

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

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ABSTRACT

⁸ We have some cool results!

9 **1. Introduction**

10 There will be a whole bunch of papers cited here...

11 **2. Model Setup**

12 Put description of Fig. 1 in this section.

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

14 **3. Budget Computation**

15 Add details of budget computation here...

16 **4. Results**

17 *a. Static stability evolution*

18 The average N^2 over the first day of the simulation (Fig. 2a) indicates the presence of a static
19 stability maximum about 400 m above the cold-point tropopause. This lower-stratospheric stable
20 layer had begun to erode during the initial spin-up period, with the maximum destabilization
21 occurring at the innermost radii. This decrease in static stability continued into the second day
22 of the simulation (Fig. 2b) as the storm intensified to hurricane strength (Fig. 1). Destabilization
23 was particularly pronounced over the developing eye, where the time-mean cold-point tropopause
24 height increased by up to 400 m compared to the previous day. Over the developing eyewall
25 and outer rainband regions, meanwhile, the tropopause height remained nearly constant. During
26 the third day of the simulation (Fig. 2c), static stability over the eye continued to decrease, and
27 the cold-point tropopause height rose to 18.3 km at the storm center. The tropopause sloped
28 sharply downward over the innermost radii, reaching the 16.4-km level near the 50-km radius. This
29 local minimum in tropopause height corresponded to the eyewall region, where upper-tropospheric

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 m s^{-1} (Fig. 1), the upper-tropospheric static stability within the eyewall region continued to strengthen, along with the static stability within the lower stratosphere 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

53 Section 3, except with 1-hour averaging intervals instead of 24-hour intervals. The absolute values
 54 of these tendencies are then averaged over the radius-height domain depicted in Fig. 3 and plotted
 55 as a time series¹. Advection (Fig. 4, red line) plays an important role in the mean tropopause-
 56 layer static stability tendency at all times, and vertical turbulence (Fig. 4, blue line) and radiation
 57 (Fig. 4, dark green line) both become important after 48 hours. Although the contribution from
 58 horizontal turbulence (Fig. 4, purple line) becomes more important after 72 hours, it is confined
 59 to a very small region immediately surrounding the eyewall tangential velocity maximum (not
 60 shown), and is negligible throughout the rest of the tropopause layer. The remaining two processes
 61 - microphysics and dissipative heating (Fig. 4, orange and light green lines, respectively) - lie atop
 62 one another near zero. These time series indicate that, at all times, three budget terms dominate the
 63 tropopause-layer static stability tendency: advection, vertical turbulence, and radiation. Variations
 64 in the magnitude and spatial structure of these terms drive the static stability changes depicted in
 65 Fig. 2; subsequent sections will focus on these variations and what causes them.

66 *(i) 0-24 hours*

67 *(ii) 24-48 hours*

68 *(iii) 48-72 hours*

69 *(iv) 72-96 hours*

70 *Acknowledgments.* Start acknowledgments here.

¹It 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.

71 **References**

- 72 Duran, P., and J. Molinari, 2018: Dramatic inner-core tropopause variability during the rapid
73 intensification of Hurricane Patricia (2015). *Mon. Wea. Rev.*, **XXX (X)**, XXX–XXX.

74 LIST OF FIGURES

- 75 **Fig. 1.** The maximum 10-m wind speed (top panel; m s^{-2}) and minimum sea-level pressure (bottom
76 panel; hPa) in the simulated storm (blue lines) and from Hurricane Patricia's best track (red
77 stars). 9
- 78 **Fig. 2.** Twenty-four-hour averages of squared Brunt-Väisälä frequency (10^{-4} s^{-2}) over the first four
79 days of the simulation. Orange lines represent the cold-point tropopause computed from the
80 mean temperature field over the same time periods. 10
- 81 **Fig. 3.** Left panels: Twenty-four-hour changes in squared Brunt-Väisälä frequency (10^{-4} s^{-2}) over
82 (a) 0-24 hours, (b) 24-48 hours, (c) 48-72 hours, (d) 72-96 hours. Middle Panels: The N^2
83 change over the same time periods computed using Eq. XXX. Right Panels: The budget
84 residual over the same time periods, computed by subtracting the budget change (middle
85 column) from the model change (left column). 11
- 86 **Fig. 4.** Time series of the contribution of each of the budget terms to the time tendency of the
87 squared Brunt-Väisälä frequency (N^2 ; 10^{-4} s^{-2}). For each budget term, the absolute value
88 of the N^2 tendency is averaged both temporally over 1-hour periods (using output every
89 minute), and spatially within the radius-height domain depicted in Fig. 3. 12
- 90 **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
91 to that change from (b) the sum of horizontal and vertical advection, (c) vertical turbulence,
92 and (d) the sum of longwave and shortwave radiation. 13
- 93 **Fig. 6.** As in Fig. 5, but for the 24-48-hour period. 14

