

Technical Report:

Observations and reanalyses data: comparison and trends in Southeast Asia

Richard Washington

Helen Pearce

Sebastian Engelstaedter

Thien-Kim Diep

Climate Research Lab

University of Oxford

January 2014

1 Part 1: Observations and reanalyses data: comparison and trends

Reanalyses data sets, being temporally and spatially complete and available on six hourly timescales, are extremely convenient to use. Real observations represent the climate system with greater fidelity than reanalyses can, given that the latter are a complicated blend of observations and models via an assimilation scheme and rely heavily on the assimilation scheme where observations are absent. Knowing whether the reanalyses data reflects real data can be difficult to establish. In this part of the report, the observed data is compared with three reanalyses data sets for the SE Asia region. We use observations from SYNOP and METAR reports. SYNOP and METAR data are, in effect, observations taken at met stations and delivered to the Global Telecommunication System (GTS). Once in the GTS, they can be archived by institutions such as those delivering weather forecasts. Access to these data via the archives is generally much easier than through the individual Met Agencies. This is particularly true in the case of a study covering multiple nation states. These datasets are described in more detail in Sections 1.1 and 1.2.

1.1 Methods

This section provides an overview of the data and data processing.

Surface observations and data processing

Basic measurements made at meteorological stations all over the world are distributed through surface synoptic observations (SYNOP) and météorologique aviation régulière (METAR) reports. SYNOP reports generally include more variables than the METAR reports which are distributed primarily for the aviation industry. The UK Meteorological Office compiled SYNOP and METAR reports in the Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-present) archive. We use data from the MIDAS Global Weather Observations (GL) table which includes 3-hourly observations from global non-UK stations from 1974 to present (http://badc.nerc.ac.uk/data/ukmo-midas/GL_Table.html).

The observation period, as well as the frequency of observations, varies significantly between stations and may vary significantly over time. Basic quality control is performed by the observer at each station before the data are transmitted as SYNOP or METAR reports. Before the data are

included in the MIDAS archive, they undergo a range of quality checks outlined in the 'Met Office Surface Data User Guide' Section 7 (http://badc.nerc.ac.uk/data/ukmo-midas/ukmo_guide.html).

In order to derive a consistent, quality assured dataset, the SYNOP and METAR data were further processed in the following way. At stations where observations from both SYNOP and METAR reports were available for the same observation time, the observations from the SYNOP report were used in preference to METAR because SYNOP observations are more frequent then METAR observations (thereby keeping the dataset as consistent as possible). Gaps in the SYNOP observations times were substituted by METAR observations where possible to make observations as complete as possible. Although for some stations 3-hourly observations are available, we only use observations made at the synoptic hours (00, 06, 12 and 18 UTC). All mean sea-level pressure (MSLP), air temperature at 2m (T2m) and wind speed at 10m (WSPD10m) observations between 1 January 1989 00:00 UTC and 31 December 2009 18:00 UTC were extracted.

Reanalyses (ERAI, CFSR and MERRA)

Surface observations from SYNOP/METAR of mean sea-level pressure, air temperature at 2m and wind speed at 10m are compared with the corresponding fields of three reanalysis datasets. For this comparison, fields for three reanalysis datasets were obtained in 6-hourly time steps (00, 06, 12 and 18 UTC) between 1 January 1989 and 12 December 2009. This 21 year period was chosen because all three reanalyses are available for this period.

European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERAI) [Dee et al., 2011] full resolution global fields were obtained from the ECMWF website (http://data-portal.ecmwf.int/data/d/interim_full_daily). The fields are available in netCDF format and in 0.703125° by 0.703125° spatial resolution. For the trend analysis, the MSLP, T2m, WSPD10m and total precipitation fields were obtained for the whole ERA-Interim period 1 January 1979 to 31 December 2012. Whereas MSLP, T2m and WSPD10m are available as reanalysis fields, total precipitation is only available as 3-hourly forecast fields with forecasts being initialised at 00 and 12 UTC every day.

A subset of the reanalysis domain covering SE Asia was extracted from the National Aeronautics and Space Administration (NASA) modern-era retrospective analysis for the research and applications (MERRA) dataset [Rienecker et al., 2011] and was obtained from the Goddard Earth DISC) Sciences (GES Data and Information Services Center website (http://disc.sci.gsfc.nasa.gov/daac-bin/FTPSubset.pl). We use the SLP (Sea level pressure), T2M (Temperature at 2m above the displacement height) and U10M/V10M (Eastward/Northward wind at 10m above displacement height) fields of the 'IAU 2d atmospheric single-level diagnostics (tavg1_2d_slv_Nx)' product. The fields are available in netCDF format and come in a 2/3° longitude by 0.5° latitude resolution.

The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) fields [Suranjana et al., 2010] for MSLP, air temperature at 2m as well as U and V wind components at 10m were obtained through the National Oceanic and Atmospheric Administration (NOAA) National Operational Model Archive & Distribution System (NOMADS, ftp://nomads.ncdc.noaa.gov/CFSR/HP_time_series/). The MSLP field is available at a resolution of 0.5° by 0.5° whereas the 2m air temperature and 10m wind speed fields are 0.3125° by 0.3125°.

Station selection and minimum data availability thresholds

There are normally many missing variables in the SYNOP/METAR data set and the number of observations available for the period 1989 to 2009 varies between stations, synoptic hours and variables. In order to deal with this, a minimum data availability threshold of 400 observations over the record 1989-2009 was chosen for a station to be included in this analysis. For the analysis of the seasonal statistics, this threshold was lowered to a quarter of 400 (n=100). These thresholds were chosen as a compromise that allows a large enough sample for statistical analysis while maintaining a reasonably good spatial coverage.

Figures 1.1 to 1.6 show the spatial distribution of stations with T2m measurements for each synoptic hour when thresholds of 6 (n=460), 10 (n=767), 20 (n=1533), 30 (n=2300), 40 (n=3066) and 50% (n=3833) minimum data availability are applied, respectively. The relatively low minimum data availability threshold of 400 observations was chosen so that Cambodia and western Indonesia (Papua) are represented in the analysis. Cambodia is the country with the least number of

observations (<500). The 400 observations threshold is justifiable because when comparing the station availability for the different thresholds (Figures 1.1 to 1.6), it becomes evident that increasing the threshold to 20% does not significantly change the station distribution apart from over Cambodia and for one station in the centre of Papua, Indonesia. Only for thresholds larger than 20% (e.g., 30, 40 and 50%, Figure 1.4, 1.5 and 1.6) do larger gaps in the station availability become apparent, especially in Indonesia.



Figure 1.1 Spatial distribution of stations with a minimum data availability threshold of 6% for 2m temperature for the period 1989 to 2009



Figure 1.2 Spatial distribution of stations with a minimum data availability threshold of 10% for 2m temperature for the period 1989 to 2009.



Figure 1.3 Spatial distribution of stations with a minimum data availability threshold of 20 % for 2m temperature for the period 1989 to 2009.



Figure 1.4 Spatial distribution of stations with a minimum data availability threshold of 30 % for 2m temperature for the period 1989 to 2009.



Figure 1.5 Spatial distribution of stations with a minimum data availability threshold of 40 % for 2m temperature for the period 1989 to 2009.



Figure 1.6 Spatial distribution of stations with a minimum data availability threshold of 50 % for 2m temperature for the period 1989 to 2009.

The distribution of stations for observations at 00, 06 and 12 UTC are very similar (e.g., Figure 1.1). The number of stations available for statistical analysis drops, however, for observations made at 18 UTC which corresponds to night time in the South-East Asia domain. See the end of this section for a brief discussion of time zones. The number of stations available for analysis does not vary significantly between the different variables (not shown).

As the stations will have different numbers of observations, a meaningful comparison of their climatology is difficult. To overcome this problem we extract 400 random samples from the record of each station and calculate means based on them. To avoid the chance of accidentally poor sampling, we repeat the extraction of 400 random samples 100 times. The 100 means will be Gaussian distributed around the 'true' mean of the station. Therefore, calculating the mean of them will give a more realistic representation of the climatology while still maintaining the same sample size at each station.

Reanalyses comparison

The SYNOP/METAR observations are compared with the ERA-Interim, CFSR and MERRA reanalysis products. The following approach was taken for the comparison. For each observation used from the SYNOP/METAR data, the corresponding reanalysis value was extracted by interpolating the gridded reanalysis field to the location of the observing station using bilinear interpolation. Repeating this process created a record that has the same number of reanalysis values as the observations allowing for a one-to-one comparison of the observations and the reanalysis. Climatological means were calculated using the same approach as for the observations using the same set of random indices as generated for each of the stations.

Spatial interpolation

The climatological means calculated at each station for the observations as well as all three reanalyses have been interpolated spatially using linear interpolation.

Trend analysis

The ERA-Interim reanalysis is used to identify trends in climate data between 1979 and 2012 for

the SE Asia domain. Trends in climate extremes (5th and 95th percentile), as well as the mean, are analysed for MSLP, T2m, WSPD10m and total precipitation.

For the trend analysis of the percentiles, daily MSLP, T2m and WSPD10m means were calculated from the 6-hourly values for the whole period 1979-2012. Based on the daily mean values, the 5th and 95th percentile was calculated for each year as well as for each season (DJF, MAM, JJA, JAS and SON) yielding a time series of 34 values for each grid box. For precipitation the same approach was taken but totals were calculated instead of means. A simple linear regression model was used to calculate the slope of the regression line.

