Numerical simulations of upslope fog observed at Beppu Bay in Oita Prefecture, Japan

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Abstract
The present study focussed on the formation of upslope fog. This fog causes chronic expressway closures near Beppu Bay (BB) in Oita Prefecture, Japan. A dense fog event, occurring on 3 and 4 May 2020, resulting from the passage of an extratropical cyclone through the southern Japanese islands, was simulated using the Weather Research and Forecasting (WRF) numerical model. The simulation results indicated that warm and humid air with a lifting condensation level less than 20 m flowed into a plain from BB. Simulated fog and poor visibility were more severe on mountain slope adjacent to BB than on the surroundings. Here, the westward horizontal flux of water vapour by the wind flow was prolonged at lower heights. Analyses of the simulated elements verified that the upslope fog was induced by moist adiabatic cooling of the air lifted by the upslope winds. At the mature stage of upslope fog, a simulated local vertical circulation generated in conjunction with the upper synoptic flow extended the dense fog into the upper atmosphere over BB. During the decaying stage of upslope fog on mountain, a fog covered on the entire BB. This was associated with weakening winds at lower heights. Sensitivity experiments for model boundary conditions supported the importance of mountain steepness and the rectangular shape of BB for the generation of upslope fog. Finally, an application possibility of dense fog forecasts was discussed by using a simulated difference in the equivalent potential temperature between the base of the mountain and Beppuwan expressway interchange located midslope.

KEYWORDS
Beppu Bay, numerical simulation, upslope fog, visibility, WRF

1 INTRODUCTION

As fog often causes traffic and aerial disturbances, crop damage, and ecological or environmental acidification, fog monitoring and forecasting are being examined globally over land, air, and sea (Gultepe et al., 2007; Schemenauer et al., 2016). Several fog types are observed under certain atmospheric conditions, such as radiation fog, steam fog (sometimes called evaporation fog or sea smoke), advection fog, frontal fog, and upslope fog.
(Gultepe et al., 2007; Gultepe et al., 2017; Gultepe & Milbrandt, 2007; Toth et al., 2010). Numerous observational and experimental studies have been conducted on radiation fog (e.g., Bari et al., 2015; Bergot & Gueldalia, 1994; Duanyang et al., 2011; Mason, 1982; Meyer & Lala, 1990; Nakanishi, 2000; Ohta & Tanaka, 1986; Price, 2019; Roach et al., 1976), advection fog (e.g., de Wolf et al., 1999; Fan et al., 2003; Hung & Liaw, 1981; Liu et al., 2016; Pithani et al., 2019; Yang et al., 2018), and steam fog (Heo & Ha, 2010; Khvorostyanov et al., 2003; Magono et al., 1974; Raymond & Schmit, 1989; Saunders, 1964). However, there are fewer studies regarding upslope fog than other fog types (Gultepe et al., 2014; Gultepe et al., 2016; Magono, 1985; Pu et al., 2016).

In the United States, upslope fog forms in the Great Smoky Mountains (Petersen et al., 2010), the eastern side of the Rockies (Shepard, 1996), and the mountains in Utah (Gultepe et al., 2016; Pu et al., 2016). A typical upslope fog is attributed to the adiabatic cooling of an air mass rising over a mountain slope (Clapp, 1938). Although an upslope wind can create fog where a mountain, wind, and humid air coexist, meteorological studies focusing on upslope fog have not been conducted thus far. Additionally, upslope fog often induces poor visibility due to heavy fog, similar to other types of fog. In Japan, expressways near Beppu Bay (BB) in the Oita Prefecture are often closed by upslope fog (Figure S1).

The expressways around BB due to fog remained closed for 200–300 h annually; in contrast, other expressways throughout Japan remained closed for approximately 10 h annually (Japanese Ministry of Land, Infrastructure, Transport and Tourism, 2016). Additionally, the number of closure hours was considerably longer than those due to rainfall (maximum of 30–40 h) or snowfall (approximately 100 h maximum). Despite the chronic closures recorded in the BB expressways, no research has been conducted regarding dense fog.

The present study serves to clarify the dense fog features that occur around the BB and its life stages from formation to dissipation in relation to the upslope fog. To this end, a numerical model was used to investigate the phenomenon of dense fog, considered to be upslope fog, occurring at BB in Oita Prefecture, Japan, where the lifting condensation level (LCL) of air and the visibility are considered to be important factors. Overall, the study aims to clarify the upslope fog formation processes and improve operational fog forecasting accuracy and the involved methodology.

Moreover, the roles of boundary conditions, such as terrain and sea surface temperature (SST), were determined through sensitivity experiments using the model. As will be mentioned later, the fog occurrence area in this study has an interesting geography, including mountains surrounding a rectangular shape bay (i.e. BB). Previous studies have shown that fog growth can be altered by surface boundary conditions, terrain, and SST (e.g., Bari et al., 2015; Gultepe, 2015; Tang, 2012; Wainwright & Richer, 2021). Hence, it is considered that potential surface conditions are important for fog occurrence and development in this study area.

The remainder of this paper is organized as follows. The geographical features and fog characteristics in this study area are introduced in Section 2. A case study of the upslope fog event and numerical model settings is presented in Section 3. Section 4 discusses the simulated fog results and sensitivity experiments on lower boundary conditions. Finally, our findings are summarized in Section 5.