94	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	
95		to that change from (b) the sum of horizontal and vertical advection, (c) vertical turbulence,	
96		(d) the sum of longwave and shortwave radiation, (e) the sum of horizontal advection, ver-	
97		tical advection, and vertical turbulence, and (f) the sum of horizontal advection, vertical	
98		advection, vertical turbulence, and longwave and shortwave radiation.	15
99	Fig. 8.	As in Fig. 7, but for the 72-96-hour period.	16

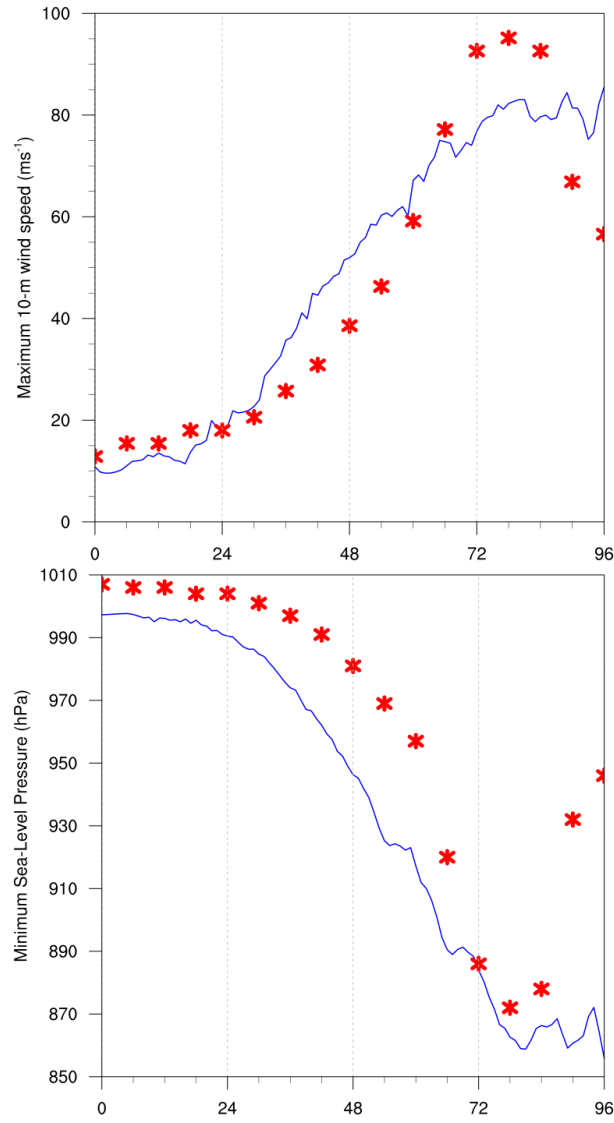


FIG. 1. The maximum 10-m wind speed (top panel; m s^{-2}) and minimum sea-level pressure (bottom panel; hPa) in the simulated storm (blue lines) and from Hurricane Patricia's best track (red stars).

