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Regional climate model performance in the Lake Victoria basin

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Abstract Lake Victoria, the second largest freshwater lake in the world, plays a crucial role in the hydrology of equatorial eastern Africa. Understanding how climate change may alter rainfall and evaporation patterns is thus of vital importance for the economic development and the livelihood of the region. Regional rainfall distribution appears, up to a large extent, to be controlled by local drivers which may be not well resolved in general circulation model simulations. We investigate the performance over the Lake Victoria basin of an ensemble of UK Met Office Hadley Centre regional climate model (HadRM3P) simulations at 50 km, driven by five members of the Hadley Centre global perturbed-physics ensemble (QUMP). This is part of the validation of an ensemble of simulations that has been used to assess the impacts of climate change over the continent over the period 1950–2099. We find that the regional climate model is able to simulate a lake/land breeze over Lake Victoria, which is a significant improvement over the driving global climate model and a vital step towards reproducing precipitation characteristics in the region. The local precipitation correlates well with large-scale processes in the Pacific Ocean and Indian Ocean, which is in agreement with observations. We find that the spatial pattern of precipitation in the region and the diurnal cycle of convection is well represented although the amount of rainfall over the lake appears to be overestimated in most seasons. Reducing the observational uncertainty in precipitation over the lake through future field campaigns would enable this model bias to be better quantified. We conclude that increasing the spatial resolution of the model significantly improves its ability to simulate the current climate of the Lake Victoria basin. We suggest that, despite the higher computational costs, the inclusion of a model which allows two-way interactions between the lake and its surroundings should be seriously considered for any new climate projections for the region.

Keywords Lake Victoria · Regional scale modelling · Climate · Perturbed-physics ensemble · Nile basin

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1 Introduction

Lake Victoria is the largest tropical lake in the world and the second largest freshwater lake. Its catchment extends into Uganda, Tanzania, Kenya, Rwanda and Burundi and forms the southern part of the Nile basin. The rainy seasons in East Africa are primarily influenced by the annual migration of the Inter-Tropical Convergence Zone (ITCZ) from north to south and back again across the continent (Nicholson et al. 1996). The rainfall pattern associated to this seasonal movement represents the first EOF of the seasonal rainfall in the region (Indeje et al. 2000). The northward progression of the ITCZ during March, April and May (MAM) is locally referred to as the 'long rains' and the southward progression in October, November and December (OND) referred to as the 'short rains'. Asymmetries in the temporal evolution of global sea surface temperatures (SSTs) and currents throughout the annual cycle means that the two rainy seasons have different characteristics and different balances of local to global atmospheric driving mechanisms.

In the Lake Victoria basin, the diurnal cycle of convection is strongly influenced by lake/land breezes driven by the thermal gradient between the lake surface and the surrounding land. As the land warms during the course of the day, a lake breeze is generated, which converges with large scale easterlies and promotes convection over the land on the eastern side of the lake (Ba and Nicholson 1998). Anyah et al. (2006) found that the lake–land breeze circulation is effectively enhanced by an anabatic (upslope) component due to the presence of the mountains surrounding the lake basin. While this lake breeze generates convergence over these mountains, it also generates a divergent flow over the lake which in turn promotes subsidence that suppresses vertical development of storms during the daytime. Datta (1981) suggested that latent heating aloft from convection on the eastern shore advects over the lake and stabilises the atmosphere, effectively suppressing convection during the daytime.

The circulation is effectively reversed at night, when the land surface becomes cooler than the lake surface, leading to convergence over the lake and an associated thermal instability (Ba and Nicholson 1998; Yin et al. 2000; Song et al. 2004). This nocturnal process is also enhanced by the presence of the mountains (Anyah et al. 2006) through a drainage current (katabatic wind). This circulation pattern is largely responsible for the convection over the lake in the early hours of the morning, which occurs roughly 175 days per year (Flohn and Burkhardt 1985) and is believed to generate a significant proportion of the water resource for the lake.

Ba and Nicholson (1998) conducted a study using brightness temperatures from geostationary satellites to calculate cold cloud duration over the region, using it as a proxy for rainfall. The resulting data suggests that the diurnal cycle of convection varies by season over the lake and the surrounding catchment. During the long rains, peak rainfall occurs over the lake in the early hours of the morning (0200 LST) and later in the morning over the west coast (0800 LST). During the short rains the lake maximum occurs at 0800 LST, whilst the west coast maximum shift to early afternoon (1400 LST). On the east coast, the peak rainfall occurs at 1700 LST throughout the year. These diurnal patterns were validated against station data from Datta (1981) and also in a subsequent study of cloudiness over the lake by Yin et al. (2000).

The influences of large scale phenomenon in the Pacific and Indian Ocean on precipitation in East Africa is a subject of much research and discussion. Semazzi et al. (1996) used a general circulation model (GCM) to study the teleconnections between African climate and SSTs, finding that variability in African climate due to SST influences is balanced against internal variability of local dynamics meaning that 2 years with the same SST patterns can yield different rainfall regimes. Despite this, there are some more stable SST–rainfall relationships and strong teleconnections influencing East Africa. El Niño years are typically associated with a ~15–20 % increase in precipitation during the short rains over the Lake Victoria catchment area (see e.g. Birkett et al. 1999). Nicholson and Kim (1997) found that rainfall was enhanced during the short rains of an ENSO year but also observed that rainfall in the subsequent long rains was reduced, to a lesser degree. Indeje et al. (2000) concluded that ENSO has an important effect on the monthly and seasonal rainfall patterns in the East African region, including a tendency for more precipitation in the short rainy season. Ntale et al. (2004) found that the Lake Victoria basin and surrounding area had some significant positive ENSO response for November, December and January but also that this region is more likely to experience wetter conditions in the long rains following an El Niño year than a non-El Niño year, in contrast to the findings of Nicholson and Kim (1997). While pointing out that this is an area which is not yet understood, they also suggest a number of mechanisms for the teleconnection between ENSO and East African rains, including a shift in the Walker circulation in central Africa towards East Africa.

The relationship between Indian Ocean SSTs and rainfall anomalies in East Africa is also well established, with the effect also being realised through changes in the Walker circulation over Africa (Hastenrath 1990). There has been much discussion about this relationship, particularly in the context of the anomalously high East African precipitation in the short rains of 1997. This event had serious human, agricultural, hydrological, ecological and economic impacts, including loss of life, housing and infrastructure, crop damage, loss of livestock, an outbreak of Rift Valley Fever in Somalia and high levels of locust outbreaks in Eritrea (see Conway 2004 for a summary). This did coincide with an El Niño event, but the precipitation anomaly was much higher than would usually be expected for such an event: Birkett et al. (1999) identify a ~20–160 % precipitation excess over the Lake Victoria catchment basin during the short rainy season of this year, based on gauge data and satellite measurements. In addition, they quote lake-side reports which said that Lake Victoria levels went up by ~1.8 m in 8 months, an increase which had not been observed since 1961. The large precipitation excess in OND of 1997 has been linked to the behaviour of the Indian Ocean. Strong warming in the West Indian Ocean caused easterly wind anomalies to develop over the equatorial Indian Ocean in SON (Bell and Halpert 1998). A number of feedbacks including extra precipitation over the West Indian Ocean enhanced the warming of the West Indian Ocean further, resulting in the absolute SST gradient between the East and West being temporarily reversed (see Conway 2004 for a summary). Saji et al. (1999) created a climate index [the Dipole Mode Index (DMI)] from the difference between SST anomalies in the West and South-East Tropical Indian Ocean, which is governed by a separate mechanism to ENSO. For example, Webster et al. (1999) identified 16 years between 1950 and 1998 where the equatorial Indian Ocean SST gradient reversed for at least a month but found that only three of these were El Niño years (none were La Niña years). There is an strong relation between the DMI and anomalously high precipitation during the short rainy seasons in East Africa (see e.g. Saji and Yamagata 2003 and references therein). The extent to which ENSO influences or interacts with this system is not yet known (see e.g. Conway 2004).

