

## Response to Referee #3

We sincerely thank the editor and all reviewers for your time and the constructive comments on our manuscript. We have carefully considered all the comments and suggestions. Below is our point-by-point response detailing how we have addressed each issue in the revised manuscript. In the following, paragraphs in **black** are reviewers' comments; paragraphs in **blue** are point-to-point responses; paragraphs in **red** are revisions in the manuscript.

### General Comments:

This is an interesting paper that employs interpretable machine-learning techniques to investigate the key controlling factors, dynamic thresholds, and synoptic patterns of foehn winds on the eastern foothills of the Taihang Mountains in China. The authors have conducted a lot of analysis and synoptic analysis, which are good for elaborating the main arguments. Overall, the paper employs novel methods, presents solid analysis, and draws clear conclusions.

**Response:** We greatly appreciate the reviewer's comment on the novelty of our research.

### Specific Comments:

**Comment 1:** Line 139: This study explicitly used the potential temperature difference ( $\Delta\theta > 2\text{K}$ ) as one of the defining criteria for foehn events in Table 1. However, in the subsequent machine learning modeling (Table 2), the 28 predictor variables used for training and interpreting the model did not include any variables related to potential temperature (such as  $\theta_{\text{Wind}}$ ,  $\theta_{\text{Lee}}$ , or  $\Delta\theta$ ). This needs clarification.

**Response:** This is a really good question. We have our explanations below.

Potential temperature  $\theta$  is calculated from temperature  $T$  and pressure  $P$  ( $\theta = T(\frac{1000}{P})^{0.286}$ ).

This equation shows that the combined changes in  $T$  and  $P$  lead to changes in  $\theta$ —that is,  $T$  and  $P$  are the causes, while  $\theta$  is the result. Therefore, we prefer using  $\theta$ , a variable that reflects the outcome to distinguish whether foehn occurs. In the subsequent machine learning modeling, we actually

consider  $\theta$  as a predictor in the 28 predictor variables in our earlier work, however, the model did not perform well. Therefore, we did not include  $\theta$  in the model.

**Comment 2:** Line 192-194: There remains a gap between the statistical association and the physical causation. To bridge this, it is recommended to: (a) Whether the Fr (Froude) number is directly calculated from observational data and indeed falls within this specific range during foehn wind events. (b) Why the Fr between 0.8 and 1.2 is conducive to the foehn development? There seems still some physical process gap between your proofs and current conclusions.

**Response:** Thank you for your question. We had our explanations as below.

Based on the classical theory (Prósper et al., 2019; Wiesner et al., 2024), the mountain Froude number (Fr) is defined by this formula:

$$Fr = \frac{u}{Nh}$$

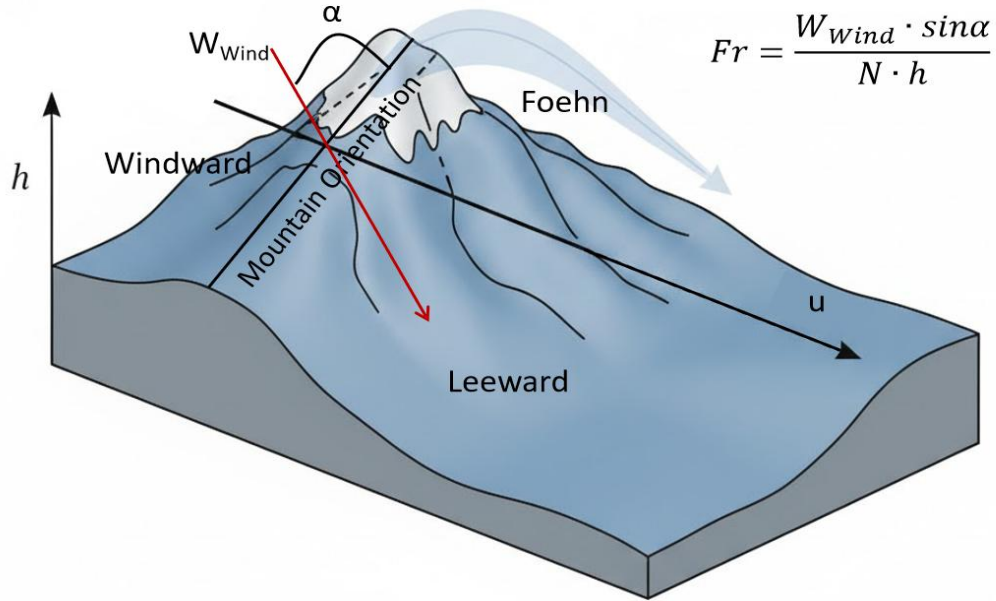
Where  $u$  is the velocity of the flow normal to the topographic barrier,  $N$  is the Brunt Väisälä frequency, and  $h$  is the height of the topographic barrier. The Brunt Väisälä frequency, which also represents the static stability, was calculated by:

