

Assimilation Of Radar Data for Identifying Downslope Windstorms Using The 3DVAR Method

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Abstract

Assimilation of radar data is highly important for improving the accuracy in simulating atmospheric conditions. Radar data are used to refine initial data to align with the actual atmospheric conditions. This technique can be applied to detect complex atmospheric dynamics involving mountainous topography. Mountain waves and downslope windstorms are two phenomena typically interconnected, where intense downslope winds in deep cross-mountain flow trigger strong mountain waves in the stable lower atmospheric layer. The research was conducted from October 8 to 10, 2024, with simulation data covering October 7 to 11, 2024, for the spin-up process. The objectives of this study are to understand the atmospheric dynamics conditions, identify the types of mountain waves and downslope windstorms, and simulate mountain wave and downslope windstorm phenomena using WRF-CTL and WRF-DA. The research findings indicate that the atmospheric stability before the event showed strong static stability with speeds reaching 2.4 m/s, while after the event, there was an increase in dynamic turbulence. The parameters used include the Brunt-Väisälä Frequency with values ranging from 0.09001948 N^2 to 0.134224952 N^2 , the Richardson Number with values ranging from 2.05 to 10.00, the Scorer Parameter with values from 0.1 1/m to 0.3 1/m, and the Froude Number with values indicating 0.2 to 1.4. The research results show that radar data assimilation successfully enhanced the simulation accuracy compared to WRF-CTL. Mountain waves were identified as vertical propagating waves during the day with vertical propagation up to 400 mb and trapped lee waves at night with horizontal oscillations spanning 18-25 km. The downslope windstorm was classified as a shallow cross-mountain flow with a depth less than 1 km.

Keywords: downslope windstorm, mountain waves, WRF-CTL, radar data assimilation

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INTRODUCTION

Atmospheric dynamics in a region are greatly influenced by its topography. Topography refers to variations in elevation, slope, and landform on the Earth's surface. These landforms include valleys, mountains, fields, and land masses. Variations in landform can accelerate, slow down, and change the direction of wind. The meteorological phenomenon that occurs due to atmospheric interaction in mountainous topography is called a mountain wave, and when it occurs on a mountain slope, it is called a downslope windstorm. Previous studies have simulated how mountain waves are influenced by the height of the tropopause and how vertical wavelength affects orographic precipitation and rainfall distribution. The impact of mountain waves on precipitation patterns occurs through the process of orographic uplift on the windward side, which then loses its moisture and descends on the leeward side of the mountains, creating a rain shadow (Siler and Durran, 2015).

In general, the formation of mountain waves must meet two main conditions, namely a stable environment and strong wind flow that are perpendicular to the orographic barrier. (CLIMATE, 2019). Mountain waves have two types of waves, namely vertically propagating waves and trapped lee waves (Durran et al., 2015). One phenomenon that indicates the presence of mountain waves is lenticular clouds (COMET, 2007). Lenticular clouds (single bands) are formed by vertically propagating mountain waves, and lenticular cloud formations (multiple bands) are formed by trapped lee waves (Durran, 2013). However, it can be dangerous if there are no clouds indicating the presence of mountain waves, because the turbulence created by mountain waves turns into Clear Air Turbulence (CAT), which is often associated with wind shear (Evans, 2014).

Downslope windstorms are a type of mountain wave phenomenon that occur on the leeward side of mountains as a result of mountain wave activity. This phenomenon occurs when stable air masses are forced over mountain peaks by strong winds, resulting in very fast air currents on the leeward slopes. Wind speeds in this phenomenon can reach more than 22 m/s, and in some cases even exceed 45 m/s, depending on atmospheric conditions and topography (Durran, 1990). Downslope windstorm had three formation conditions according to (Durran, 2002). These conditions create different forms of downslope windstorms. These conditions include: deep cross-mountain flow, shallow cross-mountain flow, and without wave breaking.

Atmospheric numerical models such as Weather Research and Forecasting (WRF) have been widely used to simulate atmospheric phenomena, including mountain waves (Tian and Miao, 2019). The WRF model, supported by a data assimilation system (WRF-DA), allows the integration of observational data such as radar into the model. This method works by combining observational data and model simulation results mathematically to produce a more representative atmospheric analysis (Liu et al., 2021). Weather radar, as one of the main instruments in atmospheric observation, is capable of detecting wind patterns, rainfall, and turbulence (Bringi, 2023). Radar data is very important in providing a more detailed picture of mountain wave characteristics, including wind speed, cloud height, and rainfall distribution in mountainous areas (Hastuti et al., 2023). This study aims to utilize radar data in identifying mountain wave events using the 3DVAR data assimilation method in WRF-DA.

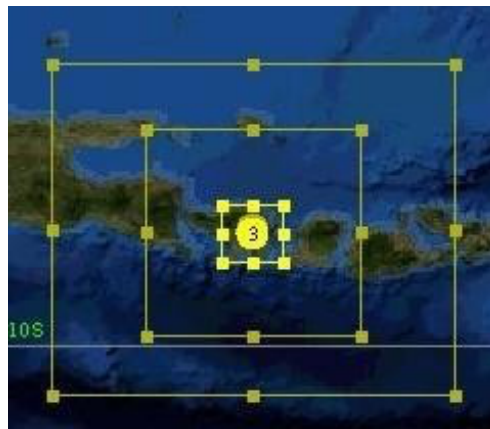
METHOD

The simulation was conducted through WRF processing in two ways: WRF-CTL, where processing is performed using the standard WRF model without any additional adjustments, and WRF-DA, where the WRF model is integrated with radar data to refine the initial data to better match the actual atmospheric conditions. The assimilation parameters used in WRFDA are a combination of reflectivity and radial velocity. Configuration for WRF processing is shown in Tabel 1.

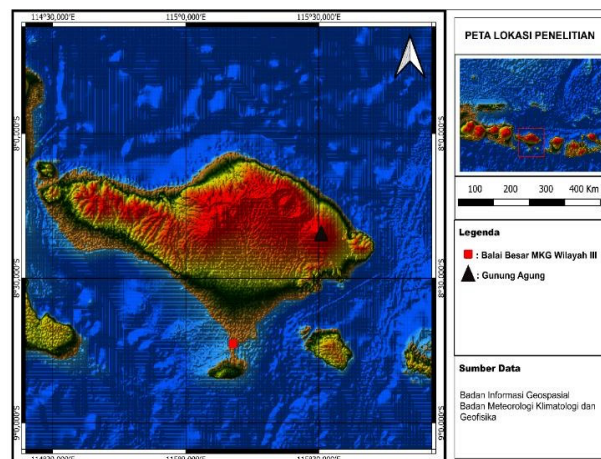
Tabel 1. WRF configuration

Configuration	Domain 1	Domain 2	Domain 3
Parameterization scheme <i>Trophycal Suite</i>			
Running Time 3 Days 12 Hour			
Spatial Resolution	9 Km	3 Km	1 Km
Time_step	60		
e_we	29	55	82
e_sn	21	31	52
e_vert	31		
Interval_seconds	21600		

To analyze mountain wave and downslope windstorm in detail, nested grid is used. This nested grid is divided in to 3 domains, as shown in Figure 1.

