

Katabatic and convective processes drive two preferred peaks in the precipitation diurnal cycle over the Central Himalaya

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The diurnal cycle of precipitation over the Central Himalaya

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is governed by a complex interaction between the diurnal cycle of tropical convection and local orographic flow. Understanding this interaction is crucial for model evaluation, where the simulation of such processes is highly sensitive to model resolution and choice of parameterisation schemes. In this study, the mean diurnal cycle is computed using GPM-IMERG data and is shown to be bimodal, with one peak in the late afternoon (1700 LT) and a stronger one in the early morning (0200 LT). This structure is an artefact of compositing, as individual days are typically associated with single peaks. The late afternoon 'convective' peak is shown to be linked to the diurnal cycle of tropical convection, whereas the early morning 'katabatic' peak is shown to be triggered by nocturnal downslope flow converging with the background monsoon circulation. As such, the katabatic peak is strongly favoured by an active monsoon trough, which provides greater southeasterly moisture flux to the foothills, resulting in increased low-level moisture flux convergence upon interaction with the katabatic northerlies. In contrast, when the trough is less active, precipitation is brought to the region by mesoscale convective systems, ranging in scale from tens to thousands of kilometres, resulting in convective peaks. We hypothesise that these peaks may be enhanced by anabatic flow. It is shown that the BSISO does not play a significant role in modulating either the timing or amplitude of the diurnal cycle; however, low-pressure systems do: either by intensifying the trough (and hence the katabatic peak), or, when further north, by providing deep convection (hence supporting the convective peak). Reanalyses and a 17-km model with parameterised convection capture both peaks, but overestimate the magnitude of the convective peak and underestimate the magnitude of the katabatic peak.

KEYWORDS

diurnal cycle, Himalaya, precipitation, orographic, convection

1 | INTRODUCTION

Over much of monsoonal India, the diurnal cycle of precipitation is dominated by tropical convection: solar heating warms the surface, which then warms and moistens the boundary layer through sensible and latent heat transfer. Eventually, the updrafts become strong enough to overcome convective inhibition and, by the late afternoon, deep convection is widespread. This picture gets increasingly complicated near the coasts – where the land-sea breeze plays an important secondary role – and near the Himalaya – where localised dynamics such as the nocturnal jet can dramatically alter atmospheric stability. It is this latter problem that is the focus of this study.

A full understanding of the processes at play, and how they interact with each other to produce the observed diurnal cycle across the Himalaya, is vital for model evaluation. In particular, parameterisation of these localised processes (e.g. to represent convection or subgrid orography) can lead to significant biases even on the synoptic scale. Marsham et al. (2013) showed that in simulations of the West African monsoon, parameterised convection occurred too early in the day, leading to mistimed feedbacks between radiative heating, latent heating and the meridional pressure gradient. This resulted in a much poorer simulation of the monsoon circulation than a parallel run with explicit convection. More generally, coarse-resolution models with parameterised convection tend to rain too early in the tropics and this premature initiation suppresses the build-up of CAPE, resulting in too light and too frequent rainfall over tropical land, with similar implications for the simulation of monsoonal circulation (Dai and Trenberth, 2004).

1.1 | The observed diurnal cycle of precipitation over the Himalaya

Satellite-based precipitation products have allowed a near-global assessment of the diurnal cycle of precipitation. Kikuchi and Wang (2008) showed that the strongest diurnal cycle exists over tropical land, where the peak (1500 local solar time – or LT) usually matched local heating. They also found that near large mountain ranges, the peak tended to be in the local early morning. This was corroborated by Sahany et al. (2010) who used spectral analysis to draw out the diurnal cycle over nine years of TRMM data over India. They found that inland, away from the coasts or orography, the rainfall peaked at 1430 LT; however, this was later over the Western Ghats (1430–1730 LT) and much earlier over the Himalayan foothills, where they recorded a single peak at 0230 LT. More recently, Watters et al. (2021) expanded these results for GPM-IMERG, ERA5, and three CMIP6 AMIP models. They found that IMERG also captured an early morning precipitation maximum over the Himalaya, with a cross-slope gradient (earlier maximum at higher altitudes), as well as a late afternoon maximum both further south (over the Indo-Gangetic Plain) and further north (over the Tibetan Plateau). The ERA5 reanalysis was able to capture most of these features, but had a late afternoon peak over much of the Himalaya.

More directed studies, combining satellite data with ground-based observations, have reached similar conclusions. Barros et al. (2000) explored the diurnal cycle of precipitation over Nepal for a single monsoon season. They found that the diurnal cycle was often bimodal, with a late afternoon and an early morning peak, though in the valleys, only the early morning peak was present. This was later complemented by a longer radiosonde campaign (Barros and Lang, 2003). Similarly, Bhatt and Nakamura (2006) explored the diurnal cycle over the Himalayas in a range of data sources, finding a mid-afternoon peak in the pre-monsoon and an early morning peak during the monsoon.

1.2 | Proposed mechanisms

Fitzjarrald (1984) constructed a one-dimensional model of katabatic winds in ambient flow. He found that the onset

time of katabatic (i.e. nocturnally-forced downslope) winds is sensitive to opposing flow and reduced cooling rates (e.g. from monsoon cloudiness). Over the Central Himalaya, the katabatic winds are northerly, and the opposing flow is thus the local southeasterly monsoonal circulation. The model had about an eight hour delay between sunset and the initiation of katabatic flow over humid tropical slopes, but, because it was one-dimensional, missed the effects of local convergence due to local topography. He also found that entrainment into katabatic winds might be an important control on downslope initiation of precipitation. Bluestein (1993) suggested that the nocturnal low-level jet that arises in response to differential heating/cooling across the orographic gradient could advect moisture into such a region, causing the early morning precipitation maximum seen in the Rockies. Using an intensive sonde and observation campaign over central Nepal, and supported by the NCEP/NCAR reanalysis, Barros and Lang (2003) found that precipitable water peaked around midnight, slightly after CAPE. They found that anabatic winds were more intense than katabatic winds, in agreement with many previous studies (Egger et al., 2000; Ueno et al., 2001; Bollasina et al., 2002) as well as Fitzjarrald (1984), as climatological monsoon winds are directed slightly upslope. They argued that convergence along the foothills was reduced during the day because of anabatic flow, favouring increased convergence at night (when the flow was katabatic). This way, as the monsoon continues to moisten the boundary layer, instability builds up during the whole day before it is finally released during the nocturnal precipitation. Barros and Lang (2003) found little evidence of a nocturnal low-level jet, but noted that this may have been due to the data sparsity of the region. Bhatt and Nakamura (2006) analysed the diurnal cycle using a combination of TRMM, radiosonde data, and two reanalyses. Following Fitzjarrald (1984), they attributed the early morning maximum to convergence from the interaction between katabatic flow and the southeasterly moisture flux of the summer monsoon. They further suggested that the radiative cooling at top of clouds may be an important driver and found that the cross-slope gradient in peak timing could be explained by cold pool density currents moving downslope, causing southward movement of precipitation systems in the morning. They also hypothesised that convection over the foothills could be triggered by gravity waves generated in response to the Himalaya acting to block the monsoon flow, arguing that this effect would be strongest in the early morning.

Indeed, R  thrich et al. (2013) found that maximum cloudiness over the Central Himalayan foothills occurred at 0200 LT but hypothesised that this was due to katabatic flow helping initiate mesoscale convective systems. Other studies have also investigated satellite-derived cloud data over the Himalaya to improve understanding of the diurnal cycle. Barros et al. (2004) found a strong link between cloudiness and precipitation over the Himalaya at all scales, from the synoptic, which they linked to mesoscale convective systems (MCSs) and monsoon depressions, to the mesoscale, which they linked to valleys and ridges in the orography. They found that the timing of heavy precipitation over the Himalaya was driven on the synoptic scale (which they defined as larger than 70 km), although convective cloud clusters are comparatively rare there compared to the Indo-Gangetic Plain and the Tibetan Plateau. Analysing extreme convection over the whole of South Asia, using the TRMM precipitation radar, Romatschke et al. (2010) found that different types of organised convection have differing diurnal cycles: deep convective cores peak at about 1700 LT, wide convective cores peak at either 1700-1800 LT or 0300-0400 LT, and broad stratiform regions have a weak diurnal cycle that peaks at about 0600 LT. Romatschke and Houze Jr (2011) investigated this further over the Central Himalayan foothills, concluding that small and medium sized (<44000km²) convective systems develop as monsoon flow is forced upslope, concluding that medium-sized systems were triggered at lower elevations by katabatic flow.

1.3 | Aims and outline

In this paper, we intend to disentangle the bimodal structure of the diurnal cycle over the Central Himalaya, to quantify the respective roles of katabatic and convective processes, to understand how these processes interact with each

other, and whether forcing from large-scale modes of intraseasonal variability offers additional predictability for rainfall over the Central Himalaya.

We outline the data and methods used in Sec. 2. The results are discussed in Sec. 3: the diurnal cycle is investigated and decomposed in Sec. 3.1, the synoptic-scale elements associated with each component are explored in Sec. 3.2, and responsible modes of intraseasonal variability are discussed in Sec. 3.3. Finally we discuss the implications of our results in Sec. 4 and conclude in Sec. 5.

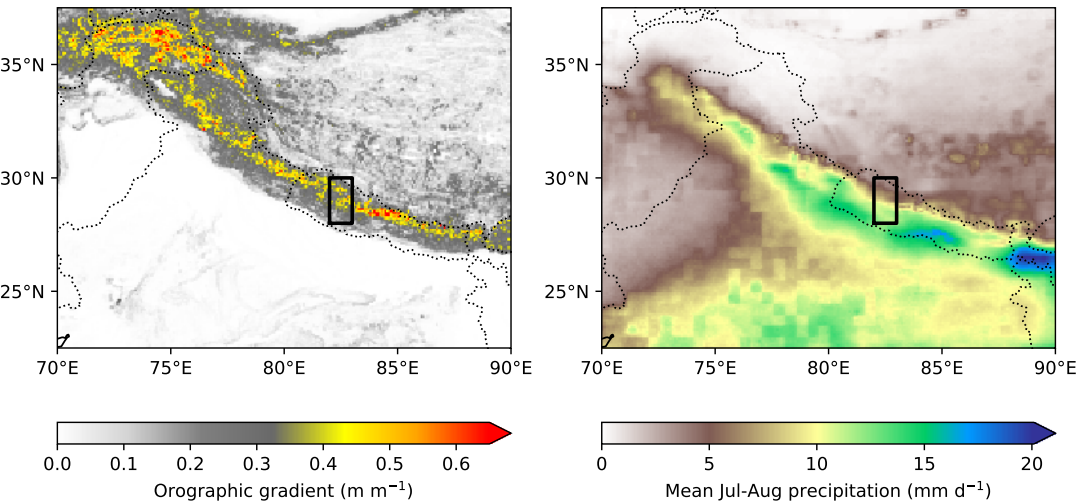


FIGURE 1 The environment of the Central Himalayan foothills. (a) Orographic gradient (m m^{-1}) computed using ETOPO1, downscaled to 8 km using a maximum filter. (b) Mean July–August precipitation (mm d^{-1}) computed using GPM-IMERG data (2000–2019). In each panel, the study region is marked by a black rectangle.