$$N = \sqrt{\frac{g}{\theta} \frac{\partial \theta}{\partial z}}$$

Considering  $u$  is the velocity of the flow normal to the topographic barrier and Fr describes the air flowing over a mountain, we can use  $W_{Wind}$  and the angle ( $\alpha$ ) between  $W_{Wind}$  and the mountain orientation to represent Fr.

$$Fr = \frac{W_{Wind} \cdot \sin\alpha}{N \cdot h}$$

Taiyuan and Shijiazhuang lie at almost the same latitude. When the influence of small-scale terrain on wind direction is neglected, the wind directions on the windward and leeward slopes are consistent. Therefore, the above formula can be easily understood by the following new added Figure S8.



**Figure S8: Schematic diagram illustrating the Froude number in relation to wind direction when the influence of small-scale terrain on wind direction is neglected.  $Fr$  is the Froude number;  $u$  is the velocity of the flow normal to the topographic barrier;  $N$  is the Brunt Väisälä frequency;  $h$  is the height of the topographic barrier; and  $\alpha$  is the angle between  $W_{Wind}$  and the mountain orientation.**

According to the classical theory, there are significant nonlinear effects and blocking when  $Fr \ll 1$ , whereas for  $Fr \gg 1$ , the opposite occurs (Smolarkiewicz & Rotunno, 1989, 1990).  $Fr$  around 1 indicates a transitional regime between the two states and favorable conditions for the formation of downslope lee windstorms and hydraulic jumps (Prósper et al., 2019; Wiesner et al., 2024). Therefore, wind direction can be calculated or verified by aiming  $Fr (\approx 1)$ , in which the airstream will descend the leeward slope smoothly while converting potential energy into kinetic energy, and this process accelerates wind speed and enhances adiabatic warming via isentropic drawdown, which are two key characteristics of foehn.

Here is the specific calculating process which will better answer your questions (a) and (b):

First, we verified the most conducive wind direction by aiming  $Fr$ :

$$Fr = \frac{W_{Wind} \cdot \sin\alpha}{N \cdot h} = 1$$

$W_{Wind} = 3$  m/s according to SHAP analysis;  $\alpha$  is the aiming unknown quantity;  $N$  is usually

0.01–0.03s<sup>-1</sup>, here we calculated  $N = 0.01\text{s}^{-1}$  according to the results in Figure 5h;  $h$  = the difference between the minimum mountain height (between the two stations) and the altitude of the pre-mountain weather station, approximately 200 m. And the answer  $\alpha$  is equal to 41.81°, which is really close the most conducive angle (90°-52°=38°) to the foehn development in line 226.

Then we can calculate the favorable Fr range by the conducive wind direction (237°-294°, which means  $\alpha = 33^\circ\text{-}90^\circ$ ) given by SHAP method in the “Section 3.1”. And the answer Fr is equal to 0.82-1.5 (Thank you for your question, we calculated again and revise the 0.8-1.2 by this more precise consequence), which is conducive to the foehn development.

