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Fine-scale regional climate patterns in the Guianas, tropical South America, based on observations and reanalysis data

C. Isabella Bovolo,[a,b]* Ryan Pereira,[a] Geoff Parkin,[a] Chris Kilsby,[a] and Thomas Wagner[a]
[a] *School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne NE1 7RU, UK*
[b] *Iwokrama International Centre for Rainforest Conservation and Development, Guyana*

ABSTRACT: The dense, intact rainforests of the Guianas (northern Amazonia) are important for the regulation of the local and regional climate, but preclude easy access so a large data gap exists. The rainforest–savannah boundary may also be particularly susceptible to increasing pressures from ecosystem exploitation and climate change. It is important therefore to establish a baseline climate regime so that the impacts of any future change can be determined. Currently this area is not covered by the publicly available climate data sets, so interpolated data sets are not an accurate representation of the climate of this area, emphasizing the need for a more detailed analysis in this region. Here, we collate the available data sets and use these to derive maps of observed precipitation and temperature across the region. To overcome the limitations in the inadequate observational data sets, we also test and use the ECMWF ERA-40 reanalysis data set for the period 1958–2001 at a $\sim$125 km^2 (1.125°) resolution. Mean differences (biases) and annual average spatial correlations are examined between modelled and observed time series comparing the seasonal cycles and the yearly, monthly and monthly anomaly time series. The results show that with the exception of sub-grid resolution mountain environments, reanalysis data for the Guianas provide a consistent and relatively accurate spatial distribution of temperature. Precipitation is modelled less accurately, with best results for the average timings, length and severity of the dry periods. This study provides consistent and quantitative details on the spatial variations in seasonality, particularly in areas lacking observations, thereby advancing beyond previous studies. Precipitation is highly variable in the region so care must be taken when averaging modelled data over large geographical areas for comparisons with gridded data sets based on few observations. This is the first comprehensive study of the recent historical climate and its variability in this area.

KEY WORDS ERA-40 reanalysis; inter-tropical convergence zone (ITCZ); precipitation; temperature; correlation; bias; Guyana; Suriname; savannah; rainforest; climate–vegetation interactions

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1. Introduction

The future of the rainforest is not only of vital ecological importance, but also central to the future evolution of the global carbon cycle and as a driver of regional climate change (IPCC, 2007).

In comparison to the Brazilian Amazon, the Guianas of South America, located along the northern rim of Amazonia, have been largely overlooked and unresearched, yet their tropical rainforests are home to several Amerindian communities, hold high levels of biodiversity and, importantly, hold some of the world's most intact rainforests.

Rainforests have key functions not only in the global carbon cycle but also in the recycling and generation of rainfall and in the regulation of the local and regional climate (Lean and Warrilow, 1989, Shukla *et al*., 1990, Dickinson and Kennedy, 1992; Zhang *et al*., 1996a): trees return water to the atmosphere through the process of evapotranspiration; the process of cloud formation above the rainforests releases energy as latent heat which helps drive aspects of the general atmospheric circulation (especially the Walker and Hadley cells) (Osborne *et al*., 2004); and the clouds themselves reflect incoming sunlight, shading the land and helping to reduce surface temperature (Pielke *et al*., 1998; Jackson *et al*., 2008). The rainforests are therefore responsible for generating rain over vast distances (Zhang *et al*., 1996b; Wang and Fu, 2007; Werth and Avissar, 2002; Da Silva *et al*., 2008; Hasler *et al*., 2009); for example the South American Low Level Jet east of the Andes takes moisture from the Amazon Basin to the Brazil – Northern Argentina region of the Parana-La Plata Basin (Marengo *et al*., 2004), and deforestation in the Amazon may have far-reaching effects in precipitation over Europe through Rossby wave propagation (Gedney and Valdes, 2000). The forests of the Guianas are an important part of this system.

Despite their significance, the climate and hydrology of the Guianas is poorly understood. The dense rainforests in the interior and south of the Guianas and northern

* Correspondence to: C. I. Bovolo, School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne NE1 7RU, UK. E-mail: isabella.bovolo@ncl.ac.uk

Brazil preclude easy access and a large data gap exists in this area (Bovolo *et al.*, 2009). A delicate balance also exists between the rainforests and the savannahs of south-western Guyana, southern Venezuela and the far north of Brazil, with the rainforest–savannah boundary envisaged to be particularly sensitive to environmental change. Both biomes are threatened by climate change, deforestation and anthropogenic activities, but it is impossible to determine the impacts of possible future change at the local or regional scale without a suitable baseline from which to make comparisons. Owing to the small number of observations in this area (of which few time series if any, are included in global data sets), currently available gridded data sets do not form an accurate representation of the climate of this area, emphasizing the need for a more detailed climate analysis in this region.

Here, we collate and examine existing precipitation and temperature data sets of the Guianas and the surrounding areas and derive regional maps of mean precipitation and temperature based on available data. To overcome the limitations in the inadequate coverage of observational data however, we also make use of a modelled reanalysis data set providing a spatially consistent global climate based on historical data sets at a 1.125° resolution. This data set provides the ability to examine key climate variables such as the spatial distribution of monthly precipitation and temperature over the region, at a fine resolution, including in areas with little or no observational data. An improved and more detailed understanding of the regional climate is necessary to establish baseline conditions useful for determining the impacts of future environmental change, for investigating the interdependencies between climate regimes, vegetation systems and their boundaries, and for informing decision makers and local communities about the local climate for management purposes.

Mean differences (biases) and spatial correlations are examined between modelled reanalysis data and observed time series comparing the seasonal cycles and the yearly, monthly and monthly anomaly time series to evaluate if the reanalysis data correctly reproduces the observed interannual variability and seasonal cycles over the region. Once the degree of reliability of the reanalysis data for the region is assessed, the reanalysis data is then used to determine the precipitation and temperature regime of the Guianas. Grid-cell by grid-cell analysis provides a complete picture of monthly precipitation and temperature variability across the area at a fine resolution.

This article has the following objectives:

1. To highlight the data gap that exists in the southern Guianas and the north of Brazil and to encourage hydroclimatological research in this area.
2. To collate and review the available observed precipitation and temperature data sets for the region.
3. To test the use of reanalysis data sets for deriving regional climates in data-poor areas.
4. To use reanalysis data to derive a detailed regional climatology for the Guianas once validated against available observations.

2. An introduction to the Guianas and their climate

The Guianas, consisting of Guyana (~215 000 km^2), Suriname (~163 800 km^2) and French Guiana (~91 000 km^2) are located along the northeast coast of South America between the Orinoco basin in Venezuela to the west and the Amazon Basin in Brazil to the south and east. The highest point in the Guiana Highlands is Mount Roraima (2810 m) bordering Guyana, Venezuela and Brazil; most of the Guianas however, lie below 200 m (Figure 1). A coastal strip 10 to 60 km wide, consisting of mangrove swamps, rainforests and agricultural land (mainly sugar plantations), holds most of the population of the region. Further inland, open tropical rainforest leads into dense rainforest. A north-west to south-east band of savannah-type landscape (Baruch, 2005) runs from Venezuela through the southern third of Guyana reflecting a different climatic zone (Trewartha and Horn, 1980).

The Guianas, like all of South America north of the equator, lie well within the tropics and have a tropical climate so that the mean annual temperature is equal to or above 25 °C at sea level, the annual temperature range (i.e. the difference between the mean temperatures of the warmest and coolest months) does not exceed 5 °C and the range of diurnal temperatures exceeds the annual range (Snow, 1976). A 'Tropical Wet' marine (or 'Tropical Rainforest') climate (Trewartha and Horn, 1980), where mean annual precipitation is greater than about 2000 mm year^{-1}, dominates coastal areas and is distinguishable by two wet and two dry periods (the dry periods correspond with two temperature maxima). A drier 'Tropical Wet-Dry' (or 'Savannah') climatic region separates the Guyana coast from the upper Amazon Basin. This more continental type climate is found in most of the Orinoco basin in Venezuela, adjacent eastern Colombia and the Guyana savannah (Figures 2, 3) and is distinguishable by a single wet season (June to August) and a single dry season (November to January) with a temperature maxima occurring around the dry season. This zone has a smaller total precipitation than the Tropical Wet climate and rainfall is less well distributed throughout the year. The wet season is shorter and the dry season longer and drier. A recent climate classification system is shown in Figure 2 (Peel *et al.*, 2007).

The principal factors controlling the climate in South America are the subtropical high-pressure zones over the South Atlantic and South Pacific and their seasonal shifts in position. The North Atlantic semi-stationary high-pressure zone dominates just north of the equator. These high-pressure zones determine both large-scale patterns of wind circulation and the location of the cloud and rain-bearing inter-tropical convergence zone (ITCZ), a latitudinal belt of rising air movement and relatively low pressure where the trade winds of both hemispheres converge between the subtropical highs of the Northern and Southern Hemispheres. The seasonal movement of the ITCZ is generally greater over land and follows but lags the annual migration of the Sun bringing with it

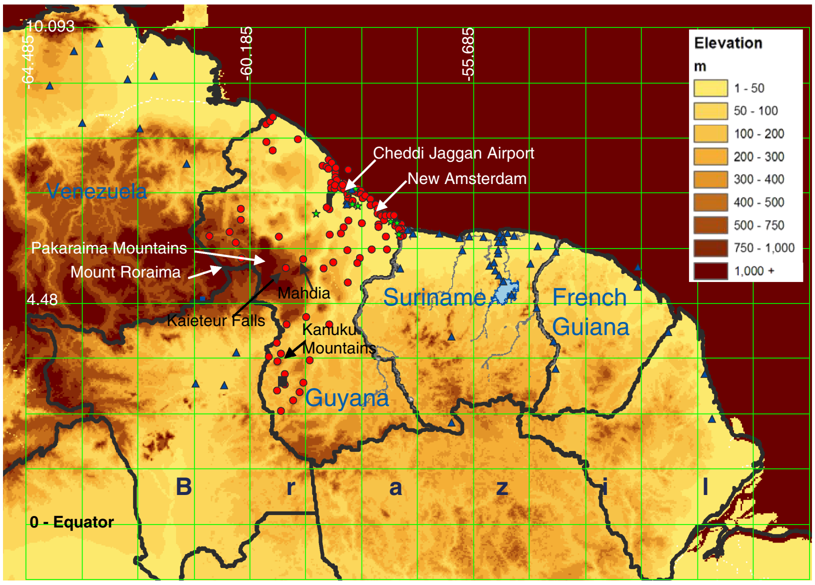

Figure 1. Digital elevation model (from USGS Earth Resources Observation and Science Centre http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30/hydro/samerica) and raingauge locations: dots indicate data was obtained from HydroMet (Guyana); squares from the Guyana Sugar Corporation (GuySuCo); and triangles from the Climatic Research Unit's (CRU) database. Raingauge data in Suriname were also obtained from the Suriname Meteorological Service. Dadanawa Ranch is highlighted as a black square. The ERA-40 reanalysis grid is superimposed. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

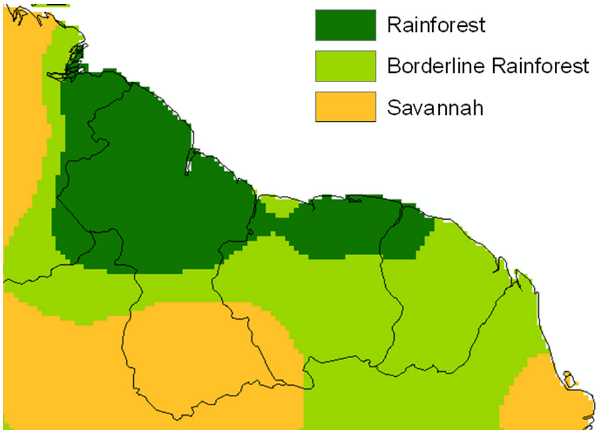

Figure 2. Global Climate Classification based on the Köppen-Geiger system for the Guianas (Peel *et al.* 2007). Temperature of the coldest month is $\geq$18 °C. Precipitation in the driest month is $\geq$60 mm or < [100 mm − (mean annual precipitation/25)] for 'rainforest' or 'savannah' respectively; borderline-rainforest lies between rainforest and savannah. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

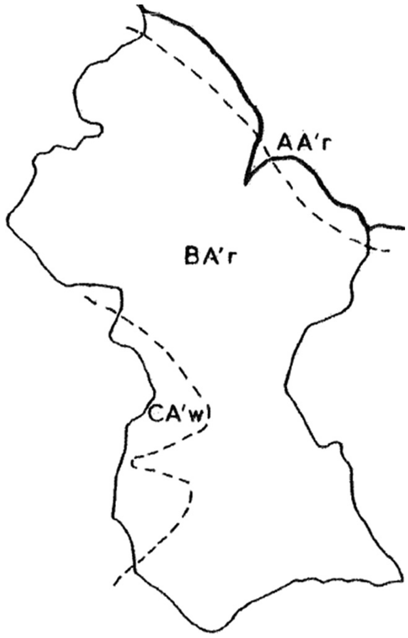

Figure 3. Climate zones in Guyana based on forest boundaries (Persaud, 1977). AA'r refers to a Coastal Climate, BA'r refers to Forest Climate and CA'w refers to Savannah.

periods of prolonged, abundant precipitation. It moves north during May–July to a position approximately 7°N and southwards during November–January to a position around 15 °S placing it well over the Amazon (Walsch, 1998). It can be seen over South America in Figure 4. In its absence, the trade winds, always blowing from the east, dominate. When the ITCZ is to the north, south-easterlies prevail south of the equator, whilst north of the equator winds are of variable direction and heavy rain is produced. When the ITCZ is to the south, north-easterlies prevail north of the zone of convergence (McGregor and Nieuwolt, 1998).

The deep Amazon interior is very wet partly due to the invasion by humid unstable north-westerly air whilst the ITCZ is south during the Southern Hemisphere summer. In contrast, lower precipitation occurs during the Southern Hemisphere winter when the South Atlantic subtropical high and its stable easterly flow penetrate deep inland (Trewartha and Horn, 1980).

