 2011: Gravity wave influences in the thermosphere and ionosphere: 759 Observations and recent modeling, Aeronomy of the Earth's Atmosphere and Ionosphere, M. 760 Abdu and D. Pancheva, Eds., Springer, 109-130. 761 Fritts, D. C., T. Tsuda, T. E. VanZandt, S. A. Smith, T. Sato, S. Fukao, and S. Kato, 1990: 762 Studies of velocity fluctuations in the lower atmosphere using the MU radar: II. Momentum 763 fluxes and energy densities. J. Atmos. Sci., 47, 51-66. 764 Fritts, D. C., S. L. Vadas, K. Wan, and J. A. Werne, 2006a: Mean and variable forcing of the 765 middle atmosphere by gravity waves, J. Atmos. Solar-Terres. Phys., 68, 247-265. 766 Fritts, D. C., S. A. Vadas, and Y. Yamada, 2002: An estimate of strong local gravity wave body 767 forcing based on OH airglow and meteor radar observations, Geophys. Res. Lett., 29 (10), 768 10.1029/2001GL013753. 769 Fritts, D. C., and R. A. Vincent, 1987: Mesospheric momentum flux studies at Adelaide, 770 Australia: Observations and a gravity wave/tidal interaction model, J. Atmos. Sci., 44, 605771 619. 772 Fritts, D. C., and L. Yuan, 1989: Measurement of momentum fluxes near the summer 773 mesopause at Poker Flat, Alaska, J. Atmos. Sci., 46, 2569-2579. 774 Fritts, D. C., L. Yuan, M. H. Hitchman, L. Coy, E. Kudeki, and R. F. Woodman, 1992: 775 Dynamics of the equatorial mesosphere observed using the Jicamarca MST radar during June 776 and August 1987, J. Atmos. Sci., 49, 2353-2371.

777 Fukao, S., T. Sato, T. Tsuda, and S. Kato, 1988: VHF Doppler Radar Determination of the 778 Momentum Flux in the Upper Troposphere and Lower Stratosphere: Comparison between 779 the Three- and Four-Beam Methods, J. Atmos. Ocean. Tech., 5(1), 57-69. 780 Hertzog, A., G. Boccara, R. A. Vincent, F. Vial, P. Cocquerez, 2008: Estimation of Gravity Wave 781 Momentum Flux and Phase Speeds from Quasi-Lagrangian Stratospheric Balloon Flights. Part II: 782 Results from the Vorcore Campaign in Antarctica, J. Atmos., Sci., 65, 3056-3070, 783 doi:10.1175/JAS2710.1. 784 Hertzog, A., and F. Vial, 2001: A study of the dynamics of the equatorial lower stratosphere by use 785 of ultra-long-duration balloons, J. Geophys. Res., 106, 22,745-22,761. 786 Hitchman, M. H., K. W. Bywaters, D. C. Fritts, L. Coy, and E. Kudeki, 1992: Mean winds and 787 momentum fluxes over Jicamarca, Peru during June and August 1987, J. Atmos. Sci., 49, 788 2372-2383. 789 Hines, C. O., 1960: Internal gravity waves at ionospheric heights, Can. J. Phys. 38(11): 1441– 790 1481, 1960. 791 Hocke, K. and K. Schlegel, 1996: A review of atmospheric gravity waves and traveling 792 ionospheric disturbances: 1982–1995, Ann. Geophys., 14, 917–940. 793 Hocking, W. K., 2005: A new approach to momentum flux determinations using SKiYMET 794 meteor radars, An. Geophys., 23, 1–7. 795 Hocking, W.K., 2005: A new approach to momentum flux determinations using SKiYMET 796 meteor radars, Ann. Geophysicae, 23, 2433-2439. 797 Hocking, W.K. and G. Kishore Kumar, 2011: Long Term Behaviour of the MLT Quasi 7 day 798 Wave at two Radar-sites at Northern Polar Latitudes, J. Atmos. Solar Terr. Phys., 73, 1616– 799 1628. 800 Kim, Y.-J., S. D. Eckermann, and H.-Y. Chun, 2003: A overview of the past, present and future

