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1       **High-Resolution Observations and Modeling of Turbulence**  
2       **Sources, Structures, and Intensities in the Upper Mesosphere**

3  
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26 **Abstract**

27 New capabilities for imaging small-scale instabilities and turbulence and for modeling  
28 gravity wave (GW), instability, and turbulence dynamics at high Reynolds numbers are  
29 employed to identify the major instabilities and quantify turbulence intensities near the summer  
30 mesopause. High-resolution imaging of polar mesospheric clouds (PMCs) reveal a range of  
31 instability dynamics and turbulence sources that have their roots in multi-scale GW dynamics at  
32 larger spatial scales. Direct numerical simulations (DNS) of these dynamics exhibit a range of  
33 instability types that closely resemble instabilities and turbulence seen in PMC imaging and by  
34 ground-based and *in-situ* instruments at all times and altitudes. The DNS also exhibit the  
35 development of “sheet-and-layer” (S&L) structures in the horizontal wind and thermal stability  
36 fields that resemble observed flows near the mesopause and at lower altitudes.

37 Both observations and modeling suggest major roles for GW breaking, Kelvin-Helmholtz  
38 instabilities (KHI), and intrusions in turbulence generation and energy dissipation. Of these,  
39 larger-scale GW breaking and KHI play the major roles in energetic flows leading to strong  
40 turbulence. GW propagation and breaking can span several S&L features and induce KHI  
41 ranging from GW to turbulence scales. Intrusions make comparable contributions to turbulence  
42 generation as instabilities become weaker and more intermittent. Turbulence intensities are  
43 highly variable in the vertical and typically span 3 or more decades. DNS results that closely  
44 resemble observed flows suggest a range of mechanical energy dissipation rates of  $\epsilon \sim 10^{-3}$ - $10$   
45  $\text{Wkg}^{-1}$  that is consistent with the range of *in-situ* measurements at ~80-90 km in summer.

46  
47 **Key Words:** polar mesospheric clouds, gravity waves and instabilities, turbulence, MLT  
48 dynamics

## 52 **1. Introduction**

53 Turbulence has been recognized to be a ubiquitous component of the motion spectrum  
54 throughout the atmosphere for more than five decades (e.g., Panofsky, 1959; Blamont and  
55 DeJager, 1961; Obukhov, 1962; Witt, 1962; Lumley and Panofsky, 1964; Rees et al., 1972;  
56 Woodman and Guillen, 1974; Zimmerman et al., 1977; Lilly, 1983; Wyngaard, 1992, 2010;  
57 Gibson, 1996; and references therein). At all altitudes below the turbopause at ~105-110 km,  
58 above which kinematic viscosity and thermal diffusivity largely suppress turbulence sources,  
59 turbulence is believed to play multiple roles. In the mesosphere and lower thermosphere (MLT),  
60 direct turbulence effects include 1) heating due to turbulence dissipation (Hocking, 1985;  
61 Lübken, 1997; Becker and Schmitz, 2002; Lübken et al., 2002) and 2) mixing and transports of  
62 heat, momentum, and constituents (e.g., Weinstock, 1978a, b; Schoeberl and Strobel, 1983; Chao  
63 and Schoeberl, 1983; Fritts and Alexander, 2003, hereafter FA03; Bishop et al., 2004; Rapp et  
64 al., 2004; Hecht et al., 2004). Importantly, however, the efficiency of turbulent transports  
65 remains uncertain and strongly debated (Fritts and Dunkerton, 1985; Coy and Fritts, 1988;  
66 Strobel et al., 1987; McIntyre, 1989; Becker and Schmitz, 2002; Becker and McLandress, 2009).  
67 Turbulence also contributes indirectly to 3) the dissipation of, and heat and momentum  
68 deposition by, gravity waves (GWs) and larger-scale motions (Hodges, 1967; Lindzen, 1981;  
69 Walterscheid, 1981; Holton, 1982; Garcia and Solomon, 1987; FA03; Medvedev and Klaassen,  
70 2003; Yigit, 2015) and 4) the generation of GWs accompanying larger-scale inhomogeneities in  
71 turbulence layers (Dohan and Sutherland, 2005).

72 The importance of turbulence in the MLT derives from the various motions that  
73 contribute to local instabilities at these altitudes. The large majority of the wind shear variance in  
74 the MLT is due to propagation of GWs, tides, and planetary waves (PWs) from sources at lower  
75 altitudes, and to their superpositions and interactions in the MLT accompanying their amplitude  
76 increases with altitude. Of these motions, GWs contribute the major energy and momentum  
77 fluxes because of their much larger vertical group velocities (FA03). GW interactions with the  
78 larger-scale motions, and other GWs, cause refraction to smaller vertical scales, amplitude



79 increases, instabilities, and dissipation, resulting in only  $\sim 0.1\%$  of the GW energy generated in  
80 the troposphere reaching altitudes of  $\sim 80\text{-}90$  km (Fritts and VanZandt, 1993, hereafter FV93).  
81 Despite this severe dissipation, GW velocity variances are  $\sim 2$  decades larger near the mesopause  
82 than near the tropopause (Balsley and Carter, 1982; Balsley and Garello, 1985) and mechanical  
83 energy dissipation rates in the mesosphere, typically  $\varepsilon \sim 10^{-3}\text{-}1$   $\text{Wkg}^{-1}$ , are similarly  $\sim 2$  decades  
84 larger than in the troposphere and lower stratosphere under stable conditions (Lawrence and  
85 Balsley, 2013; Schneider et al., 2014; Fritts et al., 2016, hereafter F16).

86 High-resolution observations at multiple altitudes suggest that the dynamics accounting  
87 for systematic GW energy dissipation, and energy and momentum deposition, often involve  
88 “sheet-and-layer” (S&L) structures comprising thinner, strongly stratified and sheared sheets and  
89 thicker, weakly stratified and sheared layers (e.g., Gossard et al. 1985; Dalaudier et al. 1994;  
90 Coulman et al. 1995; Luce et al. 1995, 1999; Balsley et al. 1998, 2003, 2012; Muschinski and  
91 Wode 1998; Nastrom and Eaton 2001; Fritts et al., 2004, hereafter F04; Rapp et al., 2004; Chuda  
92 et al. 2007; Clayson and Kantha, 2008). High-resolution direct numerical simulations (DNS)  
93 reveal that such S&L structures arise naturally from superposed and interacting GWs and larger-  
94 scale winds having various spatial and temporal scales (Fritts et al., 2013, 2016; Fritts and Wang,  
95 2013; hereafter F13, F16, and FW13, respectively). Both observations and DNS modeling reveal  
96 that S&L structures tend to exhibit the strongest potential temperature and horizontal wind  
97 gradients,  $d\theta/dz$  and  $du/dz$ , up to  $\sim 10$  times the mean gradients or larger, during the most active  
98 instabilities and strongest turbulence. These decay with time in the absence of continued energy  
99 inputs, but they can nevertheless extend for 10’s of buoyancy periods (FW13; F16). Though  
100 studied independently, these same dynamics also play major roles in oceans and lakes (e.g.,  
101 Osborn and Cox, 1972; Gregg, 1975; Thorpe, 1977, 2005; Osborn, 1980; Dillon, 1982; Wesson  
102 and Gregg, 1994; Moum, 1996; Ferron et al., 1998; Gargett, 1999).

103 Recent DNS modeling has suggested that the “multi-scale dynamics” (MSD) that drive  
104 S&L structures and evolutions comprise superposed and interacting GWs and larger-scale flows,  
105 sporadic instabilities of several types, and sporadic turbulence events (F13; F16). The major

106 instabilities accompanying MSD include GW breaking, Kelvin-Helmholtz instabilities (KHI),  
107 and intrusions, and these can have very different influences on S&L evolutions.

108 GW breaking within MSD occurs on scales comparable to and deeper than local S&L  
109 scales, and leads to turbulence and mixing largely within the weakly-stratified layers. GWs also  
110 enhance the potential for KHI, both in the absence of, and accompanying, breaking. Hence, GW  
111 breaking and KHI often occur together or in close proximity. However, KHI occurs only on  
112 more strongly stratified and sheared sheets because the shears that enable KHI can only be  
113 sustained in high stratification. Sufficiently strong KHI can also lead to splitting of the initial  
114 sheet, as observed by Woods and Wiley (1972) in the ocean and modeled earlier with high-  
115 resolution DNS or large-eddy simulation (e.g., Werne and Fritts, 1999; Fritts et al., 2012;  
116 hereafter WF99 and F12, respectively). When the MSD flows are energetic, e.g., a buoyancy  
117 Reynolds number  $Re_b = \epsilon / \nu N_0^2 > 20$  (Smyth and Moum, 2000), where  $\nu$  and  $N_0$  are kinematic  
118 viscosity and the mean buoyancy frequency, GW breaking and KHI predominate and the nearly  
119 laminar sheets have strong stratification and shear. As MSD become less energetic, intrusions  
120 compete with smaller-scale GW breaking, turbulence events are weaker, and the underlying  
121 GWs no longer contribute the strong shearing needed to maintain strongly stratified and sheared  
122 sheets (F16).

123 While considerable observational evidence for MSD has come from the lower  
124 atmosphere and oceans, multiple stratospheric and MLT observations have also revealed  
125 apparent S&L structures and/or instability dynamics that are suggestive of MSD. Evidence of  
126 layering and multi-scale spatial and temporal variability in temperatures, winds, tracers, and/or  
127 turbulence intensities includes the following:

- 128 1) high-resolution balloon observations (Barat, 1982; Dalaudier et al., 1994; Gavrilov et al.,  
129 2005; Clayson and Kantha, 2008; Schneider et al., 2014),
- 130 2) MF, VHF, and UHF radar measurements of radar backscatter and/or spectral widths in  
131 the stratosphere and mesosphere (Woodman and Guillen, 1974; Sato and Woodman,  
132 1982; Gage and Balsley, 1984; Hocking, 1985; Luce et al., 1995, 2006), and

133 3) in-situ rocket and falling-sphere measurements (Lübken, 1997; Lübken et al., 2002; Rapp  
134 et al., 2004; Goldberg et al., 2006; Lehmacher et al., 2011; Szewczyk et al., 2013).

135 Additional evidence of instability dynamics suggestive of MSD influences and/or specific  
136 instability forms seen in airglow, polar mesospheric clouds (PMCs, also referred to as  
137 noctilucent clouds when viewed from below), chemical release imaging, and/or new DNS  
138 modeling includes the following:

139 4) localized GW enhancements, breaking, and/or instabilities (Yamada et al., 2001; Fritts et  
140 al., 2002, 2014a, hereafter F14a; Bossert et al., 2015),

141 5) localized KHI, several at peak GW vertical displacements, or along their descending  
142 phases (Witt, 1962; Fritts and Rastogi, 1985; Hecht, 2004; Hecht et al., 2005, 2014;  
143 Lehmacher et al., 2007; Pfrommer et al., 2009; Baumgarten and Fritts, 2014, hereafter  
144 BF14; Fritts et al., 2014b, c, hereafter F14b and F14c),

145 6) potential deep convective rolls (Larsen, 2000; Larsen et al., 2004), and

146 7) apparent intrusions of turbulent air into quiescent air seen in high-resolution PMC  
147 imaging (Miller et al., 2015, hereafter M15).

148 Thus, there is significant evidence for fairly ubiquitous MSD and S&L features at all  
149 altitudes from the surface to  $\sim 100$  km. This is not a universal characterization of atmospheric or  
150 MLT instability dynamics, however, as there is also evidence of more idealized instability  
151 dynamics accompanying large-amplitude, nearly-monochromatic or superposed GWs having  
152 vertical wavelengths larger than S&L vertical scales. Importantly, larger vertical wavelengths  
153 and intrinsic phase speeds may allow such GWs to contribute to MSD at lower altitudes and  
154 amplitudes, and also attain larger amplitudes and rapid instability evolution without strong  
155 influences by smaller-scale S&L features at higher altitudes. Examples include the following:

156 1) idealized GW and KHI dynamics predicted by theory and singular vector analysis and  
157 identified by DNS, such as GW breaking fronts, streamwise-aligned vortices, vortex  
158 rings, and KHI secondary instabilities observed in PMC and airglow imaging to date

159 (e.g., Achatz, 2005, 2007; F09a; F09b; Fruman and Achatz 2012; F13; Remmler et al.  
160 2013; BF14; F14b; F14c; Fruman et al., 2014; Hecht et al., 2014; M15), and

161 2) nonlinear dynamics comprising various wave-wave and wave/mean-flow interactions,  
162 including “self-acceleration” (SA) dynamics, modulational instabilities, and overturning  
163 of localized GW packets at large amplitudes and/or intrinsic frequencies (Sutherland,  
164 2001, 2006a, 2006b; Doser and Sutherland, 2011; Fritts et al., 2015, hereafter F15),

165 Summarizing, various analysis and modeling methodologies are now providing important  
166 insights into the various instability dynamics contributing to GW dissipation and turbulence  
167 production throughout the atmosphere. DNS, in particular, is identifying specific instability  
168 features at finite amplitude that resemble those observed by high-resolution imaging in the MLT.

169 Our goals in this paper are to explore the ability of high-resolution DNS to describe  
170 realistic GW and MSD instability and turbulence events and aid in the interpretation of observed  
171 events in the MLT. To achieve these goals, our efforts will include three components:

172 1) employ ground-based and balloon-borne PMC imaging to identify the types, scales, and  
173 stages of instability dynamics accounting for MLT turbulence,

174 2) use these results to select and scale DNS of idealized GW breaking and MSD energetics  
175 that best approximate the observed events, and

176 3) employ the DNS results to assess the implied turbulence intensities and variability.

177 Overviews of PMC observations from the ground and from a stratospheric balloon over  
178 Antarctica are presented in Section 2. DNS methods and results employed for comparisons with  
179 these observations are described in Sections 3 and 4. Applications of the DNS results to the  
180 interpretation of PMC observations are discussed in Sections 5 and 6. These results are employed  
181 to estimate the magnitudes and variability of  $\epsilon$  for the dynamics observed in the PMC fields in  
182 Section 7. A discussion of these results in relation to previous studies is provided in Section 8,  
183 and our summary and conclusions are presented in Section 9.

## 184 **2. Observations of MLT Dynamics in PMCs**

### 185 *2.1. PMC Ground-Based Imaging in Norway*

186 Ground-based PMC imaging was performed by G. Baumgarten from Trondheim, Norway  
187 (63.4°N) on 1 August 2009. A Canon 50D with a 135-mm lens provided continuous imaging at a  
188 cadence of  $\sim 0.5$  s in a narrow field-of-view (FOV) of  $\sim 28 \times 41$  km (horizontal and range) at a  
189 central elevation angle of  $\sim 21^\circ$  and a horizontal range of  $\sim 250$  km yielding zonal and meridional  
190 resolution of  $\sim 10$  and 20 m. A Canon 450D with a 24-mm lenses provided wide FOV imaging of  
191 the PMC layer over an area of  $\sim 600 \times 600$  km at a cadence of  $\sim 30$  s.

## 192 2.2. Lidar Measurements of PMC in Norway

193 The Rayleigh lidar at the Arctic Lidar Observatory for Middle Atmosphere Research  
194 (ALOMAR) in northern Norway (69.3°N) supports multiple measurement modes (see, e.g., von  
195 Zahn et al., 2000; Baumgarten et al., 2012; Kaifler et al., 2013). For our purposes, it employed a  
196 lidar single-shot acquisition (LISA) capability to measure PMC backscatter and vertical  
197 displacements at range and time resolutions of 25 m and 0.033 s. The implications of these  
198 measurement will be discussed below.

## 199 2.3. PMC Observations from the Southern Hemisphere Stratosphere

200 PMC imaging was obtained serendipitously by star cameras for the E and B Experiment  
201 (EBEX), which measured the polarization of the cosmic microwave background from a  
202 stratospheric balloon over Antarctica from 29 December 2012 to 9 January 2013 (M15). Star  
203 camera field-of-views (FOVs) of  $4.1 \times 2.7^\circ$  from an altitude of  $\sim 35$  km at zenith angles of  $\sim 39$  and  
204  $43^\circ$  yielded  $\sim 4.4 \times 3.9$ -km projected FOVs at the altitude of maximum PMC brightness,  $\sim 82$  km, a  
205 range of  $\sim 62$  km, and a central image separation of  $\sim 5.8$  km. The narrow star camera FOVs  
206 yielded spatial resolution of  $\sim 2.2$  m, thus resolving the inner scale of turbulence,  
207  $l_0 = 9.9(\nu^3/\epsilon)^{1/4} \sim 10$  m, for  $\nu \sim 1 \text{ m}^2\text{s}^{-1}$  and  $\epsilon \sim 1 \text{ m}^2\text{s}^{-3}$  at 82 km (see comparisons with rocket  
208 measurements below), when apparent PMC advection was small. The close alignment of the two  
209 star camera FOVs, and the imaging cadence of  $\sim 450$  ms, provided multiple cases in which the  
210 same dynamics in the same or closely-spaced regions were imaged 2 or more times. During the  
211 11-day experiment, the star cameras collected  $\sim 40,000$  images, of which  $\sim 50\%$  provided usable  
212 images for purposes of assessing small-scale instability and turbulence dynamics.