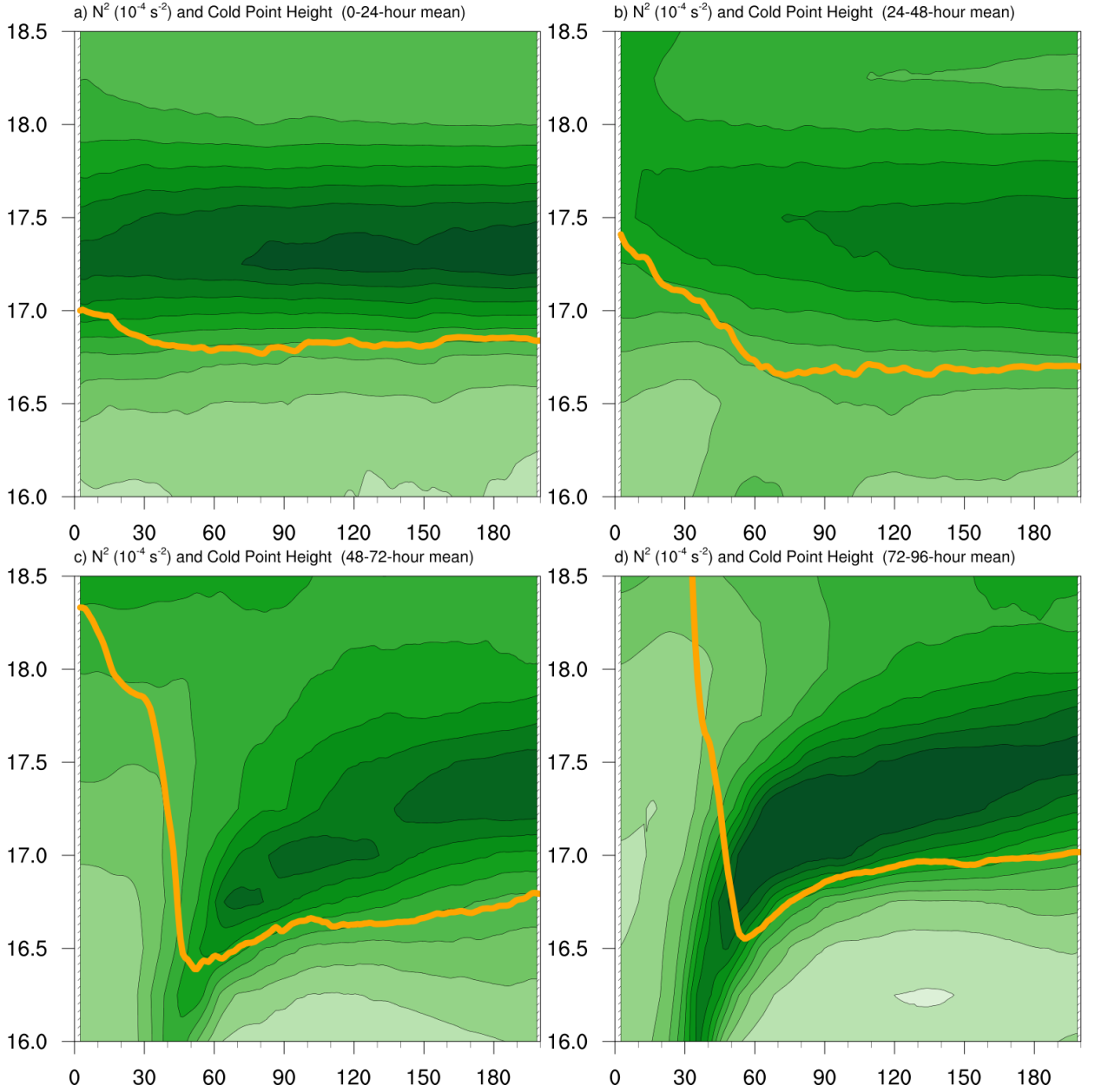


FIG. 2. Twenty-four-hour averages of squared Brunt-Väisälä frequency (10^{-4} s^{-2}) over the first four days of the simulation. Orange lines represent the cold-point tropopause computed from the mean temperature field over the same time periods.

