

1 **Tropopause Evolution in a Rapidly Intensifying Tropical Cyclone: A Static**  
2 **Stability Budget Analysis in an Idealized, Axisymmetric Framework**

3 Patrick Duran\* and John Molinari

4 *University at Albany, State University of New York, Albany, NY*

5 \**Corresponding author address:* Department of Atmospheric and Environmental Sciences, Univer-  
6 sity at Albany, State University of New York, 1400 Washington Avenue, Albany, NY.

7 E-mail: pduran2008@gmail.com

## ABSTRACT

8 Large changes in tropopause-layer static stability are observed during the  
9 rapid intensification (RI) of an idealized, axisymmetric tropical cyclone (TC).  
10 Over the eye, static stability near the tropopause decreases and the cold-point  
11 tropopause height rises by up to 4 km at the storm center. Outside of the eye,  
12 static stability increases considerably just above the cold-point tropopause,  
13 and the tropopause remains near its initial level.

14 A budget analysis reveals that advection contributes to the static stability  
15 tendencies at all times throughout the upper troposphere and lower strato-  
16 sphere. Differential advection is particularly important within the eye, where  
17 it acts to destabilize the layer near and above the cold-point tropopause.  
18 Outside of the eye, a radial-vertical circulation develops during RI, with  
19 strong outflow below the tropopause and weak inflow above. Vertical wind  
20 shear above and below the upper-tropospheric outflow maximum induces tur-  
21 bulence, which provides forcing for both destabilization and stabilization  
22 in the tropopause layer. Meanwhile, as organized convection reaches the  
23 tropopause, radiative heating tendencies at the top of the cirrus canopy gen-  
24 erally act to destabilize the upper troposphere and stabilize the lower strato-  
25 sphere. Turbulent mixing and radiative heating combine to play an important  
26 role in the development of the strong stable layer immediately above the cold-  
27 point tropopause during RI. The results suggest that turbulence and radiation,  
28 alongside advection, play fundamental roles in the upper-level static stability  
29 evolution of TCs.

## 30 **1. Introduction**

31 After undergoing a remarkably rapid intensification (RI), Hurricane Patricia (2015) set a new  
32 record as the strongest tropical cyclone (TC) ever observed in the Western Hemisphere (Kim-  
33 berlain et al. 2016; Rogers et al. 2017). High-altitude dropsonde observations taken during the  
34 Tropical Cyclone Intensity (TCI) experiment captured this RI in unprecedented detail (Doyle et al.  
35 2017). These observations revealed dramatic changes in the structure of the cold-point tropopause  
36 and upper-level static stability as the storm intensified (Duran and Molinari 2018).

37 When Patricia was at tropical storm intensity, shortly before RI commenced, a strong inversion  
38 layer existed just above the cold-point tropopause. During the first half of the RI period, this  
39 inversion layer weakened throughout Patricia’s inner core, with the weakening most pronounced  
40 over the developing eye. By the time the storm reached its maximum intensity of  $95 \text{ m s}^{-1}$ , the  
41 inversion layer over the eye had disappeared almost completely, which was accompanied by a  
42 greater than 1-km increase in the tropopause height. Meanwhile over the eyewall region, the static  
43 stability increased and the tropopause remained near its initial level. The mechanisms that might  
44 have led to this tropopause-layer variability will be investigated in the current paper using idealized  
45 simulations.

46 Despite the importance of tropopause-layer thermodynamics in theoretical models of hurri-  
47 canes (Emanuel and Rotunno 2011; Emanuel 2012), most observational studies of the upper-  
48 tropospheric structure of TCs are decades old. Recently, however, Komaromi and Doyle (2017)  
49 found that stronger TCs tended to have a higher and warmer tropopause over their inner core than  
50 weaker TCs. Their results are consistent with the evolution observed over the inner core of Hur-  
51 ricane Patricia, in which the tropopause height increased and the tropopause temperature warmed  
52 throughout RI (Duran and Molinari 2018).

53 Idealized simulations of a TC analyzed by Ohno and Satoh (2015) suggested that the develop-  
54 ment of an upper-level warm core near the 13-km level acted to decrease the static stability near the  
55 tropopause within the eye (compare their Figs. 9,10). Although the mechanisms that might drive  
56 this static stability evolution have not been examined explicitly, Stern and Zhang (2013) described  
57 the development of the TC warm core using a potential temperature ( $\theta$ ) budget analysis. They  
58 found that radial and vertical advection both played important roles in warm core development  
59 throughout RI, and subgrid-scale diffusion became particularly important during the later stage of  
60 RI. To our knowledge, the only paper that has examined explicitly the static stability evolution in  
61 a modeled TC is Kepert et al. (2016), but their analysis was limited to the boundary layer. The  
62 analysis herein is based upon that of Stern and Zhang (2013), except using a static stability budget  
63 similar to that of Kepert et al. (2016), with a focus on the upper troposphere and lower stratosphere.

## 64 **2. Model Setup**

65 The numerical simulations were performed using version 19.4 of Cloud Model 1 (CM1) de-  
66 scribed in Bryan and Rotunno (2009). The equations of motion were integrated on a 3000-km-  
67 wide, 30-km-deep axisymmetric grid with 1-km horizontal and 250-m vertical grid spacing. The  
68 computations were performed on an  $f$ -plane at 15°N latitude, over a sea surface with constant  
69 temperature of 30.5°C, which matches that observed near Hurricane Patricia (2015; Kimberlain  
70 et al. 2016). Horizontal turbulence was parameterized using the Smagorinsky scheme described  
71 in Bryan and Rotunno (2009, pg. 1773), with a prescribed mixing length that varied linearly from  
72 100 m at a surface pressure of 1015 hPa to 1000 m at a surface pressure of 900 hPa. Vertical  
73 turbulence was parameterized using the formulation of Markowski and Bryan (2016, their Eq. 6),  
74 using an asymptotic vertical mixing length of 100 m. A Rayleigh damping layer was applied out-  
75 side of the 2900-km radius and above the 25-km level to prevent spurious gravity wave reflection

at the model boundaries. Microphysical processes were parameterized using the Thompson et al. (2004) scheme and radiative heating tendencies were computed every two minutes using the Rapid Radiative Transfer Model for GCMs (RRTMG) longwave and shortwave schemes (Iacono et al. 2008). The initial temperature and humidity field was horizontally homogeneous and determined by averaging all Climate Forecast System Reanalysis (CFSR) grid points within 100 km of Patricia's center of circulation at 18 UTC 21 October 2015. The vortex described in Rotunno and Emanuel (1987, their Eq. 37) was used to initialize the wind field, setting all parameters equal to the values used therein.

Although hurricanes simulated in an axisymmetric framework tend to be more intense than those observed in nature, the intensity evolution of this simulation matches reasonably well with that observed in Hurricane Patricia. After an initial spin-up period of about 20 hours, the modeled storm (Fig. 1, blue lines) began an RI period that lasted approximately 30 hours. After this RI, the storm continued to intensify more slowly until the maximum 10-m wind speed reached  $89 \text{ m s}^{-1}$  and the sea-level pressure reached its minimum of 846 hPa, 81 hours into the simulation. Hurricane Patricia (red stars) exhibited a similar intensity evolution prior to its landfall, with an RI period leading to a maximum 10-m wind speed of  $95 \text{ m s}^{-1}$  and a minimum sea-level pressure of 872 hPa.

### 3. Budget Computation

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

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

where  $g$  is gravitational acceleration,  $T$  is temperature,  $R_d$  and  $R_v$  are the gas constants of dry air and water vapor, respectively,  $q_s$  is the saturation mixing ratio,  $q_t$  is the total condensate mixing

ratio, and  $\Gamma_m$  is the moist-adiabatic lapse rate:

$$\Gamma_m = g(1 + q_t) \left( \frac{1 + L_v q_s / R_d T}{c_{pm} + L_v \partial q_s / \partial T} \right), \quad (2)$$

where  $L_v$  is the latent heat of vaporization and  $c_{pm}$  is the specific heat of moist air at constant pressure. In the tropopause layer,  $q_s$ ,  $\partial q_s / \partial T$ , and  $\partial q_t / \partial z$  approach zero. In this limiting case, Eq. 1 reduces to:

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

where  $\theta$  is the potential temperature.

To compute  $N^2$ , CM1 uses Eq. 1 in saturated environments and Eq. 3 in sub-saturated environments. For simplicity, however, only Eq. 3 will be employed for the budget computations<sup>1</sup>.

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

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

where the potential temperature tendency,  $\partial \theta / \partial t$ , can be written, following Bryan (cited 2018):

$$\frac{\partial \theta}{\partial t} = -u \frac{\partial \theta}{\partial r} - w \frac{\partial \theta}{\partial z} + HTURB + VTURB + MP + RAD + DISS \quad (5)$$

Each term on the right-hand side of Eq. 5 represents a  $\theta$  budget variable, each of which is output directly by the model every minute. Since the first term on the right-hand side of Eq. 4 is larger than the second term throughout most of the tropopause layer (not shown), the contribution of each of the terms in Eq. 5 to the  $N^2$  tendency can be interpreted in light of a vertical gradient of each term.