### 213 3. DNS Models and Simulation Parameters

214 As noted above, we expect many types of instabilities to lead to turbulence in the MLT.  
215 Of these, GWs having vertical wavelengths  $\lambda_z \sim 2$  km or larger and relatively high intrinsic  
216 frequencies,  $\omega_i \gg f$ , where  $f$  is the inertial frequency, readily lead to breaking via either 2D  
217 and/or 3D instabilities, depending on the environment and the relevant Reynolds number,  
218 defined as  $Re = \lambda_z^2 / \nu T_b$  with buoyancy period  $T_b = 2\pi / N_0$  (Fritts et al., 2009a, b, hereafter F09a,  
219 F09b). At much smaller  $\omega_i$ , e.g., within a factor of  $\sim 2$ -3 of  $f$ , the dominant instabilities at  
220 Richardson numbers  $Ri = N^2 / (dU/dz)^2 = N^2 h^2 / U^2 < 1/4$  and  $Ri < 0$  are KHI (Lelong and Dunkerton,  
221 1998a, b; Thorpe, 1999). GW distortions and intensification of local sheets of high stability and  
222 wind shear also lead to KHI that may be highly localized (e.g., Hecht et al., 2005, 2014; F13,  
223 F14b, F14c, F16). However, F14b found very weak turbulence to occur for  $Ri = 0.2$  and  $Re = 2500$ ,  
224 while flows for  $Ri = 0.05$  and  $Re = 1000$  become 3D but remain laminar. Thus, the latter are a very  
225 conservative threshold for turbulence generation and these yield  $h = 15(\nu / N)^{1/2}$ . Taking  $\nu \sim 1 \text{ m}^2 \text{ s}^{-1}$   
226 and  $N \sim 0.03 \text{ s}^{-1}$  for a weakly stratified sheet (as opposed to a layer having  $N \sim 0.01 \text{ s}^{-1}$  or less), we  
227 obtain a threshold wavelength  $\lambda_{xT} \sim 4\pi h \sim 1.1$  km below which KHI remain laminar. KHI at  
228 smaller  $Ri$  and larger  $Re$  have already been studied via DNS and high-resolution observations  
229 (e.g., F14b, F14c), and will not be considered here. Importantly, those studies suggested an often  
230 significantly larger effective turbulent viscosity,  $\nu_{turb}$ , that could further decrease  $Re$  and  $\lambda_{xT} \sim$   
231  $\nu_{turb}^{1/2}$  by  $\sim 3$  times or more for new instabilities. The other major instabilities occurring in  
232 observed flows and simulated MSD are intrusions (see M15 and F16). These do not appear to  
233 provide direct evidence of the spatial scales of the MSD, however they do distinguish MSD from  
234 more idealized flows. Given this, our focus here will be on modeling of GW breaking and MSD  
235 for comparisons with observations.

#### 236 3.1. Equations

237 Our applications of DNS of GW breaking and MSD to MLT turbulence employ our  
238 previous results scaled to MLT events and turbulence intensities (e.g., F09a; F09b; F13; F16).  
239 These involve solutions of the 3D, Boussinesq, nonlinear Navier-Stokes equations, which are

240 nondimensionalized with respect to a primary GW vertical wavelength  $\lambda_z$ , a uniform buoyancy  
 241 period  $T_b$ , and the velocity scale  $U_0=\lambda_z/T_b$ . The resulting equations may be written as

$$242 \quad \partial \mathbf{u} / \partial t + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + Ri \theta \mathbf{z} + Re^{-1} \nabla^2 \mathbf{u} \quad (1)$$

$$243 \quad \partial \theta / \partial t + \mathbf{u} \cdot \nabla \theta = (Pr Re)^{-1} \nabla^2 \theta \quad (2)$$

$$244 \quad \nabla \cdot \mathbf{u} = 0 \quad (3)$$

245 Here  $\mathbf{u}=(u,v,w)$ ,  $p$ , and  $\theta$  are the total velocity vector, pressure, and potential temperature,  
 246  $N^2=(g/\theta_0)d\theta_0/dz=g\beta/\theta_0$ ,  $g$ ,  $\theta_0$ , and  $\beta$  are gravity, mean  $\theta$  and its gradient, and  $\mathbf{z}$  is a unit vector in  
 247 the vertical. As previously,  $Re=U_0\lambda_z/\nu=\lambda_z^2/\nu T_b$ ,  $Ri=N^2\lambda_z^2/U^2=4\pi^2$ , and the Prandtl number,  
 248  $Pr=\nu/\kappa=1$  (where  $\kappa$  is thermal diffusivity), is assumed for computational efficiency (e.g., F09a).

249 The linear inviscid dispersion relation arising from Eqs. (1-3) is given by

$$250 \quad m^2=(k^2+l^2)(N^2/\omega_i^2-1) \quad (4)$$

251 where  $k$  and  $l$  are the horizontal wavenumbers along, and normal to, the direction of GW  
 252 propagation,  $m$  is the vertical wavenumber,  $\omega_i=k_h c$  is the GW intrinsic frequency (assuming zero  
 253 large-scale mean wind),  $k_h^2=k^2+l^2$ ,  $c$  is the GW horizontal phase speed, and we assume mean  
 254 wind shear and curvature to be negligible. The primary GW wavenumber vector for each DNS is  
 255  $\mathbf{k}=(k,l,m)=(2\pi/\lambda_x, 0, -2\pi/\lambda_z)$  in geographic coordinates. A tilted computational domain is employed  
 256 for both GW breaking and MSD applications (see Fig. 1), yielding a primary GW wavenumber  
 257 of  $\mathbf{k}'=(k',l',m')=(0,0,-1)$ , which allows a much more compact computational domain for  $m/k \gg 1$ .

258 Following Andreassen et al. (1998), we employ the negative eigenvalue ( $\lambda_2$ ) of the tensor  
 259  $\mathbf{L}=\mathbf{\Omega}^2+\mathbf{S}^2$ , where  $\mathbf{\Omega}$  and  $\mathbf{S}$  are the rotation and strain tensors, to identify flow features having  
 260 strong rotational character (Jeong and Hussain, 1995). Such features have large negative  $\lambda_2$ ,  
 261 whereas pure shearing motions yield  $\lambda_2=0$ . Thus  $\lambda_2$  allows us to follow the transition from initial  
 262 instability structures, through vortex interactions and instabilities, to fully developed turbulence  
 263 and decay. We also compute the mechanical energy dissipation rate, defined as  $\varepsilon=2Re^{-1}\langle S_{ij} S_{ij} \rangle$ ,  
 264 to provide estimates of  $\varepsilon$  for these various dynamics for the observed MLT event scales.

### 265 3.2. GW Breaking Configuration

266 We employ previous DNS of GW breaking (F09a; F09b) for initial GW amplitudes  
 267  $a=u'/c_i=0.9$  and 1.1 (for intrinsic phase speed  $c_i=(c-U)$  and mean wind  $U$  along  $c$ ), an intrinsic  
 268 frequency  $\omega_i=N/3.2$  ( $T_{GW}=3.2T_b$ ), and  $Re=\lambda_z^2/\nu T_b=10,000$ . The computational domain has  
 269 dimensions  $(X',Y',Z')=(3.4,2.22,1)\lambda$ , where  $\lambda=2\pi/|k|$  is the GW wavelength (see Fig. 1a). The  
 270 two cases require comparable spectral resolution, with as many as  $(N_x,N_y,N_z)=(2400,1600,800)$   
 271 Fourier modes employed at the times of strongest small-scale turbulence. The underlying  
 272 dynamics are described in detail by F09a and F09b. Applications to instability forms and  
 273 turbulence structures observed in PMCs are described in Section 4.

### 274 3.3. *MSD Configuration*

275 MSD employed here are those described by F16 at  $Re=100,000$ , which achieve  $Re_b\sim 20-$   
 276  $30$  during the strongest turbulence, and scaled to the MLT. As in F16, initial conditions include a  
 277 convectively stable GW and a stable small-scale shear flow. The GW has an amplitude  $a=0.5$ ,  
 278  $\omega_i=N/10$  ( $T_{GW}=10T_b$ ), wavenumber  $(k',l',m')=(0,0,-1)$ , and exhibits a minimum  $Ri\sim 4$  where  
 279  $d\theta'/dz\sim 0$  and  $du'/dz\sim N/2$ . The initial mean motion is given by a sinusoidal streamwise velocity  
 280 having 5 cycles across the vertical projection of the GW  $\lambda$  having  $(dU/dz)_{\max}=2N$  such that the  
 281 minimum mean shear is  $Ri=1/4$ . The streamwise and spanwise domain extents are  
 282  $X'=Z'/(5\tan\phi)=1.999Z'$  and  $Y'=0.5\lambda_z=0.4975Z'$  (see Fig. 1b). The highest model resolution used  
 283 for this DNS is  $(4320,1080,2160)$  Fourier modes. These MSD, and their implications for  
 284 instability and turbulence structures observed in PMCs, are described in Sections 4 and 5.

### 285 3.4. *Simulation of PMC images*

286 The instability dynamics examined here occur on timescales of only a few minutes. Over  
 287 such short intervals, PMC brightness can be approximated as a passive tracer (G. Thomas, PC,  
 288 2016; Chandran et al., 2016). Hence, we parameterize PMC brightness as a function of the initial  
 289  $\theta_0$ , which is monotonically increasing and nearly conserved following the air motion, as

$$290 \quad B(z) = B_0 \exp[-(z - z_{PMC})^2/2\sigma_z^2] = B_0 \exp[-(\theta_0 - \theta_{PMC})^2/2\sigma_\theta^2] \quad (5)$$

291 where  $z_{PMC}$  and  $\theta_{PMC}$  are PMC altitude and  $\theta_0$  at the peak of PMC brightness and  $\sigma_z =$   
 292  $z_{FWHM}/2(2\ln 2)^{1/2}$  corresponds to an PMC layer having a typical full width-half maximum



293 (FWHM) brightness of  $z_{FWHM}$ . Examples of Rayleigh lidar observations at ALOMAR described  
294 above are shown for reference in Fig. 2. These reveal that the PMC brightness layer can have  
295  $z_{FWHM}$  as small as  $\sim 50$ -100 m, and perhaps less, accompanying strong layering in the presence of  
296 energetic small-scale GW and instability dynamics. Additional evidence for such thin layers  
297 accompany observed and DNS MSD flows that yield  $d\theta/dz$  and  $N^2$  maxima up to 10 times mean  
298 values or larger and high  $Re$  (F16, and references therein). This is a particularly useful feature of  
299 PMC layers because it provides a potential to observe structures occurring at very small scales.

#### 300 **4. DNS of Idealized GW Breaking and MSD**

##### 301 *4.1. DNS of GW breaking, instabilities, and turbulence*

302 Floquet theory employed by F09a suggested initial GW instabilities comprising  
303 streamwise-aligned (streamwise vorticity, spanwise wavenumber) counter-rotating rolls. The  
304 parallel DNS show these to be approximately horizontal initially, and to evolve to finite-  
305 amplitude and induce intensifying vortex sheets above (below) having negative (positive)  
306 streamwise vorticity (Andreassen et al., 1998). These dynamics are illustrated in Figs. 3 and 4  
307 with volumetric views of  $\lambda_2$  at  $1T_b$  intervals beginning before strong breaking for GW amplitudes  
308  $a=0.9$  and 1.1 and other parameters specified above. Note that we have displayed these fields  
309 with GW propagation upward and to the right in order to have the same orientation as in the  
310 ground-based PMC imaging discussed below.

311 Where these vortices dip below the coldest phase of the GW (above the maxima of  $u'$  and  
312  $w'$ ), they interact with the spanwise vortex sheets above the most unstable (smallest  $N^2$ ) phase of  
313 the GW. The downward motions induce stretching and intensification of the opposite spanwise  
314 vortex sheets below, and these structures link to form a succession of vortex rings along the GW  
315 phase that expand in time and advect upward at the maxima of  $u'$  and  $w'$  along  $c$ , though at a  
316 velocity smaller than  $c$  (Figs. 3 and 4; panels a, b, e, and f). The resulting vortex rings yield  
317 plunging motions downward and in the direction of GW propagation (Figs. 3 and 4; panels f and  
318 g). They also cause coherent linkages between adjacent GW fronts that act to organize the  
319 transitional instability structures that cannot be seen in the  $\lambda_2$  volumetric views in Figs. 3 and 4.

320 Thereafter, strong interactions among adjacent vortices induce “twist-wave” perturbations of the  
321 various vortex structures that cause their fragmentation and rapid collapse to smaller scales  
322 comprising the turbulence cascade (Figs. 3 and 4; panels b-d and f-h; F09b; Andreassen et al.,  
323 1998; Fritts et al., 1998). The evolutions from coherent vortex rings to strong turbulence span  
324  $\sim 1T_b$  or less, or a few minutes for a typical mean  $N$ , with a more rapid evolution at a larger  
325 amplitude and/or higher  $\omega_i$  (new paper in preparation).

#### 326 4.2. *DNS of MSD, instabilities, and turbulence*

327 As noted above, instabilities exhibit many forms in MSD flows throughout their  
328 evolutions. These arise as a result of interactions among the larger-scale mean and GW motions  
329 that largely account for the S&L structures and the instability and turbulence dynamics induced  
330 within them. Examples of the S&L structures and instabilities occurring at several stages of an  
331 MSD DNS described by F16 are shown in the  $N^2(x,z)$  and  $\log_{10}\varepsilon(x,z)$  fields at left and right in  
332 Fig. 5. Color scales in both cases are from weak (blue) to strong (red),  $N^2$  varies by more than a  
333 decade, and  $\varepsilon$  varies by more than 4 decades at each time. Strong GW breaking and large-scale  
334 KHI arise at early stages following S&L formation when large GW amplitudes and shears  
335 provide significant energy sources for instabilities and turbulence (e.g., Fig. 5, panels a-d and g-  
336 j). At later stages, instabilities are weaker and more intermittent, turbulence is weaker and more  
337 confined vertically, and intrusions (e.g., Fig. 5, panels e, f, k, and l) play a competitive role with  
338 weaker GW breaking events.

339 Finally, we note that both the idealized GW breaking and MSD dynamics are described  
340 in a Boussinesq DNS having specified initial conditions. As such, they are “spin-down” DNS  
341 without continuous energy inputs by GWs propagating from below. This does not limit the  
342 ability to compare instability dynamics and/or turbulence intensities with atmospheric  
343 observations at low or high altitudes (e.g., F13, F14b, F16) at sufficiently high  $Re$ . But the earlier  
344 times in each DNS having more energetic GWs, instabilities, and turbulence are more  
345 representative of atmospheric conditions in which there are significant GW fluxes of energy to  
346 higher altitudes. In contrast, the later times in each DNS more closely approximate times where

347 GW vertical energy fluxes are relatively weak. The DNS of idealized GW breaking and MSD  
348 described here are employed below to interpret and quantify instability dynamics and turbulence  
349 intensities observed in PMCs from the ground and a stratospheric balloon. The former provides  
350 continuous viewing of dynamics that may span multiple  $T_b$ ; the latter does not track the  
351 evolutions of specific dynamics, but does provide valuable insights into small-scale instability  
352 and turbulence dynamics that are impossible to obtain at any other altitude in the atmosphere.

### 353 **5. GW Breaking Dynamics Observed in Ground-Based PMC Imaging**

354 We first examine an apparent GW breaking event observed over northern Norway on 1  
355 August 2009. These dynamics occurred following an extensive display of KHI beginning  $\sim 22:30$   
356 UT, having constant phases aligned roughly northwest to southeast (NW-SE), advecting towards  
357 the southwest ( $\sim 40^\circ$  W of S) at  $\sim 70 \text{ ms}^{-1}$ , and exhibiting very slow evolutions in time (e.g.,  
358 individual KH billow events spanning  $\sim 10$  min or longer). This display includes the KHI  $Ri \sim 0.20$   
359 event described in detail by Baumgarten and Fritts (2014) and F14b. Throughout, the KHI  
360 structures exhibited significant modulations in phase and amplitude (see Fig. 6a), suggesting a  
361 complex shear environment likely reflecting spatial variations accompanying small-scale GWs.

362 Measurements of large-scale winds at these altitudes were available only by the meteor  
363 radar at ALOMAR,  $\sim 450$  km N of the observations from 22 to 24 UT. These had 2-km and 1-hr  
364 resolution, but appeared to be consistent with observed PMC advection at  $\sim 82$  km and our  
365 expectation of mean winds towards the SW decreasing with altitude during summer.

366 Beginning at  $\sim 23:10$ , larger-scale PMC brightness variations became apparent that  
367 suggest GW modulations of the wind and temperature fields and the PMC layer on larger spatial  
368 scales. Extended KHI structures persisted in the presence of the larger-scale GWs at several  
369 locations beyond  $\sim 23:20$  (see Fig. 6). Despite more complex KHI structures at small spatial  
370 scales, their evolution timescales did not change appreciably. However, the wind shears enabling  
371 KHI apparently diminished with time, and evidence of KHI disappeared thereafter (e.g., see the  
372 outer edges of the PMC images at 23:30 and thereafter in Fig. 6).

373           The GW field contributing to the changing instability environment had several apparent  
374 components: 1) one having a horizontal wavelength  $\lambda \sim 70$  km and propagating slowly towards  
375 the southeast (SE) throughout, 2) a second having  $\lambda \sim 30$  km and propagating more rapidly  
376 towards the north-northeast (NNE) from 23:30-50, and 3) a third localized GW having  $\lambda \sim 50$  km,  
377 a large amplitude from  $\sim 23:30-50$ , and propagating towards the south-southeast (SSE). These  
378 GW phases and propagation directions are shown with the white, red, and pink lines and arrows  
379 in Fig. 6b-d, respectively. Of these, the large-amplitude, smaller-scale GW propagating towards  
380 the SSE appears to have had the largest influences on instability forms and alignments in the  
381 region highlighted by the yellow circles in Fig. 6. Hence, we will assume this GW was the major  
382 cause of the instabilities seen to occur after 23:30 in Fig. 6, though the others likely also  
383 contributed to the local shear and stability fields. Shown with a green trapezoid in Fig. 6c is the  
384 region in which we will focus our discussion of the instability dynamics during this event.