801 of gravity-wave drag parameterization for numerical climate and weather prediction models, 802 Atmos. Ocean, 41, 65-98. 803 Kudeki, E., and S. J. Franke, 1998: Statistics of momentum flux estimation, J. Atmos. Solar804 Terres. Phys., 60, 1549-1553. 805 Kumar, K. K., T. M. Antonita, and S. T. Shelbi, 2007: Initial results from SKiYMET meteor 806 radar at Thumba (8.5°N, 77°E): 2. Gravity wave observations in the MLT region, Radio Sci., 807 42, RS6009, doi:10.1029/ 2006RS003553. 808 Lighthill, M. J., 1978: Waves in Fluids, Cambridge University Press, Cambridge, England. 809 Lilly, D. K., and P. J. Kennedy, 1973: Observations of a stationary mountain wave and its 810 associated momentum flux and energy dissipation, J. Atmos. Sci., 30(6), 1135-1152. 811 Lilly, D. K., J. M. Nicolls, P. J. Kennedy, J. B. Klemp, and R. M. Chervin, 1982: Aircraft 812 measurements of wave momentum fluxes over the Colorado Rocky Mountains, Q. J. Roy. 813 Met. Soc., 108, 625-642. 814 McIntyre, M. E., 1989: On dynamics and transport near the polar mesopause in summer. J. 815 Geophys. Res., 94, 14,617-14,628. 816 Meyer, W., R. Siebenmorgen, and H.-U. Widdel, 1989: Estimates of gravity wave momentum 817 fluxes in the winter and summer high mesosphere over Scandinavia, J. Atmos. Terres., Phys., 818 51(4), 311-319. 819 Mitchell, N. J., and C. L. Beldon, 2009: Gravity waves in the mesopause region observed by 820 meteor radar: 1. A simple measurement technique, J. Atmos. Sol. Terr. Phys., 71, 866–874. 821 Murayama, Y., T. Tsuda, and S. Fukao, 1994: Seasonal variation of gravity wave activity in the 822 lower atmosphere observed with the MU radar, J. Geophys. Res., 99(D11), 23,057–23,069.

823 Murphy, D. J., and R. A. Vincent, 1993: Estimates of momentum flux in the mesosphere and 824 lowere thermosphere over Adelaide, Australia, from March 1985 to February 1986, J. 825 Geophys. Res., 98(D10), 18,617-18,638. 826 Murphy, D. J., and R. A. Vincent, 1998: Mesospheric momentum fluxes over Adelaide during 827 the 2-day wave: Results and interpretation, J. Geophys. Res., 103(D22), 28,627–28,636, 828 doi:10.1029/1998JD200001. 829 Nakamura, T., T. Tsuda, M. Yamamoto, S. Fukao, and S. Kato, 1993: Characteristics of Gravity 830 Waves in the Mesosphere Observed With the Middle and Upper Atmosphere Radar 1. 831 Momentum Flux, J. Geophys. Res., 98(D5), 8899–8910. 832 Nappo, C. J., 2002: An Introduction to Atmospheric Gravity Waves, Academic Press. 833 Nastrom, G. D., and D. C. Fritts, 1992: Sources of mesoscale variability of gravity waves, I: 834 Topographic excitation, J. Atmos. Sci., 49, 101-110. 835 Placke, M., P. Hoffmann, E. Becker, C. Jacobi, W. Singer, and M. Rapp, 2011: Gravity wave 836 momentum fluxes in the MLT—Part II: Meteor radar investigations at high and midlatitudes 837 in comparison with modeling studies, J. Atmos. Solar-Terres. Phys., 73, 911-920. 838 Reid, I. M., and R. A. Vincent, 1987: Measurements of mesospheric gravity wave momentum 839 fluxes and mean flow accelerations at Adelaide, Australia. J. Atmos. Terres. Phys., 49, 443840 460. 841 Reid, I. M., R. Rüster, P. Czechowsky, and G. Schmidt, 1988: VHF radar measurements of 842 momentum flux in the summer polar mesosphere over Andenes (69o N, 16o E), Norway, 843 Geophys. Res. Lett., 15, 1263-1266. 844 Sato, K., 1990: Vertical Wind Disturbances in the Troposphere and Lower Stratosphere 845 Observed by the MU Radar, J. Atmos. Sci., 47(23), 2803-2817.