**Figure 1.** Domain nested grid

The input data consist of C-Band Doppler radar data from the Regional Office of Meteorology, Climatology, and Geophysics III Denpasar, including reflectivity and radial velocity, as well as FNL data from the website of National Centers for Environmental Prediction with a resolution of $0.25^{\circ} \times 0.25^{\circ}$ which can be accessed in <https://rda.ucar.edu/datasets/ds084.1/>. This research was conducted in the province of Bali, specifically in the Mount Agung area located at coordinates $8^{\circ} 20' 34.44''$ S and $115^{\circ} 30' 25.92''$ E at an altitude of 3,142 m (10,308 ft). Figure 2 shows a map of the research location.

**Figure 2.** Research Location in Mount Agung, Bali

There are several parameters used in this study, Richardson number that used in determining the static stability value of the atmosphere. Calculation of Richardson number is expressed in the following formula (Holton and Hakim, 2013):

$$Ri = \frac{|g| \Delta\theta v \Delta z}{Tv. [(\Delta U)^2 + (\Delta v)^2]} \quad (1)$$

With $\Delta\theta v$ is the change in potential temperature (K); g is the gravitational acceleration constant (9.8 m s^{-2}); ΔV is the change in north-south wind speed with elevation (m/s); ΔU is the change in east-west wind speed with elevation (m/s); Δz is Change in altitude (m); Tv is Absolute temperature (K) at altitude z_a , $z_a = (z_1 - z_2) \frac{1}{2}$. Brunt-Väisälä frequency (N) calculation were using potential temperature parameters and geopotential height from the WRF simulation, expressed in the following formula (Mccann, 2001):

$$N = \sqrt{\frac{g}{\theta} \frac{d\theta}{dz}} \quad (2)$$

Where g is the acceleration due to gravity; θ is the potential temperature; $\frac{g}{\theta} \frac{d\theta}{dz}$ is the vertical gradient of potential temperature. The Froude number is calculated once the Brunt-Vaisala value has been obtained, using the following formula (Holton, 2004).

$$Fr = \frac{U}{Nh} \quad (3)$$

With U is the wind speed above the mountains; h is the height of the mountains. A value of $Fr > 1$ supports the formation of downslope windstorms, while $Fr < 1$ indicates flow over the peak without significant oscillation (Bao and Tan, 2012). Scorer parameter (l^2) is used to assess the stability and vertical propagation of atmospheric waves. This parameter is very useful for determining whether mountain waves can propagate upward or be attenuated in the atmosphere. The scorer parameter was formulated by (Scorer, 1949), where:

$$l^2 = \frac{N^2}{U^2} - \frac{\partial^2}{\partial z^2} \frac{1}{U} \quad (4)$$

Where N^2 is the Brunt-Väisälä frequency (atmospheric stability); U is the horizontal wind speed (m/s); $\frac{\partial^2}{\partial z^2} \cdot \frac{1}{U}$ is the second derivative of the horizontal wind speed with respect to height. Results of calculation determine if l^2 decreases significantly: mountain waves can oscillate repeatedly and propagate horizontally toward the leeward slope, and these waves are called trapped lee waves and if l^2 decreases insignificantly: mountain waves propagate vertically near the mountain peak, and these waves are called vertically propagating waves.

RESULTS AND DISCUSSION

WRF-CTL

Table 1 shows that during the period from October 9 at 00:00 to 23:00 UTC, the N value ranged from 0.0955 to 0.1165 s^{-1} , with N^2 remaining positive throughout the period (0.0091 to 0.0136 s^{-2}), indicating a stable atmosphere conducive to the formation of mountain waves. The dominant Ri was > 0.25 (average 9.0), except for a few hours where Ri approached or fell below the critical threshold (e.g., 5.52 at 08:00 UTC), indicating a potential transition to dynamic turbulence. Mountain

wave characteristics were dominated by vertical propagating waves for most of the period, with a transition to trapped lee waves during hours with low Ri, where stability inversions limited vertical propagation. Wave onset is detected in the early morning (at 00:00-06:00 UTC) with increasing N , reaching a peak at midday (at 12:00-18:00 UTC) where air parcel oscillations are maximal (N^2 0.012-0.013 s^{-2}), and dissipated at night (at 19:00-23:00 UTC) with Ri decreasing to 6. At 00:00-05:00 UTC, N increases from 0.1084 to 0.1160 s^{-1} (N^2 0.0117-0.0134 s^{-2}), with Ri constant at 10.0, indicating a strong stable layer without significant turbulence. The mountain wave is a vertically propagating wave. At 06:00-11:00 UTC, N decreases to 0.0955 s^{-1} (N^2 0.0092 s^{-2}) then rises again, with Ri decreasing to 6.57 (at 06:00) and 5.52 (at 08:00), indicating the onset of dynamic turbulence (Ri <10).

Tabel 1. Value Parameter of WRF-CTL on 9 October

Hour (UTC)	Brunt Vaisala Frequency (s^{-2})	N^2	Richardson Number
0	0.108369723	0.011744	10.00
1	0.111986675	0.01254102	10.00
2	0.111119969	0.01234765	10.00
3	0.115568121	0.01335599	10.00
4	0.114269397	0.0130575	10.00
5	0.105961581	0.01122786	10.00
6	0.095781003	0.009174	6.57
7	0.095542802	0.00912843	10.00
8	0.102186687	0.01044212	5.52
9	0.099558216	0.00991184	10.00
10	0.100241064	0.01004827	10.00
11	0.108245471	0.01171708	10.00
12	0.109590668	0.01201011	10.00
13	0.105784821	0.01119043	10.00
14	0.104159923	0.01084929	10.00
15	0.103593829	0.01073168	10.00
16	0.104528119	0.01092613	10.00
17	0.105767107	0.01118668	10.00
18	0.108299509	0.01172878	9.94
19	0.110615639	0.01223582	6.72
20	0.111205629	0.01236669	5.94
21	0.115107743	0.01324979	6.24
22	0.116517441	0.01357631	6.38
23	0.11545858	0.01333068	5.92