The interactions between the ITCZ and Lake Victoria itself are also significant. For example, Anyah and Semazzi (2004) have found, in simulations, that cooler lake surface temperatures weaken the ITCZ locally, causing more divergence over the lake, while warmer lake surface temperatures strengthen the ITCZ locally, thus promoting the formation of storm clouds.

The complicated nature of the climate in the Lake Victoria basin and the variety of influences pose particular difficulties for climate models. It is desirable to use a climate model with at least sufficient resolution to resolve the lake itself and the presence of the mountain ranges to the west and the east of the basin. Regional climate models (RCMs) are run over limited areas and therefore can be run at higher resolution. Several previous studies have used RCMs to investigate the climate over Lake Victoria with both realistic (e.g. Anyah and Semazzi 2004) and idealised (e.g. Anyah et al. 2006; Anyah and Semazzi 2009) conditions. Anyah and Semazzi (2004) used the RCM RegCM2 to investigate the sensitivity of rainfall to lake surface temperature. They showed a significant relationship between lake temperatures and rainfall which varied depending on season and began to explore the mechanisms for the differences. Later work in Anyah and Semazzi (2009) used idealised experiments to show the influence of surface currents as well as temperature on rainfall and pointed towards the need to use coupled models to fully realise the lake–atmosphere relationship.

In the wider Africa context, the COordinated Regional climate Downscaling EXperiment (CORDEX, Giorgi et al. 2009) has produced many studies using RCMs to investigate model processes over Africa. CORDEX is an ensemble of dynamical and statistical downscaling models, driven by global climate model runs from phase 5 of the Coupled Model Intercomparison Project (CMIP5), sponsored by the World Climate Research Programme (WCRP). In this context, Mariotti et al. (2011) demonstrated a general model intercomparison of multiple RCM performance whilst Nikulin et al. (2012) focussed in specifically on precipitation. Whilst both of these studies were continent wide, they provide a useful benchmark for RCM investigations over Lake Victoria.

In this study we focus in exclusively on the performance of an RCM over Lake Victoria. RCMs are increasingly being called upon for practical use in downscaling climate projections and for decision making, hence it is extremely important that performance, limitations and recommendations are documented clearly. This study will investigate the capability of the UK Met Office Hadley Centre Regional Climate Model (HadRM3P) as compared to observations. This model underlies the PRECIS regional climate modelling system which is widely distributed and used in many modelling studies (e.g. Bhaskaran et al. 2012; Druyan et al. 2010; Buonomo et al. 2007; Marengo et al. 2009; Xu et al. 2006; Cerezo-Mota et al. 2011). We will use five model runs, each initialised from a different member of a perturbed-physics global climate model ensemble.

We aim to assess the RCM's ability to capture key meteorological processes, such as the annual cycle of rainfall and the diurnal lake–land breeze circulation. In addition we will investigate the large scale influences on precipitation over the lake in the RCM and teleconnections with the Indian and Pacific Oceans. The primary objective of this study is to gain insight into high-resolution climate model performance as well as providing guidance for the interpretation of climate change projections in the region.

Section 2 provides details of the RCM set-up and the ensemble of runs used in this study, along with the available observational precipitation data sets. In Sect. 3.1 we investigate the climatology given by the RCM runs for the Lake Victoria basin and compare to observations, paying particular attention to precipitation and circulation patterns. We discuss correlation in the model between local precipitation and large scale influences such as ENSO and the Indian Ocean Dipole in Sect. 3.2. In Sect. 4, we comment on the evolution of the lake–land temperature contrast with time in the model. We finish with a summary of our main findings and the implications for the interpretation of climate projections.

2 Materials and methods

2.1 Regional climate model runs

Our analysis uses a five-member ensemble of RCM projections for Africa. This ensemble was created using the regional climate modelling system developed at the Met Office Hadley Centre (PRECIS) at a resolution of 50 km

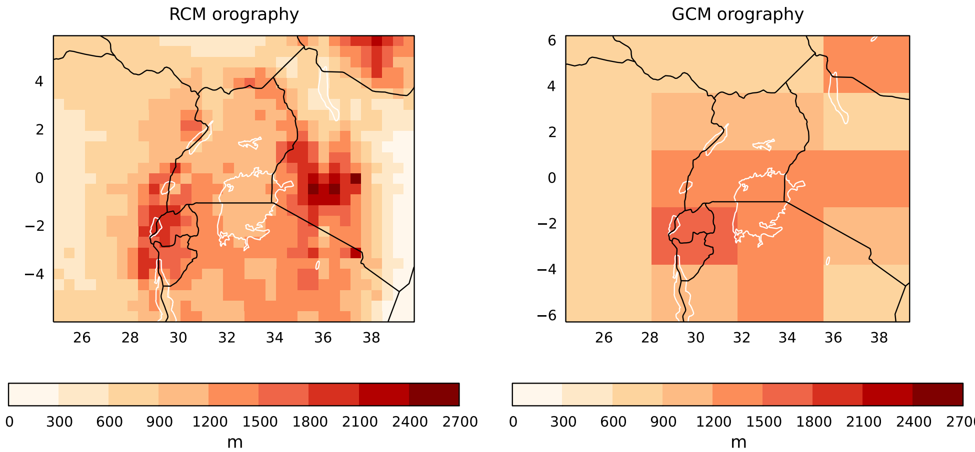

Fig. 1 *Left* the orography of the RCM runs (PRECIS at 50 km). *Right* the orography of the GCM runs (QUMP) in a region of East Africa centred on Lake Victoria. Lakes are outlined in *white*, coastline and political borders in *black*

for the SRES A1B scenario (Nakicenovic et al. 2000). The RCM domain extends from 24.64°W to 60.28°E and 45.76°S to 42.24°N. This domain has been chosen to coincide with that used by CORDEX for Africa (AFR-44).

The lateral boundary data for our five simulations were taken from a sub-set of the Hadley Centre's perturbed-physics GCM ensemble [Quantifying Uncertainty in Model Predictions (QUMP)]. The five ensemble members were selected in order to capture the spread in outcomes produced by the full ensemble, whilst excluding any members unable to represent the African climate realistically. The RCM simulations were run from December 1949 to November 2099 with PRECIS, which used the HadRM3P (Jones et al. 2004) model with the MOSES2.2 tiled land-surface scheme (Essery et al. 2001) and the A1B SRES scenario (Nakicenovic et al. 2000). The set-up of these runs and choice of driving GCM data is described in detail in (Buontempo et al. 2013).

The 50 km resolution model orography over the Lake Victoria basin can be seen in Fig. 1 (left), compared to the resolution of the QUMP runs (right). The location of the mountain ranges to the west and east of Lake Victoria are represented at the resolution of the RCM, which have a significant effect on the local climate. As for the vast majority of the CORDEX Africa runs,[1] HadRM3P and MOSES2.2 have no specific lake model and therefore, in the model simulations we are using here, the lake surface temperatures of Lake Nyasa, Tanganyiki and Victoria have been prescribed as a boundary condition (Buontempo et al. 2013). These values were obtained by taking the mean temperature of the nearest sea point in the unperturbed QUMP run and bias correcting. The twelve values used for the bias correction (one for each month) were calculated from the difference between the climatology of the RCM over a baseline period and the observed climatological mean lake temperature for that month. The observed climatology was provided by the ARClake project (MacCallum and Merchant 2010, 2011), and was based on observations from 1995–2009. In contrast, the two grid boxes covering Lake Victoria in the GCM were both treated as land.