385           The dominant GW initiated a series of bright bands aligned nearly along its direction of  
386 propagation at two phases at 23:30 and 23:40 (see the features within the yellow circles in Fig.  
387 6b and 6c). These features are very similar to those previously associated with GW breaking seen  
388 in PMC (Fritts et al., 1993), and seen prior to the formation of vortex rings in the DNS shown in  
389 Figs. 3 and 4. In this case, however, the two primary GW phases were neither linear nor parallel  
390 due to the influences of other GWs also present. Initial streamwise-aligned features were more  
391 distinct at 23:30 prior to the occurrence of instabilities between these phases. Changing GW  
392 superpositions and induced instabilities in this region thereafter extended beyond 24:00.

393           By 23:40, small-scale instabilities having 3D character appeared in the lee of the leading  
394 GW phase at lower right (to the NW). These initial dynamics are shown from 23:42-45 UT at 1-  
395 min intervals in Fig. 7a-d. The volume viewed is shown with the green trapezoid in Fig. 6c and  
396 the viewing angle for these images is from ahead and to the right of the primary GW propagation  
397 direction, and below the horizontal plane of the PMC by  $\sim 21^\circ$ . The images in Fig. 7a and 7d are  
398 also shown mapped and viewed from above to show their true spatial scales in Fig 7e and 7f. As  
399 in the DNS, the initial bands assigned the scales of the subsequent 3D instability features seen in

400 their lee. Additionally, the time scales of the instability dynamics changed dramatically between  
401 23:30 and 23:40. Whereas KHI observed prior to  $\sim 23:40$  evolved over several  $T_b$ , the apparent  
402 GW breaking dynamics shown in Fig. 7 evolved significantly over 3 min ( $\sim 0.6 T_b$ ).

403 The images at top reveal complex structures that we identify as vortex rings that appear  
404 to be overlapping because of the shallow imaging slant view. In reality, the vortices are likely  
405 displaced horizontally rather than vertically within the GW field, as they occur at only one phase  
406 of the DNS of GW breaking seen in Figs. 3 and 4. Their alignments appear to have been at  
407 successive positions along the plane of GW propagation (lower left to upper right in Fig. 7a-d),  
408 with apparently overlapping vortex rings staggered at adjacent horizontal locations normal to the  
409 plane of GW propagation, as seen in the DNS, especially Fig. 3. Their diameters at these times  
410 were as large as  $\sim 8$ - $10$  km, and likely  $\sim 20$ - $50\%$  larger than when they first formed at smaller  
411 amplitudes, based on the expansions seen in the DNS results. Our DNS reveal that vortex ring  
412 spacing along the plane of GW propagation, and between vortex rings occurring on adjacent  
413 vortex sheets, varies with GW amplitude and intrinsic frequency, and likely with the background  
414 wind shear and orientation, however. In particular, new DNS reveal that vortex ring spacings and  
415 evolution timescales decrease with increasing  $\omega_i$  (L. Wang, pers. comm., 2016).

416 The three initial vortex rings at the more southward locations (upper and lower portions  
417 of the yellow ovals in Fig. 7a and 7e, respectively) exhibit bright trailing vortices extending  
418 generally upward and to the west from their interiors (as in Figs. 3b and 4b) due to the viewing  
419 geometry. Especially significant in this sequence is the rapid decay of the coherent vortex rings  
420 over its 3-min ( $\sim 0.6 T_b$ ) duration that is consistent with their decay time scale seen in the DNS  
421 results in Figs. 3 and 4. This is dramatically faster than the evolutions of the earlier KHI at the  
422 PMC altitude and is a clear distinction between KHI and GW breaking dynamics. Additional, but  
423 less distinct, features are also seen to the west and north (left and below in Fig. 7a-d) of those  
424 highlighted, and they likewise decay over the same interval.

425 We explore these comparisons further using Eq. (5) to compute PMC brightness fields for  
426 the GW breaking events shown in Figs. 3 and 4 at four times with a PMC layer thickness of

427  $z_{FWHM}=0.1 \lambda_z$ . The results for  $a=0.9$  from 21-22  $T_b$  and  $a=1.1$  from 10.2-11.2  $T_b$  at  $0.33 T_b$   
428 intervals are shown viewed from below at left and right in Fig. 8, respectively. In each case, the  
429 PMC layer was placed to coincide with the vortex rings in the most unstable phase of the GW.  
430 Both cases exhibit trailing vortices, as seen in the PMC images, and a rapid evolution from  
431 coherent vortex rings to turbulent motions over  $\sim 1 T_b$ . That with  $a=0.9$  more clearly illustrates  
432 vortex ring expansion; that with  $a=1.1$  exhibits a more rapid vortex ring breakdown to turbulence  
433 and a smaller vortex ring spacing (given periodic boundaries, Fig. 11d).

434 The subsequent evolution of this region shown from 23:47-50 UT in Fig. 9a-d reveals the  
435 further breakdown of the vortex rings discussed above (see yellow ovals). These images also  
436 suggest the development of new vortex rings at even larger scales (see the brightening curved  
437 features at the right edges of Fig. 8e and 8f), but these are seen primarily in the wide FOV, as  
438 they advect out of the narrow FOV to the SW over the next  $\sim 5$  min.

## 439 **6. GW Breaking Dynamics and MSD Observed in Stratospheric PMC Imaging**

440 Miller et al. (2015) reported an initial exploration of serendipitous PMC imaging from a  
441 stratospheric balloon in the interpretation of dynamics near 82 km. Here, we perform additional  
442 comparisons of stratospheric imaging of PMCs and DNS modeling to quantify the character,  
443 scales, and energetics of key instability dynamics arising due to GW breaking and MSD at PMC  
444 altitudes. This process enables estimates of the contributions of these dynamics to the energy  
445 dissipation rate  $\varepsilon$  in the MLT presented in Section 7 below.

446 Many PMC images obtained by the EBEX stratospheric balloon experiment include  
447 features that appear to be evidence of either relatively monochromatic GW breaking, smaller-  
448 scale KHI, or more complex MSD events (Miller et al., 2015). These can often be identified by  
449 PMC brightness variations arising due to advection and deformation of the PMC layer by larger-  
450 and smaller-scale GWs, their various instability forms, and turbulence structures. The unique  
451 aspect of these observations is the extremely high spatial resolution that can be achieved in cases  
452 where the PMC layer is very thin accompanying the underlying dynamics, e.g., resolving  
453 features having spatial scales as small as  $\sim 10$ -20 m.

454 6.1. *GW breaking dynamics observed in stratospheric PMC imaging*

455 Two examples that appear to be at relatively early stages in the evolution of a breaking  
456 GW are shown in Fig. 10a and 10b. These do not correspond to the same event, as EBEX  
457 imaging only occasionally, and accidentally, acquired images of the same PMC field spaced by  
458 10's of seconds or more. Nevertheless, the two images appear to capture features that we  
459 recognize as slightly different stages of breaking GW. That in Fig. 10a closely resembles a  
460 simulated PMC (Fig. 10c) suggesting the overturning “front” for the GW breaking case with  
461  $a=1.1$  and  $z_{FWHM}=100$  m at a time just after that in Fig. 4b. That in Fig. 10b suggests a strange  
462 diagonal pattern that likewise resembles a simulated PMC (Fig. 10d) for the GW breaking case  
463 with  $a=0.9$  and  $z_{FWHM}=100$  m at a time near that in Fig. 3b. These images indicate that there are  
464 occasions when the larger-scale MLT dynamics (i.e., vertical scales larger than the S&L scales in  
465 MSD) are characterized locally by approximately monochromatic GW breaking rather than less  
466 energetic MSD. The apparent overturning front reveals approximately streamwise vortices at the  
467 initial stages of instability that may allow an estimate of the depth of the layer that is unstable,  
468 based on the spanwise (along the front) spacing of the major vortex features. Comparing the  
469 characteristic spacing with the DNS suggests a vertical wavelength of  $\lambda_z \sim 2-4$  km, but provides  
470 little guidance on  $\lambda_h$  or  $\omega_i$ . The diagonal patterns in Fig. 10b and 10d suggest a  $\lambda_h > 5$  km, given  
471 that the true PMC image does not capture the full streamwise GW phase structure.

472 More quantitative assessments are possible in cases where specific instability dynamics  
473 directly related to intrinsic GW parameters are observed. The clearest examples of such at larger  
474 spatial scales identified to date appear to be vortex rings, as simulated in the GW breaking DNS  
475 shown in Figs. 3 and 4, and as seen in initial EBEX PMC imaging (Miller et al., 2015). Images  
476 of apparent vortex rings in three different events are shown in Fig. 11a-c. That in Fig. 11a shows  
477 the full image having a horizontal FOV of 4.4x3.9 km and reveals a well-developed vortex ring  
478 diameter of  $\sim 4$  km and a spacing between rings of  $\sim 4$  km. The diameter is indicative of a GW  
479  $\lambda_z \sim 8-10$  km, and the close spacing is suggestive of  $\omega_i \sim N/3$  or greater. Additionally, the apparent  
480 bright trailing vortices extending to the lower right of the vortex rings suggest vortex ring self-

481 advection and GW propagation towards the upper left. A simulated PMC from the DNS shown  
482 in Fig. 11d for a GW propagating upward (as seen from below) is shown for comparison in Fig.  
483 11d. This captures the darker vortex rings, their successive displacements, and an indication of  
484 brighter trailing vortex features, suggesting agreement of the underlying dynamics.

485 Fig. 11b shows another apparent vortex ring that was propagating largely away from the  
486 viewing platform (downward in the PMC image), based on the orientation of the bright trailing  
487 vortices. This vortex ring had a diameter of  $\sim 1.5\text{-}2$  km and appeared to be undergoing  
488 breakdown (as seen in Figs. 3c and 4c), or to have occurred in an already turbulent region. It had  
489 no other vortex rings in close proximity, suggesting an  $\omega_i$  comparable to, or lower than, shown in  
490 Figs. 3 and 4, based on DNS observations of closer vortex ring spacing at  $\omega_i \sim N/2$  to  $N/1.4$ .

491 Fig. 11c shows a PMC image that reveals an apparent succession of vortex rings that had  
492 similar character, were apparently linked by trailing vortices, and were self-advection towards  
493 the right, suggesting GW propagation in this direction. These features are strikingly similar to a  
494 simulated PMC using the DNS for  $a=1.1$  at  $\sim 10.5 T_b$ , a short time following the image in Fig. 4b.  
495 The diameters of these structures are up to  $\sim 1$  km and they appear to be closely spaced along the  
496 GW propagation direction, suggesting a GW  $\lambda_z \sim 2$  km and  $\omega_i \sim N/3$  or larger in this case.

## 497 6.2. *MSD observed in stratospheric PMC imaging*

498 EBEX stratospheric PMC imaging has also yielded multiple examples that confirm DNS  
499 predictions of various MSD flows, several of which are described below. Fig. 12a shows what  
500 appear to have been cusp-like structures having longitudinal scales of up to  $\sim 1$  km, lateral scales  
501 of  $\sim 100\text{-}300$  m, some organization of these features in lateral rows, and apparent strong shearing  
502 of the lower edges towards the lower left (along the arrow).

503 The simulated PMC image in Fig. 12b was obtained using the method described in  
504 Section 3.4 with  $z_{FWHM}=200$  m at the bottom edge of the region of local GW breaking having  
505 large  $\varepsilon$  shown in the black oval in Fig. 5h. Inspection of the corresponding  $N^2$  field in Fig. 5b  
506 reveals this to be a sheet having elevated stability, and the corresponding velocity field (not  
507 shown) confirms a significant wind shear with increasing winds at lower altitudes along the



508 arrow. As in Fig. 12a, cusp-like features seen in Fig. 12b exhibit apparent shearing consistent  
509 with the wind direction below, some lateral alignments, and lateral scales of  $\sim 5\text{-}10\%$  of the MSD  
510 domain width ( $\sim \lambda_z/2$ ). Finally, we note that the cusp-like features in Fig. 12 have many  
511 similarities to the vortex rings identified at larger spatial scales, including ring-like highlights  
512 and streamwise vortices extending from their centers a multiple sites in the observed and  
513 simulated fields. Thus, they could be manifestations of small-scale GW breaking in a more  
514 chaotic environment.

515 Equating the cusp scales between the EBEX and MSD simulated PMC images suggests  
516 an MSD overall depth of  $\sim 6$  km. This scale is less important in this case than the S&L spatial  
517 scales that constrain this event. This depth is likely  $\sim 1$  km in this region of the MSD flow, based  
518 on the DNS shown in Fig. 5. Hence, we expect the MSD DNS to provide a reasonable  
519 approximation of the associated  $\varepsilon$  for these specific dynamics in the discussion below.

520 Other instabilities that are seen in a number of stratospheric PMC images are intrusions.  
521 Two examples are shown in Fig. 13a and 13b. Their apparent directions of motion are shown  
522 with arrows and the image widths are  $\sim 3$  and 4.4 km, respectively. These observations confirm  
523 the occurrence and importance of these dynamics predicted by the MSD DNS, at least in cases  
524 where other dynamics that lead to stronger turbulence are not present (F13, F16). An intrusion  
525 occurring in the MSD DNS at late times is shown evolving from a laminar to a turbulent flow in  
526 Fig. 5k and 5l. Simulated PMC responses assuming a PMC  $z_{FWHM}=100$  and 300 m in the region  
527 within the black oval in Fig. 5l are shown in Fig. 13c and 13d to illustrate the sensitivity of the  
528 PMC response to the PMC layer depth. These reveal that thinner layers provide greater  
529 sensitivity to smaller-scale dynamics, as argued above. Unlike GW breaking, there is no current  
530 way to evaluate  $\varepsilon$  for intrusions without a means of assessing their scales. This may change in  
531 cases where their depths, relative motions, and/or turbulence spectra can be directly assessed.

## 532 7. Energy Dissipation Rates in the MLT

533 The discussion above identified four events observed in PMC imaging from the ground  
534 and stratosphere that compare reasonably with DNS of GW breaking for idealized and MSD

535 flows and enable some quantification of GW parameters. These allow DNS results to be scaled  
536 to the observed dynamics that enable estimates of  $\varepsilon$  for the observed events at PMC altitudes.  
537 The cases for which this can be done with some confidence include the following:

538 Case 1: GW breaking over Norway (Fig. 7) exhibiting vortex rings having initial diameters  
539 of  $\sim 7$  km or larger suggesting a GW having  $a > 1$ ,  $\lambda_z \sim 15$  km or larger, and  $\omega_i > N/3$ ,

540 Case 2: vortex rings (Fig. 11a) having diameters of  $\sim 4$  km suggesting GW breaking for  $a \sim 1$ ,  
541  $\lambda_z \sim 8-10$  km, and  $\omega_i > N/3$ ,

542 Case 3: vortex rings (Fig. 11c) having maximum diameters of  $\sim 1$  km suggesting GW  
543 breaking for  $a \sim 1$ ,  $\lambda_z \sim 2$  km, and  $\omega_i > N/3$ , and

544 Case 4: cusp patterns in a MSD S&L flow (Fig. 12) suggesting GW breaking over  $\sim 1$  km and  
545 an MSD domain depth of  $\sim 6$  km.

546 Estimates of MLT turbulence intensities for these events require scaling the  
547 nondimensional DNS to the observed dynamics and inferred spatial scales. For both idealized  
548 GW breaking and MSD, the scaling factor is  $S = \lambda_z^2 / T_b^3$ .  $S$  will vary by  $\sim 2$  decades because of the  
549 large range of  $\lambda_z \sim 2-15+$  km inferred in our discussions of the events above.  $S$  will also vary with  
550  $N$ , which is determined by temperature fields on larger scales than the GW breaking event, i.e.,  
551 mean, tidal, planetary wave, and larger-scale GWs, that can be measured by ground-based and  
552 *in-situ* instruments. Where these are unknown, uncertainties could be as large as  $\sim 2$  in the large-  
553 scale  $N$  based on *in-situ* measurements to date. We have no direct measurements of  $N$  for any of  
554 the PMC events discussed here. However, the mean PMC environment at  $\sim 82$  km over  
555 ALOMAR has  $T \sim 150$  K,  $N \sim 0.023$  s $^{-1}$ , and  $T_b \sim 270$  s (Rapp et al., 2004). Below, we examine the  
556 implications of each of the above cases for MLT instability event scales and turbulence  
557 intensities, assuming these values for our analyses. Event parameters are listed in Table 1.

#### 558 7.1. Case 1: GW breaking with $\lambda_z \sim 15+$ km

559 The GW breaking event observed over Norway revealed large-scale vortex rings  
560 implying a GW having  $a > 1$ ,  $\lambda_z \sim 15$  km or larger, and  $\omega_i > N/3$ . Together, these parameters imply

561 that the GW breaking DNS for  $a=1.1$  shown in Fig. 4 represents a conservative estimate of the  
562 instability and turbulence intensities for this case, perhaps by a significant factor.

