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LETTER

The impact of monsoon intraseasonal variability on renewable power generation in India

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Abstract

India is increasingly investing in renewable technology to meet rising energy demands, with hydropower and other renewables comprising one-third of current installed capacity. Installed wind-power is projected to increase 5-fold by 2035 (to nearly 100GW) under the International Energy Agency's New Policies scenario. However, renewable electricity generation is dependent upon the prevailing meteorology, which is strongly influenced by monsoon variability. Prosperity and widespread electrification are increasing the demand for air conditioning, especially during the warm summer. This study uses multi-decadal observations and meteorological reanalysis data to assess the impact of intraseasonal monsoon variability on the balance of electricity supply from wind-power and temperature-related demand in India. Active monsoon phases are characterized by vigorous convection and heavy rainfall over central India. This results in lower temperatures giving lower cooling energy demand, while strong westerly winds yield high wind-power output. In contrast, monsoon breaks are characterized by suppressed precipitation, with higher temperatures and hence greater demand for cooling, and lower wind-power output across much of India. The opposing relationship between wind-power supply and cooling demand during active phases (low demand, high supply) and breaks (high demand, low supply) suggests that monsoon variability will tend to exacerbate fluctuations in the so-called *demand-net-wind* (i.e., electrical demand that must be supplied from non-wind sources). This study may have important implications for the design of power systems and for investment decisions in conventional schedulable generation facilities (such as coal and gas) that are used to maintain the supply/demand balance. In particular, if it is assumed (as is common) that the generated wind-power operates as a *price-taker* (i.e., wind farm operators always wish to sell their power, irrespective of price) then investors in conventional facilities will face additional weather-volatility through the monsoonal impact on the length and frequency of production periods (i.e. their load-duration curves).

1. Introduction

Economic growth, rising prosperity, rapid urbanization and increasing electrification are all acting to increase the global electrical energy demand (International Energy Agency (IEA) 2012), especially in countries that are rapidly developing. India's total power capacity more than doubled from 1998 to 2013 in order to meet rising demand (Ernst and Young 2013). Increasing demand for energy for cooling purposes is a significant factor driving this increase; the number of households with temperature control devices in urban Delhi increased from 32.9% in 1993 to 60% in 2009 (Gupta 2012).

A proportion of the rising demand for electricity is met by renewable sources, and India aims to meet 15% of its electricity requirements through renewables by 2020 (Ernst and Young 2013). Wind and hydro-power are already large contributors in the Indian Power Sector, with shares of 8.4% and 17.7% respectively (Ernst and Young 2013). India is the world's fifth largest wind energy producer, with 19.1GW of installed capacity;

however, this represents less than one-fifth of the estimated wind-power potential for India, and increasing wind-power production, both on- and offshore, is a key component of India's future energy strategy (Ernst and Young 2013).

The production of electricity from renewables is highly dependent upon the prevailing meteorology. The seasonal cycle in India is dominated by the South Asian monsoon. Stronger solar irradiance during the boreal spring and summer heats the Asian landmass and leads to the formation of a heat low and reversed pole-to-equator temperature gradient. This influences the circulation patterns over the Indian Ocean, diverting winds north across the equator, bringing strong westerly winds and heavy rain over India (Turner and Annamalai 2012). Weakening of the solar insolation in the boreal autumn, and movement of the region of maximum solar heating south of the equator, concludes the monsoon season.

The monsoon circulation is not consistent throughout the entire season. Over India there are two preferred locations for convection during the monsoon: the so-called continental tropical convergence zone (TCZ) over the Indian subcontinent and the oceanic TCZ over the equatorial Indian Ocean. Variation between these two centres gives large changes in rainfall and wind patterns (Annamalai and Sperber 2005, Lau *et al* 2012), resulting in active phases bringing heavy rainfall over India and break phases with stronger rainfall near the equator and central India features increased surface pressure, a weaker low-level westerly jet and reduced precipitation (Krishnan *et al* 2000, Ramesh Kumar and Prabhu Dessai 2004, Annamalai and Sperber 2005, Rajeevan *et al* 2010, Lau *et al* 2012). In 2002 and 2009 significant break phases during July and August led to low monsoon rainfall totals with profound socio-economic implications (Goswami and Xavier 2003, Munot and Kothawale 2014). Forecasting active and break periods within the South Asian monsoon has been a focus of research for many years due to the impact of such variations on agriculture, and various methods to do so have been proposed (Goswami and Xavier 2003, Chattopadhyay *et al* 2008, Krishnamurthy and Shukla 2007, Borah *et al* 2013). If these methods can ever become skilful out to lead times of two weeks or more then they may be useful for predicting a variety of environmental impacts and, as we will show, such forecasts would also be very relevant to the power sector. Furthermore, irrespective of the ability to produce successful meteorological forecasts of individual monsoon events, an understanding of the climatological possibility for such events occuring and their impact on the power system is likely to be of value to both long-term planning for power system resilience and the wider contextualization of day-to-day operational decision making.