[1] Colin Jones, personal communication.

2.2 Observational datasets of precipitation

In this study we will make use of precipitation observation datasets that are gridded and freely available. The advantage of these is that they are often used in modelling studies to evaluate performance (e.g. Mariotti et al. 2011; Nikulin et al. 2012) and that any gaps in data in space and time have been dealt with so they can easily be compared to model data. There are many rain gauge stations available around the Lake Victoria region but this data does have limited access. Kizza et al. (2009, 2012) make excellent use of the rain gauge network, with Kizza et al. (2012) demonstrating the construction of a new dataset which merges a great number of stations with satellite data. Despite this, no surface stations or weather buoys are present over the lake itself, meaning that all observation records of lake precipitation have been compiled exclusively from satellite data and/or interpolated from nearby surface stations.

In this paper we make use of four observational datasets:

1. The Climate Research Unit (CRU) precipitation dataset (Fig. 2 top row) from the University of East-Anglia consists of a long record of rain-gauge data from ground stations from 1901 to the present day and uses a complex interpolation method to fill in gaps between stations (Mitchell and Jones 2005). This dataset does not provide values for precipitation over the ocean. While this dataset does provide an estimate for precipitation over Lake Victoria, this has been interpolated from nearby stations on the land. The dataset has 0.5° resolution.

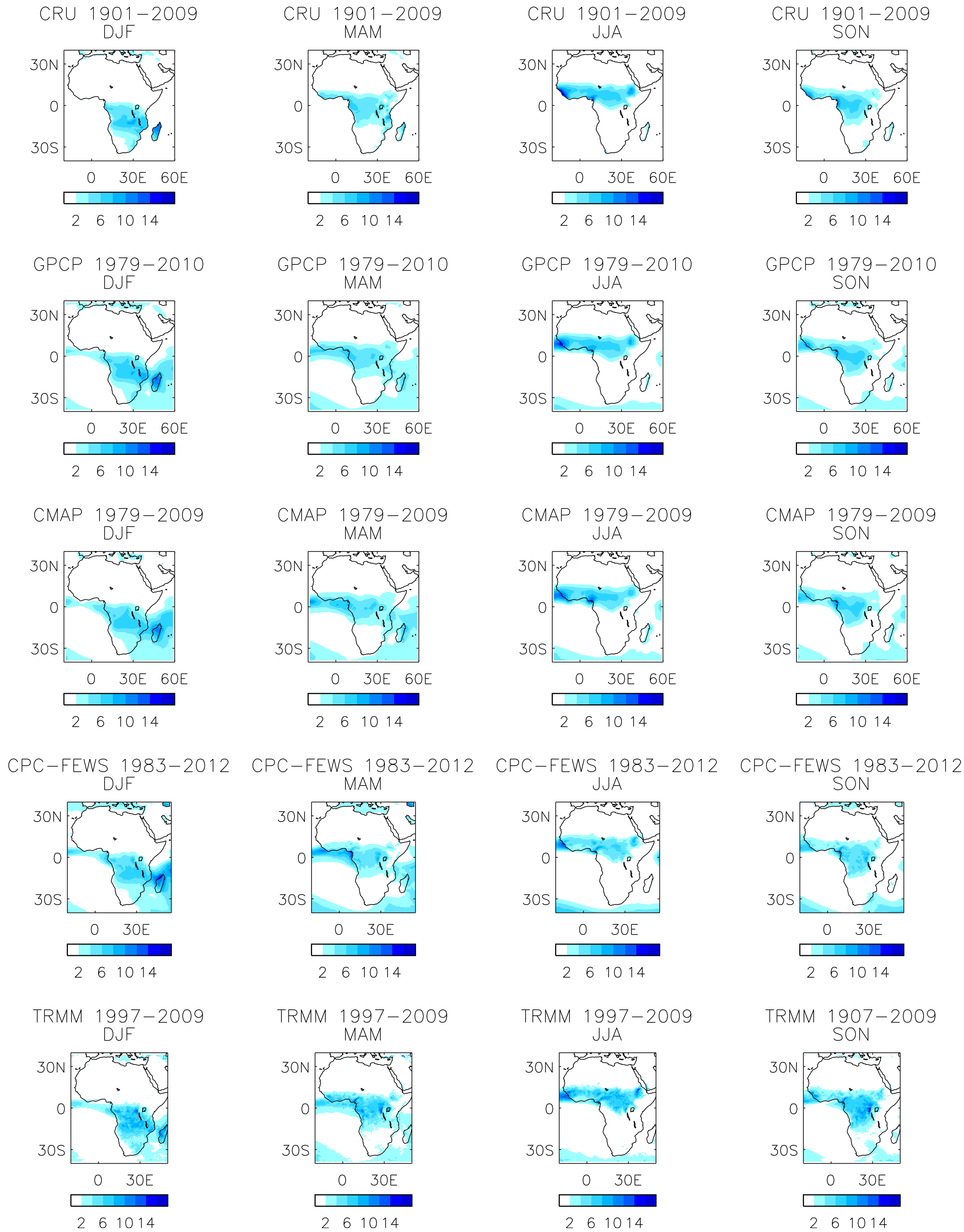

Fig. 2 Precipitation over Africa (in mm/day) averaged over each season for each of the observational data sets referred to in Sect. 2.2

2. The Global Precipitation Climatology Project (GPCP) dataset (Fig. 2 second row) provides rainfall estimations by blending microwave emission recorded by polar satellites (e.g. SSMI) with infrared emissions measured by geostationary satellites and gauge station observations (Adler et al. 2003). The dataset has 2.5° resolution.
3. The Climate Prediction Center Merged Analysis of Precipitation (CMAP) dataset (Fig. 2, third row) uses a similar method to GPCP but blends satellite information from 5 sources (infrared and microwave sensors) and bias corrects them using gauge data and model reanalysis (Xie et al. 1997). The dataset has 2.5° resolution.
4. The Climate Prediction Center—Famine Early Warning System (CPC-FEWS) rainfall product (Fig. 2, fourth row), which combines infrared data from geostationary satellites with gauge data from automatic weather stations on the African continent (Love et al. 2004). The dataset has 0.1° resolution.
5. The TRMM and Other Data Precipitation dataset (Fig. 2, fifth row), 3B-43 product, combines the estimates generated by the TRMM and Other Satellites product (3B-42) and gridded rain gauge data (Huffman et al. 2007, 2010). The dataset has 0.25° resolution.