563 Horizontal distributions of nondimensional  $\varepsilon$  at the times of largest mean  $\langle\varepsilon\rangle$  (where  
564 brackets denote a domain average) for  $a=0.9$  and 1.1 (i.e., Figs. 3d, 3h, 4d, and 4h) viewed from  
565 below and the side (with GW propagation up and to the right) are shown in Fig. 14a, 14b, 14e,  
566 and 14f. The same views of the thermal energy dissipation rate in the energy equation,  $Ri\chi$  (F16),  
567 are shown in Fig. 14c, 14d, 14g, and 14h. These reveal that despite strong vortex interactions,  
568 turbulence generation, and mixing along the most unstable phase of the GW spanning several  $T_b$ ,  
569  $\varepsilon$  and  $Ri\chi$  are highly variable spatially. These fields in Fig. 14 are reasonably correlated at larger  
570 spatial scales, but their maxima often are not. In particular, there are many cases in which  $\varepsilon$  and  
571  $Ri\chi$  maxima occur in close proximity, but are displaced horizontally and/or vertically where  
572 strong mixing has driven the strong thermal gradients to the edges of the mixing regions.

573 Probability distribution functions (PDFs) of  $\log_{10}\varepsilon$  for  $a=0.9$  at 21, 22, 24, 30, and 40  $T_b$   
574 are shown in Fig. 15a. Those for  $a=1.1$  at 9.2, 10.2, 12.2, 20, and 30  $T_b$  are shown in Fig. 15b.  
575 The two earliest times in each case are during the onset of turbulence at larger spatial scales. As  
576 the initial vortex rings evolve, the PDFs acquire approximately log-normal distributions, and  
577 these persist to very late times. The strongest turbulence in each case occurs  $\sim 2 T_b$  after vortex  
578 ring formation, and  $\langle\varepsilon\rangle$  and  $\varepsilon_{high}$  (above which the highest 1% of  $\varepsilon$  occur) are shown with  
579 vertical lines in Fig. 15a and 15b. These are  $\sim 0.7$ -1.1 decades larger than at the times of initial  
580 coherent vortex rings for  $a=0.9$  and 1.1, respectively. Hence, we expect maximum turbulence to  
581 occur  $\sim 8$ -10 min after the appearance of coherent vortex rings (and large-scale  $u'$ ,  $w'$ , and  $T'$  for  
582 typical summer mesopause stability profiles). PDFs of  $Ri\chi$  (not shown) exhibit similar behavior  
583 following the onset of instabilities and turbulence (e.g., F09b). Because of the broad,  
584 approximately log-normal distributions of  $\varepsilon$  and  $\chi$  accompanying turbulence (they span  $\sim 4$   
585 decades at the times of strongest turbulence), only  $\sim 15$ -20% of the values are above their domain  
586 means. Even for the vertical and spanwise means shown in Fig. 14 (which have narrower

587 distributions spanning only  $\sim 2$  decades, see the color bars in Fig 14; also see the local PDFs in  
588 Fig. 8 of FW13), the largest values are strongly localized at the sites of the previous vortex rings.

589 To explore the relations between the maxima of  $\varepsilon$  and  $Ri\chi$  more directly, we average  
590 these quantities over 64 adjacent points to provide high confidence in these values, yielding  
591 values at  $\sim 10^8$  locations. As above, this reduces the range of values, but these still span  $>3$   
592 decades. Scatter plots of these values for the larger 0.1-0.01% (black dots) and 0.01-0.001%  
593 (green triangles), and the largest 0.001% (red squares) of  $\varepsilon$  and  $Ri\chi$  are shown in Fig. 16a and  
594 16b, respectively.

595 Examining first Fig. 16a, we see that the largest  $\varepsilon$  are clustered at quite small  $Ri\chi$ , but that  
596 there are also multiple sites where  $Ri\chi$  is comparable or larger. The former likely arise where  
597 strong mixing of the thermal gradients has already occurred, the latter likely are from regions  
598 within the strongly stratified and sheared sheets within which turbulence events first arise and  
599 strong thermal and velocity gradients are still entwined. Distributions for the largest  $Ri\chi$  exhibit  
600 different behavior. And there is almost no overlap between the largest 0.001% of  $\varepsilon$  and  $Ri\chi$ , at  
601 most 4 locations in  $\sim 10^8$ . The largest  $Ri\chi$  typically accompany  $\varepsilon$  values between  $\sim 1$  and 10% of  
602 the maximum, thus apparently do not have much smaller associated  $\varepsilon$ . This is because small-  
603 scale velocity gradients (and significant  $\varepsilon$ ) are required to maintain strong thermal gradients.

604 Turning to implications of these dynamics for turbulence intensities, we dimensionalize  
605 the PDFs for  $a=0.9$  and 1.1 by  $S=\lambda_z^2/T_b^3=11 \text{ Wkg}^{-1}$  (or  $\text{m}^2\text{s}^{-3}$ ), yielding maxima of  $\langle\varepsilon\rangle\sim 0.22$  and  
606  $0.55 \text{ Wkg}^{-1}$  and  $\varepsilon_{high}\sim 2.4$  and  $6 \text{ Wkg}^{-1}$  for these cases, given the separations between their  
607 locations shown with vertical lines in Fig. 15a and 15b. The mean values  $\langle\varepsilon\rangle$  are comparable to,  
608 or larger than, the largest estimates by in-situ probes at PMC altitudes of  $\sim 0.3 \text{ Wkg}^{-1}$  (e.g.,  
609 Strelnikov et al., 2009). The implied  $\varepsilon_{high}$  are much larger than have been observed at these  
610 altitudes, especially as the inferred GW parameters suggest that the likely  $\langle\varepsilon\rangle$  and  $\varepsilon_{high}$  are larger  
611 than those for  $a=1.1$ .

612 There are several explanations that appear plausible. Very large  $\langle\varepsilon\rangle$  and  $\varepsilon_{high}$  likely  
613 accompany very strong events that are infrequent and most often highly localized spatially and

614 temporally; see, e.g., the strong spatial localization implied by the broader PMC fields shown in  
615 Fig. 6 and the transience (i.e., a duration of  $\sim 1-2 T_b$ ) of strong maxima implied by Figs. 14b, 14f,  
616 15a, and 15b. Hence, the likelihood that any single rocket measurement would observe such an  
617 event at the location and time of maximum  $\langle \varepsilon \rangle$  is very small, perhaps less than 0.1%. This  
618 fraction would increase significantly, of course, where ground-based measurements were able to  
619 provide real-time identification of specific events and expected times of maximum turbulence.  
620 The likelihood of observing  $\langle \varepsilon \rangle$  and/or  $\varepsilon_{high}$  even sampling such an event is also small because  
621 of the limited portions of the GW and turbulence field that have large  $\langle \varepsilon \rangle$  and/or  $\varepsilon_{high}$  along a  
622 single near-vertical rocket trajectory implied by the horizontal  $\varepsilon$  fields in Fig. 14a and 14b.  
623 ***Indeed, sampling a turbulence field having high intermittency would require multiple vertical***  
624 ***profiles to develop confidence that a representative mean value was likely to be obtained.***

625 Another reason that sampling  $\langle \varepsilon \rangle$  and/or  $\varepsilon_{high}$  using current in-situ instruments is  
626 challenging is that they measure temperature rather than velocity fluctuations, hence estimate the  
627 turbulence spectral shape where  $Ri\chi$  may be small and thus have a low spectral amplitude,  
628 despite large  $\varepsilon$  (see Fig. 16a). Finally, smaller measured than predicted  $\varepsilon_{high}$  may arise because  
629 in-situ measurements typically average over  $\sim 30-100$  m along the rocket trajectory, whereas  $\varepsilon_{high}$   
630 occur accompanying the strongest small-scale vortices (and largest velocity shears) near the  
631 turbulence inner scale,  $l_0 = 9.9(\nu^3/\varepsilon)^{1/4} \sim 10$  m or less (Lübken, 1997), accompanying the strongest  
632 events. Several of these influences can be evaluated by employing current in-situ measurement  
633 methods to sample our various DNS data, and we expect to perform such studies in the future.

## 634 7.2. Case 2: GW breaking with $\lambda_z \sim 8-10$ km

635 The vortex rings shown in Fig. 11a have diameters of  $\sim 4$  km and appear to have been  
636 observed prior to further instabilities (and ring expansion), implying GW breaking for  $a \sim 1$ ,  $\lambda_z \sim 8-$   
637  $10$  km, and  $\omega_r \sim N/3$ . These parameters yield  $S \sim 3-5$   $\text{Wkg}^{-1}$ , hence maximum  $\langle \varepsilon \rangle \sim 0.06-0.1$  and  
638  $0.15-0.25$   $\text{Wkg}^{-1}$  and maximum  $\varepsilon_{high} \sim 0.7-1.1$  and  $1.6-2.6$   $\text{Wkg}^{-1}$  for the two cases shown in Figs.  
639 3 and 4. These  $\langle \varepsilon \rangle$  values are comparable to the larger values measured at the PMC altitude, i.e.,  
640  $\langle \varepsilon \rangle \sim 0.1-0.3$   $\text{Wkg}^{-1}$  (e.g., Rapp et al., 2004; Strelnikov et al., 2009). These magnitudes suggest

641 that such GW and instability scales may be somewhat more representative of those occurring  
642 more frequently at  $\sim 82$  km.

### 643 7.3. Case 3: GW breaking with $\lambda_z \sim 2$ km

644 The smaller vortex rings shown in Fig. 11c having maximum diameters of  $\sim 1$  km imply  
645 GW breaking for  $a \sim 1$ ,  $\lambda_z \sim 2$  km, and  $\omega_i > N/3$ , hence  $S \sim 0.2$   $\text{Wkg}^{-1}$  or somewhat larger. These  
646 imply much weaker turbulence than suggested by the larger-scale vortex rings in Cases 1 and 2.  
647 Scaling in this case implies  $\langle \varepsilon \rangle \sim 0.004$  and  $0.01$   $\text{Wkg}^{-1}$  and  $\varepsilon_{high} \sim 0.04$  and  $0.1$   $\text{Wkg}^{-1}$  for  $a = 0.9$   
648 and  $1.1$ , with larger values if  $\omega_i$  exceeds  $N/3$  by a significant amount. These and smaller  
649 turbulence magnitudes should be expected for GW breaking events at quite small horizontal and  
650 vertical scales, such as might be implied by  $\sim 2$ -km vertical scales in lidar or in-situ  $T'(z)$  profiles  
651 obtained with very little temporal averaging. Similar  $\lambda_z$ , but  $\lambda_h \sim 10$ - $30$  km or larger, imply  
652 smaller  $\langle \varepsilon \rangle$  and  $\varepsilon_{high}$  because of the smaller GW vertical group velocities of such motions.

### 653 7.4. Case 4: MSD with $\lambda_z \sim 6$ km

654 The cusp patterns seen in Fig. 12a suggest GW breaking similar to that in a shallow layer  
655 of the MSD DNS shown in Fig. 5h assuming a domain depth of  $6$  km. PDFs of  $\varepsilon$  for this event  
656 are shown at  $5, 10, 12, 22,$  and  $32 T_b$  in Fig. 15c. For reference, time series of domain mean  $[\varepsilon]$   
657 are compared for the two GW breaking events and the MSD event described above in Fig. 15d.  
658 That for the MSD DNS is shown at  $5x$  amplitude for comparison with the GW breaking DNS.

659 From the  $\varepsilon$  field shown in Fig. 5h, we see that the cusp-like features occur in a region that  
660 spans nearly the full range of  $\varepsilon$  in the full domain at the time of the cusp-like event. The inferred  
661 domain depth implies  $S \sim 2$   $\text{Wkg}^{-1}$ , thus a maximum  $\langle \varepsilon \rangle \sim 0.016$   $\text{Wkg}^{-1}$  at the time of the cusp  
662 occurrence, and  $\varepsilon_{high} \sim 0.25$   $\text{Wkg}^{-1}$ .

## 663 8. Discussion

664 Our study has focused on identification of GW instability dynamics observed in PMC  
665 imaging, their spatial and/or temporal scales, and the turbulence intensities,  $\langle \varepsilon \rangle$  and  $\varepsilon_{high}$ ,  
666 anticipated via comparisons with high-resolution DNS of these dynamics. To achieve results  
667 with the highest confidence, we have focused on dynamics that were well defined in our various

668 PMC imaging, thus on events that exhibited the largest instability scales that could be identified.  
669 Because turbulence intensities vary as  $\lambda_z^2$  for any event, our studies likely emphasized the  
670 stronger turbulence sources during these observations due to their more easily identified and  
671 quantified dynamics. Hence, the  $\langle \varepsilon \rangle$  and  $\varepsilon_{high}$  accompanying the most energetic phases of these  
672 events are surely significantly larger than mean values at these altitudes.

673 As an example, our range of estimates of  $\langle \varepsilon \rangle \sim 0.06-0.55 \text{ Wkg}^{-1}$  at the most intense phases  
674 of the stronger events analyzed in detail mostly exceed the values observed in a PMC  
675 environment at  $\sim 82 \text{ km}$  of  $\sim 0.001-0.3 \text{ Wkg}^{-1}$  inferred in previous radar and in-situ assessments  
676 by up to  $\sim 20$  times (e.g., Lübken, 1997; Lübken et al., 2002; Rapp et al., 2004; Engler et al.,  
677 2005; Latteck et al., 2005; Strelnikov et al., 2009; Szewczyk et al., 2013) and elsewhere at the  
678 same altitudes (e.g., Hocking, 1988). This is especially true given that we regard  $\langle \varepsilon \rangle$  and  $\varepsilon_{high}$   
679 estimated using the GW breaking DNS for  $a=1.1$ ,  $\lambda_z \sim 15 \text{ km}$ , and  $\omega_i = N/3.2$  to be quite  
680 conservative for Case 1 with estimated GW parameters of  $a > 1$ ,  $\lambda_z \sim 15 \text{ km}$  or larger, and  $\omega_i > N/3$ .  
681 The estimate of  $\varepsilon_{high} \sim 6 \text{ Wkg}^{-1}$  for this case far exceeds all estimates at  $\sim 82 \text{ km}$  and is comparable  
682 to the largest magnitudes ( $\sim 1-10 \text{ Wkg}^{-1}$ ) reported near the mesopause in the papers cited above.  
683 The largest  $\varepsilon$  in Fig. 15 are another  $\sim 3$  times higher.

684 Possibly more interesting, but to which PMC estimates can contribute only peripherally,  
685 are the larger and more continuous estimates of  $\langle \varepsilon \rangle$  as atmospheric stability increases  
686 approaching and above the polar summer mesopause. In-situ measurements at these altitudes  
687 have revealed relatively continuous turbulence intensities increasing from PMC altitudes to  
688  $\langle \varepsilon \rangle \sim 0.03-1 \text{ Wkg}^{-1}$  above  $\sim 85 \text{ km}$ , with peak values as high as  $\langle \varepsilon \rangle \sim 2-10 \text{ Wkg}^{-1}$  in each profile,  
689 and often occurring just above the mesopause (Rapp et al., 2004; Szewczyk et al., 2013). These  
690 measurements suggest that strong turbulence near the mesopause is apparently not intermittent,  
691 but more nearly continuous in space and time, despite the potential for under-estimates of true  
692  $\langle \varepsilon \rangle$  magnitudes noted above.

693 Several aspects of MLT GW dynamics contribute to sustained, strong turbulence near  
694 and above the polar summer mesopause. There is a ubiquitous spectrum of GWs having various

695 (and evolving) intrinsic parameters ( $a$ ,  $\lambda_z$ ,  $\lambda_h$ ,  $\omega_i$ , direction of propagation) that account for  
696 continuous fluxes of energy and momentum into the polar summer MLT from sources primarily  
697 at lower altitudes (e.g., Balsley and Garello, 1985; FV93; FA03). There are also environmental  
698 influences that cause GWs to increase in relative amplitude and lead to instabilities and  
699 turbulence throughout the atmosphere. These include the following:

- 700 1) continuous increases in GW amplitudes with increasing altitude due to decreasing density,
- 701 2) successive instability cycles at similar altitudes for GWs having large  $\omega_i$  and  $\lambda_z$  due to  
702 only partial GW attenuation accompanying breaking (F09a, F09b),
- 703 3) successive instabilities at higher altitudes for large GWs with  $\omega_i$  and  $\lambda_z$  due to only partial  
704 GW amplitude reductions accompanying breaking at lower altitudes,
- 705 4) wind shears due to mean, tidal, planetary wave, and larger-scale GWs that can induce  
706 decreasing  $\lambda_z$  and increasing  $a$  for GWs experiencing decreasing  $\omega_i$ ,
- 707 5) increasing  $N^2$  that drives decreasing  $\lambda_z$ , increasing  $u'/w' \sim \lambda_h/\lambda_z$  and  $a$ , hence increasing  
708 GW instabilities (VanZandt and Fritts, 1989, hereafter VF89; FV93), and
- 709 6) nearly continuous interactions among GWs that drive MSD instabilities in S&L flows.

710 The consequences of these dynamics are that GWs are always present in the MLT. To our  
711 knowledge, there are no PMC (or airglow) movies or images that do not reveal GW activity at  
712 larger and/or smaller spatial scales. The large majority of these also exhibit instability and/or  
713 turbulence dynamics, but these are often localized within the GW field and their detection  
714 depends on their amplitudes and the spatial resolution of the imager. Large-scale instabilities  
715 (horizontal scales up to 10 km or larger) that are easily detected can occupy from a few % to a  
716 majority of a large FOV. However, strong, local instabilities that evolve rapidly are often closely  
717 associated with the largest-amplitude (brightest) GWs having  $\lambda_h \sim 30$ -60 km or smaller. Strong  
718 turbulence likely accompanies the stronger instabilities, whereas weaker turbulence is long-  
719 lasting and thus assured and likely widespread, but very difficult to observe.

