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Defining sowing and harvest dates based on the Asian Summer Monsoon

Camilla Mathison[1], Chetan Deva[2], Pete Falloon[1], and Andrew J Challinor[2]

[1]Met Office, FitzRoy Road, Exeter, EX1 3PB, UK
[2]School of Earth and Environment, Institute for Climate and Atmospheric Science, University of Leeds, Leeds, LS2 9AT, UK

Correspondence to: Camilla Mathison (camilla.mathison@metoffice.gov.uk)

Abstract. Sowing and harvest dates are a significant source of uncertainty within crop models especially for regions where high-resolution data are unavailable or, as is the case in future climate runs, where no data are available at all. Global datasets are not always able to distinguish when wheat is grown in tropical and sub-tropical regions, they are also often coarse in resolution. South Asia is one such region where large spatial variation means higher resolution datasets are needed, together with greater clarity for the timing of the main wheat growing season. Agriculture in South Asia is closely associated with the dominating climatological phenomena, the Asian Summer Monsoon (ASM). Rice and wheat are two highly important crops for the region, rice being mainly cultivated in the wet season during the summer monsoon months and wheat during the dry winter. We present a method for estimating the crop sowing and harvest dates, for rice and wheat, using the ASM onset and retreat. The aim of this method is to provide a more accurate alternative to the global datasets of cropping calendars than are currently available and generate input for climate impact assessments.

We first demonstrate that there is skill in the model prediction of monsoon onset and retreat for two downscaled General Circulation Models (GCMs) by comparing modelled precipitation with observations. We then calculate and apply sowing and harvest rules for rice and wheat for each simulation to climatological estimates of the monsoon onset and retreat for a present day period. We show that this method reproduces the present day sowing and harvest dates for most parts of India. Application of the method to two future simulations demonstrates that the estimated sowing and harvest dates are successfully modified to ensure that the growing season remains consistent with the internal model climate. The study therefore provides a useful way of modelling potential growing season adaptations to changes in future climate.

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1 Introduction

Field studies dominate the modelling literature on crops and agriculture. Many crop models are developed and applied at the site scale using site specific observations to drive models and optimize outputs. The growing awareness of climate change and the likely impact this will have on food production has generated a demand for regional and global assessments of climate impacts on food security through for example, projects such as Agricultural Model Intercomparison and Improvement Project (AgMIP-Rivington and Koo (2010); Rosenzweig et al. (2013, 2014)),the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP-Warszawski et al. (2013, 2014)) and Global Gridded Crop Model Inter-comparison (GGCMI-Elliott et al. (2015)). Recent work in such climate-crop impact studies has sought to quantify uncertainty from the quality and scale of input data. A result from this work is that for global scale simulations, planting dates are a significant source of uncertainty (Frieler et al., 2016; Elliott et al., 2015).

Aside from their use in modelling studies, deciding when to plant crops is a significant challenge particularly in water scarce regions such as parts of Sub-Saharan Africa (SSA - Waongo et al. 2014), South and South East Asia (Kotera et al., 2014). These regions have crop sowing dates that are closely associated with the onset of the rainy season. Any prolonged dry spells of more than 2 weeks after sowing could have serious consequences leading to crop failure or significant yield reduction because top soil layers dry out preventing germination (Laux et al., 2008). For large parts of SSA deciding when to sow determines the length of the crop duration for the agricultural season and is therefore an important tactical decision (Waongo et al., 2014).

Planting dates can be determined using a number of different methods, for example, Kotera et al. (2014) propose a cropping calendar model for rice cultivation in the Vietnam Mekong Delta (VMD). The Kotera et al. (2014) model estimates the sowing date based on the the suitability of the land for crops given any flooding, salt water intrusion or erratic monsoon rains; these are important factors for the water resources of the VMD region. Alternatively Laux et al. (2008, 2010) use a fuzzy logic-based algorithm developed to estimate the onset of the rainy season in order to examine the impact of the planting date for the SSA. In the General Large Area Model (GLAM-Challinor et al. (2004)), the sowing date can be estimated by the model based on the soil moisture conditions, with the crop sown when surface soil moisture exceeds a specified threshold during a given time window and crop emergence occurring a specified time after sowing. Waha et al. (2012) base their estimates of sowing dates at the global scale on climatic conditions and crop specific temperature thresholds, therefore providing a suitable method for taking climate change into account. However the Waha et al. (2012) method is not really intended for use in irrigated multiple cropping regions. Elliott et al. (2015) describe how sowing dates are defined in the GGCMI project. The GGCMI protocols use a combination of Sacks et al. (2010), Portmann et al. (2010) and model data to define sowing dates, thus highlighting the challenges in defining a complete, accurate dataset of sowing and harvest dates. This has influenced and driven the development and application of crop models on broader scales. In this study we are considering the whole South Asia region, this is a large scale problem with complicated cropping patterns, which means that assumptions and generalizations need to be made across a region with a wide variety of climatic conditions. Waha et al. (2013) highlight that global crop calendars such as those used in the GGCMI often only report individual crops, therefore limiting their usefulness for regions with multiple cropping systems.

The growing interest in climate change and food security has influenced the development of crop models for use in future climate impact assessments (Frieler et al., 2016); this represents a different challenge for crop models in terms of the input data used. ISIMIP simulations use time varying crop management data until 2005 after which the data are held fixed at 2005 levels for the remainder of the simulations (Frieler et al., 2016). Fixing crop management to present day practices is not really suitable for adaptation studies (van Bussel et al., 2015). The assumption that there will be no large shifts in climate causing sowing and harvest dates to change significantly from the present day, could lead to the sowing and harvesting of crops in the model in the future at unrealistic times of the year. Thus the appropriate sowing and harvest dates used in future simulations depends on the intended application for the simulations. In many adaptation studies, impacts without adaptation are assessed using present day estimates of sowing dates, then the sowing dates are adjusted in response to climate change to assess the benefits of adaptation (Lobell, 2014). Challinor et al. (2017) suggest using autonomous adaptation in simulations in order to avoid overestimating the effects of adaptation. On this basis there is a requirement for estimates of sowing and harvest dates for climate simulations that remain consistent with the future model climate. Thus making estimates of sowing and harvest dates important not only for understanding the present day, but also for use in future simulations especially when considering potential adaptation to climate change.

Agriculture in South Asia is dominated by the Asian Summer Monsoon (ASM). Kharif and Rabi are the two main seasons in South Asian agriculture and these correspond to summer and spring growing seasons respectively. Kharif crops include rice, usually sown with the first rains of the monsoon and harvested in the autumn while rabi crops include wheat which is mainly cultivated during the dry season (Erenstein and Laxmi, 2008; Singh et al., 2014). The close association of the sowing dates of these crops and the ASM offer the potential for a new method of defining the cropping calendar for this important rotation.

Rice-wheat systems, particularly those in the Indo Gangetic Plain (IGP), tend to plant rice late into June when the monsoon is fully established, and tend to plant varieties like Basmati that take a long time to mature. Since this delays wheat planting, this has a direct impact on wheat yield. In the Eastern IGP this is a particular problem as the season for which wheat is viable is relatively short (Erenstein and Laxmi, 2008; Laik et al., 2014; Jat et al., 2014). Any delay between the rice harvest and wheat planting can have a large impact on the success of the wheat crop as this will reduce the time available before the temperatures get too high for the successful cultivation of wheat (Joshi et al., 2007). The time between the rice harvest and wheat sowing also depends on the time it takes to

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ensure the soil is in a suitable condition for wheat sowing after the rice harvest. Erenstein and Laxmi (2008) describe the zero-tillage approach which allows for a reduced turn-around time between the harvest of rice and sowing of wheat. Potential avenues by which the uncertainty from sowing and harvest dates can be reduced in inputs to crop simulations include:

- The use of higher resolution regional data sets of recorded sowing and harvest dates for crop calendars rather than existing global data sets.
- The use of new methods for estimating crop calendars in the absence of higher resolution regional data sets.

1.1 Motivation

The correct representation of the crop duration within crop models are crucial for the interpretation of the important outputs from the model. For example if the datasets used for sowing and harvest dates are inaccurate, the simulations could grow crops during the wrong season, thereby affecting the reliability of the simulated water use and crop yield. Figure 1 compares observed sowing and harvest dates from a high resolution regional dataset from the Government of India, Ministry of Agriculture from Bodh et al. (2015) with a coarser scale global dataset over India from Sacks et al. (2010). Fig. 1 shows that the main differences are for spring wheat (plot a and b) with Sacks et al. (2010) providing sowing windows for spring wheat between 120 and 200 days earlier than the Bodh et al. (2015) data. This large difference is caused by the misclassification of spring wheat grown in winter as winter wheat in the Sacks et al. (2010) data. This is discussed by Sacks et al. (2010) as a potential limitation when using the data for tropical and subtropical regions. Spring wheat is the more common type of wheat grown in the South Asia region (Hodson and White, 2007) because minimum temperatures there are not low enough to allow vernalization to take place, which is needed for winter varieties of wheat (Sacks et al., 2010; Yan et al., 2015).

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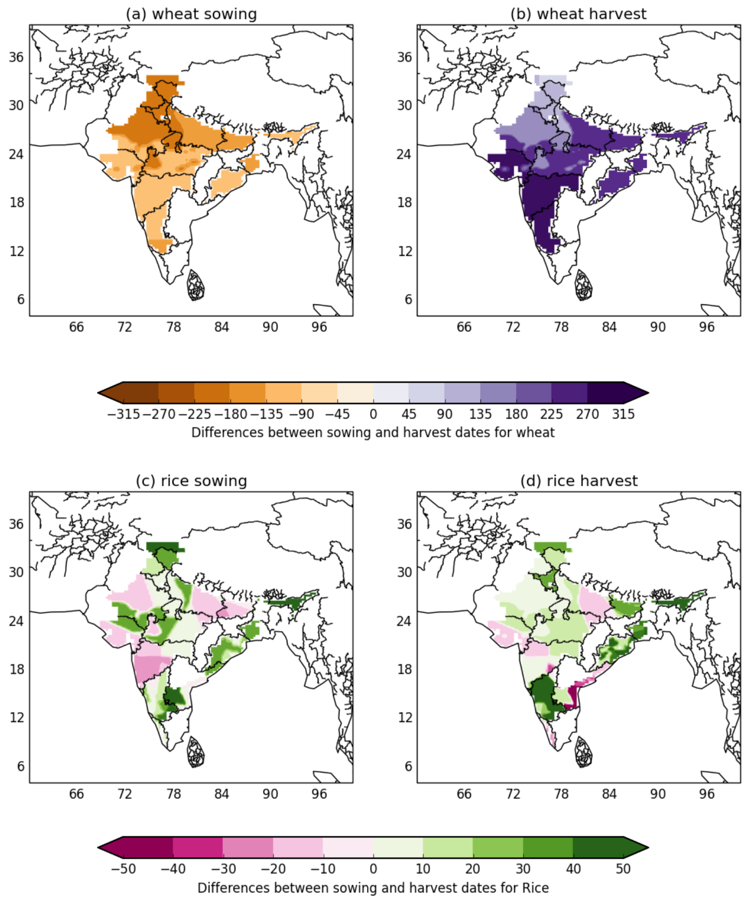

Figure 1. The difference in the end points of the sowing (plot a and c) and harvest (plot b and d) windows between the global dataset from Sacks et al. (2010) and the regional dataset from Bodh et al. (2015) for wheat (plot a and b) and rice (plot c and d) for 1990-2007 climatologies.