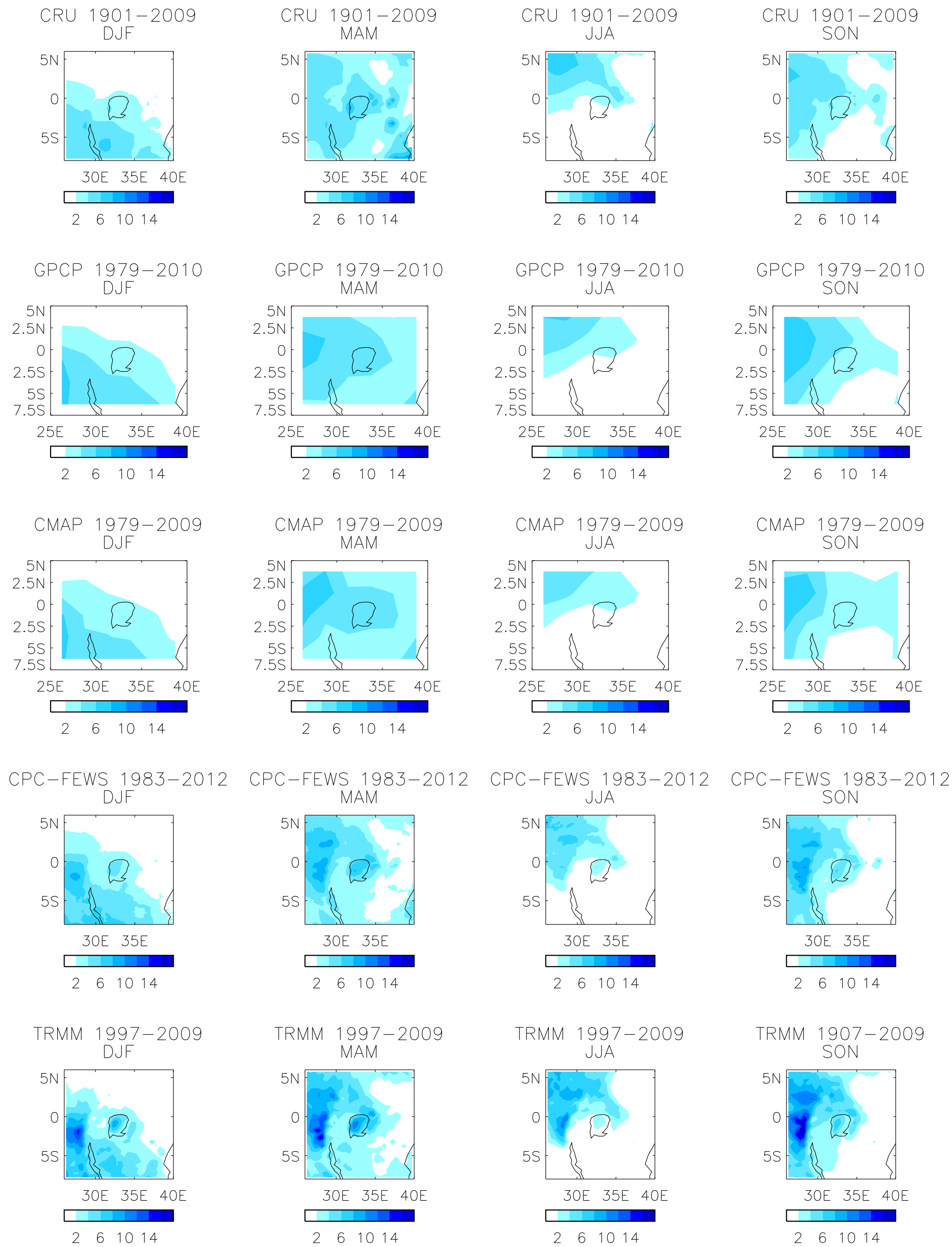

Fig. 3 Precipitation over the Lake Victoria region (in mm/day) averaged over each season for each of the observational data sets referred to in Sect. 2.2

Figure 2 displays the mean seasonal cycle of the precipitation datasets on their native grid, averaged over the time period available for each dataset (given in the plot titles). The main pattern of precipitation is captured by the five datasets in a very similar way, especially in relation to the rainfall maxima in each season, although there are some noticeable differences. The CPC-FEWS and TRMM datasets (fourth and fifth rows) both show regional maxima over some geographic features such as the Cameroon Highlands which are not captured in the other datasets and can potentially be attributed to the higher resolutions of these datasets with respect to the other three. The TRMM dataset appears to be the wettest dataset over the easternmost part of the Congo basin in all seasons but particularly in MAM and SON.

The differences between observational datasets become more obvious when looking specifically at the Lake Victoria region (Fig. 3). Both the CPC-FEWS and TRMM

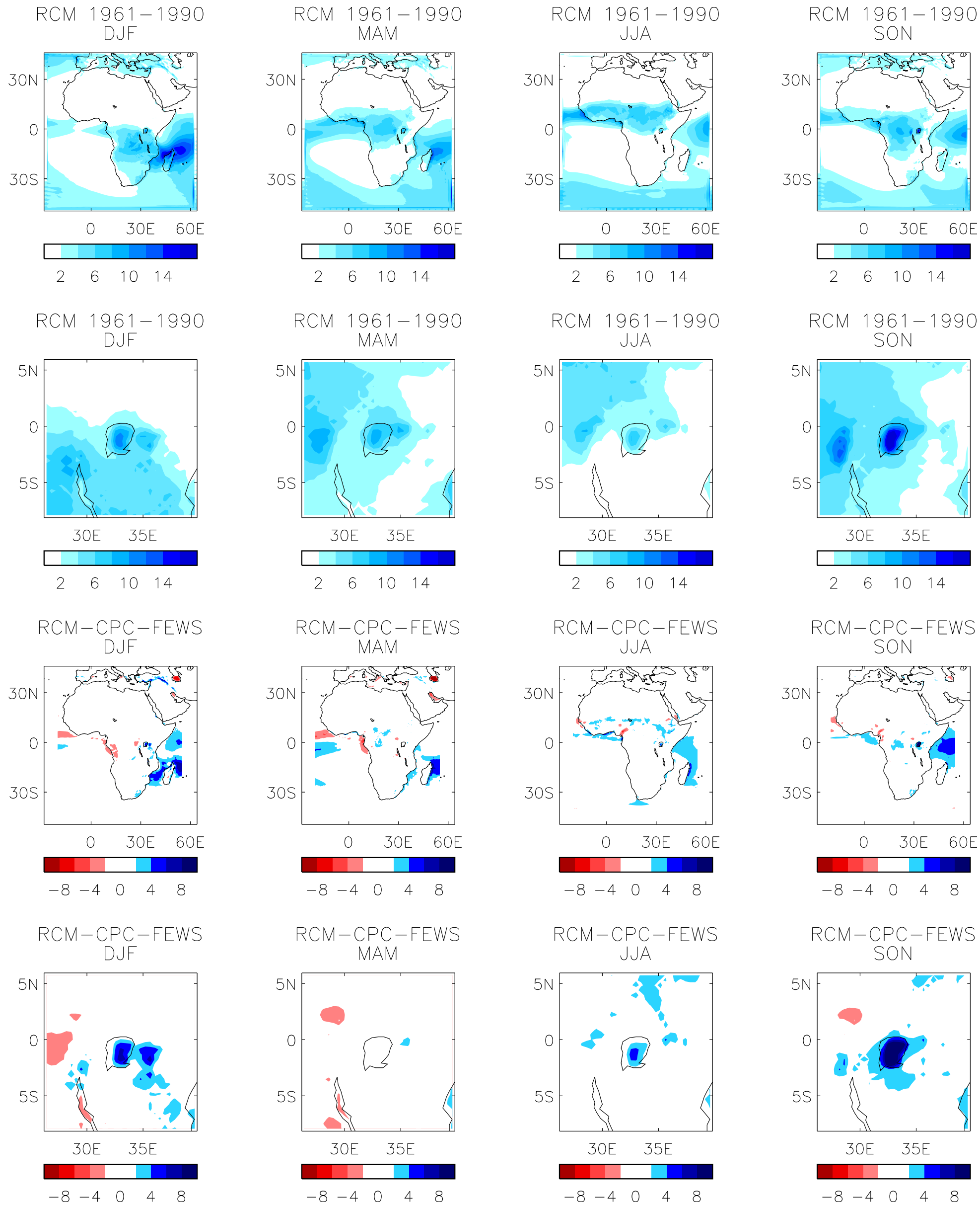

Fig. 4 Average rainfall (in mm/day) for each season over the African continent (*first row*) and over the Lake Victoria region (*second row*) from the baseline model runs, averaged over the five ensemble members, and model bias (*third* and *fourth* rows) when compared to CPC-FEWS