2 | DATA AND METHODS

2.1 | Data

2.1.1 | GPM-IMERG

For our precipitation dataset, we use the gridded surface product Integrated Multi-Satellite Retrievals for GPM (IMERG; Huffman et al., 2015). This has global coverage at a half-hourly, 0.1° resolution, starting June 2000 and continuing to the present day. Over the tropics, IMERG primarily ingests retrievals from (for 2000–2014) the now-defunct Tropical Rainfall Measuring Mission (TRMM; Kummerow et al., 1998, 2000) 13.8 GHz precipitation radar and microwave imager (Kozu et al., 2001) and (for 2014–) the Global Precipitation Measurement (GPM; Hou et al., 2014) Ka/Ku-band dual-frequency precipitation radar. When an overpass is not available, precipitation is estimated by calibrating infrared measurements from geostationary satellites. While GPM-IMERG performs well when compared against gauge-based products, performance falls at higher elevations or when quantifying extreme rainfall events (Prakash et al., 2018), although it performs well over the Western Himalaya (Baudouin et al., 2020). IMERG has good skill in capturing the diurnal cycle over tropics and subtropics; e.g. for Africa (Dezfuli et al., 2017) and China (Tang et al., 2020).

2.1.2 | CMORPH

CMORPH (Joyce et al., 2004) is also a multi-satellite precipitation dataset, though unlike GPM-IMERG it does not undergo a gauge calibration adjustment process. It is available at hourly, $0.1^\circ \times 0.1^\circ$ resolution from 2000 onwards. We use CMORPH as an alternative to GPM-IMERG to replicate results and quantify uncertainty. Data were downloaded from ftp://ftp.cpc.ncep.noaa.gov/precip/global_CMORPH/3-hourly_025deg/.

2.1.3 | Kalpana OLR

To identify regions of deep convection, we use gridded OLR derived from the very-high resolution radiometer onboard the Kalpana satellite (Mahakur et al., 2013; Singh et al., 2007). The data are available from 2004–2017 at three-hourly, $0.25^\circ \times 0.25^\circ$ resolution from 40°S – 40°N and 25°E – 125°E . Data are curated by the Indian Institute of Tropical Meteorology and were downloaded from https://www.tropmet.res.in/~mahakur/Public_Data/index.php?dir=K10LR/3Hrly.

2.1.4 | ERA5

To investigate the local and synoptic-scale structure of the boundary layer and troposphere, we use data from the ECMWF ERA5 reanalysis (Hersbach et al., 2020). Data are available globally, at hourly resolution from 1950 onwards, on a $0.25^\circ \times 0.25^\circ$ grid. Data are available over 37 pressure levels from 1000 to 0.01 hPa, as well as at selected heights above the surface. Data are assimilated into the forecasting system from a large variety of sources, including satellites, automatic weather stations, and radiosondes.

2.1.5 | LPS tracks

We use the database of low-pressure system (LPS) tracks from Hunt and Fletcher (2019) in this study. Using six-hourly ERA-Interim data, they tracked LPSs by computing the mean relative vorticity in the 900–800 hPa layer, then performing a spectral truncation at T63 to filter out short-wavelength noise. They then identified regions of positive relative vorticity within this field and determined the centroid location for each one. These centroids were then linked in time, subject to constraints in distance and steering winds, to form candidate LPS tracks. This algorithm has been used for monsoon LPSs by a number of authors (e.g. Martin et al., 2020; Dong et al., 2020; Arulalan et al., 2020). Track data are available at <https://doi.org/10.5281/zenodo.5575336>.

2.1.6 | BSISO indices

Data for the BSISO were downloaded from http://iprc.soest.hawaii.edu/users/kazuyosh/Bimodal_IS0.html, whose methodology is described in Lee et al. (2013). It is used to assess the role of large-scale intraseasonal variability in modulating the diurnal cycle of precipitation over the Himalayas. The dataset has daily resolution, available from 1979–2018. It contains the normalised values of the first two principal components (or RMMs), as well as the resulting phase and amplitude.

2.2 | Methods

We start with the selection of an appropriate study region. The region must be small, so that competing processes do not smear out the mean diurnal cycle across it. It must also be representative of the rainfall and orography across the Central Himalaya (i.e. avoiding extremes in either). To this end, we selected 82–83°E, 28–30°N as our study region (see Fig. 1). Unless stated otherwise, throughout the manuscript, averages and climatologies are computed for July and August, when the monsoon fully covers the Himalaya. We use UTC and local time (LT, equivalent to Indian Standard Time; UTC+5:30) in parallel throughout the study to aid the reader while maintaining a standardised time format. Where phrases such as ‘morning’, or ‘late afternoon’ are used, this always refers to the local time.

2.2.1 | Circular standard deviation

When dealing with angular data (such as hours of the day), the conventional standard deviation is inadequate as it does not appropriately handle the discontinuity at 2π . To compute the circular, or ‘directional’ standard deviation, we use the following calculation (Fisher, 1995) for a one-dimensional series a with cycles of length Ω :

$$S = \frac{1}{n} \sum_1^n \sin\left(\frac{2\pi}{\Omega} a_n\right); \quad C = \frac{1}{n} \sum_1^n \cos\left(\frac{2\pi}{\Omega} a_n\right), \quad (1)$$

then the circular variance, R , is given by:

$$R = \sqrt{S^2 + C^2}, \quad (2)$$

and hence the circular standard deviation, σ_c :

$$\Omega \cdot \sqrt{(-2 \log R)}. \quad (3)$$

For the diurnal cycle, $\Omega = 24$ hours.

2.2.2 | Choice of study region

This study is concerned with the diurnal cycle along the foothills and Himalaya. However, this is a broad region and the synoptic conditions in the western Himalaya are often very different from those in the east. We therefore select a representative study region, over which the dynamics will be locally coherent, but which can still capture the range of processes potentially governing the diurnal cycle in both the foothills and the Himalaya. To this end, using data shown in Fig. 1 we choose the box [82–83°E, 28–30°N]. This is in the Central Himalaya, which feels the full force of the summer monsoon between July and August, and contains surface elevations ranging from ~500 m in its southwest to over 5000 m in its northeast, and has a footprint much smaller than the typical length scale of the synoptic-scale dynamics that typically dominate the region. It also has no significant valleys or bodies of water, but captures the band of steep orographic gradient that stretches along the Central Himalaya.

3

RESULTS

3.1

Disentangling the diurnal cycle

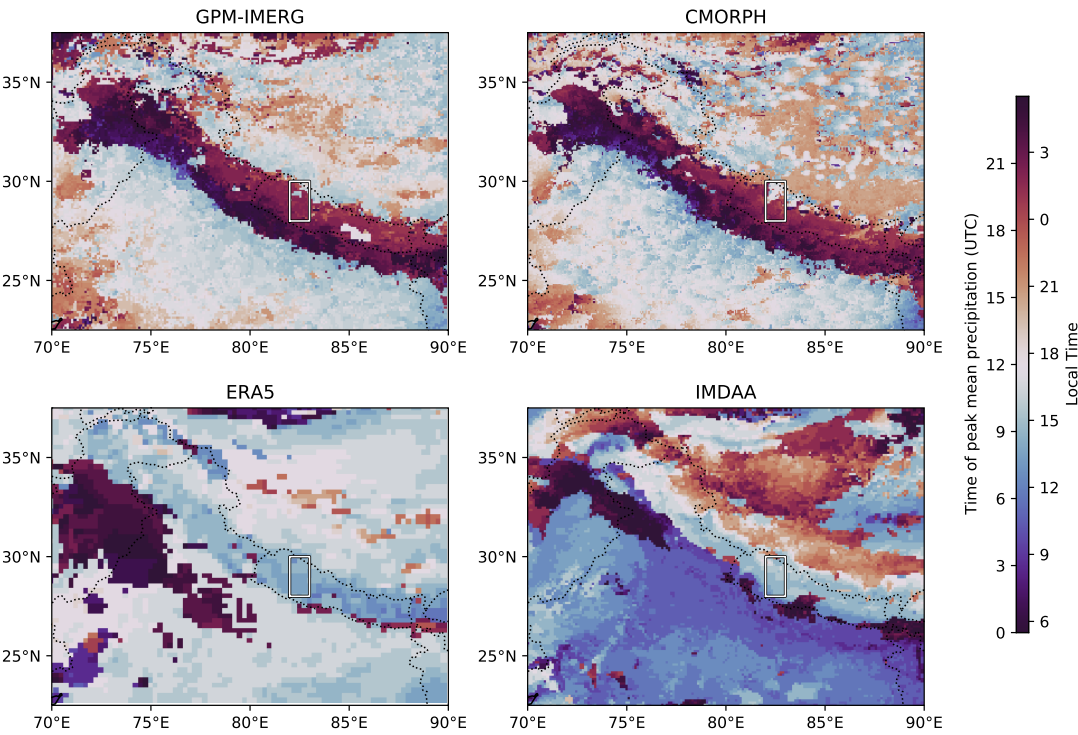


FIGURE 2 Time of the peak of the mean diurnal cycle of July–August precipitation over the Himalayas computed for selected datasets. Top: GPM-IMERG and CMORPH are primarily satellite-based products. Bottom: ERA5 and IMDAA are high-resolution reanalyses with parameterised convection. The study region is marked by a white rectangle.

We start by quantifying the diurnal cycle in a range of satellite and reanalysis products before using composite synoptic charts and vertical cross sections to quantify the underlying processes.