The Guianas sit on the transitional position between the conditionally unstable air masses associated with the

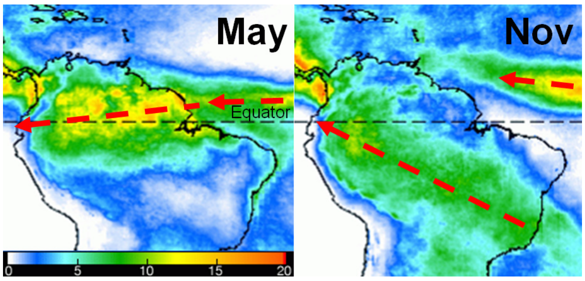

Figure 4. Monthly average precipitation (mm d^{-1}) for northern South America between 1998 and 2008 as determined by the Tropical Rainfall Measuring Mission (TRMM) (NASA, http://trmm.gsfc.nasa.gov/trmm_rain/Events/trmm_climatology_3B43.html). The ITCZ, shown by the zone of highest rainfall (marked by a dashed arrow), is at its most northerly position over land between May and July and its most southerly position between November and January. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

ITCZ and equatorial westerlies (convergent) during the Southern Hemisphere summer, and by the drier parts of the trade winds and subtropical anticyclones (divergent) in the Southern Hemisphere winter. The ITCZ moves over the Guianas twice a year. When the ITCZ is to the north, the subtropical high weakens and rainfall is high. When the ITCZ is to the south, the subtropical high is strong over the Caribbean, northeast coast of Brazil, the Guianas and Venezuela. The north-easterlies, forming around the southern edge of the subtropical high-pressure cell in the North Atlantic, generally bring reduced rainfall amounts to these areas, except on the coastal areas of the Guianas, where the northeast trade winds are onshore (Lydolph, 1985; Shaw, 1987; Walsch, 1998).

The Pacific El-Niño Southern Oscillation (ENSO) influences the climate of the Guianas on an interannual to decadal timescale through the Walker and Hadley circulation. The oceanic component of ENSO, El-Niño, is characterized by a weakening of the trade winds and positive sea surface temperature (SST) anomalies in the central and eastern equatorial Pacific, whereas La-Niña is characterized by stronger than normal trade winds and anomalously cool SSTs. However, direct correlations between the Southern Oscillation Index (SOI) and precipitation time series are weak (Wardlaw *et al.*, 2007). If filtering of SOI data is conducted however, it can be deduced that for coastal Guyana, El-Niño (negative SOI) events are likely to result in drought conditions, whereas La-Niña (positive SOI) events result in significantly higher than normal precipitation; the most significant influences of ENSO occur in November to December and October to January wet seasons (Wardlaw *et al.*, 2007).

Like ENSO, the 'Atlantic Niño' or tropical Atlantic equatorial mode, a phenomenon similar but weaker to ENSO, also affects the Guianas. During a warm phase, trade winds in the equatorial western Atlantic are weak and SST is high in the equatorial eastern Atlantic, whereas during a cold phase, the reverse occurs (Wang, 2005). An Atlantic meridional gradient variability (or 'Tropical Atlantic Variability'), defined by the SST anomaly difference between the tropical North Atlantic and tropical South Atlantic, is correlated with north-south displacements of the Atlantic ITCZ with strong climate anomalies over the surround land regions (Marshall *et al.*, 2001; Wang, 2005; Nurmohamed *et al.*, 2007).

The North Atlantic Oscillation (NAO) is associated with the variations of surface westerly wind in the middle and high latitudes of the North Atlantic (Wang, 2005). However, according to Marshall *et al.* (2001), it may be that the tropical Atlantic Variability and the NAO are interrelated on inerannual-to-decadal time scales: the NAO may provide an important extratropical forcing which excites tropical Atlantic Variability, and the TAV may feedback on the NAO at interannual to decadal time scales by rearranging the Hadley circulation.

Climate is a major factor determining the location and structure of the savannah (Frost, 1968), but landscape characteristics such as soil and topography also affect the development of savannah vegetation by influencing water availability through variations in drainage and soil water retention capacity, and basic nutrient availability (Sinha, 1968; Hills, 1969; Medina and Silva, 1990). Water and (natural or human induced) fire interactions combine to produce a stable boundary between the savannah and forest biomes (Medina and Silva, 1990) which may be disrupted by increased exploitation of the ecosystem (Baruch, 2005). Conversion of savannah to grassland for agricultural purposes may also feedback to the climate by reducing precipitation and increasing temperature through changes in albedo and surface roughness (Hoffmann and Jackson, 2000). Changes in the length and timing of the dry season may also affect plant competition, stress and growth.

The bounding edge of the savannah against the rainforest is often extremely abrupt in this region, possibly due to fire and the direction of prevailing winds or forest shifting cultivation (Sinha, 1968; Hills, 1969). Fragmented forest margins (especially the large diameter trees) are more vulnerable to the stresses brought about by increased wind speed, turbulence and vorticity whilst the elevated temperatures, reduced humidity, increased sunlight and vapour pressure deficits found on the forest boundaries cause increased evaporation and desiccation levels making vegetation more susceptible to the stresses of drought and fire (Laurence, 2005). The forest–savannah boundary may therefore be particularly susceptible to environmental change and may be an early indicator of the impacts from a changing environment or climate on the rainforest.

3. Datasets

3.1. Observed meteorological data sets

Meteorological data was collated from several different sources during an intensive data-gathering campaign. Within Guyana the Hydro-Meteorological Service (HydroMet), part of the Ministry of Agriculture, is the main organization responsible for collecting, processing and storing hydro-meteorological data, although other organizations, such as the Guyana Sugar Corporation (GuySuCo), also maintain their own records. Outside of Guyana organizations such as the Caribbean Institute for Meteorology and Hydrology (Barbados), the Caribbean Community Climate Change Centre (Belize), Météo-France (for French Guiana), the Suriname Meteorological Service and others can provide regional climate records under license. For this study, the precipitation and temperature data sets for Guyana have been provided by HydroMet, GuySuCo and Dadanawa Ranch (Guyana) whereas monthly data sets for the region have been provided by the Suriname Meteorological Service and the Climatic Research Unit (CRU) at the University of East Anglia, UK.

HydroMet have a network of 147 current and/or historical rainfall gauges across Guyana plus five weather stations (three of which are automatic and located at Kaiteur Falls, Timehri International Airport and New Amsterdam). The distribution of the existing rainfall stations is uneven, mainly due to uneven population distribution and inaccessibility issues, especially in the interior of the country (Figure 1). Although the Guyanan coast (where 90% of the population live) has a relatively good raingauge network, the interior region has many gaps and has far less than the minimum density of raingauges recommended by the World Meteorological Organisation (WMO). This is also the case in nearby Suriname and French Guiana. There are also only a few existing gauges in northern Brazil. There is therefore an urgent need to bring the climatological network in Guyana and the surrounding regions up to minimum WMO recommendations.

On the coast however, several long-term records are available which are of obvious benefit for establishing long-term climatic trends. Both Guyana and Suriname have several records dating from the late 1800s and early 1900s, whereas digitized records for French Guiana and Venezuela (from CRU) date mainly from 1961 and 1921 respectively. Inland, Boa Vista (Brazil) has a good record from 1938. However, in Guyana (and likely elsewhere) several old, hand-written records have not yet been digitized. These paper records may be lost if not committed to digital form in the near future.

Accurate, long-term hydro-meteorological records are needed in order to examine and understand past and current climates and to establish a baseline from which to monitor future change. Many precipitation and weather station records for this region however, have significant gaps not only in the spatial coverage but also in the continuity of the records (Bovolo *et al.*, 2009). This is mainly from the reliance on manual measurement resulting in gaps during absence or holidays (Figure 5). Also data quality is sometimes questionable. Several types of human errors are possible. Errors could be introduced through the data collection process (for example from the incorrect recording of units or incorrect use of equipment) and through incorrectly digitizing hand-written records. There is evidence of both sources of error in the collated data sets. Additionally, geographical locations of the gauges require checking and the height of gauges above sea level are not usually recorded. Meteorological offices also generally lack the resources to physically collect data from remote locations. Capacity building in the region (in terms of numbers and training of staff, and of resources) is therefore also an urgent requirement.

3.2. ERA-40 reanalysis data set

Retrospective analysis (or reanalysis) data sets derive from modified operational weather forecast and analysis models. Reanalysis models, such as the European Centre for Medium-Range Weather Forecasts (ECMWF) data set (ECMWF, 2010), known as ERA-40 (Uppala *et al.*, 2005), takes as input a range of spatially and temporally variable historical atmospheric observations including: soundings from radiosonde and pilot balloons; synoptic surface observations from land stations and ships; and

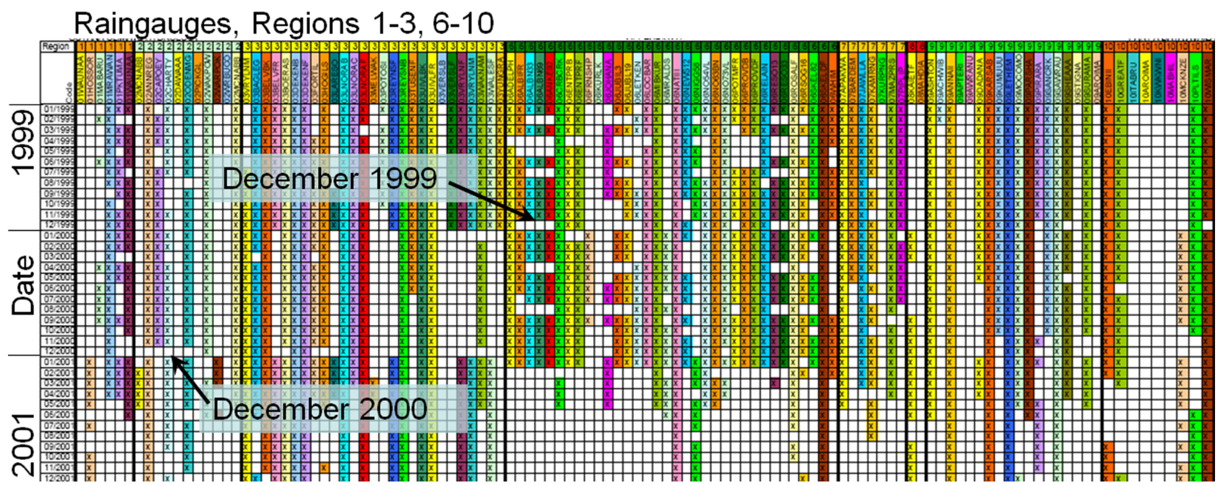

Figure 5. Sample showing available precipitation observations in Guyana. Columns show all available precipitation gauges for a sample subset of regions (1, 2, 3, 6, 8, 9 and 10) for each month (row) between 1999 and 2001. Where available, complete monthly observations are shown as an 'x' within a shaded square. There are several gaps in the records and the Christmas holidays (December) are particularly noticeable. For full details see Bovolo *et al.* (2009). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

satellite data. It provides as output, a spatially consistent global climate on an N80 reduced Gaussian grid with a spatial resolution of 1.125° (~125 km on the equator) for the period September 1957 to August 2002. For this study, we restricted the period of interest to complete years from 1958 to 2001.

The ERA-40 analysis, producing an estimate of the state of the atmosphere at a particular time, is carried out at 00, 06, 12 and 18 h UTC (assimilating the previous 6-h forecast) whilst model forecasts are commonly available at the 6, 12, 24 and 36 h time steps from each analysis. The British Atmospheric Data Centre (BADC), from which the ECMWF ERA-40 data set was obtained, stores data in a mean monthly format consisting of data accumulated at the 6-h resolution. This data set was used for comparisons at the monthly resolution. We have tested the data and have shown that there are only negligible differences in the precipitation and temperature forecast data for this region at different time resolutions (for example daily data made up of one 24 h forecast compared with daily data made up of four 6 h forecasts) in line with findings for the Amazon (Betts *et al.*, 2005).

ERA-40 assimilates surface synoptic observations including temperature into the model to produce the 2 m temperature analysis output. Precipitation observations are not assimilated into the model however, so output data consisting of short-range forecast accumulations such as precipitation and other hydrological variables are a good test of model performance (Bosilovich *et al.*, 2008). This also means that, compared with observations, larger discrepancies are to be expected for precipitation than temperature.

Reanalysis data is considered to be the best source of data for areas where there is a lack of observations. However, the outputs are dependent on the quantity and quality of the model inputs and these may have substantial uncertainties (Adler *et al.*, 2001). Data coverage is generally good in the Northern Hemisphere, but poorer in the Southern Hemisphere. Global climate data sets do not always have access to all the data within specific countries, and general coverage of Guyana and the surrounding regions in the global data sets is poor. These points should also be kept in mind when considering the accuracy of the ERA-40 outputs.

4. Data processing

Within this study, all precipitation data sets have been aggregated to monthly or annual levels. A basic data quality check was made to the daily and monthly data sets similar to the method of Liebmann and Allured (2005). Particularly, care was taken to deal correctly with daily data which was recorded as having been accumulated over two or more days, however it was difficult to ascertain if values recorded as zero were actually missing values or not, so these were retained within the data set meaning that aggregated precipitation totals may be slightly underestimated.

Monthly records were only accepted as complete and used in this study if there were no missing daily data within that month and yearly values were only accepted where all months were present. Where multiple sources of data for a particular gauge were available, differences between the data sets were sometimes apparent. In this case, data were averaged as it was impossible to ascertain which of the data sets were correct. Finally, incorrectly recorded geographical coordinates were adjusted to the nearest known village based on identification name and region.

Mean monthly or annual temperature data sets were used for this study. Temperature data, although less plentiful, were available either as daily records (HydroMet, Suriname Meteorological Service), as monthly maximum/minimum values, or as mean monthly values (CRU). Unlike for precipitation data sets, monthly records were accepted for use in this study even if a month contained a small proportion of missing data because mean annual temperature does not vary much in this region and does not vary much day to day. Where multiple data sets for the same gauge spanned different time periods, these were aggregated if there were no obvious differences in trends or values.

Despite the problems identified above, the collated precipitation and temperature data sets provide a valuable insight into the climate of the region. It should be borne in mind however, that the uncertainties associated with these data sets make conclusions less robust.