It is worth noting that this conclusion cannot be provided by traditional theoretical research. Following your suggestion, we have added more explanation and revised the relevant section to fix this gap in the revised manuscript as follows.

**The “Section 3.1”, Pages 10, lines 228-246:**

“This wind-direction-dependent foehn formation mechanism is fundamentally supported by the Froude number (Fr) dynamics and terrain-airflow coupling effects, consistent with the principles of trans-barrier flow and orographic modification documented in foehn research (Durran, 1990). Froude number, defined as  $Fr = \frac{u}{N h}$ , (where  $u$  is the flow velocity normal to the topographic barrier,  $N$  is the Brunt-Väisälä frequency, and  $h$  is the height of the topographic barrier), quantifies the balance between inertial forces and buoyancy restoring forces, thereby determining the flow behavior when encountering topographic obstacles (Prósper et al., 2019; Wiesner et al., 2024). When  $Fr \ll 1$  there are significant nonlinear effects and blocking, whereas for  $Fr \gg 1$  the opposite occurs (Smolarkiewicz & Rotunno, 1989, 1990). The Fr around 1 indicates a transitional regime between the two states and favorable conditions for the formation of downslope lee windstorms and hydraulic jumps (Prósper et al., 2019; Wiesner et al., 2024). Within this range, the airflow neither fully circumvents the range ( $Fr \gg 1$ ) nor is completely blocked ( $Fr \ll 1$ ), thereby sustaining a persistent downslope warming that favors foehn occurrence. Considering the  $u$  is the velocity of the flow normal to the topographic barrier, wind direction can be calculated or verified by aiming Fr ( $\approx 1$ ) (Figure S8). Calculations show that the  $\alpha$  (the angle between  $W_{Wind}$  and the mountain orientation) is equal to 41.81° and the wind direction is equal to 278.81°, which is really close the most conducive wind direction (275°) to

the foehn development given by our SHAP method. Based on the obtained favorable wind direction ( $237^{\circ}$ - $294^{\circ}$ , which means  $\alpha = 33^{\circ}$ - $90^{\circ}$ ) identified in the SHAP model, the favorable Fr range is calculated as 0.82 to 1.5 for the formation of foehn on the eastern foothills of the Taihang Mountains. This finding not only agrees with classical theory but also extends it to a specific range for the first time, thereby enriching the global understanding of foehn dynamics. Such a result cannot be obtained from traditional theoretical studies.”

### **New added references**

- Durrán, D. R. (1990). Mountain Waves and Downslope Winds. In *Atmospheric Processes over Complex Terrain* (pp. 59-81). American Meteorological Society. [https://doi.org/10.1007/978-1-935704-25-6\\_4](https://doi.org/10.1007/978-1-935704-25-6_4)
- Prósper, M. A., Sosa Tinoco, I., Otero-Casal, C., & Miguez-Macho, G. (2019). Downslope windstorms in the Isthmus of Tehuantepec during Tehuantepecer events: a numerical study with WRF high-resolution simulations. *Earth System Dynamics*, 10(3), 485-499. <https://doi.org/10.5194/esd-10-485-2019>
- Smolarkiewicz, P. K., & Rotunno, R. (1989). Low Froude Number Flow Past Three-Dimensional Obstacles. Part I: Baroclinically Generated Lee Vortices. *Journal of Atmospheric Sciences*, 46(8), 1154-1164. [https://doi.org/https://doi.org/10.1175/1520-0469\(1989\)046<1154:LFNFPT>2.0.CO;2](https://doi.org/https://doi.org/10.1175/1520-0469(1989)046<1154:LFNFPT>2.0.CO;2)
- Smolarkiewicz, P. K., & Rotunno, R. (1990). Low Froude Number Flow Past Three-Dimensional Obstacles. Part II: Upwind Flow Reversal Zone. *Journal of Atmospheric Sciences*, 47(12), 1498-1511. [https://doi.org/https://doi.org/10.1175/1520-0469\(1990\)047<1498:LFNFPT>2.0.CO;2](https://doi.org/https://doi.org/10.1175/1520-0469(1990)047<1498:LFNFPT>2.0.CO;2)
- Wiesner, L., McGowan, H., Sturman, A., & Dale, T. (2024). Subtropical Foehn Winds, Southeast Queensland, Australia. *Journal of Geophysical Research: Atmospheres*, 129(13), e2023JD040410. <https://doi.org/https://doi.org/10.1029/2023JD040410>