Figure 2 shows the averaged rice (green rectangles) and wheat (orange rectangles) growing season durations for Sacks et al. (2010) (diagonal hatching) and the Bodh et al. (2015) dataset (perpendicular hatching-labeled MinAg) over-laid on the present day South Asia averaged precipitation climatology and estimates of the monsoon onset and retreat. This illustrates the differences between the Bodh et al. (2015) and Sacks et al. (2010) datasets showing that in Sacks et al. (2010), the main growing period for both rice and wheat appears to be during the monsoon. While rice is usually grown during the monsoon it is not typical that wheat should be grown during this period for this region. The growing season durations for the Bodh et al. (2015) dataset (See Fig. 2 - perpendicular

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hatching rectangles labeled MinAg) are more typical of this region with rice (green) growing during the monsoon and wheat (orange) growing during the dry season. Figure 2 highlights that where a global dataset is unable to establish exactly when wheat is grown in tropical regions, an alternative is needed.

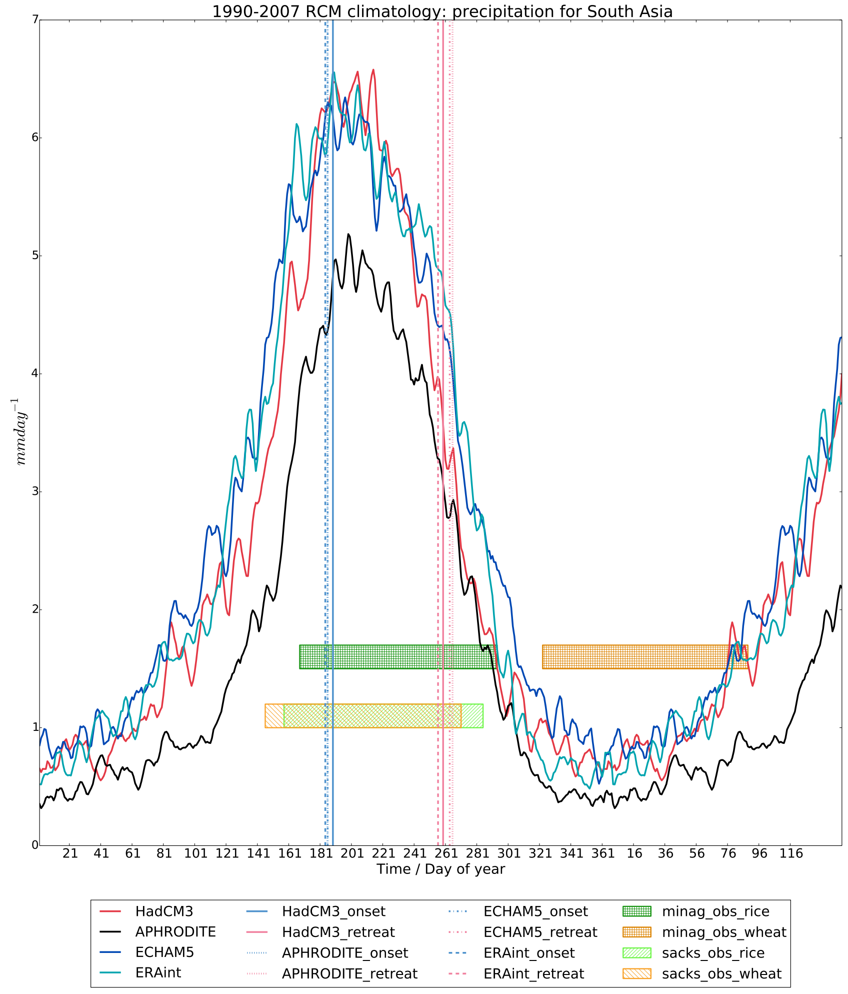

Figure 2. The one and a half year precipitation climatology for the 1990-2007 period averaged for South Asia for each simulation (ERAint-cyan line, ECHAM5-blue line, HadCM3-red line) and APHRODITE observations (black line) using a 5-day smoothed rolling mean. Also shown are the growing seasons also averaged for 1990-2007 for South Asia for wheat (orange) and rice (green) from two datasets; Sacks et al. (2010) (diagonal hatching -labeled sacks) and Bodh et al. (2015) (perpendicular hatching-labeled minag) and the monsoon onset (blue vertical lines) and retreat (pink vertical lines) from each of the simulations (APHRODITE-dotted, ERAint-dashed, HadCM3-solid,ECHAM5-dash dot).

Reliable high resolution datasets for sowing and harvest dates are often unavailable for either the region or the time period that is needed. In addition there is a demand for sowing and harvest dates that maintain consistency with the model climate. Therefore, in this paper we propose a new method, outlined in Fig 3, for estimating sowing and harvest dates for the rice-wheat rotation in South Asia using estimates of monsoon onset and retreat. The main objectives of this study are:

- To develop a method for determining sowing and harvest dates for the rice-wheat rotation in South Asia based on the ASM.
- To test the method in current and future climates.

We therefore present the methodology in Sect. 2. We show the proposed method is viable and show it works in Sect. 3. Discussion of the results and conclusions are provided in Sect. 4 and Sect. 5 respectively.

2 Methodology

The methodology is summarized in the flow chart in Fig. 3. The model datasets, described in detail in Sect. A of the Appendix, include General Circulation Models (GCMs) and a Regional Climate Model (RCM). GCMs provide spatially consistent boundary data to an RCM, which generates 25km regional fields (see Fig.3 blue boxes). RCMs are based on the same physical equations as GCMs and therefore represent the entire climate system including the carbon and water cycle. Their higher resolution allows a better representation of the regional-scale processes adding detail to fields like precipitation (Mathison et al., 2015). The individual RCM simulations (also called HNRCMS - see Appendix Sect. A) used in this analysis are referred to using their global driving data abbreviations; HadCM3, ECHAM5 and ERAint as described in Appendix Sect. A. Precipitation fields are used to generate a precipitation climatology which are used to calculate monsoon statistics (See Sect. 2.2) from which sowing and harvest dates are estimated; shown by the pink rectangles (see Sect. 2.3). These estimated sowing and harvest dates are referred to as relative monsoon sowing and harvest dates (see Fig. 3). Observations are used throughout the process to ensure the method is viable and produces sensible results, these are described in Sect. 2.1 and shown by the green boxes.

2.1 Observations

In order to demonstrate the viability of the methodology outlined in Fig. 3 we compare the simulated precipitation with observations from the Asian Precipitation-Highly Resolved Observational Data Integration Towards the Evaluation of Water Resources (APHRODITE –Yatagai et al., 2012) dataset. APHRODITE is a daily, 0.25° resolution land only gridded dataset that is also used in Mathison et al. (2015) to show that the RCMs in this analysis capture the general hydrology of the region.

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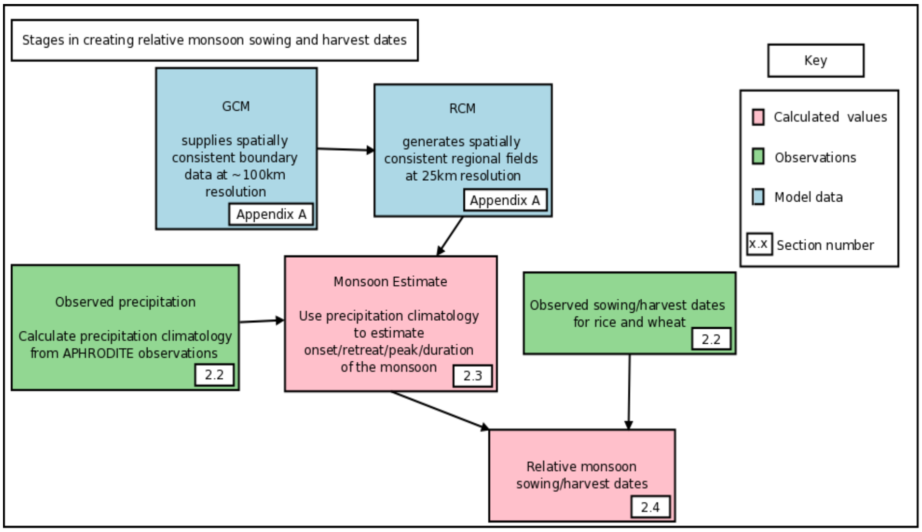

Figure 3. A flow chart summarizing the methodology. The blue rectangles represent datasets that are used within the methodology, green rectangles represent observations and pink rectangles represent any calculations parts of the methodology.

The datasets used for sowing and harvest dates include a global dataset, Sacks et al. (2010) and a regional dataset, Bodh et al. (2015) from the Government of India, Ministry of Agriculture & Farmers welfare. The Bodh et al. (2015) data are referred to from here on as MinAg data. The MinAg observations of sowing and harvest dates for rice and wheat are given as a range of days of the year. The midpoints of these observed ranges are calculated and compared against the midpoints of the model pentads for onset and retreat in days of the year. As a post-processing step the differences are then masked using the (ICRISAT, 2015) crop areas, so that only the areas where rice or wheat are grown are considered.

2.2 Estimating monsoon onset and retreat

There are a wide variety of metrics for estimating the monsoon onset and retreat, some use a combination of meteorological variables such as 850hPa wind and precipitation (Martin et al., 2000), others such as Sperber et al. (2013) and the Normalised Pentad Precipitation Index (NPPI) (Lucas-Picher et al., 2011) only use precipitation. The NPPI metric provides a climatological estimate of the monsoon onset, retreat, peak and duration and is calculated using Eq.(1). The NPPI metric uses the climatology of precipitation to estimate the monsoon statistics for a climatological period because the data are too noisy to calculate the monsoon statistics per year. The NPPI metric has been suc-

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cessfully applied previously by Lucas-Picher et al. (2011) to analyse the monsoon of models of a similar resolution to the simulations used here (See Fig 3).

$$NPPI = \frac{P - P_{min}}{P_{max} - P_{min}} \tag{1}$$

where P is the unsmoothed pentad precipitation climatology and P_{min} and P_{max} are the annual minimum and maximum at each gridbox respectively. The monsoon onset is then defined as the pentad in which the NPPI exceeds 0.618 for the first time and withdrawal as the last time the NPPI drops below this threshold in the year. The NPPI only reaches a value of 1.0 once in the annual cycle which corresponds to the monsoon peak. In this analysis we use the NPPI metric to calculate the pentad of the monsoon onset, retreat, peak and duration for the APHRODITE observations and the three HNRCM simulations.