An overview of the diurnal cycle of monsoon precipitation in two satellite products (GPM-IMERG and CMORPH) and two reanalysis products (ERA5 and IMDAA) is given in Fig. 2. Here, the peak time of the diurnal cycle is computed by creating the mean diurnal cycle of July–August precipitation at each pixel in each dataset and then identifying the time of the maximum value of that cycle. The two satellite products bear a strong similarity and highlight several key features. First, along the region of steepest orographic gradient (from the foothills to the peaks), stretching from the east to the west Himalaya, the peak precipitation occurs predominantly during early local morning (~21 UTC, or 03 LT). Within this ‘foothill’ band is a slight meridional gradient, such that the peak precipitation at its southern boundary occurs 1–2 hours later than at the northern boundary. The foothill band is also punctuated, particularly in GPM-IMERG, by smaller regions where the peak precipitation occurs in the local late afternoon (~12 UTC, or 18 LT), which are collocated with larger valleys embedded within the foothills. To the south of the foothills lies the Indo-Gangetic

Plain, for which both satellite datasets agree that the peak monsoon rainfall occurs in the local mid-afternoon (~09 UTC, or 15 LT), about twelve hours apart from the peak activity in the foothills. This is consistent with the diurnal cycle of tropical convection, and varies little in this region, although both GPM-IMERG and CMORPH agree that it occurs a little earlier in the north and up to a few hours later towards the southwest (Gujarat). Finally, north of the foothills and the Himalaya, lies the Tibetan Plateau. This is a region of comparatively low precipitation and the satellite datasets disagree here more than in any other region, although both suggest that precipitation peaks generally in local mid or late afternoon.

The two reanalyses show a mixed ability to capture this regional variability. Over the plains, both ERA5 and IMDAA put the diurnal peak, correctly, in the mid-to-late local afternoon. However, ERA5 does not capture the subtle meridional gradient, and IMDAA is several hours too early. Regardless, this is a significant improvement over earlier reanalyses, whose parameterisation schemes tended to prefer triggering tropical convection at local noon (Dai and Trenberth, 2004; Dirmeyer et al., 2012). The reanalyses both appear to extend the tropical convection signal northward over the foothills, placing a mid-afternoon peak along much of the region, at odds with the two satellite-based datasets. Early morning peaks are only present, for both reanalyses, towards the far northwest and at small, isolated locations along the very southern boundary. It is interesting that despite having different underlying models – ERA5 uses the ECMWF IFS and IMDAA uses the Met Office Unified Model – and assimilating different data, the two reanalyses suffer similar errors along the foothills. In the western Himalaya, where monsoon precipitation is weak (see Fig. 1), this error can be explained by the tendency of the models to produce too much convective precipitation or advect it too far north. This bias would likely disappear should the nocturnal dynamics cause the observed early morning peak to take over. Over the Tibetan Plateau, ERA5 captures the broad mid-to-late afternoon peak, but IMDAA has significant difficulty, tending to place rainfall around local midnight, but with a large spatial variability. Model precipitation here is typically produced by the underlying large-scale microphysics schemes (Sharma et al., 2021), and so is probably not related to IMDAA's convective scheme, rather the fact that it assimilates substantially fewer observations from outside India (Rani et al., 2021).

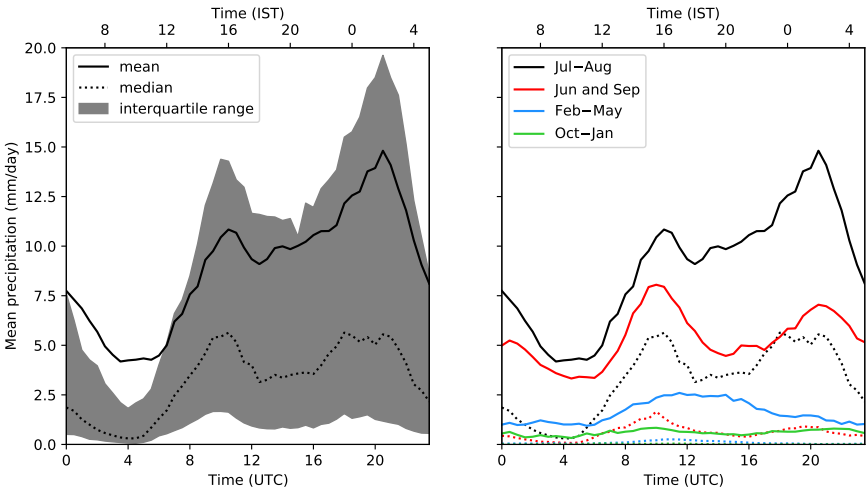


FIGURE 3 The diurnal cycle of precipitation over the study region (82–83°E, 28–30°N). Left: the mean (solid black), median (dotted black), and interquartile range (grey) of the diurnal cycle in July and August. Right: the mean (solid) and median (dotted) diurnal cycles for selected seasons. Computed using GPM-IMERG data from 2000–2020.

Figure 3 shows some characteristics of the diurnal cycle over the study region (82–83°E, 28–30°N; see Sec. 2.2.2). Precipitation here is not marked by a single nocturnal peak, but instead by two distinct peaks: one in mid-afternoon centred at 09–10 UTC (15–16 LT) and a larger one just after local midnight centred at 20–21 UTC (02–03 LT). This suggests a greater complexity to the processes underlying the diurnal cycle than analysis of the satellite data in Fig. 2 first suggested – although the nature of the reanalysis errors hinted that more than one mechanism may be at play. The peaks have approximately equal magnitude when the median diurnal cycle is considered, implying a longer tail in the nocturnal distribution (i.e., populated by comparatively heavier rainfall events). Both peaks are broad, as well, suggesting that either the rainfall events involved have a reasonable duration, and/or that the timing of the trigger mechanisms can vary from day to day.

The diurnal cycle changes throughout the year, as well. When the monsoon is undergoing onset or withdrawal (June and September), it is considerably less active over the Himalaya. During this period, the earlier, mid-afternoon peak has a higher mean than the nocturnal peak – indicating that the underlying mechanisms respond differently to the cloudiness and moisture brought by the presence of an active monsoon trough – the northern edge of which can often reach the foothills. The post-monsoon season (October to January) has a very similar pattern to June and September, though with a much smaller magnitude. In contrast, the pre-monsoon season (Feb–May), has an altogether different diurnal cycle: it is unimodal, with a much broader peak around the late afternoon and early evening. Precipitation during these months is typically brought by isolated convective events that take longer to build up than during the monsoon due to the more stable, drier atmosphere (Shrestha et al., 2012).

To start to untangle the processes responsible for these peaks, and their variability, we look at composite daily data, split according to the timing of peak precipitation. We do this for anomalous rainfall over north India and the surrounding region in Fig. 4. These composites are constructed thus: mean daily precipitation (00–00 UTC) is computed over the study region for days in July and August during the available GPM-IMERG period (2000–2020). Days with precipitation in the lowest quartile are then separated, and labelled in Fig. 4 as ‘weak rain’. Remaining days are then categorised according to the timing of peak precipitation in the study region, binned into three-hourly groups, and composited. Anomalies are computed relative to the mean of days not included in ‘weak rain’. For each composite, the mean diurnal cycle in the study region is also given. These composite diurnal cycles each have a distinct, unimodal peak, varying in magnitude between 1 and 2 mm hr⁻¹, and contributions from events not associated with the main peak are largely reduced (see, for example, the suppressed nocturnal precipitation in the 09–12 UTC composite). Associated rainfall anomalies have a footprint much larger than the study region itself, often spanning several hundred kilometres. Combined with the presence of distinct peaks, this implies that day-to-day variability of larger-scale conditions is responsible for modulating the timing of the diurnal cycle, even if the driving mechanisms themselves are localised. Using the structure of the rainfall anomalies, we can start to speculate on what these sources of variability might be, as the spatial scale is consistent with an active BSISO, monsoon trough, or monsoon LPS.

3.2 | Synoptic-scale drivers

To explore these structures in more detail, we extract days associated with the two diurnal peaks and construct vertical-meridional cross-section composites through the middle of the study region (82.5°E) but extending further north (32.5°N) and south (22.5°N). Fig. 5 shows this for days in which the diurnal peak occurs between 06 and 09 UTC, and between 18 and 21 UTC. The anomalies for each field are computed relative to the daily mean for each subset – that is, the sum of the four panels in each of (a) and (b) is zero. The two sets of days share many common features: the diurnal cycle of solar heating and radiative cooling of the surface and boundary layer results in a pair of counterflowing jets in the valley between the foothills and the Deccan Plateau that semidiurnally reverse direction,

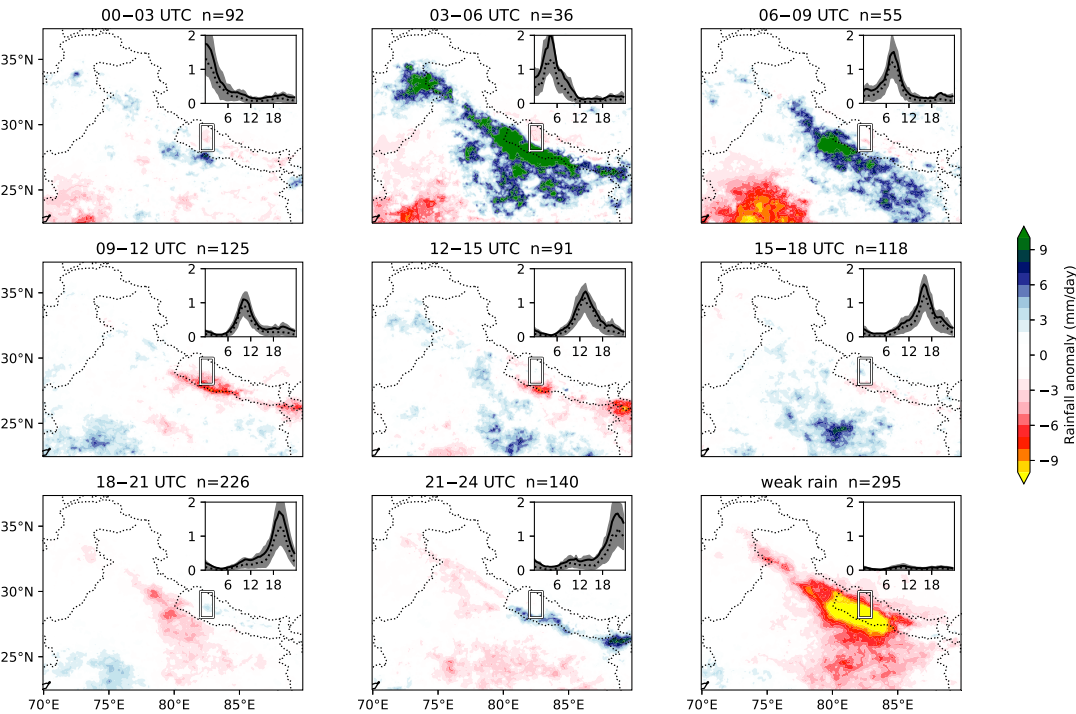


FIGURE 4 Composite anomalous daily rainfall, stratified by the timing of the peak of the diurnal cycle in the study region (marked by a white rectangle). Inset are the mean (black line), median (dotted line) and interquartile range (grey) of the composite UTC diurnal cycles of precipitation (mm hr^{-1}) for each subset, computed over the study region. The number of days included in each composite is given in the panel title, with ‘weak rain’ days – those on which the mean rainfall within the study region is below the 25th percentile – are considered separately. Uses GPM-IMERG data from July and August 2000–2020. The study region is marked by a white rectangle.

consistent with numerical predictions (de Wekker et al., 1998). The most significant difference between the two sets of days is the timing of ascending moisture flux on the slopes. At the peak, ascent is strongly tied to diurnal heating with the maximum occurring consistently at 12 UTC; however, further downslope, over our study region, the maximum upward vertical moisture flux occurs near to, or slightly before, the time of maximum rainfall. This is perhaps surprising given the reanalysis still prefers nocturnal rainfall, even on days in which late afternoon precipitation is observed. The strong ascent at 06 UTC in Fig. 5(a) is supported by continued surface heating through 12 UTC. The boundary layer subsequently cools (18 UTC), either through evaporative cooling by precipitation or increased cloud cover. Either way, this results in increased stratification and a more stable lower troposphere along the slopes, suppressing any later nocturnal rainfall. This may explain why days on which afternoon precipitation occurs over the study region do not then continue to rain the following early morning, which is supported by the behaviour of ERA5 precipitation in Fig. 5(b), where a positive bias in afternoon precipitation comes at the cost of a negative bias in early morning precipitation. A brief caveat here: these composites use pressure level data, and so near-surface katabatic and anabatic winds and related density currents may not be appropriately represented. This will be addressed later.