2 | BACKGROUND OF THE STUDY

2.1 | Geographical feature

Figure 1a–c shows the geographical maps of the study area, including BB in Oita Prefecture. Large-scale mountainous regions of the Kyusyu Mountains and Shikoku Mountains, containing terrain with elevations greater than 1500 m above sea level (ASL), are located in this region. The Pacific Ocean extends southward from the Japanese islands.

Upslope fog often appears on a plain and on a mountain slope on the west side of BB located in Beppu City. In Figure 1b, the locations of the expressway interchange (IC) are also marked by a circle, comprising the Hiji Bypass, Higashi-Kyushu Expressway, and Oita Expressway. Specific ICs were closed due to increasing fog on the abovementioned plain and mountain slopes (red circles in Figure 1b). The plain (strictly alluvia fan) located in the west of the BB narrowly extends in a north–south direction, and a steep mountainous terrain with elevations of 900–1000 m ASL lies adjacent to the west of the plain. The unique rectangular shape of BB is observed from the maps with scales of 10 km in the north–south direction and 20–30 km in the west–east direction.

2.2 | Fog characteristics

Fog appearances are captured by surveillance cameras, which the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and the West Nippon Expressway Company (NEXCO West) operated on rivers and roads. In Figure S2, images captured at the Beppuwan IC (site A in Figure 1b) and Yufuin IC (site B in Figure 1b) are
displayed for pre-fog and fog conditions during a day when the expressway was closed. From these images, a dense fog, which often obstructs the view with a visibility of less than 100 m, can be observed at the Beppuwan IC. Hence, the actual visibility at the fog stage was estimated from invisible objects at predetermined distances in the image.

The closing of an expressway due to dense fog occurred simultaneously for the ICs, as shown by the red circle in Figure 1b. The results of summarizing the frequency of expressways closures due to fog each month for 6 years from 2014 to 2019 showed two occurrence peaks from April to July and September to October (Figure S3a). In particular, the frequency in June surpassed that of the other months. The most frequent meteorological event inducing fog-related expressway closure was a stationary front, which is referred to as ‘Baiu’ front in Japan (Figure S3b). Fog-related expressway closures in June and July were attributed to the Baiu rainy season from June to late July. The increase in expressway closure due to fog, primarily in April and May, corresponded to an extratropical cyclone passing south of the Japanese islands. Figure S3b shows that the fog closure caused by the Baiu stationary front and extratropical cyclone located south of Japan accounted for more than half of all events. The peak of the closure frequency due to fog in September and October is frequently attributed to typhoon events.

3 | METHODS

3.1 | Targeting event

Dense fog caused by the passage of an extratropical cyclone through the southern Japanese islands occurred on 3 and 4 May 2020. Figure 2a,b shows the weather charts for Japan at 1500 local time (LT) on 3 May and 0900 LT on 4 May 2020. These charts demonstrate that an extratropical cyclone treks eastward in the south of the Japanese islands. The results of the grid point value (GPV) analysis by the Japan Meteorological Agency (JMA) are shown in Figure 2c,d. These results indicate synoptic patterns of equivalent potential temperature
(θₑ), and wind vectors at 850 hPa representing inflows of warm and humid air from the Pacific Ocean to the Kyushu region on 3 May 2020 and northerly or westerly winds over the Kyushu region on 4 May 2020.

Due to the occurrence of fog, the maximum speed on expressways around BB was regulated at 0806–0836 LT on 3 May 2020. The BB expressways closed after 1900 LT by NEXCO West, and were opened after 1200 LT on 4 May the next day (provided by the Japan Road Traffic Information Center, JARTIC). Therefore, an expressway traffic obstacle was maintained for a total of 29 h until 1306 LT on 4 May when it cleared without any speed regulation.

3.2 | Numerical model

The Weather Research and Forecasting (WRF) model was used to simulate mesoscale atmospheric flows. The present study used the WRF ver. 3.8.1, known as the Advanced Research WRF (ARW), developed by the National Center for Atmospheric Research (NCAR), USA. Descriptions of WRF-ARW ver. 3 were published by Skamarock et al. (2008). This numerical model is based on fluid dynamics equations that incorporate fully compressible fluids and a non-hydrostatic equilibrium. Many meteorological physical processes are calculated in the model: atmospheric radiation, cloud microphysics (including rain, snow, and graupel), atmospheric boundary layers (turbulence parameterization), and land-surface processes. The model configurations used in this study are summarized in Table 1. The single-moment 5-class scheme (WSM5) proposed by Hong et al. (2004) was selected as the microphysics process. WSM5 predicts the mixing ratios of vapour, cloud water, rain, ice, and snow phases. Here, the cloud water found in the lower atmosphere of the model was recognized as fog. The Mellor-Yamada Nakanishi and Niino (MYNN) Level 2.5 of the 1.5-order turbulent closure scheme was applied for the boundary-layer parameterizations. Both parameterizations of microphysics and boundary layer were chosen as a suitable performance for computational cost and meteorological reproduction (e.g. Chen et al., 2020; Nakanishi & Niino, 2009; Pithani et al., 2019). The gravitational settling of fog droplets was calculated using the fog deposition scheme at the ground surface (Katata et al., 2008) and Duynkerke’s (1991) scheme in the atmosphere.

The ERA5 reanalysis data of the European Centre for Medium-Range Weather Forecasts (ECMWF) were used as initial and hourly boundary conditions for the atmosphere, soil, and SST. These data have a horizontal
resolution of approximately 30 km. The ERA5 product is a global reanalysis data, which were improved in model physics, core dynamics, and data assimilation with higher spatio-temporal resolution than the old product and reliable data through performance verification (Hersbach et al., 2020).

