Large-Scale Gravity Current over the Middle Hills of the Nepal Himalaya: Implications for Aircraft Accidents

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ABSTRACT

Nepal has been the location of a series of fatal aircraft accidents, raising serious concerns about civil aviation security and the safety of passengers. However, significant studies on weather patterns associated with the airports and air routes of the Himalayan complex terrain and their implications for aviation activities are yet to be carried out. The present study numerically reconstructs the prevailing weather conditions and puts forward some possible causes behind the most recent fatal aircraft accident in the foothills of the western Nepal Himalaya at 0730 UTC (1315 LST) 16 February 2014. The weather patterns have been numerically simulated at 1-km² horizontal grid resolution using the Weather Research and Forecasting (WRF) modeling system. The reconstructed weather situation shows the existence of a low-level cloud ceiling, supercooled cloud water and hail, trapped mountain waves, supercritical descent of a strong tail wind, and the development of turbulence at the altitude of the flight path followed by the aircraft. The aircraft might have gone through a series of weather hazards including visibility obstruction, moderate turbulence, abnormal loss in altitude, and icing. It is concluded that the weather situation over the region was adverse enough to affect small aircraft and therefore that it might have played an important role leading to the fatal accident. The development of hazardous weather over the region may be attributed to a previously unanticipated large-scale easterly gravity current over the middle hills of the Nepal Himalaya. The gravity current originated from the central high Himalayan mountainous region located northeast of the Kathmandu valley and traveled more than 200 km, reaching the foothills of the western Nepal Himalaya.

1. Introduction

The Himalayan complex terrain effectively modifies synoptic-scale weather systems and forms its own characteristic mesoscale systems. These mesoscale flows may trigger highly localized extreme weather (Regmi et al. 2003; Regmi and Maharjan 2015). Thus the weather patterns associated with middle hills of the Nepal
Himalaya have remained beyond the current forecast capability. Unpredictable weather patterns together with the extreme topographic complexities of the region often pose unprecedented risks for aviation activities in Nepal (Regmi 2014a). Moreover, Nepalese airports are mostly located in deep valleys, narrow river basins, short strips on mountain slopes, or in the southern plains in proximity to high Himalaya Mountains. Air routes connecting these airports cross numerous high mountain ridges, pass through mountain gaps, and often plunge deep into and follow innumerable narrow winding river gorges.

Indeed, Nepal has been the location of a series of aircraft accidents. Since the first aircraft accident in 7 May 1946, there have been 32 fatal accidents, with 701 casualties and numerous other minor accidents. These frequent aircraft accidents have raised serious concerns about civil aviation and the safety of passengers. However, necessary thought and serious research on aviation weather hazards are yet to be seen in the country. To our best knowledge, no comprehensive numerical and observational studies on the prevailing meteorological conditions or aviation weather hazards have been reported from the region except a couple of preliminary numerical simulation studies on the aviation weather hazards (Regmi 2014a) in the sky of the Thada waypoint in the southern foothills of Mount Masina Lek (see Fig. 1 for location) and over one of the world’s extreme airports, the Jomsom Airport (Regmi 2014b; see Fig. 3 for location).

Recent studies using high-resolution meteorological modeling systems were devoted to investigating extreme phenomena that affected aircraft via turbulence. For example, Kim and Chun (2010) analyzed clear-air turbulence (CAT) at altitudes of 9–12 km over South Korea with a high-resolution Weather Research and Forecasting (WRF) modeling simulation. With the WRF simulation, Kim and Chun (2012) also investigated severe turbulence at an altitude of 11.2 km above mean sea level (MSL) generated by strong vertical wind shear associated with dissipating deep convection. Sharman et al. (2012) found that a CAT encounter incident of a commercial aircraft at 10-km elevation was due to mountain-wave turbulence by analyzing both digital flight data recorder (DFDR) and numerical simulation results of the Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS; Hodur 1997).

While these studies focus on the turbulence affecting aviation at high altitudes in the lower stratosphere or upper troposphere, this paper investigates a meteorological situation that caused the crash of a small aircraft at a lower altitude in the upper boundary layer. Namely,
the present study thus aims to reconstruct the prevailing weather situation in and around the most recent fatal aircraft accident site (Fig. 1) and to understand the origin of hazardous mesoscale weather systems over the middle hills of the central Nepal Himalaya using the WRF modeling system (Skamarock et al. 2008). The state-run 9N-ABB, DHC6/300 Twin Otter aircraft had a fatal accident at 0730 UTC (1315 LST) 16 February 2014 at an altitude of 2127.5 m MSL on Mount Masina Lek, at 2210-m height, located at 27.91°N, 83.12°E in the foothills of the western Nepal Himalaya (Fig. 2). All 18 people on board lost their lives.

The applicability of the WRF Model to simulate atmospheric processes over complex mountainous terrain has been rigorously tested around the world (e.g., Jiménez et al. 2013; Kumar et al. 2015; Lee et al. 2015), including the Nepal Himalaya. A few examples of WRF modeling over the Himalaya region were in studies of precipitation patterns over the greater Himalaya (Maussion et al. 2014), the large-scale interaction between topography and precipitation (Bookhagen and Burbank 2006), atmosphere–glacier feedback (Collier and Immerzeel 2015), extreme snowfall (Norris et al. 2015), mountain-wave excitations (Regmi and Maharjan 2015), aviation weather hazards over one of the world’s most extreme airports, the Jomsom Airport (Regmi 2014b), and so on. The above examples may demonstrate the strength and suitability of the WRF modeling system for the present study.

