

Article

Impacts of Erratic Snowfall on Apple Orchards in Kashmir Valley, India

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Abstract: Kashmir Valley has been witnessing erratic snowfall events in recent autumns which severely impacted apple orchards and harvests. Here, we combine remotely sensed data and field observations to map snowfall distribution and snow depths during the recent snowfall events in November 2018 and November 2019. Besides, we used ERA-5 reanalysis climate datasets to investigate the causes of these erratic snowfall events, pointing to an early arrival of Western Disturbances (WD) to the area. Analysis of these untimely snowfall episodes indicates that snow depths varied from 5–122 cm and 31–152 cm during the 2018 and 2019 snowfall events, respectively. In turn, satellite data analysis reveals that the apple orchards cover roughly 9.8% (1329 km²) of the entire surface of Kashmir Valley, out of which 32.6% were mildly to severely damaged by snow. The areas in South Kashmir suffered the most from the untimely snowfall with an area affected estimated to ~264 km², followed by North Kashmir (~151 km²) and Central Kashmir (18 km²). The snowfall caused substantial harvest losses in orchards ranging from 4–50% with an average of ~35%. The geopotential analysis from the ERA-5 dataset provides insights into the synoptic weather patterns leading to the snowfall events and point to a trough in the high-troposphere (200 mb), along with a col at lower levels (850 mb) over the Kashmir Valley from November 2–5, 2018. The lower levels (850 mb) experienced intense cyclonic circulation which favored advection of moisture from the Arabian Sea during the November 6–7, 2019, snowfall event. The large economic losses related to early arrival of WD led to a virtual grounding of the horticultural sector in 2018 and 2019. Therefore, more baseline research is critically needed along with a comprehensive evaluation of the suitability of horticulture as an economically viable sector that is being promoted over the Kashmir region, also under climate change.

Keywords: snowfall variability; western disturbances; erratic snow precipitation; Kashmir Himalaya; horticulture

1. Introduction

The Himalayan region constitutes one of the most vulnerable areas as it suffers from extreme weather events under present climate conditions and also in light of climate projections [1]. Over the

last few decades, changing climate has had adverse impacts on several processes and key ecosystems to human wellbeing across the Himalayan arc, including the quantity and seasonality of snow cover [2–4], glacier changes [5,6], natural disasters [7,8], and land degradation and vegetation cover changes [9,10], with repercussions on strategic socio-economic sectors, such as hydropower [11,12], tourism [13,14], and, ultimately, on local livelihoods [15–17]. According to the observational records and climate projections, the ongoing climatic change over the Himalayas has not only impacted the pristine ecosystems and earth surface processes but also altered weather circulation patterns over the region [18,19].

Kashmir Valley, with an area of $\sim 15,000 \text{ km}^2$, is a nappe zone interlaced between the Greater Himalayas and the Pir Panjal Range (Lat: $33^\circ 22' - 34^\circ 42' \text{ N}$; Lon: $73^\circ 54' - 75^\circ 35' \text{ E}$) in northern India (Figure 1).