Figure 1 shows the calculated domains being downscaled from eastern Asia to an area surrounding BB. A parent domain (D01), child domain (D02), and grandchild domain (D03) are also displayed. The horizontal spatial resolutions were 4500, 1500, and 500 m for D01, D02, and D03, respectively. Meteorological results outputted in D03 were analysed. The vertical spatial resolution was 7.8 m for elevations less than 70 m above ground level (AGL) and stretched gradually with model height. In the WRF simulations, the meteorological data and the SST of ERA5 were hourly inputted at lateral boundaries of D01 and surface boundaries of D01–D03, respectively. The land-use and topography data utilized in the model were based on 50-m meshed data by the Geospatial Information Authority of Japan (GSI) and 100-m meshed data from the MLIT, respectively. These data were smoothed as assigned to the model spatial resolutions. The maximum slope angles of the terrain gridded along x1–x2 shown in Figure 1c were 34.5° and 11.6° for the original data with a 50-m resolution and model input with a 500-m resolution, respectively. However, the average slope angles along x1–x2 were 7.6° and 6.1°. Therefore, mountain slopes around BB in the area with upslope fog can be sufficiently represented in D03 with a model resolution of 500 m.

Temporal integration was initiated at 0900 LT on 2 May 2020 and terminated at 1500 LT on 4 May 2020. The first 15 h output values were eliminated from the analysis to avoid the influence of the initial conditions of the simulations. Therefore, the output data from 0000 LT on 3 May of the simulations were used for the analysis. While Román-Cascón et al. (2016) presented a better validation of the simulated radiation fog after 24 h under a model spin-up time of 6 h, our study confirmed that the calculated results were essentially unaltered under spin-up times of 12 or 24 h as opposite to under a duration of 15 h.

### 3.3 Analysed variables

In the present study, observational data provided by the JMA were analysed to understand meteorological conditions as the background occurring in the fog and to validate the model calculations. The four surface observation stations (marked as ‘a’–‘d’ in Figure 1c) measured temperature, wind speed and direction, rainfall, and sunshine duration every 10 min; each station was known as Innai (a), Kuitsuki (b), Yufuin (c), and Oita (d). Relative humidity was measured at the Oita site. The wind profiler observation by the JMA was also conducted every 1 h at the Oita of these stations. The LCL of the air mass can be estimated at the Oita observation site from a physically sophisticated estimation proposed by Daidzic (2019), using the surface air temperature, dew point temperature, and specific humidity.

| Table 1: WRF configuration and physics options selected in this study |
|-------------------------------------------------|
| **D01 (parent)** | **D02 (child)** | **D03 (child)** |
| Grid intervals | Horizontal | 4500 m | 1500 m | 500 m |
| Vertical | 7.8 m below 70 m level and stretched gradually with height |
| The number of grids | Horizontal | 100 (west–east) \(\times 100\) (south–north) | 100 (west–east) \(\times 100\) (south–north) | 170 (west–east) \(\times 170\) (south–north) |
| Vertical | 75 layers |
| Initial and boundary conditions | Atmosphere | Hourly data of the ECMWF ERA5 re-analysis (30 km resolution) |
| Soil | SST |
| Model top level | 100 hPa |
| Cloud microphysics | WRF single-moment 5-class scheme (Hong et al., 2004) |
| Radiation | Shortwave | Revised rapid radiative transfer model (Iacono et al., 2008) |
| Longwave |
| Atmospheric boundary layer and surface layer | Mellor-Yamada Nakanishi and Niino Level 2.5 (Nakanishi & Niino, 2006) |
| Land surface | Unified Noah land-surface model (Chen & Dudhia, 2001) |
| Others | Gravitational settling of fog droplets in the atmosphere (Duynkerke, 1991) and at the surface (Katata et al., 2008) |
| One-way nesting |
The data obtained from calculations performed using the numerical model were also analysed for primitive meteorological elements in addition to cloud water content. Moreover, the liquid water path (LWP) was used to detect fog layers from possible low clouds located below a few kilometres (e.g. Chen et al., 2020):

\[
\text{LWP} = \int_{z_0}^{z_1} \text{CWC} \, dz
\]  

(1)

Here, CWC is the cloud water content (kg m\(^{-3}\)). The LWP (kg m\(^{-2}\)) is vertical integration of the CWC from the surface of \(z_0\) to approximately 2000 m AGL of the model height \(z_1\).

Horizontal visibility (VIS, km) is given by the following equation (Koschmieder, 1924), which is related to the meteorological optical range (MOR). This estimation has been extensively used in fog research (e.g. Gultepe et al., 2006; Gultepe & Milbrandt, 2010; Musson-Genon, 1987; Nakanishi, 2000; Policarpo et al., 2017).

\[
\text{VIS} = \frac{-\ln(0.02)}{\beta}
\]  

(2)

where \(\beta\) is the extinction parameter for cloud water (Kunkel, 1984) or rainwater (Stoelinga & Warner, 1999), which is related to the CWC (g m\(^{-3}\)) and rainwater content (RWC, g m\(^{-3}\)):

\[
\beta_{\text{cw}} = 144.7 \text{CWC}^{0.88}
\]  

(3)

and

\[
\beta_{\text{rw}} = 1.1 \text{RWC}^{0.75}
\]  

(4)

Hence, \(\beta\) is given as the addition of \(\beta_{\text{cw}}\) for cloud water and \(\beta_{\text{rw}}\) for rainwater. The international definition of fog corresponds to a horizontal visibility of less than 1000 m (World Meteorological Organization, 2018). In addition to this criterion, the JMA defines dense fog as corresponding to a horizontal visibility of less than 100 m (JMA homepage, 2021).