2. **Investigation of aircraft accident**

The state-run 9N-ABB, DHC6/300 Twin Otter aircraft departed from Kathmandu at 0610 UTC (1155 LST) on its scheduled flight to Jumla via Pokhara on 16 February 2014 (see Fig. 3 for locations). The aircraft stopped at Pokhara Airport and then departed for Jumla at 0658 UTC (1243 LST). After 25 min, its contact with Bhairahawa Airport was lost from around the Thada waypoint (see Figs. 1 and 3 for locations) beyond 0730 UTC (1315 LST). During the period, the aircraft was requesting permission for an emergency landing citing bad weather ahead toward the destination. The cockpit voice recorder (CVR) readout revealed that the pilots were concerned about possible aircraft icing as hailstones hit the windshields. Just 2 min before it lost contact, the aircraft was in cloud and the copilot was strongly and repeatedly suggesting the pilot in charge not descend. Just a few seconds before it lost contact with the Bhairahawa Airport, the copilot was insisting the pilot in charge not turn the aircraft. The aircraft was found fatally crashed at Mount Masina Lek on the following afternoon. The wreckage was scattered up to 2 km over and beyond Mount Masina Lek, with heavy deposits of graupel/hail on the top of the wreckage (Figs. 2a,b).

The aircraft was flying under visual flight rules (VFR) in instrument meteorological conditions (IMC) from east to west initially at an altitude of about 3.2 km MSL. Upon leaving Pokhara, the pilot in charge realized that the prescribed track to Jumla Airport that passed about 30 km north of Tamghas was not possible because of bad weather and decided to proceed more to the south. After flying for about 25 min from Pokhara Airport, possibly reaching Tansen (see Fig. 1 for location), the copilot planned a route farther south of their position aiming to fly via Dang Valley (see Ghorahi in Fig. 3) and determined a required altitude of about 2.6 km MSL. As the aircraft was not equipped with a flight data recorder (FDR), an exact flight track and a time series of altitude maintained by the aircraft were not available. With its final heading at 280°, the aircraft hit the southern slope of Mount Masina Lek with its left wing first at the altitude of 2127.5 m MSL; it then toppled down to the relatively lower peak (Dihi Danda) on the northern slope of the Lek with multiple impacts (Air Accident Investigation Commission 2014). The cruising speed was not reported but could be about 300 km h⁻¹ as per the aircraft catalog. The accident investigation commission report (Air Accident Investigation Commission 2014) concluded that the most probable cause for the fatal accident was the loss of situational awareness on the part of the pilot in charge while flying into instrument meteorological weather conditions to the extent of collision with terrain, along with the other contributing factors such as deteriorated weather associated with the western disturbance, unstable and embedded cumulonimbus (Cb) clouds, and inappropriate and insufficient crew coordination while changing the course of action.

3. **Model configuration and initialization**

The WRF modeling system was configured and initialized to reconstruct the prevailing weather situation in and around the aircraft accident site as summarized in Table 1. The domain system consists of a triply nested two-way interacting mesh (Fig. 3). The first and second coarse domains include 51 × 51 × 35 grid points, and the horizontal grid sizes are 9 and 3 km, respectively, whereas the third fine domain includes 70 × 70 × 35 grid points with a horizontal grid size of 1 km. The centers of all the three domains were placed at Tamghas municipality in the western development region of Nepal (28.067°N, 83.250°E). The area covered by nested domains and important locations are shown in Fig. 3. A bird’s-eye view of the terrain enclosed by the innermost domain with location details is shown in Fig. 1.
FIG. 2. Wreckage of the 9N-ABB, DHC6/300 Twin Otter aircraft crash in Mount Masina Lek in the western foothills of the western Nepal Himalaya at 0730 UTC (1315 LST) 16 Feb 2014. (a),(b) Heavy graupel/hail deposits around the wreckage indicate rain, snow, and ice on the day of the accident; (c) improved weather the next day. (Photograph: K. Dulal).
The model was initialized with meteorological data from the operational analysis performed every 6 h at the National Centers for Environmental Prediction (NCEP Final Analysis) and the 24-category land-use and 30-s terrain elevation data of the U.S. Geological Survey (USGS). The simulation was carried out for the period of 0000 UTC (0545 LST) 13 February to 0000 UTC (0545 LST) 19 February 2014 with WRF, version 3.4.1. The Thompson graupel scheme (Thompson et al. 2004) for microphysics, RRTM scheme (Mlawer et al. 1997) for longwave radiation, Dudhia scheme (Dudhia 1989) for shortwave radiation, Yonsei University (YSU) scheme (Hong et al. 2006) for planetary boundary layer, and the Noah land surface model (Chen and Dudhia 2001) have been used for the calculation. The WRF output history interval was set at 15 min. For the estimation of subgrid-scale turbulent kinetic energy and other associated quantities, a separate simulation was performed with the MYJ planetary boundary layer scheme (Janjic’ 2001) in place of the YSU scheme, keeping all the other settings the same. Moreover, several test simulations were carried out for several different days with 60-, 30-, and 15-min output history intervals with different physics options as well as different vertical grid points ranging from 23 to 50 vertical levels. Examining the model predictions against the available observations, we have the impression that the above chosen schemes are sufficient to reflect the prevailing weather situation over the region.