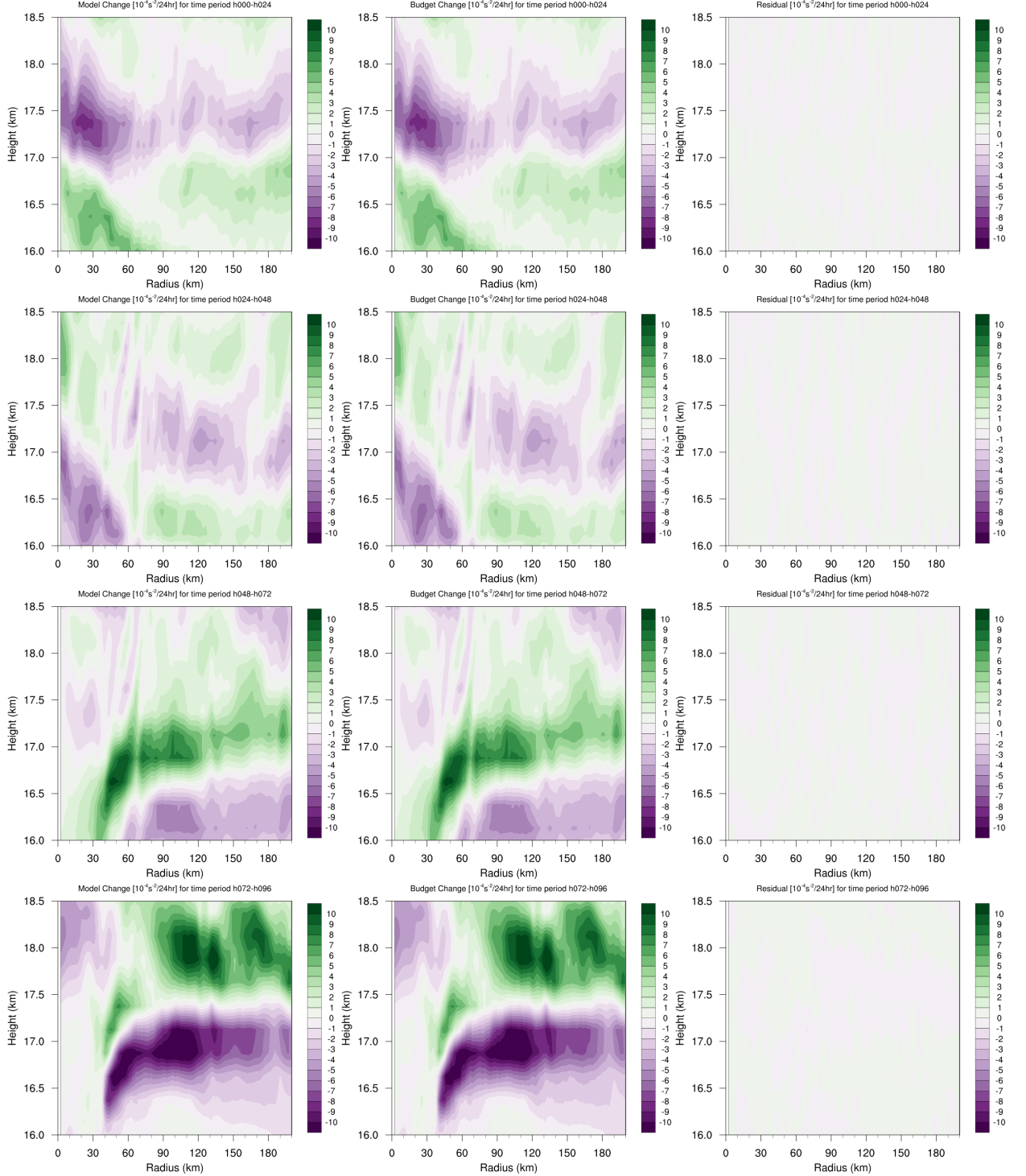


FIG. 3. Left panels: Twenty-four-hour changes in squared Brunt-Väisälä frequency (10^{-4} s^{-2}) over (a) 0-24 hours, (b) 24-48 hours, (c) 48-72 hours, (d) 72-96 hours. Middle Panels: The N^2 change over the same time periods computed using Eq. XXX. Right Panels: The budget residual over the same time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

