Numerical simulation study of the effects of foehn winds on white head incidences in Yamagata Prefecture, Japan

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Abstract
Numerous studies have elucidated that white heads and chalky rice are caused by hot, dry and strong winds at night. However, these studies have only used synoptic weather charts and near-surface observation data to confirm the role of foehn in white head occurrences. This study used a high-resolution three-dimensional numerical weather prediction model to show that strong foehn effects induced a significant number of white heads in rice in Yamagata Prefecture, Japan. The model accurately predicted and represented the location and timing of the observed white heads, occurring only in a limited area (<87.1 ha) on the southwest side of Mt. Chokai during the nighttime. Specifically, the simulated nocturnal $F_{TP}$ (transpiration forcing) continuously exceeded 30 at that location. This high $F_{TP}$ was caused by high temperature (>24°C), strong wind speed (>8 m s$^{-1}$) and low humidity (<65%) caused by the strong foehn winds descending over the southwest slope of the mountain. In the other areas, $F_{TP}$ did not exceed 30 because either wind speed, water vapour deficit or both were insufficiently high.

KEYWORDS
dynamical foehn, forecast experiment, rice, white head damage, WRF model

1 INTRODUCTION

White heads are white and sterile panicles found in rice plants (Figure 1; Kimura, 1950). White heads are observed throughout Japan, resulting in a reduction in rice yield and quality. Preventing white heads is a significant requirement for the Japanese agriculture industry because rice is a staple Japanese food.

It is well known that white heads and chalky rice are caused by nighttime hot, dry and strong winds (Hatakeyama et al., 2018; Muramatsu, 1976, 1982; Muramatsu & Kamota, 1981; Tashiro et al., 1980; Wada et al., 2011; Wada et al., 2014; Xi et al., 2014). In particular, white heads occur when rice plants are exposed to these winds within approximately 1 week after the heading date. As the index of white head risk, $F_{TP}$ (transpiration forcing; Kimura, 1950) is widely used. $F_{TP}$ expresses the strength of transpiration forced by hot, dry and strong winds and is represented by Equation (1).

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here, \( e_s \), \( e \) and \( U \) represent the saturated water vapour pressure (hPa), water vapour pressure (hPa) and ground wind velocity (m s\(^{-1}\)), respectively. High \( F_{TP} \) during the daytime does not increase the occurrence risk of white heads; however, the occurrence risk is increased if \( F_{TP} \) continues to be high at night (Kimura, 1951; Muramatsu, 1976). This is because the physiological activity of rice is inactive at night. Muramatsu (1976) conducted wind tunnel experiments and revealed that white heads tended to occur in the Hokuriku region when \( F_{TP} \) exceeded 30 for several hours during the night.

Generally, foehns are hot, dry and strong winds. Thus, nighttime foehn tends to increase \( F_{TP} \) and the occurrence risk of white head incidents. However, not all foehns cause white heads because the intensity and timing of foehn must satisfy the criteria of causing the white head incident, for example, the nocturnal \( F_{TP} \) must be >30.

