

1 **Tropopause Evolution in a Rapidly Intensifying Tropical Cyclone: A Static**  
2 **Stability Budget Analysis**

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## ABSTRACT

<sup>8</sup> We have some cool results!

## 9 **1. Introduction**

10 Perhaps introduce upper-tropospheric static stability and its relationship to the diurnal cycle  
11 before going into Patricia? Include references to Dunion, Navarro, and O'Neill here.

12 After undergoing a remarkably rapid intensification (RI), Hurricane Patricia (2015) set a new  
13 record as the strongest tropical cyclone (TC) ever observed in the Western Hemisphere (Kimber-  
14 lain et al. 2016; Rogers et al. 2017). High-altitude dropsonde observations taken by the Tropical  
15 Cyclone Intensity (TCI) Experiment captured this RI in unprecedented detail (Doyle et al. 2017).  
16 These observations revealed remarkable changes in the structure of the cold-point tropopause and  
17 upper-level static stability as the storm intensified (Duran and Molinari 2018). At tropical storm  
18 intensity, shortly before RI commenced, a strong inversion layer existed just above Patricia's cold-  
19 point tropopause, which was located near 17.2 km. During the first half of the RI period, this  
20 inversion layer weakened throughout Patricia's inner core, with the weakening most pronounced  
21 over the developing eye. By the time the storm reached its maximum intensity, the inversion layer  
22 over the eye had disappeared almost completely, which was accompanied by an increase in the  
23 tropopause height to a level at or above the highest-available dropsonde data point (18.3 km) at  
24 two locations. Meanwhile over the eyewall region, the static stability re-strengthened and the  
25 tropopause was limited to a level at or below 17.5 km. The mechanisms that led to these changes  
26 in upper-level static stability and tropopause height are the subject of the current paper.

27 More recently, Dunion et al. (2014) documented a periodic oscillation of infrared brightness  
28 temperature in hurricanes, which they call the "TC diurnal pulse." There will be a whole bunch of  
29 papers cited here...

30 At some point (probably in the Discussion) mention the possible importance of static stability  
31 asymmetries, in the context of the Dunion diurnal pulse

## 32 2. Model Setup

33 The numerical simulations were performed using version 19.4 of Cloud Model  
34 1 (CM1) described in Bryan and Rotunno (2009) and available online at  
35 <http://www2.mmm.ucar.edu/people/bryan/cm1/>. The equations of motion were integrated  
36 on a 3000-km-wide, 30-km-deep grid axisymmetric grid with 1-km horizontal and 250-m vertical  
37 grid spacing. The computations were performed on an  $f$ -plane at 15°N latitude, over a sea surface  
38 with constant temperature of 30.5°C, which matches that observed near Hurricane Patricia (2015;  
39 Kimberlain et al. 2016. Horizontal turbulence was parameterized using the Smagorinsky scheme  
40 described in Bryan and Rotunno (2009, pg. 1773), with a prescribed mixing length that varied  
41 linearly from 100 m at a surface pressure of 1015 hPa to 1000 m at a surface pressure of 900 hPa.  
42 This formulation allows for realistically-large horizontal mixing lengths near the hurricane’s inner  
43 core, consistent with the results of Bryan (2012), while not over-representing horizontal turbu-  
44 lence in convection at outer radii. Vertical turbulence was parameterized using the formulation of  
45 Markowski and Bryan (2016, their Eq. 6), using an asymptotic vertical mixing length of 100 m.  
46 A Rayleigh damping layer was applied outside of the 2900-km radius and above the 25-km level  
47 to prevent spurious gravity wave reflection at the model boundaries. Microphysical processes  
48 were parameterized using the Thompson et al. (2004) microphysics scheme and radiative heating  
49 tendencies were computed every two minutes using the Rapid Radiative Transfer Model WHAT  
50 DOES THE G STAND FOR? (RRTMG) longwave and shortwave schemes (Iacono et al. 2008). A  
51 horizontally-homogeneous temperature and humidity field was initialized with a mean sounding  
52 computed using all dropsondes deployed during the TCI flight conducted within and around  
53 Tropical Storm Patricia on 21 October, 2015 (see Doyle et al. 2017 for details.) Above 19 km,  
54 where few TCI observations were available, the temperature profile was taken from the Climate

55 Forecast System Reanalysis (CFSR) grid point nearest Patricia's storm center, valid at 18 UTC  
 56 21 October, 2015. Since relative humidity measurements were unreliable at temperatures below  
 57  $-40^{\circ}\text{C}$  (Bell et al. 2016), relative humidity was set equal to 50% above 11.5 km (the level above  
 58 which temperature dropped below  $-40^{\circ}\text{C}$ ). The vortex described in Rotunno and Emanuel (1987,  
 59 their Eq. 37) was used to initialize the wind field, setting all parameters equal to the values used  
 60 therein.