Gridded ERA-40 precipitation forecasts (available as convective and large-scale components) and 2 m temperature analyses were extracted for land-based grid points and mapped to the grid-cells shown in Figure 1. Being located near the equator, the derived Gaussian grid-cells are relatively equally spaced.

ERA-40 data is usually analysed in three epochs: 1958–1972 (before satellite), 1973–1986 (incorporation of satellite data) and 1987–2001 (incorporation of radiances from satellite microwave channels) (Betts *et al.*, 2005). This is because although observational accuracy and data coverage have tended to improve steadily between 1957 and 2002, changes in the observing systems (see http://www.ecmwf.int/research/era/Data_Services/section3.html) such as the introduction of radiosondes and satellite instruments have caused pronounced step changes, for example in 1972, 1979, 1987, 1991 and 1998, making it difficult to determine trends especially in precipitation (Betts *et al.*, 2003; Hagemann *et al.*, 2005). Following established procedures, all analyses in this study were therefore conducted for the full 1958–2001 period and for each epoch in turn.

Each observed precipitation and temperature data set was matched to an ERA-40 grid-cell. Where more than one set of observations were present within a grid-cell, only observations with over 75% of data (Jones and Hulme, 1996) present within the period 1958–2001 were included in the analysis (or the best data set was used if this criteria was not met), whilst if only one gauge was available in a particular grid-cell this was included even if less than 75% of data was available (and marked as such) so as not to disregard valuable observations. For temperature, if more than one data set was available for a particular grid-square, only the best data set was used.

ERA-40 must be validated against ground-based observations before any confidence can be given to the results. However, coarse-resolution model data should not be directly compared with observations from a point source unless the observations are representative of the area. This is usually more of an issue with precipitation than for temperature, which is less spatially variable. It is therefore the usual practice to average multiple precipitation observations in the area of interest so that the spatial variability across the area is captured. Here, precipitation observations were areally averaged across individual ERA-40 grid-cells using arithmetic means. This method works best where there are several gauges uniformly spaced across the area and where the area has no significant variations in topography. Unfortunately, the lack of observations meant that in most cases areal averaging was not possible. Additionally, single gauges in areas where precipitation is spatially highly variable (such as in the savannah, or along the coast), may not be fully representative of the area.

Mean differences (biases) and cross-correlations between the observed and modelled data sets were examined for each year (1958–2001), for each month (1958–2001) and for monthly averages (January–December). Additionally, averaged monthly anomaly time series were calculated by taking the observed (or modelled) monthly time series for 1958–2001 and subtracting the observed (or modelled) mean monthly (January–December) precipitation time series respectively so that comparisons could be made between the two data sets without the consideration of seasonal variability. In a separate calculation, the averaged monthly precipitation anomalies were also standardized by dividing the averaged monthly anomaly time series by the standard deviation of the entire observed monthly time series for 1958–2001 (Jones and Hulme, 1996). In all cases, observations were compared to the equivalent ERA-40 time series with the aim of evaluating if the reanalysis data is able to capture the observed interannual variability and seasonal temperature and precipitation cycles. Reanalysis data is then used to provide a complete picture of spatial precipitation and temperature patterns in the region.

5. Results and discussion

5.1. Temperature

Modelled ERA-40 data is able to capture the observed temperature distribution of the region relatively well (Figures 6 and 7, cross reference with Figure 1). The region experiences annual mean daily temperatures of between 25 and 27 °C with the warmest area on the coast. However, temperatures are cooler (<22 °C) in the areas of high elevation in the Guianan Highlands (the high elevation area of north east Guyana leading into Venezuela, encompassing Mount Roraima). A high temperature zone in south-west Guyana and northern Brazil (southwest of Mount Roriama) corresponding to the savannah region (Figures 2, 3) is also apparent in both data sets.

Seasonally, there is relatively little temperature variation across the region, although there are slightly higher temperatures in the August to October (ASO) primary dry season, especially in the interiors of Suriname and French Guiana, whilst the May to July (MJJ) primary wet season has overall cooler temperatures. In the November–January (NDJ) secondary wet season (not affecting the savannahs), the area corresponding with savannah (southwest of Mount Roriama) has particularly elevated temperatures, and these persist into the February to April (FMA) secondary dry season, whereas the cooler temperatures found in the interior of Suriname and French Guiana become more enhanced in FMA and MJJ.

Comparisons of the biases and cross-correlations between observed single-station and modelled grid-cell ERA-40 2 m temperature are shown in Figure 8. Biases are positive (+0.5 to +1 °C) in some regions and negative (−0.5 °C) in others, so it is unclear if ERA-40 has an overall temperature bias for the region. Nevertheless, ERA-40 mean temperature biases are small.

Correlations involving long time series (mainly along the coast) are good for yearly, monthly and particularly for averaged monthly data sets, where correlations are mostly close to 1. Correlations of monthly anomalies however, are slightly lower with values between 0.4 to 0.8 along the coast. As mentioned previously, ERA-40 2 m temperature analysis output is expected to have a good fit to observations because the model has been fitted to synoptic surface observations including temperature. Nevertheless, inputs to the model for this region are scarce and there are significant gaps in the coverage of synoptic observations from land prior to 1967 (and coverage declines from 1958 to 1966) with Brazil and the Guianas being particularly data-poor. Simmons *et al.* (2004) found that discrepancies between ERA-40 and gridded temperature data sets for the Southern Hemisphere were much more marked before 1967 and still significant until the 1980s, linked to limited availability of surface observations for ERA-40 at this time. The high correlations found in this study are therefore considered to be a good result.

Figure 9 compares modelled and single-point observed mean temperature time series for each year between 1958 and 2001 on a grid-cell by grid-cell basis across the region. Generally ERA-40 data matches observations well where available (Figure 9a), except in the Guyana Highlands (Figure 9b) where ERA-40 temperature is overestimated (the Guyana Highlands are discussed in more detail below). Figure 9 also shows ERA-40 1958–2001 monthly mean temperatures. It can be seen that the monthly temperature range varies considerably over the region and is much larger over the savannah and Amazonia regions in northern Brazil (south and south west of 'b' in Figure 9) than for coastal regions.

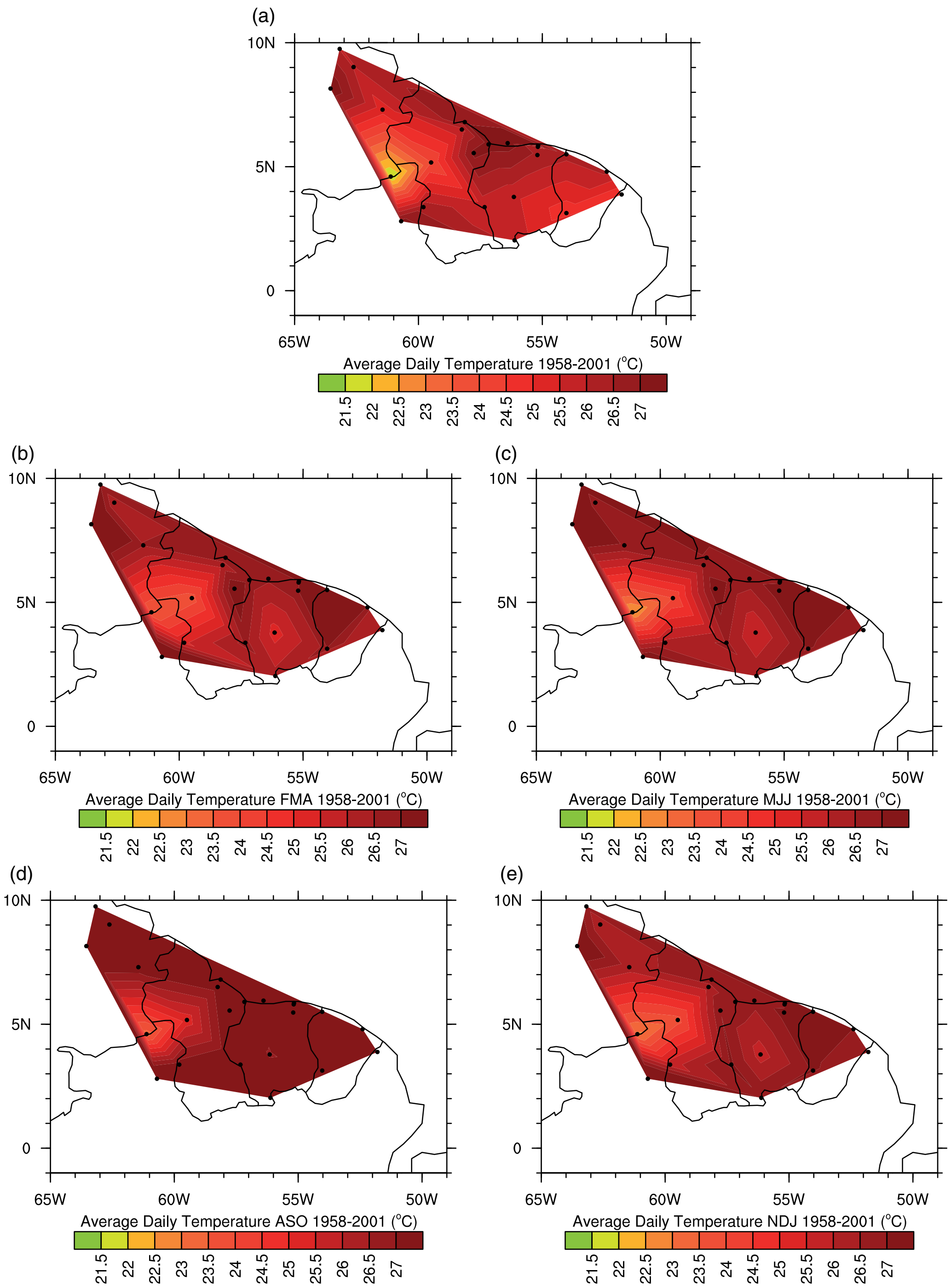

Figure 6. Cylindrical equidistant contour plots of annual (a) and seasonal (b–e) average daily temperature based on available observations (black dots) for 1958–2001. Seasons are: February to April (b) secondary dry season; May to July (c) primary wet season; August to October (d) primary dry season; November to January (e) secondary wet season. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Figure 10 is similar to Figure 9 except that it compares mean monthly rather than annual time series. Correlations between observations and ERA-40 data are particularly good (Figure 8). Mean monthly variations in temperature are particularly small across the region (shown by relatively 'flat' lines) and are much less than the typical diurnal temperature range (not shown). However ERA-40 data show that in the savannah area, where observations are not available, temperatures are generally higher and seasonal variations become much more pronounced with biannual seasonal maxima occurring in February and October. On the Brazilian coast south of French Guiana, ERA-40 data suggests that temperatures are relatively steady throughout the year but have a pronounced peak in November.

5.2. Precipitation

Accurate fine-scale precipitation maps of the region as a whole do not yet exist. Gridded regional precipitation data sets covering the Guianas are generally reliant on

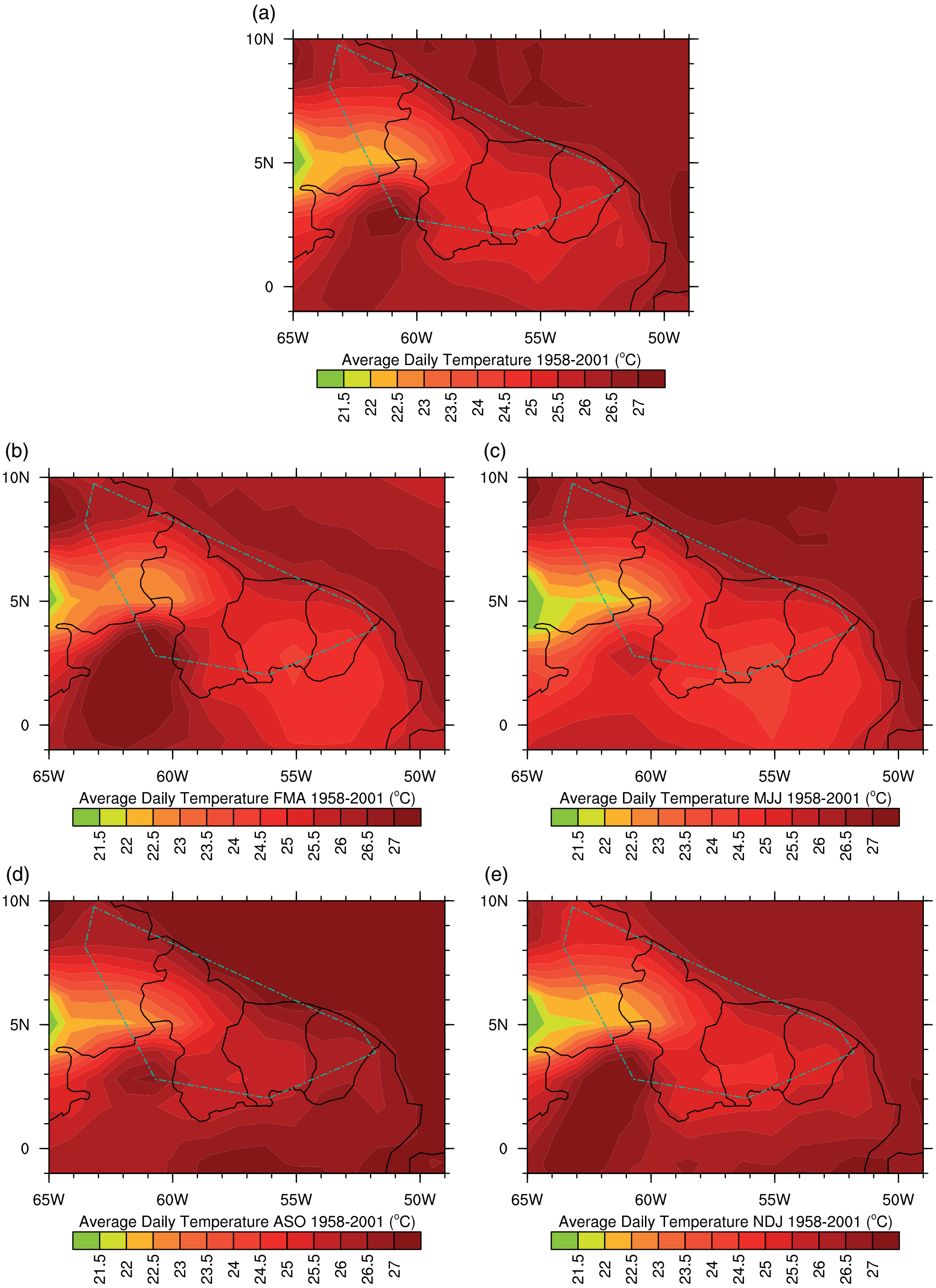

Figure 7. As for Figure 6 but for modelled ERA-40 data. Dashed polygon shows area covered by observed data in Figure 6. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

interpolation and are based on only few, if any, observations specifically within the Guianas (e.g. the NOAA Climate Prediction Center unified gauge-based analysis of global daily precipitation data sets for 1970–2005; http://www.cpc.ncep.noaa.gov/products/precip/realtime/GIS/SA/SA-precip.shtml, see also Chen *et al*., 2008). Other data sets concentrate only on Brazil (Shi *et al*., 2000; Silva *et al*., 2007). Some data sets (e.g. CMAP, Xie and Arkin, 1997 or GPCP, Adler *et al*., 2003) combine similar sets of limited observations with satellite or model outputs. Owing to the lack of fine spatial detail in these data sets however, comparisons with this work, which employs a much denser network of raingauges, is not beneficial. Existing country-specific precipitation maps based on observations however, include one for Guyana by Persaud and Persaud (1995) (see also Ramraj, 2003) and one for Suriname by Nurmohamed *et al*. (2007).