datasets, show an enhancement of precipitation over the lake in all seasons which is not apparent in the other datasets, likely due to a combination of their high resolution and their inclusion of satellite data, allowing the lake to be resolved. The precipitation maximum over the lake is particularly pronounced in TRMM in DJF and MAM. CRU, CPC-FEWS and TRMM all show a precipitation enhancement on the north-east coast of the lake in many seasons, which GPCP and CMAP are unable to capture given their lower resolution. The north-east coast is an area where forecasters have observed storms regularly forming[2] in the afternoon/evening, which then subsequently move over the lake and increase in size and intensity. These meteorological details can have significant impacts on local climatology. Figure 3 demonstrates that the increased resolution of the CRU, CPC-FEWS and TRMM datasets allow us to gain more information on the heterogeneity of precipitation in the Lake Victoria basin, though the lack of reporting stations over the lake inevitably makes the rainfall estimation less constrained by observation and potentially more dependent on the calibration of the satellite sensors in the case of CPC-FEWS and TRMM.

This uncertainty in observational data must therefore be taken into account when assessing model performance.

[2] Chris Tubbs, personal communication.

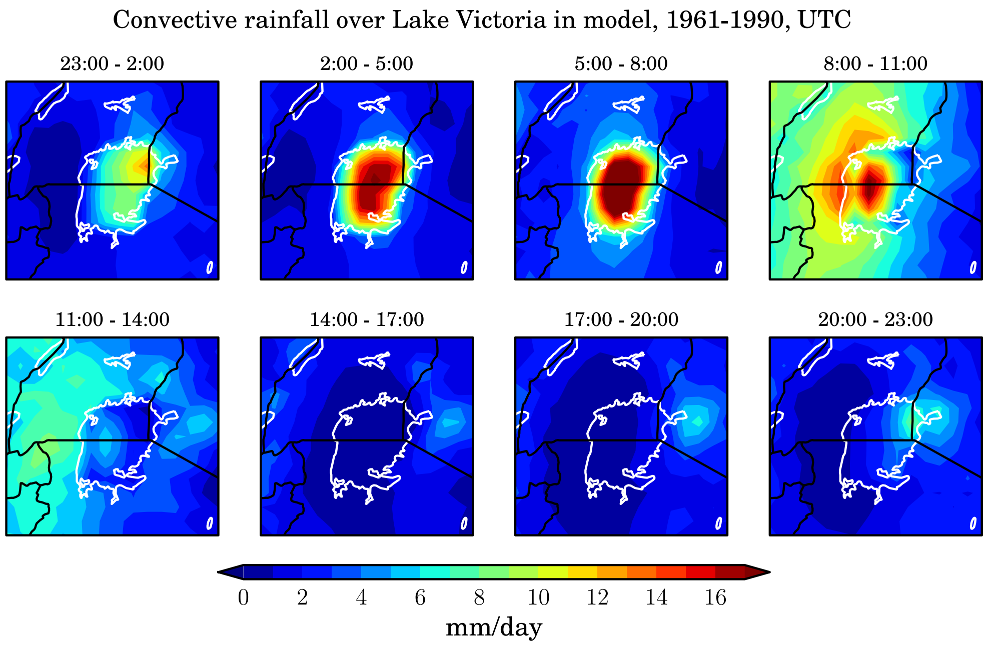

Fig. 5 Convective rainfall in the model, averaged over each day in a baseline period of 1961–1990 and averaged over the RCM ensemble

3 Results and discussion

3.1 Regional climate model performance over Lake Victoria

3.1.1 Spatial distribution of seasonal precipitation

In this section, we use the observational precipitation datasets described in Sect. 2.2 to evaluate RCM precipitation. Figure 4 shows the model annual cycle over the whole continent (first row) and just for the region around Lake Victoria (second row), using the mean of the five-member ensemble of RCM runs. To provide a visual aid in the comparison, the last two rows of Fig. 4 show anomalies from CPC-FEWS observations, chosen due to its inclusion of satellite data and its ability to capture more heterogeneity in the Lake Victoria basin climatology due to its high resolution, but we will consider all of the observational datasets in the following discussion.

Comparing the RCM ensemble mean against the observational datasets shown in Fig. 2 indicates that the RCM ensemble is able to reproduce the spatial distribution of precipitation across the African continent reasonably well in each season (Fig. 4). The RCM ensemble mean also reproduces with some accuracy the seasonal migration of the ITCZ. However, there are some differences: the northern edge of the rain-belt during the boreal summer (June–August), extends further north in the RCM ensemble than in the observations, a characteristic which it shares with the global model HadCM3 on which it is based (see e.g. Buontempo et al. 2013). With the exclusion of these areas, rainfall biases in the ensemble means are generally smaller than 2 mm/day over land. It should also be noted that the RCM ensemble mean appears to be substantially wetter than observations over parts of the Indian Ocean and Madagascar.

Focussing on the Lake Victoria basin (last row Fig. 4), however, reveals more significant model deficiencies. When compared with the observational datasets available, the regional model runs appear to be much wetter over the lake (biases as large as 8 mm/day with respect to CPC-FEWS). The discrepancy between the amount of rain in the model and in observations is particularly pronounced in the late rainfall season (SON), but the bias is also present in the off-peak seasons. The bias is present in all of the individual ensemble members in these seasons (not shown). However, it is also worth noting that very little bias in the ensemble mean is noticed in MAM with respect to the CPC-FEWS dataset and that the MAM ensemble mean has a negative bias with respect to the TRMM dataset. Of course, as discussed in the previous section, it should be considered that there is large uncertainty in precipitation observations arising from the lack of rain gauges over the lake itself. Despite this, the large magnitude of this bias does suggest that the RCM mean has a positive rainfall bias tied to the location of the lake itself, particularly in SON.

On a positive note, the spatial pattern of precipitation compares well with the high-resolution observational datasets which include satellite observations (CPC-

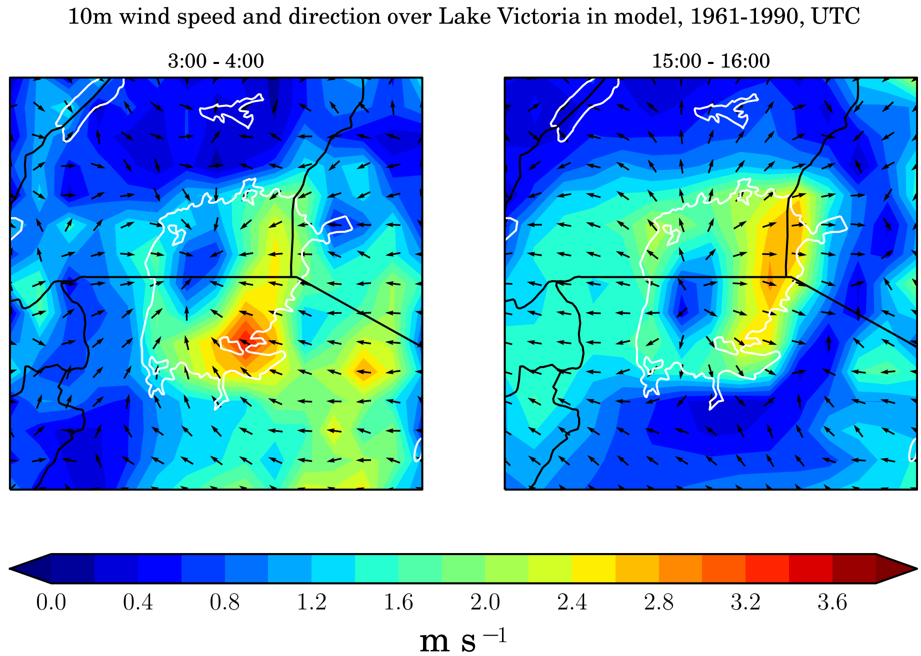

Fig. 6 10 m wind speed (*colour bar*) and wind direction (*arrows*) for 0300–0400 UTC (*left*) and 1500–1600 UTC (*right*) averaged both over the baseline period 1961–1990 and over the RCM ensemble