720 The various effects noted above are accounted for statistically in a spectral model of the  
721 evolution and dissipation of GWs with altitude (and varying  $N^2$ ) that is constrained by



722 observations and theory. The model initially addressed only increases in  $N^2$  (VF89), but was later  
723 generalized to include realistic altitude variations throughout the atmosphere (FV93). This theory  
724 yields an estimate of  $\langle \varepsilon \rangle \sim 0.28 \text{ Wkg}^{-1}$  near the mesopause without the enhanced contribution due  
725 increasing  $N$  (FV93); the enhanced  $\langle \varepsilon \rangle$  (and  $\varepsilon > \varepsilon_{high}$ ) may be significantly larger, depending on  
726 the degree and depth of  $N^2$  variations at the polar summer mesopause (VF89).

727 Finally, turbulence typically survives for long times following its initiation. As examples,  
728 instabilities leading to turbulence have shear and buoyancy energy production terms that span  
729 several  $T_b$  (F09b), and  $\langle \varepsilon \rangle$  decreases by only  $\sim 3$ -4 times over the final 10  $T_b$  of the PDFs shown  
730 in Fig. 14. While not a component of this study, KHI secondary instabilities and turbulence have  
731 comparable time scales for their evolutions (WF99; F12, F14b). Thus, successive, or unrelated,  
732 new GW or MSD instabilities have significant time over which to evolve prior to cessation of  
733 turbulence due to previous events.

734 Significant unknowns related to these studies at present include the following:

- 735 1) definition of the local environmental  $N$  needed to quantify estimates of  $S$  and  $\varepsilon$ ,
- 736 2) influences of background turbulence, and a smaller “turbulent” Reynolds number,  
737  $Re_{turb} = \lambda_z^2 / \nu_{turb} T_b$  (where  $\nu_{turb} > \nu$  is the turbulent viscosity, F14b, F14c), on the character  
738 and intensities of new instabilities and turbulence, and
- 739 3) implications of DNS at lower  $Re$  than are realistic when background turbulence is weak.

740 Evidence for the influences of background turbulence on KHI seen in PMCs and OH airglow  
741 was provided in the studies by Baumgarten and Fritts (2014), F14b, Hecht et al. (2014), and  
742 F14c. In these cases, background  $\nu_{turb} > \nu$  (and  $Re_{turb} < Re$ ) were inferred due to larger observed  
743 spatial scales of secondary instabilities than were anticipated by DNS of KHI in the absence of  
744 an elevated viscosity. Estimates in these cases ranged from  $\nu_{turb} \sim 5$ -40  $\nu$  (and  $Re_{turb} \sim 0.025$ -0.2  
745  $Re$ ), though much higher values are likely to accompany stronger turbulence sources. Assuming  
746 the same influences occur for other types of instabilities, we should expect our DNS of GW  
747 breaking and MSD to be appropriate for larger spatial scales that would otherwise have much  
748 higher  $Re$ . As an example, the GW breaking assumed to cause the vortex rings in Case 1 had

749  $Re = \lambda_z^2 / \nu T_b \sim 8 \times 10^5$ , assuming no turbulent viscosity. The Floquet theory for the DNS shown in  
750 Figs. 3 and 4 (F09a) suggests that a higher  $Re$  does not likely change the instability character,  
751 scales, or growth rates. However, larger  $\varepsilon$  accompany larger  $Re$  for the same underlying  
752 dynamics (F16). Hence smaller  $\nu_{turb}$  and larger  $Re_{turb}$  would yield even larger  $\varepsilon$  estimates than  
753 discussed above.

754 Additional effects that accompany strong instabilities and turbulence in the MLT (and  
755 throughout the atmosphere) include local heating and turbulent mixing and transport. Turbulence  
756 heating rates are  $\sim 100$  K/day for  $\varepsilon \sim 1$  Wkg<sup>-1</sup> and thus comparable in magnitude to the adiabatic  
757 cooling driven by GW-induced upwelling near the polar summer mesopause. Turbulence is also  
758 anticipated by many to contribute a strong downward heat flux near and above the polar summer  
759 mesopause, but modeling of these dynamics has yet to confirm (or contradict) these expectations.

## 760 **9. Summary and Conclusions**

761 We have employed high-resolution DNS to explore the implications of instability  
762 features observed in high-resolution imaging of PMCs for turbulence sources and intensities near  
763 the polar summer mesopause. Imaging by ground-based cameras in Norway and serendipitously  
764 by star cameras as part of a cosmology experiment flown on a stratospheric balloon over  
765 Antarctica yielded evidence of various instability types suggesting idealized and multi-scale GW  
766 dynamics at PMC altitudes. Observations of instability features and scales enabled estimates of  
767 the underlying GW intrinsic properties and amplitudes in four cases.

768 Specific results and implications of our study include the following:

- 769 1) PMC imaging reveals an active dynamical environment with larger-scale GWs always  
770 present and smaller-scale instabilities occurring frequently, as also noted previously,
- 771 2) the dominant instabilities include KHI, GW breaking, and intrusions at multiple scales,
- 772 3) vortex rings are a frequent instability form accompanying GW breaking at various scales,
- 773 4) vortex rings occurring at large scales with close spacing imply large GW amplitude  $a$ ,  
774 vertical wavelength  $\lambda_z$ , and intrinsic frequency  $\omega_i$ , and large corresponding energy and  
775 momentum fluxes,

- 776 5) large GW  $a=|u'/c_i|=|du'/dz|/N\sim 1$ ,  $\lambda_z$ , and  $\omega_i$  yield strong instabilities and turbulence,  
777 6) MSD instabilities include local GW breaking, KHI, and intrusions, but these are often  
778 weaker and more challenging to quantify due to shallower instability depths,  
779 7) while strong turbulence can arise rapidly ( $\sim 1-2 T_b$ ), turbulence decay can be very slow,  
780 e.g., a factor of  $\sim 3$  or less over  $10 T_b$ , and turbulence may thus persist for a long time,  
781 8) estimates of  $\langle \varepsilon \rangle$  employing PMC imaging and numerical modeling are broadly  
782 consistent with the magnitudes inferred from *in-situ* measurements at the PMC altitudes.  
783 9) larger  $\varepsilon$  within the modeled distributions also compared well with the larger measured  
784 values near the polar summer mesopause, where theory anticipates more continuous  
785 turbulence generation and larger magnitudes.

786 There remain uncertainties over the roles and implications of a turbulent viscosity,  $\nu_{turb}$ ,  
787 and an implied turbulent Reynolds number,  $Re_{turb}$ , in defining MLT instability dynamics, scales,  
788 and turbulence intensities. DNS of these dynamics appear to predict mean and maximum  $\varepsilon$  that  
789 agree reasonably with *in-situ* observations, despite having smaller than physical  $Re$  in the  
790 absence of background turbulence. Possible explanations are that pre-existing turbulence  
791 typically imposes a larger  $\nu_{turb}$  and a smaller  $Re_{turb}$  or that  $\langle \varepsilon \rangle$  may be larger than measured  
792 because of the spatial intermittency of turbulence events, and strong turbulence within these  
793 events. Of these, the former appears to be more likely. The role of turbulence in heat and  
794 momentum transports is also unknown, but will likely need to rely on high-resolution DNS for  
795 its resolution.

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Case	Event type	$\lambda_z$ (km)	$a$	$\omega_0$ (N)	$\lambda_h$ (km)	$C=\lambda_z^2/T_b^3$	$Re=\lambda_z^2/\nu T_b$	$\epsilon_{mean}$ (Wkg <sup>-1</sup> )	$\epsilon_{high}$ (Wkg <sup>-1</sup> )
1	ideal. GWB	>15	>1	>0.3		7.3	$8.3 \times 10^5$	>0.55	>6
2	ideal. GWB	8-10	~1	>0.3		2.1-3.2	$2.4-3.7 \times 10^5$	~0.06-0.25	~0.7-2.6
3	ideal. GWB	2	~1	>0.3		0.13	15,000	~0.004-0.01	~0.04-0.1
4	MSD GWB	1	>1			1.2	$1.3 \times 10^5$	0.016	0.25

808 **Table 1.** GW parameters and  $\epsilon$  estimates for idealized and MSD GW breaking (GWB) cases.

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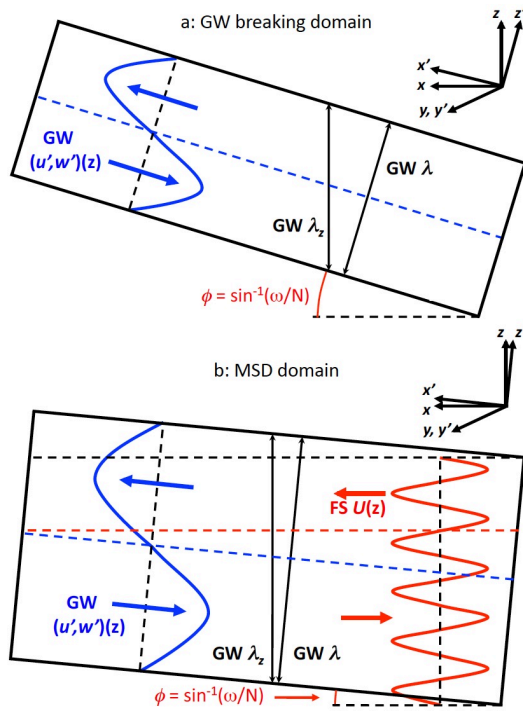
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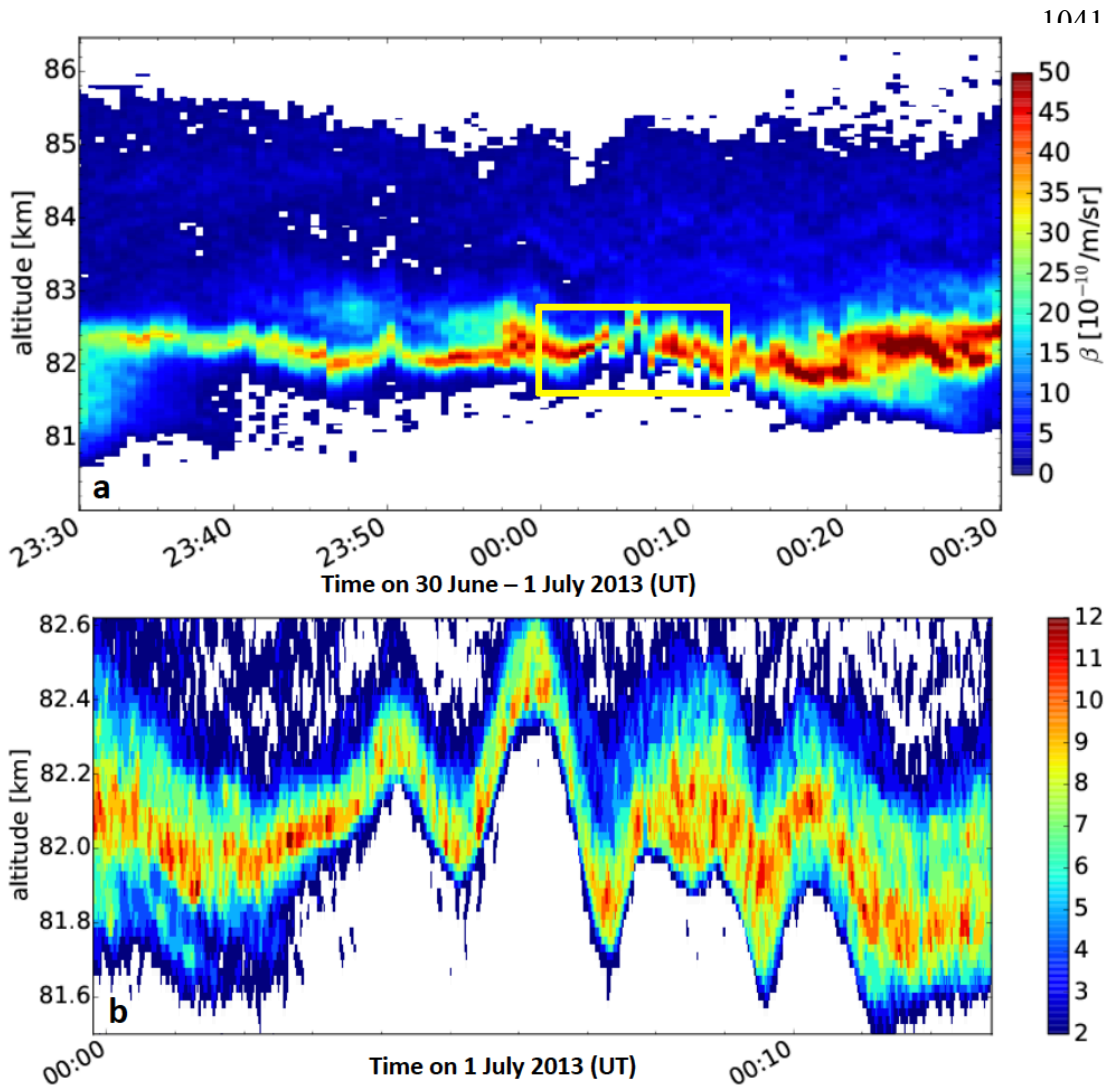
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1032 **Figures**

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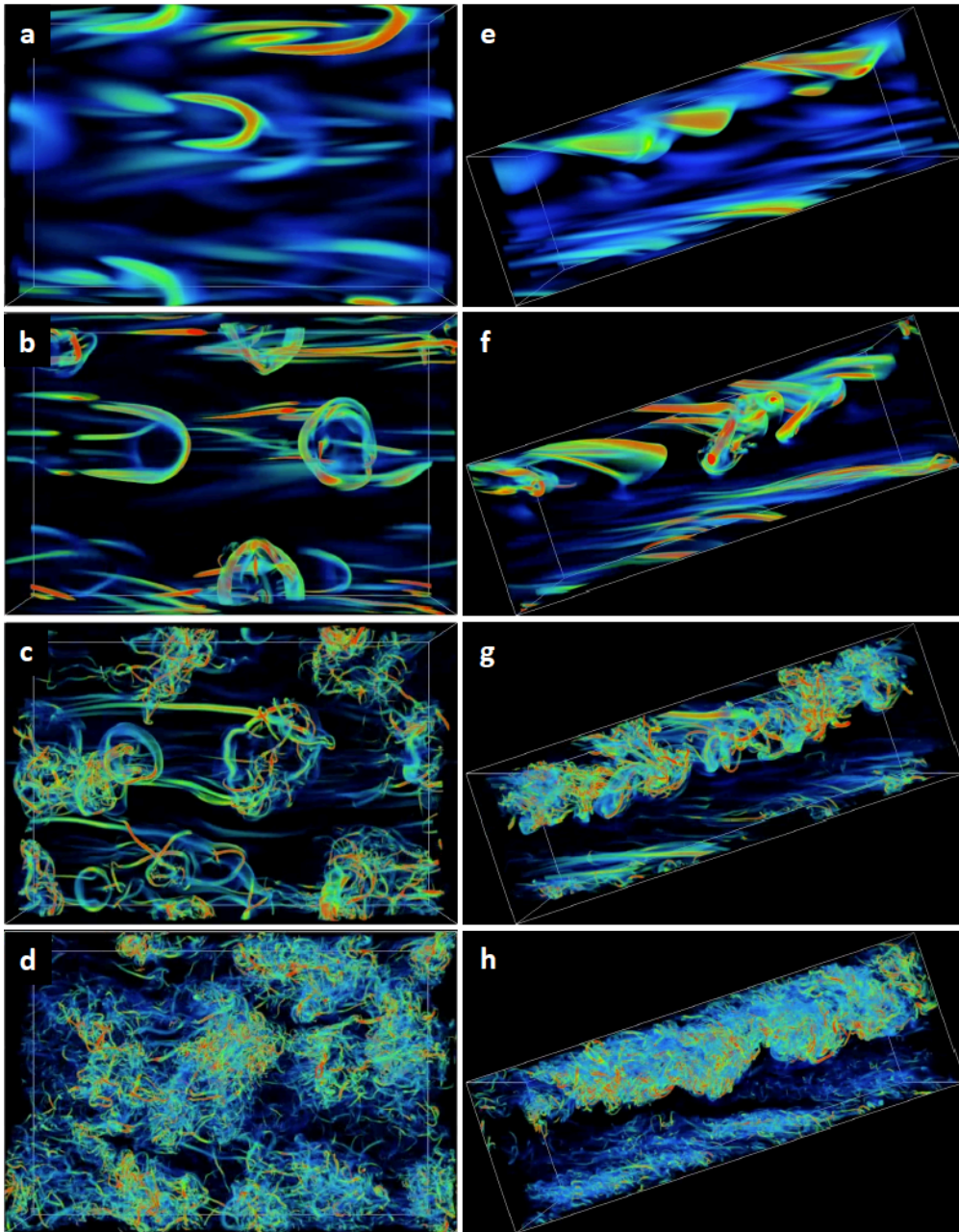


1035 **Figure 1.** Tilted computational domains aligned along the primary GW for (a) the idealized DNS  
1036 of GW breaking for  $\alpha=0.9$  and 1.1 and (b) the MSD DNS of a superposed initial GW and mean  
1037 small-scale shear flow. The domain and geophysical coordinates are  $(x', y', z')$  and  $(x, y, z)$  in each  
1038 case and blue and red arrows and oscillatory curves show the initial GW and mean shear flows.  
1039 See text for additional details on other initial conditions and flow parameters.