4. Results

In the following subsections, we describe model validation and the diurnal and spatial distribution of important meteorological fields, particularly close to the time the aircraft went missing, and examine if they played any deterministic role in the fatal accident.

a. Model validation and overview of synoptic-scale weather

An absence of meteorological observatories in and around the aircraft accident site prevents us from presenting the desired quantitative validation of model predictions. Very limited, scattered, and manually collected surface observations—such as minimum and maximum temperatures, humidity, rainfall, and wind speed—and a few satellite images were available for us to check the rationale of model predictions. Nevertheless, the observed patterns of these meteorological parameters are well reflected in model predictions (Figs. 4a–e). Moreover, a series of 10.3-μm Fengyun 2E (FY-2E) satellite images from 0531 to 0902 UTC [e.g., Fig. 4f at 0732 UTC (1317 LST)] 16 February 2014 reveals a southwesterly movement of clouds over the region consistent with the predicted southwesterly synoptic wind at 500 hPa (Fig. 11f; Fig. 11, which shows the
Fig. 4. Comparison of calculated and observed (a) daily min temperature, (b) daily max temperature, (c) relative humidity, (d) rainfall at different stations, and (e) diurnal variation of wind speed at 30-m height above the ground at Neta located 20 km west of Mount Masina Lek. Satellite images: (f) FY-2E 10.3-μm cloud image at 0732 UTC (1317 LST) and (g) 11.45-μm Suomi-NPP satellite at 0720 UTC (1305 LST) 16 Feb 2014. The center of the dotted circles in (f) and (g) at the central area of each image shows the aircraft crash site.
calculated winds in domain 1, will be discussed in detail later in section 4d); the southwesterly is a geostrophic wind as inferred from the geopotential height distribution at 500 hPa in Fig. 11c. The pattern and types of clouds clearly suggest the presence of both low- and high-level clouds over the region. The high Himalayan mountainous region, the Tibetan Plateau, eastern India, Bangladesh, and northern Myanmar appear heavily cloud covered. Southern parts of far-western and west-central Nepal appear relatively less cloudy. Patches of convective clouds can be seen along the flight paths of the aircraft, Kathmandu–Pokhara–Mount Masina Lek. The cloud pattern over and around Mount Masina Lek indicates deep convection over the area as shown by a dashed circle in Fig. 4f. Likewise, the 11.45-μm image received from the VIIRS sensor on the Suomi National Polar-Orbiting Partnership (Suomi-NPP) satellite at 0720 UTC (1305 LST) 16 February 2014 (Fig. 4g) shows cold tops over and around the aircraft accident site (dashed circle in central area) confirming convective clouds over the area and a front to the northern and northeastern high Himalaya areas including the northeast of Kathmandu valley (27.7°N, 85.3°E). The image also suggests the development of barrage clouds over the mountainous areas north, east, and south of the Kathmandu valley by the synoptic southerly and southwesterly flow above 700 hPa shown in Fig. 11e and 500 hPa in Fig. 11f.

A large-scale easterly flow originating from high mountains and valleys located northeast and east of the Kathmandu basin can be found in central Nepal in the calculated flow field at 850 hPa in Fig. 11d. The convective cloud near Mount Masina Lek (shown with a circle in the satellite image of Fig. 4f) partially supports that the strong convection (see Figs. 6a,b, shown below) was formed by the convergence of this large-scale easterly with the flow from southern plains (Fig. 5c). It will be discussed later that this easterly layer has the nature of a gravity current with a depth of about 1 km (see Figs. 10a,b, which will be discussed in detail later in section 4d).

Furthermore, model predictions of weather events have been found to be consistent with information gathered by interviewing local witnesses, CVR readout, and site inspections (Aircraft Accident Investigation Commission 2014). Heavy deposits of graupel/hail on the top and beneath the wreckage of the aircraft (Figs. 2a,b) confirm graupel/hail-fall before and, particularly, after the accident, indicating that the weather became even worse after the accident. An improvement in the weather situation, as reported, from the evening of 16 February 2014 is well reflected in the afternoon picture of the search and rescue efforts (Fig. 2c) the next day.

In reference to the available surface observations and satellite imagery, numerical predictions are expected to represent the prevailing weather situations over the area during the day and at the time of the 9N-ABB, DHC6/300 aircraft accident on 16 February 2014.

b. Local flow characteristics

Weather conditions are often manifested in the characteristics of local flows. Thus, understanding the spatial and temporal distributions of local flows over the area of interest is important to assess prevailing weather features and their impacts. In this subsection we will discuss the spatial and temporal distribution of local flows in and around the aircraft accident site on 16 February 2014. Figure 5 shows the spatial distribution of the near-surface wind there at about 27 m above the ground level (AGL) at some representative times. According to weather reports from the meteorological authorities of Kathmandu, Pokhara, Ghorai, etc., the skies over those mountain areas in central Nepal remained heavily cloud covered from early morning to late afternoon on 16 February 2014 (Aircraft Accident Investigation Commission 2014). Thus, there was no favorable condition for the development of the usual up-valley wind during the daytime. In this meteorological background, the typical nighttime drainage flows (Fig. 5a) remained relatively the same even at 0415 UTC (1000 LST) as shown in Fig. 5b. After 0415 UTC (1000 LST) the local flow pattern becomes more dominated by westward winds with the intrusion of a large-scale easterly flow (a gravity current to be discussed later); the near-surface speed of the easterly was about 8–12 m s⁻¹ around noontime (Fig. 5c). During the aircraft accident time, 0730 UTC (1315 LST), the easterly flow was creating convergence with the southwesterly flow over about a 20-km distance along the line A–B crossing over the mountain pass located east of Mount Masina Lek (Fig. 5c). Over and around Mount Masina Lek, the deep easterly layer reaching up to 2 km MSL was entirely covering the Chutrabeshi valley (see Fig. 1 for its location) and partly covering its south-bordering mountains (Fig. 5c); this easterly flow, together with the southwesterly flow from the southern plains, formed a strong updraft aloft over Mount Masina Lek (Figs. 5c and 6a), which became more pronounced a little later (Fig. 6b).