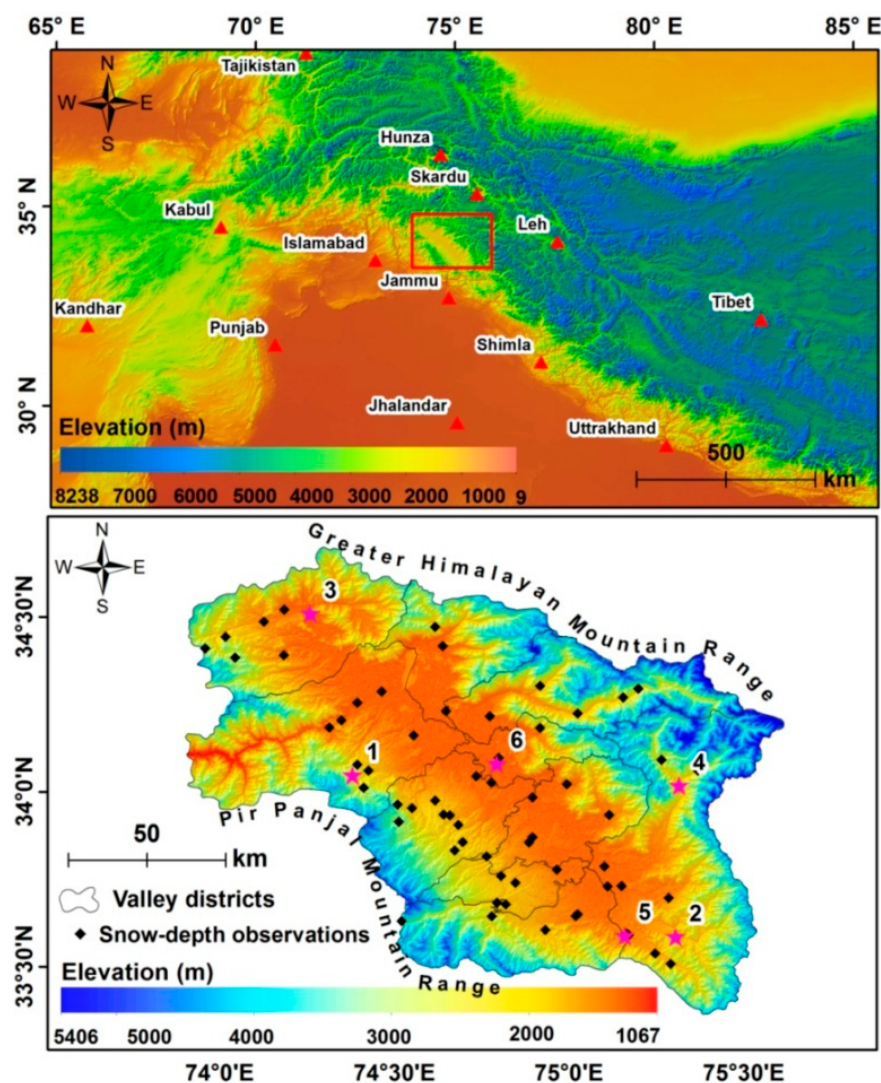


Figure 1. Location of the study area. **Top Panel:** Location of Kashmir Valley (shown as a red rectangle) with relevant cities found across the western Himalayas. Background elevation data is from Global Topography 30 Arc Second (GTOPO30). **Bottom Panel:** Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) of Kashmir Valley, a region that is interspersed between the Pir Panjal and the Greater Himalayan Mountain ranges. Stars indicate locations of the six weather stations used in this study: 1—Gulmarg, 2—Kokernag, 3—Kupwara, 4—Pahalgam, 5—Qazigund, 6—Srinagar.

The Kashmir region, located toward the western part of the Himalayan arc, has experienced erratic weather patterns frequently in the past [20–22]; with further warming, erratic weather events are projected to become much more frequent by the end of this century [23]. Erratic weather regimes

have—among others—caused the megaflood of 2014 during which the Kashmir Region suffered massive economic losses totaling 1 trillion INR (corresponding to roughly US\$13.7 billion) [24]. Besides floods [25], the Kashmir Region is also affected by other weather-related events, including the heavy snowfall event in February 2005 which caused widespread damage to infrastructure [26,27].

Climatologically, the Kashmir area belongs to the temperate zone [28,29] characterized by four seasons (spring, summer, autumn, and winter). Srinagar, the region's capital, is located in the center of the valley at an altitude of 1580 m asl. The city receives an annual precipitation of ~750 mm, predominantly during Western Disturbances (WDs), but a weak influence from the Indian summer monsoon exists, as well [30]. The mountains experience more precipitation. Mean seasonal temperatures range from 5–25 °C at Srinagar and decrease along an altitudinal gradient [31,32]. The elevation of the valley ranges from 1073 to 5400 m asl. Kashmir Valley witnessed untimely, widespread snowfall on 3–4 November 2018 and 6–7 November 2019, driven by WDs. These two erratic snowfall events were not only surprising to the residents but also severely dented the horticultural sector in Kashmir. It is pertinent to mention that the six meteorological stations maintained by the India Meteorological Department in the Kashmir Valley do not gather any information about the snowfall records over the region.

WDs are known to produce severe weather over the northern Indian subcontinent [33]. These synoptic-scale weather systems occur at mid-latitudes during the winter season and originate from frontal systems in the Mediterranean Region [34] before reaching the north-western part of India with the subtropical jet stream [35,36]. WDs advect moisture not only from the Mediterranean basin and the Caspian Sea, but occasionally are also supplied with fresh moisture from the Arabian Sea, which may then cause extreme weather with snowfall or intense rain [33,37]. WDs can also interfere with monsoon activity, which again can enhance the intensity of precipitation events [38]. Much of the snowfall and precipitation recorded in the Himalayas can be attributed to the passage of WD [36,39], and even more so in Jammu and Kashmir where the occurrence of spells of snowfall has been linked to the occurrence and persistence of WDs, which often last from 2 to 4 days [40]. Besides, the occurrence of WDs has also been linked to the occurrence of floods or snow avalanches [41]. Linking such extreme events with the intra-seasonal occurrence of WDs is important, not only to forecast future events [34], but also to anticipate intra-sectoral impacts in a context of climate change, for which enhanced WD activity is expected in the region [42].

In this paper, we focus on the causes and impacts of the erratic snowfall events that took place in early November 2018 and November 2019. By doing so, we provide insights into their climate causative factors and analyze snowfall data obtained through the physical surveying of the area at the end of the snowfall event. This was done through the combination of observations with outputs from the European Centre for Medium-Range Weather Forecasts Re-analyses (ERA-5) climate dataset.

2. Materials and Methods

This study relies on a suite of data from remote sensing platforms, ground surveys, as well as ancillary data of damage assessment (Table 1).

Whereas satellite data of 2018 (Sentinel 2A with a spatial resolution of 10m) and 2019 (Landsat 8 Operational Land Imager, OLI) with a spatial resolution of 30 m) provided first-hand insights into the extent of the areas affected by snowfall over the Kashmir Valley, snow depth was measured manually at 65 locations across the Kashmir Region (Figure 1) using a handheld GPS device and a meter scale. Optical satellite data from Sentinel 2A and Landsat 8 OLI was used since none of the datasets captured both the snowfall events. In addition, long-term precipitation data for November have been collected from six meteorological stations across the Kashmir Valley and for the period 1980–2019, so as to gain more insights into the dynamics of late autumn precipitation over the region. Data was collected from the regional center of the India Meteorological Department located at Srinagar. The area under apple orchards was mapped using freely available high-resolution satellite imagery (Basemap in ESRI ArcMap 10.1) for 2016–18 at a scale of 1:5000 employing manual digitization. Since the apple trees are planted in rows and columns, we identified apple orchards based on the pattern using high-resolution