For the trend analysis of the monthly means, data were computed from daily means (based on 6-hourly values). From the monthly means annual and seasonal (DJF, MAM, JJA, JAS and SON) means were computed yielding a time series of 34 values for each grid box. Regression was computed in the same way as for the percentile trend analysis described above.

Notes on time zones

The geographical domain covers four time zones spanning from UTC+6.5 to UTC+9. The times of observations in the MIDAS dataset as well as the availability of the reanalysis products are 00, 06, 12 and 18 UTC. It is important to keep the relationship between observation times at the synoptic hours and local time in mind when interpreting the climatological plots for specific synoptic hours. Table 1.1 shows the relationship between UTC and local time.

Table i	1.1:	Relationshi	ip between	GMT an	d local	time
10010 1	• • • •	1 contronsint	p berneen	Oni i con	a woodi	vunve

GMT, UTC+0	UTC+6.5	UTC+7	UTC+8	UTC+9
	Myanmar	Laos, Thailand, Cambodia, Vietnam	Malaysia, Philippines, western Indonesia	eastern Indonesia
00 UTC	6:30am	7am	8am	9am
06 UTC	12:30pm	1pm	2pm	3pm
12 UTC	6:30pm	7pm	8pm	9pm
18 UTC	12:30am	1am	2am	3am

1.2 Analysis of observations: climatology

This section shows the baseline climatology of the region derived from observations (using linear interpolation) for the annual mean (Figure 1.7) and each season DJF, MAM, JJA, JAS and SON (Figures 1.8 to 1.12). In each case the climatology is shown for six hourly times (00, 06, 12, 18 UTC) and therefore resolves the diurnal cycle.

Peak long term annual mean observed temperatures are in Thailand. Topographic effects are evident for isolated stations in Myanmar (2 stations at 12 UTC), Sumatra (1 station at 00 UTC) and Papua (2 stations show much lower T2m).

Wind speed maxima occurs at 06 UTC (daytime) and minima at 18 and 00 UTC (night time). Strong winds are found along the Vietnamese cost, mainland Malaysia, Java, Sulawesi and Sumatra, especially during the daytime. Generally low winds occur in Myanmar and Thailand. Strong winds

are found at a single station in Laos at 06 UTC (which is likely a local control). Coastal stations show in general higher winds.

Mean annual sea level pressure (MSLP) generally decreases from north to south in DJF and reverses in JJA consistent with the monsoon regime which dominates the area. Lowest MSLP occurs in Myanmar in JJA.

As expected, surface temperature (T2m) peaks at 06 UTC although the T2m spatial distribution and values are similar at 00 and 18 UTC. Temperature differences between seasons are small but DJF emerges as the hottest season. Colder temperatures in central Papua reflect topography; there are similar effects at other stations.



Figure 1.7 1989-2009 long term mean climatology of observed MSLP, T2m and WSPD for 00, 06, 12 and 18 UTC employing linearly interpolated between stations.



Figure 1.8 1989-2009 long term seasonal mean climatology for DJF of observed MSLP, T2m and WSPD for 00, 06, 12 and 18 UTC employing linearly interpolated between stations.



Figure 1.9 1989-2009 long term seasonal mean climatology for MAM of observed MSLP, T2m and WSPD for 00, 06, 12 and 18 UTC employing linearly interpolated between stations.



Figure 1.10 1989-2009 long term seasonal mean climatology for JJA of observed MSLP, T2m and WSPD for 00, 06, 12 and 18 UTC employing linearly interpolated between stations.



Figure 1.11 1989-2009 long term seasonal mean climatology for JAS of observed MSLP, T2m and WSPD for 00, 06, 12 and 18 UTC employing linearly interpolated between stations.



Figure 1.12 1989-2009 long term seasonal mean climatology for SON of observed MSLP, T2m and WSPD for 00, 06, 12 and 18 UTC employing linearly interpolated between stations.

1.3 Comparison with reanalysis products

This section compares reanalyses with observations. In subsequent sections, trend analysis is applied to the reanalyses data and global climate models are compared with reanalyses. Therefore it is useful to establish the bias evident in reanalyses products.

MSLP

Figure 1.13 shows the reanalyses annual mean MSLP from the three reanalyses compared in this study. Figure 1.14 shows the reanalysis minus the observed. CFSR and ERAI are similar with both models overestimating MSLP apart from over Borneo and mainland Malaysia. MERRA shows a somewhat different picture, mainly under prediction at 00, 06 and 18 UTC and over prediction at 12 UTC (evening).

T2m

Figure 1.15 shows the reanalyses annual mean T2m from the three reanalyses compared in this study. Figure 1.16 shows the reanalysis minus the observed. All three reanalyses underestimate T2m during daytime. The strongest underestimate is for continental countries at 12 UTC. During night time a mixed pattern emerges with ERAI and MERRA overestimating T2m at many stations in Sumatra, Java, Borneo and mainland Malaysia. Overall, all three reanalyses are similar.

WSPD

Figure 1.17 shows the reanalyses annual mean T2m from the three reanalyses compared in this study. Figure 1.18 shows the reanalysis minus the observed. Spatial distribution of over and underestimation are similar for all reanalyses although the magnitude varies. CFSR is closest to observations. The largest underestimation of winds is during daytime (06 UTC) in non-continental countries.



Figure 1.13 1989-2009 CFSR, ERAI and MERRA long term mean reanalysis MSLP for 00, 06, 12 and 18 UTC linearly interpolated between stations.



Figure 1.14 1989-2009 reanalysis (CFSR, ERAI and MERRA) minus observed MSLP 00, 06, 12 and 18 UTC linearly interpolated between stations.



Figure 1.15 1989-2009 CFSR, ERAI and MERRA long term mean reanalysis T2m for 00, 06, 12 and 18 UTC linearly interpolated between stations.



Figure 1.16 1989-2009 reanalysis (CFSR, ERAI and MERRA) minus observed T2m 00, 06, 12 and 18 UTC linearly interpolated between stations.



Figure 1.17 1989-2009 CFSR, ERAI and MERRA long term mean reanalysis WSPD10m for 00, 06, 12 and 18 UTC linearly interpolated between stations.



Figure 1.18 1989-2009 reanalysis (CFSR, ERAI and MERRA) minus observed WSPD10m 00, 06, 12 and 18 UTC linearly interpolated between stations.

Seasonal mean climatologies are included in the following figures for reference, which are found in the Appendix.

MSLP

DJF: Figure 1.19 (reanalyses) and Figure 1.20 (reanalyses minus obs)

MAM: Figure 1.21 (reanalyses) and Figure 1.22 (reanalyses minus obs)

JJA: Figure 1.23 (reanalyses) and Figure 1.24 (reanalyses minus obs)

JAS: Figure 1.25 (reanalyses) and Figure 1.26 (reanalyses minus obs)

SON: Figure 1.27 (reanalyses) and Figure 1.28 (reanalyses minus obs)

T2m

DJF: Figure 1.29 (reanalyses) and Figure 1.30 (reanalyses minus obs)

MAM: Figure 1.31 (reanalyses) and Figure 1.32 (reanalyses minus obs)

JJA: Figure 1.33 (reanalyses) and Figure 1.34 (reanalyses minus obs)

JAS: Figure 1.35 (reanalyses) and Figure 1.36 (reanalyses minus obs)

SON: Figure 1.37 (reanalyses) and Figure 1.38 (reanalyses minus obs)

WSPD10m

DJF: Figure 1.39 (reanalyses) and Figure 1.40 (reanalyses minus obs)
MAM: Figure 1.41 (reanalyses) and Figure 1.42 (reanalyses minus obs)
JJA: Figure 1.43 (reanalyses) and Figure 1.44 (reanalyses minus obs)
JAS: Figure 1.45 (reanalyses) and Figure 1.46 (reanalyses minus obs)
SON: Figure 1.47 (reanalyses) and Figure 1.48 (reanalyses minus obs)

1.4 Trend analysis

Warming in SEA has been similar to the global mean warming (Cruz et al, 2007) with mean temperature increasing across South-East Asia since the 1960s at a rate of up to 0.2°C/decade (Tangang et al, 2007).. Extreme rainfall and temperature are thought to have a greater impact on crop cultivation than mean climate. In this respect, there is also a reported increase in the frequency hot days/warm nights since the mid-20th century (Caesar et al, 2011; Manton et al, 2001). Strongest changes are found in the northern regions of SEA in particular, Thailand and Malaysia (Choi et al, 2009). This suggests the role of local variations in warming, especially the tendency for stronger

warming over landmass interiors than coastal regions (McGregor and Dix, 2001). Also, present trends in surface air temperature are more pronounced in winter than in summer (Cruz et al, 2007).

Manton et al (2001) note that whilst generally rainfall has decreased over South-East Asia between 1961 and 1998, the trend is not statistically significant. Nonetheless, some significant trends were found, notably, a statistically significant decrease in the number of rain days over much of the domain was found. More recently, other authors have found additional trends in South-East Asian rainfall. Lau and Wu (2007) suggest that moderate rainfall events have been decreasing in occurrence, with an increase in the amount of heavy and light rainfall events, measuring in the top 10% and bottom 5% of events respectively.

The analysis undertaken above shows less frequent and more intense precipitation for tropical regions, as evident in the HadEX2 dataset (Donat et al, 2013) and other observations (Yao et al, 2010). A strong increase in extreme precipitation is found between 1951-2010 across all seasons and the number of days with at least 2mm of rain has decreased (Manton et al, 2001); although responses are regionally variable (Choi et al, 2009; Donat et al, 2013).