Meteorological variability often leads to variability in the power sector, particularly where renewable sources are included. Ely *et al* (2013) examined the impact of the North Atlantic Oscillation (NAO) on wind-power and electricity demand in Norway and the UK during periods of low hydropower capacity. It was found that during NAO-negative states, cold calm conditions resulted in simultaneous increased demand and low wind-power, and could result in problems for a combined Norway-UK power system. Santos-Alamillos *et al* (2012) studied the production of wind and solar power over the Iberian peninsula with the aim of finding the optimal distribution of wind and solar plants to minimize the variability in the output from these non-controllable power supplies. It was found that, for the most part, combining the power production from wind and solar sources reduces the variability in the power supply due to balancing between meteorological variables. The present study adopts a simpler 'integrated weather impacts' approach to the power sector in India.

The potential for wind-power has been studied over the Indian subcontinent and was found to be a viable source of power in many regions (Khan *et al* 2004, Khadem and Hussain 2006, Mondal and Denich 2010). Both Gupta (2012) and Ranjan and Jain (1999) found a relationship between temperature and demand in Delhi, with elevated temperatures during the monsoon giving rise to increased energy demand. However, the relationship between intraseasonal variability within the monsoon and energy demand and supply has not been studied. High temperatures have resulted in power outages in recent years (Zhong and Chaturvedi 2014), as supply has not met the high energy demand. It is crucial that the balance between supply and demand is properly understood, given the rising demand for cooling energy and increasing use of non-schedulable, highly variable power generation resources with limited storage capacity. In this paper we examine the impact of intraseasonal variability within the Asian monsoon on two components of the Indian power sector: wind power supply and cooling energy demand. We particularly focus on the core monsoon season where, although the seasonal-mean temperature has typically dropped below that of the pre-monsoon months, intraseasonal variations in temperature (and hence cooling demand) are particularly marked and must be anticipated.

The remainder of the paper is structured as follows: section 2 contains a description of the methods used to study wind-power, cooling energy demand and intraseasonal variability within the monsoon. Sections 3 and 4 discuss the impacts of intraseasonal variability on wind-power supply and cooling energy demand respectively. Finally section 5 discusses the implications of these results for the Indian power sector, highlighting the main conclusions and areas requiring further research.

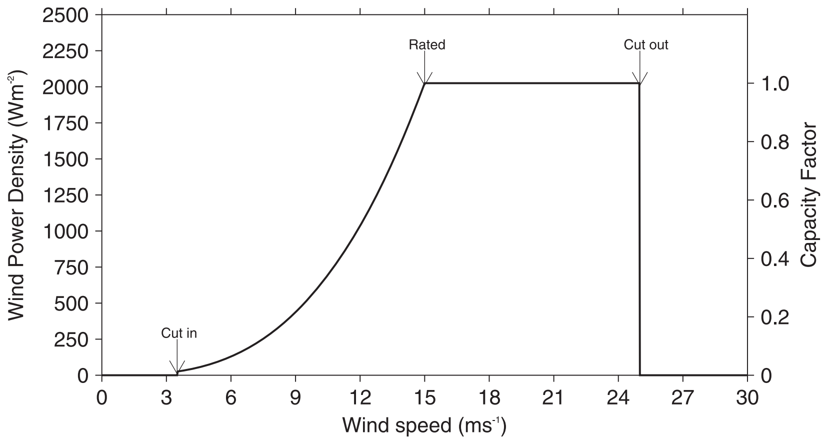

Figure 1. Idealized wind-power transformation curve relating wind speed to power output and capacity factor (the fraction of maximum power produced). Units are Wm^{-2} for power output.

2. Method

In this section the methods used to estimate wind-power production and temperature-related demand from meteorological data are described. The categorization of monsoon intraseasonal variability is also explained.

2.1. Wind power

Wind-power produced in a wind turbine is estimated using a simple idealized power curve, e.g. as in Pryor and Barthelmie (2010), Ruiz-Arias *et al* (2012) and Cannon *et al* (2015). This is shown in figure 1 and equation 1. The wind-power output (left axis) is normalized by dividing by the maximum power output to give the capacity factor (right axis); thus equation 1 makes no assumptions regarding the dimensions or efficiency of the turbine. Capacity factor is given by:

$$\text{Capacity factor} = \begin{cases} 0 & \text{if} \quad u < 3.5\ \text{ms}^{-1} \\ \dfrac{\frac{1}{2}A\eta\rho u^3}{\frac{1}{2}A\eta\rho 15^3} & \text{if} \quad 3.5 \leqslant u < 15\ \text{ms}^{-1} \\ 1 & \text{if} \quad 15 \leqslant u < 25\ \text{ms}^{-1} \\ 0 & \text{if} \quad u \geqslant 25\ \text{ms}^{-1}, \end{cases} \tag{1}$$

where A is the circular area swept by the blades, η is the efficiency of the turbine, ρ is the air density and u is the observed wind speed at the height of the turbine hub. We use cut-in and cut-out speeds of 3.5 ms^{-1} and 25 ms^{-1} respectively, common with other studies (British Wind Energy Association 2005, Brayshaw *et al* 2011, Wind Power Programme 2013).