ESRI Base map. Damage assessment data from the orchards affected by the November 2018 snowfall was procured from the Directorate of Horticulture, Kashmir. As damage assessment data for the November 2019 event are still under compilation, we inferred information remotely by using a kriging interpolation [43,44] to locate hotspots of damage for 2018 snowfall event. Additionally, we employed reanalysis data from ERA-5 to draw inferences about weather circulation patterns prevalent over the region during the first week of November 2018 and November 2019. The ERA-5 reanalysis dataset constitutes the fifth state-of-the-art reanalysis generated by European Centre for Medium-Range Weather Forecasts (ECMWF, <https://www.ecmwf.int/>). It is based on data assimilation from model and observations across the world with a spatial resolution of 0.25° and temporal (12-h) coverage from 1979 to present. To evaluate the synoptic situation related to the snow spell, synoptic charts were investigated. A more detailed description about the ERA-5 global reanalysis is provided in Hersbach et al. [45].

Table 1. Details of the datasets used in the study.

Dataset	Scene ID/Acquisition Date	Spatial Resolution
A. Remote Sensing Imagery		
Basemap in ESRI ArcMap 10.1	2016–2018	1:5000 scale
ECMWF Re-Analysis (ERA-5)	1–7 November 2018	0.25°
	1–7 November 2019	
B. Precipitation Data	November (1980–2019)	Point data
C. Field Data		
GPS measurements	5 November 2018	Point data
	7 November 2019	Point data
Photographs	5 November 2018	Point data
	7 November 2019	Point data
Damage assessment data	November 2018	Point data

3. Results

The satellite images of both severe weather episodes indicated widespread snowfall across the Kashmir Valley (Supplementary Information Figure S1); however, optical remote sensing data used in this study did not yield any information on the quantity of snow. Consequently, snow depth was measured manually at 65 locations across Kashmir Valley and interpolated in ArcMap 10.1, to produce a seamless snow depth map for the events of 2018 and 2019 (Figure 2). During November 2018, snow varied from 5 cm (areas in central and north Kashmir) to 122 cm (south Kashmir), whereas the November 2019 snowfall event left between 30 cm (in central and north Kashmir) and 152 cm (in south and south-west Kashmir) of snow. Although the amount of snowfall was temporally variable during the two events, spatial variability was similar between the events with the southern part of the valley receiving substantially more snow. Details of field-based snow depth measurements are provided in Table S1.

Analysis of long-term November precipitation data over the Kashmir Valley indicates consistently increasing precipitation (Figure 3) across time for the 5 stations located at lower altitudes (<2400 m asl). This increasing trend is heterogeneous across the five stations in Kashmir Valley but most pronounced at Pahalgam (R^2 : 0.087; Figure 3d), followed by Srinagar (R^2 : 0.059; Figure 3c), Kokernag (R^2 : 0.048; Figure 3f), Kupwara (R^2 : 0.014; Figure 3a) and Qazigund (R^2 : 0.006; Figure 3e). By contrast, precipitation data of the high-altitude station Gulmarg showed a weak declining trend (Figure 3b).