Individual regions of South-East Asia have also seen climatic trends. It has been suggested that there is a decreasing trend in extreme rainfall events in Myanmar (Chang, 2011). This contrasts to the trend over much of the northern region of the domain where extreme events have been increasing in frequency. A further regional example is peninsular Malaysia, with contrasting trends seen in total rainfall between the northeast and southwest monsoon seasons. During the northeast monsoon, total rainfall was found to have increased (Suhaila et al, 2010), but in contrast during the southwest monsoon a decrease in total rainfall has been established, despite an increase in intensity of rainfall events (Deni et al, 2010). For Indonesia, a contrast in rainfall trends between seasons has also been found, with Aldrian and Djamil, 2008) suggesting that there has been an increase in the ratio of rainfall of the wet to dry season.

For this report, trends are computed based on ERA-I reanalysis. Annual trends are discussed first, followed by seasonal trends.

Annual Trends

Mean MSLP shows a negative statistically significant trend over most large parts of SE Asia indicating a decrease in mean MSLP values over the period 1979-2012 (Figure 1.49). For the 5th percentile (low pressure extremes), a statistically significant negative trend is found south of 5N whereas the 95th percentile (high pressure extremes) shows a statistically significant trend over most parts west of 12E with a stronger slope north of 10N.

Mean T2m values show a statistically significant increase over most land areas as well as parts of the Indian and Pacific Ocean (Figure 1.50). Strongest increases occur over the northern tip of Borneo. The mean increase in T2m is accompanied by an increase in minimum and maximum extremes with the exception of Myanmar which shows a strong increase in minimum and some cooling in the maximum T2m extremes.

A statistically significant increase in mean 10m wind (Figure 1.51) occurs over the Indian Ocean west of Sumatra that comes about mainly due to an increase in the maximum extremes. The wind increase is consistent with the trends in sea level pressure noted earlier.

ERA-I shows a strong increase in rainfall near the Equator with hotspots in northern Sumatra, west Sulawesi and western Papua (Figure 1.52). There are also increases in rainfall in Myanmar with a hotspot in the north of the country. The increase in the mean trend is controlled by an increase in the maximum rainfall extremes, the distribution of which is very similar.



Figure 1.49 ERA-Interim 1989-2009 MSLP slope of the annual 5th percentile (bottom), mean (middle) and 95th percentile (top) regression line. Dots indicate a significant Pearson correlation coefficient at the .95 confidence level (two-tailed).



Figure 1.50 ERA-Interim 1989-2009 T2m slope of the annual 5th percentile (bottom), mean (middle) and 95th percentile (top) regression line. Dots indicate a significant Pearson correlation coefficient at the .95 confidence level (two-tailed).



Figure 1.51 ERA-Interim 1989-2009 WSPD10m slope of the annual 5th percentile (bottom), mean (middle) and 95th percentile (top) regression line. Dots indicate a significant Pearson correlation coefficient at the .95 confidence level (two-tailed).



Figure 1.52 ERA-Interim 1989-2009 total precipitation slope of the annual 5th percentile (bottom), mean (middle) and 95th percentile (top) regression line. Dots indicate a significant Pearson correlation coefficient at the .95 confidence level (two-tailed).
Seasonal Trends

Figures for seasonal trends are shown in the Appendix. Seasonal trends in MSLP are shown in Figure 1.53 to 5.57 for DJF, MAM, JJA, JAS and SON respectively. The negative trend is strongest in DJF with the strongest negative trend in 95th percentile between 10-15N and a strong positive trend in the 5th percentile over Pacific Ocean in SON. A strong positive trend (95th percentile and mean) is found in western China in MAM.

Warming on Land masses is found in all seasons (Figures 1.58-1.62 for DJF, MAM, JJA, JAS and SON respectively). A strong increase in mean, 5th and 95th percentile of temperature is found over the northern tip of Borneo in DJF and SON. There is an increase in mean, 5th and 95th percentile T2m in all seasons. Warming is pronounced on the eastern Chinese coast in DJF.

Strong positive trends are evident in mean 10m winds and 95th percentile in DJF and SON west of Sumatra and Indian Ocean in general in MAM (Figure 1.63-1.67 for DJF to SON respectively). There is a noticeable increase in wind speed maxima in JJA north of Papua. The only significant decrease in winds occurs over Pacific Ocean (mean and 95th percentile) in SON and over the ocean between Papua and Sulawesi (mean and 95th percentile) in DJF and SON.

Increasing rainfall trends surround the Equator in all seasons (Figures 1.68-1.72 DJF to SON respectively). The strongest trends occur in the minimum and maximum extremes. Strong localised positive trends are shown in the 95th percentile in all seasons with hotspots in Sumatra, Sulawesi and Papua. Local hotspots in increasing rainfall maxima are seen in Myanmar in MAM, JJA and SON. A strong decrease in the rainfall minima (5th percentile) occurs between 5 and 10N in JJA.

References

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Holm, E.V., Isaksen, L., Kallberg, P., Kohler, M., Matricardi, M., McNally, A.P.,

Monge-Sanz, B.M., Morcrette, J.J., Park, B.K., Peubey, C., de Rosnay, P., Tavolato, C., Thepaut, J.N., Vitart, F., 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society 137, 553-597.

Rienecker, M.M., M.J. Suarez, R. Gelaro, R. Todling, J. Bacmeister, E. Liu, M.G. Bosilovich, S.D. Schubert, L. Takacs, G.-K. Kim, S. Bloom, J. Chen, D. Collins, A. Conaty, A. da Silva, et al., 2011. MERRA - NASA's Modern-Era Retrospective Analysis for Research and Applications. J. Climate, 24, 3624-3648.

Saha, Suranjana, and Coauthors, 2010: The NCEP Climate Forecast System Reanalysis. Bull. Amer. Meteor. Soc., 91, 1015.1057.

Statistical significance for regression follows Chap. 10 of Tamhane and Dunlop (2000)

Tamhane, A.C. and Dunlop, D.D., 2000, Statistics and data analysis: from elementary to intermediate, London, 722p.

Part 2: CMIP 5 Model Climatology

2.1 Introduction

This section evaluates coupled climate models from the Coupled Model Intercomparison Project 5 (CMIP 5) over the SE Asia domain in relation to reanalysis data. The models used in the study are listed in Table 2.1.

Table 2.1 Models from the Coupled Model Intercomparison Project 5 (CMIP 5) used in this study

MODEL	MODELING CENTER	INSTITUTION
CCSM4	NCAR	National Center for
		Atmospheric Research
CESM1-CAM5	NSF-DOE-NCAR	National Science
		Foundation, Department
		of Energy, National
		Center for Atmospheric
		Research
CESM1-CAM5-1-	NSF-DOE-NCAR	National Science
FV2		Foundation, Department
		of Energy, National
		Center for Atmospheric
		Research
CNRM-CM5	CNRM-CERFACS	Centre National de
		Recherches
		Meteorologiques / Centre
		Europeen de Recherche et
		Formation Avancees en
		Calcul Scientifique
	39	

EC-EARTH	EC-EARTH	EC-EARTH consortium
GFDL-CM3	NOAA-GFDL	Geophysical Fluid
		Dynamics Laboratory
GISS-E2-H	NASA GISS	NASA Goddard Institute
		for Space Studies
HadCM3	МОНС	Met Office Hadley Centre
HadGEM2-CC	МОНС	Met Office Hadley Centre
IPSL-CM5A-MR	IPSL	Institut Pierre-Simon
		Laplace

Climate data for the monthly means of daily means for precipitation rates (PR) (mm/day) and nearsurface 2-metre air temperatures (2M SAT) (°C) for CMIP 5 and reanalysis data were used. The 30year historical period 1971-2000 was chosen in this study to evaluate how well models simulate the observed climate in SE Asia for these variables.

Since the datasets have different resolutions, they were re-gridded (interpolated) to the same resolution (1° x 1°) and were subset onto the SEA domain, prior to running the ensemble means. Ensemble mean and multimodel ensemble mean plots were created for the following seasons: ALL SEASONS, December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), July-August-September (JAS) and September-October-November (SON). These represented the average seasonal spatial distributions for the variables. The JAS season was included to show CMIP 5 performance in the peak monsoon season.

2.2 Temperature

Qualitatively, CMIP 5 models reproduce annual 2M temperatures patterns reasonably well (Figure 2.1). Differences between individual models are not large. Southern parts of Vietnam, the northern South China Sea and the Philippines show some variation; nevertheless this difference is small. EC-EARTH is the coolest model especially over the oceans. Overall, there is greater consensus between models for temperature compared to precipitation, consistent with many other studies.



Figure 2.1 Annual mean 2m temperature for the CMIP 5 ensemble mean (left), NCEP reanalysis (middle) and EC-Earth model.

DJF

The reanalysis plots show that 2m temperatures over the maritime section of the domain, especially over the oceans, are up to 10°C warmer than the landmass. 2m temperatures get progressively cooler towards the inner landmass section. Coastal areas (Cambodia, SW Vietnam and SW Thailand) are generally warmer due to the moderating effect of the ocean on 2m temperature. The coolest region encompasses the area to the north of 25°N (0-10°C); the northern parts of the Philippines and the South China Sea are also relatively cool (20-25°C). Islands in the maritime section receive the most effect from the oceans.

The multimodel mean plot reproduces 2m temperature patterns as shown on the reanalysis plots (Figure 2.2); however the effect of warmer 2m temperature $(25-30^{\circ}C)$ is limited to the maritime section. Individual CMIP 5 models struggle to reproduce the penetration of warmer temperatures into the S/SW coasts of the mainland section, unlike those shown on the reanalysis plots. Furthermore, the multimodel mean plot exhibits cooler temperatures than the reanalysis in the areas to the north of 25°N.