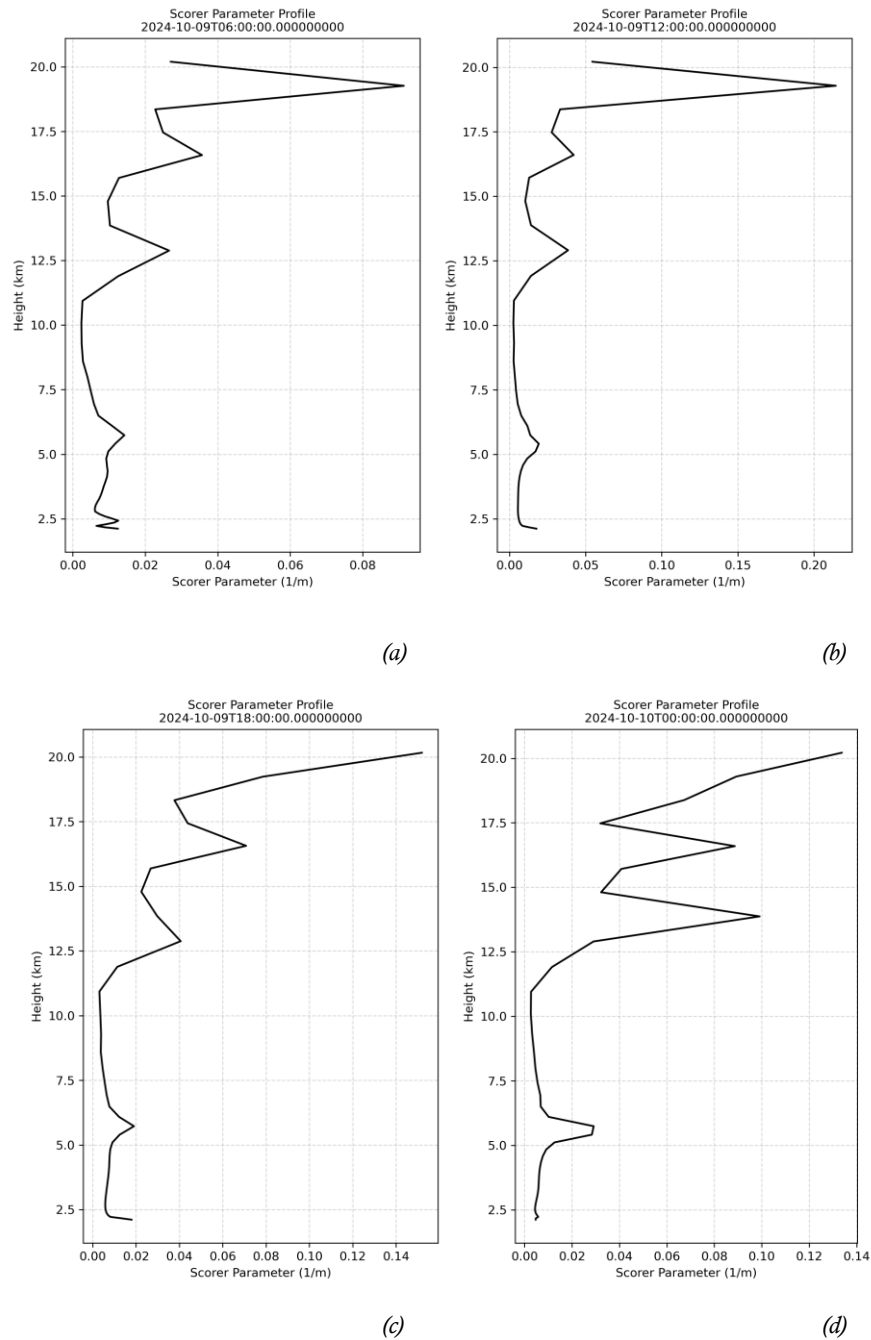


Figure 3. Vertical Profile of Scorer WRF-CTL Parameters on 9 October: (a) 06:00 UTC indicating potential for wave trapping, (b) 12:00 UTC transition to a more stable nocturnal atmosphere, (c) 18:00 UTC increased fluctuations in the lower layer and (d) 00:00 UTC formation of trapped lee waves

The vertical profile of the Scorer parameter in Figure 3 on Mount Agung was conducted during the period of October 9, 2024, representing the dynamics of atmospheric stability that affects the formation of mountain waves. The Scorer profile results show a decreasing trend with height from 0.2 1/m at $z=0$ km to 0 at $z=20$ km, with diurnal variations reflecting the transition from stable morning conditions (high l^2 below) to unstable afternoon conditions (increased fluctuations). The average l^2 is 0.1 1/m in the lower layer (z_0 below, l^2).

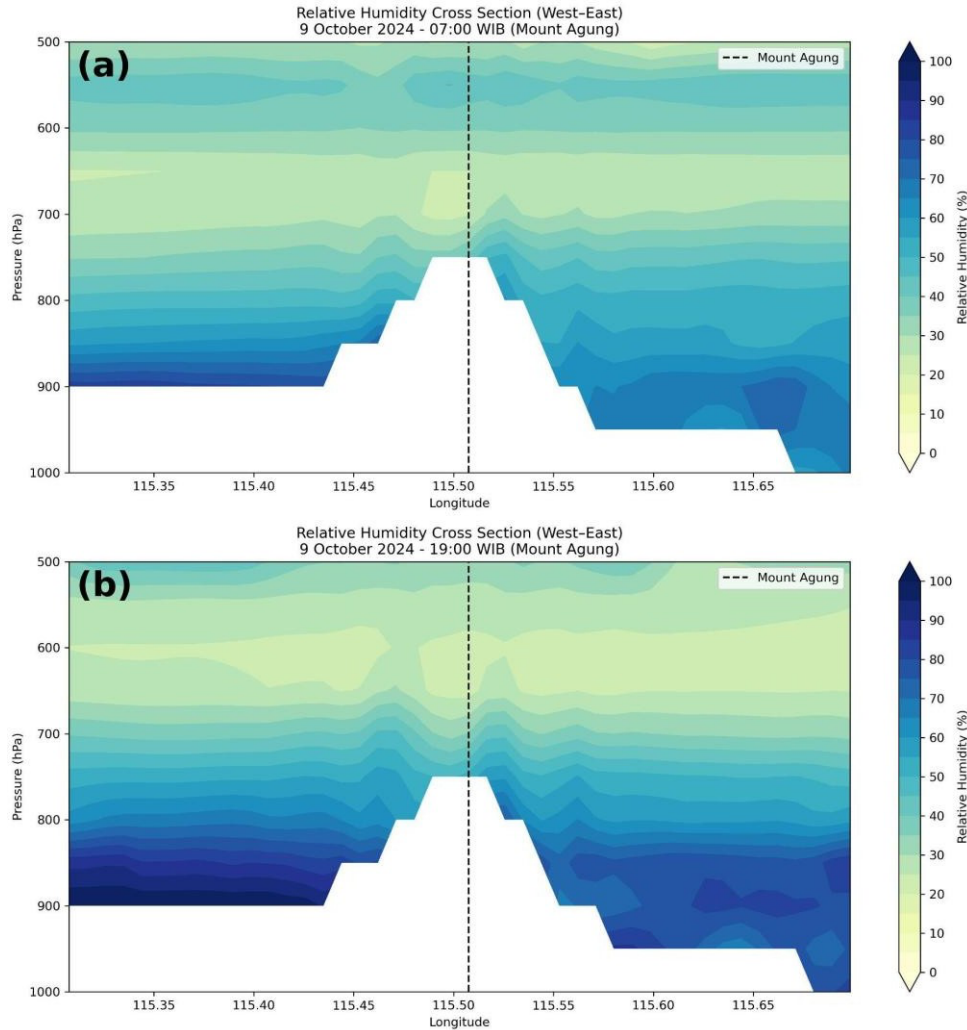


Figure 4. Distribution of WRF-CTL Relative Humidity on October 9: (a) 00.00 UTC vertically stratified humidity and (b) 12.00 UTC weakening patterns and nocturnal dissipation

Visualization of the west-east cross-section of relative humidity (RH, in %) on Mount Agung during the period of October 9, 2024, at 00:00 UTC shows Figure 4 (a) a vertically stratified distribution of humidity with smooth gradations around the mountain's topography. In the upper atmosphere, humidity dominates with high values of dark blue up to 100%, forming a large and uniform humid zone at an altitude of 4000-5000 m, covering the entire cross-section from longitude 115.3 to 115.65. As the altitude decreases to the middle level, moisture gradually decreases, transitioning through light blue and turquoise with values of around 70-90%, creating a stable transition layer without sharp fluctuations. In the lower layer, humidity is even lower, dominated by green and yellow with values of 30-50% at altitudes of 1000-2000 m, especially on the lee (right) side where the decline is steeper, approaching 10% at the surface. Figure 4 (b) at 12:00 UTC shows a weakening RH pattern with dominant trapping, 60-80% RH horizontally in the lee, indicating nocturnal dissipation of the trapped lee wave. Ri 6.72-9.94 is approaching critical, increasing shear and dynamic turbulence (potential CAT). Nighttime inversion strengthens trapping (Scorer l^2 0.1 1/m below), producing persistent clouds at the crest.