Taking the vertical gradient of the first two terms on the right-hand side of Eq. 5 yields the time tendency of the vertical  $\theta$  gradient due to horizontal and vertical advection<sup>2</sup>:

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

<sup>2</sup>These terms include the tendencies due to implicit diffusion in the fifth-order finite differencing scheme, which are separated from the advection

terms in the CM1 budget output

$$\left( \frac{\partial}{\partial t} \frac{\partial \theta}{\partial z} \right)_{adv} = -u \frac{\partial}{\partial r} \frac{\partial \theta}{\partial z} - w \frac{\partial}{\partial z} \frac{\partial \theta}{\partial z} - \frac{\partial u}{\partial z} \frac{\partial \theta}{\partial r} - \frac{\partial w}{\partial z} \frac{\partial \theta}{\partial z}. \quad (6)$$

113 The first two terms on the right-hand side of Eq. 6 represent advection of static stability by the  
 114 radial and vertical wind, respectively. These terms act to rearrange the static stability field, but  
 115 cannot strengthen or weaken static stability maxima or minima. The third and fourth terms on the  
 116 right-hand side of Eq. 6 represent, respectively, the tilting of isentropes in the presence of vertical  
 117 wind shear, and the stretching or squashing of isentropes by vertical gradients of vertical velocity.  
 118 Since these terms involve velocity gradients, they can act to strengthen or weaken static stability  
 119 maxima or minima through differential advection. For example, since the  $\theta$  of the air flowing  
 120 out of the eyewall into the upper-tropospheric outflow layer increases as the TC intensifies,  $\theta$  in-  
 121 creases locally within the outflow layer. This acts to increase  $\partial \theta / \partial z$  below the outflow maximum  
 122 and decrease  $\partial \theta / \partial z$  above, thereby modifying the static stability field. Similarly, the decay of  
 123 updrafts with height at the top of convective towers can act to increase  $\partial \theta / \partial z$  through squashing  
 124 of isentropes.

125 Returning to Eq. 5, HTURB and VTURB are the  $\theta$  tendencies from the horizontal and vertical  
 126 turbulence parameterizations, MP is the tendency from the microphysics scheme, RAD is the  
 127 tendency from the radiation scheme, and DISS is the tendency due to turbulent dissipation. This  
 128 equation neglects Rayleigh damping, since the entire analysis domain lies outside of the regions  
 129 where damping is applied. Each term in Eq. 5 is substituted for  $\partial \theta / \partial t$  in Eq. 4, yielding the  
 130 contribution of each budget term to the static stability tendency. These terms are summed, yielding  
 131 an instantaneous "budget change" in  $N^2$  every minute. The budget changes are then averaged over  
 132 24-hour periods and compared to the total model change in  $N^2$  over that same time period, i.e.:

$$\Delta N_{budget}^2 = \frac{1}{\delta t} \sum_{t=t_0}^{t_0+\delta t} \frac{\partial N^2}{\partial t} \Big|_t \quad (7)$$

$$\Delta N_{model}^2 = N_{t_0+\delta t}^2 - N_{t_0}^2 \quad (8)$$

$$Residual = \Delta N_{model}^2 - \Delta N_{budget}^2 \quad (9)$$

where  $t_0$  is an initial time and  $\delta t$  is 24 hours.

Eqs. 7-9 are plotted for three consecutive 24-hour periods in Fig. 2. For this and all subsequent radial-vertical cross sections, a 1-2-1 smoother is applied once in the radial direction to eliminate  $2\Delta r$  noise that appears in some of the raw model output and calculated fields. The left column of Fig. 2 depicts the model changes computed using Eq. 8, together with Eq. 1 in saturated environments and Eq. 3 in subsaturated environments. The center column depicts the budget changes computed using Eq. 7 together with Eq. 3 throughout the entire domain. Thus, the left column includes the effect of moisture in the  $N^2$  computations, whereas the center column neglects moisture. The right column depicts the residuals, computed using Eq. 9 (i.e. the left column minus the center column.) In every 24-hour period, the budget changes are nearly identical to the model changes, which is reflected in the near-zero residuals in the right column. This indicates that the budget accurately represents the model variability, which implies that the neglect of moisture in the budget computation introduces negligible error within the analysis domain<sup>3</sup>.

In the tropopause layer, some of the budget terms are small enough to be ignored. To determine which of the budget terms are most important, a time series of the contribution of each of the budget terms in Eq. 5 to the tropopause-layer static stability tendency is plotted in Fig. 3. 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 of these tendencies are then averaged over the radius-height domain of the plots shown in Fig. 2 and plotted as a time

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<sup>3</sup>This is not the case in the lower- and mid-troposphere, where the residual actually exceeds the budget tendencies in many places, likely due to the neglect of moisture; thus we limit this analysis to the upper troposphere and lower stratosphere.



154 series<sup>4</sup>. Advection (Fig. 3, red line) plays an important role in the mean tropopause-layer static  
155 stability tendency at all times, and vertical turbulence (Fig. 3, blue line) and radiation (Fig. 3, dark  
156 green line) also contribute significantly. The remaining three processes - horizontal turbulence,  
157 microphysics, and dissipative heating - are negligible everywhere outside of the eyewall, and do  
158 not play important roles in the mesoscale tropopause variability.

159 The preceding analysis indicates that, at all times, three budget terms dominate the tropopause-  
160 layer static stability tendency: advection, vertical turbulence, and radiation. Variations in the  
161 magnitude and spatial structure of these terms drive the static stability changes depicted in Fig. 2;  
162 subsequent sections will focus on these variations and what causes them.

## 163 4. Results

### 164 a. Static stability evolution

165 The average  $N^2$  over the first day of the simulation (Fig. 4a) indicates the presence of a weak  
166  $N^2$  maximum just above the cold-point tropopause. Over the subsequent 24 hours, during the  
167 RI period, the  $N^2$  within and above this layer decreased within the 25-km radius (Fig. 4b). This  
168 decreasing  $N^2$  corresponded to an increase in the tropopause height within the developing eye,  
169 maximized at the storm center. Outside of the eye, meanwhile, the tropopause height decreased  
170 over the eyewall region (25-60-km radius) and increased only slightly outside of the 60-km ra-  
171 dius. In this outer region, the  $N^2$  maximum just above the tropopause strengthened during RI.  
172 These trends continued as the storm's intensity leveled off in the 48-72-hour period (Fig. 4c). The  
173 tropopause height increased to nearly 21 km at the storm center and sloped sharply downward to

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<sup>4</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.

16.3 km on the inner edge of the eyewall, near the 30 km radius. Static stability outside of the eye, meanwhile, continued to increase just above the cold-point tropopause. This  $N^2$  evolution closely follows that observed in Hurricane Patricia (2015; Duran and Molinari 2018, see their Fig. 4). The mechanisms that led to these  $N^2$  changes will be investigated in the subsequent sections.

## *b. Static stability budget analysis*

### *(i) 0-24 hours*

The initial spin-up period was characterized by a steady increase of the maximum wind speed from 11 m s<sup>-1</sup> to 22 m s<sup>-1</sup> (Fig. 1a, blue line), an intensification rate that closely matched that of TC Patricia (Fig. 1a, red stars). The weakening of the lower-stratospheric  $N^2$  maximum during this period is reflected in the total  $N^2$  budget change over this time (Fig. 5a). The layer just above the cold-point tropopause was characterized by decreasing  $N^2$  (purple shading), maximizing at the storm center. At and immediately below the tropopause, meanwhile, saw increasing  $N^2$  during this time period. Although these tendencies extended out to the 200-km radius, they were particularly pronounced at innermost radii. A comparison of the contributions of advection (Fig. 5b), vertical turbulence (Fig. 5c), and radiation (Fig. 5d) reveals that advection was the primary driver of the  $N^2$  tendency during this period, acting to stabilize near and just below the tropopause and destabilize above. Although vertical turbulence acted in opposition to advection (i.e. it acted to stabilize regions that advection acted to destabilize), the magnitude of the advective tendencies was larger, particularly at the innermost radii. The sum of advection and vertical turbulence (Fig. 5e) almost exactly replicated the static stability tendencies above the tropopause. Radiative tendencies, meanwhile, (Fig. 5d) acted to destabilize the layer below about 16 km and stabilize the layer between 16 and 17 km. The sum of advection, vertical turbulence, and radiation (Fig. 5f) reproduced the total change in  $N^2$  almost exactly.

197 (ii) 24-48 hours

198 During the RI period, the maximum wind speed increased from  $22 \text{ m s}^{-1}$  to  $80 \text{ m s}^{-1}$ . Over this  
199 time,  $N^2$  within the eye generally decreased above 16 km and increased below (Fig. 6a), with the  
200 destabilization above 16 km maximizing near the level of the mean cold-point tropopause. These  
201 tendencies at the innermost radii were driven almost entirely by advection (Fig. 6b). Vertical  
202 turbulence (Fig. 6c) and radiation (Fig. 6d) contributed negligibly to the static stability tendencies  
203 in this region.

204 Outside of the eye, the  $N^2$  evolution exhibited alternating layers of positive and negative tenden-  
205 cies. Near and above 18 km existed an upward-sloping region of decreasing  $N^2$  that extended out  
206 to the 180-km radius. In this region, neither vertical turbulence nor radiation exhibited negative  $N^2$   
207 tendencies; advection was the only forcing for this destabilization. Immediately below this layer,  
208 just above the cold-point tropopause, was a region of increasing  $N^2$  that sloped upward from 17 km  
209 near the 30-km radius to just below 18 km outside of the 100-km radius. Advection and vertical  
210 turbulence both contributed to this positive  $N^2$  tendency, with advection playing an important role  
211 below about 17.5 km and and turbulence playing an important role above. The sum of advection  
212 and turbulence (Fig. 6e) reveals two discontinuous regions of increasing  $N^2$  in the 17-18-km layer  
213 rather than one contiguous region. The addition of radiation to these two terms, however, (Fig. 6f)  
214 provides the link between these two regions, indicating that radiation also plays a role in strength-  
215 ening the stable layer just above the tropopause. In the 16-17-km layer, just below the cold-point  
216 tropopause, a horizontally-extensive layer of destabilization also was forced by a combination of  
217 advection, vertical turbulence, and radiation. The sum of advection and vertical turbulence ac-  
218 counts for only a portion of the decreasing  $N^2$  in this layer, and actually indicates forcing for  
219 stabilization near the 50-km radius and outside of the 130-km radius. Radiative tendencies over-

220 come this forcing for stabilization in both of these regions to produce the radially-extensive region  
221 of destabilization observed just below the tropopause.

222 The sum of advection, vertical turbulence, and radiation (Fig. 6f) once again closely follows  
223 the observed  $N^2$  variability, except in the eyewall region, where the neglect of latent heating and  
224 horizontal turbulence introduces some differences.