2.3 Calculating sowing and harvest dates from monsoon characteristics

We use estimates of the monsoon onset and retreat together with present day rules on sowing and harvest for rice and wheat to calculate the sowing and harvest dates relative to the monsoon (See Fig.3). This method allows any crop model that uses, for example a driving dataset similar to APHRODITE or the HNRCMs, to derive sowing and harvest dates that are consistent with the monsoon of the driving data (see Fig.3). Thus growing the crop at the appropriate time of the year i.e rice is kept during the monsoon period and wheat is sown and harvested during the dry season.

2.3.1 Calculation of monsoon derived estimates of sowing and harvest dates for rice and wheat

We use the precipitation climatologies from APHRODITE precipitation observations and each of the HNRCM simulations (See Fig.3). We estimate monsoon based sowing and harvest dates for rice and wheat using these precipitation climatologies by calculating the difference between the monsoon onset (or retreat) and the observed MinAg sowing (or harvest) dates for each crop (See Fig.3). Equation 2 shows how the monsoon statistics are used along with the the sowing and harvest dates of each of the crops to calculate a croprule for each crop and stage. Collectively the crop rules given in Eq. 2 are referred to as $RelMonsoon_{croprule}$. We use an area average rather than a gridbox by gridbox difference to define the $RelMonsoon_{croprule}$ because this provides a simple rule that can be applied across the region, even where observations are not available. Although calculating the rule per gridbox would provide excellent results where observations were available, it would limit

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the usefulness of the method where observations were not available, which is more the point of this method.

$$\begin{aligned} RiceSowingCroprule &= AreaAverage(MonsoonOnset - RiceSowing) \\ RiceHarvestCroprule &= AreaAverage(MonsoonRetreat - RiceHarvest) \\ WheatSowingCroprule &= AreaAverage(MonsoonRetreat - WheatSowing) \\ WheatHarvestCroprule &= AreaAverage(MonsoonOnset - WheatHarvest) \end{aligned} \quad (2)$$

The $RelMonsoon_{croprule}$ is then applied to the monsoon onset and retreat field to provide an estimate of sowing and harvest dates for rice and wheat based on the monsoon. We refer to these estimates of sowing and harvest dates as 'monsoon derived crop dates' for brevity.

$$MonsoonDerivedCropDate = MonsoonStatistic - RelMonsoon_{croprule} \quad (3)$$

where the $MonsoonStatistic$ can be monsoon onset or retreat and the $RelMonsoon_{croprule}$ is one of the four crop rules given in Eq. 2

The spatial variability of the monsoon derived sowing and harvest dates is accounted for by the monsoon onset and retreat in the climatology used to calculate the $RelMonsoon_{croprule}$. The monsoon derived sowing and harvest dates for both the APHRODITE and HNRCM simulations are provided and compared against MinAg observed sowing and harvest dates in Sect. 3.3. The calculation of the $RelMonsoon_{croprule}$ is based on observations for India (from MinAg and ICRISAT (2015)) and therefore the analysis for the present day in Sect. 3.3 focuses on these areas. On the basis that most of the South Asia region is dominated by the ASM, the $RelMonsoon_{croprule}$, though tuned using India observations, can be applied to the whole South Asia region in order to estimate sowing and harvest dates for larger areas with a rice-wheat rotation (see Sect 3.4).

2.4 Demonstration using monsoon derived estimates of sowing and harvest dates for two future periods

The method summarised in Fig. 3 is applied to two future periods using the ECHAM5 and HadCM3 RCM simulations (described in Sect. A of the Appendix). Global mean temperatures are used (within the High-End cLimate Impacts and eXtremes project - HELIX) to define the future climate in terms of specific warming levels (SWLs), i.e considering a 2°C, 4°C and 6°C world. The simulations used here are for the period 1965 to 2100 and therefore only the 2°C threshold for global mean temperature is actually passed during these simulations. For HadCM3 this occurs in 2047 and for ECHAM5, 2055. Therefore the two future periods used in this analysis are 2040-2057 and 2080-2097. The 2040-2057 period is chosen because it includes the year that the global mean temperature exceeds 2°C in the two simulations and the 2080-2097 period is chosen because it is furthest into the

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future in these simulations and therefore likely to show the greatest warming. The length of the two future analyses periods has been chosen for consistency with the ERAint RCM simulation which is only available for the period 1990-2007. Although the threshold of 2°C is exceeded globally it is important to note that the relationship between the projected global mean change in temperature and the regional climate change in temperature for South Asia is complicated. Heat and moisture and how they vary across the globe are not evenly distributed with land warming faster than the ocean (Christensen et al., 2013), therefore the actual temperature change experienced in South Asia may be higher than the global mean change.

3 Results

We compare the model monsoon to the monsoon calculated from precipitation observations to demonstrate that the model is able to reproduce the monsoon (See Sect. 3.1) and therefore the methodology summarized in Fig. 3 and Sect. 2 is viable. In Sect.3.2 we compare the simulated monsoon with the observed sowing and harvest dates in order to calculate the monsoon derived sowing and harvest dates and compare these new simulated sowing and harvest dates with the observations. We then show results from applying the method in Sect. 3.3. As a demonstration, we also apply the method to two future periods in Sect.3.4.

3.1 Comparison of model monsoon onset and retreat with precipitation observations

Figure 4 shows plots of the onset (left column) and the retreat (right column) of the South Asian Summer Monsoon as defined using the NPPI described in Sect. 2.2. The NPPI index for the climatology of the APHRODITE precipitation observations (Yatagai et al., 2012) are shown in plots (a) and (b) of Fig. 4 for comparison with the precipitation climatology for each of the HNRCMs shown; ERAint (c and d), HadCM3 (e and f) and ECHAM5 (g and h). The white regions are areas where the threshold was exceeded at the first pentad, this implies the monsoon had already started at the first pentad which suggests a model bias and therefore these regions were masked out. In general the HNRCMS compare well with the APHRODITE observations. This is illustrated by Fig. B.1 which shows the difference between the model onset (retreat) and APHRODITE onset (retreat) for each model.

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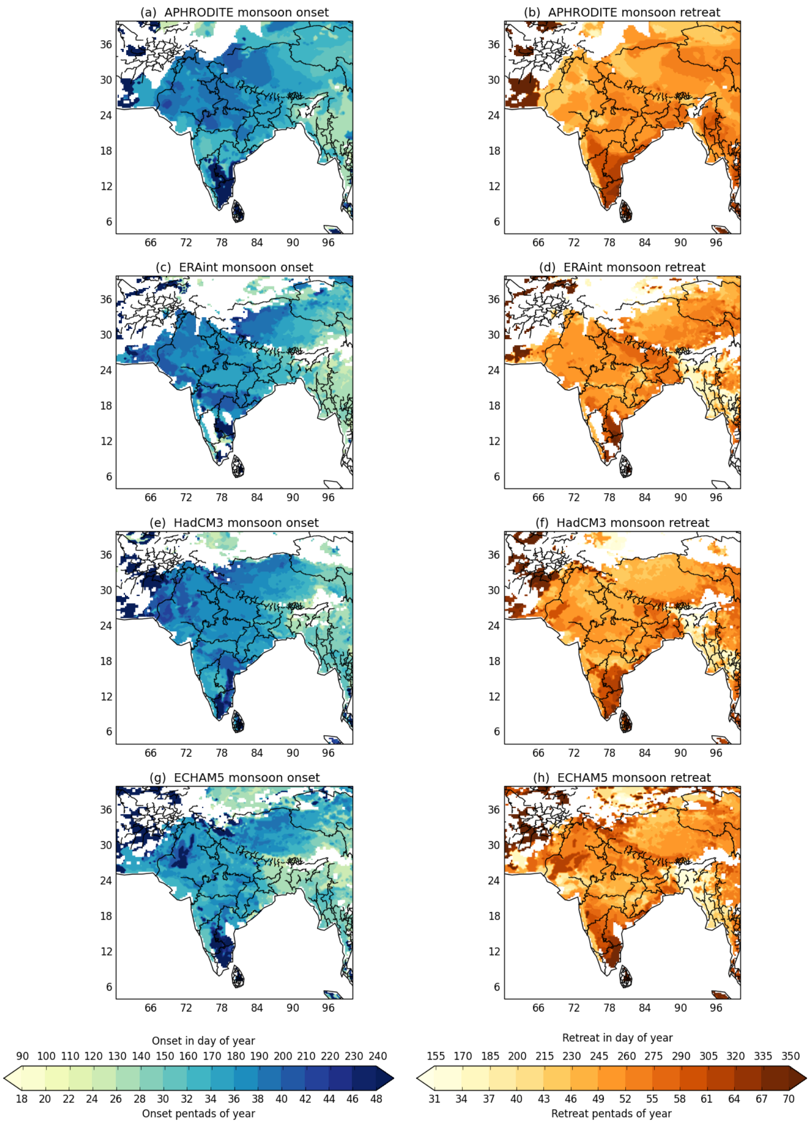

Figure 4. Plots of the 1990-2007 monsoon statistics; monsoon onset (left column) and retreat (right column). The APHRODITE precipitation observations (a and b) are shown and the three model simulations; ERAint (c and d), HadCM3 (e and f) and echam5 (g and h) calculated using the NPPI metric. White areas are the regions where the model precipitation exceeds the threshold indicating the start of the monsoon at the initial pentad, this does not imply early monsoon but more likely a model bias in the precipitation at this location.

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3.2 Comparing observed sowing and harvest dates with estimates of monsoon onset and retreat

The climatology shown in Fig. 2 shows that on average the observed rice and wheat sowing and harvest dates from MinAg align well with the monsoon onset and retreat in the simulations. Observed rice sowing dates generally compare well with the monsoon onset in the model as shown in Fig. 5 and Fig. 6.