Meanwhile, many formulae used for estimating the VIS include hydro-parameters, such as CWC and RWC, or meteorological parameters, such as relative humidity and dew point temperature. Lin et al. (2017) discussed the VIS results using eight estimation formulae from the WRF simulations and clarified the improved estimates of the effect of light extinction from hydrometers based on Equation (2) compared with the meteorological estimations. Therefore, the widely used VIS estimation indicated by the above equations was used in the present study.

### RESULTS AND DISCUSSION

#### 4.1 Surface weather on 3 and 4 May 2020

The surface weather changes measured by the four JMA sites surrounding the ICs that were closed due to dense fog are briefly discussed: the Innai, Kitsuki, Yufuin, and Oita (Figure S4). Although rainfall was intermittently observed from 0600 LT on 3 May to 0400 LT on 4 May, it corresponded to light rain, except for the period from 1000 to 1200 LT on 3 May at the Kitsuki and Innai sites. In contrast, the surface wind conspicuously weakened to <1 or 2 m s\(^{-1}\) during the closure period of expressway ICs. The wind direction differed at each observational site; easterly winds persisted at Kitsuki located north of BB, whereas northern winds were most frequently recorded at Oita, located in the southern part of BB. Moreover, the inland Yufuin site indicated westerly winds during the IC closure.

In the surface weather changes calculated by the WRF (Figure 3), two concentrated rainfall events were confirmed from 0700 to 1600 LT on 3 May and 0400–0700 LT on 4 May, which agreed with the JMA observations presented in Figure S4. However, the accumulated amount of simulated precipitation was overestimated for the observed values. Additionally, the calculated variation of wind speed reproduced an increase from 1200 to 1800 LT on 3 May and a subsequent day decrease during the expressway IC closure. The simulated winds were often stronger near the BB coast (i.e. the Kitsuki and Oita grids).

Figure 4 shows a comparison between the LCL observed at the Oita JMA site and that simulated by the WRF with precipitation results. The Oita site is located near the southern coast of the BB (cf. Figure 1c). At 0800 LT on 3 May, the LCL estimated from the observation data rapidly fell to less than 50 m. The LCL was recorded at approximately 0 m until the morning of the next day despite increasing to 100 m from 1300 to 1500 LT. An expressway closure period corresponded to the LCL condition of 0 m, suggesting that the air mass immediately condensed when lifted. The LCL simulated by WRF was underestimated at a model grid including the Oita JMA site, produced no rainfall during the expressway closure, and was less than 100 m from 2300 LT on 3 May to 0800 LT on 4 May. However, on the Beppu narrow plain, where the upslope fog occurrence is expected on the western mountain, the simulated LCLs at two grids (marked by small open circles in Figure 1c) were more comparable to the LCL observed at the Oita site, and the LCLs of less than 100 m were prolonged in comparison with the LCL simulated at the Oita-site grid.
4.2 Simulated upslope fog and its life cycle

Figure 5 shows the temporal variations of the observed and simulated VIS (as m in unit) at the Beppuwan IC marked as ‘A’ in Figure 1b. The observed VIS was inferred by detecting the distance to visible objects on live-camera images of Figure S2a,b. Only 10 data points of VIS (closed circles in Figure 5) were obtained from 1200 to 1600 LT (3 May), 1900 to 2300 LT (3 May), and 0700 to 1100 LT (4 May) and had values less than 100 m, except 120 m at 2110 LT (3 May). Simulated VIS values of the WRF were greater than those observed from 1200 to 1600 LT and 0700 to 1100 LT, exceeding 100 m. The VIS simulated from 1900 to 2300 LT corresponded well to the real conditions and was temporally stable between 50 and 150 m. Strictly, the VIS formulation must consider the fog droplet number concentration per unit air volume (e.g., Gultepe et al., 2006; Gultepe & Isaac, 2004; Meyer et al., 1980). At the WSM5 used in this study, the cloud number concentration (CNC) of $3 \times 10^8 \text{ m}^{-3}$ as a constant value was given for microphysics calculations (Hong & Lim, 2006). If a VIS formula with both the CNC and CWC values proposed by Gultepe et al. (2006) was used, the simulated VIS was less than approximately 50–100 m close to the observed VIS. However, because the actual fog number concentration was reported as wide values of $0.1–4 \times 10^8 \text{ m}^{-3}$ (e.g., Gultepe et al., 2006; Mazoyer et al., 2019; Podzimek, 1997), it may be inadequate to obtain the VIS directly using the constant value provided in the WSM5. Hence, it should be noted that the VIS indicated hereafter will be probably estimated to be greater than the observed VIS resulting from calculations using Equations (2)-(4) and neglecting the CNC.