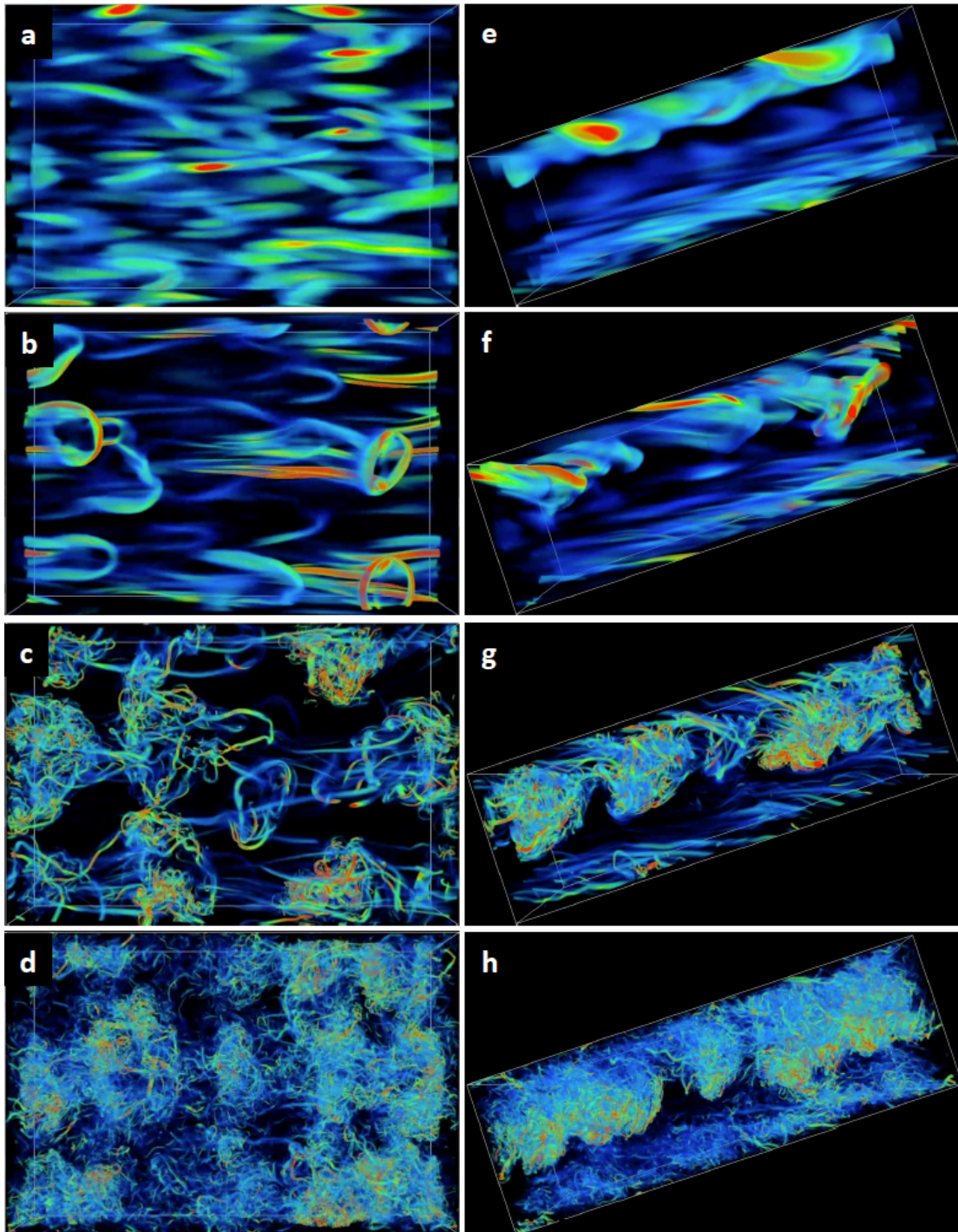
1042 **Figure 2.** Measurements of PMC layer thickness with the Rayleigh-Mie-Raman lidar at  
 1043 ALOMAR from (a) 23:30-00:30 UT on 30 June to 1 July 2013 and (b) 00:00-00:12 UT on 1 July  
 1044 2013. The times and altitudes shown in (b) are highlighted in the yellow rectangle in (a). Note  
 1045 that the layer FWHM can often be <100 m.

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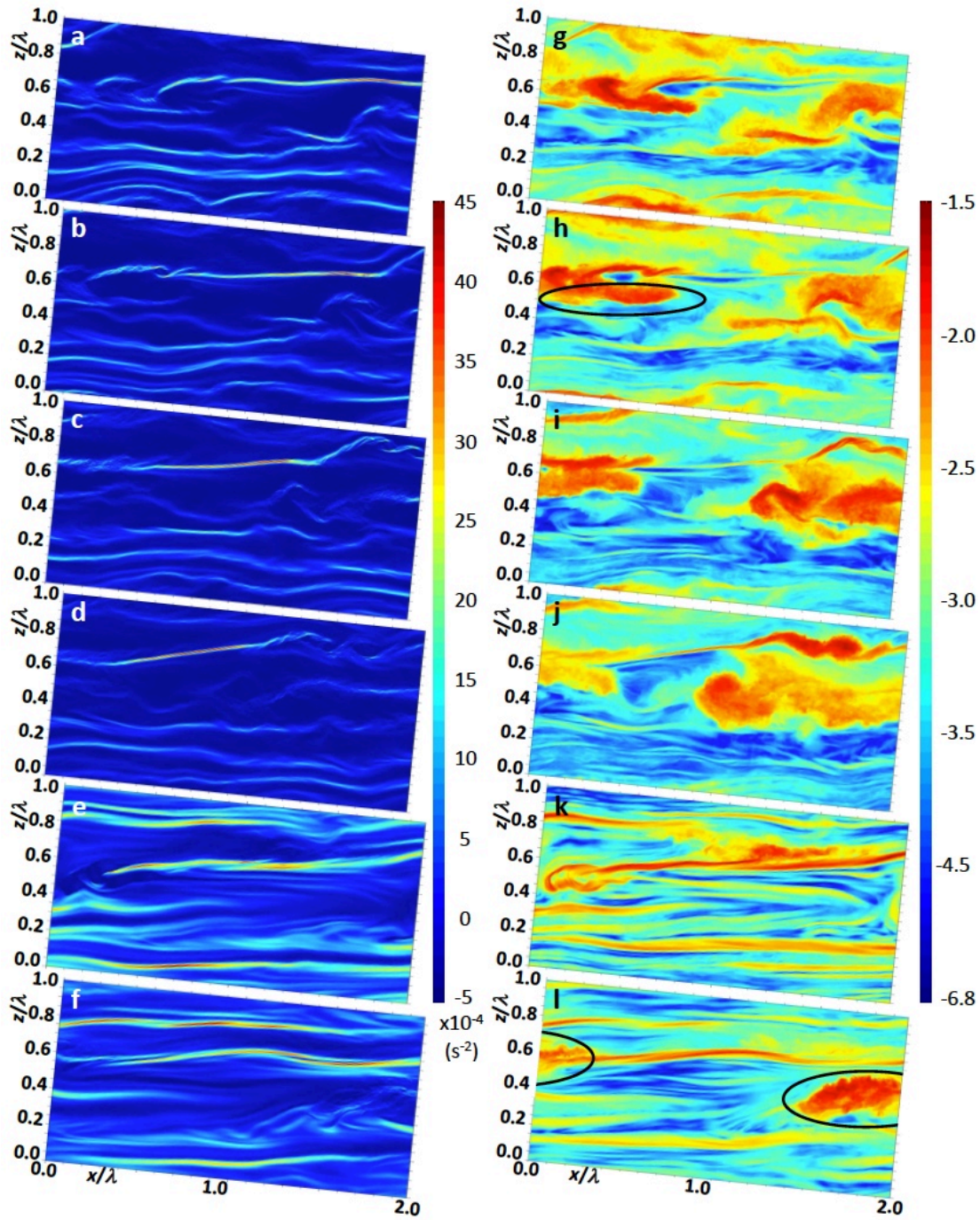
1053 **Figure 3.** 3D volumetric views of  $\lambda_2$  from (a-d) below and (e-h) the side showing the evolution  
 1054 of initial instabilities and turbulence accompanying the GW breaking DNS with  $a=0.9$  at 21, 22,  
 1055 23, and 24  $T_b$  (top to bottom). The GW is shown propagating upward and to the right for more  
 1056 convenient comparisons with the PMC imaging from the ground. The color scale varies from  
 1057 weak (light blue) to intense (yellow/red) rotation.



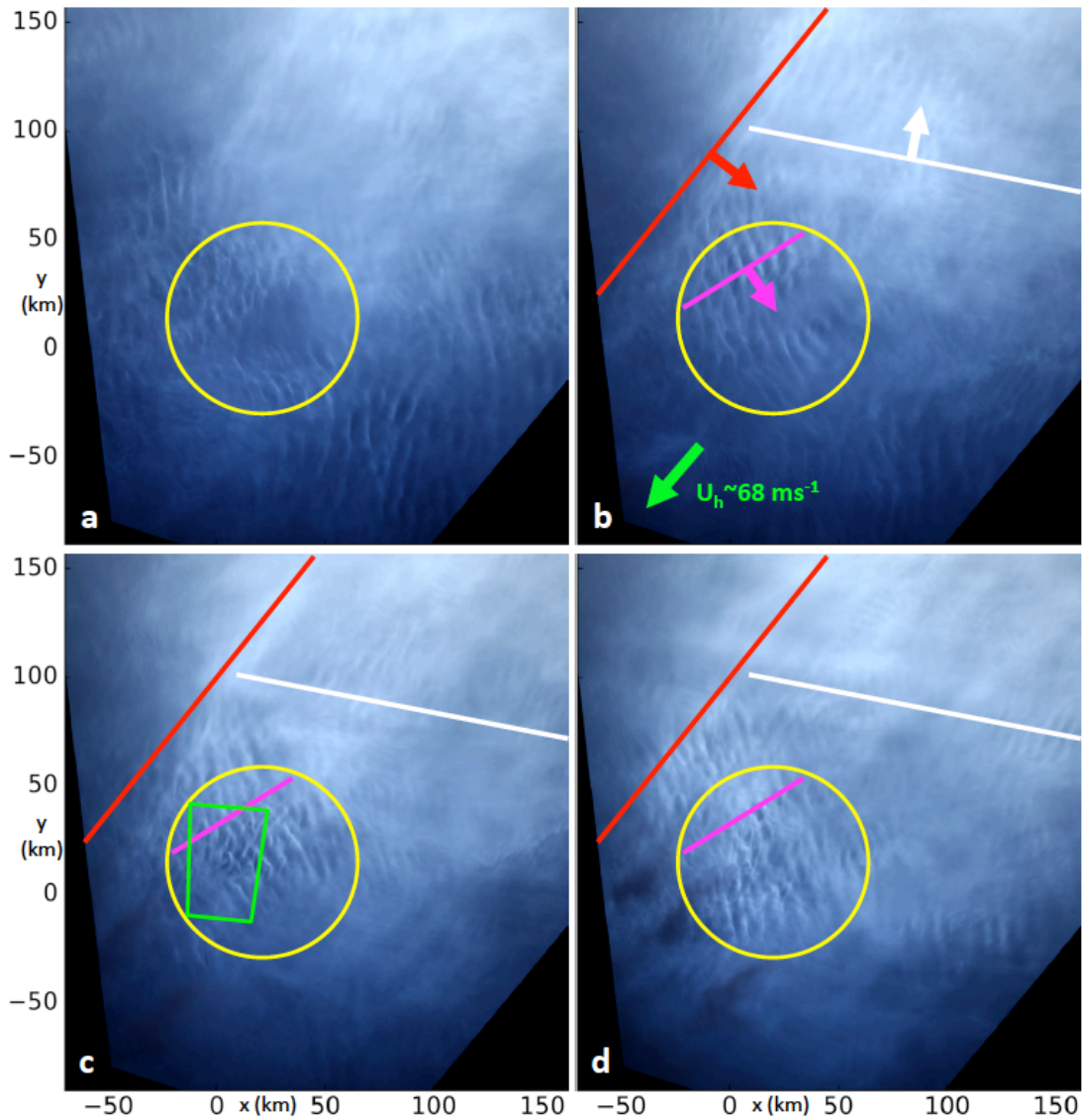


1059 **Figure 4.** As in Fig. 3 for the GW breaking DNS with  $\alpha=1.1$  at 9.2, 10.2, 11.2, and 12.2  $T_b$ .



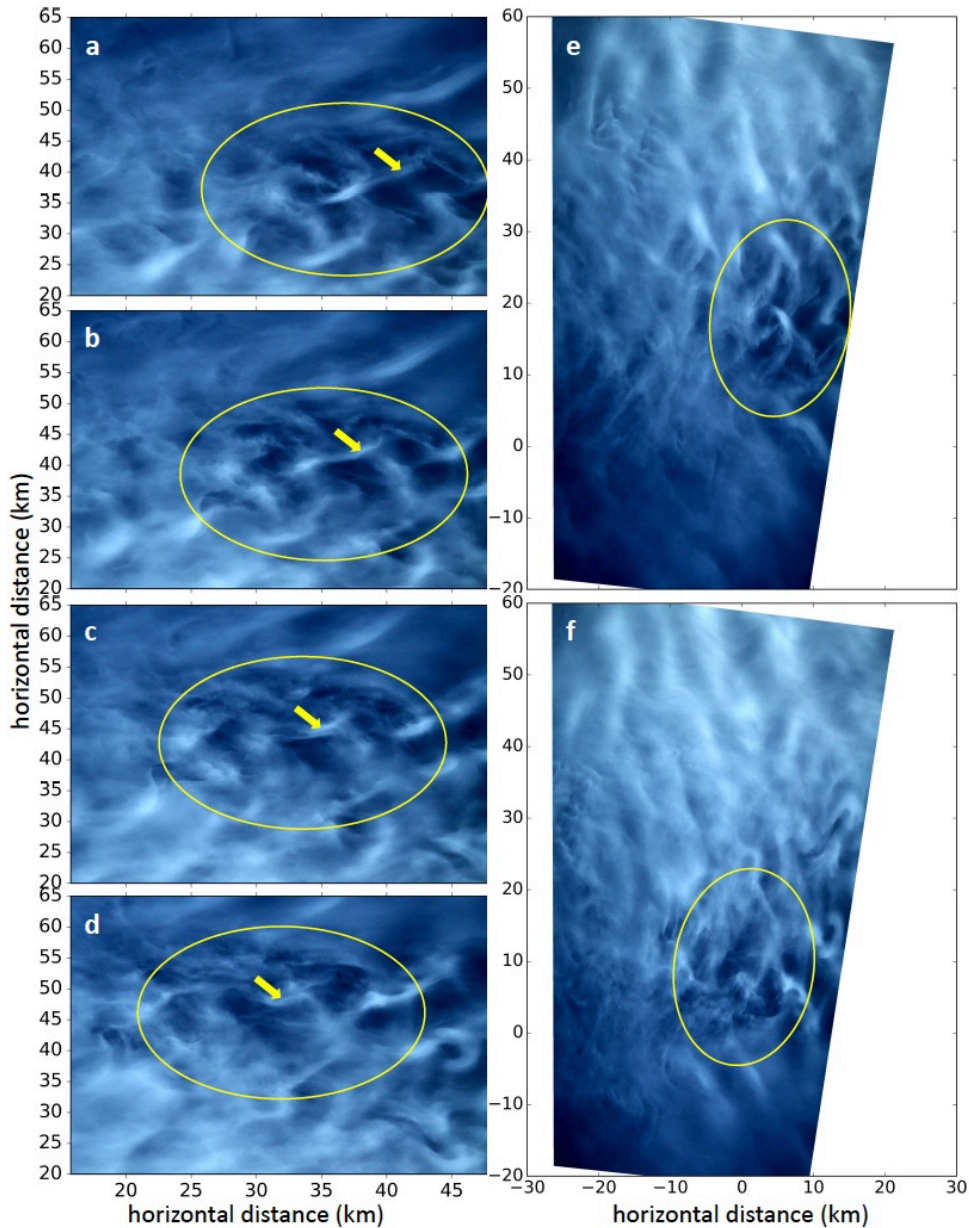


1063 **Figure 5.** Spanwise-averaged  $N^2(x,z)$  and  $\log_{10}\epsilon(x,z)$  for the MSD DNS described in Section 4.2  
 1064 showing an evolving GW breaking and KHI at 10, 10.4, 11, and 11.6  $T_b$  (a-d and g-j) and an  
 1065 intrusion event at 31.7 and 33  $T_b$  (e and f, k and l). The  $N^2$  color scale has a maximum of  $\sim 11 N_0^2$   
 1066 and the  $\log_{10}\epsilon(x,z)$  color scale is nondimensional and must be scaled by  $S=\lambda_z^2/T_b^3$ .