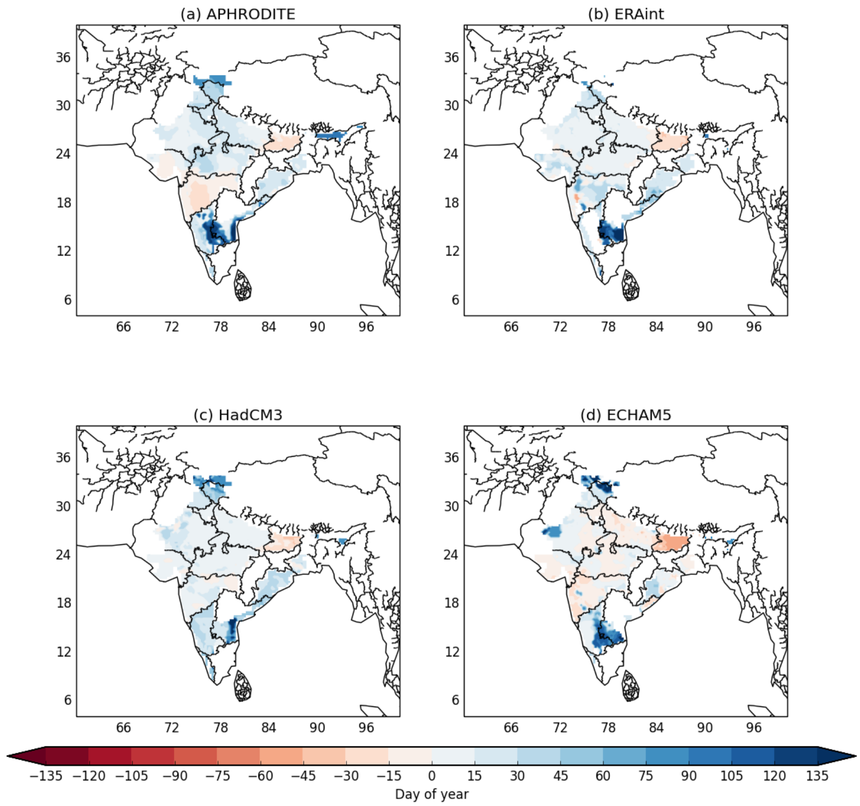

Figure 5. Plots of the difference between the midpoint of the monsoon onset in the model and the midpoint of the observed rice sowing period for 1990-2007.

Figure 6 shows the comparison between the rice sowing MinAg observations compared with the monsoon onset in the simulations and APHRODITE observations; the blue regions show that rice sowing occurs around the time of monsoon onset for a large proportion of India with the model within or at least close to (yellow regions) the range of the observations. Table 1 lists the differences between the monsoon statistics (onset and retreat) and the relevant sowing and harvest dates for each crop calculated for each of the simulations and the APHRODITE observations and averaged

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for India. Table 1 shows the that on average across India rice sowing occurs between 3 and 20-days prior to the averaged modelled monsoon onset (3rd block, Table 1).

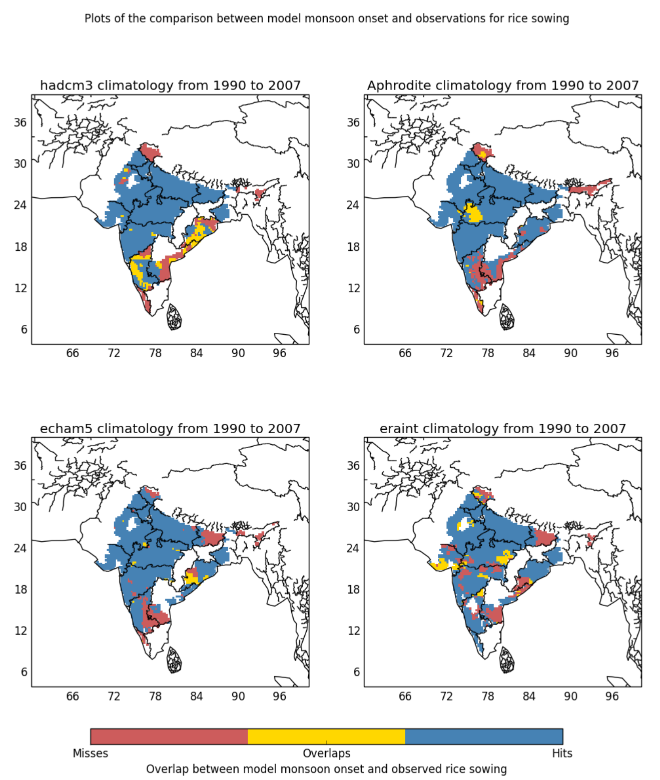

Figure 6. The comparison of the model monsoon onset in terms of the days of the year (to within the pentad) and the range of days of the year for the observed sowing date for rice. This is shown in terms of hit (blue) and overlap (yellow) or if there was no overlap this is shown as a miss (red)

In general the differences between rice harvest and monsoon retreat are larger but still consistent across the region (see Fig. C.1), with rice harvest occurring on average 30 to 46 days after monsoon retreat (see 4th block, Table 1). Wheat sowing tends to occur approximately 60-74 days after monsoon retreat (see Fig. C.2 and 1st block, Table 1) and wheat harvest tends to occur approximately 80-99 days before monsoon onset (see Fig. C.3 and 2nd block Table 1). These values (given in Table 1) provide the $RelMonsoon_{croprule}$ values introduced in Sect. 2.3.1 used to adjust the monsoon statistics and calculate the new sowing and harvest dates based on the monsoon. There are small regions with different monsoon characteristics and therefore much earlier sowing days, for example for rice sowing in the southern and far north of India. These regions have a direct impact on the values (minimum, maximum, mean and standard deviation - SD) given in Table 2 which are averages

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for the whole of India and are discussed in more detail in Sect. 4. Fig 2 highlights that the the average sowing and harvest dates for rice and wheat are closely aligned with the monsoon precipitation from all three RCM simulations.

3.3 Monsoon derived estimates of sow/harvest dates for rice and wheat

The monsoon derived sowing and harvest dates are calculated from applying the $RelMonsoon_{croprule}$ for each model (See Table 1) to the simulated monsoon onset and retreat fields (see Fig.3). Here we compare these with the gridded observations to see how well the method performs for the present day.

Figure 7 shows the monsoon derived estimates of rice sowing dates (left column) and compared with MinAg observations (right column). Fig. D.1 shows the same plots for rice harvest, with plots for wheat shown in Fig.D.2 and Fig. D.3 for sowing and harvest respectively. In general the monsoon derived estimates of sowing and harvest dates compare well with observations across much of the region for both crops.

There are small areas where the differences between the estimated sowing and harvest dates are larger. For rice in both the sowing (Fig.7) and harvest dates (Fig. D.1), there is some discrepancy in the south of India between the MinAg observations and the monsoon derived estimates of sowing and harvest dates, particularly for rice sowing. These differences may be explained by the differing monsoon characteristics (see Sect. 4), compared to the rest of India (See Fig. 4). The $RelMonsoon_{croprule}$ for wheat for both sowing and harvest are much larger than those for rice but there is still good agreement between the monsoon derived estimates and the MinAg observations (See Fig.D.2 and Fig. D.3) across the region.

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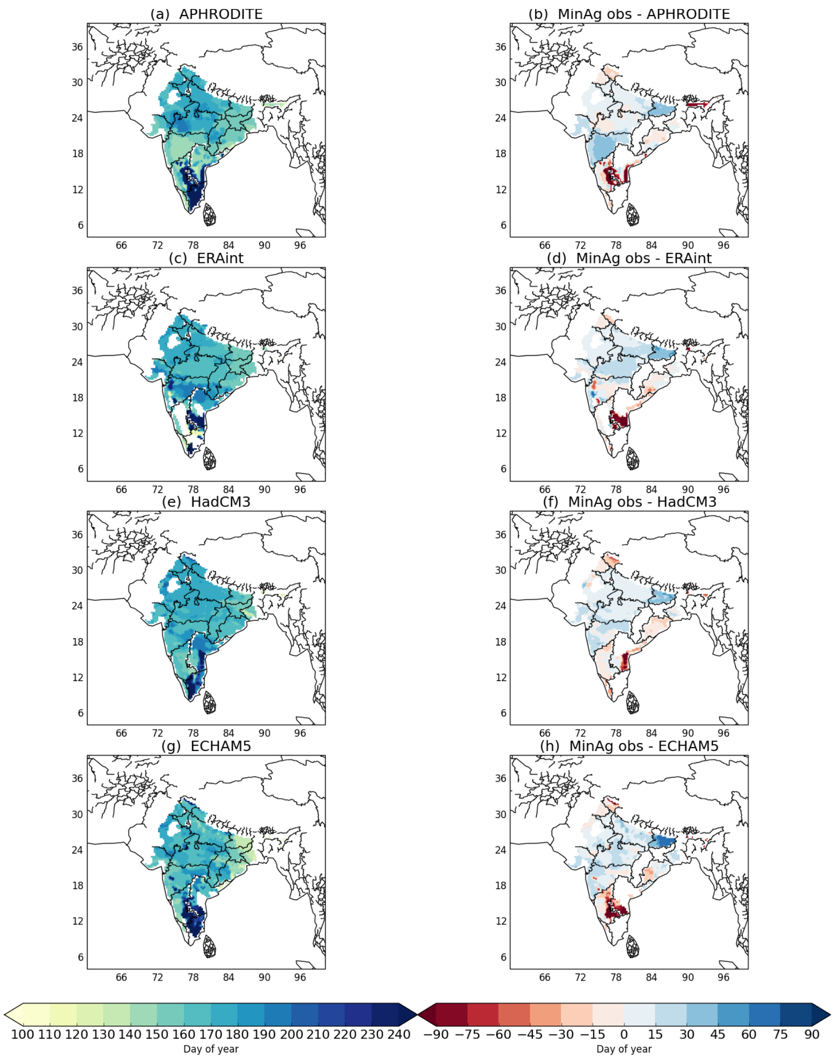

Figure 7. The monsoon derived rice sowing dates (left) and the difference between the MinAg observations and the monsoon derived rice sowing dates (right) for the period 1990-2007.

3.4 Analysis of future monsoon onset and retreat

As a demonstration of the method summarised in Fig. 3, the HELIX SWLs (described in Sec.2.4) are used to select two future periods: 2040-2057 and 2080-2097. Considering only these future periods, spatially HadCM3 and ECHAM5 show quite different future climates. HadCM3 shows a similar onset to the present day for 2040-2057 (see Fig. 8 (a) and (c)) but later onset compared with the

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present day for 2080-2097 (see Fig. E.1 (a) and (c)). ECHAM5 shows an earlier onset compared with the present day for the 2040-2057 period (see Fig. 8 (b) and (d)) but much later for the 2080-2097 period (see Fig. E.1 (b) and (d)). This suggests high variability in monsoon onset in these simulations. In fact all of monsoon onset, peak, retreat and duration show a large degree of variability as shown in Fig. 9 where each statistic has been averaged for South Asia. Each point in Fig. 9 represents a 17-year timeslice from between 1970 and 2097 for each of the APHRODITE, ECHAM5, HadCM3 and ERAint datasets. Figure 9 supports the points made regarding the spatial plots and also shows how the four monsoon statistics change between the 17 year timeslices. The 2040-2057 period has a much earlier onset for ECHAM5 than all the other periods except the 2000-2017 period, which is similar (See Fig. 9 (a)). For most of the periods ECHAM5 has an earlier onset than HadCM3, this is also true of the retreat (See Fig. 9 (b)), the duration is usually longer for ECHAM5 compared with HadCM3 (See Fig. 9 (d)).