225 *(iii) 48-72 hours*

226 After the storm's maximum wind speed leveled off near  $80 \text{ m s}^{-1}$ , the magnitude of the static  
227 stability tendencies within the eye decreased to near zero (Fig. 7a).

228 Outside of the eye, however,  $N^2$  continued to decrease in the layer immediately surrounding the  
229 tropopause. The sum of advection and vertical turbulence (Fig. 7e) indicates that the increase of  
230  $N^2$  observed in the 17-18-km layer and inside of the 80-km radius cannot be attributed to these  
231 processes, since the sum of these two terms provided forcing for destabilization. Instead, radiation  
232 (Fig. 7d) provided the forcing for stabilization in this region. Outside of the 80-km radius, both  
233 advection (Fig. 7b) and vertical turbulence (Fig. 7c) provided forcing for stabilization near and  
234 just above the 18-km level. The sum of the two terms (Fig. 7e) indicates increasing  $N^2$  near the  
235 18-km level everywhere outside of the 80-km radius, but this stabilization is slightly weaker in  
236 the 90-120-km radial band than the observed value. The addition of radiation (Fig. 7f) provided  
237 the extra forcing for stabilization required to account for the observed increase in  $N^2$ . Outside  
238 of the 120-km radius, the region of radiative forcing for stabilization sloped downward, and the  
239 increase in  $N^2$  observed near 18 km can be explained entirely by a combination of advection and  
240 vertical turbulence. The layer of decreasing  $N^2$  observed near the tropopause was forced primarily  
241 by vertical turbulence and radiation. Within most of this region, advection provided strong forcing

242 for stabilization, but this forcing was outweighed by the negative  $N^2$  tendencies induced by a  
243 combination of vertical turbulence and radiation.

## 244 5. Discussion

### 245 *a. The role of advection*

246 Advection played an important role in the tropopause-layer  $N^2$  evolution at all stages of intensi-  
247 fication, but for brevity, this section will focus only on the RI (24-48-hour) period. To investigate  
248 the advective processes more closely, the individual contributions of horizontal and vertical advec-  
249 tion during the RI period are shown in Fig. 8, along with the corresponding time-mean radial and  
250 vertical velocities and  $\theta$ . The  $N^2$  tendencies due to the two advective components (Fig. 8a,b) ex-  
251 hibited strong cancellation, consistent with flow that was nearly isentropic. There were, however,  
252 many regions in which flow crossed  $\theta$  surfaces; this flow accounted for all non-zero  $N^2$  tendencies  
253 due to advection previously seen in Fig. 6b.

254 During the RI period, strong radial and vertical circulations developed near the tropopause  
255 (Fig. 8c,d), which forced high-magnitude  $N^2$  tendencies due to advection (Fig. 8a,b). A layer  
256 of strong outflow formed at and below the tropopause during this period, with the outflow maxi-  
257 mum (dashed cyan line) curving from the 14-km level at the 50-km radius to just below the 16-km  
258 level outside of the 80-km radius (Fig. 8c). Notably, the  $N^2$  tendency due to horizontal advec-  
259 tion (Fig. 8a) tended to switch signs at this line, with stabilization below the outflow maximum  
260 and destabilization above. This is consistent with the outflow layer carrying air with increasingly  
261 large  $\theta$  from the eyewall to large radii as the storm intensified. This increase in  $\theta$  maximized near  
262 the outflow maximum, which acted to decrease  $\partial\theta/\partial z$  above the outflow maximum and increase  
263 it below. This mechanism is the same as that discussed in Trier and Sharman (2009), in which

vertical wind shear in the outflow layer of a mesoscale convective system acted to modify the upper-tropospheric static stability through differential advection of isentropes.

Meanwhile in the lower stratosphere, a thin layer of 2-4 m s<sup>-1</sup> inflow developed a few hundred meters above the tropopause, similar to that which was observed in Hurricane Patricia (2015; Duran and Molinari 2018) and in previous modeling studies (e.g. Ohno and Satoh 2015; Kieu et al. 2016). Since the isentropes in this layer sloped slightly upward with radius (i.e.  $\partial\theta/\partial r < 0$ ), this inflow acted to import lower  $\theta$  air from outer radii to inner radii. Since the negative  $\theta$  tendencies maximized at the level of maximum inflow, the layer below the inflow maximum destabilized and the layer above stabilized (Fig. 8a).

Curiously, horizontal advection contributed to the  $N^2$  tendency everywhere within the eye, even though the mean radial velocity there was near zero. Close examination of the model output revealed that these tendencies were forced by advective processes associated with inward-propagating waves. Although the radial velocity perturbations induced by these waves averaged out to zero, the advective tendencies forced by the radial velocity perturbations did not. Additionally, when these waves reached  $r=0$ , a dipole of vertical velocity resulted, with ascent above and descent below. For reasons that remain unclear, the regions of ascent were more persistent than the regions of descent, which resulted in the mean ascent observed near  $r=0$  above 17 km in Fig. 8b.

Vertical advection also played an important role in the tropopause-layer static stability evolution. Within the eye, subsidence dominated below 17 km, while mean ascent existed near the storm center above 17 km. Although the magnitude of the subsidence was larger at lower altitudes,  $\partial\theta/\partial z$  was smaller there. Because  $\partial\theta/\partial z$  was smaller, the subsidence at lower levels could not accomplish as much warming as the subsidence at higher levels in the eye, consistent with the results of Stern and Zhang (2013). As a result, vertical advection within the eye acted to stabilize the layer below 16 km during RI.

288 Outside of the 27-km radius, ascent dominated the troposphere, while a 1.5-km-deep layer of  
289 descent existed immediately above the tropopause. These regions of ascent and descent converged  
290 just above the tropopause; this convergence acted to compact the isentropes in this layer and in-  
291 crease the static stability. Above the lower-stratospheric subsidence maximum, meanwhile, verti-  
292 cal advection acted to decrease  $N^2$ . Below the tropopause, differential vertical advection increased  
293  $N^2$  within the eyewall region and also at larger radii above the vertical velocity maximum at larger  
294 radii. Outside of the eyewall and below the vertical velocity maximum, meanwhile, differential  
295 vertical advection acted to decrease  $N^2$ .

296 Comparing the  $N^2$  tendencies forced by horizontal (Fig. 8a) and vertical (Fig. 8b) advection  
297 to the total advective tendency seen in Fig. 6b reveals that horizontal advective tendencies domi-  
298 nated the troposphere, while vertical advective tendencies dominated the layer near and above the  
299 tropopause. Thus, tilting of isentropes in the vicinity of the upper-tropospheric outflow maximum  
300 appears to be the most important process governing the  $N^2$  tendency in the troposphere, whereas  
301 convergence of vertical velocity appears to be the most important process near the tropopause.

### 302 *b. The role of radiation*

303 During the initial spin-up period (0-24 hours; Fig. 9a), convection was not deep enough to  
304 deposit large quantities of ice near the tropopause and create a persistent cirrus canopy. Due to the  
305 lack of ice particles, the radiative heating tendencies during this period (Fig. 9b) were relatively  
306 small and confined to the region above a few particularly strong, although transient, convective  
307 towers. During RI (24-48 hours), the eyewall updraft strengthened and a radially-extensive cirrus  
308 canopy developed near the tropopause (Fig. 9c). The enhanced vertical gradient of ice mixing ratio  
309 at the top of the cirrus canopy induced strong diurnal-mean radiative cooling near the tropopause  
310 (Fig. 9d). This cooling exceeded  $0.6 \text{ K h}^{-1}$  in some places and sloped downward from the lower

311 stratosphere into the upper troposphere, following the top of the cirrus canopy. A small radiative  
312 warming maximum also appeared outside of the 140-km radius below this region of cooling. These  
313 results broadly agree with those of Bu et al. (2014; see their Fig. 11a), whose CM1 simulations  
314 produced a  $0.3 \text{ K h}^{-1}$  diurnally-averaged radiative cooling at the top of the cirrus canopy and  
315 radiative warming within the cloud that maximized near the 200-km radius. This broad region  
316 of radiative cooling acted to destabilize the layer below the cooling maximum and stabilize the  
317 layer above, which can be seen in Fig. 6d. The small area of net radiative heating outside of the  
318 140-km radius enhanced the destabilization above 16 km in this region and produced a thin layer  
319 of stabilization in the 15-16-km layer.

320 After the TC's RI period completed (48-72 hours), strong radiative cooling remained near the  
321 tropopause at inner radii (Fig. 9f), sloping downward with the top of the cirrus canopy to below  
322 the tropopause at outer radii. Cooling rates exceeded  $1 \text{ K h}^{-1}$  just above the tropopause between  
323 the 30- and 70-km radii. This value is more than three times the maximum cooling rate of  $0.3 \text{ K h}^{-1}$   
324 observed by Bu et al. (2014), a discrepancy that is a consequence of their larger vertical grid  
325 spacing compared to that used here, along with a contribution from differing radiation schemes. To  
326 compare our results to those of Bu et al. (2014), we ran a simulation identical to that described in  
327 Section 2, except using the NASA-Goddard radiation scheme and 625-m vertical grid spacing, to  
328 match those of Bu et al. (2014). This simulation produced a maximum 24-hour-average radiative  
329 cooling rate of  $0.3 \text{ K h}^{-1}$ , which agrees with that shown in Bu et al. (2014). Another simulation  
330 using 625-m vertical grid spacing and RRTMG radiation produced 24-hour-average cooling rates  
331 of up to  $0.6 \text{ K h}^{-1}$ , which is consistent with the WRF simulations of Bu et al. (2014). This suggests  
332 that vertical grid spacing smaller than 625 m is necessary to resolve properly the radiative cooling  
333 at the top of the cirrus canopy, and that the results can be quite sensitive to the radiation scheme  
334 used.



335 Meanwhile below the tropopause, time-mean radiative warming spread from 30- to 160-km  
336 radius within the cirrus canopy. The existence of radiative cooling overlying radiative warming in  
337 this region led to radiatively-forced destabilization at and below the tropopause, as was observed  
338 in Fig. 7d. Beneath the warming layer existed a region of forcing for stabilization, while a much  
339 stronger region of forcing for stabilization existed in the lower stratosphere, above the cooling  
340 maximum.