Figure 11 shows the average daily observed precipitation for 1958–2001 for the region based on the available observations. The distribution of precipitation over Guyana and Suriname compare favourably with Persaud

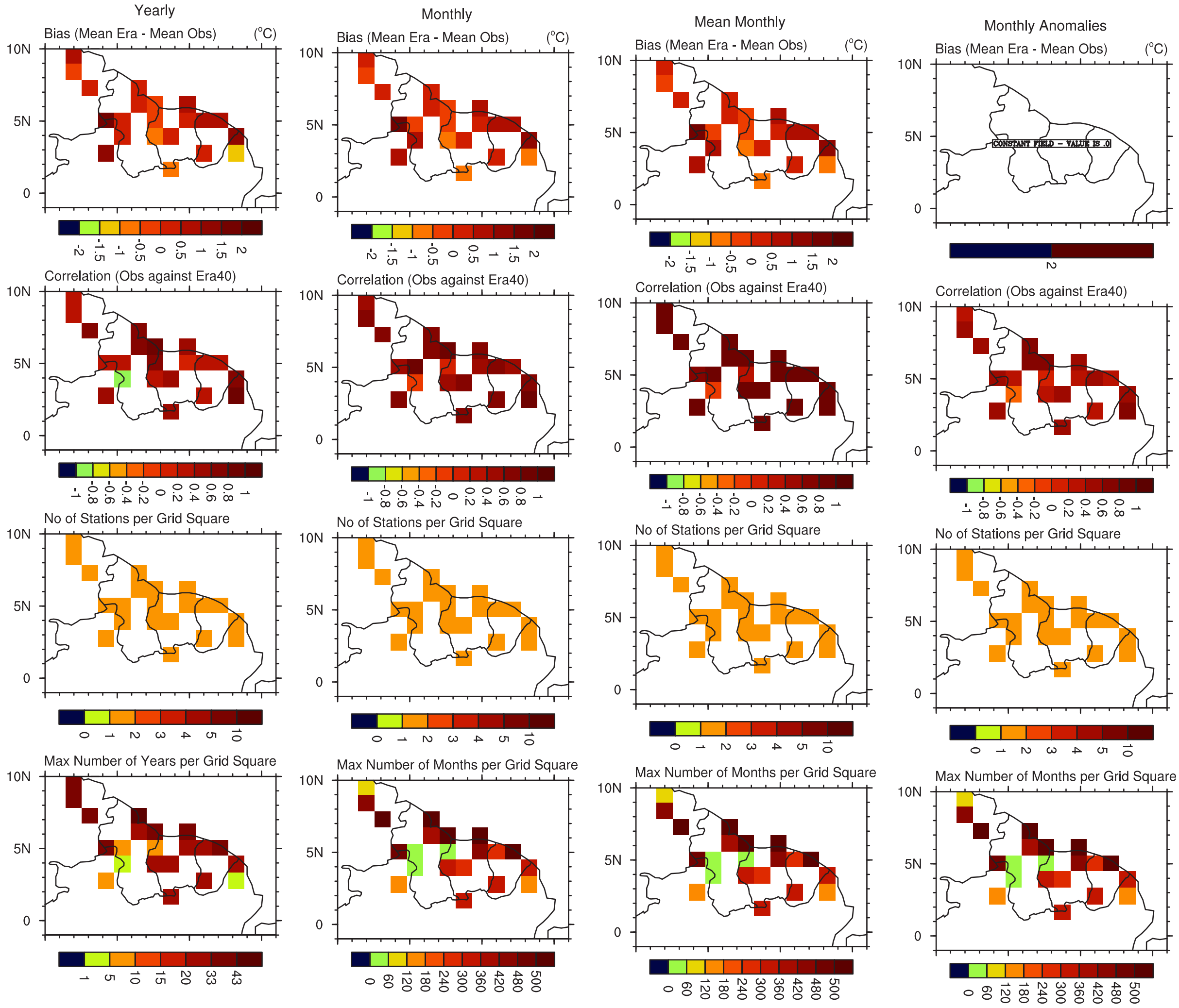

Figure 8. Cross-correlations and mean differences (biases, °C) between observations (Obs) and ERA-40 temperature for the period 1958–2001. This is done using yearly (1958–2001), monthly (1958–2001), averaged monthly (January–December) and monthly anomalies. The monthly anomaly time series were calculated by taking the observed or modelled monthly time series (1958–2001) and subtracting the observed or modelled mean monthly (January–December) precipitation time series. Also shown are the number of stations included in the comparison and the maximum number of observations (yearly or monthly) per gauge. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

and Persaud (1995) and Nurmohamed *et al.* (2007). However Persaud and Persaud (1995) show a second 'very dry area' in southwest Guyana, similar to the savannah zones defined in Figure 3. This 'very dry area' then leads into a 'very wet' region on the southern Guyana border. It is unclear if these zones are deliniated based on observations or are assumed to match vegetation biomes as there is a lack of raingauges in this area.

Figure 12 is similar to Figure 11, but shows modelled ERA-40 data rather than observations. Spatially, the modelled data compares relatively well with observations: higher rainfall is located on the Guyana coast and a drier area is located in northernmost Brazil and southwest Guyana roughly corresponding to the location of the savannah area (Figures 2 and 3). In the model, this dry area is shown to substantially expand (1973–1986) or contract (1987–2001) during different time periods suggesting that the savannah region may experience significant variability in precipitation (Figure 13). ERA-40 precipitation over Suriname and French Guiana also compare relatively well with observations, although ERA-40 underestimates precipitation slightly. The main omissions in the model are the zones of high average annual precipitation observed in northwest Guyana and in central Suriname (reaching an annual average of 8–9 mm d^{-1}) (Figure 11). In Guyana, the raingauge responsible for the observed high precipitation is located at Mahdia near the edge of the Pakaraima Mountains (Figure 1). A further station at Kaiteur Falls located within the Pakaraima Mountains gives even higher precipitation values in this area, but was not included in the analysis due to observations being outside of the period of interest but nevertheless confirms the high values displayed here. An area of high elevation also exists in central Suriname. Precipitation at these locations is generated through orographic uplift of moisture-laden air brought in by the north-easterly trade winds. Mountain slopes facing northeast receive more precipitation, whereas lee-ward slopes have reduced precipitation. These high precipitation zones are absent in ERA-40 because the model's coarse

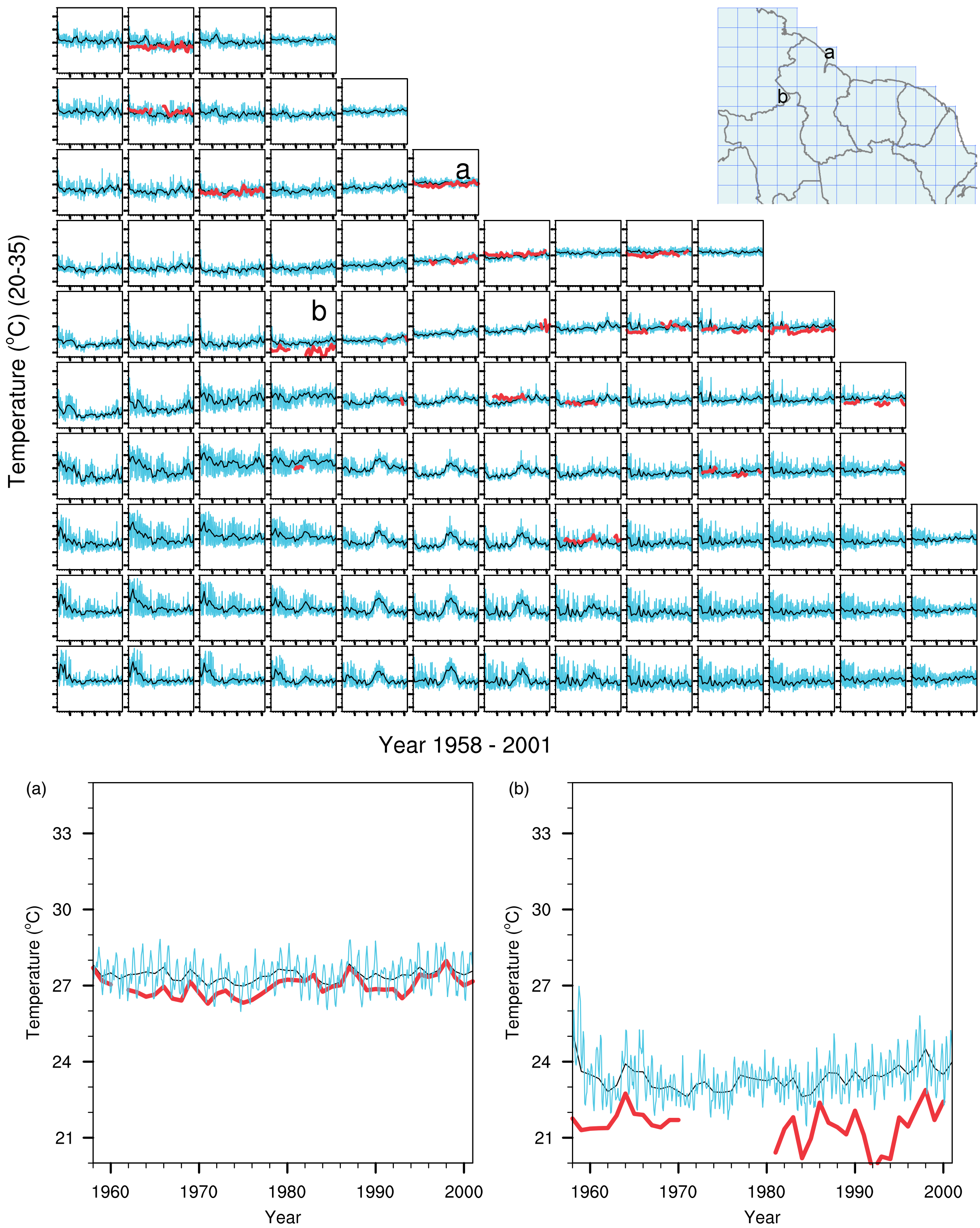

Figure 9. Average annual temperature (°C) for each year 1958–2001 for the land-based ERA-40 grid-cells (inset). ERA-40 data are shown as a thin black line, whilst single-point observations where available are shown as a thick (red) line. Also shown are the monthly mean average temperatures (thin pale lines). Two example grid-cells (labelled ‘a’ and ‘b’) are enlarged below. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

resolution topography smooths out valleys and mountain peaks and therefore the model fails to capture the sub-grid topographic variability which is important in high mountain areas (e.g. the grid-cell containing Mount Roraima with an actual elevation of 2810 m is averaged with the surrounding topography as 855 m). For this reason, ERA-40 temperature is also overestimated in these zones of higher elevation, particularly at Mahdia (Figure 9b).