### 61 3. Budget Computation

62 The static stability can be expressed as the squared Brunt Väisälä frequency:

$$N_m^2 = \frac{g}{T} \left( \frac{\partial T}{\partial z} + \Gamma_m \right) \left( 1 + \frac{T}{R_d/R_v + q_s} \frac{\partial q_s}{\partial T} \right) - \frac{g}{1 + q_t} \frac{\partial q_t}{\partial z}, \quad (1)$$

63 where  $g$  is gravitational acceleration,  $T$  is temperature,  $R_d$  and  $R_v$  are the gas constants of dry  
 64 air and water vapor, respectively,  $q_s$  is the saturation mixing ratio, and  $q_t$  is the total condensate  
 65 mixing ratio.  $\Gamma_m$  is the moist-adiabatic lapse rate:

$$\Gamma_m = \text{DETERMINEWHATTHISISFORTHENON-CONSERVATIVEEQUATIONSET} \quad (2)$$

66 In the tropopause layer,  $q_s$ ,  $\frac{\partial q_s}{\partial T}$ , and  $\frac{\partial q_t}{\partial z}$  approach zero. In this limiting case, Eq. 1 reduces to:

$$N^2 = \frac{g}{\theta_v} \frac{\partial \theta_v}{\partial z}, \quad (3)$$

67 where  $g$  is gravitational acceleration and  $\theta_v$  is the virtual potential temperature. To compute  $N^2$ ,  
 68 CM1 uses Eq. 1 in saturated environments and Eq. 3 in unsaturated environments; for mathemat-  
 69 ical simplicity, however, only Eq. 3 will be used for the budget computations herein<sup>1</sup>.

70 Taking the time derivative of Eq. 3 yields the static stability tendency:

$$\frac{\partial N^2}{\partial t} = \frac{g}{\theta} \frac{\partial}{\partial z} \frac{\partial \theta}{\partial t} + \frac{g}{\theta^2} \frac{\partial \theta}{\partial z} \frac{\partial \theta}{\partial t}, \quad (4)$$

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<sup>1</sup>The validity of this approximation will be substantiated later in this section.

71 where the potential temperature tendency,  $\frac{\partial \theta}{\partial z}$ , is:

$$\frac{\partial \theta}{\partial t} = \quad (5)$$

72 Each term on the right-hand side of Eq. 5 represents a potential temperature budget variable, each  
73 of which is output directly by the model every minute. These tendencies are substituted for  $\frac{\partial \theta}{\partial t}$  in  
74 Eq. 4, yielding the static stability tendency attributable to each budget term every minute.

## 75 4. Results

76 Put description of Fig. 1 in this section.

77 Don't forget to mention 1-2-1 smoother.

### 78 a. Static stability evolution

79 The average  $N^2$  over the first day of the simulation (Fig. 2a) indicates the presence of a static  
80 stability maximum about 400 m above the cold-point tropopause. This lower-stratospheric stable  
81 layer had begun to erode during the initial spin-up period, with the maximum destabilization  
82 occurring at the innermost radii. This decrease in static stability continued into the second day  
83 of the simulation (Fig. 2b) as the storm intensified to hurricane strength (Fig. 1). Destabilization  
84 was particularly pronounced over the developing eye, where the time-mean cold-point tropopause  
85 height increased by up to 400 m compared to the previous day. Over the developing eyewall  
86 and outer rainband regions, meanwhile, the tropopause height remained nearly constant. During  
87 the third day of the simulation (Fig. 2c), static stability over the eye continued to decrease, and  
88 the cold-point tropopause height rose to 18.3 km at the storm center. The tropopause sloped  
89 sharply downward over the innermost radii, reaching the 16.4-km level near the 50-km radius. This  
90 local minimum in tropopause height corresponded to the eyewall region, where upper-tropospheric  
91 static stability increased during this time period. Outside of the eyewall region, static stability

began to increase in the layer immediately overlying the cold-point tropopause. This stable layer  
 sloped upward with radius, which corresponded to an upward-sloping tropopause radially outside  
 of the eyewall region. Over the next 24 hours (Fig. 2d), as the storm's maximum 10-m wind  
 speed leveled off near  $80 \text{ m s}^{-1}$  (Fig. 1), the upper-tropospheric static stability within the eyewall  
 region continued to strengthen, as did the static stability just above the cold-point tropopause  
 radially outside of the eyewall. As the stable layer strengthened, its altitude rose slightly, which  
 corresponded to a slight increase in tropopause height outside of the eyewall during this period.  
 Within the upper troposphere radially outside of the eyewall, meanwhile, static stability decreased  
 such that it was nearly neutral in a thin layer between the 120- and 150-km radii. The eye region  
 likewise continued to destabilize, and the cold-point tropopause height increased to a level above  
 18.5 km. This static stability evolution closely follows that observed in Hurricane Patricia (2015;  
 Duran and Molinari 2018).

#### *b. Static stability budget analysis*

The left column of Fig. 3 depicts 24-hour changes in  $N^2$  over each of the four days of the  
 simulation. These represent bulk changes computed by subtracting the instantaneous  $N^2$  at the  
 initial time from the instantaneous  $N^2$  at the final time. The middle column of Fig. 3 represents  
 the change in  $N^2$  computed using Eq. XXX and the method described in Section 3. The residual  
 between these two computations (Fig. 3, right column) is much smaller than the change in  $N^2$ ,  
 meaning that the budget performs well within the analysis domain.