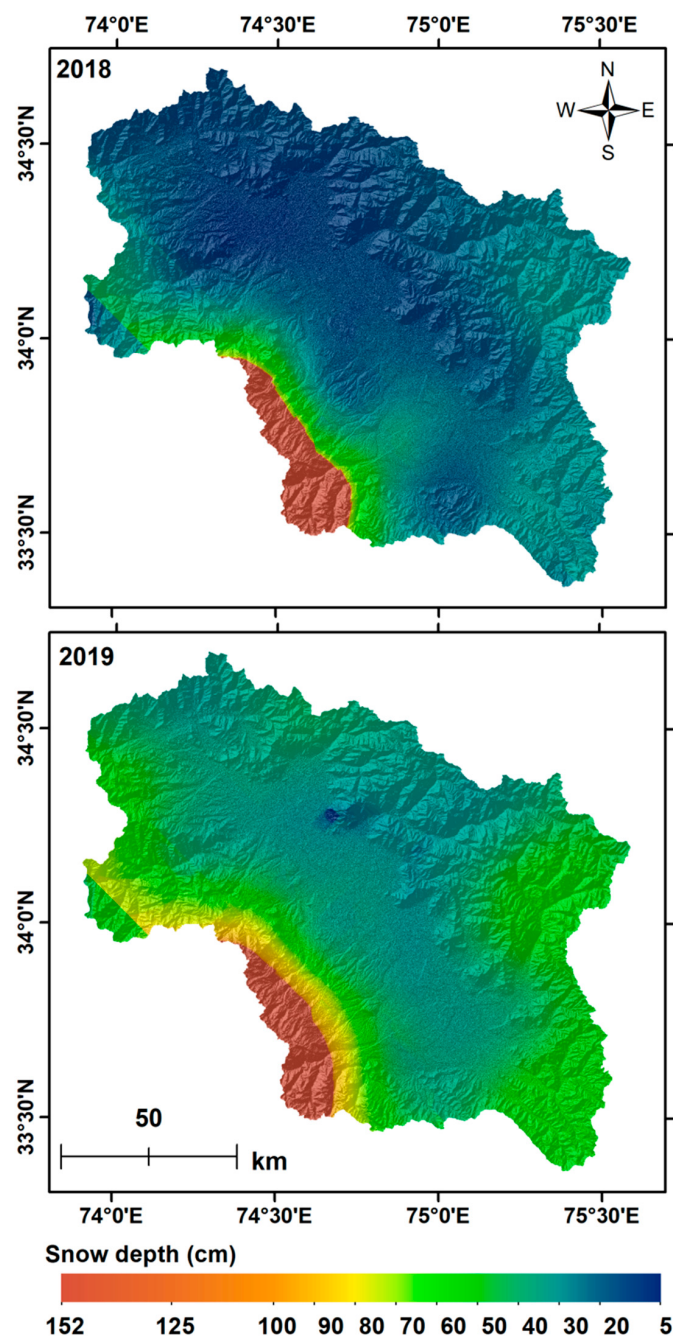


Figure 2. Snow depth during (top) November 2018 and (bottom) November 2019.

Apple orchards cover 1330 km² and are spread over 10 districts of the Kashmir Valley as mapped from the satellite data (Figure 4). The district-wise land under orchards is provided in Table S2. Analysis suggests that out of the ten districts of Kashmir Valley, Baramulla District in north Kashmir has the highest land under apple orchards (305 km²), while Srinagar has the smallest area (15.7 km²). The zone-wise statistics of area under orchards is provided in Table S3. South Kashmir accounts for ~56% of the total orchard area followed by north Kashmir (32%) and central Kashmir (12%).

The assessment of snowfall data specifically over orchards suggests that snow depth varied from 2–80 cm during the snowfall episodes. During the November 2018 event, orchards experienced 2.7–80 cm of snowfall with a mean of 20.7 cm, whereas, in November 2019, snowfall was more severe ranging from 29–76.5 cm with a mean of 40 cm. Noteworthy, south Kashmir received substantially more snow compared to other areas of the valley during both events. The apple orchards suffered

massive damage during both the 2018 and 2019 snowfall events. The damage ranged from damage to the foliage, crumbling of branches and also uprooting of apple tree in certain areas. Data compiled by the Directorate of Horticulture, Kashmir for the 2018 (Supplementary Information Table S2) event revealed that 433.55 km² of orchards were affected across Kashmir Valley by the weather event with the highest damage reported for Kulgam District (99.45 km²) and the lowest impacts around Srinagar (1.76 km²). The interpolated data for damage to orchards, expressed as percentage, for the 2018 snowfall is shown in Figure 5. Analysis indicates that areas in south Kashmir suffered most damage followed by north Kashmir and central Kashmir. Our results also suggest that orchards got damaged between 4–50% with an average damage of ~35%.