This inspection of the diurnal cycle is informative, but does not offer much to help us understand the large-scale differences in atmospheric conditions that drive the competing mechanisms. So, in Fig. 6, which otherwise has

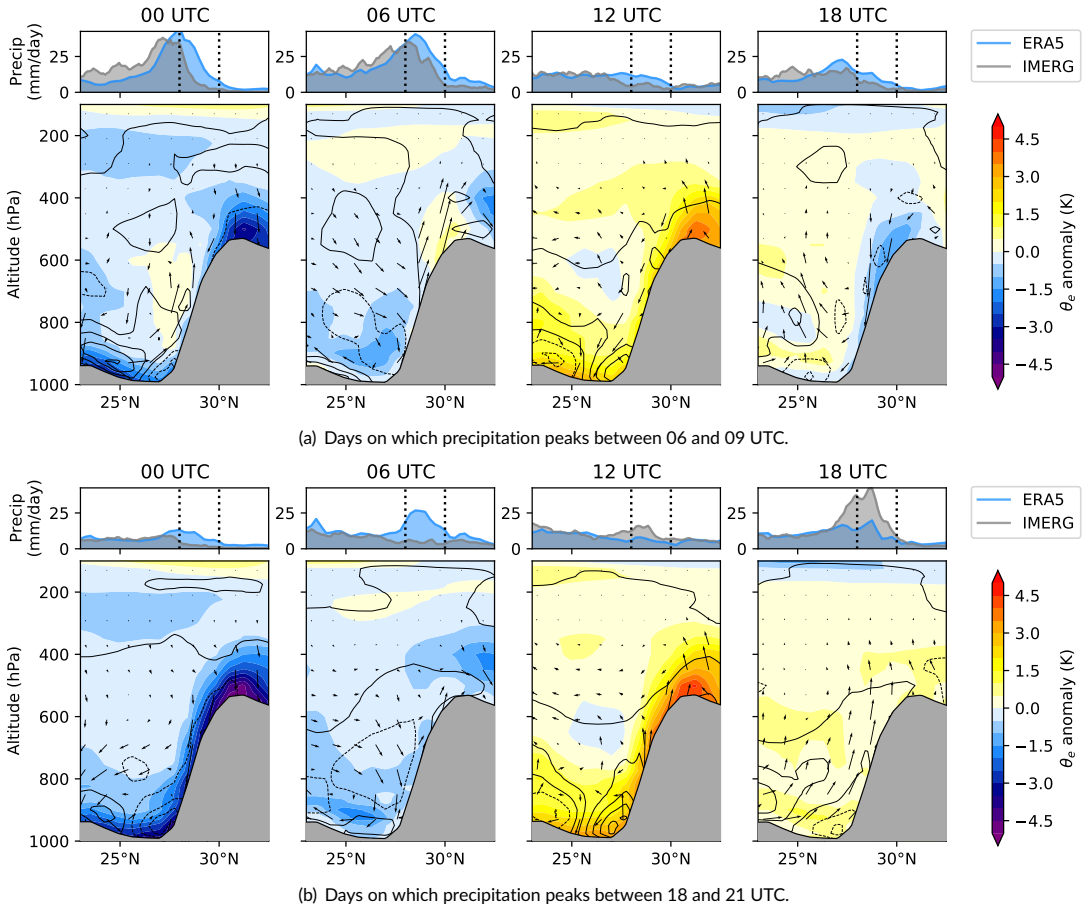


FIGURE 5 Diurnal cycle of selected instantaneous variables, shown as a cross-section through 82.5°E for days on which peak precipitation in the study region occurred (a) between 06 and 09 UTC (1130 and 1430 LT), and (b) between 18 and 21 UTC (2330 and 0230 LT). Meridional-vertical cross-sections show anomalous equivalent potential temperature (coloured contours, K), anomalous moisture flux normal to the cross-sectional plane (line contours in intervals of 5 g kg^{-1} , solid lines indicate westerly flow, dashed lines easterly) and anomalous moisture flux parallel to the cross-sectional plane (arrows, vertical exaggerated $200\times$). Anomalies are computed relative to the daily mean. Above each panel, on the same meridional axis, mean precipitation rate (ERA5: blue, GPM-IMERG: grey) over the next six hours (e.g. over 00-06 UTC in the first panel) is plotted.

identical construction to Fig. 5, we take the anomalies relative to the time of day over the full Jul–Aug climatology. For example, fields plotted at 12 UTC have the 12 UTC climatology subtracted from them, which has the effect of removing the mean diurnal cycle. In this way, we can draw out the differences between the two subsets without the signal being swamped by diurnal variability.

The most striking difference between the two sets of cycles is the presence of a low-level jet. This is distinct from the nocturnal jet in Fig. 5, and its scale is indicative of synoptic, rather than local, forcing. This anomalous moisture flux is centered at around 900 hPa, but extends up through to the mid-troposphere, it is easterly for days with peak precipitation between 06 and 09 UTC (1130 and 1430 LT) and westerly for days with peak precipitation between

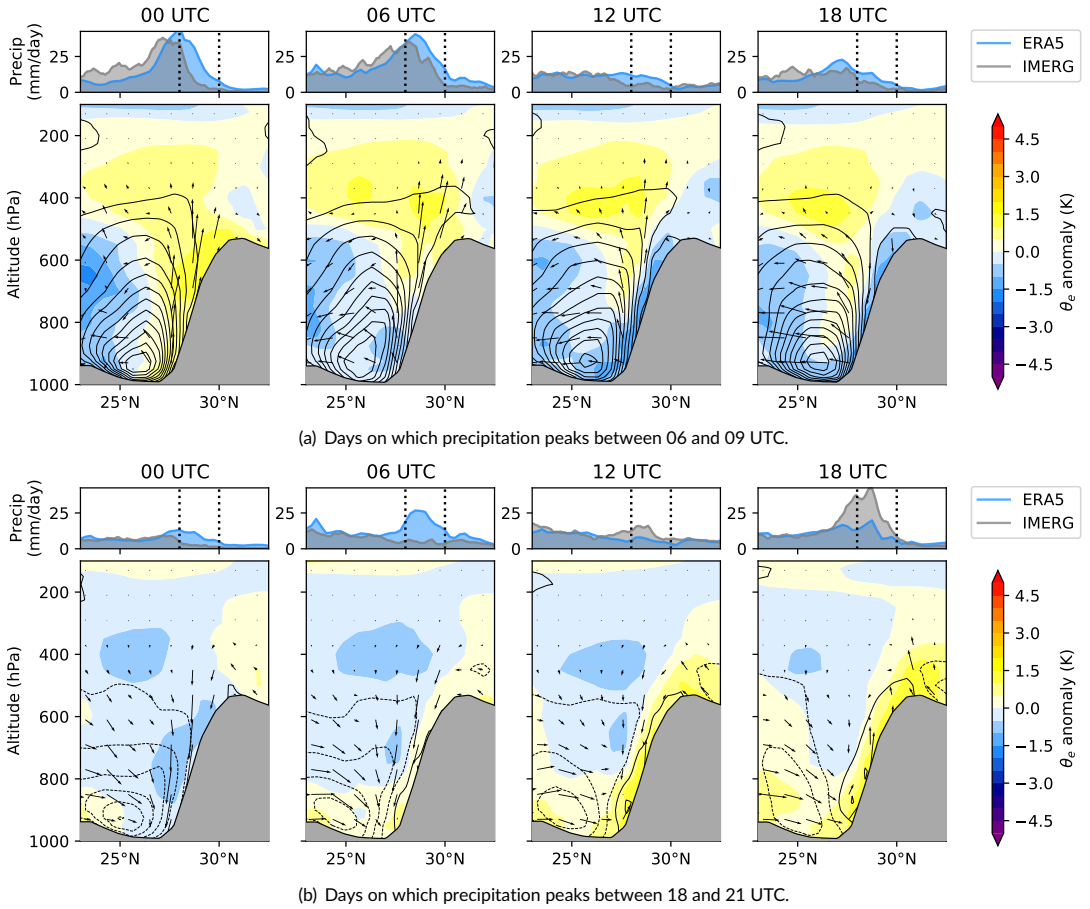


FIGURE 6 As Fig. 5 except anomalies are computed relative to the same time of day over all days. For example, the 18 UTC composite is shown as an anomaly to the 18 UTC Jul-Aug mean.

18 and 21 UTC (2330 and 0230 LT). This pattern extends over the whole set of peaks: days with peak precipitation between 09 and 21 UTC (1430 and 0230 LT) are associated with easterly anomalous moisture flux south of the foothills, whereas days with peak precipitation between 21 and 09 UTC (0230 and 1430 LT) are associated with westerly moisture flux. There is a thermal response to, and hence secondary circulation associated with, this jet. For example, the anomalous westerly jet present on days with daytime peaks is balanced by a positive meridional gradient in θ_e , the secondary circulation thus provides moisture and updrafts to the foothills, supporting the usual diurnal cycle of tropical convection (peaking during the local afternoon). In contrast, the easterly jet is associated with large-scale downdrafts over the region, suppressing canonical tropical convection and generally supporting nocturnal katabatic flow.