To determine which of the budget terms are most important, a time series of the contribution of  
 each of the budget terms in Eq. XXX to the tropopause-layer static stability tendency is plotted  
 in Fig. 4. For this figure, each of the budget terms is computed using the method described in  
 Section 3, except with 1-hour averaging intervals instead of 24-hour intervals. The absolute values

115 of these tendencies are then averaged over the radius-height domain depicted in Fig. 3 and plotted  
 116 as a time series<sup>2</sup>. Advection (Fig. 4, red line) plays an important role in the mean tropopause-  
 117 layer static stability tendency at all times, and vertical turbulence (Fig. 4, blue line) and radiation  
 118 (Fig. 4, dark green line) both become important after 48 hours. Although the contribution from  
 119 horizontal turbulence (Fig. 4, purple line) becomes more important after 72 hours, it is confined  
 120 to a very small region immediately surrounding the eyewall tangential velocity maximum (not  
 121 shown), and is negligible throughout the rest of the tropopause layer. The remaining two processes  
 122 - microphysics and dissipative heating (Fig. 4, orange and light green lines, respectively) - lie atop  
 123 one another near zero. These time series indicate that, at all times, three budget terms dominate the  
 124 tropopause-layer static stability tendency: advection, vertical turbulence, and radiation. Variations  
 125 in the magnitude and spatial structure of these terms drive the static stability changes depicted in  
 126 Fig. 2; subsequent sections will focus on these variations and what causes them.

127 *(i) 0-24 hours* The first 24 hours of the simulation was characterized by a weakening of the  
 128 lower-stratospheric static stability maximum above 17 km (Fig. ??a, purple shading) and an in-  
 129 crease in static stability below (green shading). Although these tendencies extended out to the  
 130 200-km radius, they were particularly pronounced at innermost radii. A comparison of the contri-  
 131 butions of advection (Fig. ??b), vertical turbulence (Fig. ??c), and radiation (Fig. ??d) reveals that  
 132 advection is primarily responsible for the change in static stability during this period. ...Explain  
 133 this in the context of radial and vertical velocities...

134 *(ii) 24-48 hours* During the second day of the simulation, the lower-stratospheric stable layer  
 135 continued to weaken (Fig. 6a). This weakening trend in the 16.75-17.75-km layer extended from

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<sup>2</sup>It will be seen in subsequent figures that each of the terms contributes both positively and negatively to the  $N^2$  tendency within the analysis domain. Thus, taking an average over the domain tends to wash out the positive and negative contributions. To circumvent this problem, the absolute value of each of the terms is averaged, yielding a time series of the mean magnitude of each budget term.



136 the 50 km radius outward to past 200 km, and was primarily driven by advection (Fig. 6b). Below  
137 this layer, static stability began to increase slightly. This stabilization had contributions from both  
138 vertical turbulence (Fig. 6c) and radiation (Fig. 6d) in the 16-16.5-km layer. ...Explain this in  
139 context of mean vertical mixing coefficient and mean radiative heating tendency... Meanwhile,  
140 radially inward of 60 km, static stability below 17.5 km continued to weaken, primarily due to  
141 advective processes.

142 *(iii) 48-72 hours* The third day of the simulation marked a dramatic change in the structure of the  
143 tropopause-layer static stability tendencies. During this time, static stability increased markedly  
144 in an upward-sloping region within the 30-60-km radial band (Fig. 7a), and also increased within  
145 the 16.75-17.5-km layer out to at least the 200-km radius. As this layer stabilized, the layer  
146 immediately below it destabilized in a broad region extending from 60-200 km. Examination  
147 of the contribution from total advection (Fig. 7b) reveals that advection no longer dominates the  
148 static stability tendencies. Instead, a combination of vertical turbulence (Fig. 7c) and radiation  
149 (Fig. 7d) overcomes the destabilizing influence of advection to create the layer of increasing static  
150 stability. Meanwhile, the destabilizing influence of vertical turbulence in a broad region below  
151 17 km combines with a small region of destabilization due to radiation in the 50-120-km radial  
152 band combine to destabilize the layer below 16.5 km in the 50-200-km radial band. Comparing  
153 the sum of advection and vertical turbulence (Fig. 7e) to the sum of advection, vertical turbulence,  
154 and radiation (Fig. 7f) reveals that radiation plays a fundamental role in the re-strengthening of the  
155 lower-stratospheric stable layer during this time.

156 *(iv) 72-96 hours*

## 5. Discussion

Dunion et al. speculate that the diurnal pulse only occurs in mature storms. Maybe the development of the near-tropopause stable layer could partially explain the reason for this.