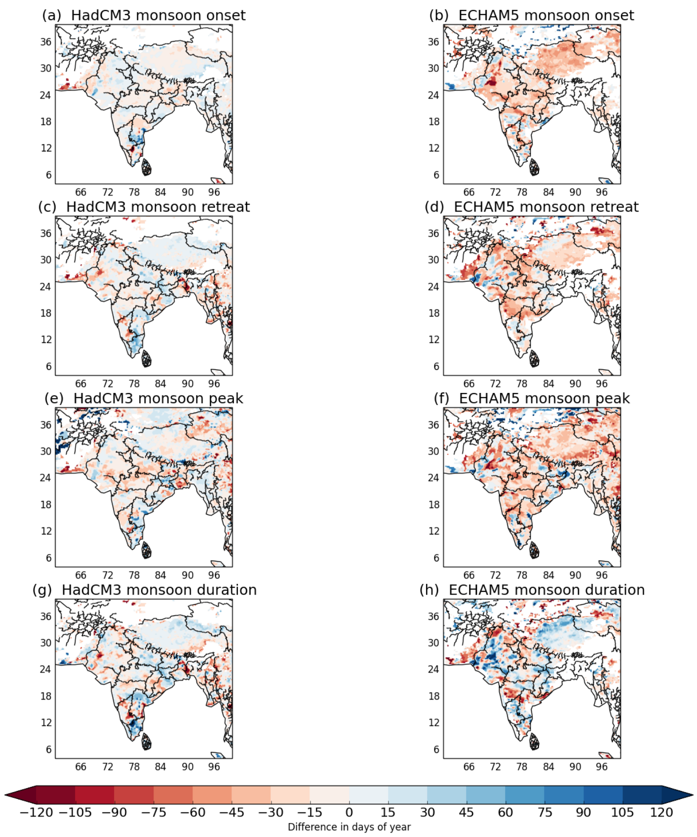

Figure 8. The difference between the monsoon statistics for the 2040-2057 future period and the present day 1990-2007 for HadCM3 (left) and ECHAM5 (right).

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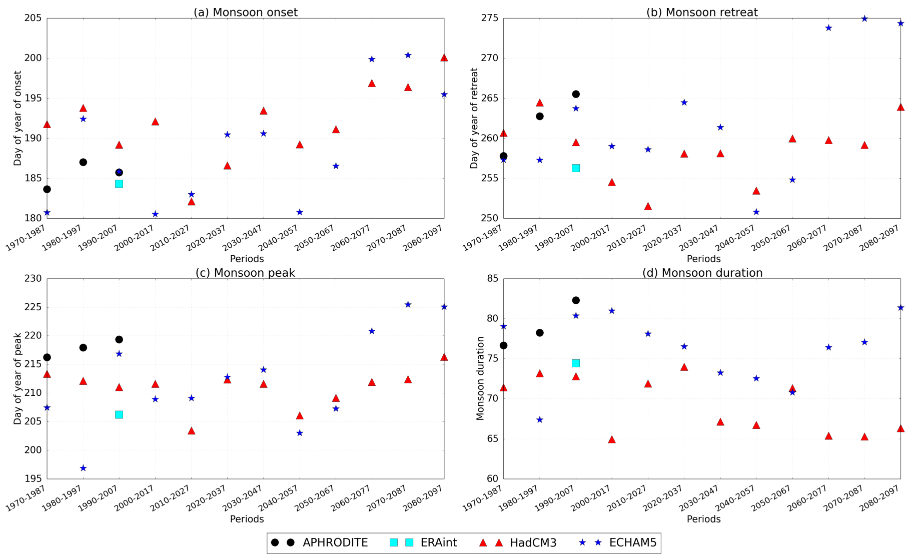

Figure 9. Monsoon statistics; onset (a), retreat (b), peak (c) and duration (d) averaged for South Asia for twelve 17-year timeslices between 1970-2097 to provide a timeseries of values for the region to assess the variability of the monsoon

In order to illustrate the method for deriving sowing and harvest dates, Fig. 10 shows the annual cycle of precipitation averaged for South Asia for the two future periods (plot a shows 2040-2057 and plot b shows 2080-2097) in the same way as the present day is shown in Fig. 2. The crop sowing and harvest dates used to provide the growing season durations in each of the plots shown in Fig. 10 for each of the simulations are calculated using the method described in Fig. 3). This shows that the proposed method provides an estimate of sowing and harvest dates that ensures the crops can continue to be grown, in the simulation, when the climate is most appropriate rather than being fixed to the present day observed values.

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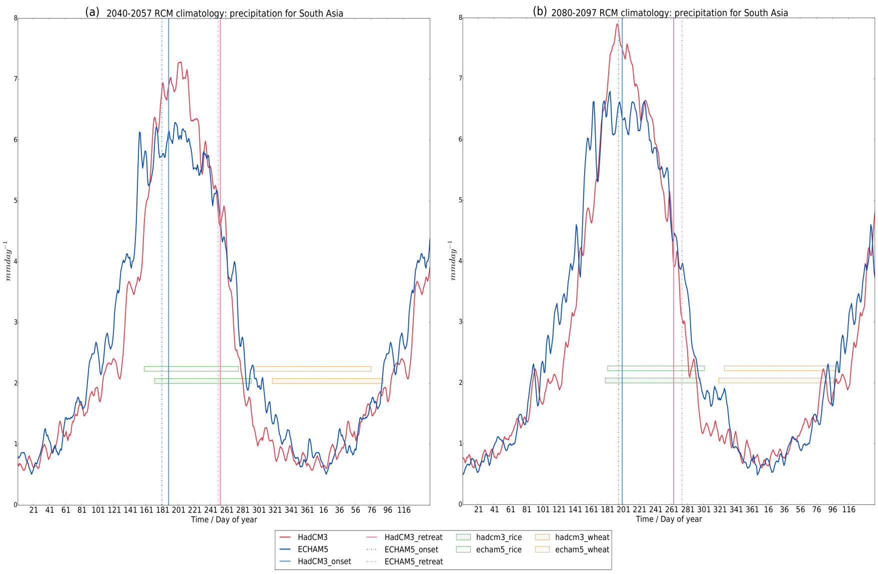

Figure 10. The one and a half year precipitation climatology for the period 2040-2057 (a) and the 2080-2097 (b) averaged for the whole of South Asia for each simulation (HadCM3-red line, ECHAM5-blue line) using a 5-day smoothed rolling mean. Also shown are the monsoon derived growing seasons for wheat (orange) and rice (green) calculated using the method described in Fig. 3 for HadCM3 (perpendicular hatching) and ECHAM5 (diagonal hatching). The monsoon onsets for each simulation are shown using blue vertical lines and retreat pink vertical lines (ECHAM5-dash dot lines, HadCM3-solid

4 Discussion

Recent climate impact studies such as AgMIP (Rosenzweig et al., 2013, 2014)) and ISIMIP (Warszawski et al., 2013, 2014) have highlighted the importance of reliable input data for models. Section 1.1 highlights the scale of the uncertainties present when solely using a global sowing and harvest dataset to simulate region specific cropping patterns. We have therefore proposed a new method for generating sowing and harvest dates for South Asia based on the ASM. In general the method reproduces observed sowing and harvest dates for much of India, these results are discussed further in Sect. 4.1. This method will also be useful in other monsoon regions where data are scarce, unreliable or unavailable such as in future climate simulations. The future results are discussed further in Sect 4.2.

4.1 Present day analysis

In general the method described by Fig. 3 works well across most of India for the present day, with the monsoon derived estimates of sowing and harvest dates falling within the range of days for sowing given by the observations (see Fig. 6). However there are regions where the estimated sowing and harvest dates do not compare as well against present day observations. Rice sowing is generally closely associated with ASM onset across most of central India, however in the south of India there is a small region where the differences between the observations of sowing dates and the monsoon are larger than everywhere else (see Fig. 5). In Sect. 3.2 this region is shown to have different monsoon characteristics to the rest of India. This part of India includes the state of Tamil Nadu, this state is located on the lee side of the Western Ghats and therefore does not receive the large amounts of ASM rainfall that is more commonly associated with this part of the world. Tamil Nadu receives up to 50 percent of its annual rainfall during October-December via the less stable North Eastern (NE) Monsoon. The NE monsoon is therefore more important for water resources for this part of India than the ASM which accounts for approximately 30 percent of the annual rainfall for this region (Dhar et al., 1982). These differing monsoon characteristics mean different agricultural practices are required to cultivate rice in this part of the country. This is illustrated by Fig. 11 (left plot) which shows that the southern region of India with differing monsoon characteristics irrigates rice more intensively than other parts of India. In the Tamil Nadu region, rivers are usually dry except during the monsoon months and the flat gradients mean there are few locations for building reservoirs, therefore approximately one third of the paddy rice crop is irrigated from a large network of water tanks (Anbumozhi et al., 2001). The Southern states of India have the highest density of irrigation tanks with large numbers also found in Andhra Pradesh and Karnataka, these are also regions shown to have a high irrigation intensity in Fig. 11. Rice harvest is typically not as closely associated with the monsoon onset as rice sowing, which usually requires the monsoon to be fully established before planting.

The widespread irrigation of wheat shown in Fig. 11 (right plot) has less of an impact on the estimates of wheat sowing/harvest dates because this crop is less closely linked to the monsoon onset than rice. Therefore the regional differences between the MinAg observations and the monsoon derived sowing and harvest dates for wheat are not as large as some of those for rice (see Sect. 3.3). Given that the method has provided reasonable estimates of sowing and harvest dates for most of India, it would be useful and interesting to extend this method to improve it for the South of India.

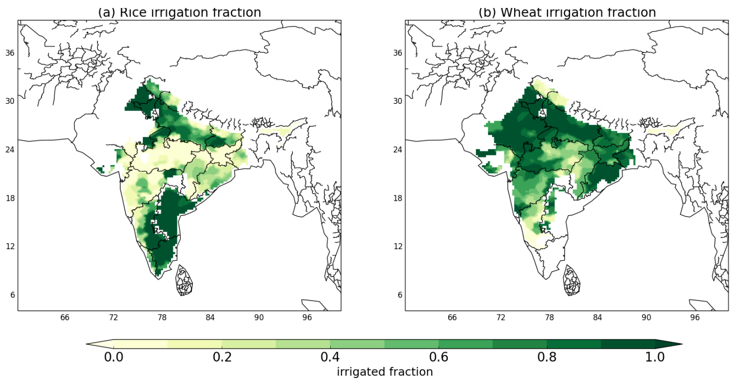

Figure 11. The average irrigation fraction for rice (a) and wheat (b) calculated from the ICRISAT observations of irrigation area and area planted

375 ## 4.2 Future analysis

Analysis of the future monsoon onset, retreat, peak and duration shown in Sect. 3.4 shows how changeable the ASM is for these simulations between time periods. Christensen et al. (2013) shows that there is a high model agreement within the ensemble from the 5th Coupled Model Intercomparison Project (CMIP5) for an earlier onset and later withdrawal in the future and therefore indicates a lengthening monsoon duration. However the simulations presented here do not show this with Fig. 9, instead highlighting the large amount of variability in the ASM for this region. It is possible that an increase in the monsoon duration does occur in these simulations for some parts of South Asia but this detail is lost through averaging over the region or as a result of the time periods selected. Christensen et al. (2013) also suggest that there is medium confidence within the CMIP5 ensemble that the ASM rainfall will increase to the end of the century. The simulations presented do indicate this as shown by the timeseries in Fig. 12.