The nonlinear transformation from wind speed to wind-power and highly fluctuating nature of wind means it is important to use data with high temporal resolution. Here MERRA reanalysis wind speed data at 50 m above ground were used, which is available at an hourly temporal resolution and spatial resolution of $\frac{2}{3}^{\circ}$ by $\frac{1}{2}^{\circ}$ (longitude by latitude) over 1979–2004 (Rienecker *et al* 2011). Although 50 m above the ground is below the height of many modern wind turbines (50–120 m, British Wind Energy Association 2005), this choice is consistent with previous wind-power assessments for India (Ramachandra and Shruthi 2005, Mondal and Denich 2010) and the overall results are robust to the application of simple logarithmic or power-law boundary layer wind scaling (results not shown). Overall, the approach adopted here resembles that of Cannon *et al* (2015) who found MERRA-derived wind-power estimates to be highly correlated with recorded wind-power data over the UK.

2.2. Cooling energy demand

Temperature-related-demand is a U-shaped function of temperature; temperature increases result in more demand for cooling energy and temperature decreases raise the demand for heating energy. The base or threshold temperature is where temperature-related demand is at it's minimum (Sailor & Munoz, 1997, Ruth and Lin 2006, Isaac and van Vuuren 2009, Gupta 2012). The absence of any available daily demand data for this study forces us instead to use a well-known proxy for demand. Cooling degree days (CDDs) indicate the level of demand, which is assumed to be a linear function of the deviation of the daily mean temperature above a threshold and the length of time the threshold is surpassed. Degree days have been widely used as a proxy for demand (Sailor & Munoz, 1997, Ruth and Lin 2006, Sivak 2009). We are thus counting the cumulative number of degree-days over a threshold temperature, above which we assume cooling systems are required in homes and offices.

In this study we focus on cooling needs only and set the base or threshold temperature at 22 °C. This is consistent with a recent study of Delhi electricity demand by Gupta (2012) but somewhat higher than

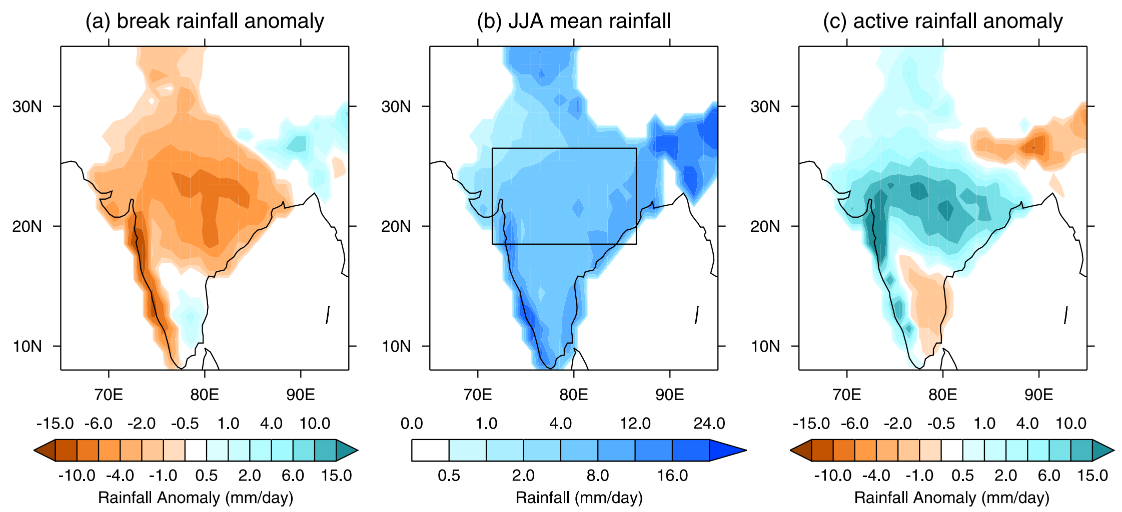

Figure 2. Precipitation distribution during the monsoon season (JJA) over 1969–2004. (a) And (c) show the precipitation anomaly during the break and active phases respectively, relative to neutral periods; (b) shows the mean JJA daily rainfall. The monsoon index used is based on rainfall over the core monsoon zone marked in (b). Units are mm per day.

might be expected in many other global cities (typically 18–22 °C, see e.g., Schaeffer *et al* 2012). The relevant threshold value may, of course, change with time or location but the qualitative relationships to be discussed in this paper are robust to changes in the threshold value across a threshold temperature range of several °C. CDD are estimated using daily mean surface (1.5 m) air temperature data produced by the Indian Meteorological Department based on observations from 395 stations and distributed as a 1° gridded product for June–August 1969–2005 (Srivastava *et al* 2009).