Unlike for temperature, precipitation in the area shows significant seasonal variation. The primary wet season (NDJ), is particularly wet with the Pakaraima Mountains, central Suriname and the French Guiana

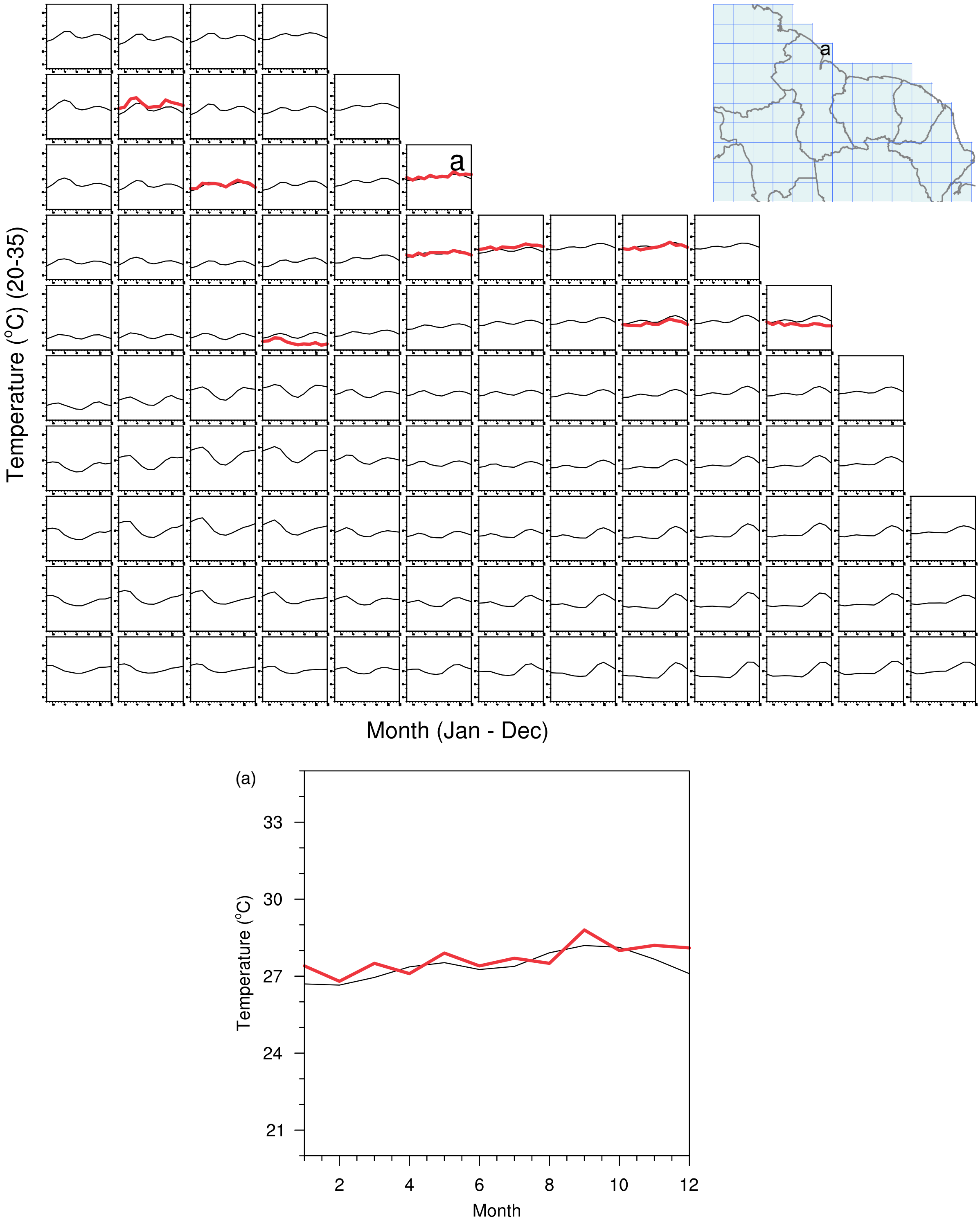

Figure 10. Mean monthly temperature (°C) for January to December based on data for 1958–2001 for the land-based ERA-40 grid-cells (inset). ERA-40 data are shown as a thin black line, whereas single-point observations where available are shown as a thick (red) line. An example grid-cells (labelled 'a') is enlarged below. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

coast having average precipitation of over 10 mm d^{-1} based on observations. These high rainfall levels are not well represented by the ERA-40 model which tends to underestimate rainfall over the whole region during this season. In contrast, the ASO primary dry season is particularly dry with most places receiving less than 3 mm d^{-1}. Again, ERA-40 does not fully capture the seasonal rainfall variation and tends to overestimate rainfall over the region at this time. During the NDJ secondary wet season, it can be seen that coastal areas in Guyana are wetter than inland areas. This is particularly noticeable when compared with the FMA secondary dry season. On the other hand, areas in central Suriname and French Guiana appear wetter during FMA. ERA-40

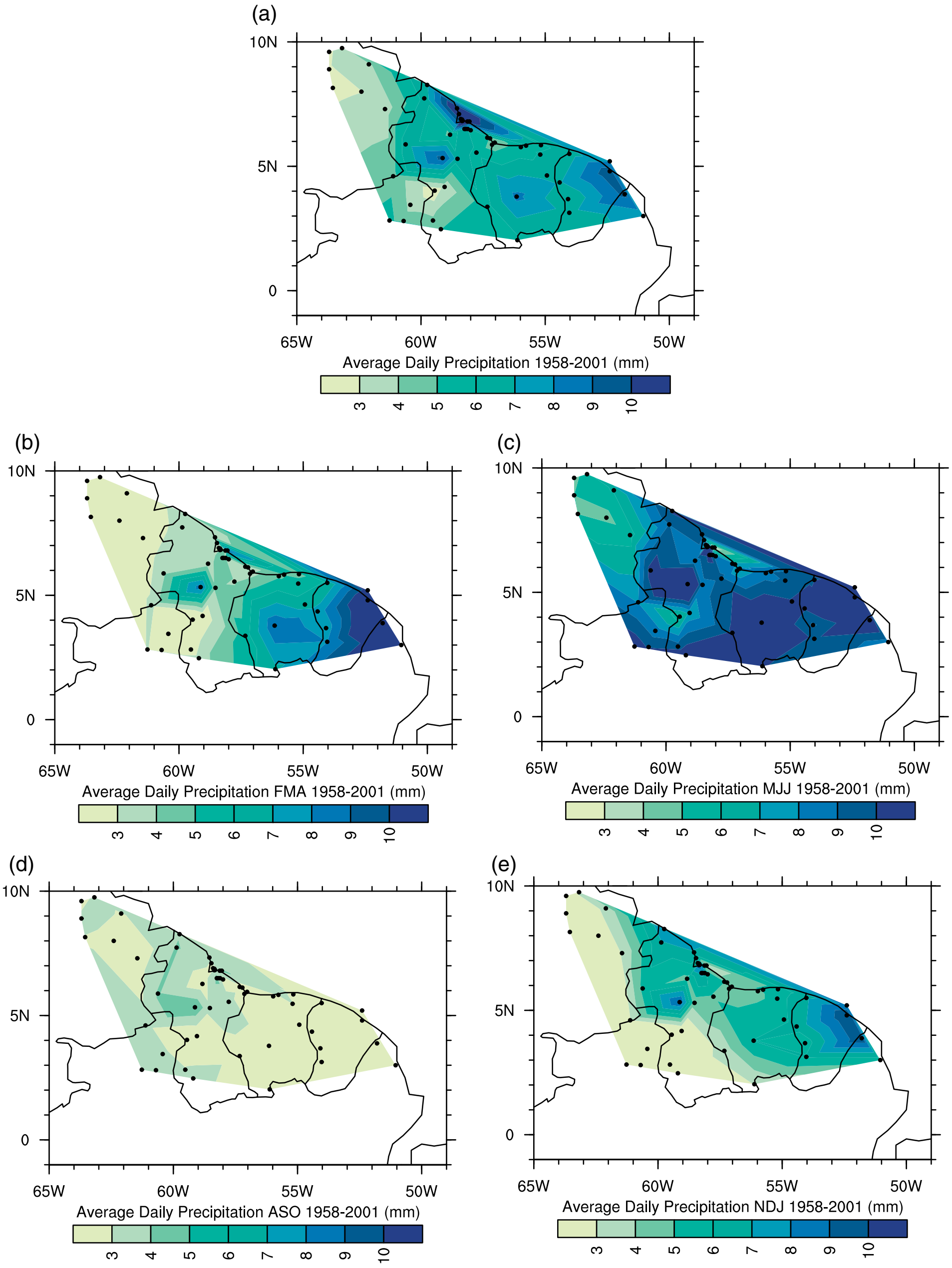

Figure 11. Cylindrical equidistant contour plots of annual (a) and seasonal (b–e) average daily precipitation based on available observations for 1958–2001. Seasons are: February to April (b) secondary dry season; May to July (c) primary wet season; August to October (d) primary dry season; and November to January (e) secondary wet season. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

manages to capture these seasonal variations relatively well.

Comparisons of the cross-correlations and biases between observed and modelled precipitation are shown in Figure 14. Generally correlations between yearly time series are relatively low (less than 0.6 and more normally between 0.2 and 0.4); coastal areas, where several gauges are present and hence where the most complete and high-quality data sets are located, are more highly correlated. Correlations based on monthly data are better (up to 0.8), whereas correlations based on averaged monthly (January–December) time series are much higher (between 0.8 and 1.0). This is partly due to the model's correct interpretation of seasonal precipitation variation. When this variability is removed, the monthly anomalies give a low correlation of <0.6. As the ERA-40 model does not assimilate precipitation observations as input and therefore does not fit to these, precipitation output is expected to be less reliable. However, considering the lack of observations and the uncertainty in both the observed and modelled data sets, the results given here are considered to be acceptable.

Yearly, monthly and averaged monthly biases (Figure 14) show that ERA-40 precipitation for the period 1958–2001 is slightly positively biased along the Guyana/Suriname coastline and is mostly negatively biased inland (the positive yearly biases on the south of Guyana do not have enough data points to be

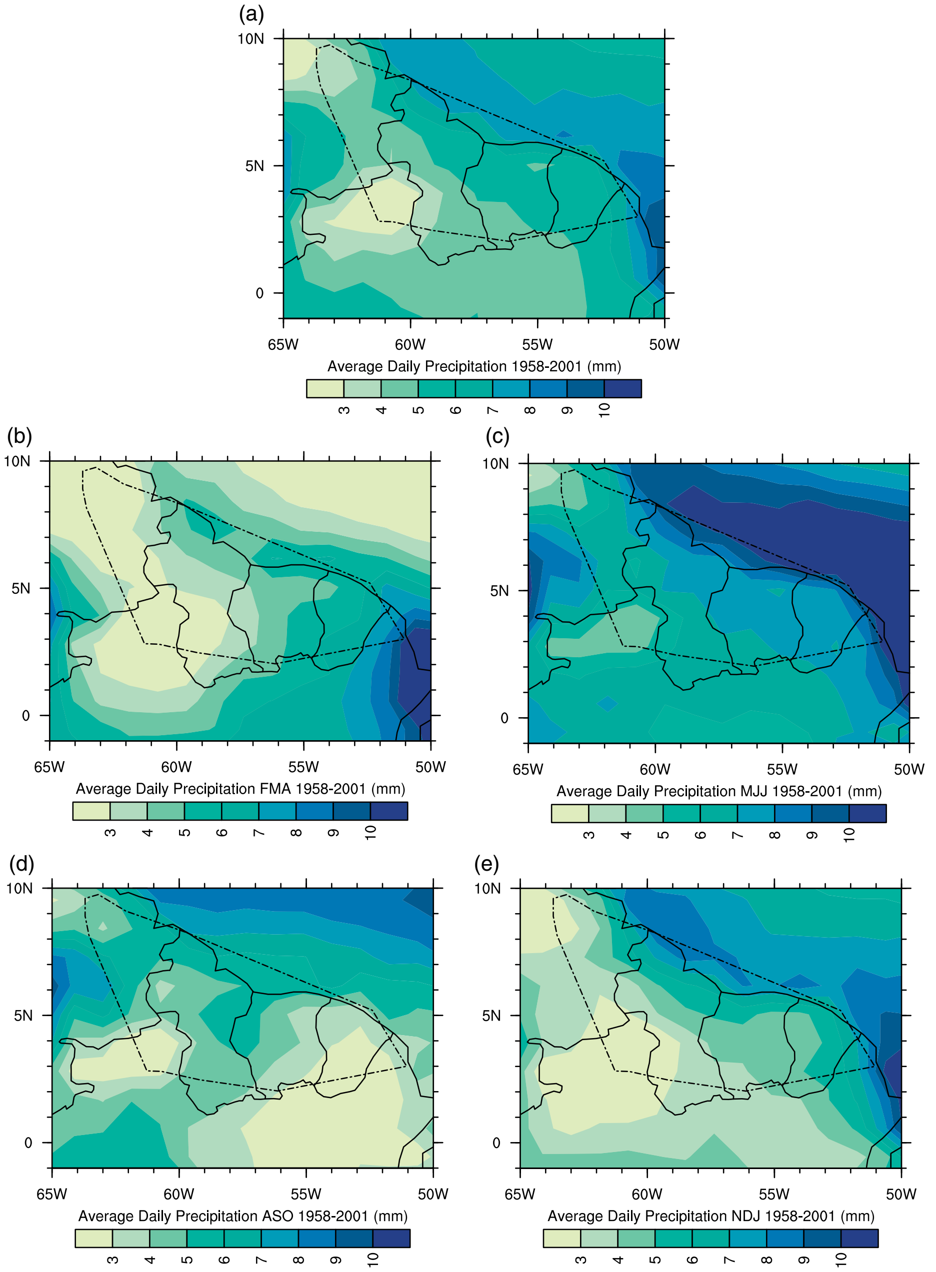

Figure 12. As for Figure 11, but for modelled ERA-40 data. Dashed polygon shows area covered by observed data in Figure 11. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

representative). The negative monthly anomaly bias for most of the Guianas shows that when the seasonal cycle is removed from the monthly precipitation time series, the difference is greater for the model than for observations. The same trends are also apparent when analysing data restricted to the three time periods 1958–1972, 1973–1986 and 1987–2001 (not shown). The biases can be examined more qualitatively in Figure 15.

Figure 15 compares modelled and single-point observed mean annual precipitation for each year between 1958 and 2001 on a grid-cell by grid-cell basis across the region. Overall, ERA-40 is able to match observations relatively well. In particular, ERA-40 is able to reproduce the observed precipitation in northern Venezuela, the increase in precipitation variability along the Guyanan coast, and some of the low precipitation levels in the savannah. Notable exceptions include the area of high average annual precipitation in northwest Guyana (Figure 15c); and the extremely high precipitation observed over the French Guiana coast, which is generally underestimated.