The easterlies over the almost regularly undulating topography to the east of Mount Masina Lek exhibited the nature of trapped mountain waves (e.g., Scorer 1949; Durran 1990; Doyle and Jiang 2006) capped by a zero-flow critical layer. The amplitude of the wave over the region appears to be more than 200 m (Figs. 6a,b). The overturning structure of the potential temperature
contours (Clark and Peltier 1977; Nicholls 1973), particularly around 30 km east of Mount Masina Lek, is of particular interest as it reflects the occurrence of turbulence (Nastrom and Fritts 1992; Lilly 1971). The cross-sectional distribution of zonal wind (see regions indicated by dotted circle in Figs. 6a–f), in fact, show some signature of wind reversal and hence formation of a weak rotor at about 2.5 km MSL over the Khidim area (Fig. 1) along the flight path of the aircraft. A series of rotating flows, though not well resolved in the present simulation with a relatively large grid size, formed over the undulating topography (Figs. 6a,b,e,f) and likely forced unstable aircraft movement that offers considerable risks for low-level aviation (Parker and Lane 2013; Wurtele et al. 1996). Actually, the shear instability and hence the turbulence at the head of gravity current and near the top of its following flow can be resolved in detail with small grid size like 100 m for 30 km in

Fig. 5. Horizontal distribution of calculated near-surface wind in domain 3 at (a) 0545 UTC (1130 LST), (b) 0415 UTC (1000 LST), (c) 0730 UTC (1315 LST) when the aircraft crashed, and (d) 1115 UTC (1700 LST) 16 Feb 2014. In (c), the crash site (Mount Masina Lek) is shown with a red circle, and line A–B, located about 10 km east of the Lek, indicates the southeast–northwest convergence line between easterly (the large-scale gravity flow) and southerly from southern plain area. Vertical cross sections of wind, potential temperature, humidity, TKE, etc. along the line C–D in (d) are discussed in the main text.
FIG. 6. Vertical cross section of potential temperature and horizontal (zonal) and vertical winds along a west–east line (line C–D in Fig. 5d) passing through the peak of Mount Masina Lek (2210 m MSL): (a) 0730 UTC (1315 LST), (b) 0745 UTC (1330 LST), (c) 1115 UTC (1700 LST), and (d) 1515 UTC (2100 LST). (e),(f) As in (a) and (b), but for zonal wind speed at 0715 UTC (1300 LST) and 0730 UTC (1315 LST), respectively. The area with circle in (a) and dashed circles in (e) and (f) at 2–2.5 km MSL shows strong wind shear/turbulent zone associated with mountain waves triggered by the easterly (the large-scale gravity flow). Dashed–dotted line in (a)–(f) indicates freezing temperature level. Mount Masina Lek (the aircraft accident site) and others are shown with short thick arrows.
horizontal distance (Droegemeier and Wilhelmson 1987). Perhaps, the use of a large (1 km) horizontal grid size and about 300-m vertical spacing in the layers from 500 to 3 km high was not sufficiently fine enough to fully resolve the turbulence associated with the present gravity current at its front and at the upper part of the following flow. In this situation, by examining the calculated wind fields at the ground surface, 850, 700, and 500 hPa (Figs. 10a and 11), it can be found that the lower atmosphere is multilayered. Namely, the winds in the middle layers above the height of 700 hPa are synoptic southwesterly winds (more prominent at 500 hPa), while below the height of 850 hPa, easterly winds dominate in the focused area. This suggests that the layer of synoptic southwesterlies caps the easterly layer and that the southwesterly layer suppresses upward propagation of the mountain waves generated by the underlying topography beyond 2.5 km MSL. Vertical profiles of potential temperature plotted at several locations east of Mount Masina Lek also suggest that the synoptic southwesterly layer above 2.5 km MSL is much more thermally stable than the lower layer, and thus dissipates the mountain-induced energy (Fig. 7a). A vertical cross section of the Richardson number (Fig. 7b) also shows large positive number in the layer between 2.5 and 3 km MSL. Meanwhile, the cross-sectional plots of zonal wind velocity (Figs. 6e,f) also show a zero wind layer, that is, a critical layer above 2.5 km MSL. All these facts further suggest that the waves developing over the undulating terrain east of Mount Masina Lek are trapped beneath 2.5 km MSL. It is believed that the natural features, such as horizontal wavelength (~10 km), of the mountain waves produced over a series of underlying hills are mostly regulated by the characteristics of the topography such as distance between the hills and height of the hills above the ground as can be seen in the vertical cross section of the horizontal wind vectors, vertical wind velocity, and the potential temperature.