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193

## LIST OF FIGURES

194	<b>Fig. 1.</b>	The maximum 10-m wind speed (top panel; $\text{m s}^{-2}$ ) and minimum sea-level pressure (bottom	
195		panel; hPa) in the simulated storm (blue lines) and from Hurricane Patricia's best track (red	
196		stars). . . . .	13
197	<b>Fig. 2.</b>	Twenty-four-hour averages of squared Brunt-Väisälä frequency ( $10^{-4} \text{ s}^{-2}$ ) over the first four	
198		days of the simulation. Orange lines represent the cold-point tropopause computed from the	
199		mean temperature field over the same time periods. . . . .	14
200	<b>Fig. 3.</b>	Left panels: Twenty-four-hour changes in squared Brunt-Väisälä frequency ( $10^{-4} \text{ s}^{-2}$ ) over	
201		(a) 0-24 hours, (b) 24-48 hours, (c) 48-72 hours, (d) 72-96 hours. Middle Panels: The $N^2$	
202		change over the same time periods computed using Eq. XXX. Right Panels: The budget	
203		residual over the same time periods, computed by subtracting the budget change (middle	
204		column) from the model change (left column). . . . .	15
205	<b>Fig. 4.</b>	Time series of the contribution of each of the budget terms to the time tendency of the	
206		squared Brunt-Väisälä frequency ( $N^2$ ; $10^{-4} \text{ s}^{-2}$ ). For each budget term, the absolute value	
207		of the $N^2$ tendency is averaged both temporally over 1-hour periods (using output every	
208		minute), and spatially within the radius-height domain depicted in Fig. 3. . . . .	16
209	<b>Fig. 5.</b>	(a) Total change in $N^2$ over the 0-24-hour period ( $10^{-4} \text{ s}^{-2} (24 \text{ hr})^{-1}$ ) and the contributions	
210		to that change from (b) the sum of horizontal and vertical advection, (c) vertical turbulence,	
211		and (d) the sum of longwave and shortwave radiation. . . . .	17
212	<b>Fig. 6.</b>	As in Fig. 5, but for the 24-48-hour period. . . . .	18
213	<b>Fig. 7.</b>	(a) Total change in $N^2$ over the 48-72-hour period ( $10^{-4} \text{ s}^{-2} (24 \text{ hr})^{-1}$ ) and the contributions	
214		to that change from (b) the sum of horizontal and vertical advection, (c) vertical turbulence,	
215		(d) the sum of longwave and shortwave radiation, (e) the sum of horizontal advection, ver-	
216		tical advection, and vertical turbulence, and (f) the sum of horizontal advection, vertical	
217		advection, vertical turbulence, and longwave and shortwave radiation. . . . .	19
218	<b>Fig. 8.</b>	As in Fig. 7, but for the 72-96-hour period. . . . .	20
219	<b>Fig. 9.</b>	Radial velocity ( $\text{m s}^{-1}$ ; filled contours), potential temperature (K; thick black contours), and	
220		cold point tropopause height (orange line) averaged over (a) 0-24 hours, (b) 24-48 hours, (c)	
221		48-72 hours, and (d) 72-96 hours. . . . .	21
222	<b>Fig. 10.</b>	Vertical velocity ( $\text{cm s}^{-1}$ ; filled contours), potential temperature (K; thick black contours),	
223		and cold point tropopause height (orange line) averaged over (a) 0-24 hours, (b) 24-48 hours,	
224		(c) 48-72 hours, and (d) 72-96 hours. . . . .	22
225	<b>Fig. 11.</b>	Total condensate mixing ratio ( $\text{g kg}^{-1}$ ) and cold point tropopause height (orange line) aver-	
226		aged over (a) 0-24 hours, (b) 24-48 hours, (c) 48-72 hours, and (d) 72-96 hours. . . . .	23

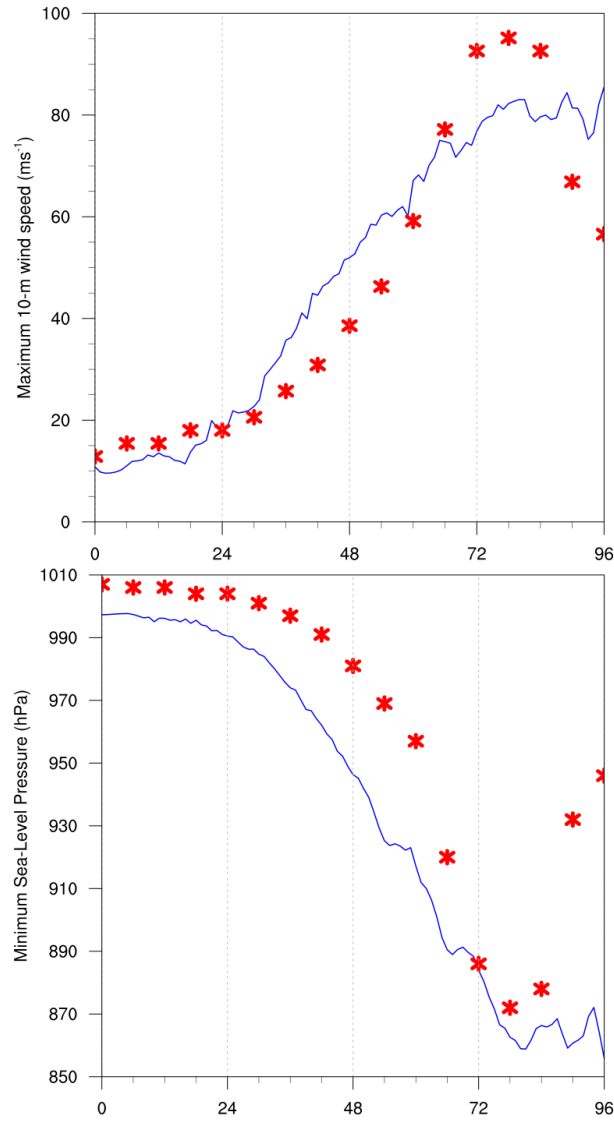


FIG. 1. The maximum 10-m wind speed (top panel;  $\text{m s}^{-2}$ ) and minimum sea-level pressure (bottom panel; hPa) in the simulated storm (blue lines) and from Hurricane Patricia's best track (red stars).

