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LAKE-EFFECT RAINFALL OVER AFRICA'S GREAT LAKES AND OTHER LAKES IN THE RIFT VALLEY

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Abstract:	This article examines rainfall over 27 lakes in eastern Africa and compares this to rainfall over the lakes' catchments or surrounding regions, using the TRMM 3B43 and 3B42 satellite rainfall products. A comparison is made for annual rainfall and for rainfall in each month. The diurnal cycle of rainfall is also examined over the lakes and over the catchments/surrounding regions. It is shown that rainfall is enhanced over nearly all lakes and in all months. Contrasts between over-lake and catchment rainfall are greatest at night and during the dry months. For the smaller lakes the enhancement is apparent in both nocturnal and daytime rainfall. Over the largest lakes (Victoria, Tanganyika, Malawi) a single rainfall maximum occurs at night and rainfall is generally lower over the lake than over the catchment during the day. The majority of lakes have a bimodal rainfall maximum, with strong peaks at 06 to 09 LST and 18 to 21 LST. The daytime maximum over the lakes might represent a drift of land systems over the lake but humidity over the lake appears to play a role as well. Except for the large lakes there is strong uniformity in the times of maximum and minimum rainfall (12 LST and 18 LST, respectively) over both the lakes and the catchments. Nocturnal rainfall is common over both the lakes and the catchments. That over the land might be a drift of the systems generated over the lakes.
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Dear Stefanie,

I would like to submit an article entitled "Lake-effect rainfall over Africa's Great Lakes and other lakes in the Rift Valley". It is a full length article and I am the sole author. It is important because it demonstrates for the first time the enhancement of rainfall by even small lakes in East Africa. A preprint has not been made available. The material has not been published previously and is not under consideration for publication elsewhere. Its publication is approved by all authors and the responsible authorities where the work was carried out. If accepted by the Journal of Great Lakes Research, it will not be published elsewhere in English or in any other language, including electronically, without the written consent of the copyright-holder.

Ted Lawrence and Jessica Ives have indicated that a special issue would be published on the African Great Lakes and suggested I consider submission for that. If possible, I would like to have this article so considered.

With best regards,

Sharon

Sharon Nicholson

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ABSTRACT

This article examines rainfall over 27 lakes in eastern Africa and compares this to rainfall over the lakes' catchments or surrounding regions, using the TRMM 3B43 and 3B42 satellite rainfall products. A comparison is made for annual rainfall and for rainfall in each month. The diurnal cycle of rainfall is also examined over the lakes and over the catchments/surrounding regions. It is shown that rainfall is enhanced over nearly all lakes and in all months. Contrasts between over-lake and catchment rainfall are greatest at night and during the dry months. For the smaller lakes the enhancement is apparent in both nocturnal and daytime rainfall. Over the largest lakes (Victoria, Tanganyika, Malawi) a single rainfall maximum occurs at night and rainfall is generally lower over the lake than over the catchment during the day. The majority of lakes have a bimodal rainfall maximum, with strong peaks at 06 to 09 LST and 18 to 21 LST. The daytime maximum over the lakes might represent a drift of land systems over the lake but humidity over the lake appears to play a role as well. Except for the large lakes there is strong uniformity in the times of maximum and minimum rainfall (12 LST and 18 LST, respectively) over both the lakes and the catchments. Nocturnal rainfall is common over both the lakes and the catchments. That over the land might be a drift of the systems generated over the lakes.

KEY WORDS: lake-effect rainfall, East Africa, Rift Valley lakes, diurnal cycle

1. INTRODUCTION TO THE PROBLEM

Dozens of major lakes lie in the Rift Valley of East Africa (Fig. 1). Of these several are considered to be "Great Lakes", based on their size and depth. The largest are Lake Victoria, the second-largest freshwater lake in the world by area; Lake Tanganyika, the second-largest freshwater lake by volume and depth; and Lake Malawi, the world's eighth largest freshwater lake by area. The Rift Valley lakes are one of eastern Africa's greatest resources, providing water for herds, agriculture and hydroelectric power and sustaining the fishing industry. Lake Victoria alone provides the livelihood for over 30 million people.