To explore the synoptic-scale conditions responsible for supporting these anomalous jets, we partition days according to Fig. 3: those with peak precipitation between 18 and 06 UTC (i.e. midnight to midday local time) are considered 'nocturnal' peak days, and those with peak precipitation between 06 and 18 UTC (i.e. midday to midnight local time) are considered 'daytime' peak days. Compositing 12 UTC (0530 LT) vertical wind speed and 750 hPa winds

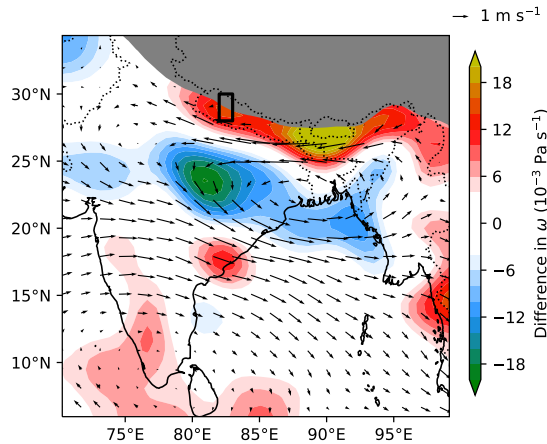


FIGURE 7 Difference between composite daily mean 750 hPa horizontal winds (arrows) and vertical wind speed (coloured contours) on days in which peak precipitation in the study region occurs between 18 and 06 UTC (2330 and 1130 LT) and days in which it occurs between 06 and 18 UTC (1130 and 2330 LT). Areas where climatological surface pressure is less than 750 hPa are greyed out. Negative values of ω indicate ascent. The study region is marked with a black rectangle.

for each and taking the difference (Fig. 7) shows that the two groups are associated with significantly different monsoon conditions. Nocturnal peak days are associated with a deepening of the monsoon trough, increased ascent over the head of the Bay of Bengal and monsoon core zone, and reduced ascent (or increased descent) along the foothills due to barrier flow effects – consistent with Fig. 6(b). The reverse is true for daytime peak days: an anomalously weak trough allows synoptic-scale anomalous westerlies to impinge on the Himalaya, with the subsequent forced ascent supporting large-scale deep convection. The composite difference of these synoptic conditions is consistent with either an active spell of the monsoon or the passage of a monsoon low-pressure system. We will explore this hypothesis further in Sec. 3.3.

To complete our understanding of the diurnal cycle, we must ask how these two driving processes – deep convection supported by synoptic-scale flow, and the more localised katabatic flow – project onto it. Are they actually coupled to the cycle, and does this coupling change meaningfully between days with different precipitation peak timing? We can explore these relationships in detail by examining the phase space of the composite diurnal cycle for different sets of days. Figure 8 shows the mean diurnal cycles of 10-m v (a proxy for katabatic flow), vertically-integrated moisture flux convergence (VIMFC; a proxy for large-scale deep convection), and precipitation, averaged over the study area. Two sets of days are included, representing the two local peaks in Fig. 3: those with peak precipitation occurring between 06 and 09 UTC, and those occurring between 18 and 21 UTC.

The two sets of days present markedly different composite diurnal cycles in this phase space. On the daytime peak days (06–09 UTC), mean VIMFC peaks at $3.6 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$ at about 08 UTC, remaining high for several hours. The peak precipitation immediately follows this event. In contrast, on nocturnal peak days (18–21 UTC), the VIMFC peak is much shorter and weaker, reaching only $2.5 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$. This means that much less moisture is available for deep convection in the afternoon and as a result, very little precipitation occurs at this time. This is corroborated (not shown) by the composite diurnal cycle of 500 hPa ω .

We can also see the relative importance of the low-level cross-slope winds. Climatologically, these are slightly upslope (positive 10-m v) because of the orientation of the monsoon trough relative to the foothills; however, at

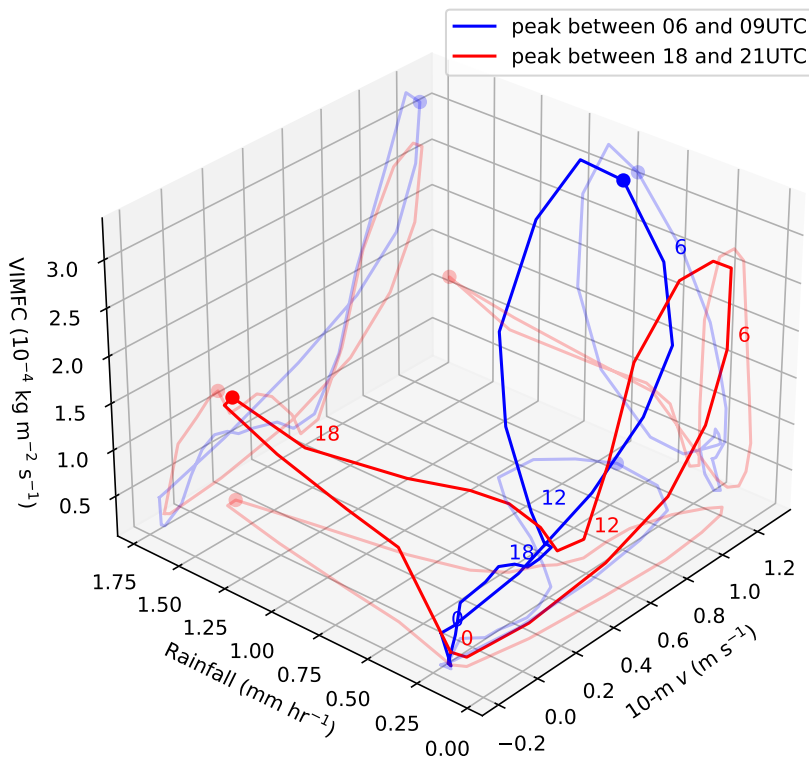


FIGURE 8 Three-dimensional phase space showing the relationship between cross-slope surface flow, vertically integrated moisture flux convergence, and rainfall over the course of the diurnal cycle. Composited for days on which peak precipitation occurs between 06 and 09 UTC (blue) and 18 and 21 UTC (red). Circle markers indicate the mean time of peak precipitation, and additional numerical markers indicate the UTC time of day for each cycle. The pale sets of red and blue lines show the projection of the cycle onto the three respective axis planes.

night, as the katabatic effect reaches a maximum, these approach zero or even become negative. Here, the role of the large-scale is again important: during nocturnal days, peak precipitation occurs as $10\text{-m } v$ approaches its lowest value, but this also coincides with an increase in VIMFC – suggesting that in such cases the katabatic flow is interacting with the monsoon environment at the north edge of the trough to produce moisture convergence along the slope. During daytime peak days, there is no simultaneous increase in VIMFC at this time, and hence no heavy precipitation. So, while the katabatic and convective processes are the primary drivers for the two sets of peaks, they do not operate entirely independently. In the same way, we see in Fig. 8 how the convective peak may be further supported by anabatic winds. These feedbacks are complementary to the mechanism proposed by Barros and Lang (2003), who found that daytime precipitation over Nepal was favoured during periods where strong anabatic flow prevented the build up of moisture convergence in the lower foothills.

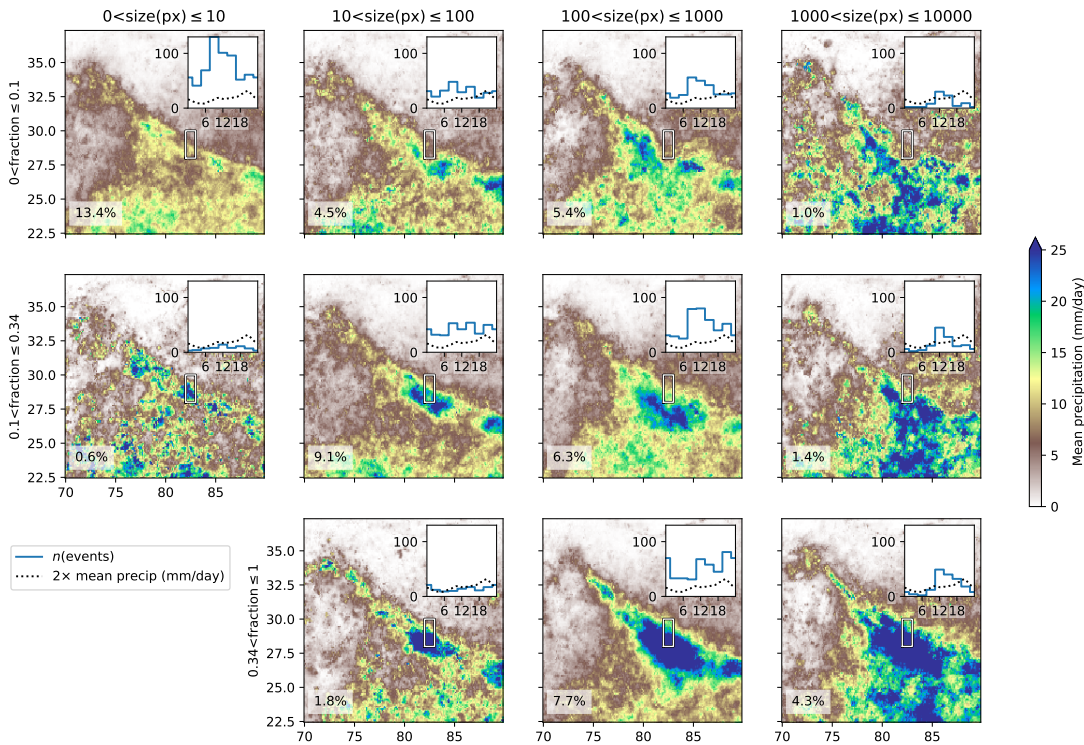


FIGURE 9 The relationship between convective organisation and the diurnal cycle. Convective regions are identified in Kalpana OLR data as contiguous areas with $OLR < 167 \text{ W m}^{-2}$. Convective regions that overlap the study region are then binned according to their area (measured in $0.25^\circ \times 0.25^\circ$ pixels, columns), and fraction of study area covered (rows). Composite mean precipitation is given for each pair of bins, with the diurnal cycle of event frequency inset (blue). Given in the inset, for comparison, is the mean diurnal cycle of precipitation (scaled for clarity) for Jul–Aug. The fraction of total Jul–Aug 06–15 UTC (precipitation that occurs during each subset) is given in the lower left of the respective panel.

3.3 | Response to intraseasonal forcing

3.3.1 | The relationship between convective organisation and the diurnal cycle

In the rest of this study, we will dedicate ourselves to understanding the drivers behind the convective processes that cause precipitation to fall over the Central Himalaya during the local afternoon or early evening. There are several reasons for this focus. Firstly, as we saw in the introduction, the katabatic processes over this region are generally well understood. Secondly, daytime precipitation over this region is the exception rather than the rule, and so it is important to quantify potential sources of variability, particularly given the challenge of simulating the diurnal cycle of convection in the tropics (Watters et al., 2021).