341 The results herein suggest that radiative heating tendencies played an important role in destabi-  
342 lizing the upper troposphere and stabilizing the lower stratosphere after the cirrus canopy devel-  
343 oped.

#### 344 *c. The role of turbulent mixing*

345 Although vertical turbulence always acts to eliminate vertical gradients of  $\theta$ , this adjustment  
346 toward a neutral state only occurs where the mixing takes place. If turbulence occurs in a stably-  
347 stratified layer, it will act to decrease  $\theta$  at the top of the layer and increase it below. Just above and  
348 just below the mixed layer, however, the  $\theta$  profile remains undisturbed. Consequently, although  
349 turbulent mixing acts to decrease  $\partial\theta/\partial z$  in the layer in which it is occurring, it actually increases  
350  $\partial\theta/\partial z$  just below and just above the layer. These vertical gradients of turbulent mixing are quite  
351 important, particularly on the flanks of the upper-tropospheric outflow jet.

352 Two distinct maxima of vertical eddy diffusivity developed in the tropopause layer as the storm  
353 intensified (Fig. 10). Comparison of these turbulent regions to the  $N^2$  tendencies in Figs. 6c and  
354 7c reveals that the layers in which vertical eddy diffusivity maximized corresponded to layers of  
355 destabilization due to vertical turbulence. Just outside of these layers, however, vertical turbulence  
356 acted to increase  $N^2$ . The large vertical gradient of vertical eddy diffusivity near the tropopause  
357 played an important role in developing the lower-stratospheric stable layer during RI. This supports

the hypothesized role of turbulence in setting the outflow-layer  $\theta$  stratification in Rotunno and Emanuel (1987).

## 6. Conclusions

The simulated  $N^2$  evolution shown herein closely matched that observed during the RI of Hurricane Patricia (2015). Three processes dominated the  $N^2$  variability in the upper troposphere and lower stratosphere: advection, radiation, and vertical turbulence. Radiation and vertical turbulence played particularly important roles in developing the strong  $N^2$  maximum just above the cold-point tropopause during RI. Since these two processes are parameterized, and radiation closely depends on yet another parameterized process (microphysics), the tropopause-layer  $N^2$  variability could be quite sensitive to the assumptions inherent to the parameterizations used. A better understanding of the microphysical characteristics of the TC cirrus canopy, its interaction with radiation, and outflow-layer turbulence is critical to understanding the tropopause-layer  $N^2$  evolution.

In this paper, all of the variables were averaged over a full diurnal cycle to eliminate the effects of diurnal variability and isolate the overall storm evolution. Diurnal variations in static stability near the tropopause are potentially of interest with respect to the tropical cyclone diurnal cycle, however, and will be the subject of future work.

*Acknowledgments.* We are indebted to George Bryan for his continued development and support of Cloud Model 1. We also thank Jeffrey Kepert, Robert Fovell, and Erika Navarro for helpful conversations related to this work. This research was supported by NSF Grant #1636799.

## APPENDIX

### Sensitivity experiments

379 The simulations exhibited some sensitivity to the initial thermodynamic profile and the pre-  
380 scribed vertical mixing length. Although the details of the intensification and the tropopause-layer  
381  $N^2$  evolution varied when these quantities were changed, the conclusions of the paper remain  
382 unchanged.

383 *a. Sensitivity to the initial thermodynamic profile*

384 A number of sensitivity experiments were conducted using a variety of initial soundings. Chang-  
385 ing the initial temperature and humidity profiles affected the timing of the onset of organized deep  
386 convection and the rapidity of intensification. In all simulations, however, convection eventually  
387 penetrated to the tropopause, at which time vertical turbulence and radiation combined with ad-  
388 vection to adjust the  $N^2$  profile toward that which was observed in the control run. By the end of  
389 the RI period in every simulation, all three processes were actively modifying the  $N^2$  profile near  
390 the tropopause.

391 As an example, 24-hour averages of  $N^2$  are plotted in Fig. A1 for a simulation that was identical  
392 to that used in this paper, except the initial sounding was determined by averaging every CFSR  
393 grid point within 1000 km of TC Patricia's storm center at 18 UTC 21 October 2015 instead of  
394 averaging only within the 100-km radius. Although the lower-stratospheric stable layer developed  
395 more slowly and was weaker than that shown in Fig. 4, the overall evolution was quite similar and  
396 the same budget terms dominated the  $N^2$  evolution.

397 *b. Sensitivity to the vertical mixing length*

398 The rate of turbulent mixing in the Smagorinsky scheme used herein is highly dependent on a  
399 prescribed length scale. The vertical mixing length used in this paper (100 m) was based on the  
400 sensitivity experiments of Bryan (2012). Prescribing a smaller mixing length produces smaller

401  $\theta$  tendencies due to turbulence, but even with a mixing length on the low end of those tested  
402 by Bryan (2012), turbulence still played an important role in the tropopause-layer  $N^2$  evolution.  
403 Fig. A2 shows the 24-hour-averaged contributions of turbulent mixing to the  $N^2$  evolution from  
404 a simulation identical to that used in this paper, except with a vertical mixing length of 50 m. At  
405 all times, vertical turbulence still played an important role in the tropopause-layer  $N^2$  evolution,  
406 particularly during the latter stages of RI (48-72 hours).

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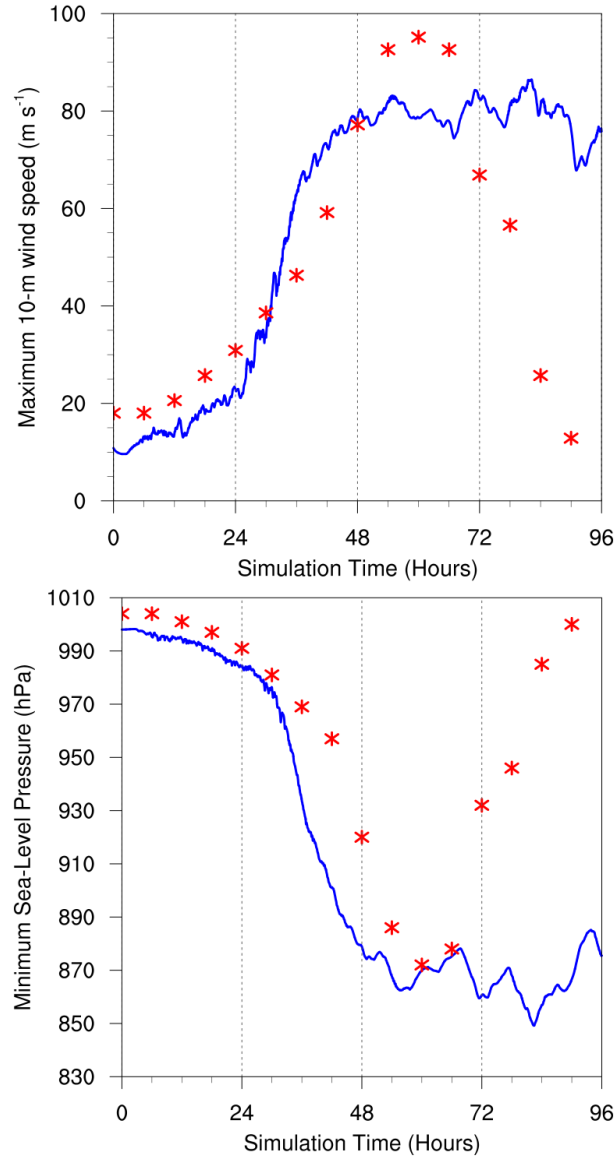


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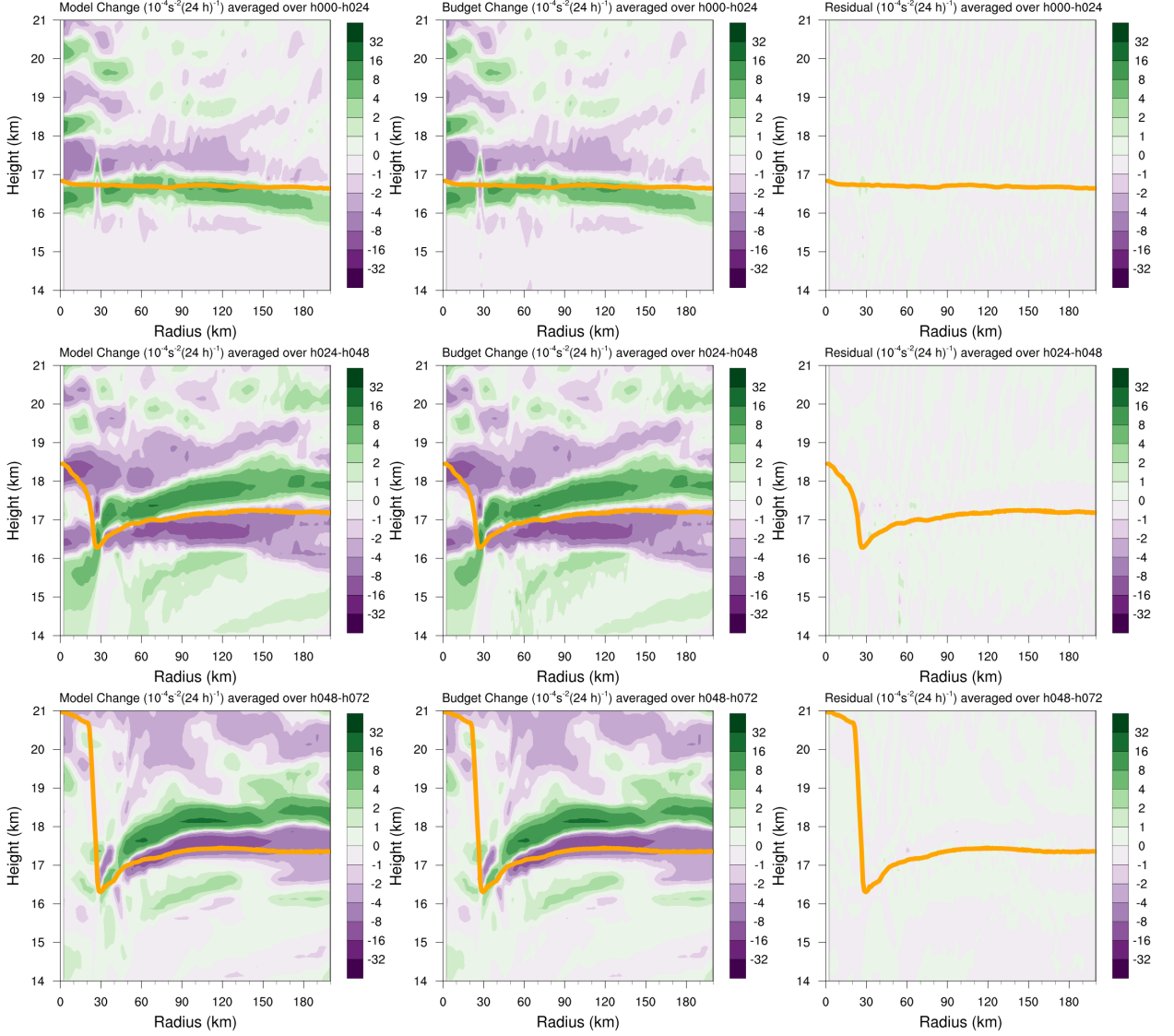