Foehn has been observed worldwide, including the European Alps (Hoinka, 1985; Mayr et al., 2007; Seibert, 1990; Würsch & Sprenger, 2015), the Rocky Mountains (Baren, 1967; Durran, 1986; Klemp & Lilly, 1975), Antarctica (Elvidge et al., 2015; Elvidge et al., 2016; Elvidge & Renfrew, 2016), the Andes (Norte, 2015; Puliafito et al., 2015; Seluchi et al., 2003) and the South Island of New Zealand (McGowan et al., 2002; McGowan & Sturman, 1996). In the Hokuriku region of Japan, foehn is observed when cyclones or typhoons pass the Sea of Japan (Arakawa et al., 1982; Koyanagi & Kusaka, 2020; Kusaka et al., 2021; Nishi et al., 2019). Severe white heads were observed only on the southwest side of Mt. Chokai, Yamagata Prefecture, during the early hours of 7 August, 2018 (Figures 2 and 3; Yamagata Shimbun 10 August, 2018). The heading date for the area was from the end of July to the beginning of August. Only 87.1 ha of rice paddies demonstrated severe white head growth, with the ratio of damaged areas exceeding 5% (Figure 3). This ratio exceeded 30% for certain rice paddies. Even in such localized white heads, the loss of income per farmer can be considerable. As the white head appearance was observed in the early hours of the following day, farmers assumed that the foehn blew in the white head area at night (Yamagata Shimbun 10 August, 2018). Indeed, the surface weather chart was a favourable type for blowing foehn (Figure 4a). However, there was insufficient evidence to conclude that foehn effects caused white heads. This is because there were
no meteorological observatories in the white head area. We speculated why the white heads occurred locally only in the damaged area if the foehn was blowing. Thus, three hypotheses were considered. The first is that the foehn only blew over a small area. The second is that the foehn was blowing over a wide area, however, was only strong enough to exceed the $F_{TP}$ criteria in a small area. The third is that the strong foehn effect area changed with time, for example, the strong foehn blew over the white head area at night and non-white-head area during the daytime.

The local characteristics of the foehn, derived from $F_{TP}$, were required to reveal the cause of the localized white heads and to predict their occurrence. In order to obtain the local characteristics, it was necessary to reproduce and predict the three-dimensional atmosphere during a white head incident with high spatial and temporal resolution. NWP models can reproduce and predict three-dimensional atmospheres, even in areas with poor observation data. The NWP model has been used in agrometeorological fields because of these advantages (e.g., Li et al., 2016; Minda et al., 2018; Partridge et al., 2021; Sridhar & Anderson, 2017). For example, Minda et al. (2018) used the NWP model to determine the effect of climate change with elevation on potato production in the Gamo Highlands, Ethiopia.

The present study had two objectives: (1) to establish that strong foehn effects caused damage to the rice plants and resulted in white heads and to determine why the extent of the effects was narrow and limited. In other words, to identify why the damage did not occur in other areas. This can be achieved by numerically simulating the three-dimensional atmosphere during white head incidents using an NWP model. (2) To verify the predictability of white head occurrence using the NWP model. We investigated how many days in advance the NWP model can predict the occurrence of white heads regionally and temporally.

## 2 | DATA AND METHODS

### 2.1 | Observation

To understand the detailed distribution of the white head area, we obtained the results of a survey conducted by the Japan Agricultural Cooperative (JA) Shonai-Midori. Moreover, we used surface and upper-level observation data to understand the atmospheric conditions: global objective analysis data, surface weather data and upper-level weather data.

For the global objective analysis data, we used the final operational model global tropospheric analysis data provided by the National Center for Environmental Prediction (NCEP-FNL). For the surface weather data, we...
used the data observed at the Automated Meteorological Data Acquisition System (AMeDAS) and Sakata Observatory (3.1 m above sea level [ASL], 38.91N, 139.84E) operated by the Japan Meteorological Agency (JMA). The AMeDAS observation sites used were Sasunabe (88 m ASL, 38.92N, 140.20E), Nikaho (7 m ASL, 39.26N, 139.91E) and Yashima (46 m ASL, 39.24N, 140.14E; Figures 5a,b). For the upper-level weather data, we used radiosonde data observed at the Akita Aerological Observatory operated by the JMA (Figure 2b).

2.2 hindcast experiment using an NWP model

A numerical simulation with an NWP model provided a high-resolution, three-dimensional atmosphere during the occurrence of the white head incident on 7 August, 2018. Furthermore, simulation results revealed whether the strong foehn was blowing and caused white head damage. In addition to the above case, the hindcast experiment was conducted for the two cases that occurred on 13 August, 2000, and 20 August, 2004.