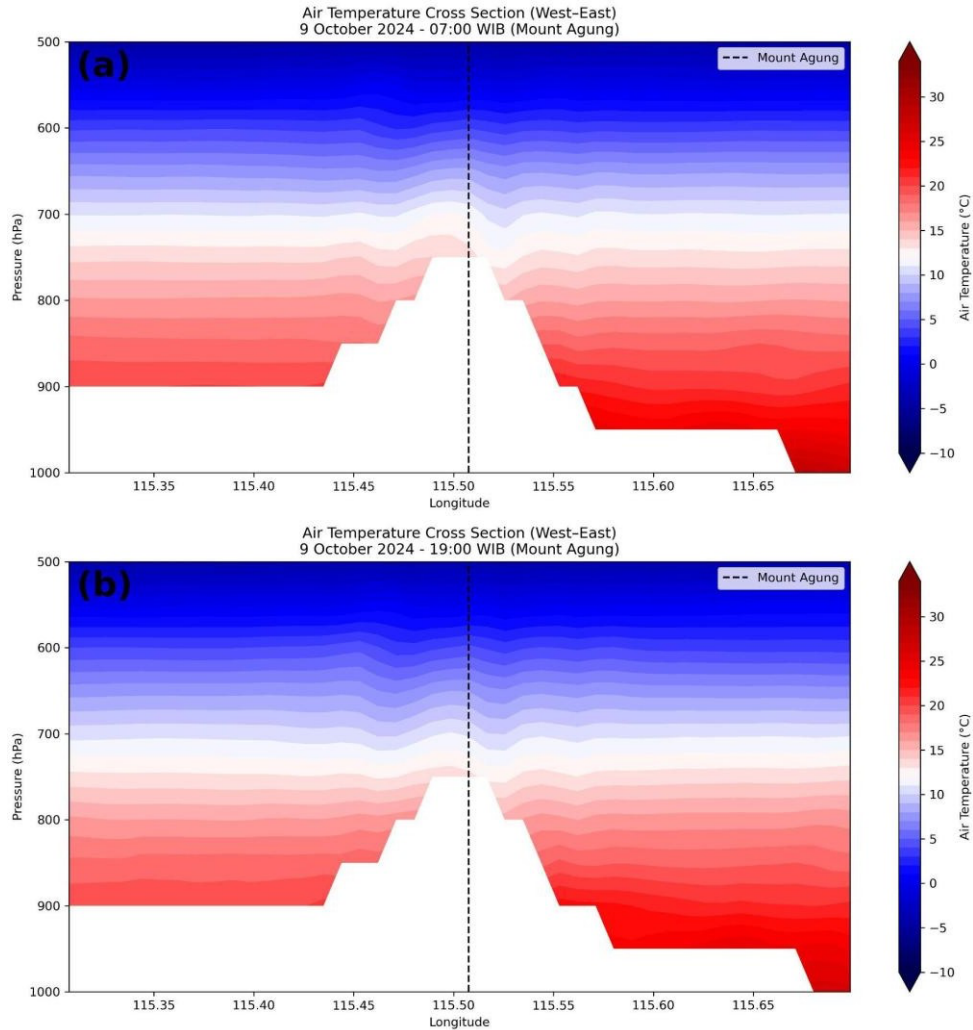


Figure 5. Distribution of WRF-CTL Air Temperature on 9 October: (a) 00.00 UTC indicating trapped lee wave with horizontal wave patterns and (b) 12.00 UTC reflecting downslope wind deceleration

In Figure 5 (a) at 00:00 UTC, the temperature pattern shows a horizontal wave on the lee side with cold temperatures of -5 to 5°C (blue-green) in the 600-800 mb layer, indicating a trapped lee wave with perpendicular phase lines. The temperature amplitude of 5 - 10°C per 0.05° longitude, with trapping by inversion, produces potential turbulence shear in the transition zone. Warm temperatures of 20 - 30°C in the downstream trough reflect an adiabatic downdraft, consistent with w -1 m/s (from vertical velocity visualization). Ri 5.52 - 10.0 indicates dynamic stability, but low shear allows for oscillations without significant breaking. Figure 5 (b) at 12:00 UTC shows a weakening temperature pattern with dominant trapping, horizontal temperatures of 0 - 15°C on the lee side, indicating dissipation of trapped nocturnal lee waves, with warm temperatures of 25°C in the southern trough reflecting downslope wind deceleration. Ri 6.72 - 9.94 is approaching critical, increasing shear and dynamic turbulence. The overall characteristics reflect a tropical diurnal cycle: trapped morning-night lee waves (horizontal lee temperatures, trapping inversion), vertical propagating daytime (vertical slant temperatures, crest oscillations).