Only the models GISS-E2-H, HadCM3 and HadGEM2-CC were able to produce some, although restricted, penetration of warmer temperatures into the south coast of Vietnam (Figure 2.3). GISS-E2-H is the warmest model for the SE parts of the domain.



Figure 2.2 DJF CMIP 5 Multimodel Mean and Reanalysis temperature.



Figure 2.3 A selection of CMIP 5 DJF temperature.

MAM

Compared with DJF, MAM temperatures in the range 25-30°C penetrate further into the landmass areas, encompassing most of Thailand, Cambodia and southern parts of Vietnam and Myanmar (Figure 2.4). The inland areas of the maritime section (Sumatra, Borneo and Celebes) are up to 10°C cooler temperatures than the coastal areas. Southern China and the northern parts of Vietnam, Myanmar and Laos are relatively cooler than the maritime section, although temperatures are in general higher than those shown in the DJF.

The multimodel mean does not differ much from the reanalysis; again supporting the fact that there is considerable skill in reproducing temperatures rather than precipitation climatologies (Figure 2.4).

On a model-by-model basis, all models reproduce the southwesterly penetration of warmer temperatures into the S/SW coasts of the mainland section. However with regards to the reanalysis, the penetration produced by CMIP 5 is too weak and does not extend enough into the landmass. For example, the areas to the north of the South China Sea and northern parts of the Philippines are considerably cooler than the reanalysis.

It is also apparent in some models that a cool tongue over the SW Myanmar coast and Bay of Bengal is simulated in some models (CESM1-CAM5; CESM1-CAM5-1-FV2; EC-EARTH; GFDL-CM3; IPSL-CM5A-MR and HadGEM2-CC), a feature not evident in the reanalysis (Figure 2.5). GISS-E2-H over-simulates 2m temperature over the SE area of the domain and is too warm for the area to the west of Bangladesh (Figure 2.6).



Figure 2.4 CMIP 5 Multimodel Mean and Reanalysis MAM temperatures.





GFDL-CM3

IPSL-CM5A-MR

HadGEM2-CC

Figure 2.5 A selection of CMIP 5 models simulating the cool tongue over the SW Myanmar coast and Bay of Bengal during MAM.



GISS-E2-H

Figure 2.6 GISS-E2-H MAM temperature.

JJA and JAS

In the summer, a tongue of cool air (up to 10° cooler than the areas south of 25°N) is evident over NE Vietnam, northern parts of Laos, NE Myanmar and SW China. The (topographically controlled) coolest temperatures (5-15°C) are present over the Himalayas, Bhutan and northern India (Figure 2.7). The maritime effects which act to modulate near coastal land temperature in the boreal summer are also clear. In this season, warmer temperatures are more extensive and penetrate further north compared to previous seasons.



ALL MODELS ERA-40 NCEP

Figure 2.7: CMIP 5 Multimodel Mean and Reanalysis Plots temperature for JJA.

For JJA and JAS, the area to the west of Bangladesh is problematic in some models which appear to be much warmer than the reanalysis data (Figure 2.8).





The regions to the north of 25°N are cooler in the multimodel mean than the reanalysis. Borneo and

Malaysia are also cooler in the multimodel mean. CMIP 5 models also over-estimate 2m temperature in the regions to the west of Bangladesh.

Overall, models reproduce the warmer temperatures in summer reasonably well though some models have difficulty in Myanmar, namely: GISS-E2-H; GFDL-CM3 and EC-EARTH (Figure 2.9).



GISS-E2-H GFDL-CM3 EC-EARTH

Figure 2.9 A selection of CMIP 5 models that fail to produce sufficiently warm conditions over the land areas.

NCEP and ERA-40 differ from each other in relation to the degree and spatial extent of cooler air over the landmass during JAS (Figure 2.10). ERA-40 shows a cool tongue that extends southwards into NE Vietnam, Northern Laos and NE Myanmar. NCEP on the other hand, presents a cooler landmass overall, with only coastal regions experiencing 2m temperatures >25°C. Warm temperatures extend quite far into Cambodia and southern Thailand. NCEP also exhibits cooler temperatures over land areas in the maritime section.



Figure 2.10 Reanalysis temperature for JAS

The multimodel mean agrees reasonably well with ERA-40 for the landmass section; the multimodel mean and NCEP agree in the case of the maritime continent (Figure 2.11).



Figure 2.11 CMIP 5 Multimodel JAS temperatures

All models reproduce the cool bulge extending southwards into NE Vietnam, Northern Laos and NE Myanmar. However some models, such as CNRM-CM5, GISS-E2-H and IPSL-CM5A-MR (Figure 2.12) overestimate the 2m temperatures to the west of Bangladesh. GISS-E2-H also overestimates temperatures over northern parts of Vietnam.



Figure 2.12 Sample of CMIP 5 models with warm bias in JAS temperature

SON

During the SON season, ERA-40 and NCEP differ on the extent of cooler temperatures over the landmass such that NCEP is cooler than ERA-40. Nevertheless, the multimodel mean reproduces temperature patterns reasonably well (Figure 2.13). A notable change from JAS is that a small, cool branch protrudes southwards into west Vietnam. This is illustrated in the ERA-40 and multimodel mean plots. Whilst there is a broad consensus amongst models, there are still some notable differences in relation to temperature over parts of Vietnam, Cambodia and Thailand. In addition the models HadCM3, IPSL-CM5A-MR and HadGEM2-CC overestimate temperatures over Sumatra, Borneo and Malaysia (Figure 2.14).



Figure 2.13 CMIP 5 Multimodel Mean and Reanalysis temperatures for SON



HadCM3

IPSL-CM5A-MR

HadGEM2-CC

Figure 2.14 Models over-estimating temperatures over Sumatra, Borneo and Malaysia.

2.3 Precipitation

All Seasons

The annual multimodel mean agrees in general with the reanalysis, although the areas to the east of 100°E are too wet and interiors of northern Thailand, Laos and Vietnam are too dry, in comparison with reanalysis. Models also differ on the precipitation patterns over the southeastern areas of the mainland regions (Figure 2.15).



Figure 2.15 CMIP 5 Multimodel Mean and Reanalysis annual mean precipitation

DJF

The multimodel mean reproduces the general precipitation patterns for DJF. There is some agreement between the models and reanalysis, such that highest precipitation occurs in a band covering the maritime continent (Indonesia, Malaysia and the Philippines). This precipitation band extends from approximately 10°N to 10°S during boreal winter (DJF). The domain is relatively drier (0-4mm/day) to the north of 10°N (Figure 2.16).



Figure 2.16 DJF Multimodel Mean and Reanalysis.

MAM

ERA-Interim shows higher precipitation over northern Myanmar compared to the other reanalysis plots. The reanalysis produces >2mm/day over the SE section of the landmass (Vietnam, Cambodia, Thailand, Laos, SE coast of Myanmar and southern China), especially in ERA-Interim.

On the whole, the multimodel mean agrees reasonably with the reanalysis (Figure 2.17). The multimodel mean reproduces the precipitation centre over northern Myanmar and Bhutan as shown in the reanalysis (ERA-Interim). Precipitation is also reproduced well over parts of eastern China and over Indonesia. However, CMIP 5 models are dry in comparison with reanalysis over Vietnam, Cambodia and Thailand.

Overall, there is little disagreement on the location of the precipitation band over the maritime continent. However, individual CMIP models show some disagreement on the precipitation

intensity within the maritime continent and also over northern Myanmar and Bhutan.



Figure 2.17 MAM CMIP 5 Multimodel Mean and Reanalysis precipitation.

JJA

According to Figure 2.18, the reanalysis shows high precipitation over the Bay of Bengal. Precipitation is highest over Myanmar and Bhutan (> 12-20mm/day) and northern parts of Laos, Vietnam and the SW coasts of Cambodia, Vietnam and Thailand. Rainfall of up to 12-16mm/day is evident over the northern Philippines. The landmass interiors, especially southern China, Myanmar, Thailand and Cambodia, are relatively dry in comparison to the SW/W coasts.



Figure 2.18 JJA CMIP 5 Multimodel Mean and Reanalysis precipitation.

The multimodel mean reproduces these patterns sufficiently, particularly for the Bay of Bengal

region, northern India and Myanmar. It also reproduces the precipitation maxima in the SW of the domain. The multimodel mean underestimates precipitation over Vietnam, Laos and Cambodia and over the SW coasts. The precipitation band over the South China Sea and the northern Philippines, as evident in the reanalysis, does not appear to be reproduced at all in the multimodel mean. SE China is also too dry.

Individual CMIP 5 models differ substantially in intensity and spatial distribution of precipitation. Some models (GISS-E2-H, CESM1-CAM5-1-FV2, CESM1-CAM5 and CCSM4), overestimate precipitation over Bhutan and north Myanmar, reaching >32mm/day. Myanmar exhibits high variability in precipitation between different models, particularly the west coasts, northern and southern parts of the region. The South China Sea, areas surrounding the Philippines and oceans over Indonesia are also problematic (Figure 2.19).



GISS-E2-H

CESM1-CAM5-1-FV2

CESM1-CAM5



CCSM4

Figure 2.19 JJA mean precipitation for a sample of CMI 5 models.

JAS

The reanalysis illustrates that the highest precipitation in JAS is concentrated around the S/SW Myanmar coast. For ERA-Interim, the region of highest precipitation is more extensive and covers most of Bhutan and Myanmar, reaching up to 24-28mm/day in some areas of northern Bhutan. A band of precipitation encompasses the SE section of the landmass, the South China Sea and northern Philippines. The SW coasts of Thailand, Cambodia and Vietnam are also wet. The interiors of southern China are relatively dry.