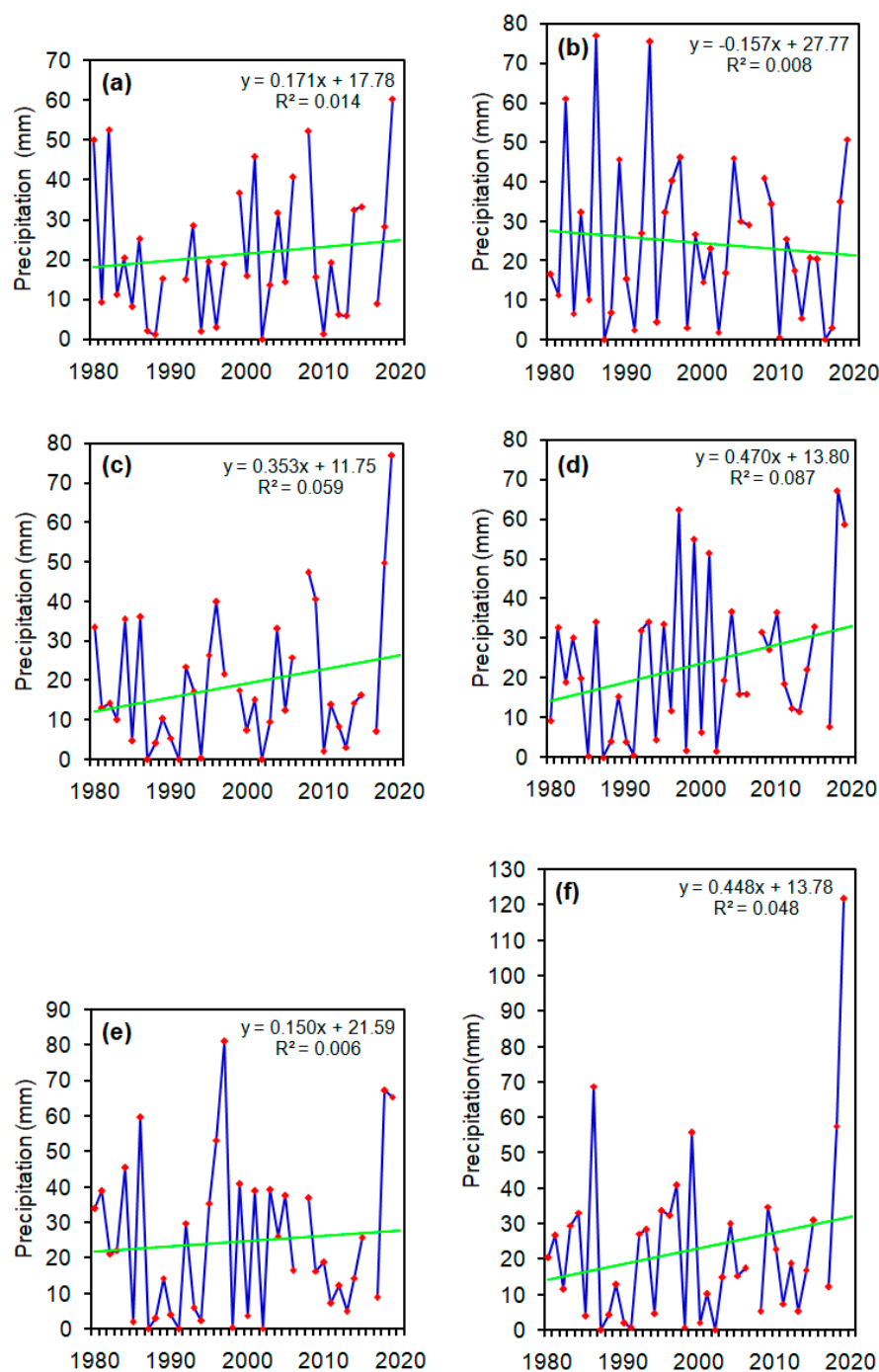


Figure 3. Historical Precipitation data (1980–2020) of November over the Kashmir Valley from six meteorological stations. (a): Kupwara, (b): Gulmarg, (c): Srinagar, (d): Pahalgam, (e): Qazigund, and (f): Kokernag.

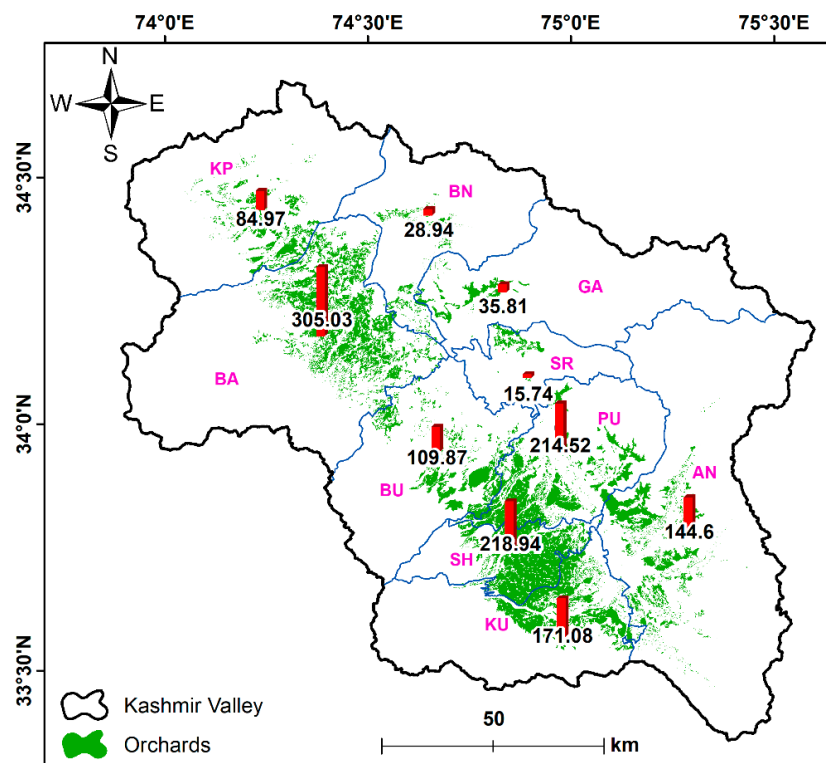


Figure 4. District-wise area under orchards in Kashmir Valley (in km²). AN: Anantnag, KU: Kulgam, SH: Shopian, PU: Pulwama, BU: Budgam, SR: Srinagar, GA: Ganderbal, BA: Baramulla, BN: Bandipora, and KP: Kupwara.