We start by exploring the structure and variability of deep convection itself over the region surrounding the Central Himalaya. Using Kalpana satellite OLR data, we located contiguous regions of deep convection by identifying $0.25^\circ \times 0.25^\circ$ pixels where $OLR < 167 \text{ W m}^{-2}$. Regions were then jointly categorised according to their area, and the fraction of the study region they covered. Composite precipitation for the twelve sets of bins (except for very small storms covering the whole study region, for which there were no cases) is shown in Fig. 9, along with the diurnal

cycle for each type, and the fraction of daytime rainfall for which that category is responsible. The total attributable fraction is 55.5%, and this would likely be higher still if we used a more relaxed threshold for identifying convection, or a higher resolution OLR product capable of resolving isolated deep convection. In contrast, only about 30% of nocturnal precipitation can be explained in this way.

Contributions come from a range of different sizes of storm. The smallest ($\leq 6250 \text{ km}^2$; length-scale $\leq 80 \text{ km}$) are associated with 14.0% of afternoon and early evening precipitation (1130 to 2030 LT – i.e., the window when convective peaks are most common) over the study region. They provide heavy precipitation to a small area, and closely follow the typical diurnal cycle of convection, peaking at 11 UTC (1630 LT) and decaying over the next few hours. Medium-sized storms ($6250 < A \leq 62500 \text{ km}^2$; length-scale between $\sim 80 \text{ km}$ and $\sim 250 \text{ km}$) contribute 15.4% of the daytime precipitation. Medium-sized storms that are further south, and thus cover only a small fraction of the box, have a diurnal cycle largely consistent with tropical convection, but those that are further north and cover much more of the region have a much flatter diurnal cycle, suggesting that the convective and katabatic modes are mixed at this scale: although the storms are highly convective, either a subset are being triggered by katabatic flow, or they are being intensified by katabatic convergence once mature.

The scale of the storm that the katabatic mode can generate is limited both by the length-scale of the orography and the ability of these storms to aggregate given the available environmental shear. Thus, our category of large storms ($62500 < A \leq 625000 \text{ km}^2$; length-scale between $\sim 250 \text{ km}$ and $\sim 800 \text{ km}$) is quite unlikely to be orographically triggered. These storms account for more daytime precipitation (19.4%) than any other size, and the mean diurnal cycle of their frequency peaks at 11 to 13 UTC (1630 to 1830 LT). This peak occurs a few hours later in storms that are further north (see bottom panel), suggesting that they may have initiated to the south and then propagated into the region. The high coverage subset also has a second peak at 20 UTC (0130 LT) which we hypothesize is due to intensification from low-level moisture flux convergence caused by katabatic flow. The largest category of storm ($> 625000 \text{ km}^2$; length-scale greater than $\sim 800 \text{ km}$) is comparatively rare but still contributes nearly 7% of the daytime precipitation to the region, having a well-defined peak in frequency at 12 UTC (1730 LT). The peak is broadest (i.e. the decay is slowest) for systems covering most of the box, again highlighting the role of local orographically-driven dynamics in supporting large-scale storms that arrive over the region.

Our discussion on the footprints of deep convection led to four conclusions: (i) deep convection contributes a majority of daytime precipitation over the Central Himalaya; (ii) regardless of scale, it typically follows the canonical diurnal cycle of tropical convection, peaking at around 12 UTC (1730 LT) except (iii) when propagating northward from the trough, in which case it occurs over the foothills several hours later or (iv) when residual storms are intensified at night through interactions with local orographic dynamics. We saw that the contributed precipitation was roughly equal across the three smaller size bins (15-20%) and a bit less for the largest size (7%). Yet, the synoptic conditions differ considerably between environments favourable for small-scale and large-scale convection. At the smaller end, intraseasonal variability tends to be controlled by the BSISO and monsoon active/break cycles; whereas at the larger end, convection is typically organised by low-pressure systems. We will now quantify the effect of each of these flavours of intraseasonal variability on the diurnal cycle of precipitation over the Central Himalaya.

3.3.2 | The BSISO

We start with the BSISO, often thought of as the meridionally-propagating component of the MJO, it is associated with northwest–southeast bands of positively or negatively anomalous OLR propagating northward across India and Southeast Asia, with a frequency of 10–60 days (Lee et al., 2013). Like the MJO, the BSISO is defined using the phase relationship between two principal component timeseries, and is thus quantified using both a phase (from 1

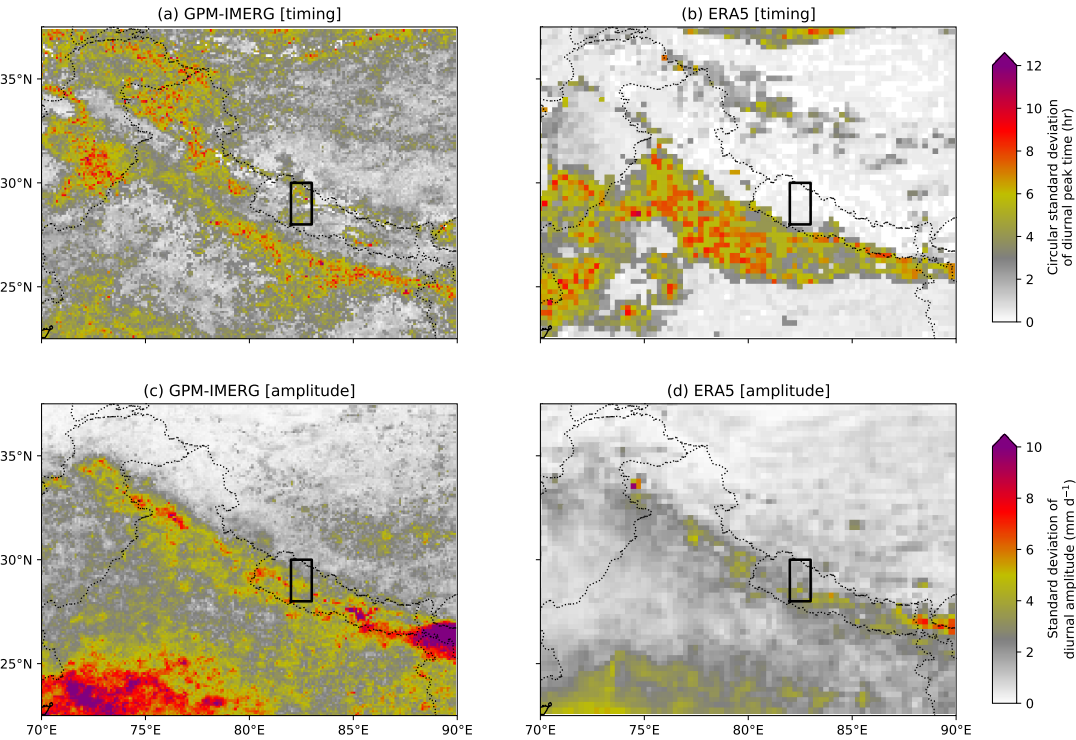


FIGURE 10 Effect of the BSISO on diurnal peak timing (a,b) and amplitude (c,d). The mean diurnal cycle for each BSISO phase is computed at each gridpoint. The circular standard deviation of the peak timing and the standard deviation of the cycle amplitude are then computed. Low values in (a) and (b) suggest the BSISO has little or no impact on the timing of the diurnal peak. The study region is marked with a black rectangle.

to 8) and a standardised magnitude. Both the diurnal cycle and the BSISO are ‘circular’ variables in this regard, but simply computing a direct circular correlation between the two is not appropriate because it relies on the assumption that the two variables covary somewhat uniformly. This may not be the case: the two peaks on the diurnal cycle, which are almost opposite in phase, could be strongly associated with neighbouring BSISO phases; but, unless the relationship with the remaining phases is consistently ordered, the correlation would be low despite plausible causality. We must take a more nuanced approach. To do this, we compute the mean diurnal cycle for each BSISO phase at each gridpoint. Then, by taking the standard deviation of the amplitude of those eight cycles, and the circular standard deviation (see Sec. 2.2.1) of the eight peak times, we can identify regions where the BSISO appreciably affects the timing and amplitude of the diurnal cycle of precipitation – in regions where the standard deviations are low, the relationship is weak; where the standard deviation is high, the relationship is strong. To quantify uncertainty, we do this for both GPM-IMERG and ERA5, the latter of which should capture intraseasonal variability well over the Central Himalaya, as it does over the Western Himalaya (Baudouin et al., 2020).

The BSISO has almost no effect on the timing of the diurnal cycle of ERA5 rainfall over the study region, and only has a comparatively weak effect on IMERG. There is also only a relatively weak effect on the cycle amplitude: the magnitude of the convective (10–11 UTC, ~1600 LT) peak averaged over the box only varies from 0.35 to 0.47 mm hr⁻¹ between the different BSISO phases (lowest in phase 4; highest in phase 8). The magnitude of the nocturnal

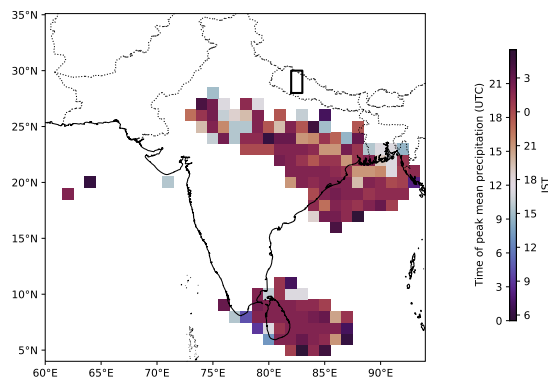


FIGURE 11 The effect of LPS presence on the timing of the diurnal cycle of precipitation over the study region. Track points of LPSs (2000–2018) are binned into a $1^\circ \times 1^\circ$ grid. Gridpoints with at least ten days of LPS overpasses are then coloured according to the peak timing of the mean diurnal cycle over the study region.

peak varies between 0.57 and 0.88 mm hr^{-1} (lowest in phase 4; highest in phase 5). These are in broad agreement with the behaviour of the BSISO, whose negative OLR anomalies reach their furthest north in phase 5, and which has significant, positive OLR anomalies over the Central Himalaya during phase 4. In summary, while the BSISO can affect the magnitude of the convective and katabatic peaks to some extent, it is not enough to invert the population so that the convective peak is stronger than the katabatic peak for any given phase. This may be because the BSISO does not propagate sufficiently far north: we see that in both IMERG and ERA5 that it does have a substantial effect on the timing and amplitude of the diurnal cycle further south, over the Indo-Gangetic Plain, a topic that we leave for further research.