2.2.1 Model descriptions

The Weather Research and Forecasting model (WRF; Skamarock et al., 2008) version 3.9.1.1 was used as the NWP model in this study. The WRF is the most widely used mesoscale meteorological model worldwide. A numerical simulation was conducted for the domains shown in Figure 2a. The first (largest) domain was set to include typhoons in southern Japan and the Okhotsk High, which is north of the Sea of Japan. The horizontal grid spacings of the 1st, 2nd and 3rd domains were 9, 3 and 1 km, respectively. The 3rd (finest) domain was set to resolve the white head area of approximately 25 of square kilometres (Figure 2b). There were 50 vertical layers in all the domains. The thickness of the lowest layer was 59 m. The simulation started at 09:00 Japan Standard Time (JST) on 5 August, 2018 and ended at 21:00 JST on August 7, 2018. Table 1 lists the physical parameterization schemes used in the simulations. We used the Yonsei University scheme (Hong et al., 2006) for the boundary layer, the Unified Noah Land Surface Model (Tewari et al., 2004) for the land surface, the WRF single-moment 6-class scheme

![Image](image-url)
TABLE 1  Physics schemes of the WRF model used for the numerical simulation

| Physics         | Scheme                                      |
|-----------------|---------------------------------------------|
| Boundary layer | Yonsei University (YSU)                     |
| Land surface   | Unified Noah land-surface model (Noah-LSM) |
| Microphysics   | WRF single-moment 6-class (WSM6)            |
| Radiation (longwave) | Rapid Radiative Transfer Model (RRTM)       |
| Radiation (shortwave)  | Dudhia simple radiation                    |

(Hong & Lim, 2006) for the cloud microphysics, the Rapid Radiative Transfer Model scheme (Mlawer et al., 1997) for the long-wave radiation and the Dudhia simple scheme (Dudhia, 1989) for the short-wave radiation. NCEP-FNL data were used to create the initial and lateral boundary conditions of the atmosphere and soil layers. The NCEP real-time global sea surface temperature (RTG-SST) was used to create the initial boundary conditions of the sea surface temperature. The lateral boundary conditions of the atmosphere and sea surface temperatures were updated every 6 and 24 h, respectively.

To better understand the airflows around Mt. Chokai, the present study conducted both back- and forward-trajectory analyses using the WRF simulation. The trajectories were calculated every 3 min after the WRF simulation, using the simulated wind fields. If a trajectory intersects the ground, the trajectory will not be calculated any further.

2.2.2  Evaluating risk of white heads

The WRF reproduced the three-dimensional atmosphere during the white head incident. The simulated atmosphere enabled us to calculate the \( F_{\text{TP}} \) at 2 m above ground level (AGL) from saturated water vapour pressure, water vapour pressure and wind speed. In the Hokuriku region of Japan, the criterion for the occurrence of white heads was that \( F_{\text{TP}} \) was over 30 during the nighttime (Muramatsu, 1976). In the present study, nighttime is from 18:30 JST on 6 August to 04:40 JST on 7 August, 2018, and the time period that meets this criterion will be referred to as the ‘high \( F_{\text{TP}} \) duration’.

3  RESULTS

3.1  Observations

The white head distribution was obtained from a white head survey conducted by JA Shonai-Midori. The white head areas and land-use categories are shown in Figure 3. The white heads occurred in a 5 × 5 km area on the southwest side of Mt. Chokai.

The sea level pressure (SLP) pattern during the white head incident was investigated using NCEP-FNL data. Figure 4a shows the SLP at 21:00 JST on 6 August, 2018. The typhoon was in southern Japan and the Okhotsk High was over northern Japan. The white head area was located in the peripheral regions of this anti-cyclone. An isobaric line was drawn from southeast to northwest in and around the white head area, suggesting that the south-easterly winds blew there. Indeed, south-easterly winds of 12 m s\(^{-1}\) or higher were observed from 486 to 834 m ASL in Akita, 20 km north of the white head area (Figure 4b). If south-easterly winds similar to those above Akita were blowing into Mt. Chokai, foehn could occur in the white head area. According to Kusaka et al. (2021), in the Hokuriku region, foehn caused by a typhoon is common in summer including the heading period.