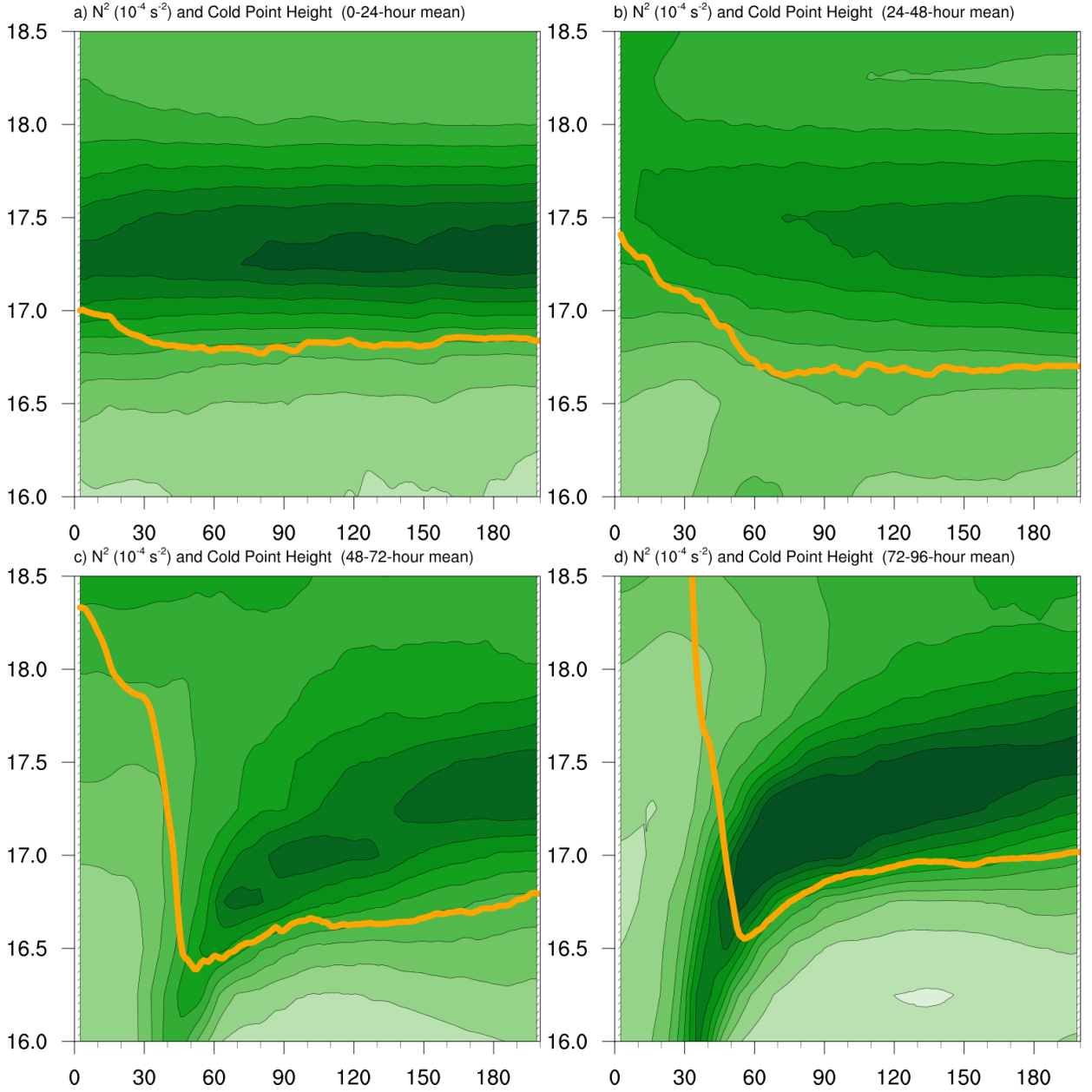
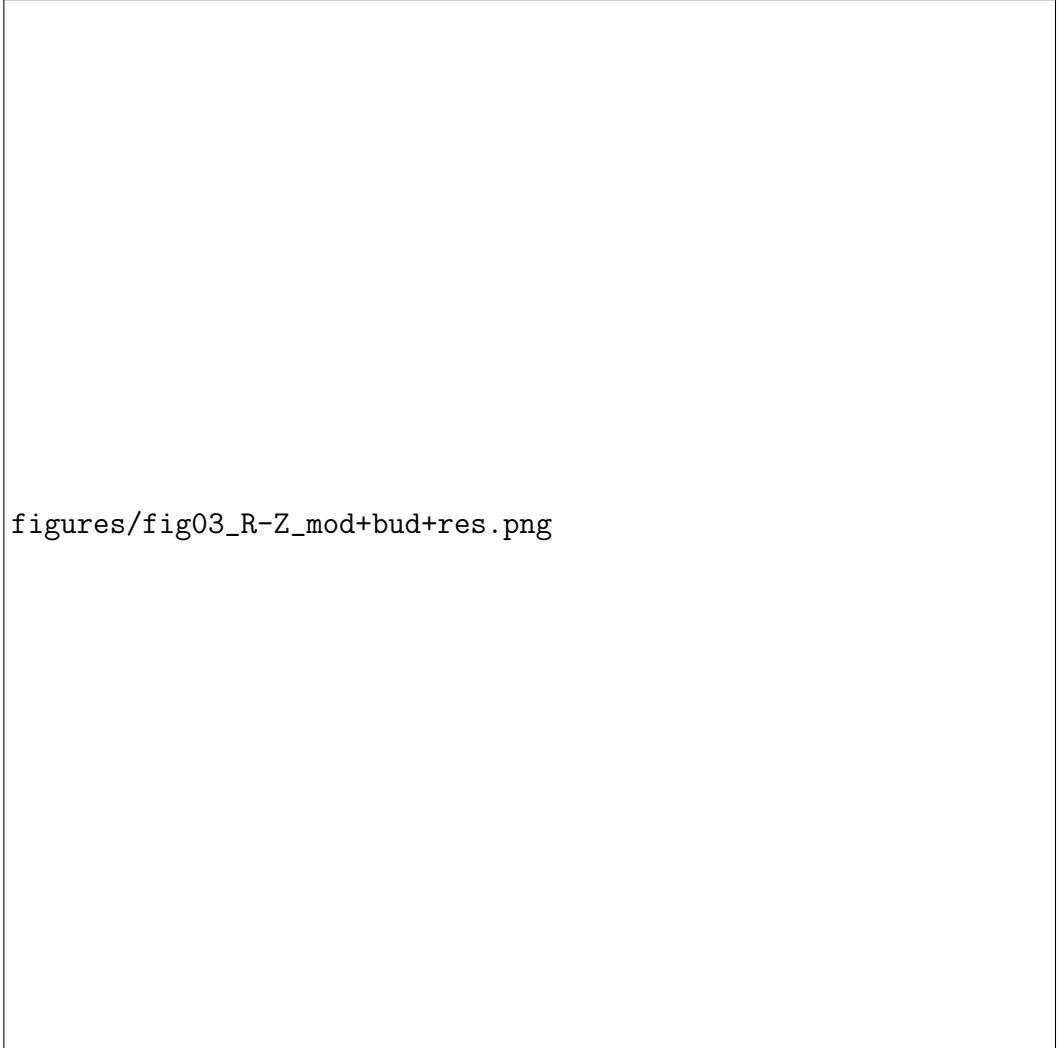