FEWS and TRMM) and it does capture the maximum in rainfall to the north-east of the lake. The RCM benefits from higher resolution orography compared to GCMs, since, as showed in Fig. 1, the RCM has a much better representation of the mountains surrounding Lake Victoria. This detail may help capture local meteorological influences and begin to somewhat resolve the anabatic/katabatic mountain flow. The higher resolution also allows the generation of a lake/land breeze in the model, as we shall illustrate.

3.1.2 *Spatial distribution of sub-daily precipitation*

As discussed in Sect. 1, rainfall in the region of Lake Victoria experiences a strong diurnal cycle, driven by changes in local circulation. It is well known that, in general, model convection parametrisations struggle with the diurnal cycle of precipitation (Stephens et al. 2010; Stratton et al. 2012; Stirling and Stratton 2012). Model tropical convection over land tends to initiate too early in the day and peak in the early afternoon, rather than in late afternoon/early evening as is observed.

Figure 5 show the diurnal variation in the RCM convective rainfall rate in the region of Lake Victoria, averaged across the entire ensemble for the period 1961–1990. Between 1400 and 2000 UTC, the convective rainfall is maximum in a region to the north-east of the lake. The peak shifts westwards over the lake and by 0200 UTC to 0800 UTC precipitation is a maximum across the entire lake surface and has substantially increased in magnitude. Between 0800 and 1400 UTC precipitation reduces and the maximum is shifted to the western side of the lake.

This compares very well with the spatial pattern of convection found by Chamberlain et al. (2013), who used the cold cloud fraction (the fraction of cloud with temperature below 210K) derived from the 2009 satellite IR data from the GridSat database (Knapp et al. 2011) as a proxy for convection at different times of the day. However, the relative magnitude of the early-morning peak over the lake and the late-afternoon peak on the north-east of the lake in the GridSat analysis differs from that produced by the RCM, which is consistent with the large precipitation bias in the RCM over the lake, which we have already identified in Sect. 3.1.1. In addition, the GridSat data shows the late afternoon peak to be split in to two distinct areas, separated by the Winam Gulf, which is the gulf extending to the North West of the lake and can be seen in the lake outline plotted in Fig. 5. This level of orographic detail is not resolved in the RCM, as illustrated in Fig. 1.

3.1.3 *Sub-daily circulation*

The diurnal cycle of rainfall over Lake Victoria is heavily influenced by the cycle of temperature differences between the lake and the land surrounding it. These temperature differences generate a land/lake breeze that enhances and suppresses convection over the lake over the course of a day. The previous section demonstrated that the rainfall pattern is reproduced in the RCM ensemble, here we look at the circulation patterns.

Figure 6 shows the 10 m mean wind speed and direction averaged over the RCM ensemble over a baseline of 1961–1990. The results have been split into two time bins: 0300–0400 UTC (left) and 1500–1600 UTC (right). These

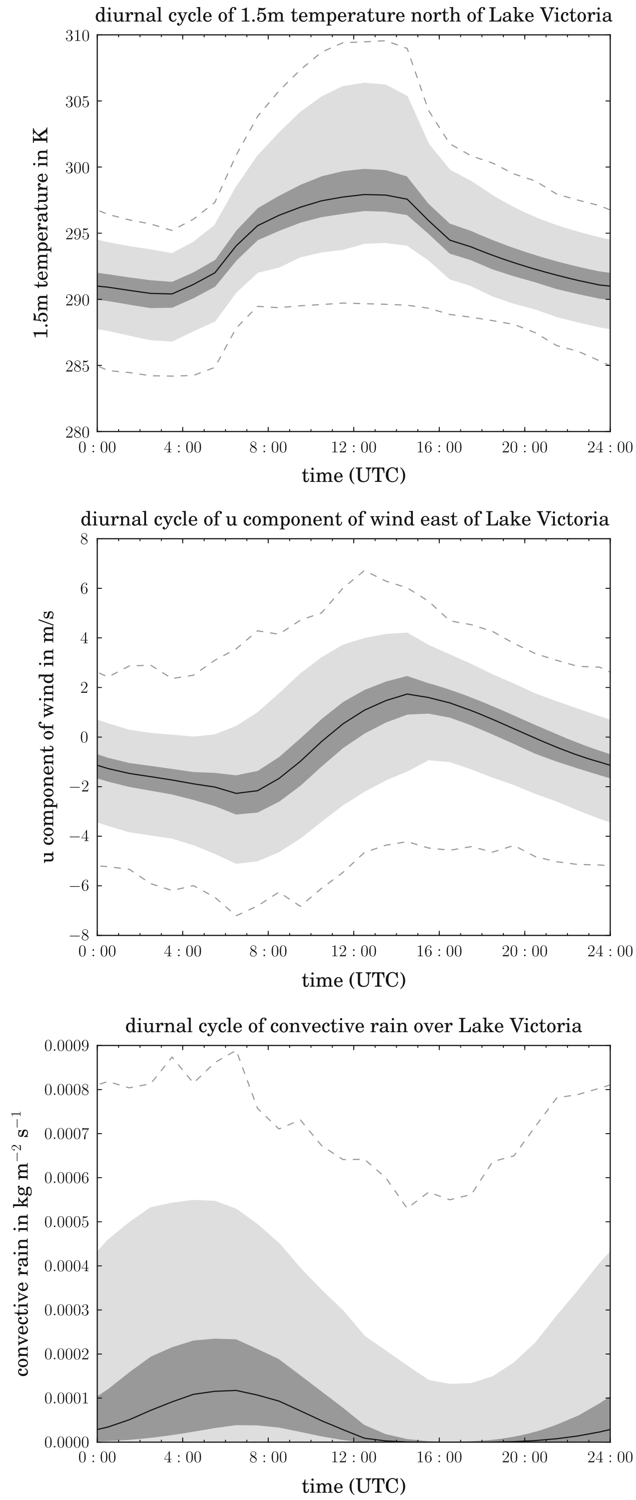

Fig. 7 The diurnal cycle in 1.5 m air temperature to the north of the lake (*top row*), the westerly component of the wind on the east of the lake (*middle row*) and convective rainfall over the lake (*bottom row*) in the model in the period 1961–1990. The median hourly value over all days and all members of the RCM ensemble is shown as a *solid line* and the minimum and maximum is shown by a *dashed line*. The *darker grey* represents the interquartile range and the *lighter grey*, the difference between the first percentile and 99th percentile

times represent the two peaks in lake–land circulation. The left plot clearly shows convergence over the lake at 0300–0400 UTC arising from a land–lake breeze. This corresponds to 0600–0700 LT, approximately the time of sun rise, when the land temperature is near its minimum. At this time, the temperature of the lake temperatures is much higher than the land, leading to a local thermal forcing of the circulation and convergence over the lake. The right hand plot shows the opposite effect and corresponds to 1800–1900 LT. This is at sunset when the land has warmed all day, setting up a positive thermal gradient from lake to land, resulting in low level wind divergence over the lake.