As we discussed, at about 1000–1200 m above the ground (2000–2400 m MSL), a turbulent layer is expected because of mountain waves, circulations, and wind shear induced by the easterly flow over the mountain range extending more than 30 km in horizontal distance from Tansen to Bhimbari (see circled area in Figs. 6a,e,f). This turbulent layer at about 2.3 km was also related to the convergence of horizontal winds east of Mount Masina Lek. Figure 7 shows the horizontal distribution of turbulent kinetic energy (TKE) at 2.1 km MSL (Fig. 7c) and its cross-sectional distribution (Fig. 7d) as well as the eddy dissipation rate (EDR) (Fig. 7e) along the line C–D of Fig. 5d. EDR was estimated using TKE and eddy length scale $L_E$, which were separately obtained by a simulation with MYJ planetary boundary layer scheme in WRF-ARW following the method of previous studies with MYJ (Ahmad and Proctor 2012),

$$\text{EDR} = [0.238(\text{TKE} - 0.1)^{3/2}/L_E]^{1/3},$$

where EDR is in meters to the two-thirds power per second, $L_E$ is in meters, and TKE is in meters squared per second squared. The maximum value of EDR is about 0.2 and 0.25 m$^{2/3}$s$^{-1}$ over the eastern slope of Mount Masina Lek and over the eastern undulating mountains, respectively (Fig. 7e). Although the obtained EDR appears to be less than the moderate turbulent intensity for large aircraft (e.g., Lane et al. 2012; Kim et al. 2014), it could be more significant for small aircraft such as a Twin Otter (DHC6/500) with a length of 16 m and width of 20 m.

The model also predicted that the large-scale easterlies stopped at around 0915 UTC (1500 LST); then a local down-valley wind (northwesterly) started and eventually reached Mount Masina Lek to form a convergence with the southwesterlies from the southern plains at about 1115 UTC (1700 LST), resulting in an enhanced vertical motion that exceeded 400 cm s$^{-1}$ (Fig. 6c) and was a convective updraft. After 1215 UTC (1800 LST) the Mount Masina Lek area was totally covered with a local down-valley wind from the north, and the strong convergence at the mountain vanished (Fig. 6d).

The appreciable convection induced by Mount Masina Lek and other nearby mountains can also make a significant contribution to the transport of water vapor and cloud constituents to upper layers (e.g., Miller et al. 1988; García-Ortega et al. 2006) below the freezing point temperature. The freezing temperature (see dashed–dotted line) lies just above (Fig. 8a) or below (Fig. 8b) the top of Mount Masina Lek, at an actual height of 2210 m MSL. From the vertical structure of the wind and potential temperature shown in Figs. 6, 7, and 8, it can be said that the whole area from Tansen to Mount Masina Lek comprises significantly hazardous flow fields most of this time for low-level aviation activities. In the evening, pronounced drainage flows commenced from the high Himalaya along the river valley down to the Churban valley and associated areas (Fig. 5d) and finally resumed almost the same pattern of the previous night by midnight.

c. Hydrometeor characteristics

Understanding the hydrometeor characteristics along the flight path of an aircraft helps to assess the risks of inflight icing (Cober et al. 2001). Inflight icing is determined to be a cause or factor for poor efficiency as well as for numerous fatal aircraft accidents (e.g., Marwitz 2013; Marwitz et al. 1997). To assess the
FIG. 7. Boundary layer characteristics at the time of aircraft accident 0730 UTC (1315 LST) 16 Feb 2014. (a) Vertical profile of potential temperature at three locations east of Mount Masina Lek; (b) vertical cross section along C–D of Richardson number; (c) horizontal distribution of TKE at 2.1 km MSL; (d) as in (a), but for TKE; (e) as in (a), but for EDR.
FIG. 8. Vertical cross sections of (a),(b) temperature and (c),(d) relative humidity along line C–D in Fig. 5d, and (e),(f) WRF Model soundings in the immediate vicinity of Mount Masina Lek, i.e., over the western mouth of the Chitrabasi valley (Fig. 1) at the northern foothills. The dashed–dotted line in (c) and (d) shows freezing temperature level. The capping dashed curved above Mount Masina Lek is drawn to indicate the actual height of the Lek.
hydrometeor situation along the flight path of the 9N-ABB, DHC6/300 aircraft, we examine the vertical distribution of temperature, humidity, and cloud water and graupel mixing ratios in the cross section along the west–east line that passes through the top of Mount Masina Lek (line C–D in Fig. 5d). The diurnal distribution of ambient temperature shows that the layer of the atmosphere at about 2300 m MSL, which lies just above Mount Masina Lek (2210 m MSL) persistently has temperatures at or below the freezing point (e.g., Fig. 8a) during the afternoon. The freezing level appears to come down well below the top of Mount Masina Lek during the night (not shown) and in the late afternoon (Fig. 8b).

The presence of a fully saturated air mass at and below the freezing temperature level (e.g., Figs. 8c,d) over Mount Masina Lek and the Tansen-Khidim area, the convective instability due to convergence of the characteristic local flows (Figs. 5c and 6a–c), and decreasing of temperature up to −20°C at 500 hPa from 0°C at 750 hPa (e.g., Figs. 8e,f), as well as the flow fields (Figs. 6a–c), strongly suggest a highly favorable environment for the formation of supercooled water and graupel during the afternoon. Indeed, the cloud water mixing ratio appears to increase from about 0.48 g kg$^{-1}$ (Fig. 9a) during the aircraft accident time to about 1.28 g kg$^{-1}$ in the late afternoon (Fig. 9b). Likewise, the distribution of graupel mixing ratio appears to vary from 0.14 g kg$^{-1}$ (Fig. 9c) around the aircraft accident time to about 0.3 g kg$^{-1}$ in the late afternoon time (Fig. 9d). Beyond 1315 UTC (1900 LST), both the cloud water and the graupel mixing ratios remain negligible (not shown) after the Mount Masina Lek area was entirely covered by the mountain (down valley) winds from the nearby Himalaya Mountains at around 1215 UTC (1800 LST) (not shown).