In the Guyana savannah, observations were taken from only the longest and best quality single-gauge precipitation records available, however these records are nevertheless discontinuous and variable in length. They are not representative of the local area and are therefore unlikely to match ERA-40 precipitation. In the savannah, precipitation appears to be highly variable both spatially and temporally. From all the available observations in the area, mean precipitation appears to be about

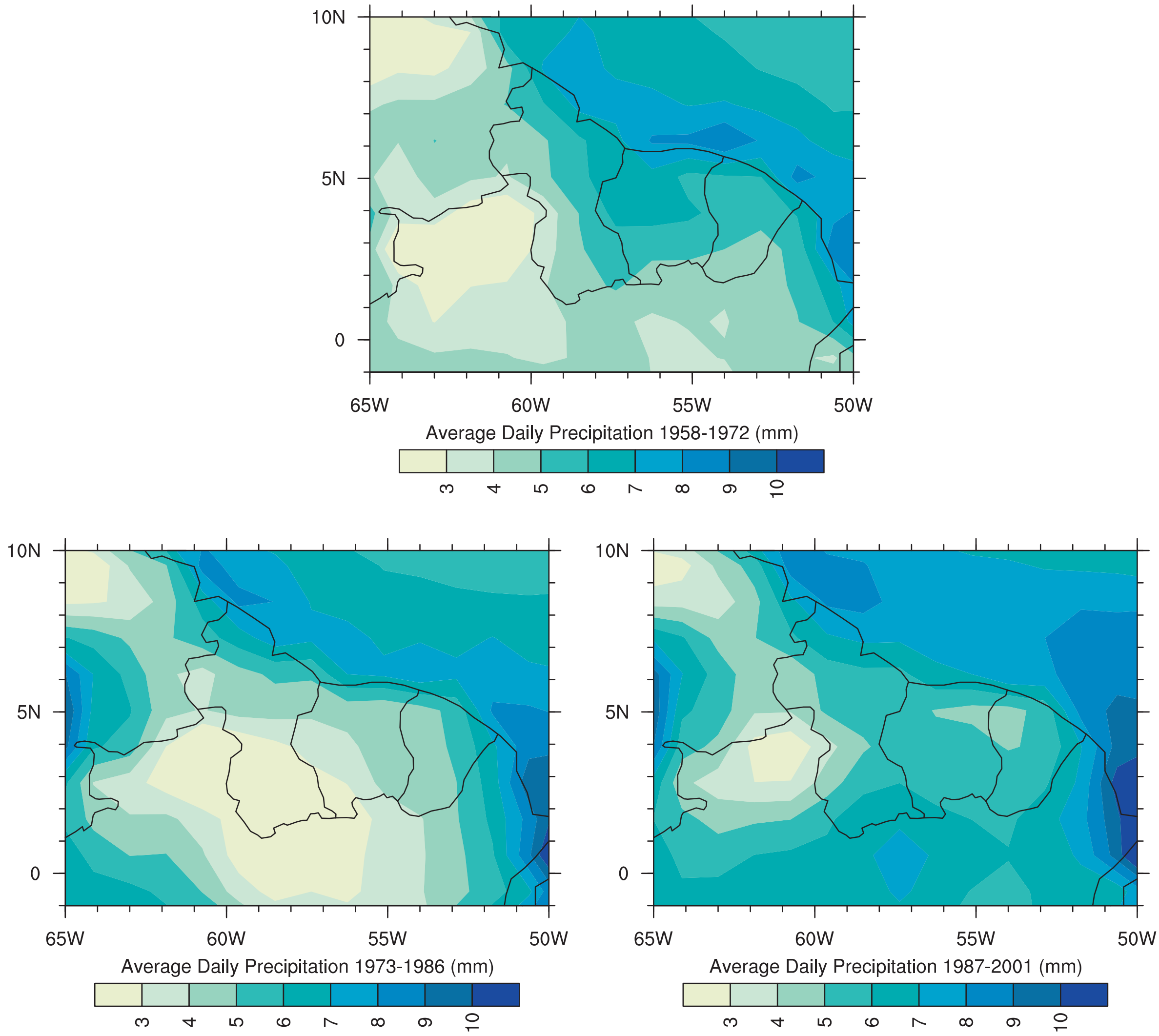

Figure 13. Cylindrical equidistant contour plots of annual ERA-40 reanalysis average daily precipitation for 1958–1972, 1973–1986 and 1987–2001. Average precipitation for 1973–1986 was particularly low (pale) in southern Guyana compared with 1958–2001 average, whereas 1987–2001 was particularly wet (dark). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

1400–1800 mm year^{-1} but, for example, St. Ignatius near the Guyanan–Brazilian border recorded 3620, 1357 and 4449 mm in 1964, 1965 and 1966 respectively, whereas Lethem, less than 10 km from St. Ignatius, recorded 2682, 3315 and 3112 mm in the same years. Similarly, Aishalton about 40 km to the southeast of Dadanawa Ranch, recorded 3757 and 3167 mm precipitation in 1999 and 2000 respectively, whereas Dadanawa Ranch only recorded 1970 and 1364 mm, respectively. Rain shadow effects from south-western edges of the Pakaraima and Kanuku Mountains affecting the savannah and giving rise to different vegetation types have been inferred in a previous study (Frost, 1968).

By examining ERA-40 time series on a grid-cell by grid-cell basis, it is possible to identify the existence and extent of model features, which may be obscured when averaging ERA-40 data over large spatial extents. Grid-cells over French Guiana (Figure 15a), show low precipitation in 1966 followed by extremely high precipitation in 1969, a feature not supported by the observations. This high modelled precipitation probably gives rise to the positive model bias along the Guyanan coast and contributes to the relatively low annual correlations shown in Figure 14. Standardized anomalies for each month between 1958 and 2001 for Figure 15a are shown in Figure 16. It can be seen that anomalously high precipitation occurs only between March–May, July and October–December 1969 and not throughout the whole year. This coincides mainly with increases in precipitation at the start of the wet seasons. There may, therefore, be problems with the model at this time possibly due to the non-closure of the ERA-40 water cycle budget causing spurious peaks in the atmospheric moisture analysis (Betts *et al.*, 2005) or problems caused by the assimilation of further observational data into the model. For example, Betts *et al.* (2005) note that Brazilian surface synoptic data are assimilated into ERA-40 only after January 1967 (although this is only applicable to the Amazon region). Furthermore, Figure 15b shows extremely low precipitation from 1980 to 1986

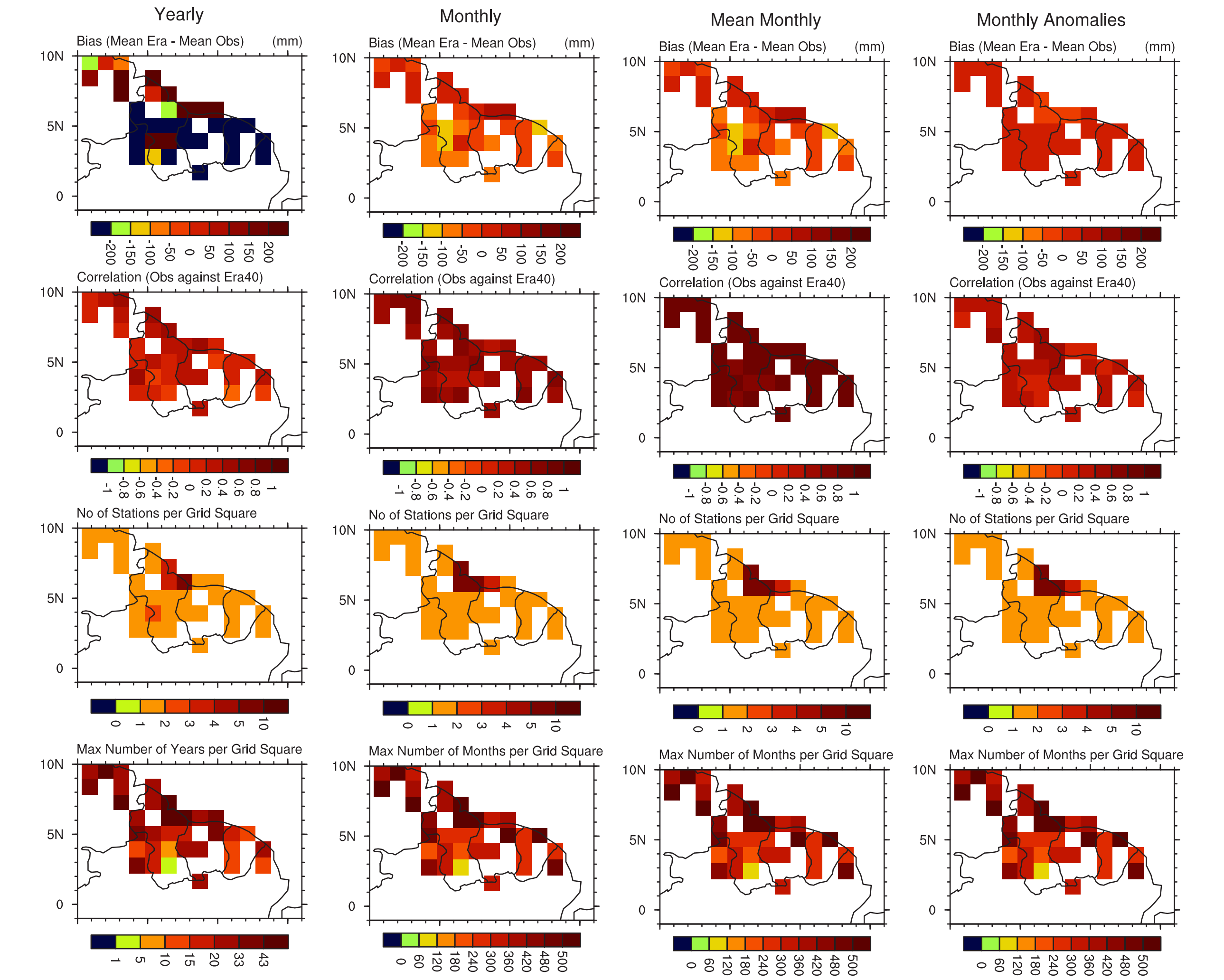

Figure 14. Cross-correlation and mean differences (biases) between observations and ERA-40 precipitation for the period 1958–2001. This is done using yearly (1958–2001), monthly (1958–2001), averaged monthly (January–December) and monthly anomalies. The monthly anomaly time series were calculated by taking the observed or modelled monthly time series (1958–2001) and subtracting the observed or modelled mean monthly (January–December) precipitation time series. Also shown are the number of stations included in the comparison and the maximum number of observations (yearly or monthly) per gauge. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

and very high precipitation in 1997–1999. There are no observations with which to compare these features, however it seems likely that these are also an artefact of the model and that these features are particularly enhanced in areas with few (if any) model-constraining observations. Although spatially averaged precipitation properties are considered accurate enough, individual time series across the region are less reliable due to the presence of these features.

The monthly standardized anomalies in Figure 16 show that precipitation is generally equally variable throughout the year on the Suriname coast. This is also the case around other coastal locations in Guyana (not shown). On the Venezuelan coast, however the monthly standardized anomalies show that precipitation is much more variable between May and September (the wetter months) than for October to April (dry months) (Figure 17).

Figure 18 is similar to Figure 15 except that it compares mean monthly rather than annual time series. Generally, ERA-40 matches observations well, particularly in the timings of maximum and minimum seasonal precipitation. However, certain differences exist: in Venezuela the October dry season is sometimes slightly overestimated; along the Guyanan coast, both dry seasons are slightly overestimated; along the French Guiana cost, wet season precipitation is significantly overestimated although the dry periods are modelled relatively accurately; and inland in the savannah, the wet season appears to be underestimated. As already mentioned however, there are few observations in the savannah to constrain the model and the observed seasonal distribution of precipitation is based on only a few measurements so observations are also less robust. Figure 18b shows that ERA-40 data cannot capture the high precipitation found in areas of higher elevation, again due to topographic relief not being captured adequately by the model.

Despite some problems with the ERA-40 data set, reanalysis data sets provide a spatially consistent, physically constrained climate for the area based on

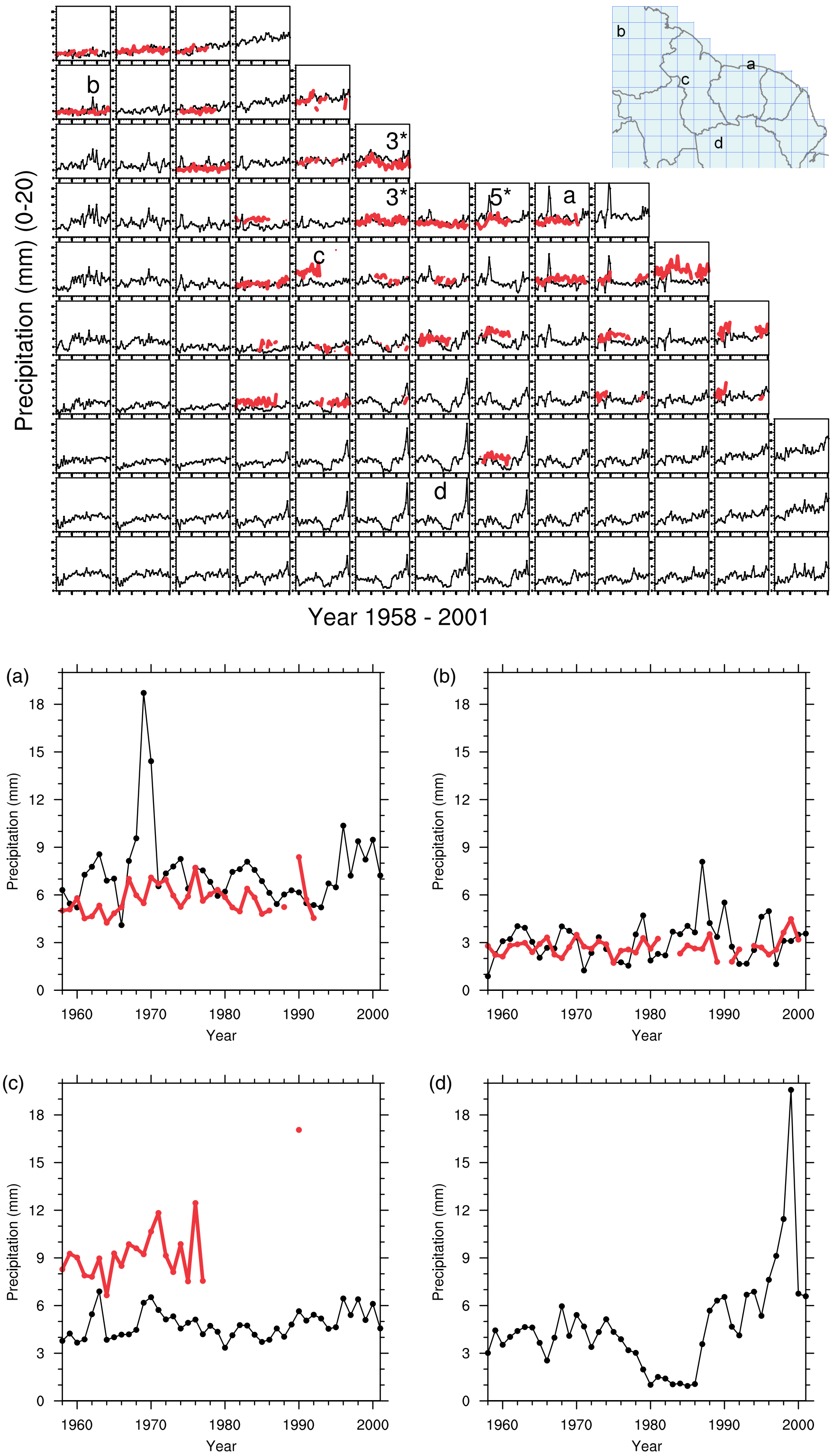

Figure 15. Average annual precipitation (mm d^{-1}) for each year 1958–2001 for the land-based ERA-40 grid-cells (inset). ERA-40 data are shown as a thin black line, whereas single-point observations where available are shown as a thick (red) line; numbers with a star denote the number of stations that have been areally averaged within the grid-cell; all others are the best available single-site observations. Example grid-cells are enlarged below. Standardized monthly anomalies for cells labelled ‘a’ and ‘b’ are shown in Figures 16 and 17, whereas ‘c’ shows where local elevation effects are not adequately represented by ERA-40. ‘a’ and ‘d’ show unrealistic model precipitation. Note that the single-gauge observations in the South of Guyana and are not likely to be representative of the area due to high spatial precipitation variability and lack of spatial and temporal observations. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

global observations and are a valuable data set for studying the climate regime of data-poor areas. Given the relatively high correlation values and low biases found in Figures 8 and 14, the spatial distribution of temperature and precipitation across the region is determined to have been modelled sufficiently well by the ERA-40 data and