FIG. 2. Left panels: Twenty-four-hour changes in squared Brunt-Väisälä frequency ( $N^2$ ;  $10^{-4} \text{ s}^{-2}$ ) computed using Eq. 8 over (top row) 0-24 hours, (middle row) 24-48 hours, (bottom row) 48-72 hours. Middle Panels: The  $N^2$  change over the same time periods computed using Eqs. 4-7, Right Panels: The budget residual over the same time periods, computed by subtracting the budget change (middle column) from the model change (left column). Orange lines represent the cold-point tropopause height averaged over the same time periods.

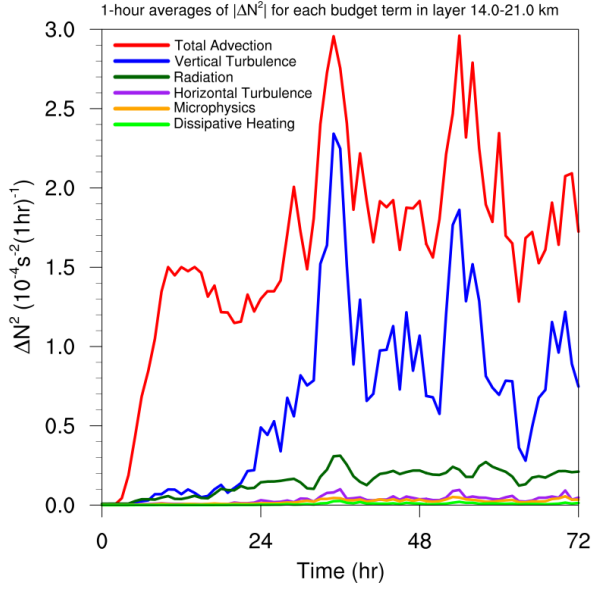


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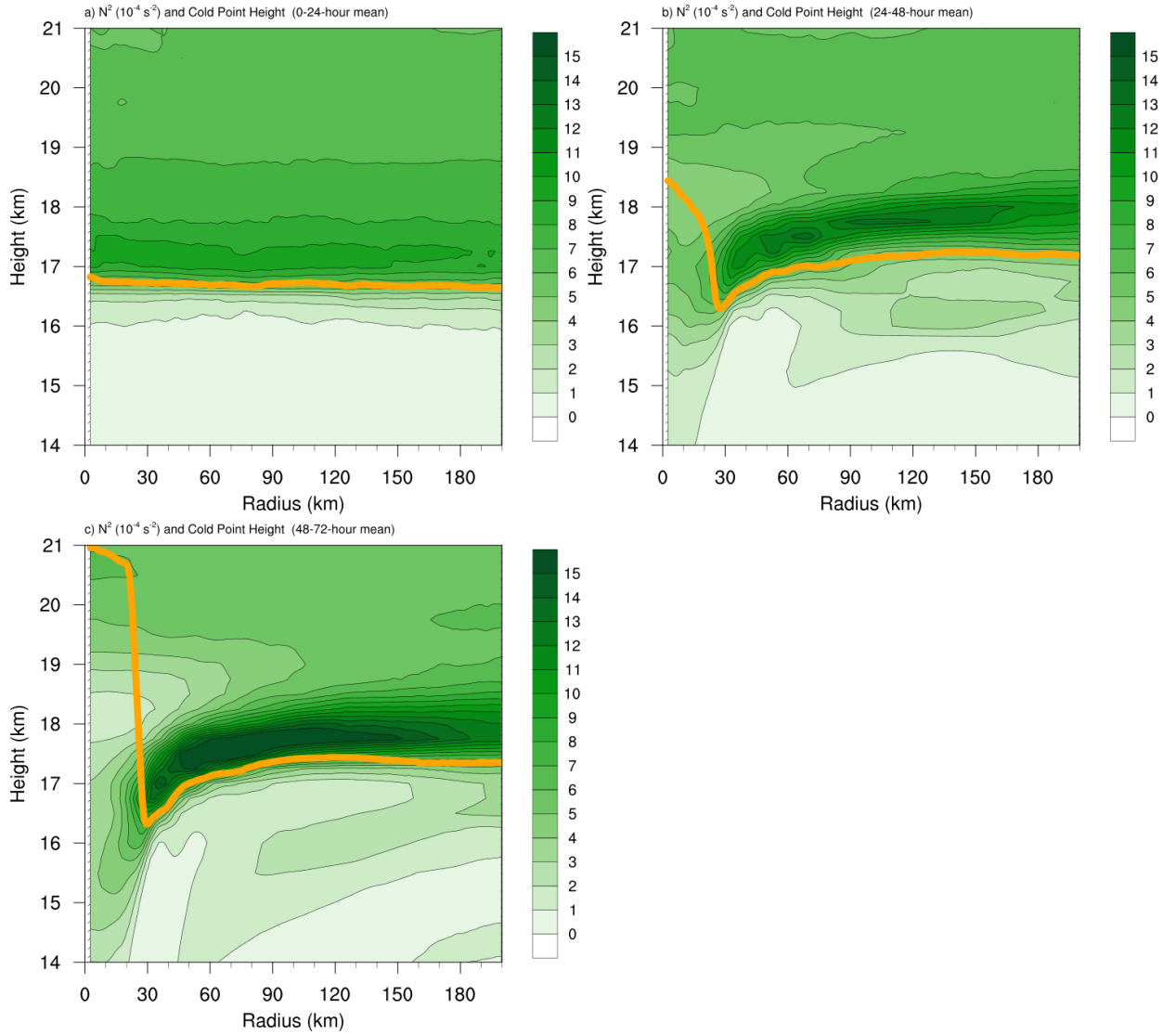
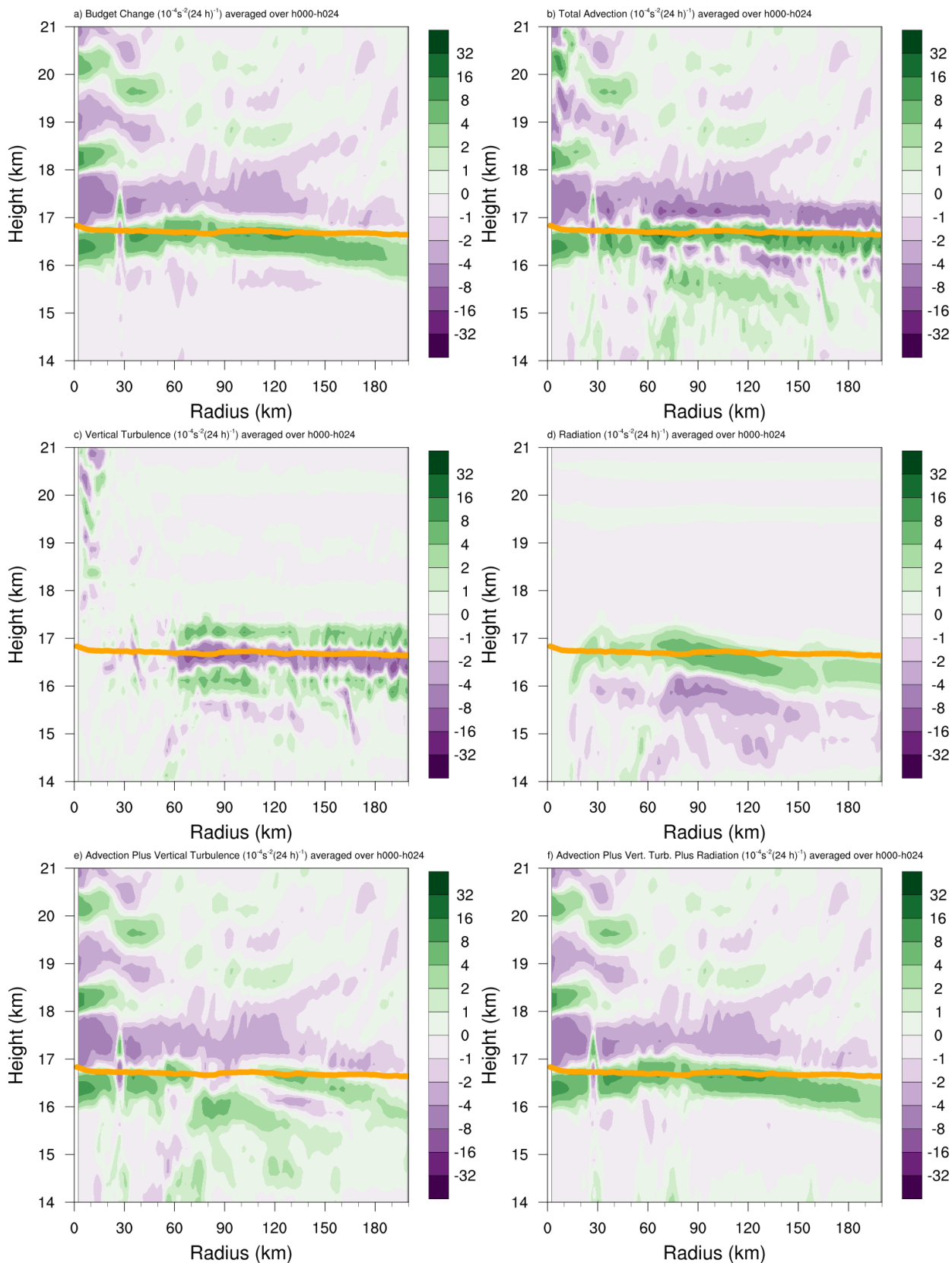