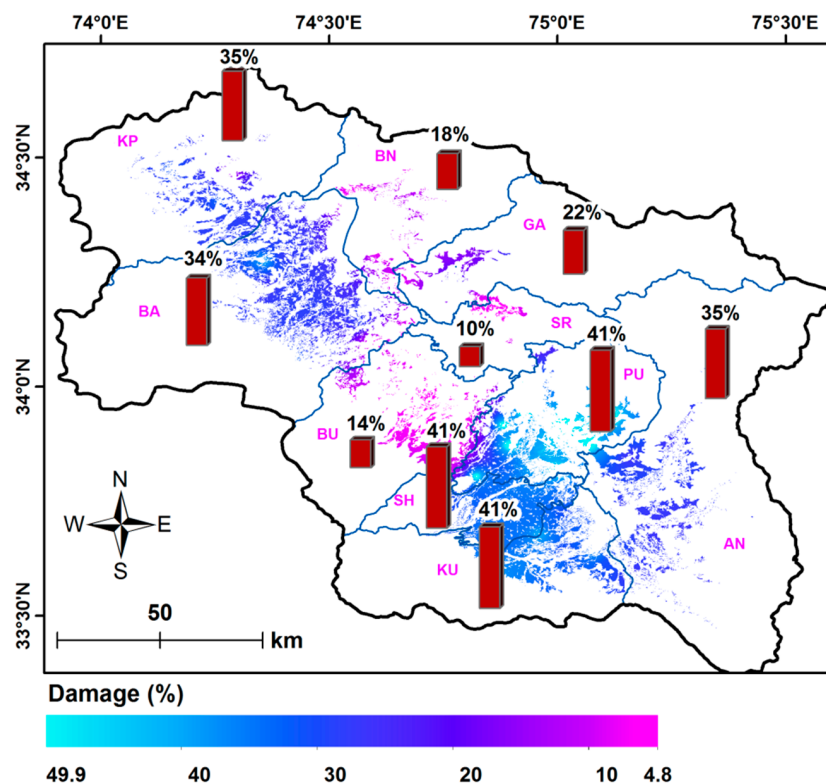


Figure 5. District-wise damage to orchards in Kashmir Valley during November 2018 (in %). AN: Anantnag, KU: Kulgam, SH: Shopian, PU: Pulwama, BU: Budgam, SR: Srinagar, GA: Ganderbal, BA: Baramulla, BN: Bandipora, and KP: Kupwara.

Synoptic analysis of the two weather events leading to unseasonal snowfall across the Kashmir Valley was related to the early arrival of WDs. In the case of the November 2018 event, geopotential analysis from the ERA-5 dataset points to the formation of a trough at high tropospheric levels (200 mb) around 67° E and 40° N on 2 November 2018 (Figure 6). In the following days, this trough evolved steadily to reach northern Pakistan and north-western India where it persisted at 75° E and 35° N until 6 November 2018. At lower atmospheric levels (850 mb), a col situation formed between 2–5 November 2018 around 75° E and 34° N (see Figure S2). This synoptic situation induced a cyclonic circulation in north-eastern Pakistan and south-west of the Tibetan plateau and led to positive potential vorticity over the region. The lack of ventilation, typical during such situations, likely favored the accumulation of moisture originating from northern and western Pakistan (Figure S2). At the same time, colder air masses from northern latitudes were transported over the Kashmir Region, where they led to a significant drop of average surface temperatures (Figure 7). Temperature and geopotential values recovered partially 4–5 days after the events (Table S4).

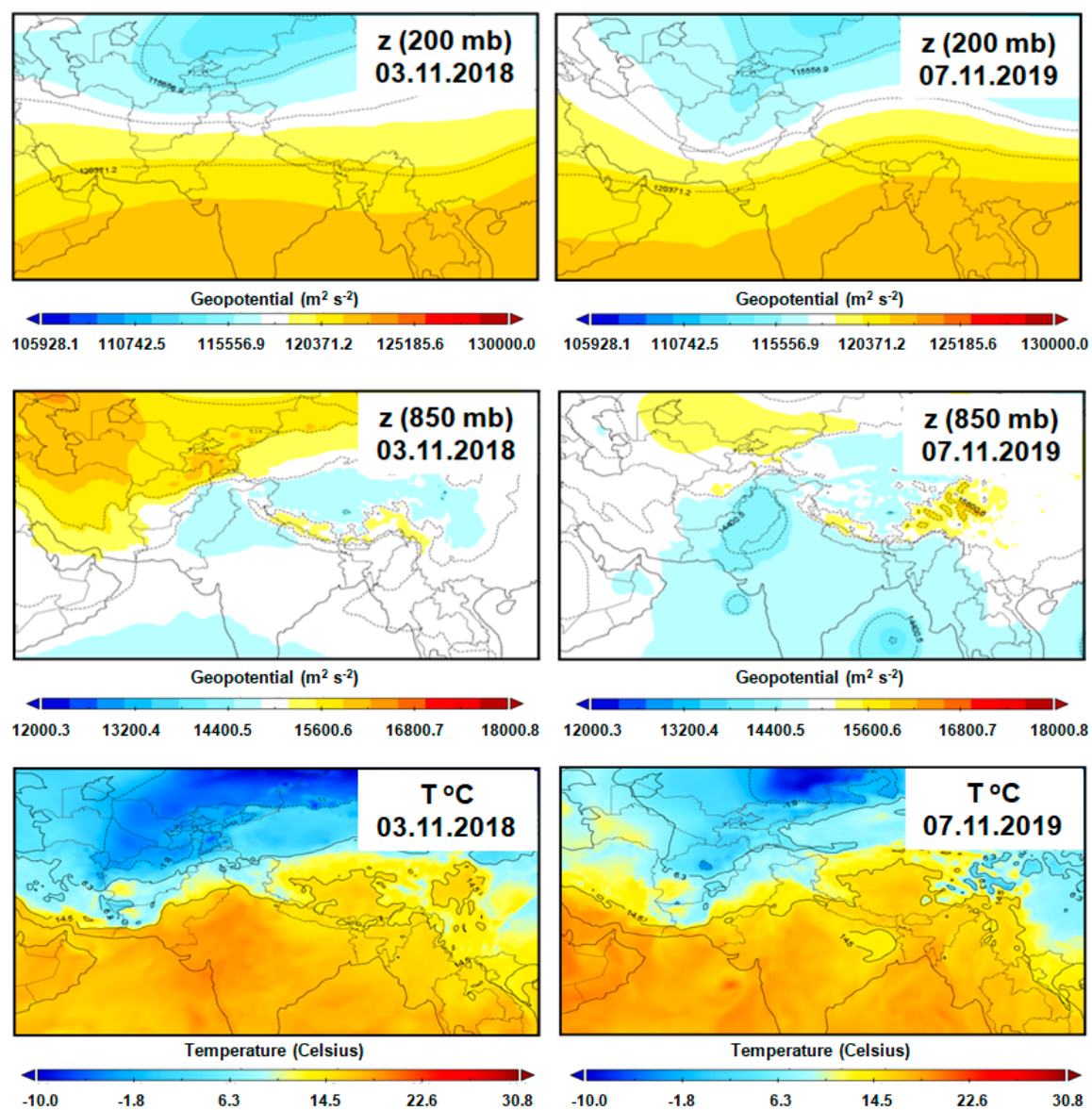


Figure 6. Geopotential (200 mb and 850 mb) and surface temperature fields from ERA-5 at the start of the snowfall spells in November 2018 (left panels) and November 2019 (right panels).