The simulated horizontal distributions of the CWC (kg kg$^{-1}$) on the lowest model grid are depicted in...
At 0800 LT on 3 May (Figure 6a), corresponding to the previous hours of speed regulation of expressway ICs, cloud water were generally absent near BB. At 1100 and 1800 LT on 3 May (Figure 6b,c), the surface wind prevailed towards the westerly mountain slope adjacent to BB, where the six expressway ICs are concentrated (enclosed by dashed circles in the figures). Abundant CWC ($1 - 5 \times 10^{-4}$ kg·kg$^{-1}$) was observed, which is considered upslope fog with an easterly wind. The rapid increase in LWP (Figure 7) appeared immediately after 1200 LT on 3 May at the Beppuwan IC grid (red line in Figure 7), which was not found in the inland grid (black line) westward of the Beppuwan IC and the sea grid (blue line) on BB. The extent of CWC simulated at 1100 and 1800 LT can be regarded as a development stage of upslope fog, combined with the easterly wind persistence blowing from the BB. Unfortunately, this upslope fog found on mountains could not be observed from weather satellite images, because the cloud broadly extended in the upper layer on the interesting area due to the extratropical cyclone. The following day (Figure 6d,e), a large amount of CWC was observed on BB, which seemed to be clearly different from the upslope fog. The easterly wind on the BB became substantially weak at this time. The LWP at the Beppuwan IC decreased rapidly after 1900 LT on 3 May, although it remained larger than those at the inland and BB (Figure 7). After 0600 LT, the LWP fluctuated intermittently at the Beppuwan IC, similar to the inland LWP. In addition, from the surface distribution of the CWC, the extent of fog on the mountain slope was almost unrecognized at 0800 LT on 4 May (Figure 6e). Hence, the upslope fog is considered as the beginning of the dissipation stage. At 1100 LT (Figure 6f), the CWC extent on the BB almost disappeared in addition to the mountain areas surrounding the BB.

The vertical distributions of the fog (Figure 8) indicate the west-east cross section (dashed line of $x_1 - x_2$ in Figure 1c) from the mountain slope, including Beppuwan IC to BB through a narrow plain. Poor VIS appeared on mountain slope higher than 100–150 m ASL with an easterly wind blowing from BB at 1100 and 1800 LT on 3 May (Figure 8b,c). The fog on the slope was reproduced with the CWC of $0.5 - 1.5 \times 10^{-4}$ kg·kg$^{-1}$ at 1100 LT, whereas the CWC of the fog at 1800 LT was an order of magnitude greater than at 1100 LT (approximately $5 - 15 \times 10^{-4}$ kg·kg$^{-1}$). In particular, the CWC at 1800 LT gradually increased with increasing elevation from the base of the mountainous terrain, as indicated by the -layered-dense contours of the CWC near the slope surface. The surface VIS was extremely poor with values of 150–200 m at 1100 LT and less than 50 m at 1800 LT. Simultaneously, this fog was extended eastward over BB by the upper westerly winds, which were opposite to the lower flow, with considerable accompanying vertical circulation (Figure 8c). Actual upper winds at heights of 2–3 km between 180° and 270° in the wind direction were persistently recorded by the JMA wind profiler observation located at the Oita site (cf. Figure S5). The westerly components of the wind that appeared at
heights of 2 km AGL were also reproduced in the model simulations of Figure 8b,c. However, similar to the simulation, they did not appear at a height of 1 km AGL in the observation. The formation mechanism of the above-mentioned circulation from the surface to 2 km was investigated by sensitivity experiments (will be discussed in Section 4.4). The fog on the slope accompanied by upslope winds corresponded to the upslope fog, which can be regarded as a developing stage around 1100 LT and a mature stage around 1800 LT, also considering the result in temporal changes of the LWP in Figure 7.

At 0200 LT on 4 May (Figure 8d), progressing from the previous stage, the westerly wind prevailed at a lower level of approximately 1 km AGL. This was also captured by the actual observations as the wind direction changed from 0200 LT on 3 May to after 0600 LT on 4 May (cf. Figure S5). Upslope fog still occurred at the base of the mountainous terrain to the height of the Beppuwan IC (marked as ‘A’ in the figure). At this time, the lowest VIS was observed at the surface close to the midslope. The CWC was indicated at approximately 2–5 × 10^{-4} kg kg^{-1} on the slope, and the LWP value (Figure 7) also rapidly decreased and was stable, compared to that of the mature
stage mentioned previously. Hence, the corresponding period of the upslope fog was considered to have changed to a decaying stage.

However, at 0800 LT on 4 May (Figure 8e), a region of the fog and poor VIS was confined below a height of 200–300 m on the BB. It was similar to a dense fog pool, which was no longer upslope fog. This phenomenon was probably attributed to the weakening of lower-level easterly winds blowing from the BB (Figure 8e), which will also be investigated by sensitivity experiments in Section 4.4.