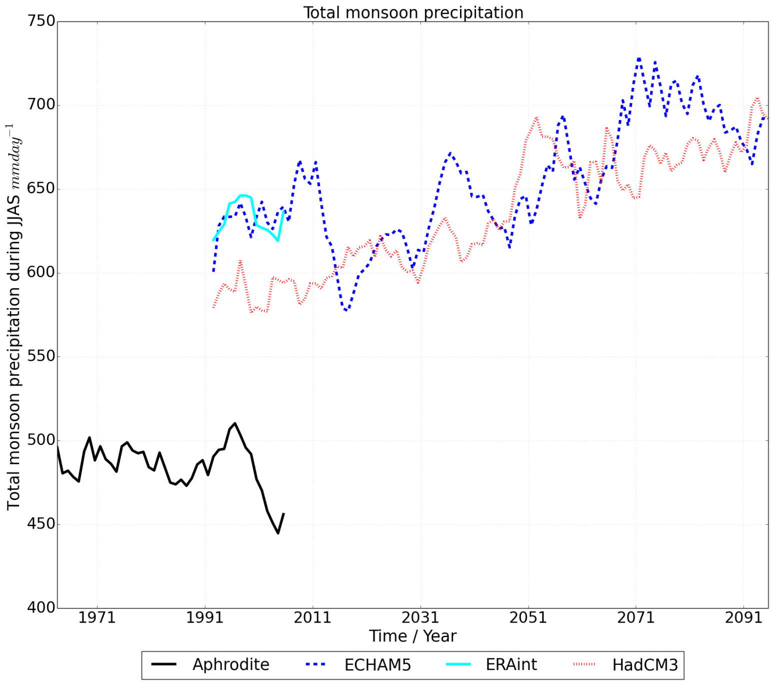

Figure 12. The annual timeseries of total monsoon precipitation, smoothed - using 5yr averaging, averaged for the whole of South Asia for all simulations; APHRODITE-solid black line, ERAint-solid cyan line, ECHAM5-blue dashed line and HadCM3-red dotted line.

Assuming that crops continue to be grown in accordance with the monsoon, Sect. 3.4 shows that the method described in Sect. 2 provides a good estimate of sowing and harvest dates for the two future periods shown. Spatial plots of the sowing and harvest dates for the two future periods (not shown) are similar to those in Sect. 3.3 for the present day with the south of the Indian peninsula continuing to show different monsoon characteristics (see Sect. 4.1) to the rest of India in the future, resulting in later estimated sowing and harvest dates for this region.

The proposed method successfully adjusts the sowing and harvest dates where the monsoon begins earlier in the future simulations and therefore provides a good estimate of sowing and harvest dates for the two future periods considered. This is a key benefit of using this method as it simulates the decision a farmer might take to sow before the usual observed date if the monsoon arrived early. This method therefore provides the capability for climate simulations to replicate the type of adaptation response that would happen in the real world. This method would also be useful for other regions that have a crop calendar that is similarly defined such as the SSA; this is a multiple cropping region with sowing and harvest dates closely associated with the main rainy season (Waha et al., 2013).

5 Conclusions

Sowing and harvest dates are an important input within crop models but are a source of considerable uncertainty. Global datasets, such as Sacks et al. (2010), cannot always distinguish when wheat is grown in tropical and sub-tropical regions therefore driving a requirement for higher resolution regional datasets. Crops across much of South Asia are heavily dependent on the ASM and therefore sowing and harvest dates tend to be closely linked to this climatological phenomena. We have therefore presented a new method for deriving sowing and harvest dates for rice and wheat for South Asia from the ASM onset and retreat. For the present day, the method generally shows good results for most areas of India. The method does not work as well for the south of the Indian peninsular, this region receives a lower proportion of annual rainfall from the ASM than much of the rest of South Asia and irrigates intensively. Monsoon derived estimates of sowing and harvest dates for rice and wheat are useful for regions where data are scarce, unreliable or in future climate impact assessments. The method presented assumes that the agricultural practices remain dependent on the monsoon in the future. Given this assumption, the method presented successfully estimates the sowing and harvest dates for two future periods by adjusting the sowing and harvest dates according to the timing of the monsoon. Future work in this area could investigate refinements to the method to take into account the different characteristics of the monsoon in the regions where the method does not work as well and the differing agricultural practices there. It would also be interesting to investigate how well the method works for different crop rotations in different monsoon regions.

Appendix A: Details of the models used

This analysis uses two General Circulation Models (GCMs) selected to capture a range of temperatures and variability in precipitation similar to the AR4 ensemble for Asia (Christensen et al., 2007) and the main features of the ASM (Kumar et al., 2013; Annamalai et al., 2007; Mathison et al., 2013, 2015). HadCM3; the Third version of the Met Office Hadley Centre Climate Model (HadCM3 – Pope et al., 2000; Gordon et al., 2000, a version of the Met Office Unified Model) provides the positive variation in precipitation and ECHAM5, (Roeckner et al., 2003, 3rd realization–) the negative variation in order to estimate the uncertainty in the sign of the projected change in precipitation over the coming century.

One RCM, the HadRM3 RCM (Jones et al., 2004) is used to downscale the GCM data to provide more regional detail to the global datasets. HadRM3 has 19 atmospheric levels and the lateral atmospheric boundary conditions are updated 3 hourly and interpolated to a 150 s timestep. These simulations include a detailed representation of the land surface in the form of version 2.2 of the Met Office Surface Exchange Scheme which includes a full physical energy-balance snow model (MOSESv2.2, Essery et al., 2003). MOSESv2.2 treats subgrid land-cover heterogeneity explicitly with separate surface temperatures, radiative fluxes (long wave and shortwave), heat fluxes (sensible, latent and ground), canopy moisture contents, snow masses and snowmelt rates computed for each surface type in a grid box (Essery et al., 2001). However the air temperature, humidity and wind speed above the surface are treated as homogenous across the gridbox and precipitation is applied uniformly over the different surface types of each gridbox (Mathison et al., 2015). This RCM was included in an assessment of four RCMs conducted by Lucas-Picher et al. (2011) for the South Asia region which demonstrated that RCMs were able to capture the monsoon.

HadRM3 is driven by boundary data from the two GCMs (See Fig.3) to provide 25 km resolution regional climate modelling of the Indian sub-continent (25° N, 79° E–32° N, 88° E) for the period 1960–2100. These RCM simulations are from the EU-HighNoon project (referred to hereafter as HNRCMs), representing currently the finest resolution climate modelling available for this region (Mathison et al., 2013; Moors et al., 2011; Kumar et al., 2013).

The HNRCMs use the SRES A1B scenario which represents a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. The A1B scenario specifically, represents this future world where there is balance across energy sources i.e. a mixture of fossil and non-fossil fuels (Nakicenovic et al., 2000).

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Appendix B: Comparison of model monsoon onset and retreat with precipitation observations

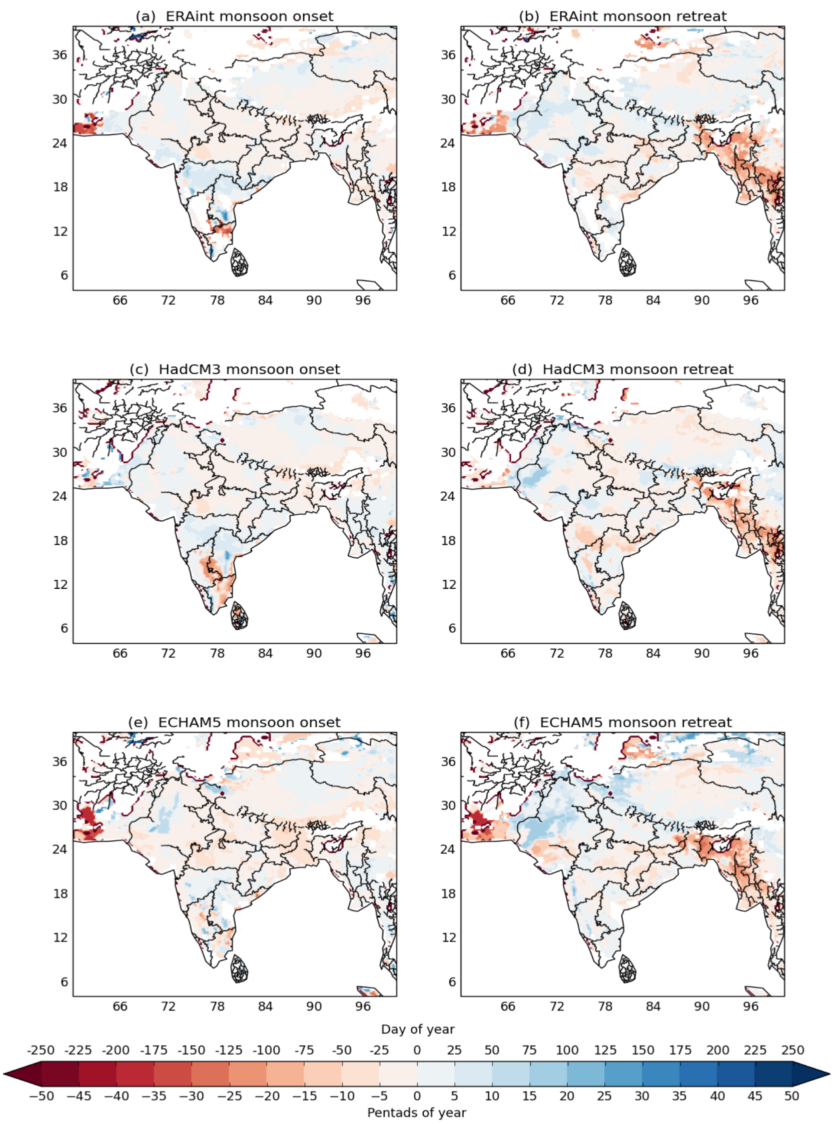

Figure B.1. Plots of the 1990-2007 difference between model simulations and APHRODITE observations for the monsoon statistics; monsoon onset (left column) and retreat (right column); HadCM3 (a and b) ECHAM5 (c and d) and ERAint (e and f) calculated using the NPPI metric.