Electricity transmission from generation source to consumer is achieved using an electricity grid. In India there is very limited grid structure — the southern grid is entirely separate from the main grid (Ernst and Young 2013), so therefore electricity generation needs to be close to areas of demand. In this study the focus has been upon 3 major cities: Bangalore, Mumbai and Delhi. Temperature-related demand was examined in each city, and wind-power generation was examined over regions surrounding each city. These three cities were chosen as they cover different parts of the country featuring different climates and the regions contain some of the current wind turbine network. The regions used are marked as white boxes in figure 3(b).

2.3. Categorisation of monsoon intraseasonal variability

Figure 2 shows the impact of monsoon intraseasonal variability on precipitation over India. The climatological distribution of mean daily rainfall during JJA (the monsoon season) is shown in figure 2(b). The high rainfall amounts, especially over central India and the west coast are clear. In order to assess the impact of intraseasonal monsoon variability on the Indian power sector, active and break phases are defined using a method based on that of Rajeevan *et al* (2010) as follows.

The box in figure 2(b) represents the 'core monsoon zone' (71.5–86.5 °E, 18.5–26.5 °N). The daily mean rainfall in that zone is normalized by subtracting the daily long term mean rainfall and dividing by its daily standard deviation to remove the effects of the seasonal cycle. Days when the normalized rainfall anomaly is less than −1 are defined as break days, days when the normalized rainfall anomaly is greater than 1 are defined as active days. Neutral phases are defined when the normalized rainfall anomaly is between -1 and 1. Gridded daily rainfall data produced by the Indian Meteorological Department based on observations from 1803 rain gauges was used from 1951–2004 (Rajeevan *et al* 2006).

Figures 2(a) and (c) show the rainfall anomaly during the break and active phases respectively. Over central India and the Western Ghats mountains on the west coast rainfall is higher during active phases and lower during break phases. Ramamurthy (1969) noted that during break phases the monsoon trough shifts northwards towards the Himalayan foothills. The positive rainfall anomaly associated with this shift is clearly seen in figure 2(a) implying that this index is capturing the general behaviour of the active and break phases. The features of the rainfall anomaly patterns in figures 2(a) and (c) closely resemble those in Krishnamurthy and Shukla (2007); in particular, the negative anomalies over NE and SE India and positive anomalies in central-west India and along the western coast during active phases are well captured.

To verify the robustness of the results, the categorisation was compared to other active/break indices. Active and break phases are also associated with variations in the monsoon circulation. Wang and Fan (1999) defined a monsoon index based on the

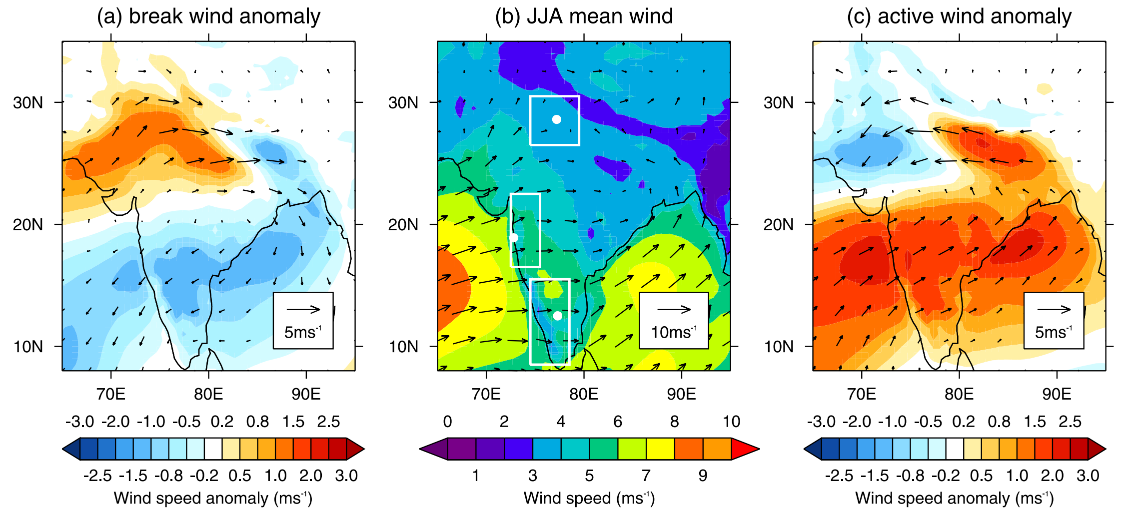

Figure 3. 50 m wind speed and direction during the monsoon season; (a) and (c) show the anomaly during break and active phases respectively, relative to neutral periods; (b) shows the mean wind during the monsoon season. The white boxes and dots on (b) indicate the locations of Bangalore, Mumbai and Delhi and the surrounding regions used for wind speed analysis. Colouration indicates the wind speed in ms^{-1} and the arrows indicate the velocity.

horizontal zonal wind shear between the southern tip of India and north of the monsoon trough that captures the dynamical signal of intraseasonal variability. Comparison of this index with the one defined above revealed that less than 1% of days were defined as active by one index and break by the other. Therefore, the strong agreement found between our results and the active/break rainfall composites of Krishnamurthy and Shukla (2007), and alternatively our own comparison using the circulation index method of Wang and Fan (1999), confirms that the normalized rainfall anomaly over the core monsoon zone shown is a suitable indicator of monsoon intraseasonal variability.