In consideration of the characteristic distributions of flow and the hydrometeors, leading to and associated with the development of convection during the afternoon, it can be said that the prevailing weather is likely to support lightning, thunder, and hailstorm activity (e.g., Borovikov 1963; Mossop 1970; Schichtel 1988; García-Ortega et al. 2006) in and around Mount Masina Lek in the afternoon and especially in the late afternoon. However, formation of large-sized hail is not expected over the region because the convective available potential energy (CAPE) shown in Figs. 9e,f over Mount Masina Lek during the period of the aircraft accident varied from only 140 J kg$^{-1}$ just above the top of the Lek down to the value of 50 J kg$^{-1}$ at the height of 2.5 km MSL (Fig. 9e) during the aircraft accident time. However, the CAPE value in the particular area can reach up to 300 J kg$^{-1}$ over the area west to Mount Masina Lek and about 220 J kg$^{-1}$ over the eastern slope of the Lek and particularly over the Bhimbari area (Fig. 9f) during the late afternoon.

Heavy deposits of graupel/hail on the top as well as under the wreckage of the aircraft (Figs. 2a,b) confirm graupel/hail fell before and after the accident. It appears that the weather was bad during the accident time and became even worse after the accident. The improvement of the weather the next day as predicted in our simulation is well reflected in Fig. 2c. Furthermore, the aerial search and rescue teams of the Nepal Army using helicopters were reported to have abandoned their operation from late afternoon on 16 February 2014 because of extremely bad weather. Similarly, the local people reported (Aircraft Accident Investigation Commission 2014) that they had witnessed a severe weather situation with rain, lightning, and hail in the afternoon and greatly improved weather in the evening. These reported weather events, though scarcely scientific and definitive, are well reflected in the model simulations.

d. Large-scale gravity current

The strong easterly flow that intrudes into the region close to noontime (e.g., Figs. 5c and 6a,b) appears to have played a decisive role in forming a low-level hazardous weather situation over the region. Thus it is worth exploring the characteristic behavior and origin of this easterly flow. The vertical cross section of winds and potential temperature (Fig. 10b) together with the horizontal wind fields at surface level (Fig. 10a) and at 850 hPa (Fig. 11d) at 0730 UTC (1315 LST) show that the easterly reaching Mount Masina Lek around noon-time is a deep large-scale local flow ranging over more than 200 km horizontally. Examining the horizontal geopotential height distributions (Figs. 11a–c) and their corresponding wind fields in Figs. 11d–f at different levels of 850, 700, 500, and 200 hPa (not shown) in the largest simulation domain, the flow field over the central Nepal area is found to be multilayered; that is, there prevail geostrophic winds such as a westerly at 200 hPa (~12 km MSL), a southwesterly at 500 hPa (~5 km MSL), and a weaker southwesterly and westerly at 700 hPa. However, no strong synoptic-scale flow is found at 850 hPa (a height close to that of the Kathmandu valley, 1350 m MSL). An absence of appreciable synoptic-scale pressure gradient in the south of the Himalaya Mountains that is apparent in the geopotential height distribution at 850 hPa (Fig. 11a) makes the region just suitable for the development of a large-scale down-valley/mountain wind as a gravity current. From Fig. 10b (vertical cross section) and Figs. 10a and 11d (horizontal flow field), the “large-scale easterly” could be regarded as down-valley/mountain wind because of...
FIG. 9. Vertical cross sections along C–D in Fig. 5d: (a), (b) cloud water mixing ratio, (c), (d) graupel mixing ratio, and (e), (f) CAPE. The horizontal dashed–dotted lines show freezing temperature level at about 2300 m MSL on 0730 UTC (1315 LST) in (a), (c), and (e) and 2100 m MSL on 1115 UTC (1700 LST) in (b), (d), and (f).
Cold air produced in the valley and on the mountain slope at high altitudes above 3 km MSL. Within the calculation domain, the easterly remains predominant in the lower layer from the ground to the height of 2–2.5 km MSL, while in the middle layer (above 700 hPa), synoptic-scale southwesterlies typically prevail (Figs. 11e,f). In and around Mount Masina Lek, the easterly flow interacting with the synoptic southwesterlies formed strong convergence and hence turbulent convective updrafts developed over the area. The development of convective clouds (cold tops) over Mount Masina Lek is clearly reflected in the satellite imagery (Figs. 4f,g) during the aircraft accident time.

From Fig. 10b, it can be observed that the depth of this easterly flow is about 1000–1200 m and is 1–2 K colder than the ambient air ahead of the tip of the “easterly flow.” To examine nature of the easterly flow as a gravity current, we have made a simple theoretical calculation (e.g., Simpson 1987). With the assumption that the easterly flow is a gravity current, its speed can be evaluated by using a simple theoretical model:

\[
U = \left[\frac{(\Delta T)}{T}gH\right]^{1/2},
\]

where \(\Delta T\) is the temperature difference between the gravity flow and ambient air; \(T\) is the temperature, that is, potential temperature in the present case, of ambient air into which colder air is intruding; \(g\) is the gravitational acceleration; and \(H\) is the depth of the cold air.