Similar to the 2018 event, on 6–7 November 2019, we observe again the arrival of a WD; identification of a trough at high tropospheric levels (200 mb) is even clearer in this case and localized at 67.5° E and 35° N. At lower levels (850 mb), a more intense cyclonic circulation (72° E and 32.5° N) formed to favor advection of moisture from the Arabian Sea. Associated to the arrival of the WD, the incursion of low temperatures from higher latitudes can be observed, favoring the snowfall episode further (Figure S3). The satellite imagery from Indian National Satellite (INSAT-3D, Figures S2 and S3) and the ERA-5 derived upper-level winds support the presence of convective cloud bands with the arrival of the WD in both years; the effects were, however, more intense during the 2019 snowfall due to advection of moisture from the north Arabian Sea.

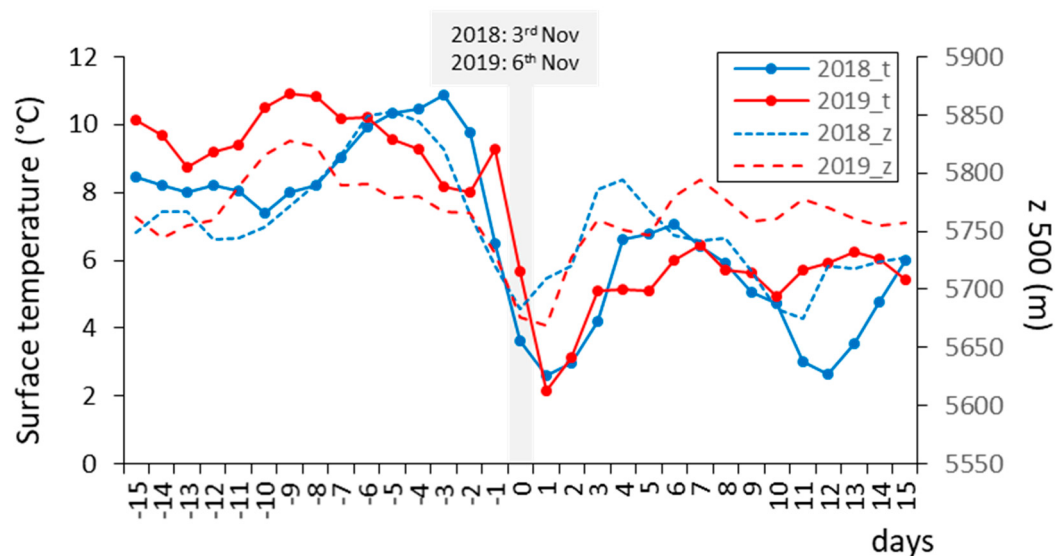


Figure 7. Pre- and post-event evolution of average surface temperatures (°C) and geopotential (z500) with the snowfall events based on ERA-5 dataset (data represent average values over the region 33.3°–34.3° N and 74.3°–75° E).

4. Discussion

In this study, we assessed the causes and impacts of untimely, strong snowfall events in Kashmir in November 2018 and November 2019, as well as looked into the consequences they have had on apple orchards in the valley. The orchard areas in south Kashmir have been affected most by the erratic snowfall in 2018 and 2019, with the latter being more intense and hence resulting in colossal damage to the apple production in the valley. Noteworthy, the occurrence of these two recent events is in line with a general tendency for the more frequent occurrence of extreme weather events over Kashmir [46,47]. Whereas the Department of Horticulture estimated losses after the November 2018 snowfall at INR 5 billion (<https://bit.ly/2TDATpR>), damage observed following the November 2019 snowfall was more pronounced and resulted in the losses amounting to INR 22.5 billion (or c. US\$302 million; <https://bit.ly/3aJxmvN>). Even if meteorological records are lacking to confirm the statement, reports suggest that the 2019 snowfall was the heaviest that Kashmir experienced over the past six decades, claiming 7 lives (<https://bit.ly/2wInowb>) and damaged power infrastructure worth INR 220 million (or c. US\$2.95 billion; <https://bit.ly/2TG99Rj>). Historical precipitation data from India Meteorological Department (IMD) also point to a consistent increase in precipitation totals across the valley, and are thus in line with what is projected to occur in the Kashmir Region by the end of this century [23].

The horticultural sector of the Kashmir Valley, dominated by apple orchard, contributes 27% (INR 50 billion or US\$670 million) to the economy of Jammu and Kashmir [48], and the government is contemplating to strengthen the sector further. This study indicates that of the total area of 1330 km² under apple orchards in Kashmir Valley, more than half of orchards (56%) are located in south Kashmir.