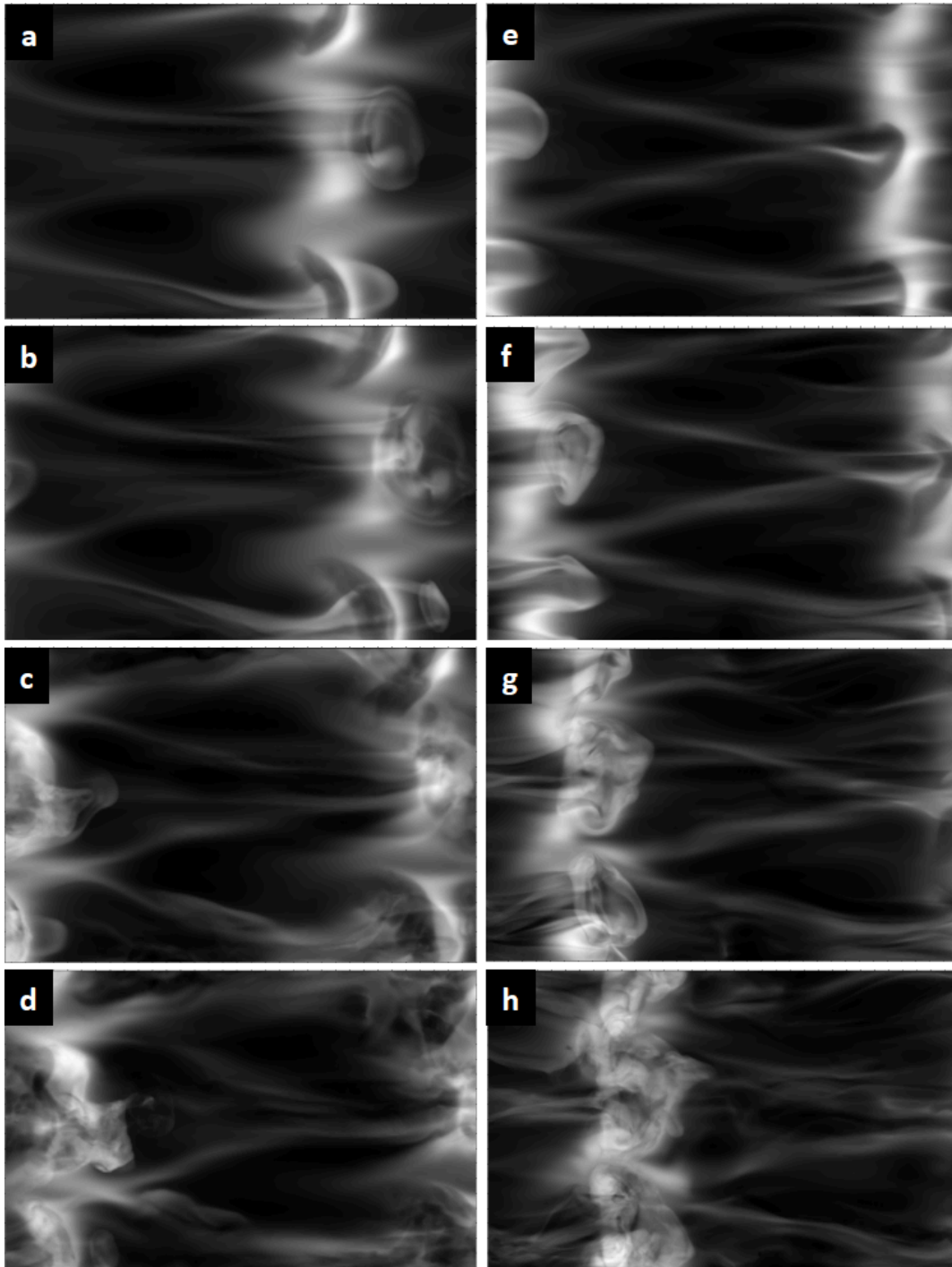


1069 **Figure 6.** Ground-based wide-FOV PMC images viewing NNE from Trondheim, Norway on 1  
 1070 August 2009 at 23:20, 23:30, 23:40, and 23:50 UT (a-d). The images are projected to the PMC  
 1071 altitude of  $\sim 82$  km viewed from above, with N and E up and to the right. The FOV spans  
 1072  $>200 \times 200$  km, yellow circles highlight the GW instability event of interest, the green trapezoid  
 1073 in (c) indicates the narrower FOV employed to examine the GW instability structures, and the  
 1074 lines and corresponding arrows show the phase orientations and propagation directions of the  
 1075 primary GWs.

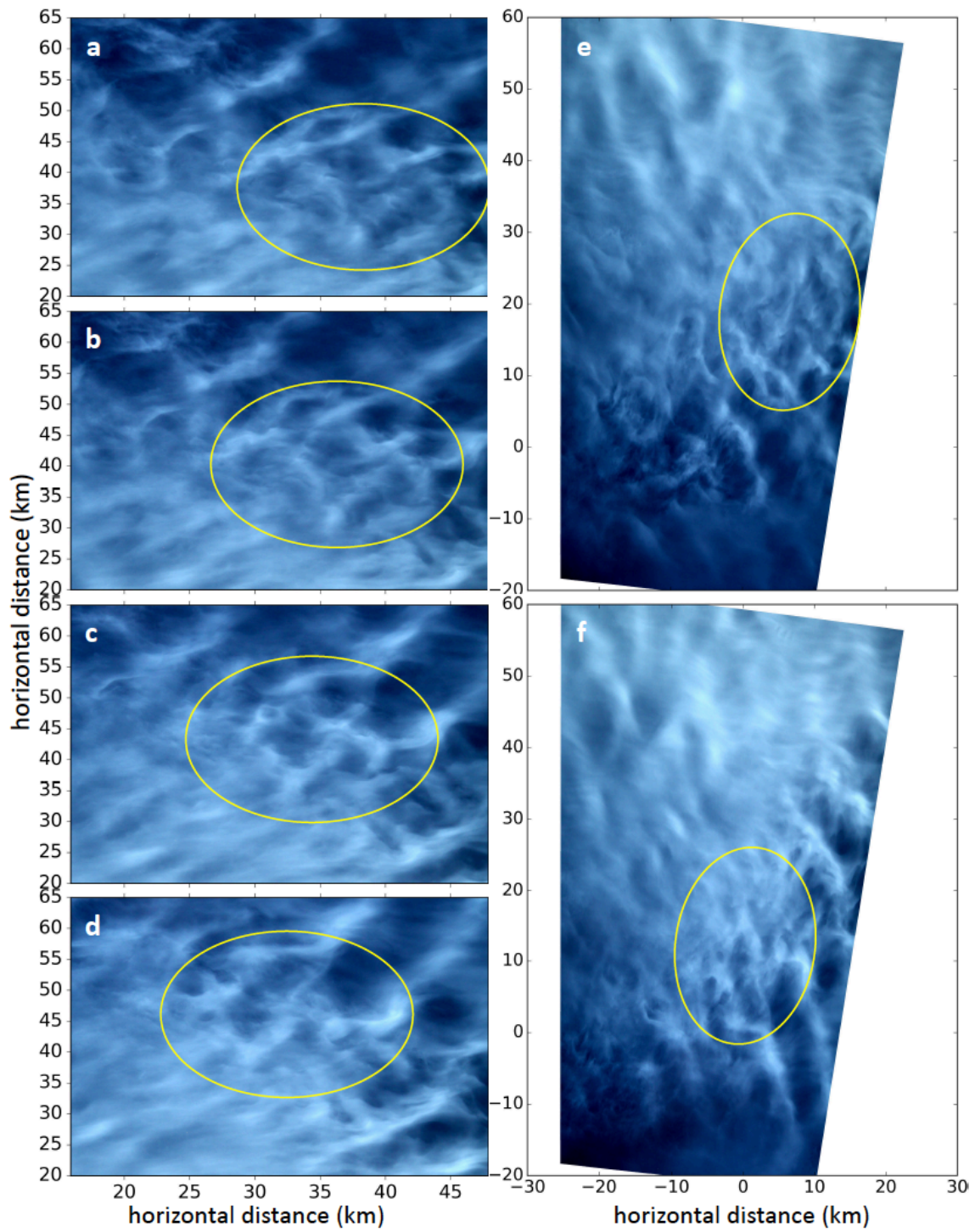




1078 **Figure 7.** Narrow FOV images of the GW breaking event showing the evolutions of vortex rings  
 1079 from 23:42-23:45 UT (a-d) at a slant angle of  $\sim 21^\circ$  below the horizontal and ahead and to the  
 1080 right of the GW propagation direction (towards the SE). Yellow ovals highlight the major vortex  
 1081 rings occurring during this phase of the event; yellow arrows show the motion of the trailing  
 1082 vortices for the most upstream (eastward vortex ring). Panels (e) and (f) show the projected fields  
 1083 in (a) and (d).



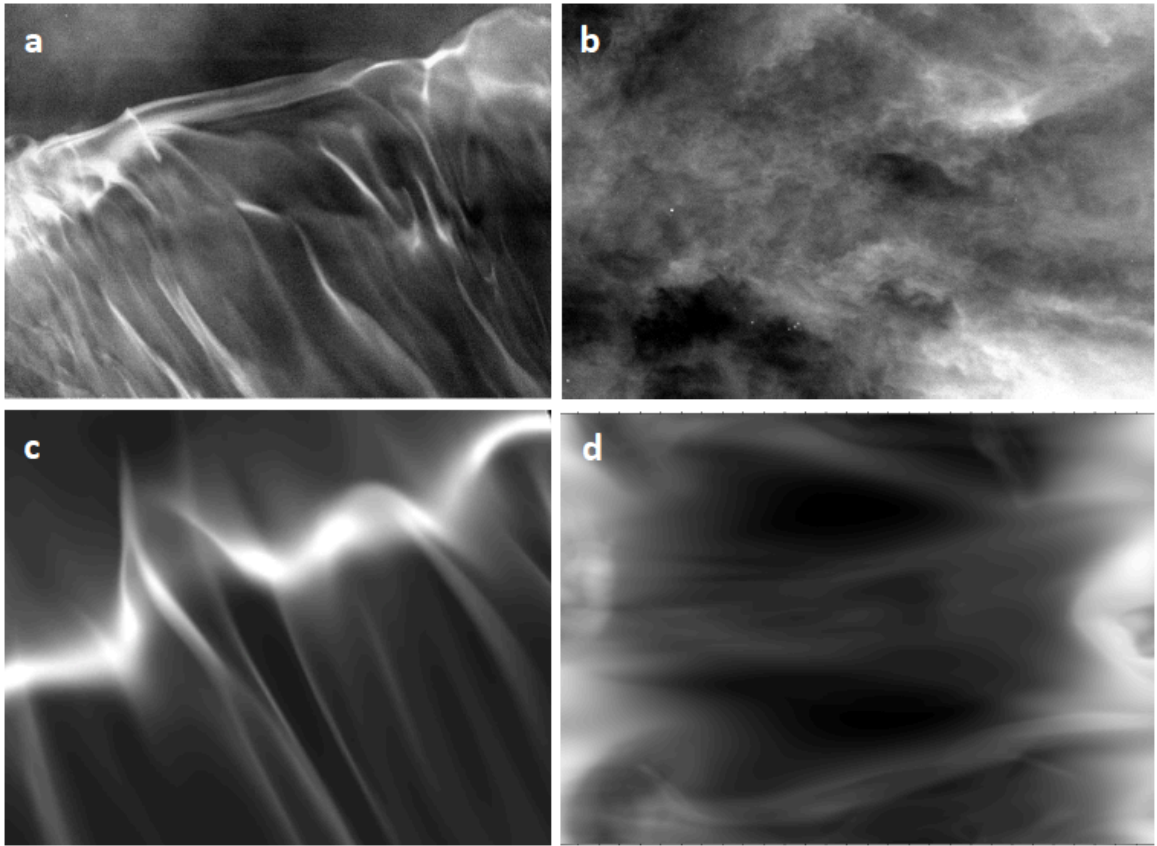
1086 **Figure 8.** Simulated PMC responses in the GW breaking DNS for  $a=0.9$  from 22-23 (a-d)  $T_b$  and  
 1087 for  $a=1.1$  from 10.2-11.2 (e-h) at  $\sim 0.33 T_b$  intervals having a PMC layer centered on the vortex  
 1088 rings in the most unstable phase of the GW with  $z_{FWHM}=0.1 \lambda_z$  in each case.



1089 **Figure 9.** As in Fig. 7 for 23:47-23:50 UT. The yellow ovals in this case show new vortex rings  
 1090 that formed to the SE of those shown in Fig. 7.  
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1094 **Figure 10.** PMC imaging by the EBEX star cameras showing a GW breaking front (a) and a zig-  
1095 zag pattern at the time of initial streamwise vortex generation (b) in projected FOVs of 4.4x3.9  
1096 km. Panels (c) and (d) show corresponding images of simulated PMCs with  $z_{FWHM}=100$  m from  
1097 the GW breaking DNS shown in Fig. 4 at  $10.25 T_b$  and Fig. 3 at  $\sim 22 T_b$ , respectively.

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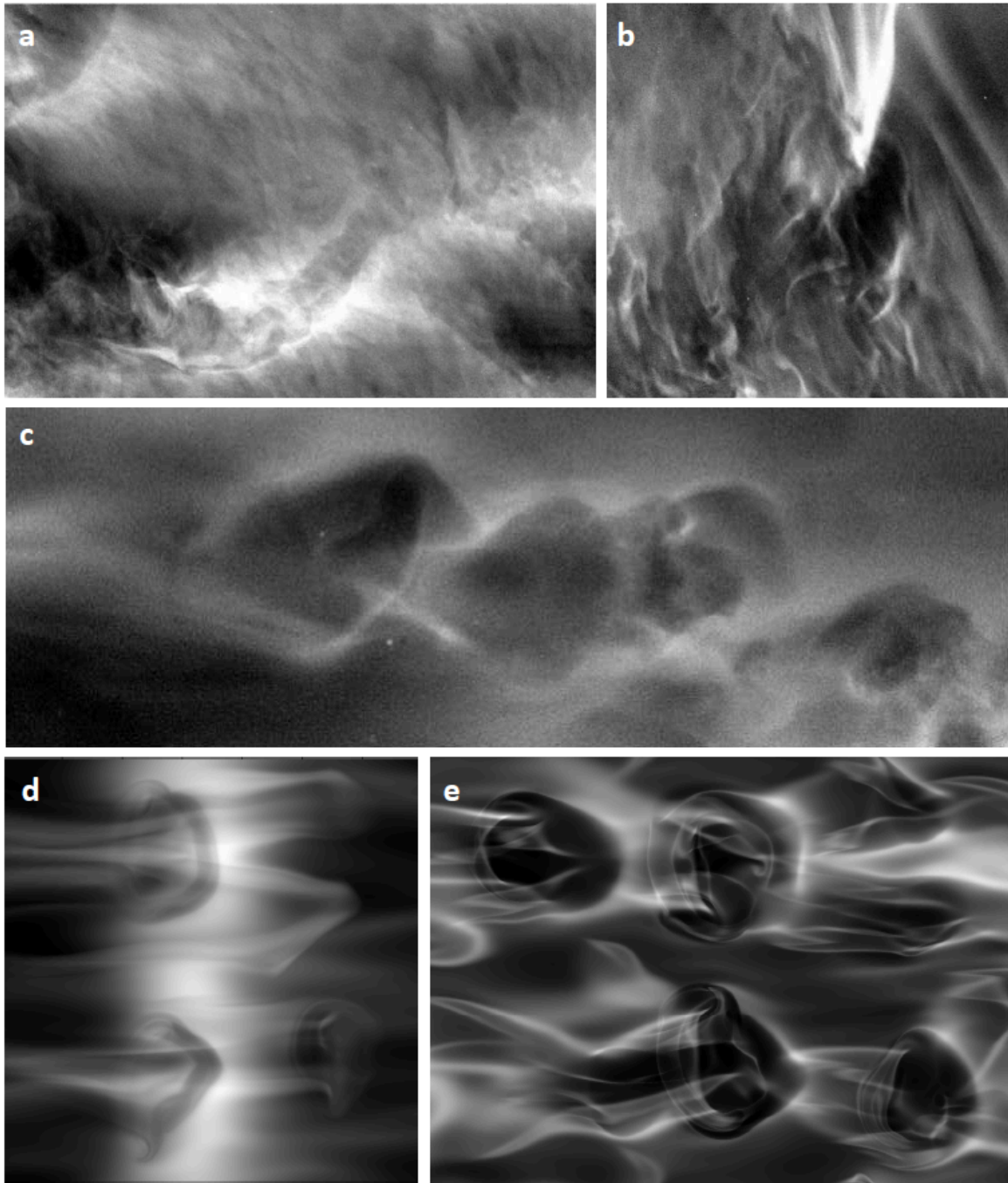
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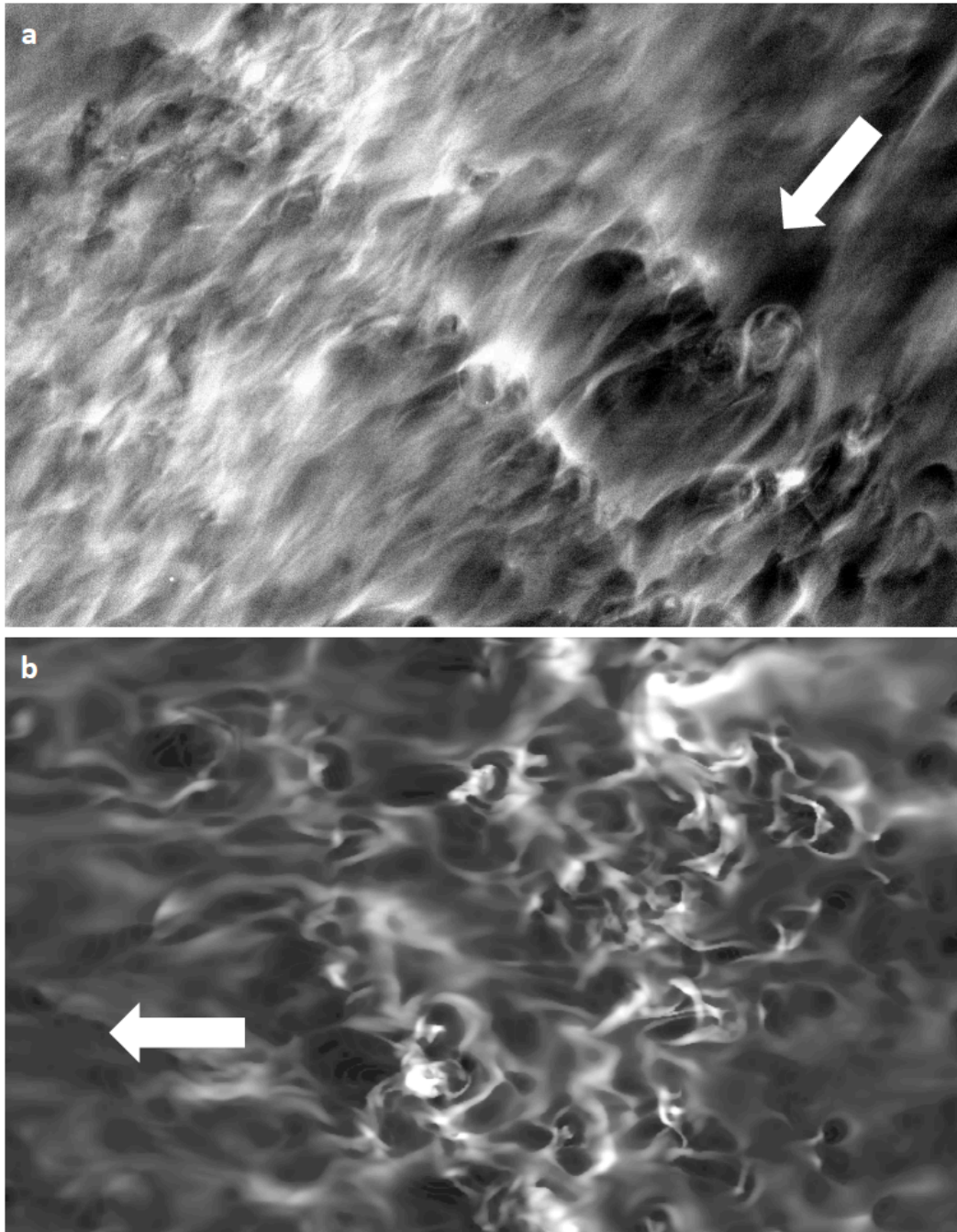
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1107 **Figure 11.** As in Fig. 10 showing PMC images of vortex rings at various scales, orientations, and  
 1108 evolution stages (a-c). PMC image FOVs are  $4.4 \times 3.9$ ,  $4 \times 3.9$ , and  $4.4 \times 2$  km, respectively. Panels  
 1109 (d) and (e) show two images of vortex rings from the GW breaking DNS for  $a=1.1$  at  $\sim 10.5 T_b$   
 1110 with  $z_{FWHM}=0.2 \lambda_z$  at the level of the vortex rings (d) and with  $z_{FWHM}=0.05 \lambda_z$  somewhat above.