FIG. 2. Twenty-four-hour averages of squared Brunt-Väisälä frequency ( $10^{-4} \text{ s}^{-2}$ ) over the first four days of the simulation. Orange lines represent the cold-point tropopause computed from the mean temperature field over the same time periods.



figures/fig03\_R-Z\_mod+bud+res.png

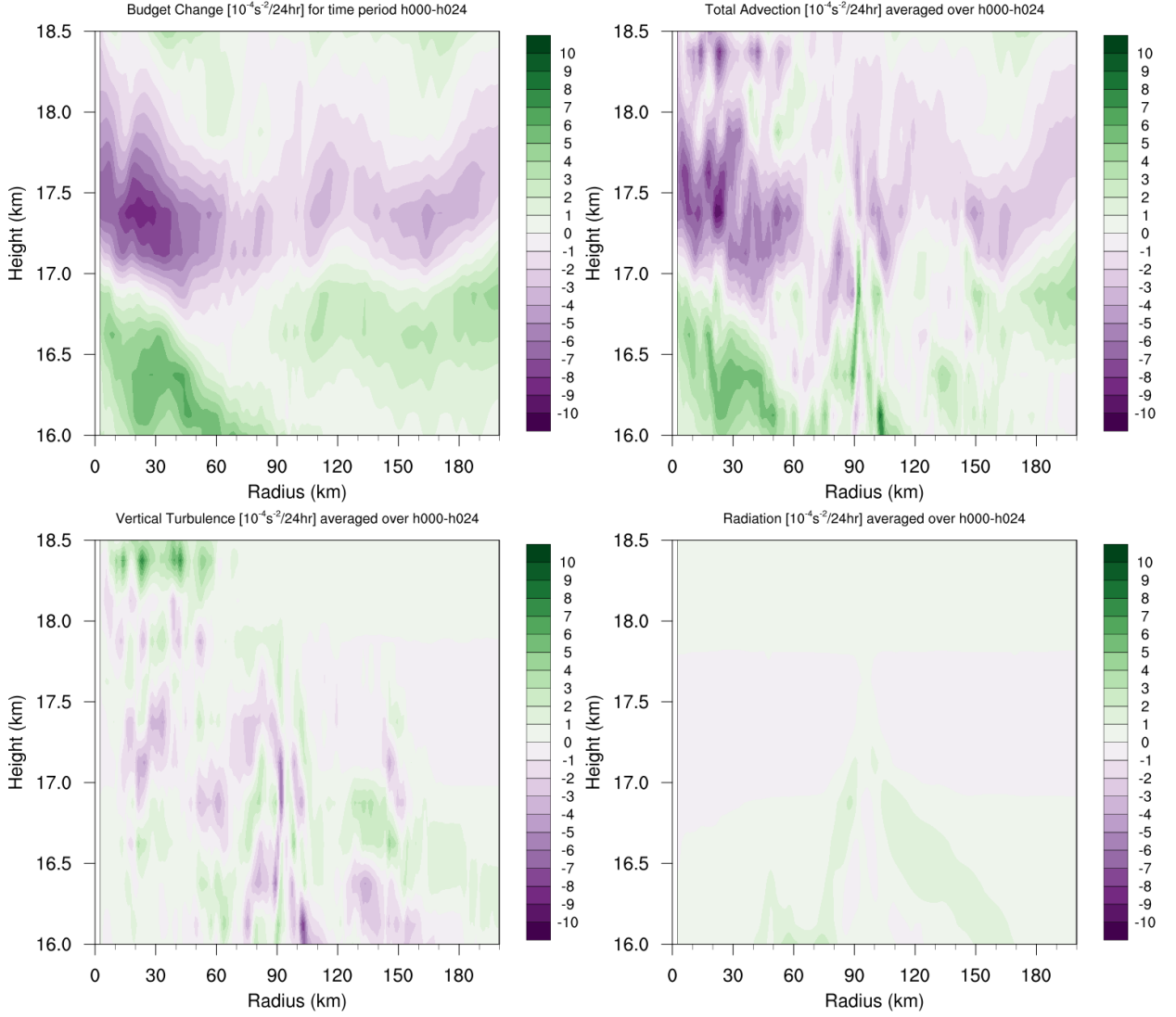
FIG. 3. Left panels: Twenty-four-hour changes in squared Brunt-Väisälä frequency ( $10^{-4} \text{ s}^{-2}$ ) over (a) 0-24 hours, (b) 24-48 hours, (c) 48-72 hours, (d) 72-96 hours. Middle Panels: The  $N^2$  change over the same time periods computed using Eq. XXX. Right Panels: The budget residual over the same time periods, computed by subtracting the budget change (middle column) from the model change (left column).