846 Sato, K., 1993: Small-Scale Wind Disturbances Observed by the MU Radar during the Passage 847 of Typhoon Kelly, J. Atmos. Sci., 50(4), 518-537. 848 Sato, K., 1994: A statistical study of the structure, saturation and sources of inertio-gravity waves 849 in the lower stratosphere observed with the MU radar, J. Atmos. Terres. Phys., 56 (6), 755850 774. 851 Smith, R. B., B. K. Woods, J. Jensen, W. A. Cooper, J. D. Doyle, Q. Jiang, and V. Grubisic, 852 2008: Mountain waves entering the stratosphere, J. Atmos. Sci., 65, 2543-2562, 853 doi:10.1175/2007JAS2598.1. 854 Swenson, G. R., R. Haque, W. Yang, and C. S. Gardner, 1999: Momentum and energy fluxes of 855 monochromatic gravity waves observed by an OH imager at Starfire Optical Range, New 856 Mexico, J. Geophys. Res., 104(D6), 6067–6080, doi:10.1029/1998JD200080. 857 Thorsen, D., S. J. Franke, and E. Kudeki, 2000: Statistics of momentum flux estimation using the 858 dual coplanar beam technique, *Geophys. Res. Lett*., **27**, 3193-3196. 859 Tsuda, T., Y. Murayama, M. Yamamoto, S. Kato, and S. Fukao, 1990: Seasonal variation of 860 momentum flux in the mesosphere observed with the MU radar. Geophys. Res. Lett., 17, 861 725-728. 862 Vincent, R. A., S. Kovalam, I. M. Reid, and J. P. Younger, 2010: Gravity wave flux retrievals 863 using meteor radars, Geophys. Res. Lett., 37, L14802, doi:10.1029/2010GL044086. 864 Vincent, R.A., I. M. Reid, 1983: HF Doppler measurements of mesospheric momentum fluxes. 865 Journal of Atmospheric Science40, 1321–1333. 866 Wang, D.-Y., and D. C. Fritts, 1990: Mesospheric momentum fluxes observed by the MST radar 867 at Poker Flat, Alaska, J. Atmos. Sci., 47, 1511-1521.

Wang, D.-Y., and D. C. Fritts, 1991: Evidence of gravity wave-tidal interaction observed near the summer mesopause at Poker Flat, Alaska, J. Atmos. Sci.,48, 572-583.

Zhang, X.,J. M. Forbes, and M. E. Hagan, 2010a: Longitudinal variation of tides in the MLT region: 1. Tides driven by tropospheric net radiative heating, J. Geophys. Res. (Space Physics), 115, 6316, doi:10.1029/2009JA014897.

Zhang, X.,J. M. Forbes, and M. E. Hagan, 2010b: Longitudinal variation of tides in the MLT region: 2. Relative effectis of solar radiative and latent heating, J. Geophys. Res. (Space Physics), 115, 6317, doi:10.1029/2009JA014898.

radar	location (lat/long)	frequency, bandwidth	peak power	resol.	TX/RX ants.	PRF (Hz)	coding, integr.	meteors /day
DrAAMER (KGI)	(62.1$_o$S, 58.7$_o$W)	36.9 MHz, 35-125 kHz	30 kW	2 km	8/5, 3-ele. cross. Yagis	1730	2 bit, 4 samp.	~9,000
SAAMER	(53.8$_o$S,	32.55 MHz,	60 kW	2 km	8/8, 3-ele.	2144,	2 bit, 4	~14,000

Wang, D.-Y., and D. C. Fritts, 1991: Evidence of gravity wave-tidal interaction observed near the summer mesopause at Poker Flat, Alaska, J. Atmos. Sci.,48, 572-583.

Zhang, X.,J. M. Forbes, and M. E. Hagan, 2010a: Longitudinal variation of tides in the MLT region: 1. Tides driven by tropospheric net radiative heating, J. Geophys. Res. (Space Physics), 115, 6316, doi:10.1029/2009JA014897.

Zhang, X.,J. M. Forbes, and M. E. Hagan, 2010b: Longitudinal variation of tides in the MLT region: 2. Relative effectis of solar radiative and latent heating, J. Geophys. Res. (Space Physics), 115, 6317, doi:10.1029/2009JA014898.