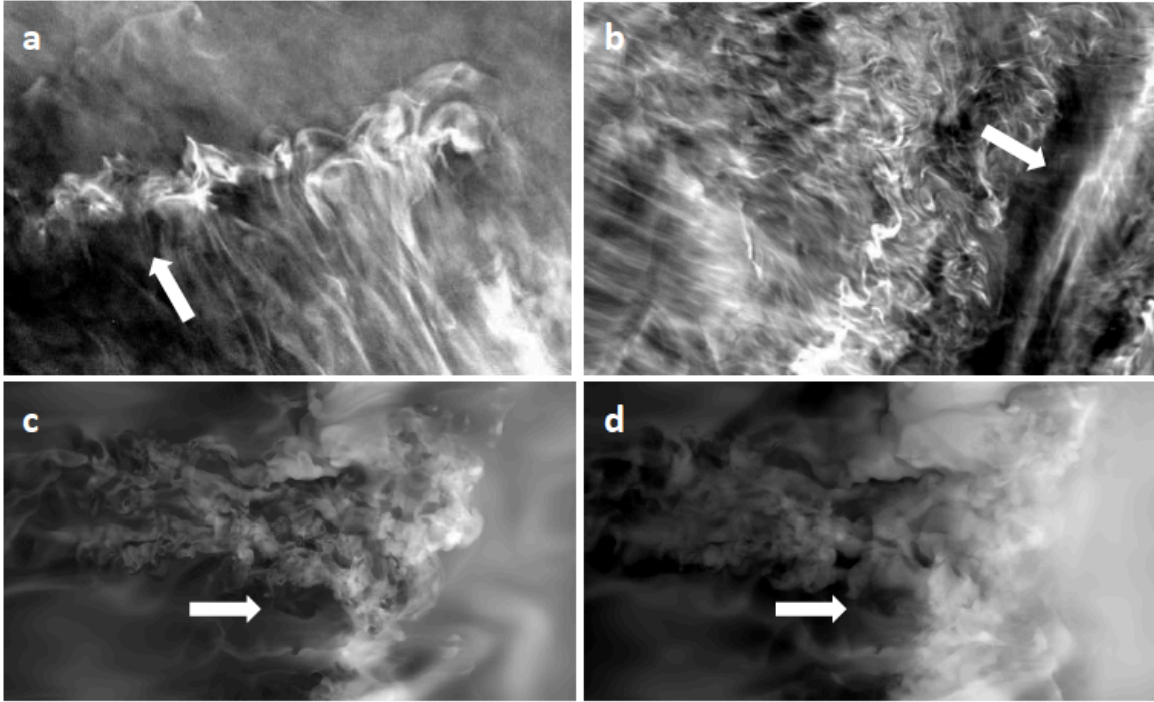
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1114 **Figure 12.** As in Fig. 10 showing a PMC image of cusp-like structures below an apparent region  
1115 of local GW breaking in an MSD environment (a) and a simulation of similar features from a  
1116 DNS of an MSD flow (b). The projected FOV of the PMC image in (a) is 4.4x3.9 km. The MSD  
1117 dynamics occur in the black oval in Fig. 5h. Arrows in each panel show the direction of shearing  
1118 below these structures.





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1120 **Figure 13.** As in Fig. 12 showing PMC images of apparent intrusions (a and b) in projected  
1121 FOVs of 3.7x2.6 and 4.4x3.9 km, respectively. Panels (c) and (d) show a simulated PMC arising  
1122 from the intrusion in the black oval in Fig. 5h with  $z_{FWHM}=100$  and 300 m (c and d) to illustrate  
1123 the increased sensitivity to small-scale features by a thinner PMC layer.

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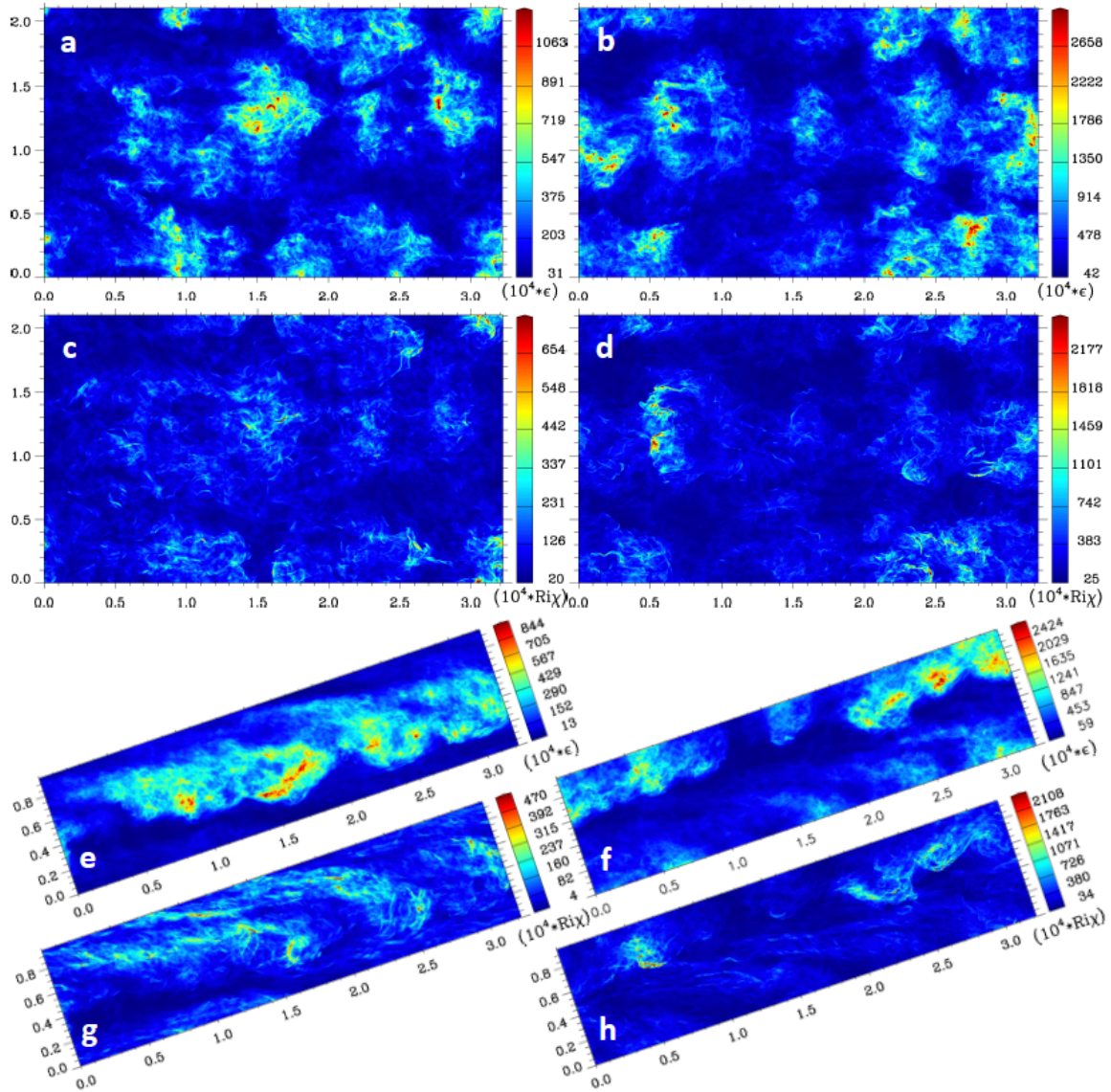
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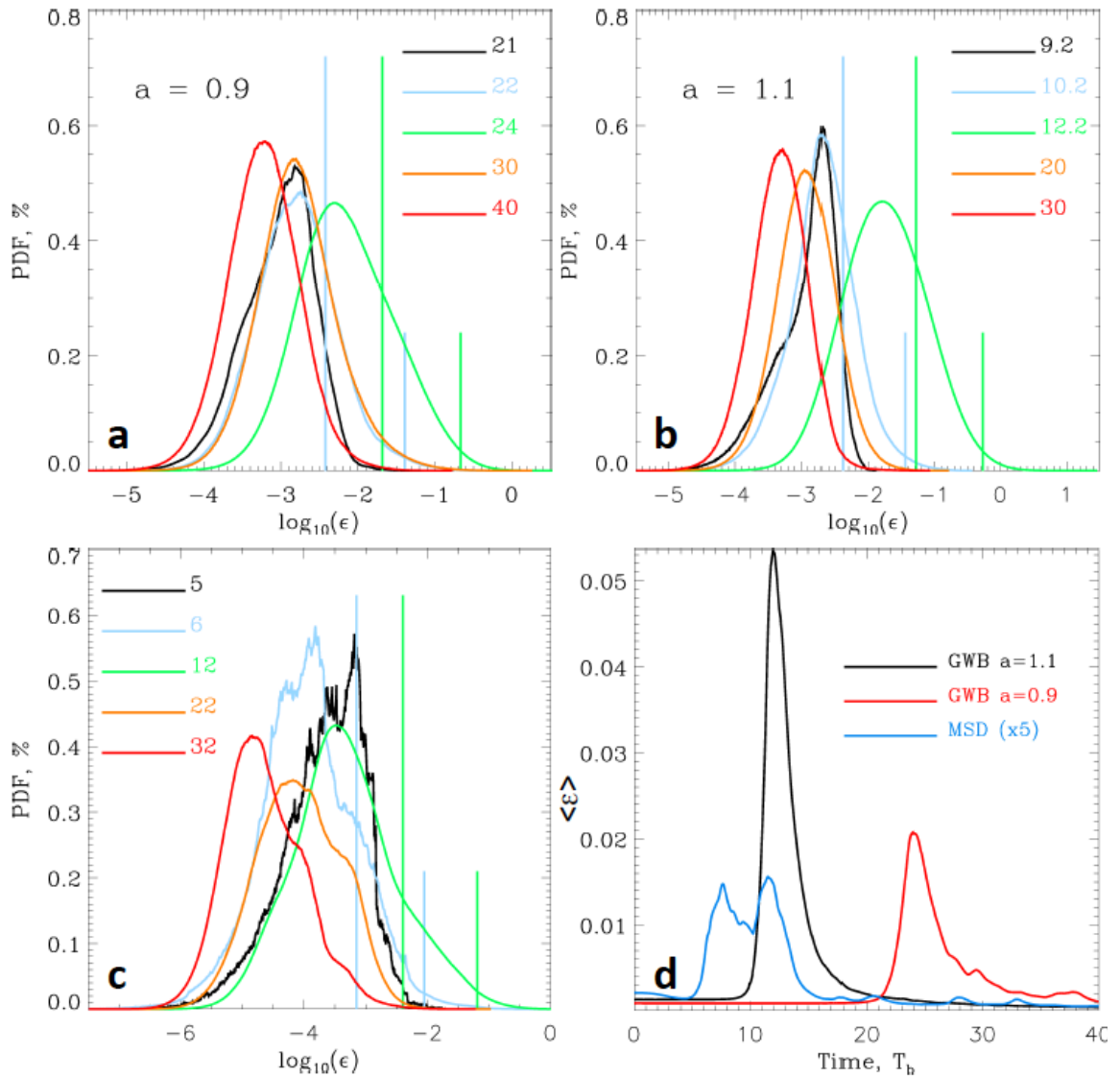
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1135 **Figure 14.** Horizontal (top panels) and vertical (bottom panels) cross sections of vertically- and  
 1136 spanwise-averaged (top and bottom, respectively)  $\varepsilon$  and the thermal energy dissipation rate,  $Ri\chi$ ,  
 1137 for the DNS of GW breaking shown in Figs. 3 and 4.  $\varepsilon$  cross sections are shown in panels (a) and  
 1138 (e) for  $a=0.9$  and in panels (b) and (f) for  $a=1.1$ . Corresponding  $Ri\chi$  cross sections are shown in  
 1139 panels (c), (d), (g), and (h). Note that due to the vertical and spanwise averaging of  $\varepsilon$  and  $Ri\chi$ , the  
 1140 ranges of values in the color scales are now  $\sim 2$  rather than  $\sim 4$  decades in each case. The color  
 1141 bars also have upper limits at the magnitude above while 0.1% of  $\varepsilon$  and  $Ri\chi$  occur.

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1147 **Figure 15.** PDFs of  $\log_{10}\epsilon$  for GW breaking with  $a=0.9$  and  $a=1.1$ , and for the MSD DNS are

1148 shown in (a-c), respectively. Times shown in each panel extend from initial instability stages to

1149 late in the turbulence decay. Vertical lines for the second and third times in each case show  $\langle \epsilon \rangle$

1150 and  $\epsilon_{high}$ . Nondimensional domain-mean  $\epsilon$  are shown from 0-40  $T_b$  for the three DNS in panel

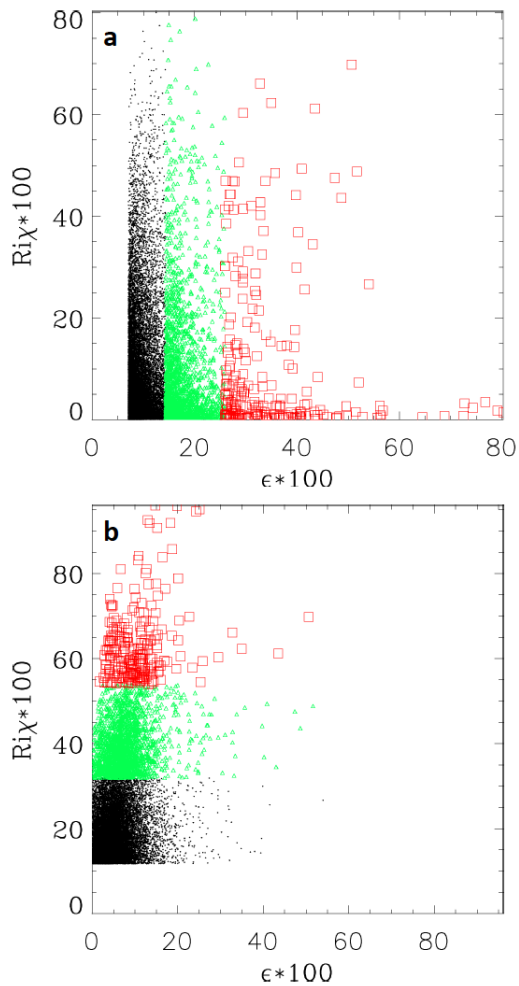
1151 (d). Note that turbulence intensities are very much smaller for the MSD than for the GW

1152 breaking cases for the same domain depths.

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1159 **Figure 16.** Comparisons of the relative values of  $\epsilon$  and  $Ri\chi$  for the largest values of  $\epsilon$  (a) and  
1160  $Ri\chi$  (b) averaged over 64 grid points. In each case, red squares, green triangles, and black dots  
1161 denote values of  $\epsilon$  (a) or  $Ri\chi$  (b) among the largest 0.1-0.01%, 0.01-0.001%, and above 0.001%,  
1162 respectively.  
1163