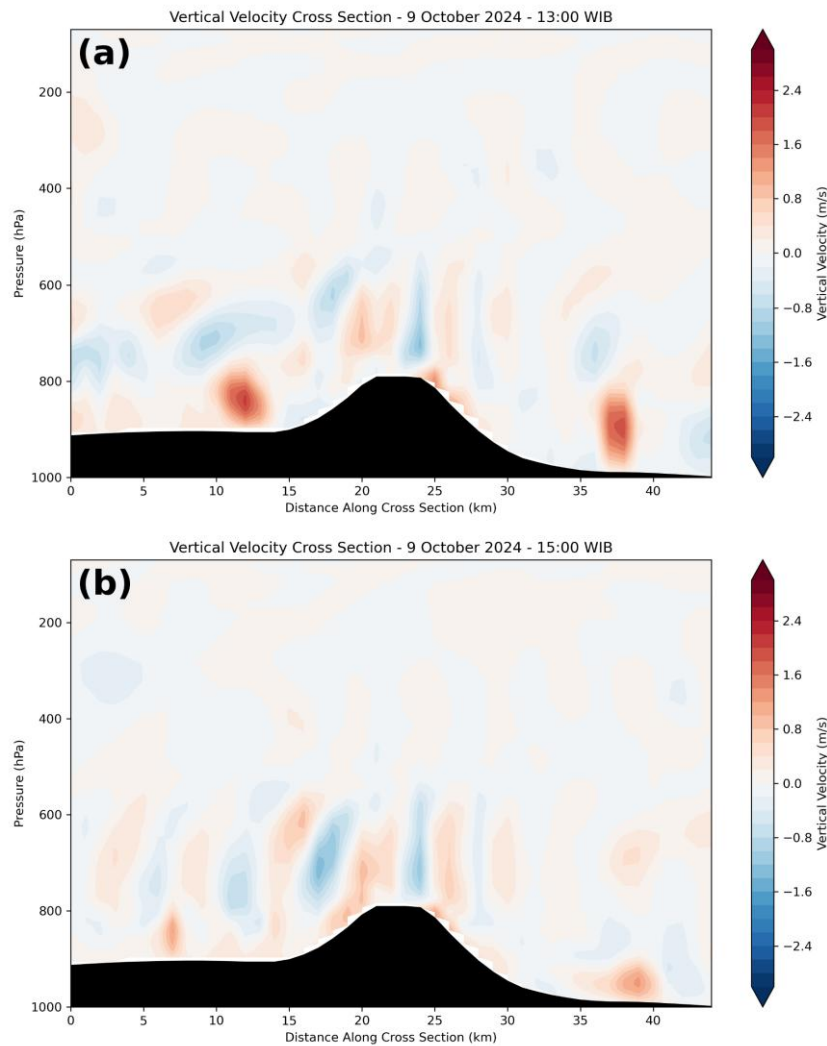


Figure 6. Vertical Air Velocity of WRF-CTL to Determine Downslope Windstorm Patterns on October 9: (a) 06.00 UTC moderate oscillations and deep flow depth and (b) 08.00 UTC downslope intensification and hydraulic jump

The image above shows Figure 6 (a) at 06:00 UTC, the vertical velocity pattern shows moderate oscillations above the mountain peaks, with a dominant updraft (1.6 m/s) on the windward side (10-20 km distance) and a strong downdraft (-2.0 m/s) on the lee side (25-35 km distance). The deep flow depth (>1 km, up to 400 mb) indicates a deep cross-mountain flow. A hydraulic jump is visible at a distance of 30 km. Figure 6 (b) vertical velocity pattern shows downslope intensification, with a wider downdraft (w -2.0 to -2.4 m/s) extending to a distance of 30-35 km at the 800-1000 mb layer, while the updraft upstream weakens (w +0.4 m/s). This reflects the peak of the downslope deep cross-mountain flow, with the hydraulic jump shifting downstream (30 km), followed by weak oscillations above (600-800 mb layer).

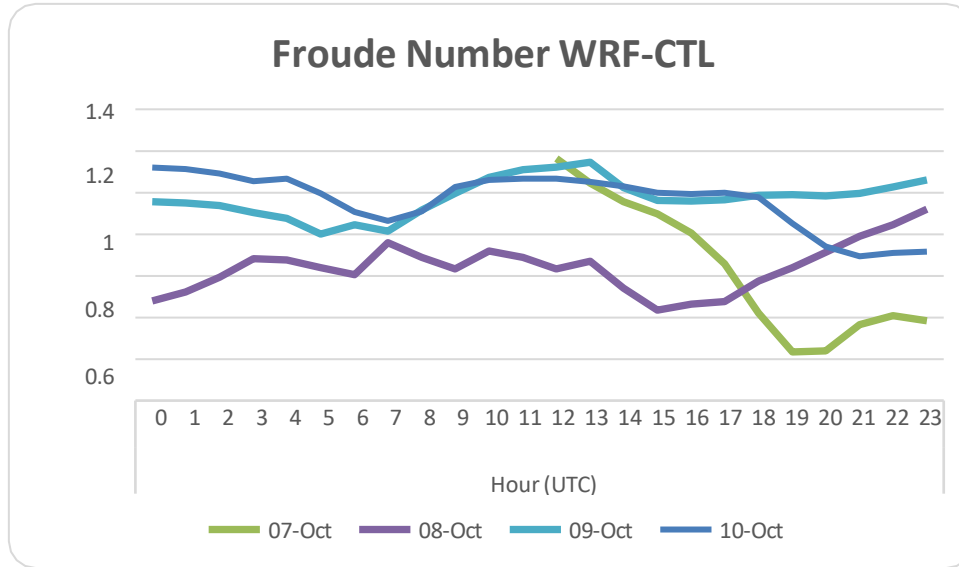


Figure 7. Time series Froude number (s^{-2}) WRF-CTL

The Froude number (Fr) time series graph illustrates Fr fluctuations over time (0-23 UTC, horizontal axis) at the 700-800 mb layer, with Fr values ranging from 0 to 1.4. On October 7 (red curve), the Fr value started at 1.0 at 0 UTC, dropped sharply to 0.8 at 3-5 UTC, then fluctuated moderately (0.6-1.0) until 15 UTC, and fell below 0.4 at 18-23 UTC. This pattern indicates a shallow cross-mountain flow type downslope windstorm, in which a stable cold flow (N^2 0:000025 s^{-2}) is shallowly dissipated (<1 km depth) due to a strong temperature inversion in the lower layer, without significant breaking waves. The downslope onset occurred when $Fr > 1$ (at 0-3 UTC), with a duration of 3-4 hours, followed by dissipation due to $Fr < 1$ (subcritical). The October 8 curve (gray) shows higher fluctuations, starting at 0.8 at 0 UTC, rising to 1.2 at 8-10 UTC, then decreasing to 0.4 at 20-23 UTC. This reflects a shallow cross-mountain flow type downslope with stronger intensity, where a supercritical transition ($Fr > 1$ at 8-12 UTC) causes a sharp hydraulic jump. Onset at 8 UTC, duration 4-5 hours. On October 9 (yellow), Fr was stable at 0.9-1.2 at 0-15 UTC, then decreased to 0.4 at 18-23 UTC. This pattern indicates a downslope shallow with peak intensity (maximum Fr of 1.2 at 10 UTC), onset at 0 UTC, duration 15 hours. October 10 (blue) shows Fr 0.8-1.0 at 0-10 UTC, rising to 1.2 at 12 UTC, then fluctuating between 0.6-0.8 until the end of the day. This reflects a downslope shallow with onset at 0 UTC, duration of 10 hours, and moderate turbulence (Ri 0.3). Repeated analysis confirms consistency: a downslope shallow is dominant at the end of the period.

WRF-DA

Table 2 WRF-DA data on October 9 shows Brunt-Väisälä frequency values (N : 0.111-0.131 s^{-1}), N^2 (0.012-0.017), and Ri : 6.88-10:00, reflecting mountain wave dynamics. Strong static stability ($N^2 > 0$) supports parcel oscillations, except for a nighttime decrease (Ri 6.88-8.09) indicating dynamic turbulence. From early morning to morning, N increases, Ri 10:00, facilitating trapped lee waves with the potential for lenticular clouds and low RH in the trough. Daytime N is stable and Ri 10:00, supporting vertically propagating waves. Nighttime N rises from 0.122-0.127 s^{-1} followed by N^2 0.015-0.016 but Ri decreases (6.88-8.09).