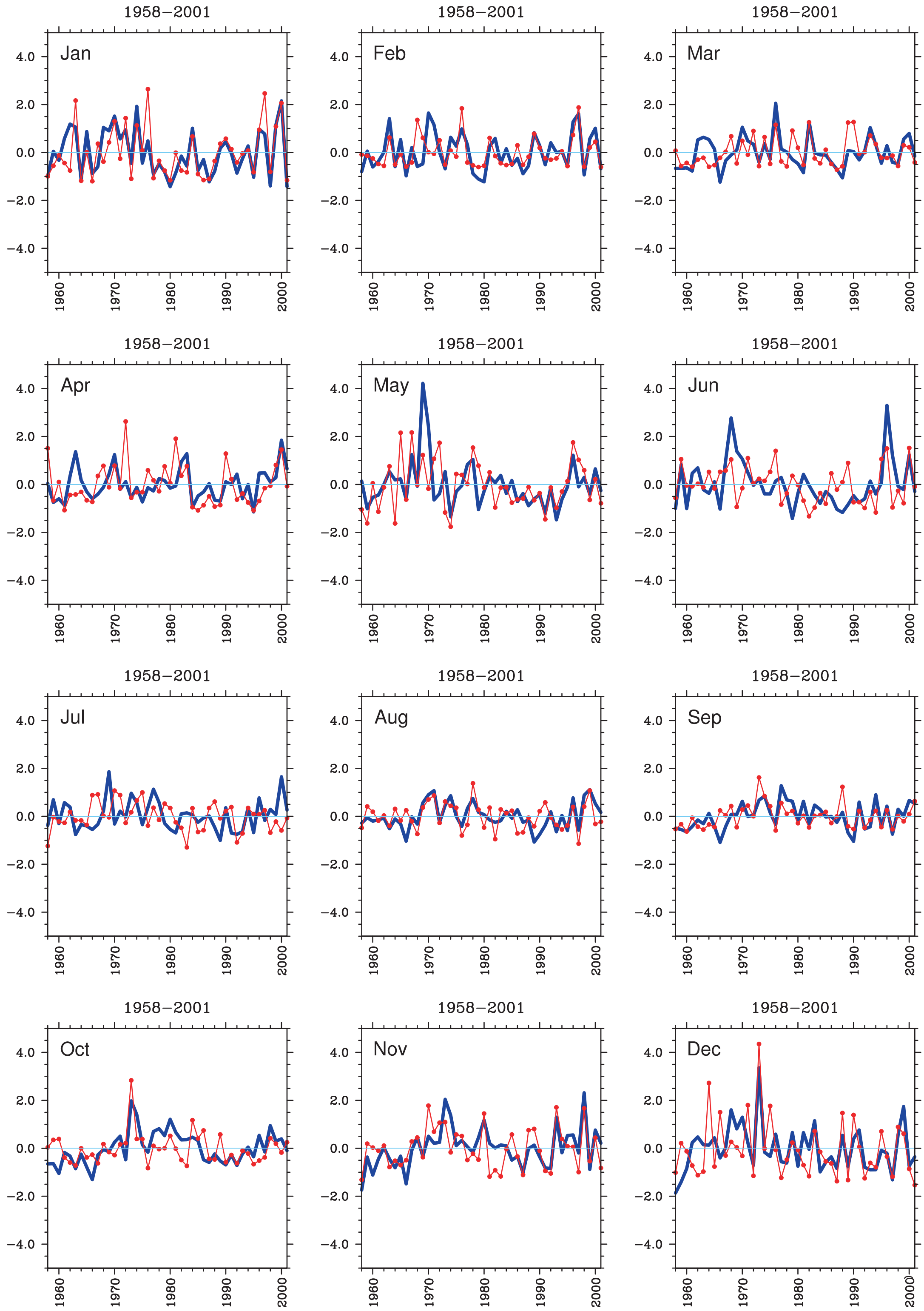

Figure 16. Standardized anomaly shown for each month between 1958 and 2001 for model grid-cell ‘a’ shown in Figure 15. ERA-40 data is shown as a thick (blue) line, areally averaged observations are shown as a thin (red) line. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

will therefore be used to determine averaged monthly temperature and precipitation zones across the region.

5.3. Regional Climate Mapping

A fine-scale and detailed understanding of the regional climate is necessary in order to establish a baseline regime with which to compare the effects of change, for investigating the interdependencies between climate regimes, vegetation systems and their boundaries, and for informing decision makers and local communities about possible changes for mitigation and management purposes. The main results of this work therefore consist

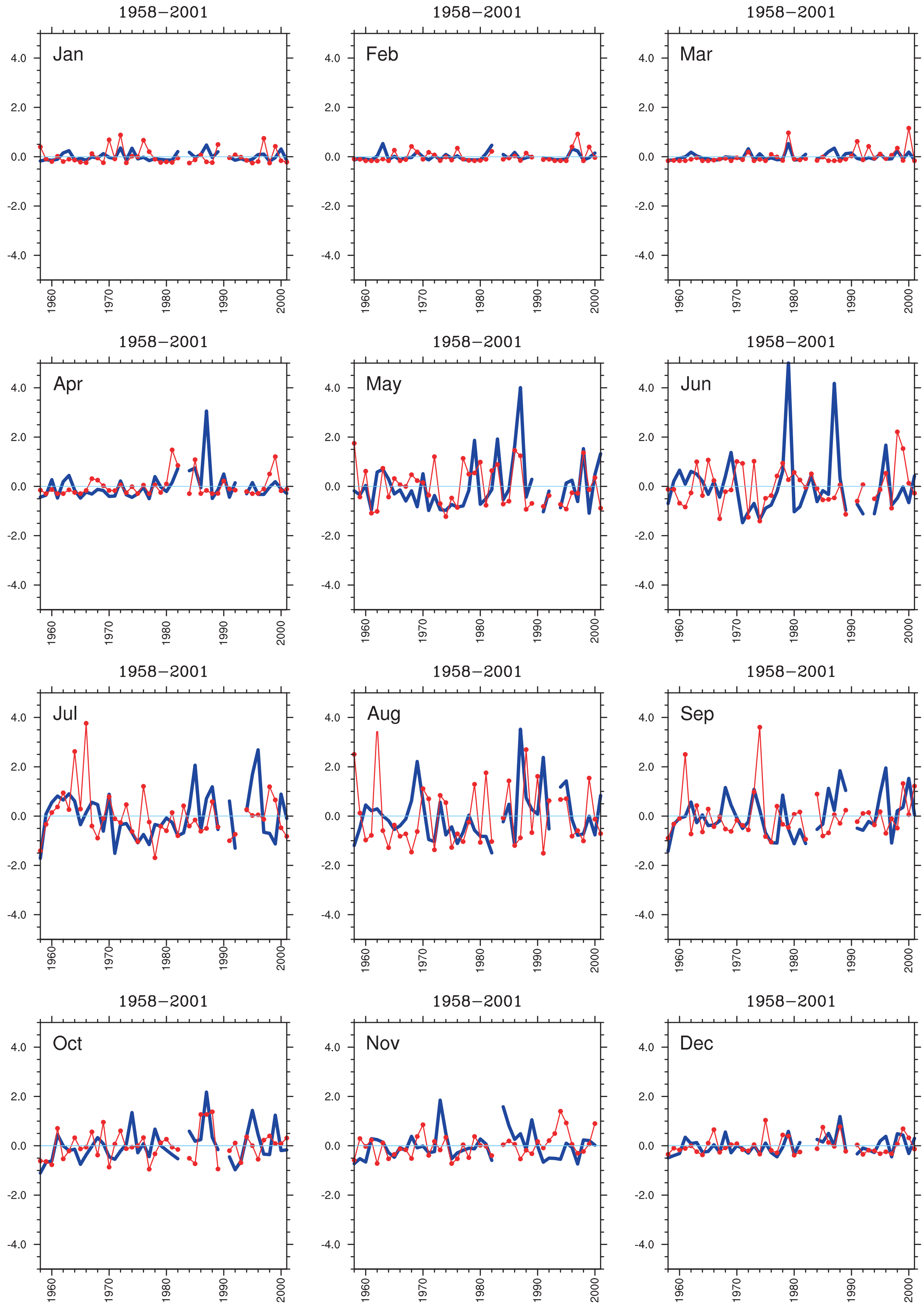

Figure 17. Standardized anomaly shown for each month between 1958 and 2001 for model grid-cell 'b' shown in Figure 15. ERA-40 data is shown as a thick blue line, areally averaged observations are shown as a thin (red) line. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

of the series of maps at a 1.125° resolution showing the spatial distribution of temperature and precipitation and their annual and seasonal variation across the region (Figures 6, 7, 11, 12 and 19). These advance previous work as they give not only the annual precipitation and temperature means but also their seasonal distributions at a fine-scale and in a consistent manner across the region, which are particularly useful in areas lacking observational data.

The annual mean daily temperature variation over the region (approximately 25–27 °C ± 3 °C) is not very large. As rainfall has the most variation, both in annual amounts

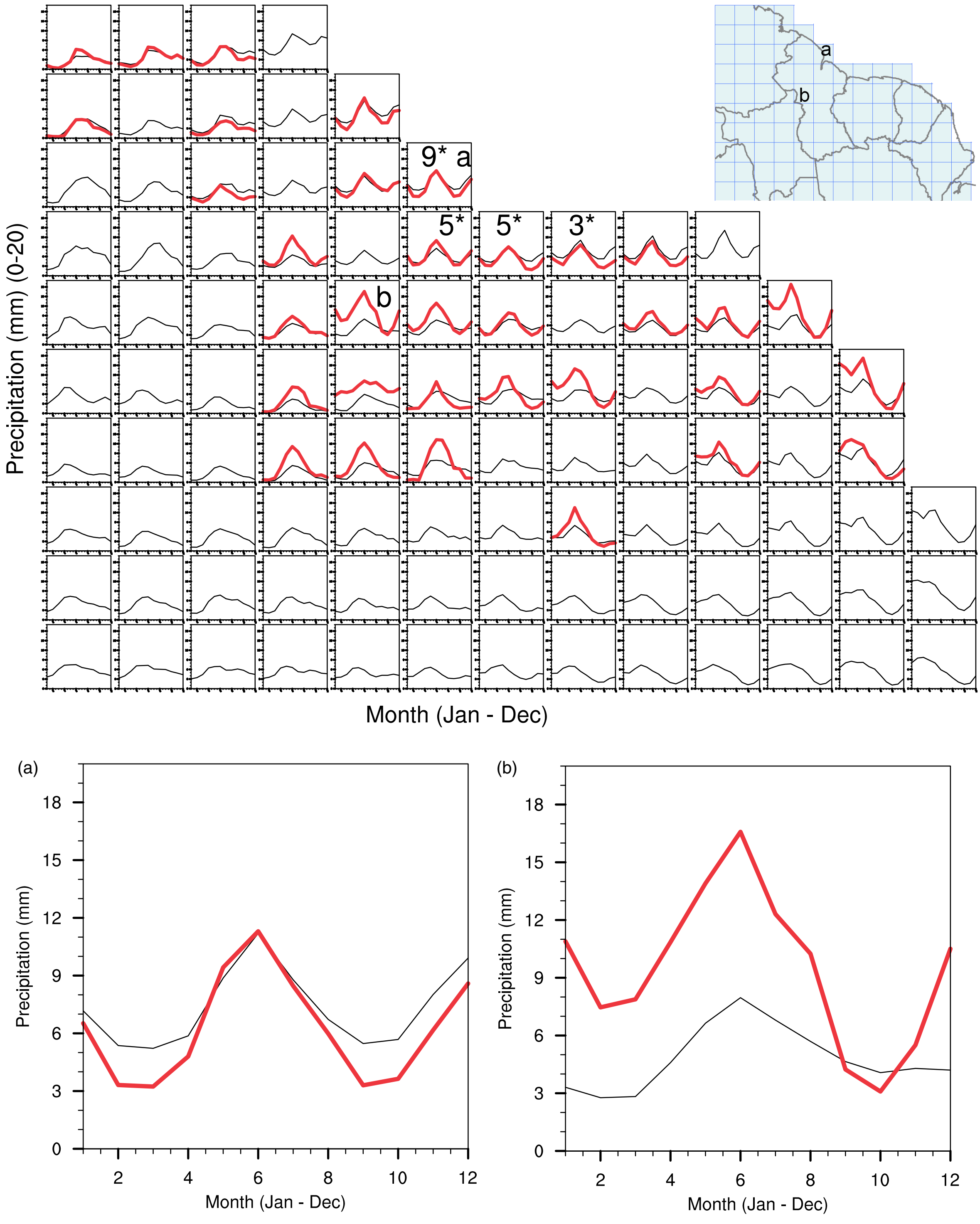

Figure 18. Mean monthly precipitation (mm d^{-1}) for January to December based on data for 1958–2001 for the land-based ERA-40 grid-cells (inset). ERA-40 data are shown as a thin black line whereas single-point observations where available are shown as a thick (red) line numbers with a star denote the number of stations that have been areally averaged within the grid-cell; all others are the best available single-site observations). Example grid-cells are enlarged below. Note that the single-gauge observations in the South of Guyana are likely not to be representative of the area due to high spatial precipitation variability. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

and in seasonal distribution, it is therefore used as the basis for determining regions. The following analysis therefore concentrates on precipitation.