3. Wind-energy supply

Firstly we investigate the impact of active and break phases on potential electricity generation by wind turbines. The wind patterns during the monsoon and impacts of monsoon intraseasonal variability on wind over India are shown in figure 3.

Figure 3(b) shows the climatological wind vectors and speed during the monsoon at the 50 m level. The strong westerly winds across the Arabian Sea, southern India and the Bay of Bengal are apparent, with weaker winds across northern India. Figures 3(a) and (c) show the wind anomalies during break and active phases respectively as defined by the precipitation index from the core monsoon region. During active periods the westerly winds across southern India strengthen, whereas break periods are associated with a weakening of the low-level westerly jet and the absence of low-level easterlies over north India (Ramesh Kumar and Prabhu Dessai 2004, Annamalai and Sperber 2005, Rajeevan *et al* 2010, Lau *et al* 2012). Another feature during active events is the strengthening of easterly winds and absolute wind speed in the north east of the peninsula, associated with strengthening of the monsoon trough.

We next transform the wind speeds in the monsoon phases of figure 3 via equation (1) into capacity factor (a measure of the wind-turbine power output), as shown in figure 4. As shown in figure 4(b), in the climatological capacity factor for JJA is highest over the Arabian Sea, southern India and the Bay of Bengal, and hence the highest potential for wind-power generation is in these regions. However, figure 4(a) shows that the capacity factor in these regions is typically strongly reduced over these 'high potential' regions during break phases (and increased in the northern Arabian Sea and Gujarat where the climatological-mean wind-power is weakest, figure 4(b)). The reverse change is seen during active periods (figure 4(c)), with higher capacity factor over the Arabian Sea, southern India and the Bay of Bengal. The magnitude of the maximum mean increase during active phases (0.22) is typically greater than the magnitude of the maximum mean decrease during break phases (–0.13).

In order to gain a more focused understanding in selected regions, the wind speed and capacity factor were then considered over the 3 regions shown in figure 3(b). Figure 5 shows the frequency distribution of different wind speeds and capacity factors during the active, break and neutral conditions of the monsoon over regions surrounding Bangalore, Mumbai and Delhi. Figures 5(a) and (b) demonstrates a clear distinction between wind speeds under active and break phases in both Bangalore and Mumbai as expected from the maps shown earlier. Modal wind speeds are 1-2 ms^{-1} higher during active phases than during break phases, translating into more frequent high capacity factors during active phases (figures 5(d) and

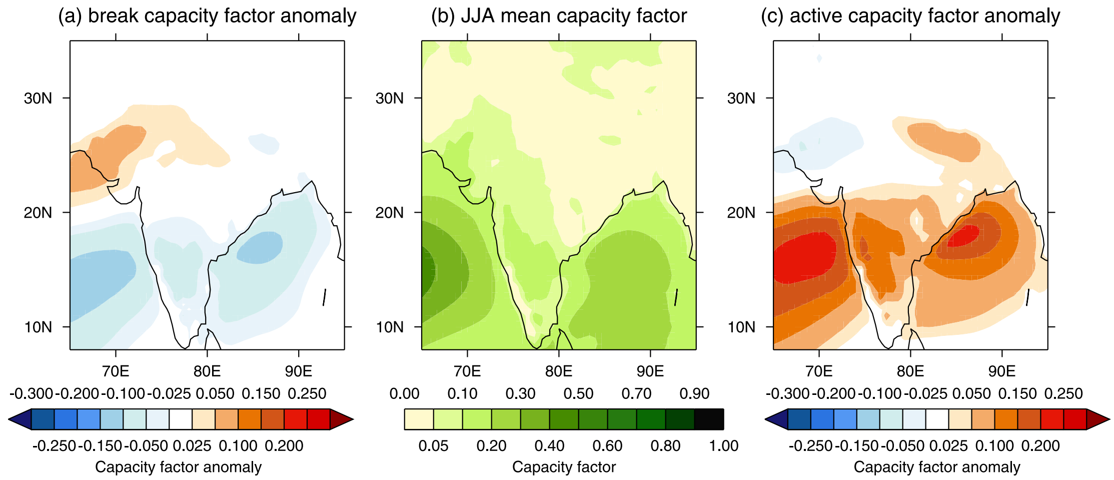

Figure 4. Wind-power capacity factor during active, break and climatological JJA conditions: (a) and (c) show the capacity factor anomaly in break and active phases respectively, when compared with neutral conditions, (b) shows the long term average capacity factor during JJA.