figures/fig04\_AVG\_budterms.png

236 FIG. 4. Time series of the contribution of each of the budget terms to the time tendency of the squared  
237 Brunt-Väisälä frequency ( $N^2$ ;  $10^{-4} \text{ s}^{-2}$ ). For each budget term, the absolute value of the  $N^2$  tendency is averaged  
238 both temporally over 1-hour periods (using output every minute), and spatially within the radius-height domain  
239 depicted in Fig. 3.





240 FIG. 5. (a) Total change in  $N^2$  over the 0-24-hour period ( $10^{-4} \text{ s}^{-2} (24 \text{ hr})^{-1}$ ) and the contributions to that change  
 241 from (b) the sum of horizontal and vertical advection, (c) vertical turbulence, and (d) the sum of longwave and  
 242 shortwave radiation.

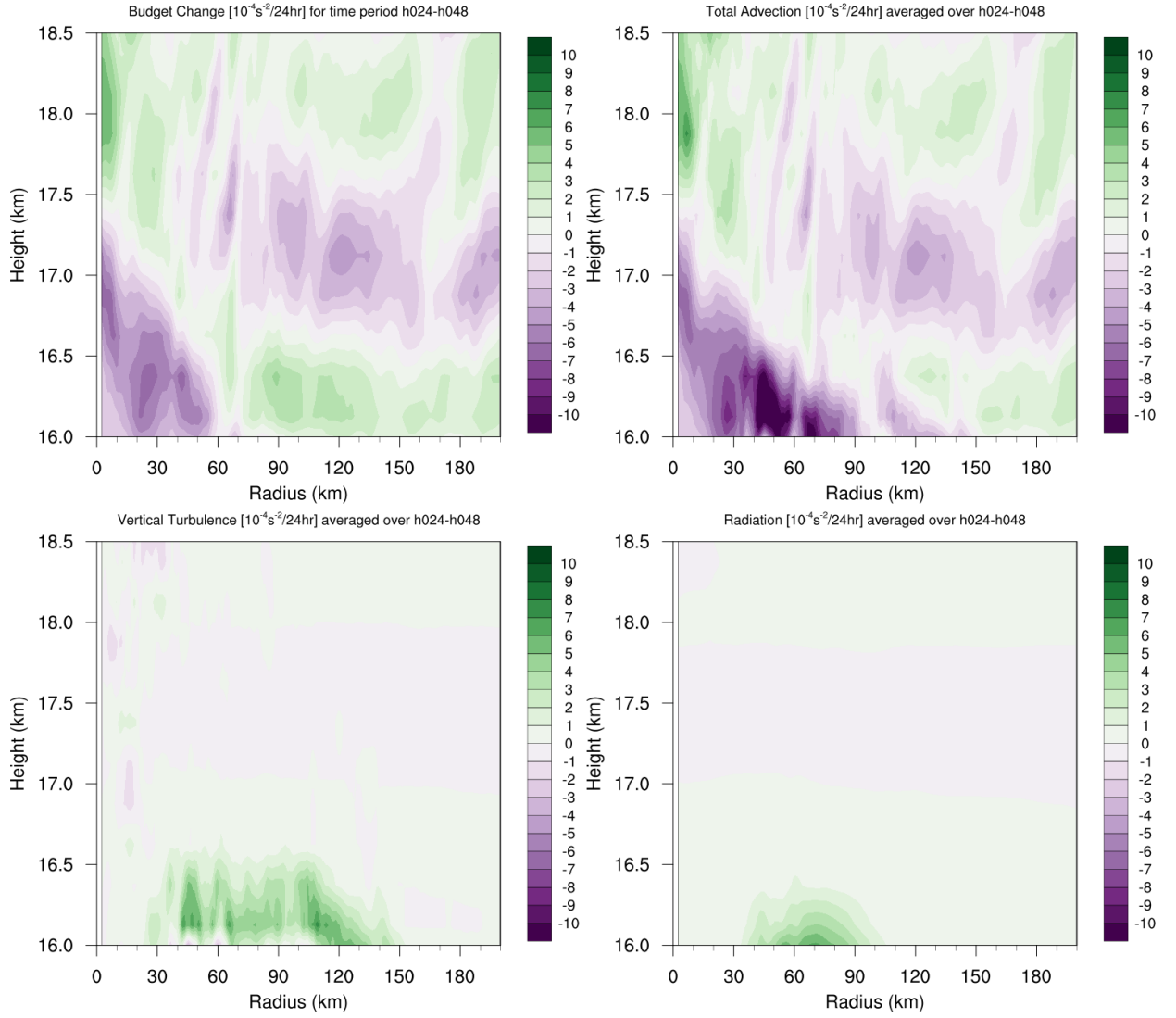



FIG. 6. As in Fig. 5, but for the 24-48-hour period.



figures/fig07\_h048-h072-budgetterms.png

243 FIG. 7. (a) Total change in  $N^2$  over the 48-72-hour period ( $10^{-4} \text{ s}^{-2} (24 \text{ hr})^{-1}$ ) and the contributions to that  
244 change from (b) the sum of horizontal and vertical advection, (c) vertical turbulence, (d) the sum of longwave  
245 and shortwave radiation, (e) the sum of horizontal advection, vertical advection, and vertical turbulence, and (f)  
246 the sum of horizontal advection, vertical advection, vertical turbulence, and longwave and shortwave radiation.