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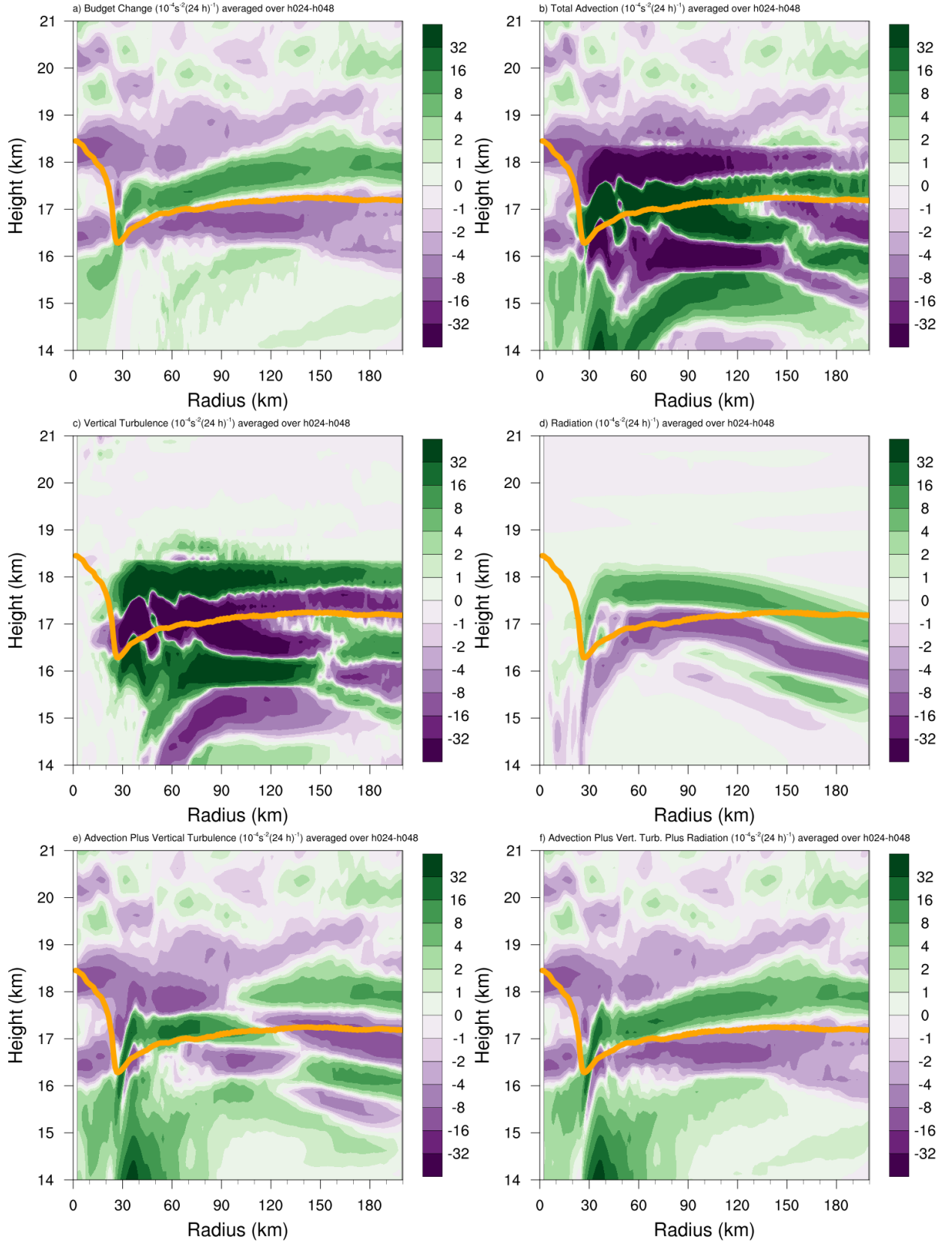


FIG. 6. As in Fig. 5, but for the 24-48-hour period.