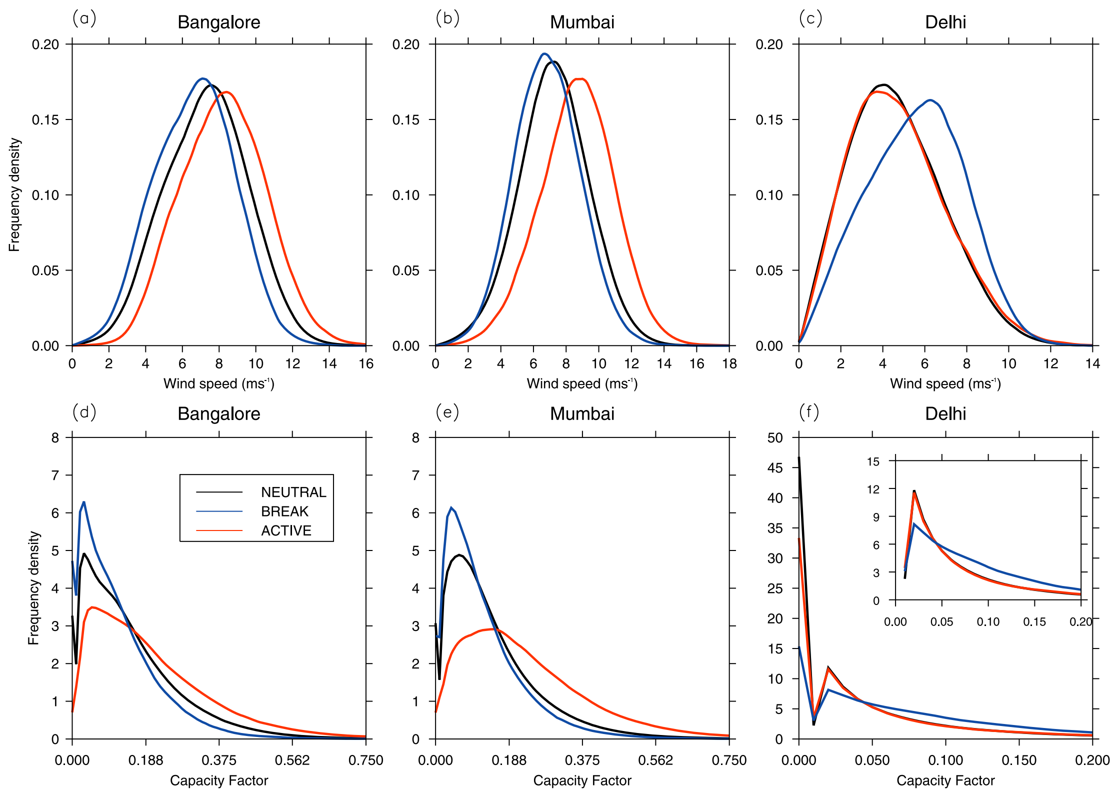

Figure 5. Impact of active/break phases on wind speed and power distribution over the 3 regions shown in figure 3(b): (a–c) show the frequency of different wind speeds during active, break and neutral periods over Bangalore, Mumbai and Delhi respectively. (d–f) Show the frequency of different capacity factors during active, break and neutral periods over the same regions, transferred using equation (1).

(e)). Figures 5(c) and (f) show a different relationship over Delhi: break phases are associated with stronger wind speeds and hence higher capacity factors compared to both active and neutral conditions. Use of the Wilcoxon–Rank–Sum test confirms that the active/break differences, in both mean wind speed and capacity factor, are statistically significant at the 5% level in all 3 locations (Wilks 2011).

The large peak on the *y*-axis of figure 5(f) is due to the conversion from wind speed to capacity factor: wind speeds below 3.5 ms^{-1} give capacity factor equal to 0 (figure 1). Whereas Mumbai and Bangalore have low frequencies of wind speeds below 3.5 ms^{-1}, Delhi has much higher frequencies, which results in the large peak at 0. In the insert in figure 5(f), the frequency at capacity factor equal to 0 is omitted, and the curve has