The surface air temperature and wind around the white head area during the incident were observed by the JMA. The surface air temperature at 1.5 m AGL and wind fields at 10 m AGL at 04:00 JST on 7 August, 2018, are shown in Figure 5a,b, respectively. The wind speed was
7.8 m s\(^{-1}\), and the wind direction was east-southeast at Sakata, indicating that the wind blew from the mountains. The air temperature at Sakata was 22.0, 4.4°C higher than that at Sasunabe. This indicates that the foehn likely blew at Sakata. These results suggest that foehn occurred in the white head area as well, located 10 km north of Sakata. However, it is impossible to prove that strong foehn with more than 30 \(F_{TP}\) occurred and caused the white heads, owing to the lack of meteorological observatories in the area. To overcome this problem, numerical simulations were performed.

### 3.2 Hindcast experiment

First, the reproducibility of the simulation with the WRF model was examined from the perspective of surface wind and temperature fields. Figure 5c,d show the simulated air temperatures at 2 m AGL and winds at 10 m AGL, respectively. The WRF model effectively represented the observed surface air temperatures and winds (Figure 5a–b,c–d). Figure 6 shows the distribution of the simulated high \(F_{TP}\) duration during the white head incident. The model accurately represented the location and timing of the observed white heads (Figures 3 and 6).

The simulation results show that hot, dry and strong winds were blowing in the white head area and caused a substantial high \(F_{TP}\) duration at night (Figures 5c–f and 6). At 04:00 JST on 7 August, 2018 the surface air temperature was >24°C (Figure 5c), wind speeds exceeded 8 m s\(^{-1}\) (Figure 5d), relative humidity was <65% (Figure 5e) and the vapour pressure deficit exceeded 10 hPa (Figure 5f) in the white head area. In the simulation, at early night, the wind speed increased and the...
wind blew from the east (Figure 7b). When the easterly wind began to blow, the air temperature increased, relative humidity decreased (Figure 7a) and the vapour pressure deficit increased (Figure 7c). The hot, dry and strong winds caused high $F_{TP}$, which exceeded 30 at midnight (Figure 7d). The wind continued blowing in the white head area during the night, resulting in a substantial high $F_{TP}$ duration.

To determine whether these hot, dry and strong winds were strong foehn, we conducted a back-trajectory analysis using the simulated results. A total of 25 parcels were released from 120 m ASL over the white head area.
at 04:00 JST on 7 August, 2018. Figure 8a shows the trajectory analysis results. The majority of the trajectories collided with Mt. Chokai from the southeast at approximately 1000 m ASL and descended on the southern and southwestern slopes of the mountain. Figure 8b shows the vertical cross section along the mean trajectory, thereby showing the mean altitude and temperature. The mean trajectory adiabatically descended at 1094 m on the slope. The temperature increased by 11.7°C during the descent, which was predominantly due to adiabatic compression. This temperature increase was similar to that demonstrated by the theoretical value (10.7°C). The theoretical value was calculated using Equation (2).

\[ \Delta \theta_{\text{theo}} = \frac{gz}{C_p} \]

where, \( \Delta \theta_{\text{theo}} \) represents the theoretical value of the temperature increase during the adiabatic descent (°C), \( g \) represents the gravitational acceleration (m s\(^{-2}\)), \( z \) represents the descending height of the mean trajectory (m) and \( C_p \) is the specific heat of air (J kg\(^{-1}\) K\(^{-1}\)). Following Miltenberger et al. (2016), the change in the potential temperature along the trajectory was confirmed to be small (+1.4 K). This indicates that the air temperature increase along the trajectory was primarily due to adiabatic heating. These results indicate that continuous hot, dry and strong winds are strong foehn.