3.3.3 | Low-pressure systems

Finally, we look at the role of monsoon low-pressure systems (LPSs), which are capable of inducing extended periods of large-scale moisture flux, organised deep convection, and deepening/extending the monsoon trough. Convective activity is most sensitive to their location rather than intensity (Hunt et al., 2021), and so in Fig. 11 we bin LPS tracks onto a $1^\circ \times 1^\circ$ grid and compute the mean diurnal cycle over the study region for the dates included in each box, as long as at least 10 LPSs were present. When LPSs are either in the centre or the south of the trough, or are located far away from the Himalaya (e.g. over Sri Lanka or the Arabian Sea), the peak of the mean diurnal cycle remains close to the katabatic peak at about 21 UTC (0230 LT). Where LPSs are at the northern edge of the trough, or extend it to the northwest, the convective peak becomes stronger, and the peak of the mean diurnal cycle moves to the afternoon (09 UTC, 1430 LT), consistent with the larger storm sizes of Fig. 7 and Fig. 9. One possible reason for this is the cloud structure of LPSs: Hunt et al. (2016) showed that monsoon depressions (their Fig. 5) were often associated with deep convective cloud near their centre and stratiform cloud at larger radii. Thus, an LPS in the centre of the trough provides moisture, but not much convective instability to the foothills – supporting the katabatic peak, whereas an LPS further north may cause deep convective to occur directly over the study region. Further work is needed to explore how LPSs interact with the orography over the Central Himalaya.

4 | DISCUSSION

Before concluding, we will briefly discuss some of the caveats and implications of this work in a modelling framework. Perhaps the most important caveat is basing many of our results on the interpretation of reanalysis data. At a horizontal resolution of ~ 25 km, many of the valleys that may be providing the more intense katabatic flow are not represented. Fig. 12 shows the mean diurnal cycle and frequency of peak timing over the study region for GPM-IMERG, ERA5, and two simulations of the 2016 monsoon season in the Met Office Unified Model (MetUM) at horizontal resolutions of 17 km (parameterised convection) and 4.4 km (explicit convection) conducted as part of the INCOMPASS project (Turner et al., 2020). We also include another reanalysis, IMDAA (Rani et al., 2021), which has higher horizontal resolution (12 km) than ERA5, and uses a version of the MetUM as its driving model. To confirm that the statistics for a single season are valid, both the climatology (dotted) and the 2016 season (solid) are plotted for the reanalyses and satellite data. In the reanalyses and 17 km MetUM experiment, we can also partition the rainfall into ‘convective’ (produced by the convection scheme) and ‘stratiform’ (produced by the microphysics scheme).

Both reanalyses and the 17 km experiment capture the convective and katabatic peaks, but overestimate the magnitude of the convective peak and significantly underestimate the magnitude of the katabatic peak. The coarsest model (ERA5) underestimates this peak the most, and the highest-resolution model (IMDAA) the least, which may imply that fine representation of orography is crucial to correct representation of the katabatic winds (and thus to the nocturnal moisture convergence required for the precipitation). Moisture not used up as precipitation during the katabatic peak is then available later for the convective peak. It is a helpful sanity check to see that the contribution of convective rainfall is much larger during the convective peak than the katabatic peak, where stratiform rainfall plays a more significant role, even overtaking the convective contribution in ERA5. Understanding the respective strengths (e.g. both peaks present and at approximately the right time) and weaknesses (e.g. the relative strengths of the peaks are inconsistent with observation) of these parameterised-convection models is left for future work. The convection-permitting 4.4 km experiment is beset by a different problem. The convection takes too long to build up during the day, since uplifting an entire 4.4 km gridbox requires a lot of instability. This means that the convective peak occurs so late that it interferes with the katabatic peak, resulting in a mean cycle with a single peak in the late evening (2000 LT). This demonstrates that the problem of correctly representing the complex and interacting processes that drive the diurnal cycle here is not simply a matter of increasing resolution. It is likely that this would be improved by models with sub-kilometre resolution (e.g. Yashiro et al., 2016), where convection is resolved rather than just permitted, and where the representation of the orography is fine enough to capture the valleys responsible for strong pulses of katabatic flow, but we leave such an assessment for future work.

5 | CONCLUSIONS

In this study, we have explored the complex diurnal cycle of precipitation over the monsoonal Central Himalaya. Using a small study region that we believe to be representative ($82\text{--}83^\circ\text{E}$, $28\text{--}30^\circ\text{N}$), we showed that the mean diurnal cycle has two broad peaks, one during the late afternoon (1700 LT) and one during the early morning (0200 LT). The early morning peak has the greater magnitude in the mean cycle during July and August, but this pattern reverses during the pre- and post-monsoon months of June and September, when the late afternoon peak has the greater magnitude.

Reanalyses and a 17 km model with parameterised convection broadly capture both peaks, but overestimate the magnitude of the afternoon peak while underestimating the magnitude of the early morning peak. Simple diagnostics that just compute the timing of the maximum of the mean diurnal cycle are thus insufficient to validate model per-

formance in this region – simply comparing the peak times of the climatological mean diurnal cycles would point to a phase bias of about 10 hours here, which is an incomplete and exaggerated description of the actual biases.

We showed that this bimodal cycle is an artefact of compositing: individual days are usually associated with a single peak that typically lasts for several hours and may occur at any time, although are most frequent during the early morning and late afternoon. Both peaks are associated with a significant low-level nocturnal jet, which can therefore be ruled out as a significant moisture source that preferentially supports one or the other.

We confirmed previous studies that showed that the early morning peak was due to katabatic winds interacting with the mean monsoon flow to drive moisture flux convergence along the foothills. We hypothesize that this explains why this peak is comparatively weaker outside the monsoon, and that underestimating the magnitude of the katabatic wind due to coarse orographic representation is a potential source of the bias in models and reanalyses.

We showed that the late-afternoon peak is linked to the canonical diurnal cycle of tropical convection, and that the responsible convection occurs at a range of scales ranging from tens (small mesoscale convective systems) to thousands (monsoon low-pressure systems) of kilometres. We found that systems present after midnight could be further intensified at low altitudes by katabatic flow. We hypothesize that anabatic flow may assist in intensifying or triggering convection at higher altitudes during the daytime.

We explored a range of sources of intraseasonal variability, finding only very weak relationships between the BSISO and the diurnal cycle, and between the monsoon active/break phases and the diurnal cycle. We also found, however, that monsoon LPSs, when sufficiently far north or west, were capable of significantly intensifying the convective peak.

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references

- Arulalan, T., AchutaRao, K., Hunt, K. M. R., Turner, A. G., Mitra, A. K. and Sarkar, A. (2020) Prediction of western disturbances tracks using NEPS. URL: https://www.ncmrwf.gov.in/event/emmda/Abstracts/TArulalan_Abstract_EMMDA.pdf.
- Barros, A. P., Joshi, M., Putkonen, J. and Burbank, D. W. (2000) A study of the 1999 monsoon rainfall in a mountainous region in central Nepal using TRMM products and rain gauge observations. *Geophysical research letters*, **27**, 3683–3686.
- Barros, A. P., Kim, G., Williams, E. and Nesbitt, S. W. (2004) Probing orographic controls in the Himalayas during the monsoon using satellite imagery. *Natural Hazards and Earth System Sciences*, **4**, 29–51.
- Barros, A. P. and Lang, T. J. (2003) Monitoring the monsoon in the Himalayas: Observations in central Nepal, June 2001. *Monthly Weather Review*, **131**, 1408–1427.
- Baudouin, J.-P., Herzog, M. and Petrie, C. A. (2020) Cross-validating precipitation datasets in the Indus River basin. *Hydrology and Earth System Sciences*, **24**, 427–450.
- Bhatt, B. C. and Nakamura, K. (2006) A climatological-dynamical analysis associated with precipitation around the southern part of the Himalayas. *Journal of Geophysical Research: Atmospheres*, **111**.
- Bluestein, H. B. (1993) *Synoptic-dynamic meteorology in midlatitudes. Volume II. Observations and theory of weather systems*. New York, NY (United States); Oxford University Press. P. 392.

- Bollasina, M., Bertolani, L. and Tartari, G. (2002) Meteorological observations at high altitude in the Khumbu Valley, Nepal Himalayas, 1994–1999. *Bulletin of Glaciological Research*, **19**, 1–12.
- Dai, A. and Trenberth, K. E. (2004) The diurnal cycle and its depiction in the Community Climate System Model. *Journal of Climate*, **17**, 930–951.
- Dezfuli, A. K., Ichoku, C. M., Huffman, G. J., Mohr, K. I., Selker, J. S., Van De Giesen, N., Hochreutener, R. and Annor, F. O. (2017) Validation of IMERG precipitation in africa. *Journal of Hydrometeorology*, **18**, 2817–2825.
- Dirmeyer, P. A., Cash, B. A., Kinter, J. L., Jung, T., Marx, L., Satoh, M., Stan, C., Tomita, H., Towers, P., Wedi, N. et al. (2012) Simulating the diurnal cycle of rainfall in global climate models: Resolution versus parameterization. *Climate Dynamics*, **39**, 399–418.
- Dong, W.-H., Ming, Y. and Ramaswamy, V. (2020) Projected changes in South Asian monsoon low-pressure systems. *J. Climate*. In review.
- Egger, J., Bajrachaya, S., Egger, U., Heinrich, R., Reuder, J., Shayka, P., Wendt, H. and Wirth, V. (2000) Diurnal winds in the Himalayan Kali Gandaki valley. part I: observations. *Monthly Weather Review*, **128**, 1106–1122.
- Fisher, N. I. (1995) *Statistical analysis of circular data*. Cambridge University Press.
- Fitzjarrald, D. R. (1984) Katabatic wind in opposing flow. *Journal of Atmospheric Sciences*, **41**, 1143–1158.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D. et al. (2020) The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, **146**, 1999–2049.
- Hou, A. Y., Kakar, R. K., Neeck, S., Azarbarzin, A. A., Kummerow, C. D., Kojima, M., Oki, R., Nakamura, K. and Iguchi, T. (2014) The global precipitation measurement mission. *Bulletin of the American Meteorological Society*, **95**, 701–722.
- Huffman, G. J., Bolvin, D. T., Nelkin, E. J. et al. (2015) Integrated Multi-satellitE Retrievals for GPM (IMERG) technical documentation. *NASA/GSFC Code*, **612**, 2019.
- Hunt, K. M. R. and Fletcher, J. K. (2019) The relationship between Indian monsoon rainfall and low-pressure systems. *Climate Dynamics*, **53**, 1–13.
- Hunt, K. M. R., Turner, A. G. and Parker, D. E. (2016) The spatiotemporal structure of precipitation in Indian monsoon depressions. *Quart. J. Roy. Meteor. Soc.*, **142**, 3195–3210. URL: <http://dx.doi.org/10.1002/qj.2901>.
- Hunt, K. M. R., Turner, A. G., Stein, T. H. M., Fletcher, J. K. and Schiemann, R. K. H. (2021) Modes of coastal precipitation over southwest india and their relationship with intraseasonal variability. *Quarterly Journal of the Royal Meteorological Society*, **147**, 181–201.
- Joyce, R. J., Janowiak, J. E., Arkin, P. A. and Xie, P. (2004) CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *J. Hydrometeor.*, **5**, 487–503.
- Kikuchi, K. and Wang, B. (2008) Diurnal precipitation regimes in the global tropics. *Journal of Climate*, **21**, 2680–2696.
- Kozu, T., Kawanishi, T., Kuroiwa, H., Kojima, M., Oikawa, K., Kumagai, H., Okamoto, K., Okumura, M., Nakatsuka, H. and Nishikawa, K. (2001) Development of precipitation radar onboard the Tropical Rainfall Measuring Mission (TRMM) satellite. *IEEE Trans. Geosci. Rem. Sens.*, **39**, 102–116. URL: <http://dx.doi.org/10.1109/36.898669>.
- Kummerow, C., Barnes, W., Kozu, T., Shiue, J. and Simpson, J. (1998) The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J. Atmos. Oceanic Technol.*, **15**, 809–817. URL: [http://dx.doi.org/10.1175/1520-0426\(1998\)015<0809:TTRMT>2.0.CO;2](http://dx.doi.org/10.1175/1520-0426(1998)015<0809:TTRMT>2.0.CO;2).
- Kummerow, C., Simpson, J., Thiele, O., Barnes, W., Chang, A. T. C., Stocker, E., Adler, R. F., Hou, A., Kakar, R., Wentz, F. et al. (2000) The status of the Tropical Rainfall Measuring Mission (TRMM) after two years in orbit. *J. Appl. Meteor.*, **39**, 1965–1982. URL: [http://dx.doi.org/10.1175/1520-0450\(2001\)040<1965:TSOTTR>2.0.CO;2](http://dx.doi.org/10.1175/1520-0450(2001)040<1965:TSOTTR>2.0.CO;2).