Being able to resolve the lake and land breeze is a significant success of the RCM, as compared to the driving GCM. An additional success of the RCM circulation is its ability to capture the increase in wind speed due to the change in surface properties as the air approaches the lake from the land. Further inspection (not shown) of the differences in model circulation patterns in different seasons showed that they were consistent with the variation in the magnitude of the diurnal cycle of air temperature over the land surrounding the lake between different seasons. For example, the night-time circulation converged over the north-west part of the lake in MAM, whilst the night-time OND circulation converged over the south west.

To further investigate the diurnal cycle over Lake Victoria in the RCM we break down the meteorological components that make up the lake–land breeze circulation. Figure 7 shows three aspects of the RCM ensemble mean for 1961–1990, using 1hr averages from the model. The first plot shows the median 1.5 m air temperature (solid line) in a region immediately north of Lake Victoria (32.34E to 33.66E, 0.22N to 1.54N), which we use here as proxy for the land surrounding the lake.

The second plot shows the median diurnal cycle of the zonal component (u) of the wind (solid line) in a region on the east of the lake (33.48E to 34.76E, −2.64N to 0N), which is used as a proxy for the diurnal cycle of the lake/land breeze. A peak in the diurnal cycle of the u-component in this region would indicate an additional westerly (lake to land) component, and therefore would imply the presence of a lake breeze. Conversely, a trough in the diurnal cycle of the u-component would indicate an additional easterly (land to lake) component, which would allow us to infer the presence of a land breeze.

Finally, the third plot in Fig. 7 shows the the median convective rainfall (solid line) in an area over the lake (31.90E to 34.10E, −2.42N to 0.22N) from the RCM data.

The maximum and minimum values are given by dashed lines. The darker grey region illustrates the interquartile range, while the lighter grey region denotes values between the first percentile and the 99th percentile. The plots

Table 1 Pearson correlation coefficients r between de-trended time series of precipitation over a region covering Lake Victoria and its surroundings (29.26E to 36.30E, −4.18N to 2.42N) in MAM or OND and either the DMI for the same season or the Nino4 ENSO index for the year ending in that season

						Mean
Precipitation in the LV region with DMI						
MAM	0.21	0.40	0.13	0.31	0.40	0.29
OND	0.56	0.81	0.60	0.70	0.52	0.63
Precipitation in the LV region with Nino4						
MAM	0.0046	0.42	0.10	0.21	−0.040	0.14
OND	0.21	0.46	0.47	0.44	0.041	0.32

The first five correlations in each row are for individual ensemble members and the final column is the mean value of these correlations

include data from all five model runs (we have also plotted each run individually to confirm that the characteristics we describe here are exhibited by each individual run).

The temperature over the land starts increasing shortly after sunrise at approximately 0330 UTC, as expected, reaching a maximum at approximately 1300 UTC. We see a clear representation of a lake and land breeze in the u-component of the wind on the east of the shore, with a peak representing the lake breeze at approximately 1500 UTC, and a trough representing the land breeze at approximately 0700 UTC.

After the u-component reaches a minimum (i.e. the land breeze is at its strongest), we see that the rate of increase of temperature over the land is less than we would expect purely from the changing solar zenith angle. We hypothesise that this is the result of the land breeze advecting air away from the heating land.

Similarly, after the lake breeze reaches a maximum in the afternoon, the temperature falls sharply, since it has contributions from both the declining position of the sun in the sky and the advection of cooler air from the region above the lake. This effect is also likely to be assisted by the effect of the lake/land breeze on cloud cover in this region.

The diurnal cycle of convective rainfall over Lake Victoria (Fig. 7, lower plot) also appears to be well represented and out of phase with the u-component of the wind, as we would expect since, as we have discussed, the land breeze enhances convection over the lake in the early hours of the morning while the lake breeze suppresses convection over the lake during the late afternoon/early evening. The peak of the lines representing the lower percentiles (1st percentile, lower quartile) happens later in the day than the lines representing the higher percentiles (upper quartile, 99th percentile), indicating that particularly high rainfall amounts tend to happen at earlier times of the day than more moderate amounts. Individual months show the same qualitative picture of the diurnal cycle in temperature, wind and rainfall, with variation between months in the mean and width of the distribution (not shown).

3.2 Large scale influences on RCM climate in the Lake Victoria basin

A vital component of the climate in the region of Lake Victoria is large-scale influences from the Pacific and Indian Ocean, as discussed in Sect. 1. In order to investigate these processes within the model, we constructed de-trended annual time series and looked at correlations between them. The time series of precipitation over a rectangular region covering Lake Victoria and its surroundings (29.26E to 36.30E, −4.18N to 2.42N) were created by averaging the rainfall in each model over either the long rains (MAM) or the short rains (OND) over the 150 year period covered by the model runs. We calculated times series for the DMI by subtracting SST anomalies in an area in the South-eastern Tropical Indian Ocean (90E to 110E, −10N to 0N) from an area in the Western Tropical Indian Ocean (50E to 70E, −10N to 10N). In addition, we created annual time series of the Nino4 ENSO index from SST anomalies in a region 160E to −150E, −5N to 5N in the Tropical Pacific for 12 month intervals ending in May or December (we used the Nino4 index created from June–May when comparing with the MAM time series of rainfall over Lake Victoria and the Nino4 index created from January–December when comparing with the OND time series of rainfall over Lake Victoria.).

Each time series was de-trended by subtracting a running mean, calculated over a window of $w = 30$ years. We chose to de-trend using a running mean rather than using linear regression since the Nino4 index, in particular, features a non-linear trend from multi-decadal variability and global warming over the course of the model runs. Each de-trended time series therefore contains $n_{ts} = 150 - w = 120$ individual data points.

Table 1 gives the Pearson correlation coefficient r for rainfall over the Lake Victoria region with the DMI or Nino4 index, for the long and short rains for each individual model run.[3] The mean correlation over the ensemble of runs is given in the last column. If we were just testing the correlation between one pair of time series, a correlation with a magnitude above 0.18 would enable us to reject

[3] We describe the analysis here in terms of the Pearson correlation coefficient for clarity. Note that non-linear relationships between the time series will not be represented by this measure. In addition, it should be noted that this measure is not resistant to outlying data, in that the Pearson correlation coefficient can be sensitive to a few extreme points. We have also looked at scatter plots of these time series and the Spearman's rank correlation coefficient (not shown).

the null hypothesis that there is no correlation at the $\alpha = 0.05$ level of significance (using a t test).

However, since we are interested in the ability of the model to capture a particular relation, we are examining the correlations between multiple sets of time series, and therefore we should consider a Bonferroni adjustment when determining whether any of the correlations are significant. When looking at the ensemble of five model runs ($n_{ens} = 5$), we reject the null hypothesis that any one model run is unable to reproduce a correlation between two variables at the $\alpha = 0.05$ significance level when the p value for this run is less than $\alpha' = \alpha/n_{ens} = 0.05/5$, which corresponds to a correlation $|r| > 0.23$.