The multimodel mean simulates the overall pattern reasonably well; but fails to reproduce enough precipitation over the SE areas of the landmass section (Figure 2.20). Precipitation over Vietnam, Thailand, Laos and Cambodia are underestimated, with modest amounts over the seas surrounding the Philippines. Precipitation is overestimated for the SW coasts and north of 25°N.



Figure 2.20 JAS CMIP 5 Multimodel Mean and Reanalysis precipitation.

In general there is poor consensus amongst CMIP 5 models in relation to spatial patterns and intensities of rainfall. Models struggle to reproduce precipitation patterns over Myanmar and areas north of 20°N. CMIP 5 models, especially CESM1-CAM5; EC-EARTH and GISS-E2-H, fail to reproduce the band of precipitation (shown in the reanalysis) over the Philippines, South China Sea and parts of Vietnam, Cambodia, Laos and Thailand (Figure 2.21).



CESM1-CAM5

EC-EARTH

GISS-E2-H



HadCM3

Figure 2.21 A selection of CMIP 5 JAS model simulations (JAS).

JAS is a problematic season for CMIP 5, especially in representing detailed Asian Monsoon precipitation patterns.

SON

Reanalysis plots exhibit a strong precipitation band located in a southerly position to encompass 20°N - 10°S. Highest precipitation is shown for the eastern coast of Vietnam and also, the SW coasts of Cambodia and Thailand (CMAP and ERA-Interim). In NCEP, this zone of high precipitation encompasses more of the SE areas of the landmass, covering most of Cambodia and southern parts of Vietnam and Thailand. Interiors are relatively dry – although for ERA-Interim, some parts of northern Myanmar are still relatively wet (Figure 2.22).



Figure 2.22 SON CMAP and reanalysis precipitation.

The multimodel mean successfully reproduces the southward migration of the precipitation band from the JJA and JAS seasons and situates the band between 20°N - 10°S. It however fails to reduce enough precipitation over northern Myanmar from the previous seasons (Figure 2.23).



Figure 2.23 SON CMIP 5 Multimodel Mean precipitation

On a model-by-model basis, there is consensus over the general location and extent of this precipitation band. The southward shift of the band due to seasonal cycle, as shown in the reanalysis, is well represented by all models. However models disagree on precipitation intensity and also, the amount east of 100°E, north of 25°N and over western coasts of the landmass. CCSM4, CESM1-CAM5, CESM1-CAM5-1-FV2, GISS-E2-H and HadGEM2-CC, are too wet (Figure 2.24).



GISS-E2-H

HadGEM2-CC

Figure 2.24 Examples of wet models in SON

Part 3 Crops and climate change

3.1 Introduction

This part of the report will examine potential changes to climate and implications for agriculture for key crops over the domain comprising the countries of Myanmar, Laos, Thailand, Cambodia, Vietnam, Malaysia, Philippines and Indonesia and covering the region of 85°E to 155°E, 25°S to 30°N.

Key agricultural crops for the South-East Asian region are examined. Current spatial distribution of crops will be mapped and climatic thresholds and limits for optimal cultivation will be explored. Crop-climate suitability maps for each crop are established on a reanalysis dataset in order to evaluate the magnitude of model error over South-East Asia, in relation to the simulation of crop-climate regions under control conditions. Climate change projections for South-East Asia in the CMIP 5 model subset for three 'time slices' of the twenty-first century; the 2030s, 2050s and 2090s under the RCP4.5 emissions scenario are examined. Potential regions of growth of our selected crops under climate change projections for the domain will be analysed and discussed. The climatic thresholds and limits established for each crop will be again applied to the model output, this time during the twenty-first century in order to establish the potential risks to food security in East Africa under anthropogenic climate change.

3.2. Key food crops of South-East Asia

This study focuses on a number of key food crops to the South-East Asian region, which are introduced in this section. The optimum and absolute climate thresholds for cultivation of the selected crops will be examined alongside the current distribution of production over the South-East Asian domain. This process will identify areas of growth for each crop which are already climatically marginal in terms of the feasibility of cultivation and therefore where a changing climate could induce food security concerns. Moreover, by creating crop-climate maps for the suitability of production and comparing it to current regions of growth it also has the potential to identify regions where the potential crop production is not currently being realised. The benefits of this are twofold. First, it could highlight non-climatic factors acting as a barrier to cultivation (in cases where climate conditions appear optimal but production is not occurring) and second, it may identify regions of potential expansion for crop cultivation, which may be necessary as climate changes in future decades.

3.2.1 Crop selection

With the study region diverse, comprising of Myanmar, Laos, Thailand, Cambodia, Vietnam, Malaysia, Philippines and Indonesia, it was necessary to use three markers to select a number of crops to study. These were the value of the crops over the eight focus counties, the number of the countries of interest in which they are grown and the importance from a food security perspective. Table 3.1 shows the selected crops, their total value to South-East Asia (internationally standardised prices), and the number of the countries in the domain where the crop is grown.

Table 3.1 Selected crops for study, the number of countries they are grown in and their total value to the eight South-East Asian countries of this study.

Сгор	No. Countries Grown In (parentheses = where in top 25 commodities by value)	Value (in \$1000s)
Paddy Rice	8 (8)	53958427
Palm Oil	4 (3)	18262823
Natural Rubber	7 (7)	9770212
Cassava	8 (6)	6521795
Sugar Cane	8 (8)	5906583
Bananas	7 (7)	5205800
Mangoes, Mangosteens,	7 (6)	4159140
Guava		
Coconuts	7 (5)	3910767
Maize	8 (4)	2242308
Green Coffee	8 (5)	2120407

3.2.2 Climatic crop growth thresholds

A review of grey literature was undertaken for each of the selected crops to examine the ideal, and tolerated, growing conditions for the selected crops in South-East Asia. Climate variables under consideration include optimal average temperatures, maximum and minimum temperatures, optimal average rainfall, maximum and minimum rainfall averages, if the crop has the capacity to deal with waterlogging or drought, length of growing period and growing altitude, photo sensitivity, harvesting period and any specific characteristics unique to a particular crop.

Key climate thresholds are shown in Table 3.2. These thresholds are employed to create masks depicting the climatic geographical limits of cultivation for each crop within South-East Asia. Specifically, each threshold variable (for example, the optimal temperature range) is taken in turn with the limits applied to the ERA-Interim reanalysis data to create a mask over the domain for each individual crop. The mask can take two possible values; zero when the threshold is not met and one when it is. The area shaded in the colour corresponding to values of one depicts the region for

which the conditions are suitable for growth of the crop in question for the variables under examination. This process is repeated for each climatic variable for the crop and the resulting maps layered over one another to result in a single map showing the suitability of growing conditions for each crop. Regions of the domain with higher values correspond with more suitable growing conditions. However, in the case of a key absolute threshold (such as minimum annual precipitation), areas outside of the appropriate rainfall range indicate conditions that are unsuitable for crop cultivation irrespective of whether all the other conditions are met. In this case the region with insufficient rainfall will cause a mask of zero to be co-located with it, to take this absolute limit of cultivation into account.

CROP	Optim	Max	Min	Optimal	Max	Min Avg	Capacity to	Capacity to	Growi	Altitude	Photo-
	al Avg	Temp	Tem	Avg Rainfall	Avg	Rainfall	deal with	deal with	ng		sensitivity
	Temp		р		Rainfall		waterlogging/	drought?	period		
Paddy	21-	35		1500		1200 for	Yes, up to 6	No			
Rice						one crop	days				
Palm Oil	25-28	33 av	22av	2000	5000	1800	Occasional	2-4 months		<500m	>2000
								<100m			sunshine
								month			hours/year
Natural	25-28	34	22 av	2500, no dry							200
Rubber			20	season							hours/year
Cassava	22-28	<30av	10	1000-4000	5000	500	No	Yes, up to 2-	365	<1500m	<13h light
		for 8m						3 months			
Sugar	22-30	38	20	1500-2000		600				<1600m	
Cane											
Bananas	21-30	38	16	2000-2500		1200		No	365		
	(27 opt)										
Mangoes,	24-29	38	12	1270	3750	750	Occasional	Yes		< 1200m	
Mangoste										(600m	
en,										commerc	
Guava										ial)	
Coconuts	22-27	38	12,	1500-2500		1000		No		<600m,	
			21 av							+close to	
										equator	
Maize	25-30	40 av		700-1100		500 (300	No	Not in	100-120	<1500m	
			10,20			if grow		pollination			
			(av)			season)		or later			
								growth			
Green	24-30	32	15	1200-1500	3000					<800m	
Coffee	robusta			arabica						robusta	
	20-24									>1000m	
	arabica									arabica	

Table 3.2 Key climate thresholds for growth of selected crops over South-East Asia

The following masks are created for each of the ten selected South-East Asian crops.

- 1. Absolute rainfall range
- 2. Optimum rainfall range
- 3. Optimal temperature range
- 4. Optimal maximum temperature
- 5. Average minimum temperature

These five masks are then combined for each individual crop over the domain, with a score of five showing optimal climatic conditions for crop cultivation and a score of zero showing unsuitable conditions for cultivation, either because none of the conditions were satisfied or because the absolute rainfall range was not met.