Given the stark promotion of the horticultural sector, massive areas under irrigation-intensive rice paddy currently undergo conversion to seemingly more viable apple orchards [49–52]. However, we argue that the ever-increasing area under orchards may well become unsustainable in economic (but also in environmental) terms given the challenges of changing climate [31,53] and the related exacerbation of extreme weather events. In addition, a massive increase of orchards could ultimately result in serious health repercussions [54] as a result of the reckless use of pesticides [55]. While the changing climate may shift the flowering patterns of apples in the long term [56–58], the erratic snowfall events like those of 2018 and 2019 have already resulted in unprecedented losses that have been affecting local economy seriously (Figures S4 and S5). Any further developments in the horticultural sector should thus be studied carefully using state-of-the-art scientific approaches to consider whether the promotion of horticulture in Kashmir will be socio-economically and ecologically viable in the long run.

Analyzing data made available by the Department of Horticulture, we find that the November 2018 snowfall damaged 35% of the orchards in Kashmir Valley. Data for the November 2019 snow episode has not been made available yet, but it is highly likely that damage will be more pronounced than the 2018 erratic snowfall event. This assumption is supported by information from the Kashmir Valley Fruit Growers cum Dealers Union who estimated that a stunning 80% of the fruit plants of all orchards of the Kashmir Valley were uprooted during the November 2019 snowfall (<https://bit.ly/2TtftKR>).

Analysis of ERA-5 reanalysis datasets suggest that the November 2018 and 2019 snowfalls were formed after a trough (i.e., a low-pressure system) developed with the arrival of a WD. Weather in Kashmir was influenced further by a cyclonic circulation that developed south of Jammu-Kashmir, as well as the intrusion of cold air masses from northern latitudes. The situation was especially intense in November 2019. Whereas the influence of WD on winter precipitation and snowfall over the Himalaya [59,60] including the Kashmir Region [40,61] is pronounced, it is more so the early arrival of the snowfall episodes in November 2018 and 2019 that made these two events special. Although snowfall linked to WDs normally occur in Kashmir between November and April, large intense events are rare in the early season and normally occur in February and March [40]. According to the records and our observation, the large snowfall events in the first weeks of November 2018 and 2019 can be considered anomalies based on existing records [39]. Some existing studies suggest that the occurrence of WD is increasing under current conditions already in winter [39], and that the frequency of WDs may increase further under climate change [62], resulting in increased winter snow precipitation [42]. Other studies, however, have found a decreasing or unchanged trend of WD over the last decades [63,64]. While it was not the goal of this study to identify changes in the occurrence of WD situations, we find that the earlier arrival of WD in early winter—along with cold temperatures arriving from northern latitudes and the advection of moisture from the still-warm Arabian Sea—indeed pose a serious threat to the agriculture and horticulture sectors in the region, even more so should the incidence of such early-season events become more frequent. We, therefore, call for research on intra-seasonal changes of WD occurrences or more reliable indicators to predict these events [34] to mitigate further economic losses in the agricultural sectors and possibly by diversifying (cash) crops with more and more resilient species.

5. Conclusions

The untimely and extreme weather patterns over Kashmir in recent years have not only impacted ecosystems but also severely dented the economic sectors. Over the past few years, Kashmir Valley witnessed two such erratic snowfall events in late autumn 2018 and 2019—both events destroyed apple orchards across the valley. This assumes importance since the government is contemplating to expand the horticulture sector from INR 60 billion to 300 billion. As a result of recent losses and to boost the production of apple, government has recently introduced a highly-subsidized High Density Apple Plantation (HDAP) scheme with plant protection mechanism (like anti-hail nets and trellis system comprising of metallic/wooden stakes and wiring). This set up minimizes damage to the apple trees in case of heavy snowfall and is getting popular among the apple orchardists of Kashmir. However, many

experts fear that the HDAP might altogether wipe out local apple cultivars in this highly competitive business, with negative impacts on local varieties and diversity of species.

Using data from multiple sources (remote sensing, ERA-5 reanalysis, field data, and ancillary information), we characterize the two erratic snowfall events to conclude that the snow depths recorded during the November 2019 snowfall were not only larger (mean snow depth = 47 cm) than during the November 2018 event (mean snow depth = 26 cm), but that the most recent event on record was probably also unique in terms of magnitude and timing over the last 60 or so years. The installation of snow gauges at all IMD-managed weather observatories are critically needed to get credible baseline data on snowfall in the region and on event-specific snowfall patterns, not only to inform policy but also to facilitate the decision makers with scientifically sound information.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/21/9206/s1>, Figure S1: Figure S1: (a) November 2018 snow extent and (b) November 2019 snow extent as observed from Sentinel 2A and Landsat satellites, Figure S2: Left column: Temporal evolution of the cloud as observed by INSAT-3D imagery for 0000UTC for 2nd, 3rd, and 4th, November 2018. Right column: ERA-5 derived upper-level winds at the same moment, Figure S3: Left column: temporal evolution of the cloud as observed by INSAT-3D imagery for 0000UTC of 6th and 7th November 2019. Right column: ERA-5 derived upper-level winds at the same moment, Figure S4: Field photographs showing damages to the Apple orchards in the snowfall events of 2018 and 2019, and Figure S5: Field photographs showing damage caused by untimely snowfall to the fruit during harvesting. Table S1: Field-measured snow depth for 2018 and 2019 November snowfall events, Table S2: District-wise area under orchards in Kashmir Valley, and Table S3: Zone-wise orchards area of Kashmir Valley.

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