- 516 Lee, J.-Y., Wang, B., Wheeler, M. C., Fu, X., Waliser, D. E. and Kang, I.-S. (2013) Real-time multivariate indices for the boreal
517 summer intraseasonal oscillation over the Asian summer monsoon region. *Climate Dyn.*, **40**, 493–509.
- 518 Mahakur, M., Prabhu, A., Sharma, A. K., Rao, V., Senroy, S., Singh, R. and Goswami, B. N. (2013) A high-resolution outgoing
519 longwave radiation dataset from Kalpana-1 satellite during 2004–2012. *Current Science*, 1124–1133.
- 520 Marsham, J. H., Dixon, N. S., Garcia-Carreras, L., Lister, G. M. S., Parker, D. J., Knippertz, P. and Birch, C. E. (2013) The role of
521 moist convection in the West African monsoon system: Insights from continental-scale convection-permitting simulations.
522 *Geophysical Research Letters*, **40**, 1843–1849.
- 523 Martin, G. M., Brooks, M. E., Johnson, B., Milton, S. F., Webster, S., Jayakumar, A., Mitra, A. K., Rajan, D. and Hunt, K. M. R.
524 (2020) Forecasting the monsoon on daily to seasonal time-scales in support of a field campaign. *Quarterly Journal of the*
525 *Royal Meteorological Society*, **146**, 2906–2927.
- 526 Prakash, S., Mitra, A. K., AghaKouchak, A., Liu, Z., Norouzi, H. and Pai, D. S. (2018) A preliminary assessment of GPM-based
527 multi-satellite precipitation estimates over a monsoon dominated region. *Journal of Hydrology*, **556**, 865–876.
- 528 Rani, S. I., Arulalan, T., George, J. P., Rajagopal, E., Renshaw, R., Maycock, A., Barker, D. M. and Rajeevan, M. (2021) IMDAA:
529 High-resolution satellite-era reanalysis for the Indian monsoon region. *Journal of Climate*, **34**, 5109–5133.
- 530 Romatschke, U. and Houze Jr, R. A. (2011) Characteristics of precipitating convective systems in the south asian monsoon.
531 *Journal of Hydrometeorology*, **12**, 3–26.
- 532 Romatschke, U., Medina, S. and Houze, R. A. (2010) Regional, seasonal, and diurnal variations of extreme convection in the
533 South Asian region. *Journal of Climate*, **23**, 419–439.
- 534 R  thrich, F., Thies, B., Reudenbach, C. and Bendix, J. (2013) Cloud detection and analysis on the Tibetan Plateau using Me-
535 teosat and CloudSat. *Journal of Geophysical Research: Atmospheres*, **118**, 10–082.
- 536 Sahany, S., Venugopal, V. and Nanjundiah, R. S. (2010) Diurnal-scale signatures of monsoon rainfall over the Indian region
537 from TRMM satellite observations. *Journal of Geophysical Research: Atmospheres*, **115**.
- 538 Sharma, N., Attada, R. and Hunt, K. M. R. (2021) Evaluating winter precipitation over the western himalayas in high resolution
539 Indian regional reanalysis using multi-source climate datasets. In preparation.
- 540 Shrestha, D., Singh, P. and Nakamura, K. (2012) Spatiotemporal variation of rainfall over the central Himalayan region revealed
541 by TRMM Precipitation Radar. *Journal of Geophysical Research: Atmospheres*, **117**.
- 542 Singh, R., Thapliyal, P. K., Kishtawal, C. M., Pal, P. K. and Joshi, P. C. (2007) A new technique for estimating outgoing longwave
543 radiation using infrared window and water vapor radiances from Kalpana very high resolution radiometer. *Geophysical*
544 *Research Letters*, **34**.
- 545 Tang, G.-Q., Clark, M. P., Papalexiou, S. M., Ma, Z.-Q. and Hong, Y. (2020) Have satellite precipitation products improved
546 over last two decades? A comprehensive comparison of GPM IMERG with nine satellite and reanalysis datasets. *Remote*
547 *Sensing of Environment*, **240**, 111697.
- 548 Turner, A. G., Bhat, G. S., Martin, G. M., Parker, D. J., Taylor, C. M., Mitra, A. K., Tripathi, S. N., Milton, S., Rajagopal, E. N., Evans,
549 J. G. et al. (2020) Interaction of Convective Organisation with Monsoon Precipitation, Atmosphere, Surface and Sea: the
550 2016 INCOMPASS field campaign in India. *Quarterly Journal of the Royal Meteorological Society*, **146**, 2828–2852.
- 551 Ueno, K., Kayastha, R. B., Yasunari, T., Nakawo, M. and Chitrakar, M. R. (2001) Meteorological observations during 1994–2000
552 at the automatic weather station (GEN-AWS) in Khumbu region, Nepal Himalayas. *Bulletin of Glaciological Research*, **18**,
553 23–30.
- 554 Watters, D., Battaglia, A. and Allan, R. P. (2021) The diurnal cycle of precipitation according to multiple decades of global
555 satellite observations, three CMIP6 models, and the ECMWF reanalysis. *Journal of Climate*, **34**, 5063–5080.

- de Wekker, S. F. J., Zhong, S., Fast, J. D. and Whiteman, C. D. (1998) A numerical study of the thermally driven plain-to-basin wind over idealized basin topographies. *Journal of Applied Meteorology and Climatology*, **37**, 606–622.
- Yashiro, H., Kajikawa, Y., Miyamoto, Y., Yamaura, T., Yoshida, R. and Tomita, H. (2016) Resolution dependence of the diurnal cycle of precipitation simulated by a global cloud-system resolving model. *Sola*, **12**, 272–276.

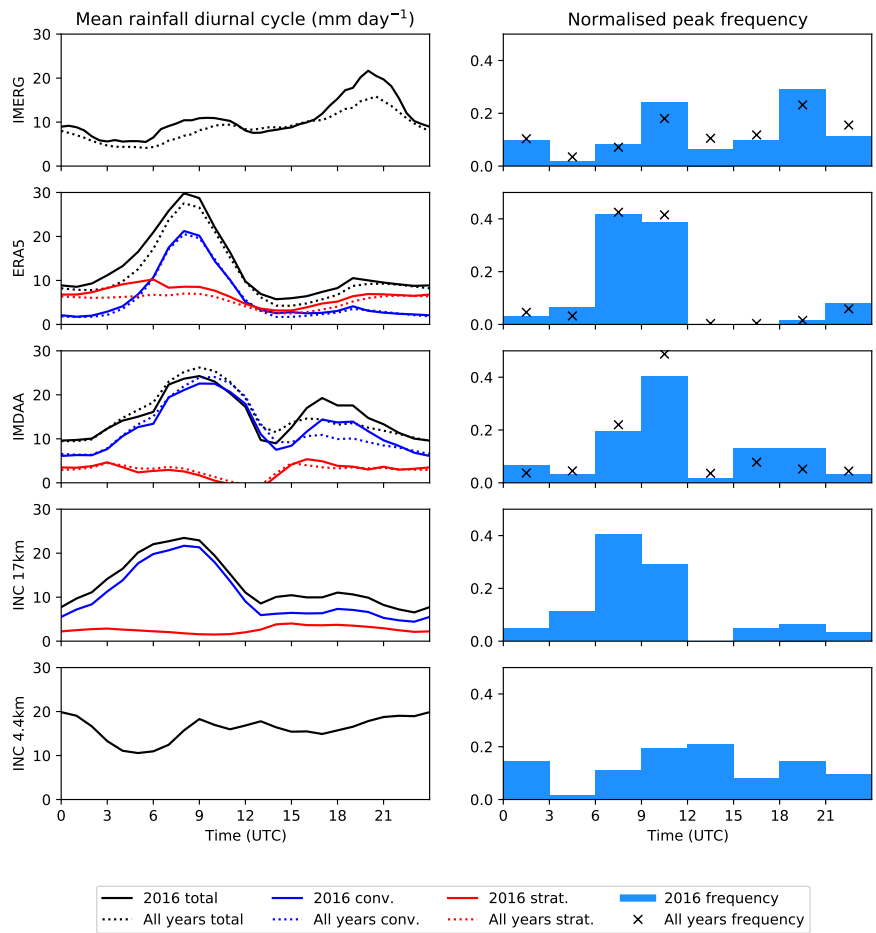


FIGURE 12 Comparison of diurnal cycle of precipitation over the study region in GPM-IMERG, ERA5 and IMDAA reanalyses, and two resolutions (17 km with parameterised convection; 4.4 km with explicit convection) of a limited area MetUM experiment simulating the 2016 season. Left: the mean Jul–Aug diurnal cycle (for 2016 with solid lines, for all available years with dotted lines), with convective (blue) and large-scale (red) contributions if available. Right: the relative frequency of days with a diurnal peak occurring in the given three-hourly bins is plotted (2016 with blue bars, all available years with black crosses).