Appendix C: Comparing observed sowing and harvest dates with estimates of monsoon onset and retreat

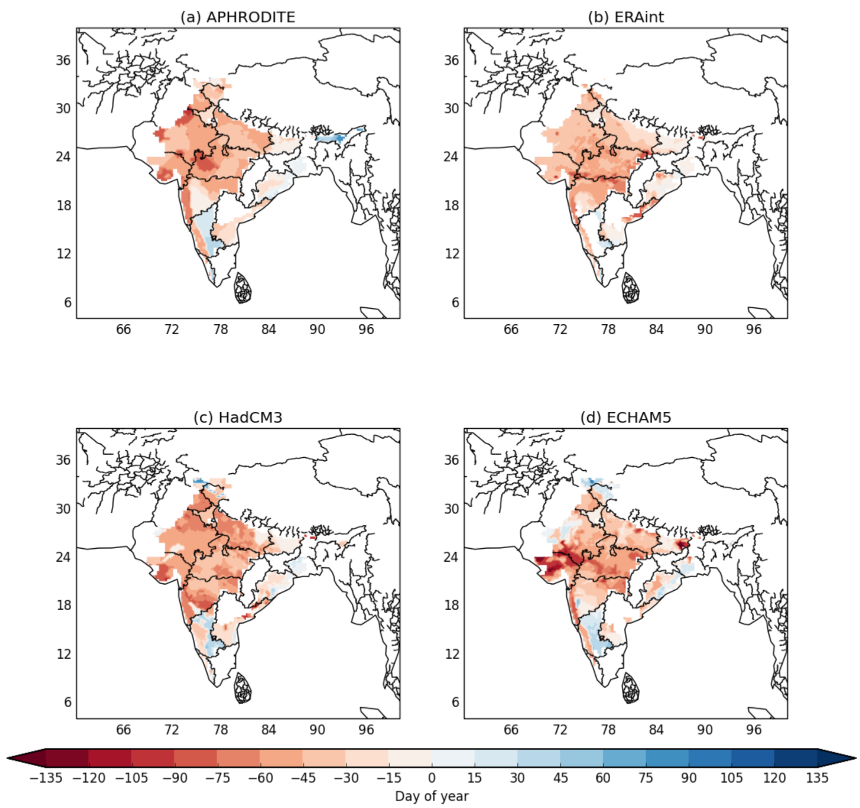

Figure C.1. The difference between the midpoint of the monsoon retreat in the model and the midpoint of the observed rice harvest period for 1990-2007.

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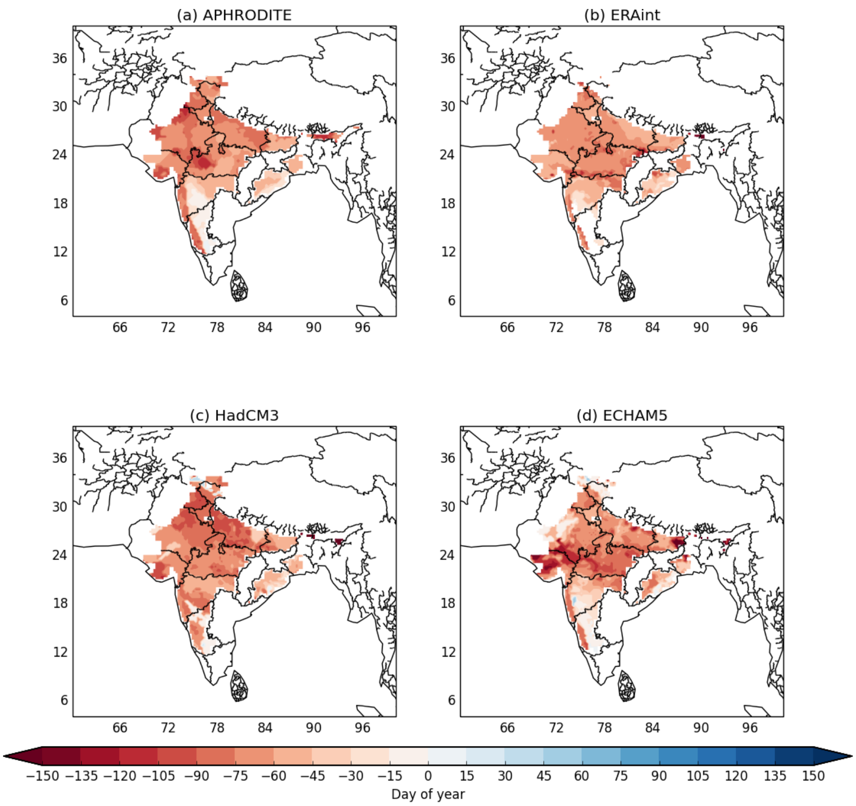

Figure C.2. The difference between the midpoint of the monsoon retreat in the model and the midpoint of the observed wheat sowing period for 1990-2007.

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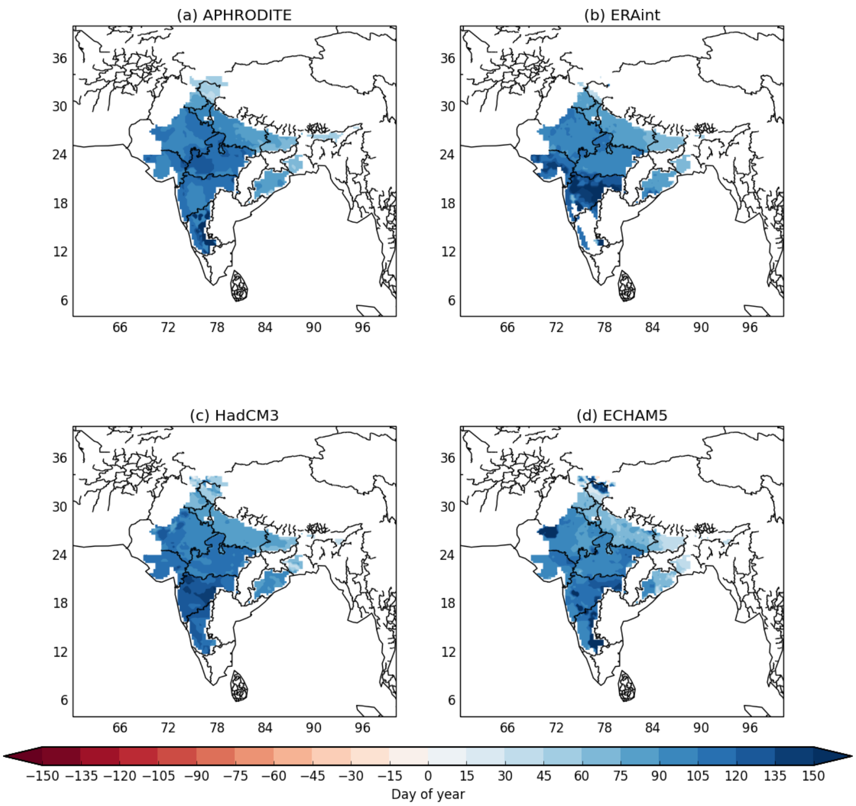

Figure C.3. The difference between the midpoint of the monsoon onset in the model and the midpoint of the observed wheat harvest period for 1990-2007.

455 **Appendix D: Monsoon derived estimates of sow/harvest dates for rice and wheat**

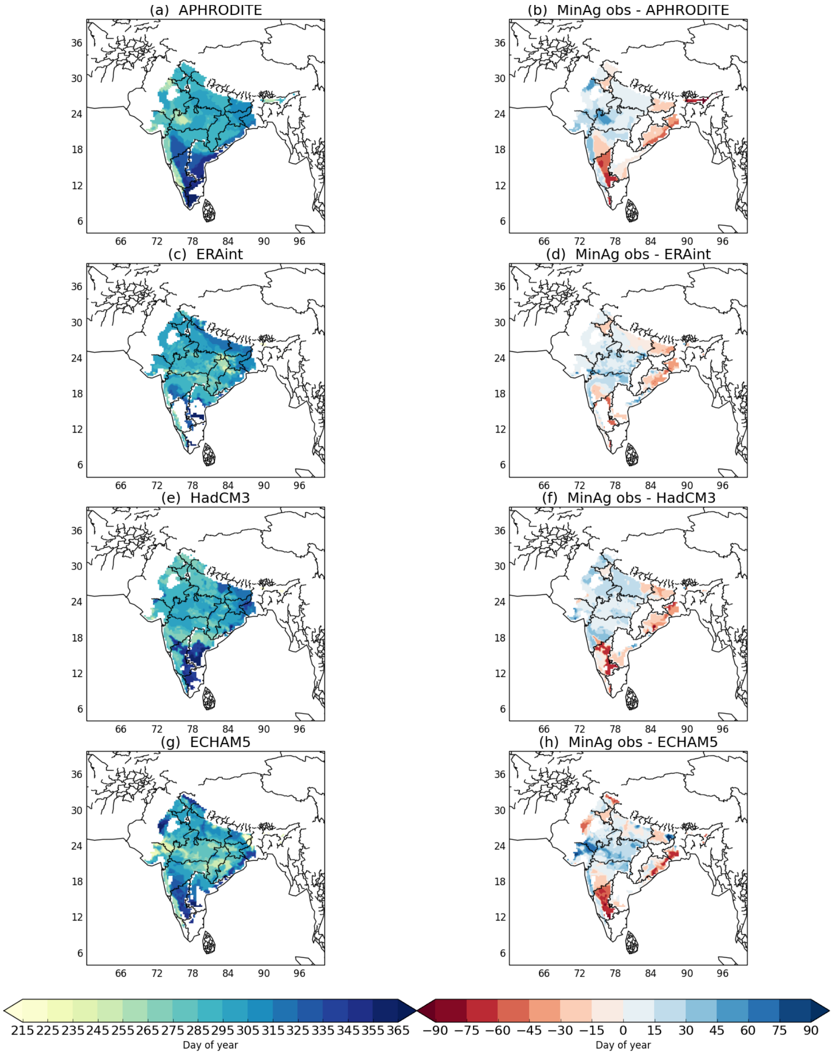

Figure D.1. The monsoon derived rice harvest dates (left) and the difference between the MinAg observations and the monsoon derived rice harvest dates (right) for the period 1990-2007.