On the inland of the central Shonai Plain, a lower vapour pressure deficit caused a lower \( F_{TP} < 30 \), even though the wind speed was higher than that in the white head area (Figure 5), which illustrates why the \( F_{TP} \) was lower in areas other than the white head area. A lower vapour pressure deficit was caused by a lower temperature and higher relative humidity (Figure 9). The reason why this area did not have a higher temperature and lower relative humidity is because the parcels did not descend to this area from a higher altitude (Figure 10).

The north-western side of Mt. Chokai is roughly divided into a strong-wind and low-temperature area and a moderate-wind and high-temperature area (Figures 5c, d and 11). In the strong-wind and low-temperature area, a lower vapour pressure deficit due to low temperature caused a lower \( F_{TP} < 30 \); Figure 12). The parcels descending from a lower altitude caused lower temperatures in this area compared to the white head area.

In the moderate-wind and high-temperature area on the northwest side of the mountain, a lower wind speed caused a lower \( F_{TP} < 30 \). The results of forward trajectories where the parcels were released from an altitude of 1000 m on the windward side of Mt. Chokai show that the parcels descended on the north-western slope of the mountain and ascended slightly on the plain (red circle in Figure 13). It is considered that this small jump weakened the wind speed over the moderate-wind and high-temperature area on the northwest side of Mt. Chokai.
FIGURE 12  Same as in Figure 7 but for at the northwest side of Mt. Chokai (39.27N, 139.95E)

FIGURE 13  Forward trajectories of parcels released from an altitude of 1000 m on the windward side of Mt. Chokai at 04:00 JST on 7 August, 2018. The colours of the trajectories represent vertical wind speed. The red circle represents small jump on the plain northwest side of the mountain

3.3  |  Forecast experiment

Figure 14 shows the distributions of the predicted high $F_{TP}$ durations during the white-head incident. The 2-day forecast most accurately predicted the occurrence of white heads from the perspective of timing and location. The 3-day forecast predicted the occurrence of white heads; however, its location was shifted to the coast side compared to the observed one. The 4-day forecast hardly predicted the occurrence of white heads, and the 5-day forecast was unable to predict the occurrence of white heads. Based on these results, we expected that the WRF could predict the occurrence of white heads 3 days in advance. Figure 15a–d shows the SLP at 03:00 JST on 7 August, 2018, predicted by the WRF. Compared to the results from the hindcast experiment (Figure 15e), the 4- and 5-day forecasts failed to predict the location and intensity of the typhoon and anticyclone and, therefore, failed to predict the direction and speed of the winds around Mt. Chokai.

4  |  DISCUSSION

 Numerical simulations during the white head incident on 7 August, 2018 (hereafter, Case 1), showed that the nocturnal strong foehn with high $F_{TP}$ (>30) caused the white heads. To strengthen this conclusion, we investigated whether the relationship between strong foehn effects and white heads could be applied to other cases. In the past 21 years, from 2000 to 2020, white heads occurred in the Shonai Plain on 13 August, 2000 (hereafter, Case 2) and 20 August, 2004 (hereafter, Case 3). For these two cases, we conducted hindcast experiments using the WRF, as in Case 1. The initial time was set to 09:00 JST on 11 August, 2000, for Case 2, and 09:00 JST on 18 August, 2004 for Case 3. All other settings for Cases 2 and 3 were identical to those for Case 1. Only the
results of Case 3 are discussed in the following paragraph because the WRF was unable to effectively reproduce the atmosphere for Case 2.

The distribution of the simulated high FTP duration is shown in Figure 16a. A substantial high FTP duration was located over the entire Shonai Plain, and the entire leeward side of Mt. Chokai. Figure 16b shows back trajectories starting from the Shonai Plain and the leeward side of the mountain at 22:00 JST on 19 August, 2004. The trajectories were calculated every 10 min because whether the calculation interval was 3 or 10 min had little effect on the trajectories in Case 1. As in Case 1, strong foehn effects enhanced FTP to 30 or greater and caused the white heads in Case 3. In other words, strong foehn effects caused white heads in both cases where WRF could reproduce the atmosphere.