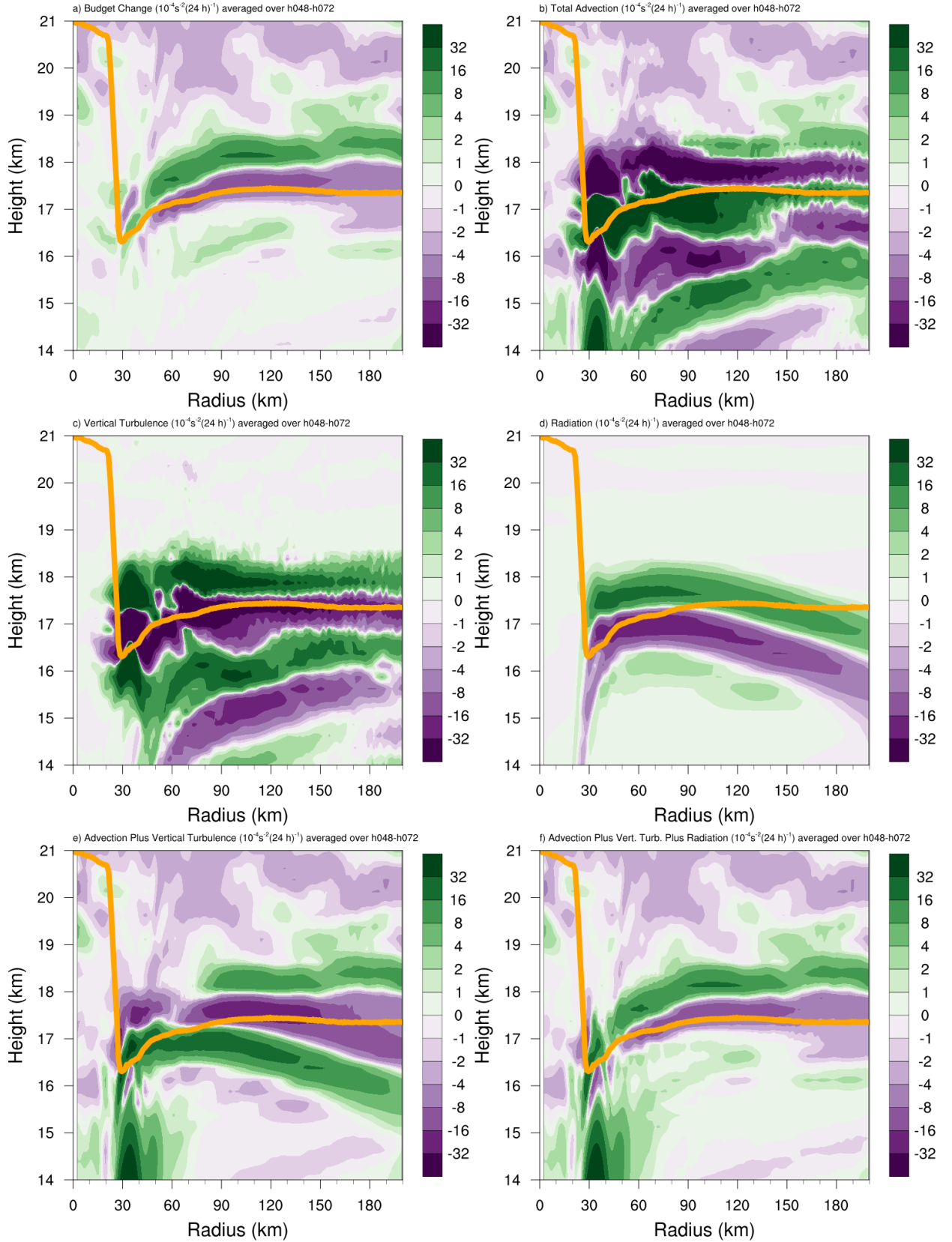


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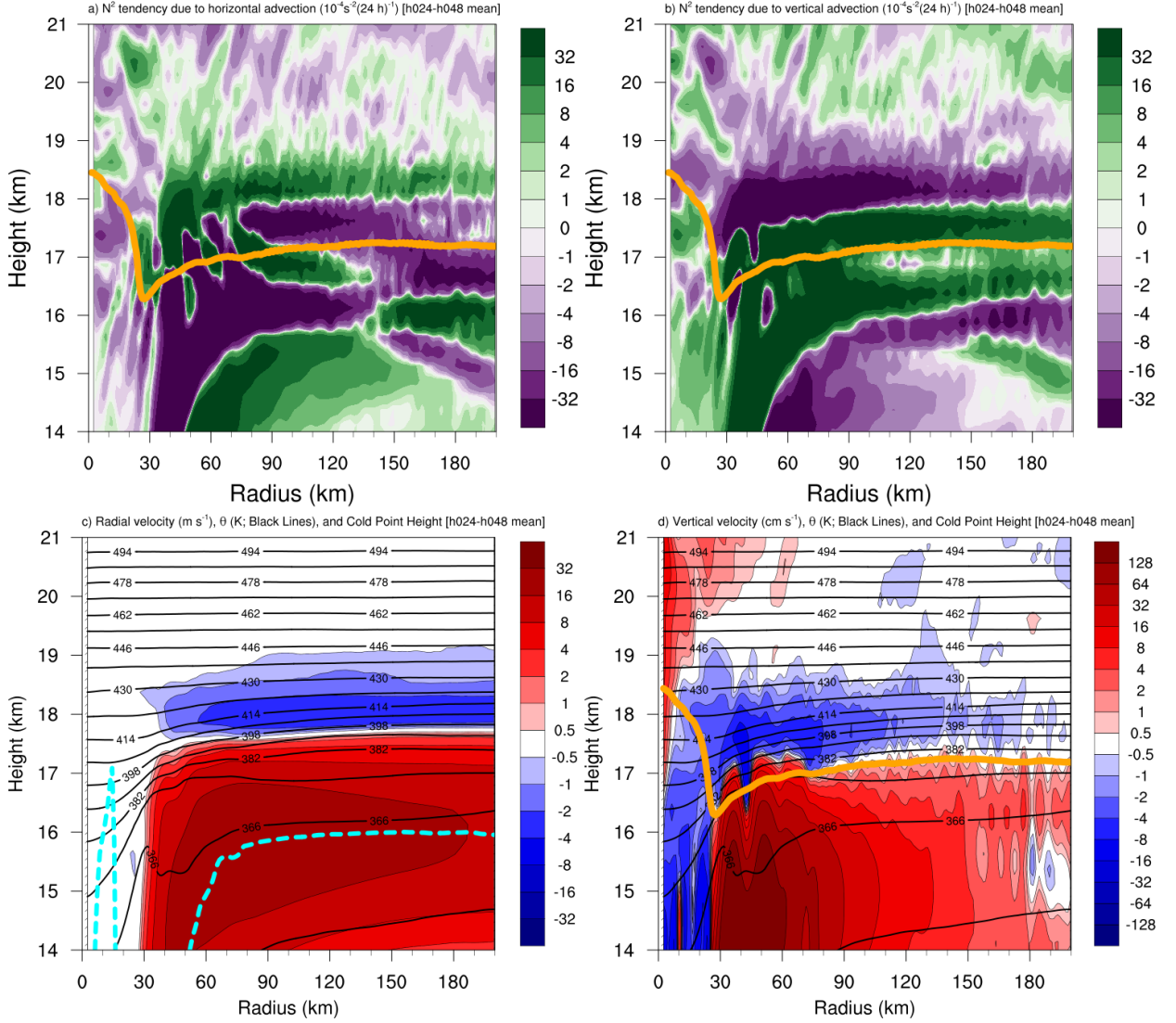
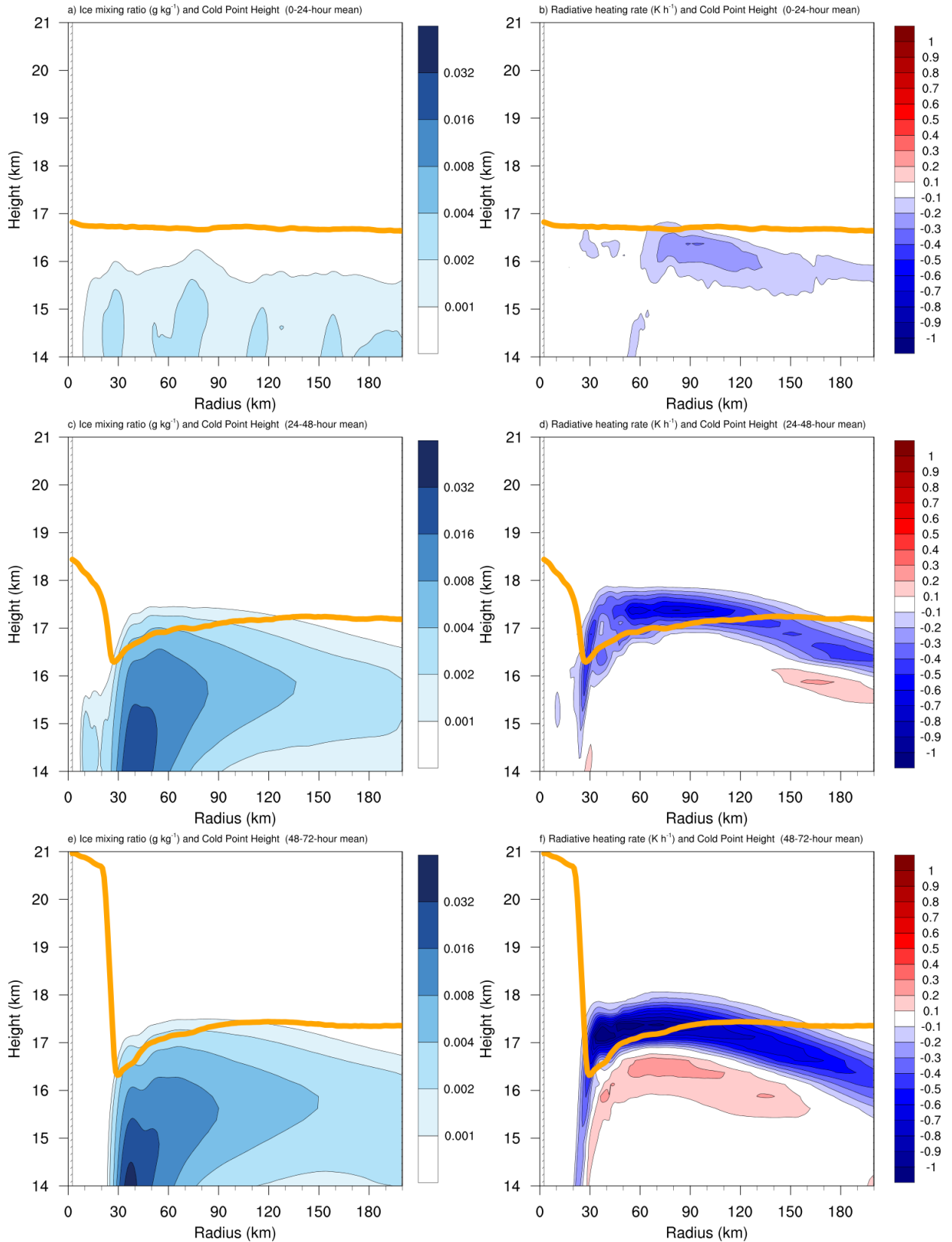


FIG. 8. The contributions to the change in  $N^2$  over the 24-48-hour period ( $10^{-4} \text{ s}^{-2} (24 \text{ h})^{-1}$ ) by (a) horizontal advection and (b) vertical advection. (c) The radial velocity ( $\text{m s}^{-1}$ ; filled contours), potential temperature (K; thick black contours), cold-point tropopause height (orange line), and level of maximum outflow (dashed cyan line) averaged over the 24-48-hour period. (d) The vertical velocity ( $\text{cm s}^{-1}$ ; filled contours), potential temperature (K; thick black contours), and cold-point tropopause height (orange line) averaged over the 24-48-hour period.



529 FIG. 9. Ice mixing ratio ( $\text{g kg}^{-1}$ ) and cold-point tropopause height (orange lines) averaged over (a) 0-24 hours,  
530 (c) 24-48 hours, and (e) 48-72 hours. Radiative heating rate ( $\text{K h}^{-1}$ ) and cold-point tropopause height (orange  
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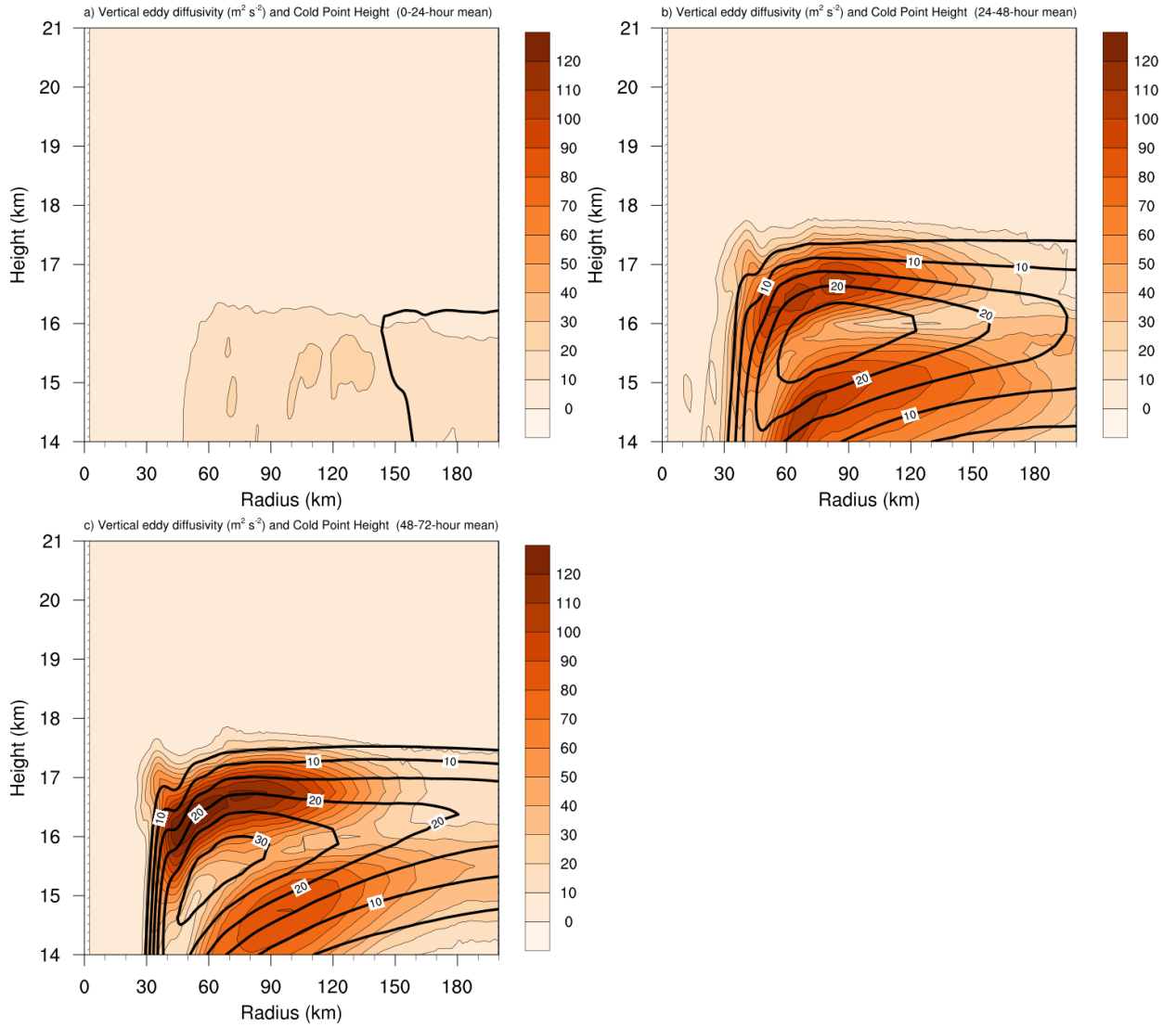