3.2.3 Results

Figure 3.1 shows the FAO crop growth maps as an indication of where each of the ten selected crops is currently being grown as a comparison for the crop-climate maps of suitable conditions of cultivation. Figures 3.2 to 3.11 show climatically optimal regions for growth through the layered mask for each of the selected crops over South-East Asia in the ERA-Interim dataset for the time period 1980 to 2010. Regions for each individual threshold (Figures 3.12 to 3.21) can be seen in the Appendix.



Rice, paddy



Natural Rubber



Palm Oil



Cassava



Sugar Cane



Mangoes, Mangosteens, Guavas



Maize



Bananas



Coconuts



Coffee, green

Figure 3.1 FAO crop growth maps, highlighting cultivation of each selected crop in South-East Asia

Paddy Rice

Paddy rice is grown in each of the eight focus countries and is the crop with the greatest value to South-East Asia, totalling 53,958,427 thousand US dollars. The crop-climate suitability map indicates that whilst there are no areas of the domain which are not suitable for growing rice, areas with the highest suitability score of five are relatively scarce. Optimal conditions for rice cultivation are found over Vietnam, Laos, Cambodia and parts of Thailand. The remainder of the focus countries (Myanmar, Malaysia, Indonesia and the Philippines) have adequate, though not optimal rainfall values for rice cultivation. This could go some way to explaining why 45% of the rice production is South-East Asia is irrigated, with the remainder rain fed.

Palm Oil

Palm oil is the second most important crop to South-East Asia by value, but it is only cultivated in four of the eight focus countries; Malaysia, Thailand, Indonesia and the Philippines. The ERA-Interim cop-climate suitability map indicates that again, it is optimal rainfall values that limit the suitability of parts of South-East Asia to cultivate palm oil. Optimal conditions for palm production are found in parts of Malaysia and western Indonesia. Additionally, although palm oil is not currently in production in Cambodia, this country is the other part of South-East Asia with optimal climate conditions in the ERA-Interim dataset and equally, suitable conditions are found over much of the region. This suggests that there is the potential to expand palm oil production in South-East Asia, in particular at low altitudes. This is not a short term strategy, however, with the oil palm not producing fruit until three to four years after planting.

Natural rubber

Natural rubber is currently in production in all of the focus countries of South-East Asia with the exception of Laos. This is reinforced by the crop-climate map which shows optimal conditions for the production of natural rubber across South-East Asia with the exception of Laos and parts of Vietnam. The limiting factors in these countries are optimal rainfall and temperature. For the remainder of the focus counties, the climate is especially suitable for the production of natural rubber, meeting the thresholds in all five climate variables.

Cassava

Cassava, a staple root crop in many tropical and subtropical countries, is grown in all eight of the South-East Asian focus countries and ranks in the top twenty-five commodities by value in all except Myanmar and Malaysia. The ERA-Interim crop-climate map for cassava shows optimal climate conditions for the cultivation of this crop across the whole of the domain.

Sugar cane

Sugar cane is cultivated across all eight South-East Asian countries and also ranks in the top twenty-five commodities by value for each country. Despite the similarities to cassava cultivation in terms of growth and value to South-East Asia, the crop-climate map calculated on the ERA-Interim data shows a different picture. Regions with optimal climatic conditions are limited to Laos, Vietnam, Cambodia and parts of Thailand. Malaysia, Indonesia, Myanmar and the Philippines show sub-optimal conditions for sugar cane cultivation. Indeed, western Indonesia show conditions unsuitable for sugar cane production due to rainfall in the ERA-Interim dataset that is outside of the absolute rainfall thresholds for this crop. Equally, for the rest of Indonesia, Malaysia, the Philippines and Myanmar also have rainfall as the limiting factor on cultivation; whilst rainfall totals are within the absolute necessary thresholds they are not within optimal totals.

Banana

Bananas are grown in all of the focus countries with the exception of Myanmar. For all countries in which bananas are cultivated they rank within the top twenty-five commodities by value. The cropclimate map shows conditions suitable for the growth of bananas across the domain. Many regions show optimal conditions by all markers. This region is located down the centre of the domain on a north-west to south-east diagonal and encompasses Malaysia and central Indonesia. The remainder of the countries where bananas are grown see potential slightly limited by rainfall; absolute rainfall thresholds are met, but not optimal. On the other hand, Myanmar sees optimal climate conditions for bananas cultivation under present conditions in the ERA-Interim dataset, indicating a possible diversification opportunity.

Mangoes, mangosteens and guava

As with bananas, mangoes, mangosteens and guavas are cultivated in all of the South-East Asian focus countries with the exception of Myanmar. They rank in the top twenty-five commodities by value in all of these countries except Laos. The whole of the South-East Asian domain has a climate suitable for the cultivation of mangoes, mangosteens and guavas with a crop-climate suitability mask score of four across the focus countries. This signals the opportunity for potential crop diversification in Myanmar. None of the region has the highest crop-climate suitability mask score of five. This is due to the optimal rainfall threshold not being met anywhere in South-East Asia, although the necessary absolute rainfall thresholds are met.

Coconut

Coconuts are cultivated in all the focus countries of South-East Asia except Laos. Conditions are

optimal for the growth of coconuts in much of South-East Asia in the ERA-Interim dataset and there would be the potential to grow them in Laos, particularly in the south of the country. The country with least optimal conditions for coconut growth is the Philippines, where rainfall within the absolute (but outside the optimal) thresholds limits the potential for cultivation slightly.

Maize

Maize is grown in all of the focus countries of South-East Asia, but only ranks within the top twenty-five commodities by value for four of these countries; Laos, Cambodia, the Philippines and Indonesia. The crop-climate suitability map gives some indication as to why this is the case. None of the focus countries have optimal climate conditions, with the majority of the region having a suitability value of four. This is due to rainfall being outside of the optimal values for maize productivity across South-East Asia. Parts of the region also have lower suitability for maize cultivation due to mean temperature values outside of the optimal range. These areas are the northern areas of Laos, Myanmar and Vietnam and also parts of Indonesia.

Green coffee

Green coffee, largely of the Robusta variety, is grown in all eight of the focus countries and ranks in the top twenty-five commodities by value in Laos, Thailand, Vietnam, the Philippines and Indonesia. The ERA-Interim crop-climate suitability map shows optimal climate conditions for the cultivation of coffee over all of the focus countries with the exception of the east and west most regions of Indonesia. Even here, conditions are suitable for the cultivation of coffee, just with rainfall totals that are within the absolute rather than optimal limits.

With the exception of palm oil, the remainder of the key crops are grown across the majority of the eight focus countries and climate conditions are often optimal in the ERA-Interim dataset. Where conditions for cultivation are slightly compromised, the key threshold causing this is the optimal rainfall. Whilst the absolute rainfall bounds are suitable for cultivation in all cases, optimal rainfall totals are not always present. This could both impact of yield under current climate conditions and also make the cultivation of crops sensitive to rainfall particularly vulnerable to anthropogenic climate change at the end of the twenty-first century. This indicates that particular attention needs to be given to rainfall in the examination of projected changes to climate over South-East Asia under increasing greenhouse gases and that this could have more impact on potential crop growth than changing temperatures.



Figure 3.2 Era-Interim derived paddy rice crop growth area, 1980-2010.



Figure 3.3 Era-Interim derived palm oil crop growth area, 1980-2010.



Figure 3.4 Era-Interim derived natural rubber crop growth area, 1980-2010



cassava erai climatic growth area

Figure 3.5 Era-Interim derived cassava crop growth area, 1980-2010



Figure 3.6 Era-Interim derived sugar cane crop growth area, 1980-2010



Figure 3.7 Era-Interim derived banana crop growth area, 1980-2010



Figure 3.8 Era-Interim derived mango, mangosteen and guava crop growth area, 1980-2010



Figure 3.9 Era-Interim derived coconut crop growth area, 1980-2010



Figure 3.10 Era-Interim derived maize crop growth area, 1980-2010



Figure 3.11 Era-Interim derived green coffee crop growth area, 1980-2010

3.3. Climate models and the South-East Asian climate

Coupled climate models are the main tool utilised for examining future climate projections, and similarities between observed climate and model values are necessary, but not sufficient, for confidence in future projections (Caminade and Terray, 2010). In recent years significant improvements have been made to GCMs, with the evolution from purely atmospheric models to those including oceans, land surface processes, ocean-ice interactions and many parameterisations of sub grid scale processes simulate future climate (Herrera et al, 2006). However, weaknesses still remain and models are able to represent the complex South-East Asian climate with varying degrees of success. This study follows a method common in climate science; to use an ensemble of multiple models alongside looking at the individual model results. The aim is that by combining models with varying parameterisations, the averaging process will retain robust responses, whilst cancelling out differences between models that have no physical basis (Giannini et al, 2008).

Nonetheless, the use of models is vital to evaluate potential anthropogenically induced changes to the South-East Asian climate and how these may impact on crop cultivation. The first stage in this process is to examine the extent to which a subset of coupled climate models from the CMIP 5 project can reproduce the current climate of South-East Asia.

3.3.1 Model selection

A subset of Climate Model Intercomparison Project 5 (CMIP 5) coupled climate models were used in this section. These models also form the basis for the work of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, released in 2013. The models were selected based on the availability of data in all three time slices (2030s, 2050s and 2090s); seven models were initially selected and an ensemble mean of these seven models was also created. Details of the selected models are shown in Table 3.3. Table 3.3 Details of the CMIP 5 models selected for this study.