The lead time limit of the WRF model for predicting the occurrence of white heads depends on the prediction accuracy of the global model for predicting typhoons and anticyclones. This is because a WRF model successfully predicted the strong foehn effects causing white heads only if a general circulation model (GCM) succeeded in predicting both a typhoon and an anticyclone. The lead time for the JMA’s reliable forecast of track and intensity of a typhoon is 5 days (Yamaguchi et al., 2018). Therefore, the lead time for a reliable forecast of the strong foehn effects causing the white heads is approximately a maximum of 5 days using the WRF model, for strong foehn caused by a typhoon. However, it is actually considerably shorter. This is because the WRF can predict strong foehn effects only if the GCM prediction is fairly accurate. Specifically, the GCM needs to accurately predict the location and intensity of the typhoon and the pressure gradient (direction of isobaric lines), wind speed and wind direction around the white head area.

5 | CONCLUSIONS

This study evaluates the cause of white heads occurring in a limited area by conducting numerical simulations with the WRF model. Specifically, we elucidated whether strong foehn effects caused damage to the rice plants and resulted in white heads and determined why the extent of the effects was narrow and limited. We also investigated how many days in advance the WRF model can predict the occurrence of white heads regionally and temporally.

White head damage occurred in limited rice paddies (87.1 ha) on the southwest side of Mt. Chokai on 7 August, 2018, according to the JA Shonai-Midori survey. The meteorological observation data indicated that the foehn likely blew at Sakata, located 10 km south of the white head area. These results suggested that foehn occurred in the white head area as well. However, it was impossible to prove that locally strong foehn effects caused the white heads in the damaged area, owing to the lack of meteorological observatories.

Establishing the cause of the localized white heads requires an understanding of the three-dimensional flow and temperature fields with regionally and temporally high resolution during the incident. These were provided by numerical simulations using the WRF model. The model accurately represented the location and timing of the observed white heads. The simulated night-time FTP continuously exceeded 30 only in the white head area. This high FTP was caused by the sufficiently hot, dry and strong winds blowing at that location. The simulated temperature exceeded 24°C, wind speed exceeded 8 m s⁻¹ and humidity was <65%. To clarify whether the hot, dry and strong winds were foehn, a back-trajectory analysis was performed. The trajectories of the parcels descended adiabatically along the southern and southwestern slopes of the mountain. The results showed that downslope wind had a strong foehn. In other words, the white heads were caused by locally strong foehn effects.

In the other areas, FTP did not exceed 30 because either wind speed, water vapour deficit or both were insufficiently high even if foehn was blowing. In the inland central Shonai Plain, foehn descended from a
lower altitude. Consequently, the vapour pressure deficit was smaller than that in the white head area. For the same reason as in the inland central Shonai Plain, $F_{TP}$ did not exceed 30 in the strong-wind and low-temperature area on the northwest side of Mt. Chokai. In the moderate-wind and high-temperature area on the northwest side of the mountain, foehn descended on the north-western slope of the mountain and ascended
slightly on the plain located on the northwest of the mountain. This small jump weakened the wind speed.

Finally, we attempted to predict white head damage using the WRF. The model allowed us to accurately forecast the location and timing of the observed white heads, thereby establishing that the WRF could predict the occurrence of white heads 3 days in advance. At present, the prediction of white head occurrence with the WRF model has been put into practical use on a trial basis. Therefore, it is expected that the usefulness of this new prediction method will be discussed in various white head incidents.

Notably, only two cases were considered in this study. Further numerical simulation studies should be conducted for multiple white head cases in the future to strengthen these conclusions.

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AUTHOR CONTRIBUTIONS
Yuki Asano: Data curation (lead); formal analysis (lead); investigation (lead); validation (lead); visualization (lead); writing – original draft (lead). Hiroyuki Kusaka: Conceptualization (lead); funding acquisition (lead); methodology (lead); project administration (lead); resources (lead); software (lead); supervision (lead); writing – original draft (supporting); writing – review and editing (equal).

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