Table 1. Radar characteristics for the five radars employed in this evaluation of measurement capabilities. Meteor counts for zenith angles between 15 and 50° are ~50% of the total counts (right column) for KGI and TdF and ~30% of the total counts for the other radars.

Table 2. Mean, tidal, and GW parameters used for test cases evaluating radar measurement capabilities

employing real meteor distributions and test motion fields. Mean GW momentum

Wang, D.-Y., and D. C. Fritts, 1991: Evidence of gravity wave-tidal interaction observed near the summer mesopause at Poker Flat, Alaska, J. Atmos. Sci.,48, 572-583.

Zhang, X.,J. M. Forbes, and M. E. Hagan, 2010a: Longitudinal variation of tides in the MLT region: 1. Tides driven by tropospheric net radiative heating, J. Geophys. Res. (Space Physics), 115, 6316, doi:10.1029/2009JA014897.

Zhang, X.,J. M. Forbes, and M. E. Hagan, 2010b: Longitudinal variation of tides in the MLT region: 2. Relative effectis of solar radiative and latent heating, J. Geophys. Res. (Space Physics), 115, 6317, doi:10.1029/2009JA014898.

radar	**location (lat/long)**	**frequency, bandwidth**	**peak power**	**resol.**	**TX/RX ants.**	**PRF (Hz)**	**coding, integr.**	**meteors /day**
DrAAMER (KGI)	(62.1^{o}S, 58.7^{o}W)	36.9 MHz, 35-125 kHz	30 kW	2 km	8/5, 3-ele. cross. Yagis	1730	2 bit, 4 samp.	~9,000
SAAMER (TdF)	(53.8^{o}S, 67.7^{o}W)	32.55 MHz, 50-250 kHz	60 kW	2 km	8/8, 3-ele. cross. Yagis	2144, 1730	2 bit, 4 samp.	~14,000
Socorro, NM (SOC)	(34.1^{o}N, 106.9^{o}W)	35.24 MHz, 35-125 kHz	6 kW	2 km	1/5, 2-ele. Yagis	2140	1 bit, 8 samp.	~5,000
Bear Lake, UT (BLO)	(41.9^{o}N, 111.4^{o}W)	35.24 MHz, 50-250 kHz	12 kW	2 km	1/5, 2-ele. cross. Yagis	2140	1 bit, 4 samp.	~11,000
Yellowknife, Canada (YK)	(62.5^{o}N, 114.3^{o}W)	35.65 MHz, 50-125 kHz	6 kW	2 km	1/5, 2-ele. Yagis	2140	1 bit, 8 samp.	~2,500

Parameter	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**
U_M, V_M	20, 10	0, 0	0, 0	20, 10	40, -20	-20, -10	-20, -10
U_D, V_D	10, 10	0, 0	0, 0	10, 10	20, 20	10, 10	10, 10
U_{SD}, V_{SD}	50, 50	0, 0	0, 0	50, 50	20+2(z - 80)sin$_2$(πt/T_M)	50, 50	50, 50
U_{GW1} V_{GW1} W_{GW1} k_1 l_1 m_1 T_{GW1}	10 0 5 2π/50 0 0 20	20 0 5 2π/50 0 2π/15 ∞	20 0 -10 2π/30 0 0 ∞	10 0 5 2π/50 0 0 20	20 abs[sin(2πt/T_M)] *sin(2πt/T_{SD}) 0 -10 abs[sin(2πt/T_M)] *abs[sin(2πt/T_{SD})] 2π/50 0 0 20	40F_6(t) 0 20F_6 (t) 2π/50 0 2π/15 20	30F_7(t) 30F_7(t) 10F_7 (t) 2π/40 2π/40 2π/15 20
U_{GW2} V_{GW2} W_{GW2} k_2 l_2 m_2 T_{GW2}	0 20 2 0 2π/100 0 30	--	0 10 2 0 2π/40 0 ∞	0 20 2 0 2π/100 0 30	0 20 abs[sin(2πt/T_M)] *cos(2πt/T_{SD}) 5 abs[sin(2πt/T_M)] *abs[cos(2πt/T_{SD})] 0 2π/100 0 30	0 30G_6 (t) 10G_6 (t) 0 2π/100 2π/20 30	30G_7(t) -30G_7(t) 20G_7(t) 2π/50 2π/50 2π/20 15
U_{GW3} W_{GW3} k_3	--	--	--	20 -10 2π/30	20 -10 2π/30 0 ∞	--	--