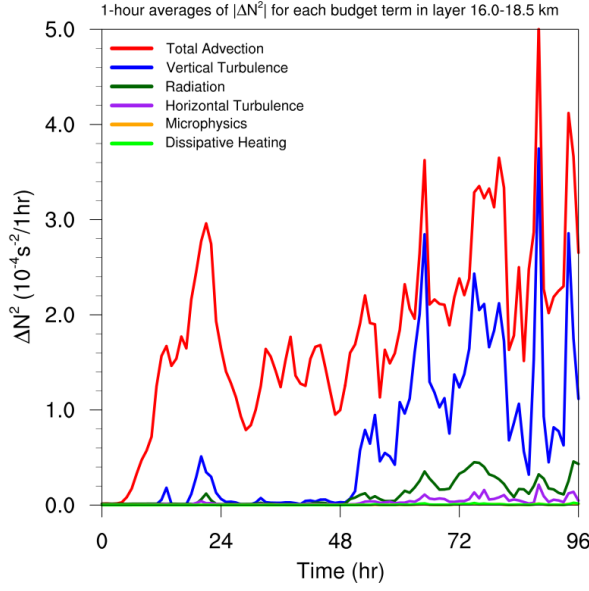


FIG. 4. Time series of the contribution of each of the budget terms to the time tendency of the squared Brunt-Väisälä frequency (N^2 ; 10^{-4} s^{-2}). For each budget term, the absolute value of the N^2 tendency is averaged both temporally over 1-hour periods (using output every minute), and spatially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