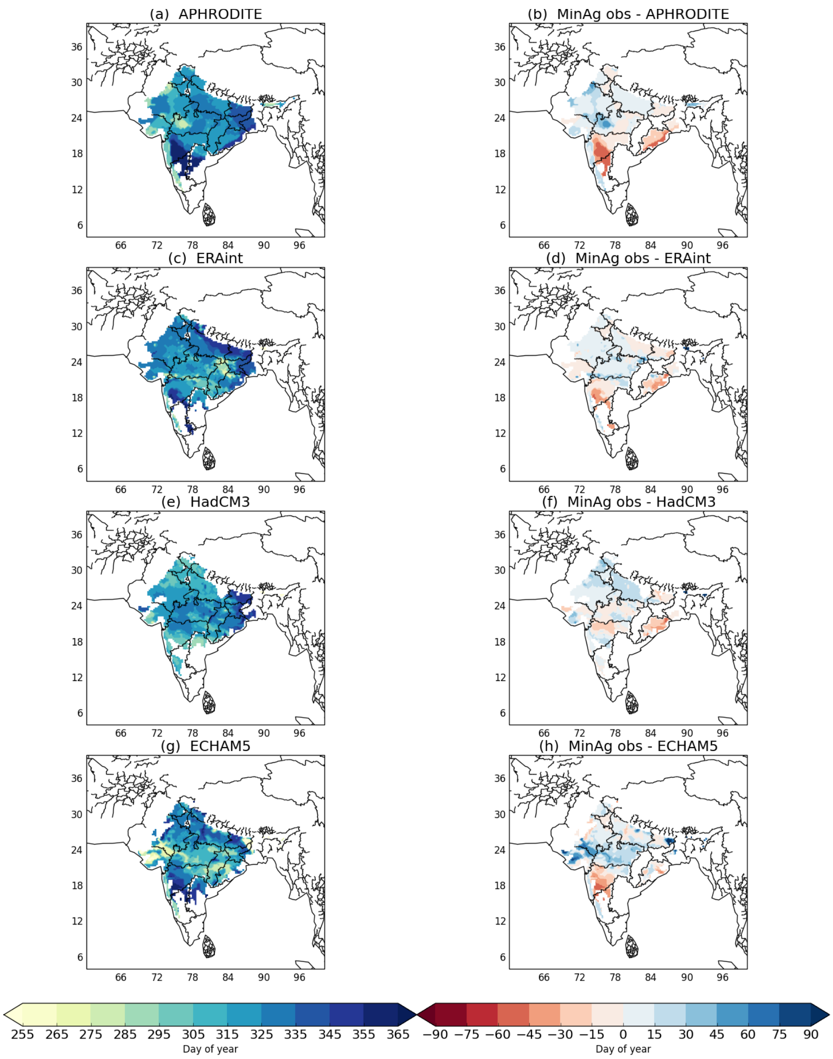

Figure D.2. The monsoon derived wheat sowing dates (left) and the difference between the MinAg observations and the monsoon derived wheat sowing dates (right) for the period 1990-2007.

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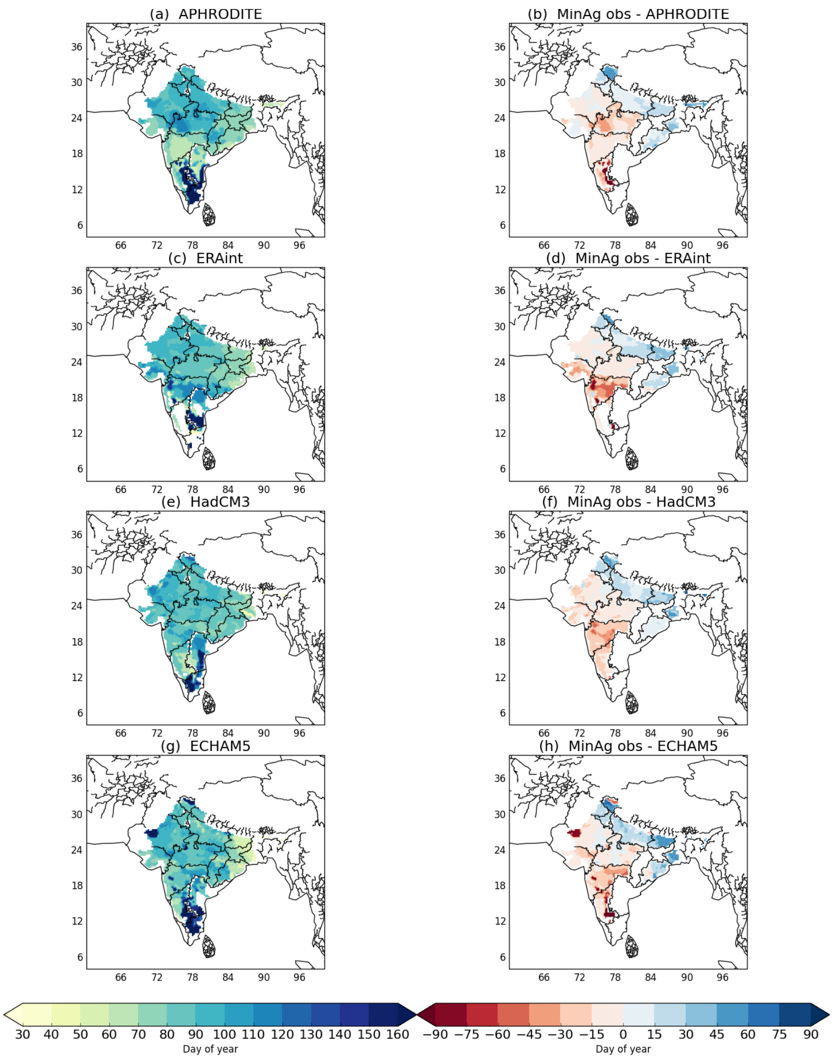

Figure D.3. The monsoon derived wheat harvest dates (left) and the difference between the MinAg observations and the monsoon derived wheat harvest dates (right) for the period 1990-2007.

Appendix E: Analysis of future monsoon onset and retreat

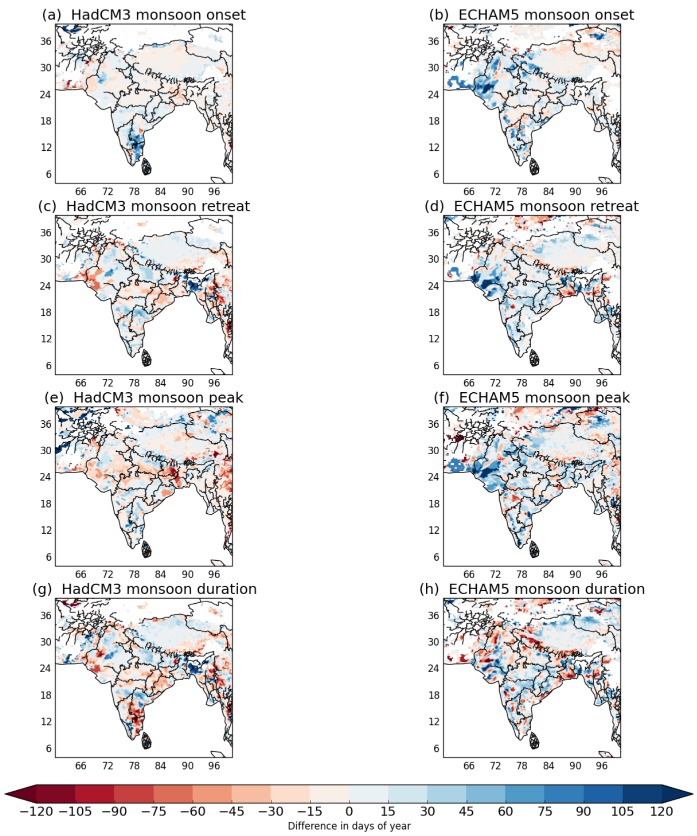

Figure E.1. The difference between the monsoon statistics for the 2080-2097 future period compared with the present day 1990-2007 for HadCM3 (left) and ECHAM5 (right).

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Table 1. Table of $RelMonsoon_{croprule}$ for each dataset, crop and stage. The $RelMonsoon_{croprule}$ is the value subtracted from the monsoon onset/retreat in order to calculate a new sowing/harvest date based on the monsoon onset/retreat. In each case the new estimate of the sowing and harvest dates is calculated by subtracting the $RelMonsoon_{croprule}$ from the Mon_{stat} where Mon_{stat} is Monsoon onset or Monsoon retreat from a HNRCM or APHRODITE precipitation observations

crop	**stage**	**source**	Mon_{stat}	$RelMonsoon_{croprule}$ **(India average)**
wheat	sowing	APHRODITE	retreat -	-63.5
wheat	sowing	ERAint	retreat -	-73.8
wheat	sowing	HadCM3	retreat -	-67.9
wheat	sowing	ECHAM5	retreat -	-63.7
wheat	harvest	APHRODITE	onset -	98.4
wheat	harvest	ERAint	onset -	84.1
wheat	harvest	HadCM3	onset -	98.9
wheat	harvest	ECHAM5	onset -	91.4
rice	sowing	APHRODITE	onset -	19.7
rice	sowing	ERAint	onset -	3.4
rice	sowing	HadCM3	onset -	17.2
rice	sowing	ECHAM5	onset -	10.1
rice	harvest	APHRODITE	retreat -	-32.8
rice	harvest	ERAint	retreat -	-45.8
rice	harvest	HadCM3	retreat -	-38.5
rice	harvest	ECHAM5	retreat -	-34.8

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Table 2. Analysis of the differences between the midpoints of the MinAg data and Monsoon onset/retreat for rice/wheat sowing and harvest dates: The table shows the minimum, maximum, mean and standard deviation (SD) averaged across South Asia where wheat or rice are planted.

crop	stage	monsoon stat	source	min	max	mean	SD
wheat	sowing	retreat	APHRODITE	-11.0	122.0	62.71	23.49
wheat	sowing	retreat	ERAint	-180.0	174.0	73.49	23.68
wheat	sowing	retreat	HadCM3	-180.0	172.5	66.94	27.91
wheat	sowing	retreat	ECHAM5	-177.5	175.0	63.27	35.26
wheat	harvest	onset	APHRODITE	-176.5	173.5	-92.28	41.34
wheat	harvest	onset	ERAint	-181.5	182.0	-84.16	29.97
wheat	harvest	onset	HadCM3	-171.5	148.5	-100.24	22.31
wheat	harvest	onset	ECHAM5	-176.5	182.5	-83.84	47.18
rice	sowing	onset	APHRODITE	-156.5	24.5	-17.96	32.12
rice	sowing	onset	ERAint	-171.5	163.5	-0.28	33.14
rice	sowing	onset	HadCM3	-181.5	40.0	-15.06	22.37
rice	sowing	onset	ECHAM5	-161.5	55.0	-6.74	31.47
rice	harvest	retreat	APHRODITE	-110.5	91.5	31.78	30.34
rice	harvest	retreat	ERAint	-68.5	146.5	46.87	26.01
rice	harvest	retreat	HadCM3	-65.5	111.5	39.03	28.45
rice	harvest	retreat	ECHAM5	-85.5	141.5	35.71	33.34