Modelling Group	Model Designation			
NCAR/UCAR Community Earth System Model	CESM1-BGC			
Center of National Weather Research	CNRM-CM5			
European Centre for Medium Range Weather Forecasting	EC-EARTH			
U.S. Dept. Of Commerce/NOAAb/ Geophysical Fluid Dynamics Laboratory	GFDL-CM3			
Goddard Institute for Space Studies, NASA	GISS-E2-R			
UK Meteorological Office	HadGEM2-CC			
Institut Pierre Simon Laplace Climate Modelling Group	IPSL-CM5A-LR			

3.4 Model derived crop-climate growth areas

The same approach as outlined in Section 3.2 was utilised to examine the realisation of crop-climate suitability regions for each crop in each of the selected CMIP 5 models and the ensemble during the control period (1980-2005). This allows for the identification of regions of model weakness in simulating accurate crop-climate suitability masks, in comparison with the ERA-Interim dataset. Figures 3.22 to 3.31 show the crop-climate suitability maps for each crop for the ensemble series.


Figure 3.22 Model-ensemble derived paddy rice crop growth area, 1980-2005



Figure 3.23 Model-ensemble derived palm oil crop growth area, 1980-2005



Figure 3.24 Model-ensemble derived natural rubber crop growth area, 1980-2005



Figure 3.25 Model-ensemble derived cassava crop growth area, 1980-2005



Figure 3.26 Model-ensemble derived sugar cane crop growth area, 1980-2005



Figure 3.27 Model-ensemble derived banana crop growth area, 1980-2005



Figure 3.28 Model-ensemble derived mango, mangosteen and guava crop growth area, 1980-2005



Figure 3.29 Model-ensemble derived coconut crop growth area, 1980-2005



Figure 3.30 Model-ensemble derived maize crop growth area, 1980-2005



Figure 3.31 Model-ensemble derived green coffee crop growth area, 1980-2005

Paddy rice

For rice, the ensemble derived crop-climate suitability map is qualitatively very similar to the ERA-Interim derived map. The optimal regions for rice cultivation are located in the same place; in a band to the south of the domain, across southern Indonesia, and over much of Vietnam, Laos and Cambodia. In terms of the individual models, they also show good representations of the suitability of climate for the cultivation of rice in South-East Asia. The weakest model is HadGEM, which depicts areas of the Philippines as being unsuitable for rice cultivation (due to rainfall totals) and also has areas of optimal growth located through Thailand and Malaysia, where ERA-Interim and the other models have a suitability score of four, not five.

Palm oil

Again, the model ensemble shows a good replication of the crop-climate map for the cultivation of oil palms in South-East Asia. This is particularly the case over the land regions of the eight focus countries, where the optimality of conditions is matched to the ERA-Interim map. The primary difference in suggested crop-climate suitability lies in the South China Sea and so does not impact on the depiction of growing conditions over a landmass. The individual models again show a good approximation to the ERA-Interim crop-climate suitability maps, in particular over the land regions. The greatest differences are found in CESM, in particular over parts of Indonesia, where conditions are not shown to be as optimal as in ERA-Interim.

Natural rubber

Once more, the seven model ensemble reproduces the ERA-Interim crop-climate suitability map well. Optimal regions of cultivation are co-located with the countries of South-East Asia, with one important difference. The ensemble shows Myanmar as being unsuitable for the cultivation of natural rubber due to the bounds of absolute precipitation. Given that natural rubber is cultivated in Myanmar, this is an inaccuracy for the ensemble for this crop-climate map. This is a weakness that is present throughout the individual models, although the depiction of crop-climate suitability across the remainder of the domain is generally qualitatively good.

Cassava

In ERA-Interim, the whole of South-East Asia showed optimal conditions for the cultivation of Cassava. The same pattern is seen in the ensemble and all of the individual models, with the exception of GISS. GISS, in places, does not replicate the optimum conditions due to a bias in temperature over parts of central South-East Asia.

Sugar cane

The crop-climate map for sugar cane shows a relatively weak depiction of the ERA-Interim cropclimate map during the control period. The main weakness of the ensemble is the representation of the central band of South-East Asia as unsuitable for the cultivation of sugar cane due to the absolute rainfall thresholds. This affects parts of Malaysia, Indonesia and the Philippines. To the north and south of this region the regions of optimal climate conditions for sugar cane cultivation are well depicted, including Vietnam, Cambodia and Laos. Some of the individual models do manage to depict suitable conditions for the cultivation of sugar cane over Malaysia including EC, HadGEM and CNRM.

Banana

For banana cultivation, the crop-climate ensemble map shows a good representation of optimal growing conditions in comparison to the ERA-Interim map. Whilst the regions of crop-climate suitability scoring five are not co-located in all cases with those in the ERA-Interim map, all countries with suitable growing conditions for bananas (suitability score of four or five) are the same and the spatial pattern of optimal suitability is also qualitatively similar. On the whole, individual models can also replicate the crop-climate suitability of South-East Asia for banana cultivation. The primary weakness is found over Myanmar, where the EC, HadGEM and IPSL models show an unsuitable climate for bananas. However, bananas are not currently cultivated in Myanmar and so this could be an instance where the ERA-Interim dataset and the models show differences which are challenging to unravel.

Mangoes, mangosteens and guavas

As with the other key crops of South-East Asia, the ensemble crop-climate suitability map is qualitatively similar to that of ERA-Interim. All of the focus countries have suitable conditions for the cultivation of this fruit. The individual models also show a good representation of optimal climate conditions for mango cultivation, with two exceptions; GISS and IPSL. Both of these models have rainfall outside of absolute thresholds over regions of Malaysia and Indonesia, with GISS also having this issue over the Philippines, meaning that these two models fail to match the ERA-Interim crop-climate map for mango cultivation suitability in these regions.

Coconut

On the whole, the ensemble successfully replicates the optimal crop-climate suitability across South-East Asia. Small differences are found Malaysia and Indonesia. These differences are found to originate in three of the individual models; EC, GISS and IPSL. In these models, there are regions of Malaysia and Indonesia with rainfall values outside of the absolute threshold for the growth of the coconuts, which impacts on the ensemble as well.

Maize

The crop-climate suitability map for maize shows close qualitative similarity between the model ensemble and ERA-interim. All of the focus countries show the same level of optimal conditions for the cultivation of maize between the two datasets. The individual models also show very similar levels of crop-climate suitability for maize cultivation. The one exception is the EC model, where conditions, while not unsuitable, are less optimal through the central part of the domain than in other depictions of crop-climate suitability.

Green coffee

As with other commodities, the ensemble mean replicates the optimal growing regions for green coffee well. Spatial patterns and crop-climate suitability scores are co-located across South-East Asia when the ensemble map is compared to the ERA-Interim map for the control period. Individual models also simulate the crop-climate suitability regions well with minimal exceptions. One exception is found to the north of the domain in HadGEM, where there are regions depicted as unsuitable for coffee cultivation over northern Thailand, Myanmar, Laos, Vietnam and the Philippines. Whilst these regions are less suitable in many of the models and ERA-Interim in comparison to further south in the domain, this model has the weakest representation of crop-climate suitability in this area.

To conclude, the models and, in particular, the ensemble mean, show representations of cropclimate suitability regions that are akin to those depicted in the ERA-interim dataset. It is important to note, however, that whilst these plots form the basis to establish whether a region is suitable to cultivate a particular crop, they are based on mean climatological thresholds and climatic extremes such as drought or heavy precipitation events can impact negatively on yields and must also be considered as to the true suitability of a region for the cultivation of any particular crop.

3.5 Model climate projections for the twenty-first century

3.5.1 Previous studies over South-East Asia

The IPCC Fifth Assessment report, released in 2013, suggests that temperatures over South-East Asia will increase under a climate change scenario. This projection is defined as *very likely*, although it is expected that considerable variation in the rate of warming within South-East Asia will occur (Christensen and Kanikicharla et al, 2013). In terms of rainfall projections under

increasing greenhouse gas emissions, the sign and magnitude of change is more uncertain. The best estimate of the IPCC is that, alongside strong regional variation, there is *medium confidence* in a moderate increase in annual rainfall (excluding Indonesian islands bordering the Southeast Indian Ocean) (Christensen and Kanikicharla et al, 2013). Both the IPCC AR4 (2007) and AR5 (2013), note that potential changes to tropical cyclone characteristics will impact on South-East Asia, specifically over the northern countries of the domain. However, modelling of cyclones is uncertain although the IPCC AR5 suggests that it is *likely* that occurrence of tropical cyclones will either remain stable or decrease. However, within these cyclones it is *likely* that maximum wind speeds and rainfall rates will increase (Christensen and Kanikicharla et al, 2013).

Individual studies also provide more information about potential changes to climate over South-East Asia under increasing greenhouse gas emissions. Chotamonsak et al (2011) use a WRF regional climate model to project greater temperature increases over the region during night than day, for all seasons. For rainfall, the model had less success in simulating present-day conditions, but the projection is for increased rainfall overall, with some local exceptions during the dry season.

Rainfall in Indonesia has a clear association with the Indian Ocean Dipole (IOD), with positive events being associated with droughts in Indonesia. It has been suggested that, relative to recent decades, a warming climate could lead to a higher incidence of positive IOD events (Cai et al, 2013). Through this association, it has been hypothesised that rainfall in Indonesia could decrease (Christensen and Kanikicharla et al, 2013).

3.5.2 Model Projections

This study employs the RCP (Representative Concentration Pathway) 4.5 emissions scenario. This scenario is a radiative forcing scenario, was one of those used in the CMIP 5 modelling runs and represents reaching stabilisation (without overshoot) at 4.5W/m² at 2100. Three time slices are used; the 2030s (2030-2039 inclusive), the 2050s (2050-2059 inclusive) and the 2090s (2090-2099 inclusive). It is expected, in the case of robust models, that changes under anthropogenic forcing will increase in magnitude over time.