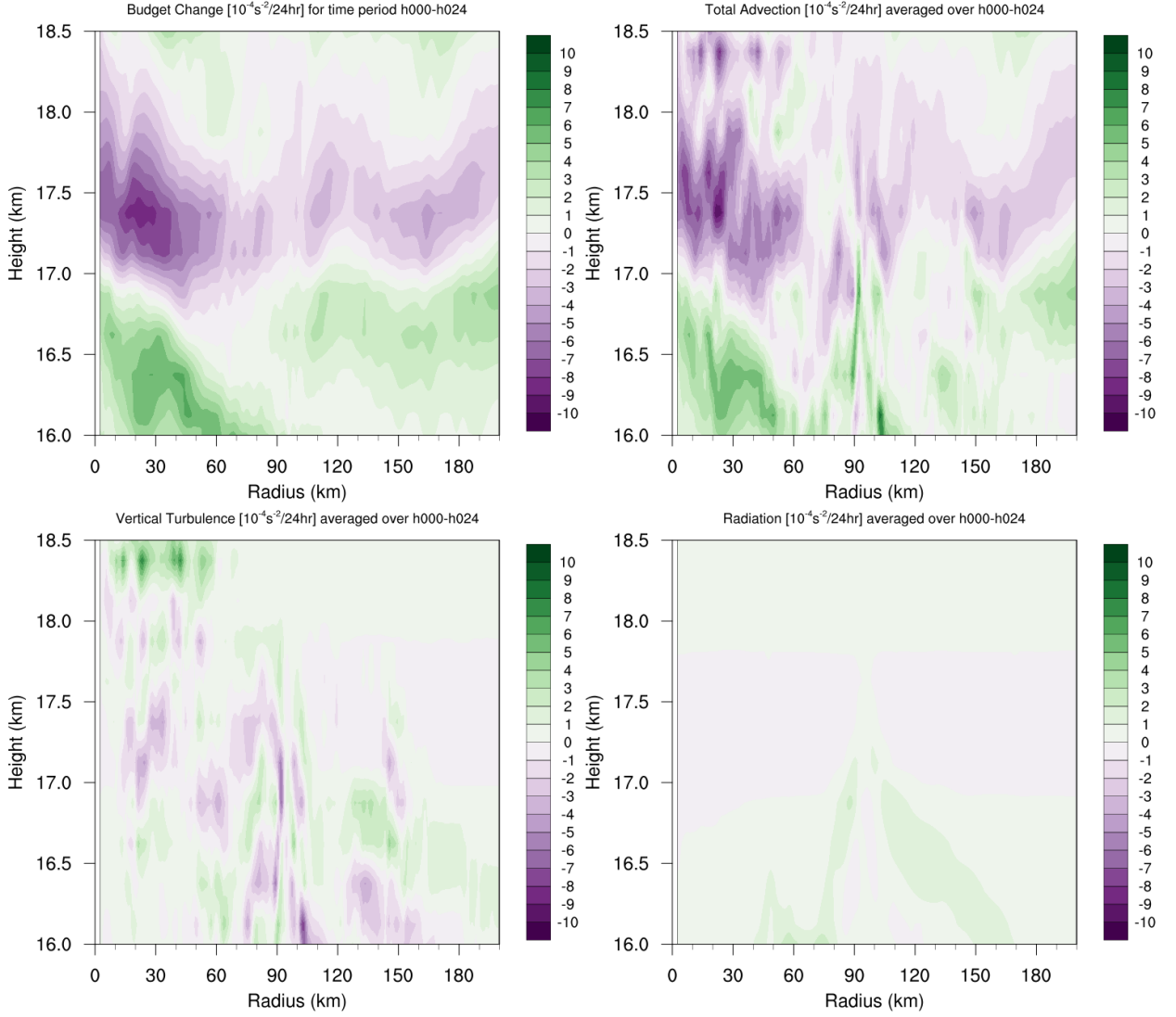


FIG. 5. (a) Total change in N^2 over the 0-24-hour period ($10^{-4} \text{ s}^{-2} (24 \text{ hr})^{-1}$) and the contributions to that change from (b) the sum of horizontal and vertical advection, (c) vertical turbulence, and (d) the sum of longwave and shortwave radiation.

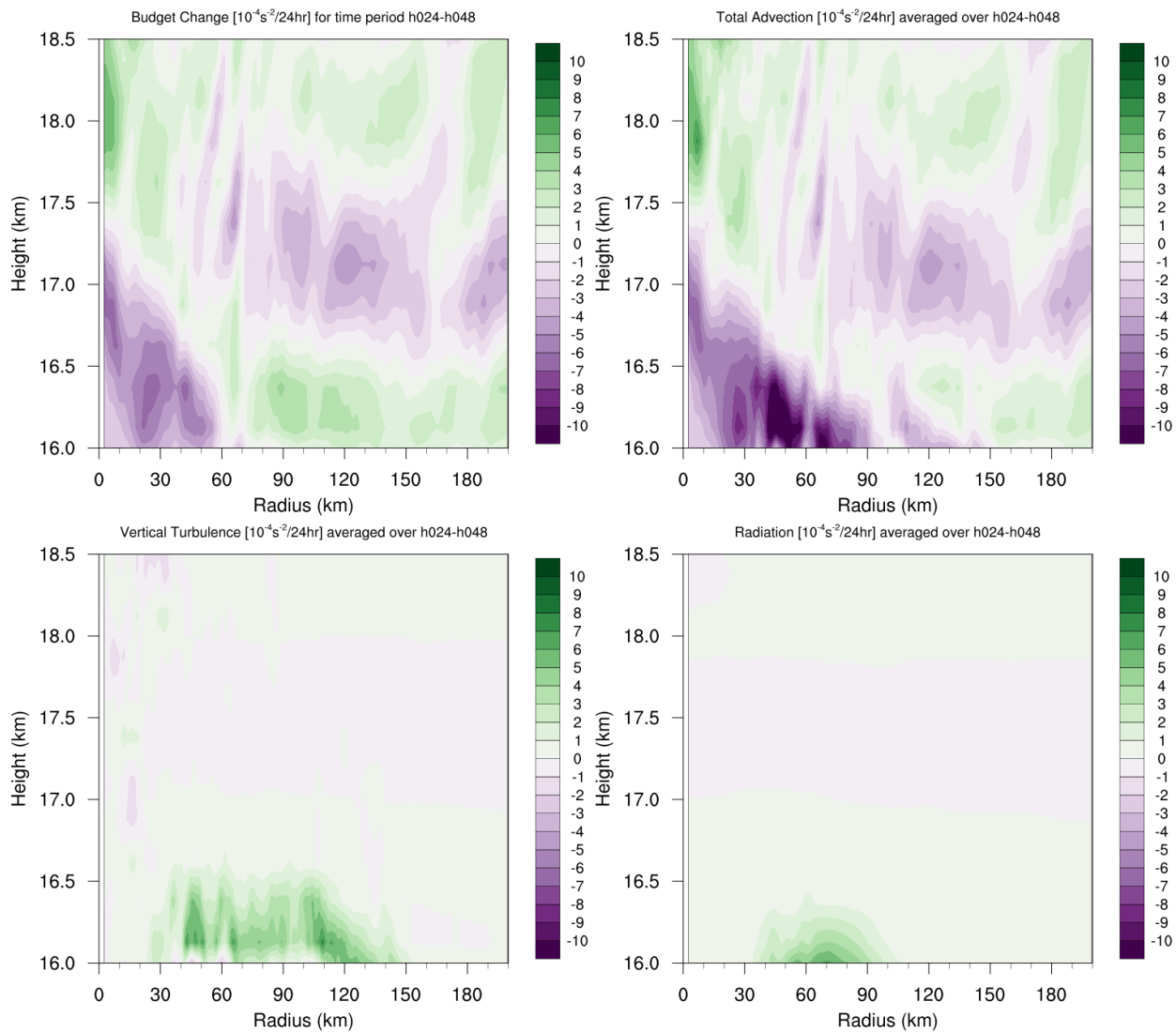


FIG. 6. As in Fig. 5, but for the 24-48-hour period.