Tabel 2. Value Parameter of WRF-DA on 9 October

Hour (UTC)	Brunt Vaisala Frequency (s^{-2})	N^2	Richardson Number
0	0.127186207	0.016176331	10.00
1	0.130048292	0.016912558	10.00
2	0.131210036	0.017216074	10.00
3	0.12981687	0.01685242	10.00
4	0.128269255	0.016453002	10.00
5	0.12784224	0.016343638	10.00
6	0.128530791	0.016520164	10.00
7	0.123016243	0.015132996	10.00
8	0.11110346	0.012343979	10.00
9	0.11422009	0.013046229	10.00
10	0.11612387	0.013484753	10.00
11	0.113390697	0.01285745	10.00
12	0.116746114	0.013629655	10.00
13	0.117076937	0.013707009	10.00
14	0.116405202	0.013550171	10.00
15	0.116479212	0.013567407	10.00
16	0.116890264	0.013663334	10.00
17	0.117692073	0.013851424	10.00
18	0.121086466	0.014661932	10.00
19	0.122687895	0.01505232	10.00
20	0.121834597	0.014843669	10.00
21	0.124497146	0.015499539	10.00
22	0.124316564	0.015454608	8.09
23	0.127051708	0.016142136	6.88

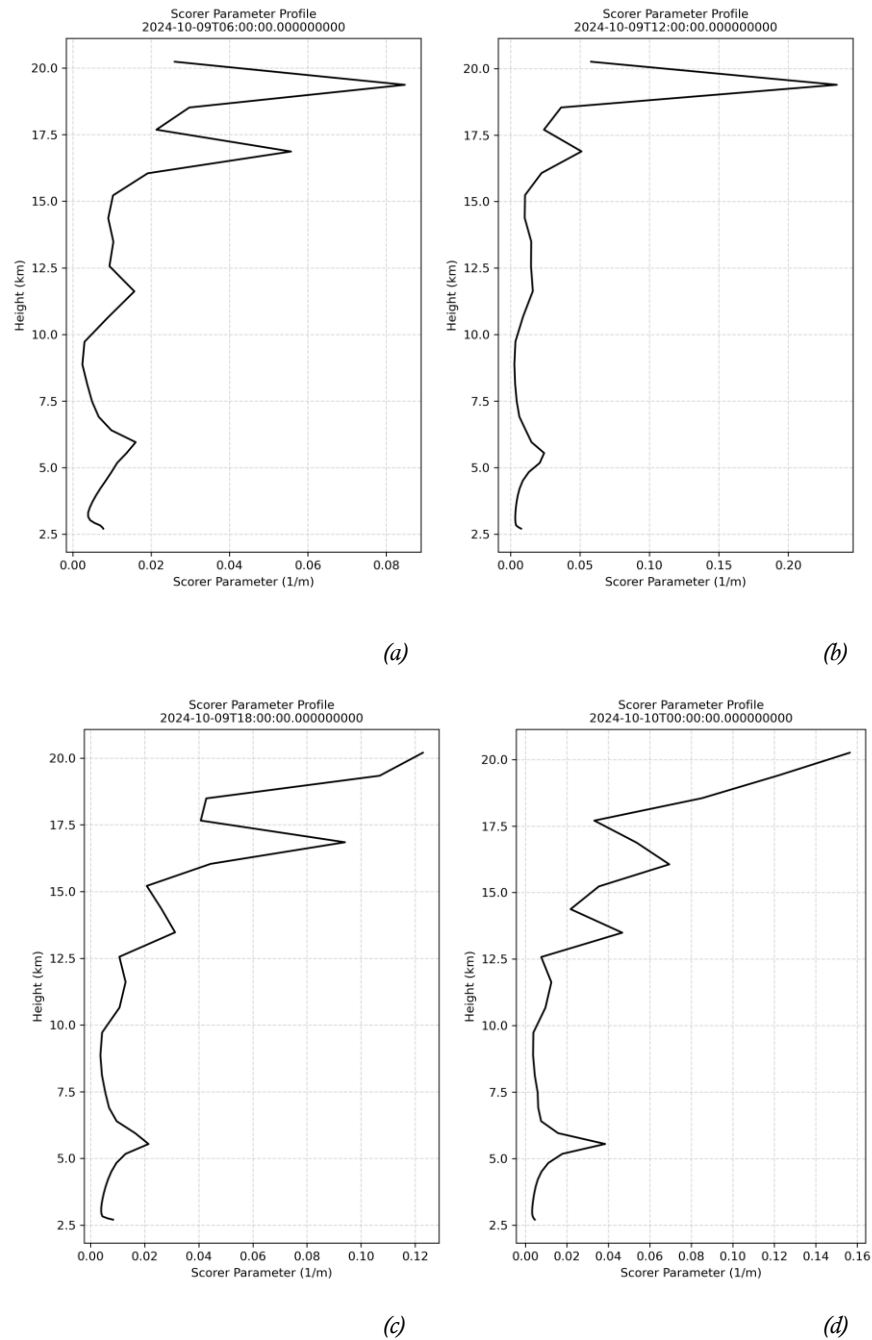


Figure 8. Vertical Profile of Scorer WRF-DA Parameters on 9 October: (a) morning profile: Shows high l^2 values (0.15-0.20 1/m) at 10-18 km, supporting trapped lee waves and for (b), (c), (d) afternoon/evening Profiles: shows increased oscillations and a transition toward vertically propagating waves as Ri decreases

Morning shows high l^2 values (0.15-0.20 1/m at 10-18 km), significant decrease below, supporting trapped lee waves with potential lenticular clouds; Ri 10:00, strong stability. Afternoon-evening shows increased oscillations (5-6 cycles), maximum l^2 0.20 1/m (15-18 km), insignificant decrease, transition to vertically propagating waves; Ri decreases (6.88-8.09), shear increases, hybrid breaking potential.