3.5.2.1 Temperature

Figure 3.32 shows the mean temperature anomalies for the model ensemble for the three time slices relative to the climatology period (1980-2005). As expected, mean temperature in South-East Asia are projected to increase across the domain throughout the twenty-first century under the RCP4.5, with the greatest projected increases present in the 2090s and no projected annual temperature decreases anywhere in South-East Asia. However, the projected increases are not uniform across

the domain. Greatest projected increases are seen to the north and south of the domain outside of the focus countries, over China and Australia respectively. Here projected mean temperature increases measure 2.6°C to 3.0°C per day by the 2090s. Over the focus countries the greatest projected temperature increases are also present during the 2090s. For the focus countries, the projected increases generally measure between 1.8°C and 2.2°C. Two exceptions are the Philippines and eastern Indonesia, where projected temperature increases measure from 1.6°C to 1.8°C by the 2090s.



GrADS: COLA/IGES





Figure 3.32 Ensemble mean temperature anomalies over South-East Asia for the 2030s, 2050s and 2090s relative to 1980-2005 under the RCP 4.5 scenario.

3.5.2.2. Precipitation

Figure 3.33 shows the projected precipitation anomalies over South-East Asia for the 2030s, 2050s and 2090s. Projected precipitation changes over South-East Asia are less clear cut than those for temperature, with both projected increases and decreases over parts of the domain. One key difference is that in the model ensemble changes to precipitation are relatively muted, measuring between -0.5mm and 1.5mm/day over all time slices. The only pattern to emerge is for a slight projected decrease in daily mean precipitation to the west of the domain, with the opposite occurring in the east and very little change over the focus countries.





Figure 3.33 Ensemble mean rainfall anomalies over South-East Asia for the 2030s, 2050s and 2090s relative to 1980-2005 under the RCP 4.5 scenario.

3.6 Future climate scenarios and crop growth in South-East Asia

Applying the same approach as in previous crop-climate suitability sections, the temperature and rainfall threshold masks are used to examine crop-climate suitability under the RCP4.5 scenario. Masks are created for each of the selected CMIP 5 models and the model ensemble for each of three time slices (2030S, 2050S and 2090s). The same ten crops as previously examined as investigated, to recap these are paddy rice, palm oil, natural rubber, cassava, sugar cane, banana, mango (and mangosteens/guavas), coconut, maize and green coffee.

Due to some model bias, the thresholds for the twenty-first century time slices are created using the ERA-Interim crop-climate suitability thresholds as a base. First, anomalies for each individual model and the model ensemble for each of the three time slices are created using the climatology period (1980-2005) for the respective model as a base. Second, these anomalies are added on to the climatology values for ERA-Interim. This mitigates climatology period model bias and thus provides a more robust assessment of potential changes to crop-climate suitability regions across South-East Asia. The same thresholds for the limits of growth of each individual crop as used during the climatology period are employed in this section. Although there is the possibility that technological development in crop modification will allow crops to be grown under different conditions, the assumption in this work is that this is not the case.

Figure 3.34 to 3.43 show the crop-climate suitability maps for the ensemble mean for the 2030s, 2050s and 2090s for each of the ten crops.



rice ensemble 90s growth area



Figure 3.34 Model-ensemble derived paddy rice crop growth areas, 2030s, 2050s and 2090s





Figure 3.35 Model-ensemble derived palm oil crop growth areas, 2030s, 2050s and 2090s



rubber ensemble 90s growth area 250 201 15N 10N 5N ΕQ· 55 105-15S 205 140E 145E 150E 155E 8ŚE 9ÚE 95E 100E 106E 110E 115E 120E 126E 130E 135E GrADS: COLA/IDES 2014-01-16-18:38

Figure 3.36 Model-ensemble derived natural rubber crop growth areas, 2030s, 2050s and 2090s



grads: cola/iges

Figure 3.37 Model-ensemble derived cassava crop growth areas, 2030s, 2050s and 2090s

2014-01-16-18:38





Figure 3.38 Model-ensemble derived sugar cane crop growth areas, 2030s, 2050s and 2090s





Figure 3.39 Model-ensemble derived banana crop growth areas, 2030s, 2050s and 2090s







Figure 3.40 Model-ensemble derived mango, mangosteen and guava crop growth areas, 2030s, 2050s and 2090s





Figure 3.41 Model-ensemble derived coconut crop growth areas, 2030s, 2050s and 2090s







Figure 3.42 Model-ensemble derived maize crop growth areas, 2030s, 2050s and 2090s



Figure 3.43 Model-ensemble derived green coffee crop growth areas, 2030s, 2050s and 2090s

Paddy rice

For paddy rice, the crop-climate suitability region remains relatively constant under the RCP4.5 climate change scenario. The main projected change is found over Myanmar and northern Thailand. Under control conditions, these regions did not show suitability to cultivate paddy rice due to rainfall outside the absolute required threshold. Under projected climate change, these regions are no longer outside of the required threshold for rainfall and now show conditions that have a crop-climate suitability score of four to five. This represents a possible new opportunity for paddy rice cultivation under climate change in South-East Asia. Over the remainder of the focus countries, suitability for rice cultivation does not show any changes, with cultivation projected to remain possible.

Palm oil

Unlike for paddy rice, where climate change is projected to have a positive impact on cultivation, for palm oil, projected climate changes under the RCP4.5 scenario is for a negative impact on cropclimate suitability. Regions of optimal crop-climate suitability have contracted to some extent, with the greatest impact seen across parts of the Philippines. Under control conditions, parts of the Philippines saw optimal conditions for palm oil cultivation. By the 2090s under the RCP4.5 scenario, shows a lower crop-climate cultivation score by two, implying that conditions for cultivation will be compromised. In contrast, over Myanmar and northern Thailand, opportunities for oil palm cultivation may arise.

Natural rubber

Ensemble crop-climate suitability for the cultivation of natural rubber under a climate change scenario shows some significant changes by the 2090s in comparison to the end of the twentieth century. Conditions for potential cultivation over eastern Indonesia and the Philippines are compromised in comparison to during the control period. In contrast, and in a similar manner to the previous two crops under consideration, conditions for the cultivation of natural in Myanmar and Thailand become increasingly optimal.

Cassava

Under control conditions, there were optimal conditions for cassava cultivation across South-East Asia in the ensemble. Under the RCP4.5 scenario, also for ensemble, this is no longer the case, with large parts of the domain showing slightly less optimal conditions for cassava growth. However, all of the eight focus countries, with the exception of the central parts of the Philippines, continue to show optimal conditions for the cultivation of cassava by the 2090s, with the main changes located over ocean locations across the domain.

Sugar cane

For the ensemble under control conditions, a large region of the central part of the domain showed conditions that were unsuitable for the cultivation of sugar cane, although in the ERA-Interim dataset parts of the central region of the domain showed some suitability. By the end of the twenty-first century, the model ensemble shows crop-climate suitability for sugar cane that is very similar to that of the control period in the ERA-Interim dataset.

Banana

The situation for banana cultivation is very similar to that for sugar cane; the ensemble crop-climate

suitability maps under climate change conditions show a projected crop-climate suitability pattern very similar to that seen in the ERA-Interim dataset under control conditions. This pattern is for optimal or near optimal conditions for banana cultivation over all of the focus countries throughout the twenty-first century.

Mangoes, mangosteens and guavas

Both the ERA-Interim and ensemble crop-climate suitability maps for the twentieth century showed good conditions for the cultivation of mango. Under the RCP4.5 scenario, the optimality for mango cultivation in the ensemble deteriorates as the twenty-first century progresses. By the 2090s, conditions are sub-optimal for mango cultivation over much of the domain, in particular through the central part of South-East Asia. Although in the time period analysed here the worst conditions are found over the ocean and conditions over land regions remain suitable for cultivation of mango, it is feasible that under a higher projected emissions increase or later into the twenty-second century, conditions for mango cultivation over the eight focus countries could be poor.

Coconut

In a similar manner to some of the other crops, conditions for the cultivation of coconut over South-East Asia show a similar spatial pattern of optimality at the end of the twenty-first century in the ensemble to the ERA-Interim map during the control period.

Maize

Conditions for maize are projected to remain stable throughout the twenty-first century under the RCP4.5 in the model ensemble over South-East Asia. Whist no regions see completely optimal conditions, there is a crop-climate suitability score of four out of five over all of the focus countries, with two small exceptions where the score is lower. These exceptions are eastern Indonesia and the far north parts of the domain.

Green Coffee

In the ERA-Interim dataset, optimal conditions for the cultivation of green coffee were found over the eight focus countries of South-East Asia. This situation does not see a significant change under the RCP4.5 scenario by the end of the twenty-first century in the model ensemble. Optimal conditions for cultivation are still found over the focus countries, with the exception of the far west and east regions of Indonesia where it is slightly lower. Additionally, there is evidence for suitability regions to be contracting; in the current scenario this is affecting the ocean regions but there is the possibility that under higher emissions scenarios this could impact on crop-climate suitability for coffee cultivation in South-East Asia.

Under the RCP4.5 emissions scenario, the extent of crop-climate suitability for many of the selected crops across South-East Asia does not see a significant change. Where there is change to the optimal growth conditions, the biggest change is generally seen to the north of the domain over Myanmar and northern Thailand. In many cases these changes are positive, with the ensemble mean projection suggesting there could be increased opportunity for crop cultivation in these regions, particularly for natural rubber, palm oil and paddy rice.