### 4.3 Thermophysical process of the upslope fog formation

Spatiotemporal variations of the simulated LCL and horizontal wind vectors in the south–north direction on a plain adjacent to the BB were analysed to understand the moist air inflows (Figure 9). The air mass with an LCL of <50 m was maintained by the easterly wind blowing from the BB at the northern part of the plain, where several ICs were located on the windward side. This feature indicated the longest duration from 0900 to 2300 LT on 3 May in the figure; this period was included with that of the regulated maximum speed or the expressway closure mentioned in Section 3.2. At the plain location of the same y-coordinate as the Beppuwan IC on the windward side (marked as ‘A’ in the figure), the LCL values of 40–100 m appeared until 1900 LT on 3 May and corresponded to the poor VIS altitude indicated in Figure 8b,c. Additionally, a persistent easterly wind was only observed in the northern part of BB. These LCL
values corresponded well with the simulated heights of the CWC on the mountain slope, as shown in Figure 8b, c. This proves the upslope fog formation around the Beppuwan IC by the adiabatic cooling process of the air penetrating from the BB. Then, the distributions of $\theta_e$ were calculated along the mountain slope (from the base to the summit), as displayed in Figure 10. At 1800 LT on 3 May as shown in Figure 8c, $\theta_e$ was close to a constant over the entire slope of mountain. This condition was accompanied by upslope winds from the direction of the BB. Therefore, the upslope air mass was moist adiabatically cooled from the base to the highest elevations of mountain, generating fog through the condensation process. Figure 10 also clarifies the mature stage of the upslope fog around 1500–2200 LT on 3 May by considering their sustainment. Simultaneously, the entire vertical circulation produced moist adiabatically extensive convection from the evidence of a vertically thick constant $\theta_e$ (cf. Figure S6c,f).

FIGURE 10 Spatiotemporal variations of the simulated $\theta_e$ (tones) and wind ($u$ and $w$ components, vectors) at the lowest model grid in the west–east direction on the slope of mountain adjacent to the BB (along a dashed line of $x_1$–$x_2$ in Figure 1c) from 0600 LT on 3 May to 1200 LT on 4 May 2020. The cross section of the terrain is depicted at the upper panel (different from the actual aspect ratio of terrain). ‘A’ on the mountain slope figure indicates the location of the Beppuwan IC

The entire plain region was covered with near-saturated air with an LCL of $<20$ m after 0000 LT on 4 May, as shown in Figure 9. Calm surface conditions were present in a south–north direction, which produced a stagnation layer until the easterly wind again increased. This fog extending over the BB was confirmed by JMA meteorological satellite images (not shown). In addition, fog or mist occurrences near the surface were intermittently recorded at the JMA Oita site with $<1$ or 2 km VIS. In the simulation, the downward sensible-heat flux of approximately 5–20 W·m$^{-2}$ was induced at the surface broadly from the plain to BB; a thermally stable layer developed (cf. Figure S6c,f).

4.4 Sensitivities of upslope fog to mountains and SST

Sensitivity experiments of the upslope fog to the model boundary conditions were performed to understand the formation mechanisms of the dense fog observed at the BB. Table 2 displays the experimental contents operated for the previous simulation (hereinafter referred to as the STD case), the SSTup case (contains SST increase of 2°C at the BB and surrounding sea), the SSTdn case (contains SST decrease of 2°C), the noFLX case (contains no sensible and latent heat fluxes at land and sea surfaces), and the MTlow case (which reduced the height of the mountainous terrain to 10% compared to that of the STD case). Here, the SST anomalies of $\pm2$°C used for the SSTup and SSTdn cases were determined by analysing the SST observation data provided by the JMA based on the SST variations measured within D02 during the past decade.

For the above-mentioned cases, temporal variations of the number of VIS sites with values greater (i.e. improved VIS) than that in the STD case at the nine expressway ICs closed due to fog were calculated at 3 h intervals (Figure 11). A VIS change greater than 100 m was a condition for calculating the variation. The value in the figure was calculated as a percentage of the 162 VIS results for the nine IC grids for 3 h of VIS values in 10 min intervals. Figure 11 displays the results of the VIS change in each case (i.e. SSTup, SSTdn, MTlow, and noFLX) for the STD case. The maximum occurrence of

### Table 2: Sensitivity experiments for the fog simulation

| Case name | Modification of boundary conditions |
|-----------|------------------------------------|
| Case STD  | Standard case with no modifications |
| Case SSTup| 2°C increase of SST for the STD case in D02 and D03 |
| Case SSTdn| 2°C decrease of SST for the STD case in D02 and D03 |
| Case noFLX| No sensible and latent heat fluxes at land and sea surfaces for the STD case in D02 and D03 |
| Case MTlow| Reducing the mountain height to 10% for the STD case in D02 and D03 |
Improved VIS sites was observed in the MTlow case, with approximately 60% from 0900 to 1800 LT on 3 May. The difference in surface spatial distribution between the STD and MTlow cases at 1700 LT during the corresponding hours (Figure 12c) revealed that terrain undulations generated the southward horizontal flux of water vapour represented by vectors \((q \times u, q \times v)\) near the mountains adjacent to the BB, which was attributed to flow deformation inside the BB. Here, \(q\) represents the water vapour mixing ratio \((\text{kg kg}^{-1})\), and \(u\) and \(v\) are the wind speeds \((\text{m s}^{-1})\) of the east–west and south–north components, respectively. This change is also distinct from the comparison of the STD (Figure 12a) and MTlow cases (Figure 12b). Moreover, the air mass was not almost uplifted on the slope due to the lowering of mountains in the MTlow case, as shown in Figure 13a. When comparing the vertical circulation in this case with the STD case (Figure 8c), this circulation was not formed, and the CWC value significantly decreased in the MTlow (Figure 13a). These issues were the reason why the most improved VIS appeared in the MTlow case. In addition, the simulation results lowered only the westward mountain adjacent to the BB in the STD case (not shown) were almost the same as those of the MTlow case. Therefore, the vertical circulation over the BB is generated by a combination of the upslope flow on the mountain slope and the upper westerly winds flowing in opposite directions. However, the influences of the SST on wind flows and this circulation were smaller than those in the above-mentioned topographical effect, in comparison with the results in the SSTup and SSTdn cases.