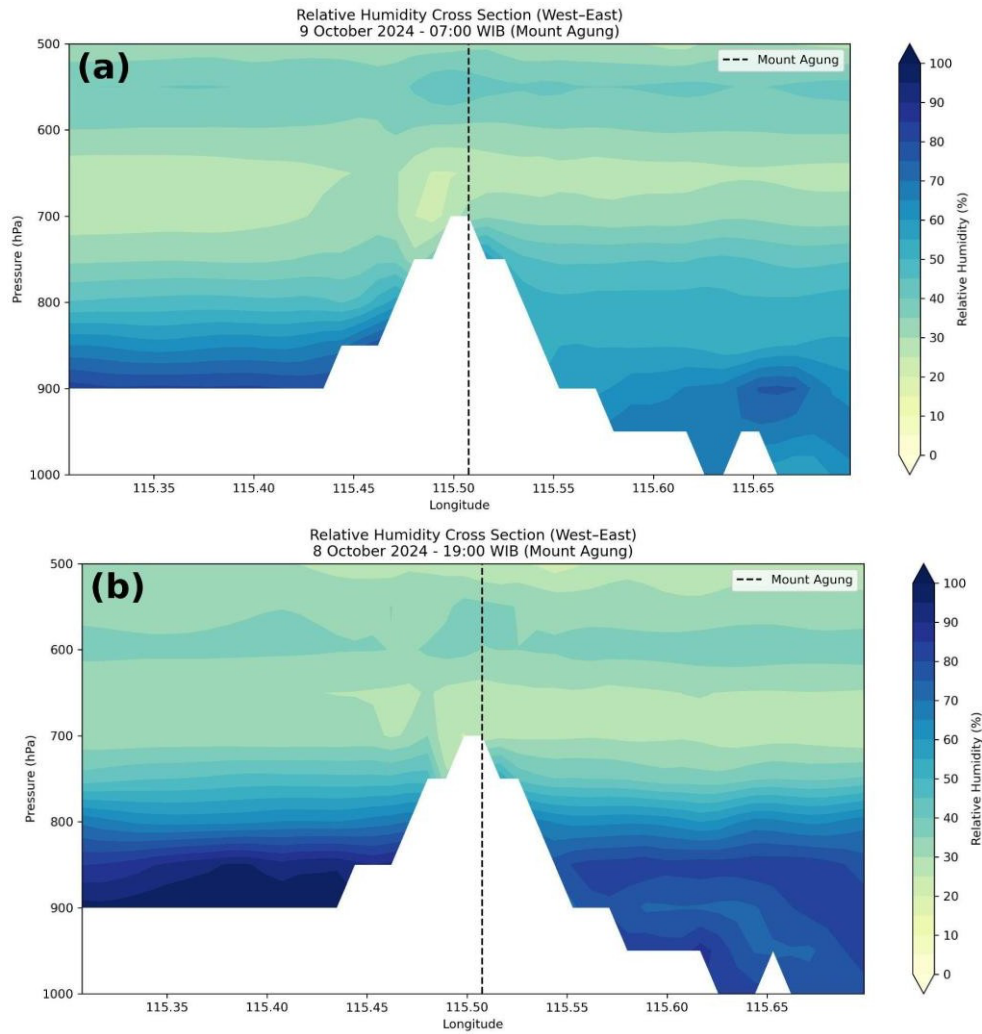


Figure 9. Distribution of WRF-DA Relative Humidity on October 9:
 (a) 00.00 UTC high RH on the lee side, confirming more defined trapped lee waves compared to WRF-CTL and (b) 12.00 UTC nocturnal dissipation with horizontal trapping still evident

Figure 9 shows the diurnal pattern of tropical mountain waves. Figure 9 (a) at 00:00 UTC shows high relative humidity (80-100% at 600-800 mb) on the lee side, indicating trapped lee waves. Low RH (30-40%) in the trough. Figure 9 (b) at 12:00 UTC shows dominant trapping again (RH 60-90% horizontal lee), nocturnal dissipation, RH trough 20-40%.

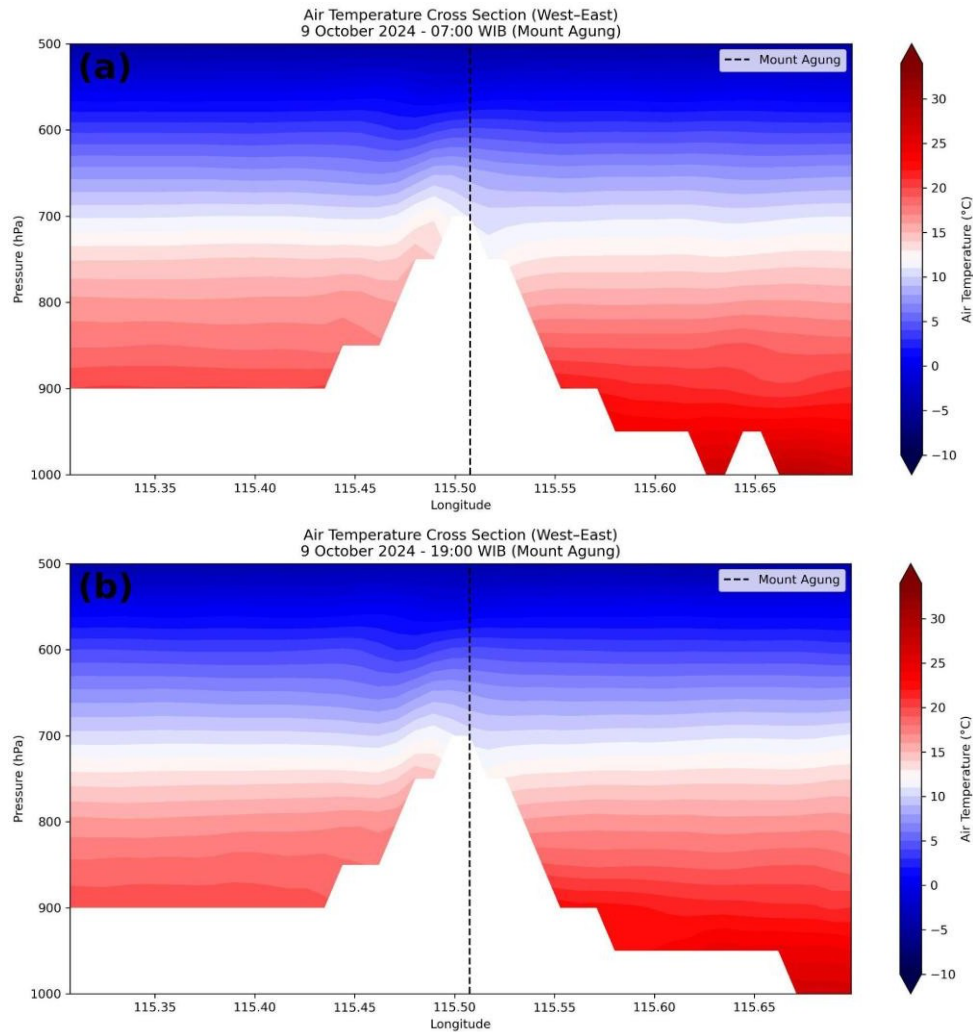


Figure 10. Distribution of WRF-DA Air Temperature on 9 October: (a) 00.00 UTC high temperatures on the lee side indicating adiabatic warming from downslope winds and (b) 12.00 increased shear and nocturnal wave dissipation

Figure 10 shows in Figure 4.25 (a) at 00:00 UTC that the temperature is quite high (20-30°C) on the lee side at 600-800 mb, indicating trapped lee waves with adiabatic warming; low temperatures (-10°C) in the trough (cooling updraft, inversion at 500 mb). Figure 10 (b) at 12:00 UTC shows dominant trapping again (temperature 15-25°C horizontal lee), nocturnal dissipation, trough temperature -5°C, increased shear (Ri 6.72-9.94).