The substitution of the values for \(\Delta T=1\text{–}2\text{ K},\ T=294.5\text{ K},\ g = 9.8\text{ m s}^{-2},\) and \(H=2000\text{ m}\) in Eq. (1) in reference to Fig. 10b, yields \(U \approx 8.2\text{–}11.5\text{ m s}^{-1}\). The value of \(H\) stands for a “total depth” of the cold air layer including the depth of the cold air at its origin of about 1200 m plus the gap of the ground elevation between valley floor and the place of origin, which is about 800 m (Fig. 10b). The estimated wind velocity is close to the speed of the near-surface easterly flow described earlier as well as the afternoon measured wind speed at Neta station located about 20 km west of Mount Masina Lek (Fig. 4e). The increased wind speed observed at Neta during the afternoon, we believe, was due to the arrival of the large-scale gravity current over the region. Thus the large-scale easterly flow over the area is possibly a gravity current/down-valley wind.

The large-scale gravity current (Figs. 10a,b) appears to start from the area of high mountains and deep valleys located northeast of Kathmandu valley (27.7°N, 85.3°E). The thin layer of lower potential temperature as indicated by folded contours adjacent to the ground over the slopes of steep mountains near the eastern boundary of the calculation domain and its gradual increase in the depth farther downward (Fig. 10b) suggest that the
FIG. 11. Multilayer flow fields over the central Nepal Himalaya region by the WRF Model simulation. (a)–(c) The geopotential height and (d)–(f) flow fields are shown, respectively, at 850, 700, and 500 hPa at 0730 UTC (1315 LST). The H and L in (b) and (c) show high and low pressure regions, respectively. Winds at 700 and 500 hPa clearly show their nature as geostrophic winds, while those at 850 hPa demonstrate they are rather local winds. The filled black circles at the center and dotted circles in the middle of right edges of each figure, respectively, show the aircraft accident site and the Kathmandu valley.
large-scale easterly gravity current first originated from that area. Over the origin area of the easterly, north and northeast of the Kathmandu basin, southwesterly flows above 700 hPa (Fig. 11e) and 500 hPa (Fig. 11f) prevail. Under these conditions, a continuous supply of humid air above the 700-hPa pressure level over the area can be expected, and this helps to sustain both the formation of clouds (as indicated in Fig. 4f,g) and snowfall over the area for a long time. Thus cloud shading, radiational cooling, and frequent downbursts of cold air in association with the convective cloud activity triggered by the synoptic southerly/southwesterly all appear to contribute to the development of persistent low surface temperatures over the area north and northeast of the Kathmandu valley. As a result, continuous cold air outbreaks may have led to the easterly gravity current that was aligned by the characteristic topography in central Nepal. Then the easterly current traveled for more than 200 km and reached Mount Masina Lek. The typical confinement of the easterly gravity current within a narrow south–north band appears to have been effectively regulated by the characteristic topography (the east–west elongated basin-shaped terrain structure between the Himalaya high mountains and the southern low mountain chains) of the region. While reaching Mount Masina Lek, a rather isolated peak, it is partially blocked with no lee jump (Bains 1995) leading to a flow toward the northwest intermingling with thermally induced southwesterly upslope flows in and around the Lek. Part of the easterly flow created convergence around Mount Masina Lek with the southerlies from the southern lowlands at the top of the Lek. This convergence resulted in strong convective cloud activity, which possibly contributed to the aircraft crash.

The weather over the Kathmandu valley and its surroundings was relatively clear at night on 15 February 2014 and in the early morning of 16 February 2014, but later in the morning and in the afternoon the weather was cloudy. Thus it can be inferred that the large-scale easterly flow tends to occur in cloudy weather during daytime over the large central Nepal area under a rather weak synoptic-scale south–north pressure gradient due to the position of the high pressure belt (e.g., Riehl 1979).

This can be inferred from the geopotential height distribution at 500 (Fig. 11c) and 200 hPa (not shown), which suggests that a west–east high pressure belt of synoptic scale is located in the southern part of the region as expected, and this can affect the midlayer winds and hence a westerly develops in the upper layer (Fig. 10b). These weather situations over the region are some of the necessary conditions for the development of large-scale gravity current/down-valley winds and are reasonably well satisfied. The development of a local high pressure area around the Kathmandu valley may be considered a result of the cold air produced and accumulated into the valley as revealed by the distribution of geopotential height at 850 hPa. It is important to note that the development of this large down-valley wind is not frequent in central Nepal. We have noticed this development only two or three times in February of 2014 and 2012, for example, on 8 February 2012 (not shown).

5. Implications for 9N-ABB, DHC6 aircraft accident

Examination of the characteristic distribution of local flows and hydrometeors against the flight history of the 9N-ABB, DHC6/300 aircraft suggests that weather factors were largely responsible for the fatal aircraft accident; first, strong southwesterlies in the middle layer at 3–5 km MSL forced the small aircraft to fly at lower heights of 2–3 km MSL that were just below the cloud ceiling height or sometimes in the clouds; second, at lower height around 2–2.5 km MSL, the strong easterly, as the large-scale down-valley wind, produced a turbulent atmospheric situation at and around Mount Masina Lek. Because of these meteorological conditions, it appears that the aircraft might have gone through a series of difficulties and finally crashed over Mount Masina Lek. Some of the important possibilities will be summarized in this section.