FIG. 10. Vertical eddy diffusivity ( $\text{m}^2 \text{s}^{-2}$ ; filled contours), cold-point tropopause height (cyan lines), and radial velocity ( $\text{m s}^{-1}$ ; thick black lines) averaged over (a) 0-24 hours, (b) 24-48 hours, and (c) 48-72 hours.

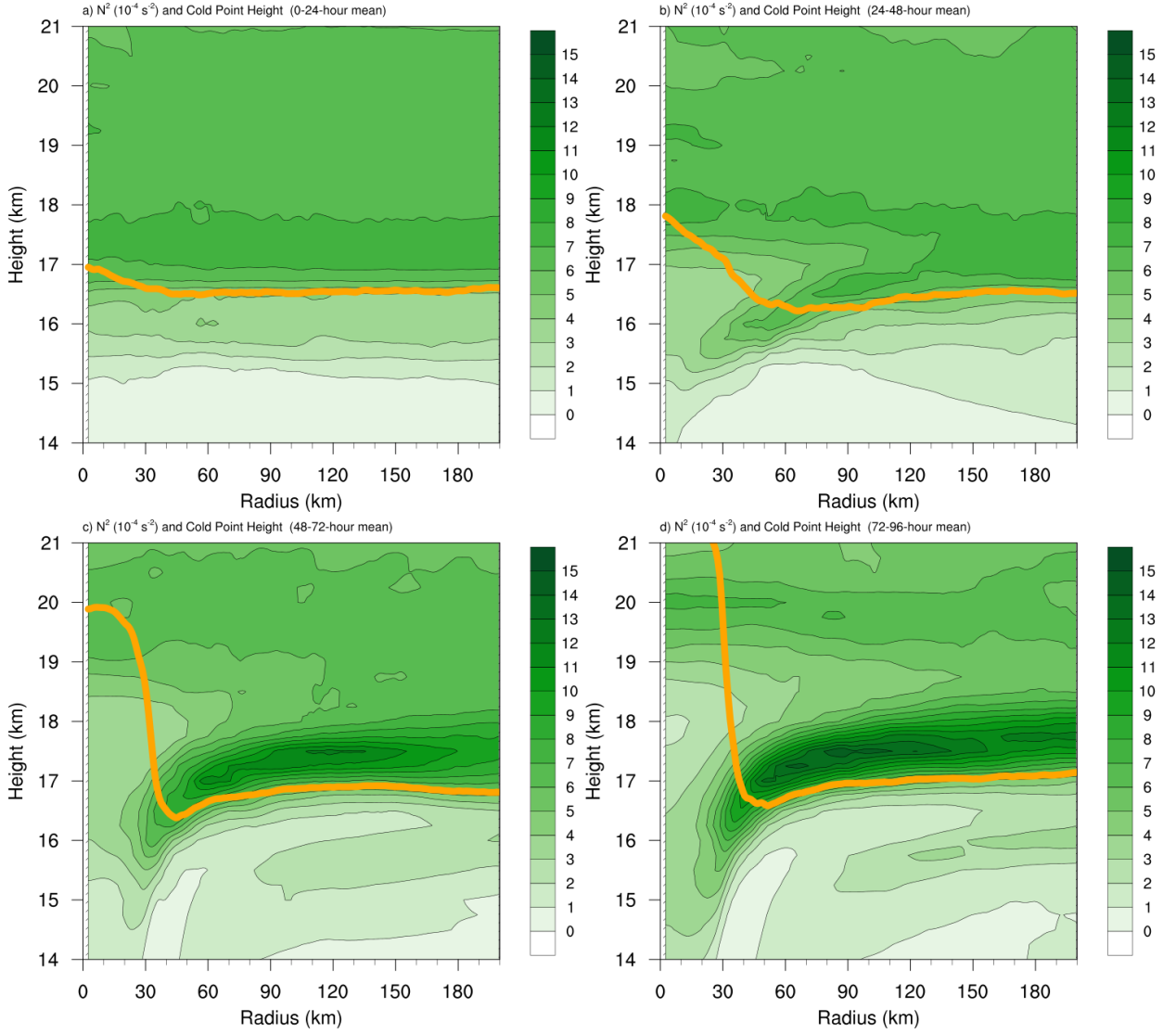


Fig. A1. Twenty-four-hour averages of squared Brunt-Väisälä frequency ( $N^2$ ;  $10^{-4} \text{ s}^{-2}$ ) over (a) 0-24 hours, (b) 24-48 hours, (c) 48-72 hours, and (d) 72-96 hours for the simulation described in Appendix Aa. Orange lines represent the cold-point tropopause height averaged over the same time periods.

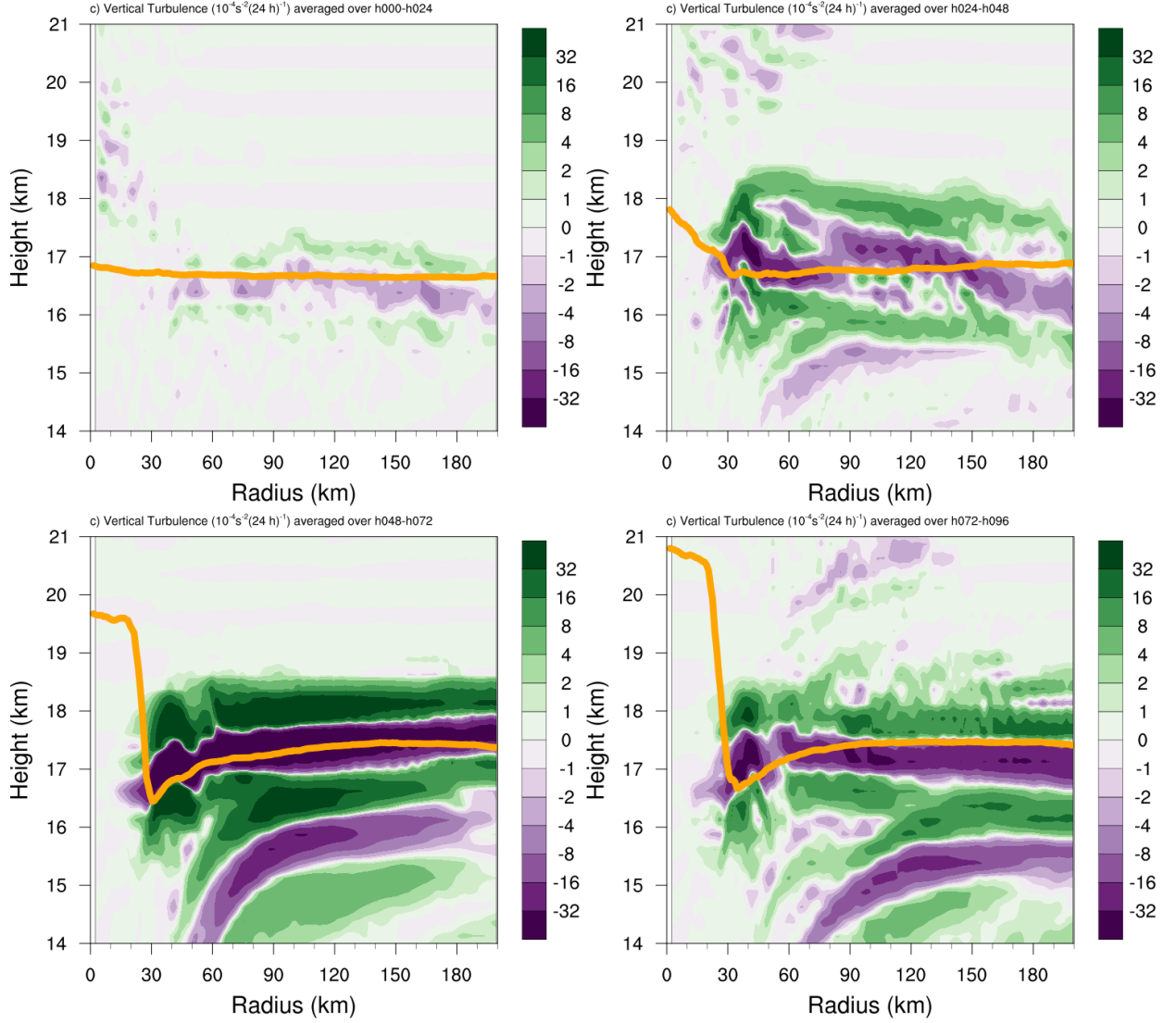


Fig. A2. The contribution of vertical turbulence to the  $N^2$  variability ( $10^{-4} \text{s}^{-2} (24 \text{ h})^{-1}$ ) averaged over (a) 0-24 hours, (b) 24-48 hours, (c) 48-72 hours, and (d) 72-96 hours for the simulation described in Appendix Ab. Orange lines represent the cold-point tropopause height averaged over the same time periods.