However, from 4 May, the topographical effect on VIS appears to have been insignificant, as indicated in Figure 11. This is verified by a fog extension in the lower atmosphere at the BB due to the lowering of mountainous terrain (Figure 13b), which differs from the upslope fog formation. Because mountains surrounding the BB play a role of pooling the air and weakening the winds (less than 5 m s\(^{-1}\)) at the lower layer as a basin effect, the fog influence was smaller at the height of the Beppuwan IC in the STD case (likely as Figure 8e) than at the MTlow. In the lower mountain case of the MTlow, the CWC exhibited stratification at heights less than 300–400 m AGL (Figure 13b). Hence, the westward mountain adjacent to the BB works to form the fog pool on the BB, which appeared on 4 May.

The second improved VIS result corresponded to the noFLX case with 20–30% from 0900 to 1800 LT on 3 May. The spatial distribution of the difference between the STD and noFLX cases (Figure 12e) indicated an increase in the CWC due to the existence of surface heat fluxes on the upslope fog areas west of BB, which was accompanied by a westward increase of water vapour horizontal flux (vectors in the figure) over BB near the mountainous terrain. By increasing the relative humidity by approximately 10% over the land and sea in the STD compared to noFLX (not shown), the existence of surface heat fluxes contributed to some extent to the generation of dense fog by the upslope fog. In addition, Figure 13c clarifies the intensification of upward winds and the CWC increase in the atmosphere on the mountain slope in the STD, compared with the noFLX. Because the warm and humid air flowing into the BB was cooled by the sea surface of BB with a downward sensible-heat flux of 40–50 W m\(^{-2}\) (not shown), lowering the LCL of the air facilitated the upslope fog occurrence. In fact, an SST of approximately 16°C was observed in this study case, which was always lower than the air temperature.

Surface heat flux effects were also observed in the results of the SSTup and SSTdn cases. Increasing SST (i.e. SSTup) decreased the relative humidity by a few percent compared with the STD case, whereas decreasing SST (SSTdn) increased the relative humidity by a few percent. This result was attributed to that a decrease (increase) in the downward sensible heat flux by rising (falling) SST weakened (strengthened) the cooling of the overlying atmosphere, as mentioned previously. However, we concluded that the climate-induced SST change of 2°C in the study region affected the upslope fog formation smaller than that of the noFLX (Figure 11).

The improved VIS for the noFLX case from 0300 to 0600 LT on 4 May showed the greatest values among all the cases (Figure 11). Figures 6e, 8e, and 9 show that weak wind conditions on the BB and neighbouring plain have difficulty generating upslope fog on mountains in

**FIGURE 11** Temporal variations of the percentage of sites with greater VIS values than those in the STD case (i.e. improved VIS) for the nine expressway ICs closed due to fog. The variations are displayed at 3 h intervals and require a VIS change of more than 100 m in each simulation case (SSTup, SSTdn, MTlow, and noFLX). Each value in the figure was calculated as a percentage for the total 162 VIS results of the nine IC grids for 3 h of VIS values produced in 10 min intervals from 0300 LT on 3 May and 1500 LT on 4 May 2020.
this period. Hence, the weakening of dense fog (i.e. improved VIS) in the noFLX due to the absence of surface heat fluxes suggests fog generated by sensible-heat exchange between the surface and the overlying atmosphere, such as advection or radiation fogs. Figure 13d indicates the vertical distribution of the difference in results between the STD and noFLX at 0500 LT on 4 May. The figure also clarifies that the fog (CWC in the figure) extending at a height lower than the mountain over the BB was maintained by the surface-sensible heat flux. In fact, the thermally stable layer was formed at a depth of 200–300 m above the BB (cf. Figure S6c).

4.5 Comparison with other fog simulations and contribution to applications

The influence of orography and SST on fog developed in coastal areas has been investigated by researchers. Coastal fogs observed in Casablanca, Morocco, are known to develop over terrains coexisting with the sea and mountains. The fog often results in adverse effects on land, air, and sea (Bari et al., 2016; Bari & Khlifi, 2015). Bari et al. (2015) confirmed that the existence of mountains blocked the extension of fog to the land by sensitivity experiments with a numerical model. This result is similar to the fog pool confined to the BB area simulated on 4 May in our study (e.g. Figures 6e and 8e). They also investigated the fog sensitivities to SST changes of 2°C, similar to our experiments, and demonstrated an increase (or decrease) in the sea fog if decreasing (or increasing) the SST. A similar response of the fog was simulated for the Yellow Sea in East Asia by Gao et al. (2007). The BB fog extension, indicating a similar behaviour to these studies, has features close to advection or radiation-type fog, as discussed in Section 4.4.

In our study area, winds easily penetrated the land perpendicular to the coastal line due to the BB shape. This is the cause of fog often initiating over the land, rather than a coastal fog such as Casablanca. In addition, because a large-scale development of fog by a vertical circulation, which was observed at the mature stage, seems to be previously unreported, further investigations and analyses are required for future studies. A vertical-
growing fog such as radiation fog often produces a linear increase in the fog water content and the abrupt decrease at the fog top with height (Bergot & Guedalia, 1994; Boute et al., 2018; Koracˇhin et al., 2005; Nakanishi, 2000). The fog life cycle is affected by the heat budget in the entire layer, such as the radiative cooling of the fog top, downward longwave radiation emitted from the fog droplets, and turbulent effects (Nakanishi, 2000; Ohta & Tanaka, 1986; Wilson & Fovell, 2018; Yang et al., 2018). Further studies should investigate the role of the interaction between radiation and turbulence in upslope fog life cycle.