The hazardous weather situation appears to be intimately connected with an exceptionally large-scale easterly gravity current (Figs. 5c, 6a,b, 10a,b) originating from the high Himalayan mountainous region northeast of the Kathmandu valley, discussed in the subsection 4d. The gravity current over the undulating topography east of Mount Masina Lek exhibited the nature of trapped mountain waves with an amplitude of more than 200 m capped by a zero-flow critical layer. Thus, the top of the gravity current at about 1000–1200 m AGL (2000–2400 m MSL) was highly turbulent (see turbulent kinetic energy distribution in Fig. 7b) because of the strong wind shear and the “trapped” mountain waves forming a series of rotating flows (Figs. 6a,b,e,f) and the convergence of horizontal winds to the east of Mount Masina Lek. In consideration of the cruising height of the 9N-ABB, DHC6/300 aircraft at 2400 m MSL with speed 300 km h \(^{-1}\) (about 5 km min \(^{-1}\)), the aircraft can be expected to have reached the turbulent region (Tansen-Khidim) 25 min after its departure from Pokhara Airport. It is thus inferred that the turbulent layer at the top of the gravity current together with the up and down flows over the area may have forced the aircraft to lose control after the 25-min flight from Pokhara.
Moreover, at about 10 km east of Mount Masina Lek or at the place 2 min before the crash (Bhimbari, see Fig. 6a for location), a relatively strong upward flow prevailed because of the sharp convergence of the easterly gravity current and the up-valley flow from the southern plains (Fig. 5c). From an aviation perspective, the immediate atmosphere over the area also appears to have supported a strongly unstable turbulent situation. At this point, we speculate that as the aircraft plunged into the region, it might have undergone an unexpected loss of altitude between Khidim and Bhimbari (which may be the reason the copilot strongly suggested they not descend), and then the aircraft was successively hit by the strong upward flow over the Bhimbari area leading to a complete loss of control. Further altitude loss would have been expected had the pilot in charge tried to pull up the nose of the aircraft in an attempt to compensate for the abnormal loss in altitude in the presence of an upward tail wind over the eastern slope of Mount Masina Lek. The Paradise Airline crash in the Sierra Nevada (Wurtele 1970) was attributed to similar meteorological conditions.

The adverse weather situation over the region further extends into microphysical processes. During the flight from Tansen to Mount Masina Lek, the weather conditions appear to be highly conducive for aircraft icing (Fernández-González et al. 2014; Korolev et al. 2007; Ellrod and Bailey 2007). A fully saturated deep layer (Fig. 8c) below freezing temperatures (Fig. 8a) can be seen together with the presence of significant amounts of cloud water (Fig. 9a) and graupel mixing ratios (Fig. 9c). All of these with a rather low amount of surface rainfall (not shown), low-level cloud ceiling (also not shown), and the CAPE (Fig. 8e) suggest that a quite favorable environment for icing and severe loss in visibility was present along the flight path followed by the aircraft at an altitude of 2.4 km MSL. The thick layers of snow and ice apparent in the pictures taken in the afternoon of the next day (Figs. 2a,b) may provide necessary evidence that there had been significant-scale snow and hail on the day of 16 February 2014.

Based on the reconstructed weather situation over the region and, particularly, along the flight path followed by the aircraft, it can be said that the weather situation became extremely hazardous for the 9N-ABB, DHC6/300 aircraft during the day of 16 February 2014. In consideration of freezing temperatures of a fully saturated air mass at the height of the flight path, trapped mountain-wave excitations, supercritical descent of an easterly flow and its convergence initiating appreciable vertical convection, as well as development of turbulence over the immediate eastern area of the crash site, it can be said that the aircraft could have gone through a series of hazards such as visibility obstructions, severe turbulent motion, icing, and abnormal loss of altitude and control. It is concluded that the weather situation over the region was adverse enough for small aircraft, and hence it might have played an important role in leading to the fatal accident.

The hazardous weather conditions can be largely attributed to a previously unanticipated exceptionally large-scale easterly gravity current over the middle hills of the Nepal Himalaya. The gravity current occasionally originates from the high Himalayan mountainous region located northeast of the Kathmandu valley. The gravity current over the undulating topography east of Mount Masina Lek exhibited the nature of trapped mountain waves with an amplitude of more than 200 m capped by a zero-flow critical layer. The top of the gravity current at about 1000–1200 m AGL (2000–2400 m MSL) thus remained highly turbulent because of the prevalence of a strong wind shear, the flow associated with mountain waves, and the convergence of horizontal winds at the east of Mount Masina Lek (Figs. 6a,b).

The study also revealed that the region from Tansen to Mount Masina Lek and farther west can generate hazardous turbulence for small aircraft provided easterly winds with suitable speed pass over the almost regularly undulating topography under the designated domestic flight path for the western region of Nepal. It is noted that this is one of the regions in which light aircraft report experiencing severe jerks most frequently; in fact,
an aircraft had already gone missing from the same area in 2011.

However, it should be noted that knowledge generation, understanding, and the interpretation of weather impacts for the 9N-ABB, DHC6/300 aircraft accident have been achieved as revealed by a numerical simulation. Lack of meteorological observatories in and around the crash site prevented us from realizing rigorous validations of model predictions. Thus, the findings of this investigation should be viewed with this limitation.

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