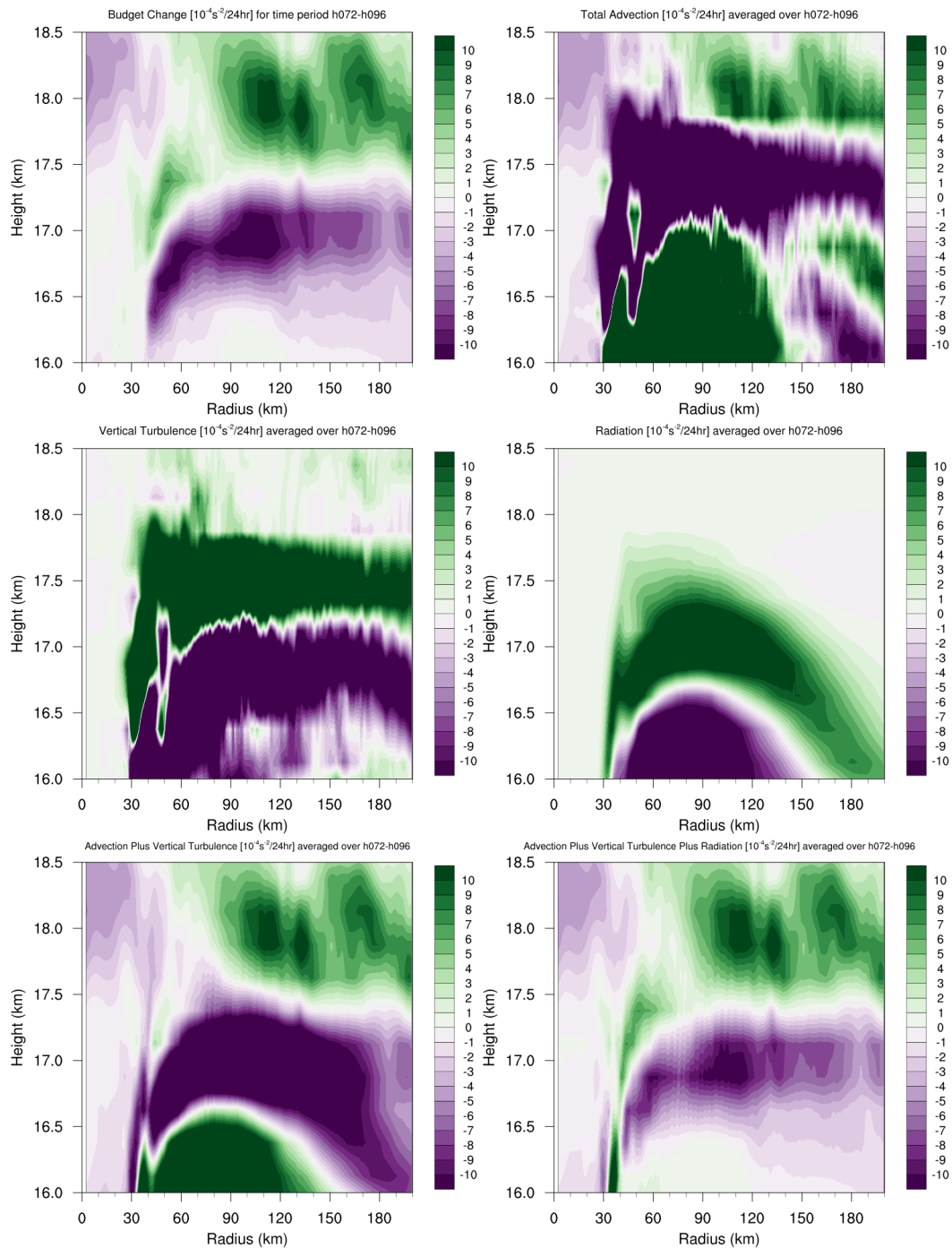


FIG. 8. As in Fig. 7, but for the 72-96-hour period.

figures/fig09\_u.png

247 FIG. 9. Radial velocity ( $\text{m s}^{-1}$ ; filled contours), potential temperature (K; thick black contours), and cold point  
248 tropopause height (orange line) averaged over (a) 0-24 hours, (b) 24-48 hours, (c) 48-72 hours, and (d) 72-96  
249 hours.

figures/fig10\_w.png

250 FIG. 10. Vertical velocity ( $\text{cm s}^{-1}$ ; filled contours), potential temperature (K; thick black contours), and cold  
251 point tropopause height (orange line) averaged over (a) 0-24 hours, (b) 24-48 hours, (c) 48-72 hours, and (d)  
252 72-96 hours.

figures/fig11\_qtot.png

253 FIG. 11. Total condensate mixing ratio ( $\text{g kg}^{-1}$ ) and cold point tropopause height (orange line) averaged over  
254 (a) 0-24 hours, (b) 24-48 hours, (c) 48-72 hours, and (d) 72-96 hours.