40 885 fluxes for each case are shown at the bottom. Units for velocities, wavenum bers, and periods are 886 ms^{-1}, km^{-1}, and min, and T_M = 10 days and T_{SD} = 12 hrs. GWs in Case 6 are modulated by 887 amplitude functions $F_6(t) = 1$ (t

= 0-3 h +

21R_1 hr)

and $F_6(t)$

= 0

otherwise,

and $G_6(t)$

= 1 (t =

0-4 888 h

+ 20R_2 hr)

and $G_6(t)$

= 0

otherwise,

with R_1

and R_2

random

variables

between 0

and 1

chosen

889

separately

for each

of the 30

days of

the test

month.

GWs in

Case 7 are

modulated

by

amplitude

890

functions

$F_7(t) = 1$ (t

= 0-2 and

8-10 h +

$14R_3$ hr)

and $F_7(t)$

= 0

otherwise,

and $G_7(t)$

= 1 (t =

0-1 h 891

and 6-7 h

and 10-11

h and

19-20 h +

$4R_3$ hr)

and $G_7(t)$

= 0

otherwise, with R_3 and R_4 random 892 variables between 0 and 1 as above.

893 894 895 896 897 898 899 900 901 902 903 904 905 906

Figure Captions

907

Figure 1. Daily meteor distributions illustratin

g the beam patterns for the five radars employed 908 in this assessment of measurement capabilities. The radar locations and frequencies are listed in 909 each panel. The radars at BL, TdF, and KGI use

crossed Yagi antennas and have nearly 910 symmetric beam patterns; The radars at YKF and SRO, however, use uncrossed (linearly-911 polarized) Yagis oriented north-sout h and east-west, respective ly, resulting

in the asymmetric 912 meteor distributions favoring east-west and north-south measurements, respectively, at those 913 sites. Nulls at various radii in the meteor detections are due to removal of meteor

detections that 914 may have ground clutter contamination. 915

Figure 2. Accepted meteors employed for mean and tidal wind and momentum flux estimates 916 for each radar (labeled at left). Meteor distributions are shown as

(left) monthly counts in each 917 500 m range bin, (center) counts per day, and (right) counts per hour for a composite day. These 918 statistics include meteors at zenith angles between 15 and 60° for all radars examined

here. 919

Figure 3. Monthly mean (left) winds, (second column) diurnal tide amplitudes, (third column) 920 semidiurnal tide amplitudes, and (right) GW momentum fluxes for Case 1. Solid and

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lines show

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Figure 4.

As in

Figure 3,

but for

Case 2.

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Figure 5.

As in Figure 3, but for Case 3.

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Figure 6. As in Figure 3, but for Case 4.

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Figure 7. As in Figure 3, but for Case 5.

Figure 8. Daily (left) zonal mean winds, (second column) meridional mean winds, (third column) zonal diurnal tide amplitudes, and (right) meridional diurnal tide amplitudes for Case 5. Vertical dashed lines show specified values.

Figure 9. Daily (left) zonal and (right) meridional semidiurnal tide amplitudes for Case 5 for the five radars (labeled at the top of the left panels). Colored lines show measured amplitudes from (black) 76.5 to (red) 97.5 km, dashed lines show specified amplitudes.

Figure 10. Hourly (left) zonal and (right) meridional GW momentum fluxes for Case 5 for a composite day for the five radars (labeled as in Figure 9). Colored lines show measured amplitudes from (black) 76.5 to (red) 97.5 km. Dashed lines show specified amplitudes.

Figure 11. As in Figure 3 for Case 6.

Figure 12. As in Figure 10, but for Case 6.

Figure 13. As in Figure 3 for Case 7.

Figure 14. As in Figure 10, but for Case 7.

Bear Lake (BL) f =35.24 MHz Yellowknife (YKF) f =36.65 MHz Socorro (SRO) f =35.24 MHz

300

300

300

200

200

20
0