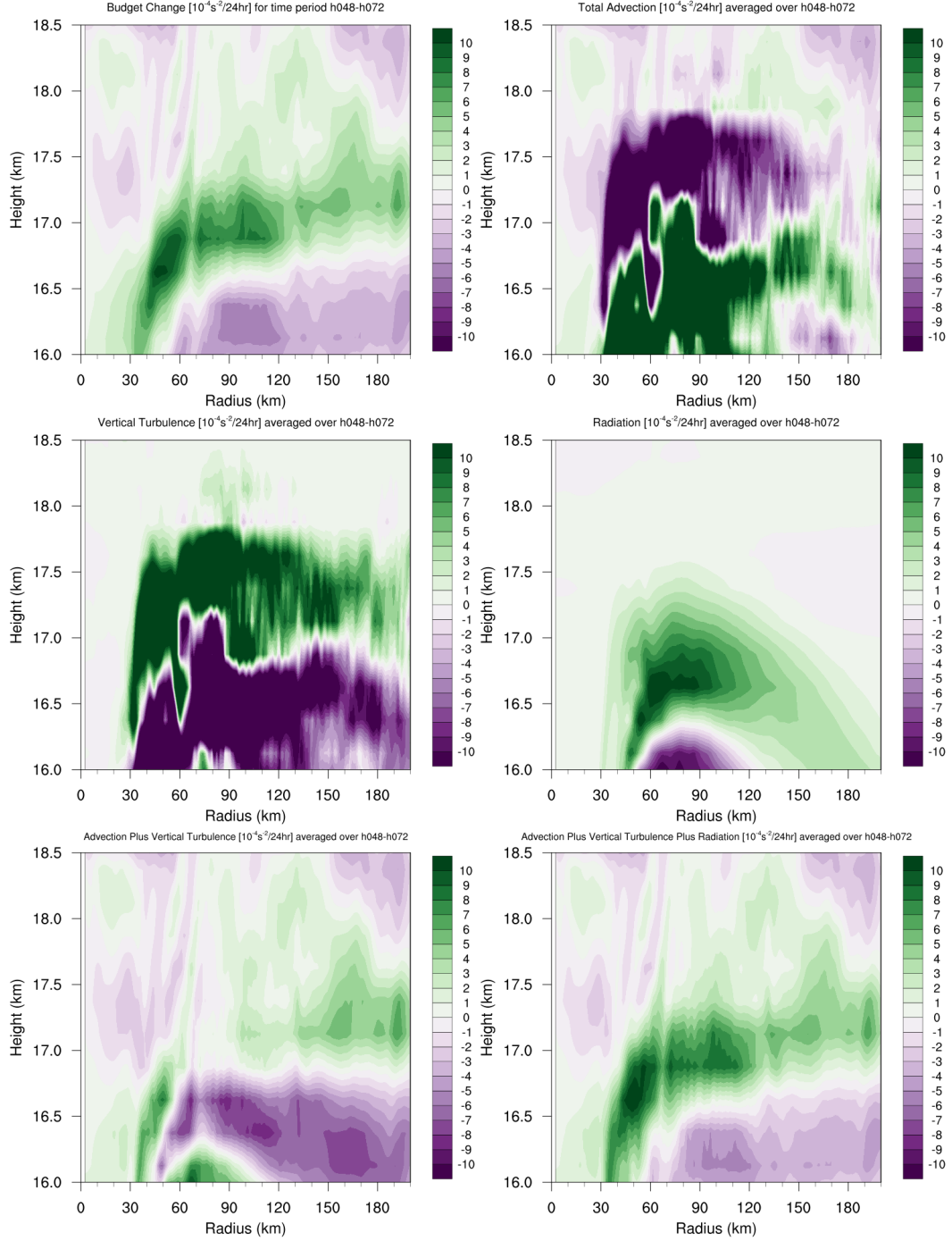


FIG. 7. (a) Total change in N^2 over the 48-72-hour period ($10^{-4} \text{ s}^{-2} (24 \text{ hr})^{-1}$) and the contributions to that change from (b) the sum of horizontal and vertical advection, (c) vertical turbulence, (d) the sum of longwave and shortwave radiation, (e) the sum of horizontal advection,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