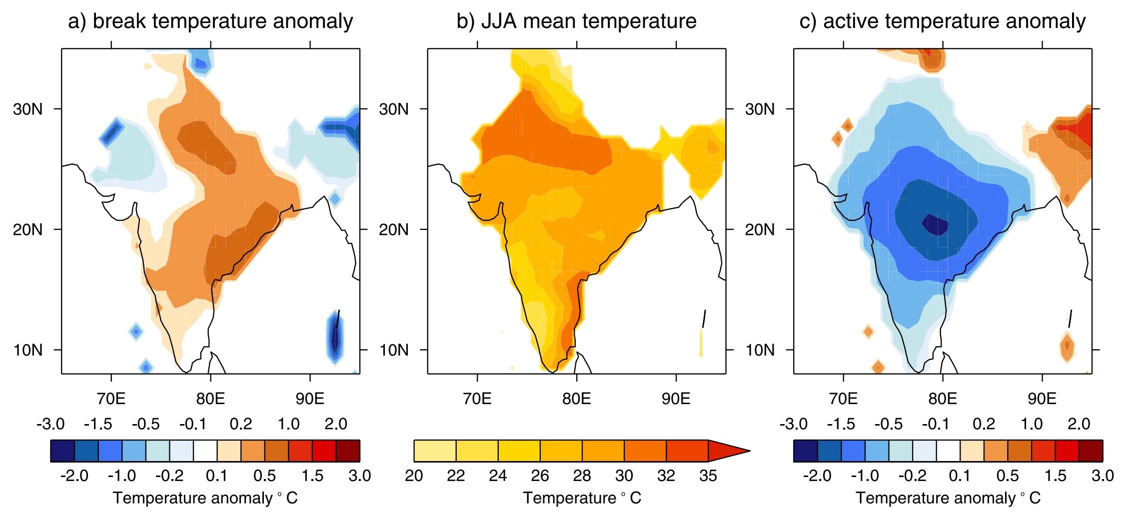

Figure 6. Surface mean temperature during active, break and climatological JJA conditions: (a) and (c) show the temperature anomaly in break and active phases respectively, when compared with neutral conditions, (b) shows the long term average surface temperature during JJA.

the same characteristics as those for Mumbai and Bangalore, with the peak in capacity factor due to the peak in wind speed distribution.

In summary, active and break phases of the South Asian monsoon lead to a dipole of wind-power anomalies between north-west and southern India. During active phases vigorous convection across central India is associated with strong winds across southern India, including the cities of Mumbai and Bangalore, suggesting high wind-power capacity in Southern India, whereas there are lower wind speeds (and therefore wind-power output) in north-west India. During break phases the movement of the main regions of convection brings lower wind speeds across southern India but higher wind speeds and hence higher wind-power capacity factors across north-west India, including Delhi, and the northern Arabian Sea.

4. Demand for cooling on hot days

In order to understand the impact of monsoon intraseasonal variability on a measure of energy demand, we use our core zone rainfall index to examine the effect of active and break phases on temperature and CDDs. Figure 6 shows the impact of intraseasonal variability within the monsoon on daily mean surface temperature over India.

Figure 6(b) shows the mean temperature distribution across India during the monsoon. Higher temperatures are found in north India (particularly in the north-west over the Thar Desert region) and in south-east India with lower temperatures along the western coast. The conditions are consistent and inversely correlated with the mean rainfall pattern shown in figure 2(b). Figures 6(a) and (c) show the mean temperature anomaly during break and active phases respectively. During active phases the temperature is much lower across much of the country, except in the north-east, where temperatures are higher, consistent with the effects of reduced rainfall on surface cooling (figure 2(c)). The pattern during break phases is more complex, with higher temperatures in central and east India, and lower temperatures in north east and north west India. Unlike the wind, the temperature pattern in break phases is not an exact reversal of the pattern in active phases.

CDDs, a proxy for temperature-related electricity demand, were calculated for Bangalore, Mumbai and Delhi. Probability distribution functions of CDDs in active, neutral and break phases are shown in figure 7. Figure 7 shows that there are higher frequencies of days with high CDD during break phases than during active and neutral phases over Bangalore, Mumbai, and Delhi. Using the Wilcoxon–Rank–Sum test it was found that these differences are statistically significant at the 5% level (Wilks 2011). Figure 7(c) suggests that the differences in CDD distribution between different phases of monsoon rainfall are less pronounced over Delhi than they are for Mumbai and Bangalore, but this is likely due to the higher mean-state temperature conditions in Delhi (30.6 °C), versus 26.5 °C and 24.0 °C in Mumbai and Bangalore respectively. This means it is more difficult for active/wet days to take temperature below the 22 °C threshold.

Overall, higher temperatures are present across India during break phases of the South Asian monsoon which is likely to lead to higher temperature-related electricity demand, including in the cities of Bangalore, Mumbai and Delhi.

5. Discussion and conclusions

The impact of intraseasonal variability of the South Asian monsoon on two components of the Indian