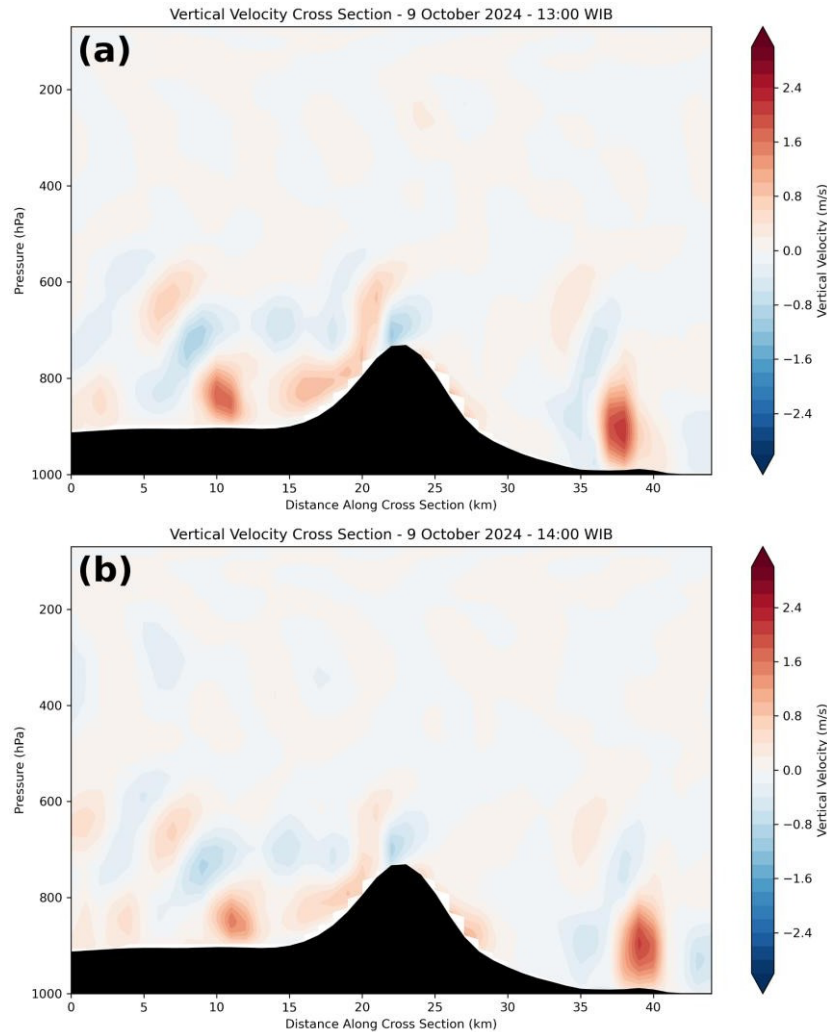


Figure 11. Vertical Air Velocity WRF-DA to Determine Downslope Windstorm Patterns on October 9: (a) 13:00 WIB (06.00 UTC) dominant downdraft on the lee side and (b) 14:00 WIB (07.00 UTC) peak shallow cross-mountain flow

Figure 11 (a) vertical velocity distribution shows a dominant downdraft on the lee side with w -1.6 to -2.0 m/s at the 800-1000 mb layer, followed by an updraft w +0.8 m/s at a distance of <15 km. This pattern indicates a downslope windstorm of the shallow cross-mountain flow type, with a shallow flow depth (<1 km) and a sharp hydraulic jump at a distance of 25-30 km, supporting wind acceleration of 10-12 m/s. Then Figure 11 (b) shows an intensified downslope pattern, with a wider downdraft (w -1.8 to -2.2 m/s) extending to a distance of 30 km at the 800-1000 mb layer, and a weak updraft. This reflects the peak of the shallow cross-mountain flow, with the hydraulic jump shifting downstream (30 km).

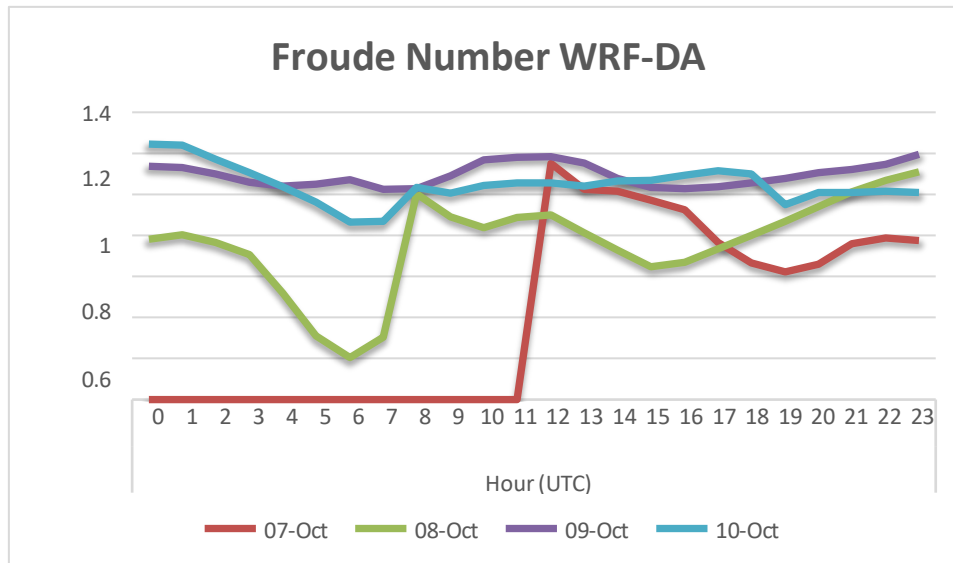


Figure 12. Time series Froude number (s^{-2}) WRF-DA

The time series graph of the Froude number 4.33 focuses on the onset, intensity, and classification of downslope where the threshold $Fr > 1$ indicates supercritical flow that triggers downslope windstorms through hydraulic transition, while $Fr < 1$ indicates subcritical flow and dissipation. On October 7 (red curve), Fr started low (0.5 at 0 UTC), rose to 1.5 at 5 UTC, then fluctuated between 1.0 and 2.0 until 15 UTC, and decreased to 0.5 between 20 and 23 UTC. This pattern indicates the onset of a downslope windstorm when $Fr > 1$ (at 5-15 UTC), with a duration of 10 hours and a classification of shallow cross-mountain flow, where stable cold flow is shallowly dissipated (< 1 km) due to strong temperature inversion. Moderate turbulence is seen from the fluctuations in Fr , with slow dissipation at night. The October 8 curve (gray) shows Fr 1.0 at 0 UTC, rising to 2.0 at 8 UTC, then decreasing to 0.5 at 18-23 UTC. This reflects a stronger downslope shallow, onset at 0-8 UTC (duration 8 hours), and a sharp hydraulic jump during the Fr peak. The subcritical to supercritical transition supports wind acceleration in the lee, consistent with N^2 0.0162 s^{-2} from the table for strong stability. On October 9 (yellow), Fr was stable at 1.5-3.0 from 0-12 UTC, then dropped to 0.5 from 18-23 UTC. This pattern confirms a long-duration (12 hours) downslope shallow, with peak intensity from 6-10 UTC and moderate dynamic turbulence from low Ri. October 10 (blue) shows Fr 3.0 at 00 UTC, rising to 4.5 at 10 UTC, then fluctuating between 3.0 and 4.0 until the end of the day. This indicates an intense shallow downslope, with an early onset (duration > 20 hours) and dominant supercritical flow.

CONSLUSION

Radar data assimilation using the 3DVAR method in WRF-DA successfully improved the identification of downslope windstorms on Mount Agung during the period of October 8-10, 2024, with a dominant shallow cross-mountain flow classification (depth 1 with a duration of 7-18 hours, shallow hydraulic jump on the lee side, and trapped oscillations (length 18-25 km) that were more accurate than WRF-CTL. This shows that WRF-DA is effective for tropical simulations despite topographical limitations, supported by stable atmospheric dynamics with a majority of Brunt-Väisälä $N^2 > 0$ and Richardson Number $Ri > 0.25$ values supporting the formation of downslope windstorm oscillations. The type of mountain wave obtained is a vertical propagating wave that dominates during the day and a trapped lee wave at night, while a downslope windstorm with shallow cross mountain flow dominates during the day and deep cross mountain flow at night.

DECLARATION OF GENERATIVE AI

The authors declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

CONFLICTING INTEREST STATEMENT

The authors states that there is no conflict of interest in the publication of this article.

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