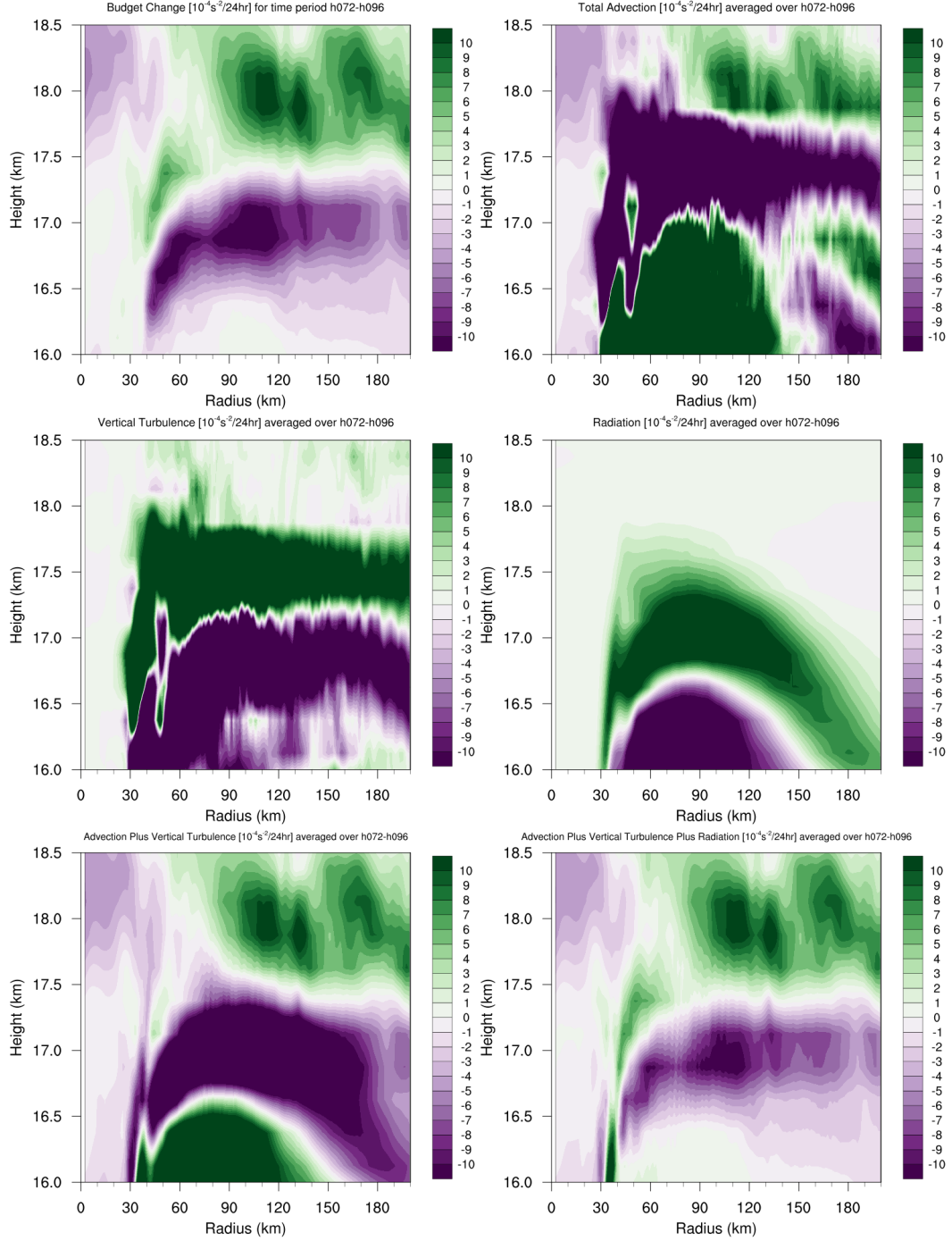


FIG. 8. As in Fig. 7, but for the 72-96-hour period.