Applying this to the results shown in Table 1, we can see that there is a clear positive correlation between model precipitation over the Lake Victoria region and the Dipole Mode Index in OND, since each individual run shows a correlation greater than 0.23 and so is significantly different from zero at the $\alpha = 0.05$ level. The mean correlation between precipitation in the Lake Victoria region and DMI in OND is $r = 0.63$. There is also some evidence for a positive correlation between precipitation and the DMI in MAM, since three of the five runs show a correlation above 0.23. The mean correlation between precipitation and the DMI in MAM is $r = 0.29$.

There is also a significant non-zero correlation between precipitation in the Lake Victoria region and the Nino4 index in OND, as three of the five runs have a correlation above 0.23. In MAM, one run shows a significant non-zero correlation ($r = 0.42$) between these variables based on the above criteria.

We have also confirmed that neither precipitation time series show significant non-zero autocorrelation (none of the autocorrelations at a lag of one year have a magnitude greater than 0.18).

As we have discussed in Sect. 1, the two rain seasons in the region are observed to have different characteristics in the real world, with the shorter OND rains being more influenced by large-scale processes than the longer MAM rains. This characteristic is shared by the model. Table 1 shows that the mean correlations for OND are much higher than those for MAM for the correlations between precipitation in the Lake Victoria region and both DHI and the Nino4 index. In fact, looking at the correlations between precipition and the DMI, we can reject the hypothesis that the mean of the difference between each of the five correlations for OND and the corresponding correlation for MAM is zero at the $\alpha = 0.05$ level, using Fisher's Z transformation and a z-test on the difference between the transformed variables. However, using the same method on the correlations between precipitation and the Nino4 index, we are unable to reject the null hypothesis that the mean of the difference between each pair of MAM and OND correlations is zero at the $\alpha = 0.05$ level (p value = 0.13).

When interpreting these correlations, it is important to consider that the surface temperature of Lake Victoria was obtained from adding a bias correction to the value of the surface temperature of the nearest point in the Indian Ocean. This means that there is an artificial link between the behaviour of the Indian Ocean and climate of Lake Victoria within the model. To examine this in more detail, we constructed de-trended time series of Lake Victoria surface temperatures and correlated these with precipitation over the Lake and its surroundings. In OND, these correlations were lower than those between the precipitation and DMI for each individual run. If precipitation in the region of Lake Victoria is more strongly correlated with the DMI than the lake surface temperature, it implies that there is a physical mechanism linking processes in the Indian Ocean to meteorological processes over Lake Victoria.

In order to examine the significance of this result, we tested the hypothesis that the mean of the difference between each of the five correlations between precipitation and lake surface temperatures and the corresponding correlation between precipitation and the DMI was zero (using a z-test, as above). We found that this hypothesis could be rejected at the $\alpha = 0.05$ level. This indicates that the correlations in the model between precipitation and the DMI have a physical component and are not solely a side effect of the approximation used for the lake surface temperatures. We repeated this analysis for MAM, but the results were inconclusive due to the weaker correlation of precipitation with the DMI in this season [we were not able to reject the hypothesis that the mean of the difference between the pairs of correlations was zero at the $\alpha = 0.05$ level (p value 0.45)].

In this section, we have assumed that correlations within the model do not change with time, and therefore that time series can be constructed out of the entire model run. We have examined this assumption by comparing correlations from the first 50 points of each time series with correlations obtained from the last 50 points and found no consistent trend across the ensemble.

To summarise the main results from this section, we find rainfall in the model in the region of Lake Victoria has a strong, positive correlation with DMI in the short rains, a relation which is also found in observational datasets (Sect. 1) and GCMs (see Rowell 2013 for a review). There is also a significant positive correlation between rainfall in this region and the Nino4 index in OND for some of the ensemble members, which, again, has been identified in observations. Some of the model runs also showed a significant positive correlation between rainfall and DMI in MAM. We find the differences between model correlations in the two rain seasons to be significant at the $\alpha = 0.05$ level, which is an important result since it is widely recognised in the literature that the rainfall in this region in the real world is subject to different large-scale influences. Since the correlation between rainfall and DMI in OND is greater and significantly different to the correlations between rainfall and the surface temperature of Lake Victoria, we conclude that these correlations are, at least in part, a result of physical processes in the model, rather than being a side-effect of the method used to obtain lake temperatures. This implies that the model is capturing teleconnections between the Lake Victoria region and large-scale processes in the Indian and Pacific Oceans.

4 Discussion of use in climate projections

As described in Sect. 2.1, the RCM used to create this ensemble does not contain an interactive lake model and instead treats the surface temperature of the lake as a boundary condition, which is calculated by applying a bias correction to the surface temperature of the nearest grid box in the Indian Ocean. This means that, by construction, the change in lake surface temperature with time in the model will follow the warming of the Indian Ocean in the driving GCM. Since we would expect the lake to respond more quickly to a changing climate than the ocean, we expect this method to underestimate the rate of change of lake temperature. Indeed, some authors have found the rate at which the lake is warming may be more comparable to the surrounding land (Schneider et al. 2010). Since the contrast between the temperature of the lake and the surrounding land influences the lake/land breeze, which in turn influences storm formation over the lake and its immediate surroundings, the evolution of this temperature contrast has important implications for the climate of the region. As Song et al. (2004) demonstrated, an interactive lake can play a significant role in determining the position and the intensity of rainfall over and around Lake Victoria. The extra computational cost induced by the presence of an interactive lake is an important practical consideration in running long-term climate simulations for use in a climate adaptation context. Our results suggest that this extra cost is warranted in the case of producing climate projections for the Lake Victoria region.

5 Conclusions

This paper forms part of an investigation into the performance of an ensemble of five 150-year climate runs (Buontempo et al. 2013) of the Hadley Centre regional model HadRM3P over Africa, which were driven at the boundaries by members of a perturbed-physics ensemble. Data from these runs are available on request via the British Atmospheric Data Centre for research purposes.[4] We have concentrated this analysis on the Lake Victoria basin, which is expected to be a particularly challenging region for the model to capture due to the lack of an integrated lake model. We have found that each model run contains a land and lake breeze and reproduces the spatial pattern and temporal pattern of precipitation well, which represents a significant advancement on the global climate model results used for lateral boundary conditions, highlighting the added value obtained from the dynamical downscaling. The ability of the RCM to reproduce important sub-daily features is particularly striking when considering that climate model optimisation tend to focus more on long-term stability of the model than on the sub-daily accuracy. In addition, model precipitation in this region is found to be influenced by processes in the Indian and Pacific Oceans, properties which have been noted in studies based on observational datasets. When comparing model precipitation to observed values, we find that there is a large and positive precipitation bias in the model in most seasons, which is closely tied to the location of the lake.

Without a lake model, a number of significant approximations need to be made in estimating the evolution of the land–lake temperature contrast with time, which has important implications for the local climate. Considering both this uncertainty and the current lack of understanding of the cause of the large precipitation bias in OND over the lake with respect to observations, projected changes in precipitation over the lake in this ensemble should be interpreted with caution. However, it should be noted that the lake represents a very small fraction of the total model domain, which covers the Africa CORDEX region, and that this ensemble remains a valuable source of climate projections for the majority of the African continent (Buontempo et al. 2013).

In order to obtain projections for the future climate over Lake Victoria, we recommend the use of models with sufficiently high resolution in this region to reproduce the key circulation features such as the lake–land breeze, as was found in this ensemble. We recommend that the model is either run globally or driven at the boundaries by a global climate model run in order to capture the influences of large-scale processes in the Indian Ocean and the Pacific. In addition, we recommend the inclusion within the climate model of a lake model which allows two-way interactions between the lake and its surroundings for a more accurate simulation of the evolution of the lake surface temperature.

[4] Please contact the authors for more information.

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