**Comment 3:** Line 290: Please add a brief explanation in the discussion (or other appropriate place) to more explicitly link the stable stratification with the physical mechanism of foehn occurrence.

**Response:** Thank you for your constructive suggestion. We have added more explanations in the discussion, highlighted in red in the following paragraph:

### **The “Section 3.3”, Pages 16, lines 328-344:**

“Figures 5g, h reveal the atmospheric stratification stability through vertical potential-temperature ( $\theta$ ) profiles. The foehn events exhibit lower  $\theta$  than the climatological mean between 700 and 300 hPa, with the largest deficit near 450 hPa on the leeward side (Figure 5h). This result shows that the presence of a mid-tropospheric cold air mass positively contributes to the foehn

formation. Compared with climatology, the leeward side exhibits lower  $\theta$  above 650 hPa, whereas the windward side shows a markedly lower  $\theta$  within the 850–700 hPa lower troposphere (Figure 5g). It indicates that a pattern, which is colder in lower troposphere on the windward side and colder in upper layer on the leeward side, provides a stable atmospheric environment highly conducive to foehn events. In fact, both the windward and leeward sides are within a stably stratified environment ( $\theta$  increases with height) overall (Figure 5h). Previous results showed that the stable stratification inhibits vertical mixing of the lower tropospheric airflow, leading to blocking of the cold air in the lower windward layer, while the warmer and drier air in the upper layer flows over the mountain and sinks along isentropic surfaces on the leeside (i.e., isentropic drawdown mechanism (Elvidge & Renfrew, 2016; Wiesner et al., 2024)). Also, the stable stratification provides favorable dynamic conditions for the development of mountain waves and hydraulic jumps (Wiesner et al., 2024), which further accelerate the sinking of leeward airflow and enhance the foehn effects of temperature increase and humidity decrease. The large-scale environmental conditions we identified in Figure 5e, f further reveal the synoptic patterns responsible for the formation of stable stratification during foehn events in the Taihang Mountains, linking large-scale synoptic conditions with local foehn formation mechanisms and deepening the systematic understanding of foehn development.”

### New added references

- Elvidge, A. D., & Renfrew, I. A. (2016). The Causes of Foehn Warming in the Lee of Mountains. *Bulletin of the American Meteorological Society*, 97(3), 455-466. <https://doi.org/https://doi.org/10.1175/BAMS-D-14-00194.1>
- Wiesner, L., McGowan, H., Sturman, A., & Dale, T. (2024). Subtropical Foehn Winds, Southeast Queensland, Australia. *Journal of Geophysical Research: Atmospheres*, 129(13), e2023JD040410. <https://doi.org/https://doi.org/10.1029/2023JD040410>

**Comment 4:** Line 315: It is suggested that the outlook section propose the future development of a regression model to predict specific foehn intensity metrics (such as wind speed or warming magnitude), and to again utilize the SHAP method to reveal its influencing factors. This would represent a natural and valuable deepening of the current classification-based research.

**Response:** Thank you for your constructive suggestion. This is a really good point, enabling the classification-based research extending and deepening. We added this revision in the Discussion and Conclusion Session as follows:

**The “Discussion and Conclusion section”, Pages 19, lines 417-420:**

“Furthermore, our future research will further develop a regression model to predict specific foehn intensity metrics (e.g., foehn wind speed and warming magnitude), and apply the interpretable method to quantify and reveal the key influencing factors governing these intensity indicators. These will serve as a useful reference for understanding foehn winds in other regions of the world.”