Figure 19 highlights the varied regional averaged monthly precipitation distribution across the region. Similar regions have been grouped and examples from various grid-cells are shown. Generally, average monthly peak precipitation (coinciding with the average minimum temperature) and the onset of the primary dry season show a consistent spatial trend with earlier timing in the east and south.

The coastal areas of Guyana (Figure 19 [1]) has a bi-modal precipitation distribution with two wet and two dry seasons. This seasonal distinction is directly related to the twice yearly passage of the ITCZ over the region. Generally, maximum precipitation corresponds with the overhead position of the sun, usually with a delay of 1 to 2 months. The ITCZ moves northwards during January– May and southwards in August–November. On the Guyanan coast, maximum precipitation occurs in June and December, however the June wet season is usually wetter than the December wet season because the ITCZ moves rapidly and more irregularly over the region in the latter period (Shaw, 1987; McGregor and Nieuwolt, 1998). The primary dry season (also distinguished further east in Suriname and French Guiana) is September–October, whereas a secondary, more local dry season occurs in February–March. The primary dry season is likely to be related to the South Atlantic trade winds, whereas the secondary dry season to those of the North Atlantic (Snow, 1976). During the dry season, coastal rainfall is produced primarily by mesoscale synoptic systems as a result of strong daily surface heating causing high local precipitation variability (Shaw, 1987).

Two-peak rainfall distributions similar to those found on the Guyanan coast are also found further east in Suriname, however peak monthly rainfall in the primary rainy season begins a little earlier in May–June rather than in June. Further east and southeast, in French Guiana and Brazil, peak monthly rainfall occurs in May (Figure 19 [3]). French Guiana lies approximately at the mean latitude of the ITCZ, which oscillates over French Guiana twice annually, first in May and then again in late December and January. When the centre of the ITCZ is to the south (February–April), the onshore trade winds are strong and the ITCZ is still close enough to produce rain (Snow, 1976) so the area of French Guiana and south lacks a secondary dry season (although a small reduction in precipitation is still apparent). The wet season therefore stretches from November through to August, although the primary dry season (September–October) is maintained. South of French Guiana on the Brazilian coast, peak rainfall occurs in February/March (Figure 19 [4]).

In contrast to the coast, the savannah region in southern Guyana and northeast Brazil exhibits a single dry season and a single wet season peaking in May-June and ranging from April to August (this precipitation pattern is also found in the low areas of Venezuela) (Figure 19 [2]). Further inland, peak precipitation occurs in April-May to the southeast (Figure 19 [4]) and in February to the southwest (Figure 19 [5]). During the wet season in the savannah, the low plains are largely under water whilst in the long, dry season there may be airborne dust as temperatures are the highest in the region. In fact, in the primary dry season, less than 100 mm month^{-1} of rain falls across most of the Guianas. Desiccation, even in the inland rainforests can become quite extreme and forest fires can occur at this time. From Figure 13, it appears that the spatial extent of the dry season in the savannah varies year to year and that the savannah region is subject to large interannual variations in precipitation (probably linked with the El Niño Southern Oscillation, Wardlaw *et al.*, 2007, and to rain shadow effects influenced by the Guianan Highlands). It is therefore envisaged that the savannah–rainforest boundary may be particularly sensitive to changes in future climate especially if these change the balance towards (potentially) drier and hotter overall conditions (McSweeny *et al.*, 2009). Further research is needed to establish if the savannah–rainforest boundary can be used as an early indicator for establishing the effects of climatic change.

Figure 19 (inset) also shows zones where precipitation of the driest month (usually the primary dry season) is <60 mm and also <(100 mm − mean annual precipitation/25), following the classification of Peel *et al.* (2007). Areas in Venezuela, southwest Guyana and northern Brazil as well as areas in southern French Guiana and north-eastern Brazil are highlighted. In the Peel *et al.* (2007) classification, these areas correspond with savannah-type vegetation (Figure 2). The savannah areas highlighted in Figure 19 are much broader than those given in Figure 2 and indicate areas where the dry season is particularly severe. The boundaries of these areas may therefore be particularly sensitive to environmental change.

6. Conclusions

The largely pristine and intact rainforests of the Guianas and northern Amazonia are vital for the regulation of the local, regional and possibly the global climate but preclude easy access, so a large data gap exists in this area. The boundary between forests and the adjacent savannah regions may also be particularly vulnerable to increasing pressures from exploitation of the ecosystem and climate change. An improved and more detailed understanding of the regional climate is therefore necessary to establish the baseline conditions necessary for determining the impacts of future change, investigating the interdependencies between climate regimes, vegetation systems and their boundaries, and informing decision makers and local communities about possible changes for mitigation and management purposes.

The main conclusions from this work are as follows:

1. The collated precipitation and temperature data sets for the region indicate that some long, daily historical records are available digitally, which are valuable for establishing long-term trends. However, many datasets have significant gaps in the time series, problems in data quality and there are gaps in geographical coverage. Observations are mainly located along the coast, leaving a large data gap in the interior of the Guianas and the northern parts of the Amazon, mainly due to accessibility issues. Nevertheless, within these limitations and constraints, the available data between 1958 and 2001 has been analysed and up to date average daily precipitation and temperature maps of the region have been produced.
2. To overcome the limitations in using the limited observations for analysing the spatial variation of precipitation and temperature across the region, the use of

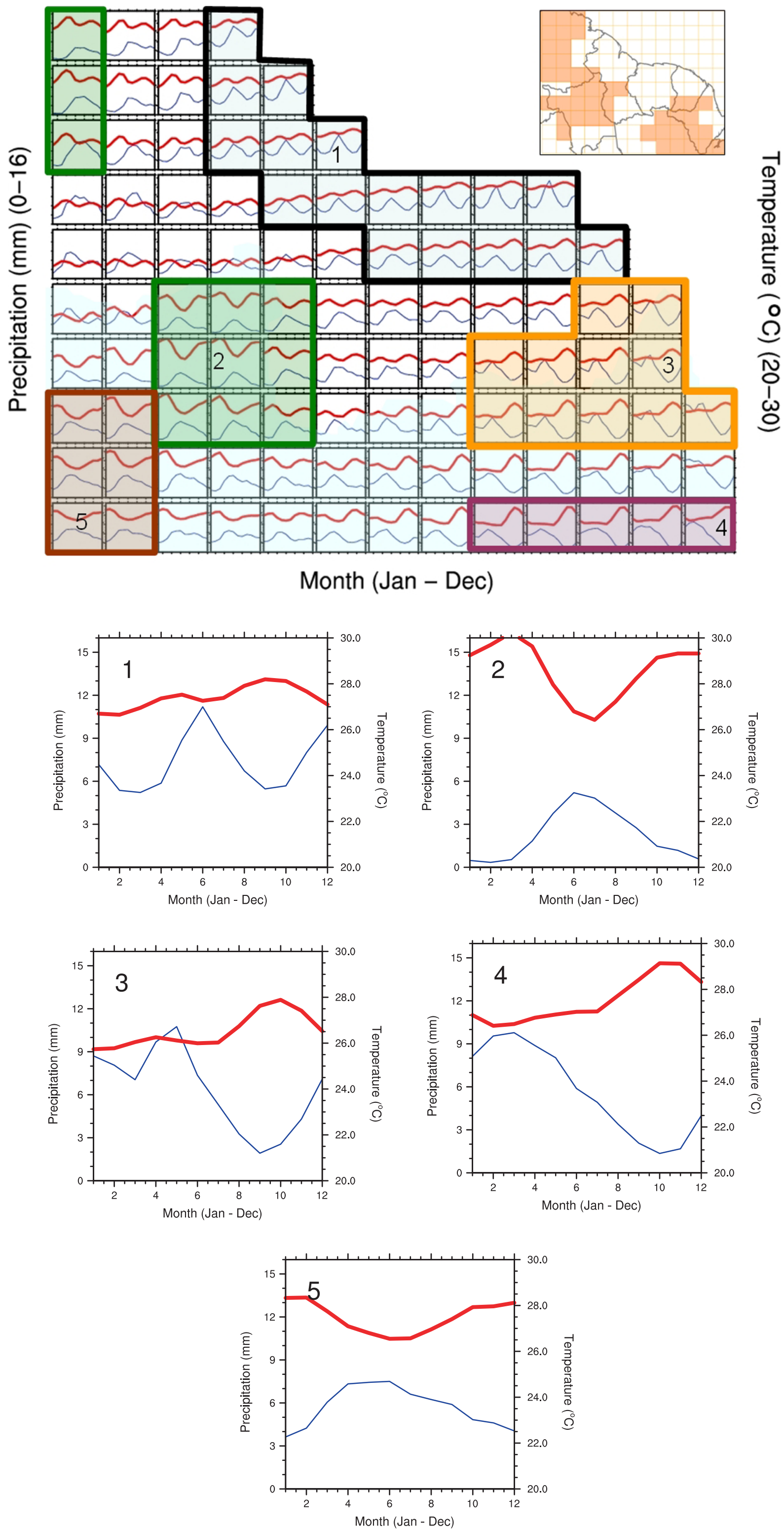

Figure 19. Averaged monthly precipitation (mm d^{-1}) (thin black line) and temperature (°C) (thick (red) line) derived from ERA-40 reanalysis data for each grid-cell over land shown in Figure 1. x axis shows months (January–December); y axis (left) shows precipitation (0–16 mm d^{-1}) and y axis (right) shows temperature (20–30 °C d^{-1}). Similar zones have been highlighted and grouped and an example grid-cell from each zone is expanded below the main diagram. Region 1 corresponds with coastal areas with a bimodal precipitation regime; region 2 has a single wet season peaking in June/July and mostly corresponds with savannah-type vegetation; region 3 shows two relatively unseparated wet seasons and a dry season in September; region 4 has a single wet season peaking in February and a dry season in October; and region 5 has a single wet season peaking in May. Also shown (inset) are the zones defined as savannah using the Peel *et al*. (2007) convention whereby the temperature of the coldest month is ≥18 °C and precipitation in the driest month is < [100 mm − mean annual precipitation/25]. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

ECMWF ERA-40 reanalysis data has been investigated. For 1958–2001, where comparisons with observations were possible, ERA-40 is found to be able to capture relatively well the observed monthly, annual and averaged seasonal temperature across the region. ERA-40 fits to various synoptic observations including temperature, but the observations available in global datasets are very limited for this region suggesting that the model can simulate temperature well in data-sparse regions. The monthly and annual variations of precipitation are modelled less accurately as precipitation is not used as an input to the model. However, the model is skilful in representing the averaged annual cycle of precipitation, and in particular the average timings, length and severity of the dry periods, useful for delineating growing seasons and for investigating climate-vegetation interactions and transitions (although generally the model underestimates the primary wet season rainfall (NDJ) and overestimates the primary dry season precipitation (ASO)). With the exception of sub-grid resolution mountain environments, reanalysis data is therefore shown to provide a consistent and relatively accurate spatial distribution of key climate variables for the Guianas. These encouraging results suggest that it would be valuable to test the validity of the approach in other data-sparse tropical regions.

3. ERA-40 reanalysis data has been used to derive maps of the averaged monthly temperature and precipitation across the region consistent with known broad climatic mapping; however the new analysis provides more quantitative details on the seasonal patterns of temperature and precipitation and their variability at a relatively fine-scale (1.125°), particularly in areas lacking observations.
   In general across the region, the timing of the primary dry season and the average monthly peak precipitation (and therefore average minimum temperature) show a consistent spatial trend with earlier onset in the east and south. However, precipitation in the region is found to be spatially and temporally very variable: along the Guyanan coast, a bimodal seasonal precipitation cycle with dry seasons between February–March and September–October and peak rainfall occurring in June and December results from the twice yearly migration of the ITCZ over the region; further southeast, the February–April dry season is much less pronounced (and is considered wet); whilst inland a climatic transition zone, broadly corresponding with the rainforest–savannah boundary, leads into a single seasonal precipitation cycle with a dry season extending from October to March and a wet season peaking in May–June. This detailed spatial information is essential for evaluating and simulating the future effects of environmental change on the main vegetation zones and boundaries and for understanding ecosystem response.
4. As the region has particularly high spatial precipitation variability, care must be taken when averaging modelled data over very large geographical areas as this will result in a loss of regional detail and may result in errors if comparisons are made between gridded data sets based on few observations and model data.
5. The rigorous assessment and evaluation of existing data highlight a clear shortfall in observational data, requiring a strategic regional approach to improve monitoring of key climate data in the region and to integrate local climate information from the Guianas into a tropical South American context.

Although ERA-40 has been used in this study, a new ERA-Interim data set based on an improved model hydrological cycle in terms of water vapour, clouds and precipitation (Uppala *et al*., 2008) is now available, which improves bias and interannual drift of precipitation over the Amazon but affects the temperature bias (Betts *et al*., 2009). Other reanalysis data sets such as ERA-interim and the NCAR/NCEP reanalysis should therefore be tested to see if their performance is better than ERA-40 in this region in the future.

This is the first study of the recent historical climate and its variability in the Guianas. The general precipitation and temperature regime of the area has been established and can be used as a basis for comparison with future research involving climate and climate change.

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