When constructing applications forecasting dense fog, various VIS estimations should be evaluated in detail. The NEXCO West determines the car speed regulation and IC closure on expressways, based on a VIS less than 50 m (Sugimachi et al., 2016) if dense fog appears in this study area. Because the present study revealed the coexistence of prolonged wind and warm/humid air flowing from the BB to mountains, investigating the relationship among these effects upon temporal variations of VIS is currently a challenge. The $\theta_e$ has the potential to be an alert indicator of dense fog occurrence, as demonstrated in Figure 10, because the value of $\theta_e$ represents the transport of warm and humid air towards the BB. A difference in $\theta_e$ between the base of the mountain and Beppuwan IC located in mid elevations of the mountain was available as a practical application for the upslope fog stage in this study area. The $\theta_e$ difference clearly correlated with the VIS at the Beppuwan IC ($r = +0.66; p < 0.01$) after 0850 LT on 3 May 2020 when the $\theta_e$ value simulated at the Beppuwan IC exceeded 45°C. Roughly, a VIS <200 m if a $\theta_e$ difference <2.5°C and VIS <100 m if a $\theta_e$ difference <0.5°C were estimated from the correlation analysis. This time of 0850 LT corresponded to the previous hour of expressway closure (starting at 1200 LT). Fog forecasting information provided several hours before the occurrence of dense fog is expected to enable the preparation and countermeasures for an expressway administrator.

5 | CONCLUSIONS

The present study focussed on upslope fog inducing chronic expressway closures at the BB in Oita Prefecture, Japan. A dense fog event due to an extratropical cyclone

FIGURE 13 Simulated vertical distributions of the CWC (kg kg$^{-1}$, contour lines) and wind (u and w components, vectors) in the west-east direction lined $x_1$–$x_2$ in Figure 1c in the (a and b) MTlow case and (c and d) difference between STD and noFLX cases (i.e. the value of STD minus noFLX). The results were shown at (a and c) 1800 LT on 3 May, (b) 0200 LT on 4 May, and (d) 0500 LT on 4 May 2020. Red and blue contour lines in (c) and (d) represent the positive and negative values of the CWC difference (the STD minus noFLX), respectively.
passing the southern Japanese islands that occurred on 3 and 4 May 2020 was simulated using the WRF numerical model. The following results were clarified, and a conceptual model was constructed, as depicted in Figure 14.

- Developing stage of upslope fog (Figure 14a).

A warm and humid air mass with a low LCL of <20 m flowed into a plain located at the base of mountain adjacent to the BB. This flow was associated with an extratropical cyclone passing through the southern Japanese islands. Denser fog and poorer visibility were reproduced by the simulation on the mountain slope adjacent to BB than those of the surrounding areas, where the lower-layer westward horizontal flux of water vapour by the wind flow was prolonged from the BB. The analyses of the simulated meteorological elements verified the upslope fog induced by the moist adiabatic cooling of the air lifted by upslope winds. Sensitivity experiments for the model boundary conditions supported the importance of mountain steepness and the penetration (rectangular) shape of BB for upslope fog formation.

- Mature stage of the upslope fog (Figure 14a).

Surface flows with a depth of 200–300 m inducing upslope fog were formed as a part of the local vertical circulation generated in conjunction with the upper westerly synoptic flow around the BB. Interestingly, a grounding upslope fog extended up to a height of 2 km over the BB under the influence of the upper flows. In addition, ±2°C SST changes, including BB, did not significantly contribute to intensify the vertical circulation and upslope fog, as confirmed from sensitivity experiments by the numerical model.

- Decaying stage of the upslope fog (Figure 14b).

The surface winds upward on the mountain slope were weakened by decays of warm and humid air flow from the BB. Subsequently, the fog began to extend to the BB at a depth of 200–300 m. The mountain blocked the upper westerly winds by separating the lower fog layer from the upper strong winds, as verified by the model sensitivity experiments. Because the fog extending over the BB was maintained by the downward surface sensible-heat flux and thermally stratified as a stable layer, this was not typical upslope fog but rather fog caused by radiation or advection.

Meanwhile, the VIS simulated in the present study was calculated from only the CWC value and consequently required an inclusion of the effects for the spatio-temporal fog-droplet number concentration (CNC). The double-moment microphysics scheme in the model can address this problem and achieve more precise VIS simulations (Gultepe et al., 2017), which will be approached as a fog prediction issue in our future study.

Finally, a practical application of dense fog prediction was discussed using $\theta_e$. A difference in $\theta_e$ between the base of mountain and Beppuwan IC located at the midslope in the mountain was available for the VIS forecasting prior to the upslope fog stage in this study area. When the $\theta_e$ value simulated at the Beppuwan IC exceeded 45°C, the VIS <200 m if a $\theta_e$ difference <2.5°C.
and VIS <100 m if a $\theta_e$ difference <0.5°C were estimated from the simulation results. These criteria are expected to bring about reductions in missed dense fog forecasting lapses as well as the false alarm rates obtained for the study area.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT
The data presented in this study are available on request from the corresponding author.

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