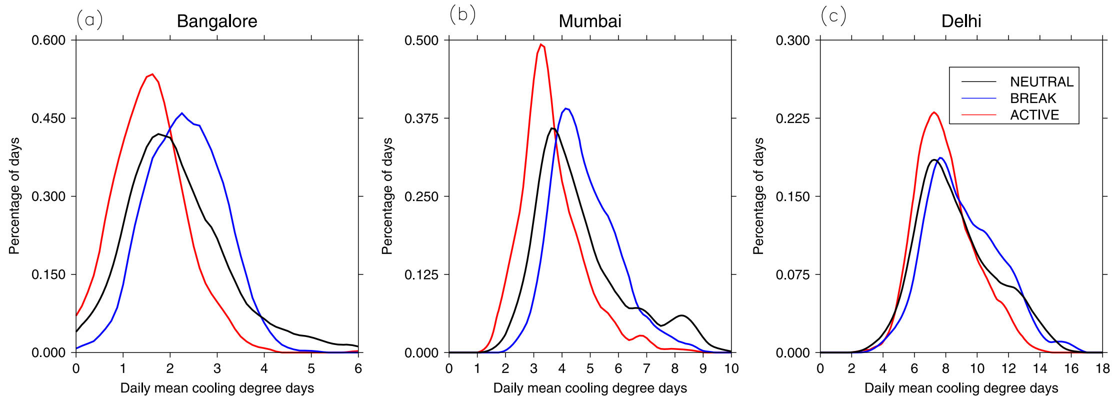

Figure 7. Probability distribution functions of cooling degree days in each city split by monsoon phase for (a) Bangalore, (b) Mumbai and (c) Delhi. Daily mean CDDs were calculated by subtracting the threshold of 22 °C from the daily mean observed surface temperature data; the PDFs show the frequency of the departure of the daily mean temperature above 22 °C. Note that the *x*-axis range is different in each plot.

power sector was examined. By transforming reanalysis wind speeds at approximate turbine height (50 m) into wind-power capacity factor, and transforming temperatures into CDDs, meteorological data was used to assess the impact of active and break phases on the balance of electricity supply and demand in India. The active and break phases of the monsoon rainfall form the dominant mode of intraseasonal variability over India. Break phases are characterized by suppressed precipitation across central India, increased incoming solar radiation and higher temperatures which are associated with greater demand for cooling energy (measured by CDD). The movement of the main convection centres and monsoon trough during breaks results in lower wind-power output across most of India (although with some small areas of increase in north-west India due to stronger winds in this region, as seen in Krishnan *et al* 2000). In contrast, during active phases there is vigorous convection across central India and heavy rainfall. This is consistent with lower temperatures giving low cooling energy demand (CDD) and strong westerly winds giving high wind-power output. The opposing sense of the relationship between the monsoon phase and each of wind-power supply, and demand for cooling energy potentially has several important consequences for the large-scale development of wind-power in the Indian power system.

Firstly, the monsoon variability exacerbates the volatility of the residual demand that must be met by generation sources other than wind (i.e., the so called 'demand-net-wind' or DNW). As demand and supply for power must maintain approximate balance at all time-scales, at least some of this is likely to take the form of schedulable conventional plant (e.g., gas or coal fired power stations). During break phases we have high electricity demand for cooling needs as well as a shortage of available power from wind generation. Thus a significant amount of alternative generation by schedulable plants is likely to be necessary to meet high levels of DNW during break phases, yet the same schedulable plant may be needed much less frequently in neutral or active monsoon conditions. Solar power was not investigated here due to lack of available high-quality observations but may offer greater opportunities for supply-demand compensation at the intra-seasonal timescale.

Secondly, given the significant role that hydropower plays in the Indian power system (approximately 20% of the total; Ernst and Young 2013), it is worth noting the additional relationship between the monsoon phase and precipitation. Precipitation is reduced during the high DNW break phases and enhanced in low DNW active phases. While a direct link between hydropower and precipitation has not been investigated in this present study, qualitatively this suggests that hydropower availability may also be lower during periods of increased DNW. Further research will, however, be necessary to quantitatively understand these relationships as the time scales connecting precipitation to hydropower are likely to be significantly longer than those linking wind-power and demand to meteorological drivers, due to integration of rainwater over the river catchment scale.

Thirdly, at the present time the majority of the wind turbines in India are in the southern part of the country and along the western coast. The results presented here suggest that an over-reliance on wind energy from this region could lead to problems during break periods due to high levels of DNW. Currently all Indian turbines are onshore but proposed offshore wind turbines in the north-east Arabian Sea (Mani Murali *et al* 2014) may allow greater dependence on wind-power without risking tight error margins during break phases, since that offshore region experiences increased wind speeds during break phases.

In summary, this study identifies how the dominant mode of monsoon variability may act to qualitatively exacerbate the problems facing wind-power integration over India. In particular, it is demonstrated that the impact of the monsoon variability can be enhanced by its simultaneous impact on both the demand for and supply of power. This illustrates firstly the need to consider the compound impact of weather on power systems (in addition to its isolated impacts on individual power system components); and, secondly, the need to understand the time-varying climate as an inherently 'dynamic' driver of the power system rather than as a static climatological input. Recent studies have begun to explore some of these issues (e.g., IRENA 2015 in the context of the water-food-energy nexus) but much work remains.

In the immediate context of this study, further research is required to quantify the effects of monsoon variability on the individual components of the Indian power sector, including their interaction with sub-daily variations in human and meteorological behaviour, and to extend it to include an assessment of other renewable sources, such as solar power and hydropower. Ongoing efforts to improve the forecast skill of monsoon intraseasonal variability (active and break events; e.g. Fu *et al* 2013) will therefore be rewarded through economic impacts felt in the Indian power sector. Moreover, the uncertain outlook projected for monsoon variability under future warmer climate conditions (Turner and Annamalai 2012) will also present challenges to the power industry and therefore warrants further investigation.

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