In recent years, droughts, increasing temperatures, and increased water consumption have led to dramatically decreased levels of lakes such as Turkana and Victoria. This has created considerable hardship in the population around the lakes. In view of the changes already occurring and the sensitivity of the region to climatic change, the longer-term response of the lakes to global warming is a serious concern (Akurut et al. 2014, di Baldassarre et al. 2011). Reliable estimates of lake water balance are critical in evaluating this response and in projecting future water resources. Such estimates are important in interpreting the vast paleoclimatic records obtained from the lakes. They are also required to translate the now routinely disseminated seasonal rainfall forecasts into surface water availability (Ogallo et al. 2008). Assessing water balance for the East African lakes is a complex task, hindered by the difficulty in obtaining meteorological and hydrological data. Estimates have been published for several of the East African lakes. Most estimates are for Lake Victoria (Swenson and Wahr 2009, Vanderkelen et al. 2018, Kizza et al. 2012, Tate et al. 2004, and Yin and Nicholson 1998) and Lake Tana (Tigabu et al. 2019, Rientjes et al. 2011, Wale et al.2009, Chebud and Melesse 2009, Kebede et al. 2006). Estimates have also been made for Lake Tanganyika (Bergonzini et al. 2002), Lake Turkana (Velpuri et al. 2012), Lake Malawi (Lyons et al. 2011), Lake Kivu (Bergonzini 1998, Muvundja et al. 2014), Lake Rukwa (Bergonzini 1998), Lake Edward (Lehman 2002) and Lake Ziway (Goshime et al. 2021).

For most of the Rift Valley lakes the greatest input into the lake's water balance is from rainfall directly over the lake. This is a critical variable because the combined effects of mountain/valley winds and land/lake breezes often enhance rainfall over the lake (e.g., Anyah et al. 2006, Thiery et al. 2015). The best known case is that of Lake Victoria (Flohn and Fraedrich 1966, Flohn and Burkhardt 1985, Kayiranga 1991, Ba and Nicholson 1998, Yin and Nicholson

1998, Nicholson and Yin 2002, Kizza et al. 2012, Thiery et al. 2015, Onyango et al. 2020). Estimates of its enhancement compared to catchment rainfall range from 27 to 82%, but the value is probably around 43 % (Nicholson et al. 2021a). The enhancement is apparent in every month, reaching as much as 50% during some months of the March-to-May "long rains" season and during some dry season months. Satellite-based estimates of over-lake rainfall have also been made for Lakes Tanganyika and Malawi (Nicholson and Yin 2002). Thiery et al. (2015) used a model to estimate rainfall enhancement over Lakes Victoria, Tanganyika, Albert and Kivu. Establishing this component of the water balance is a major challenge (Kizza et al. 2012).

Another striking feature of Lake Victoria is the contrast between rainfall over the lake and over the catchment. As first noted by Flohn and Fraedrich (1966), rainfall over the lake occurs primarily at night, when rainfall over the catchment is at a minimum. During the day, when the maximum occurs over the catchment, clear skies generally prevail over the lake. That contrast is clearly visible in Fig. 2, showing mean rainfall during April at 06 Local Standard Time (LST) and 18 LST (Nicholson et al. 2021b), as is the reversed cycle over the surrounding catchment. Several other early papers also examined the diurnal cycle of rainfall over Lake Victoria (Ba and Nicholson 1998, Nicholson and Yin 2002), demonstrating both its nocturnal character and enhancement compared to catchment rainfall. Nicholson and Yin (2002) also showed a nocturnal maximum over parts of Lakes Tanganyika and Malawi, especially during the boreal winter. Haile et al. (2013) further examined the diurnal cycle over Lake Victoria.

Tan et al. (2019), using the recently available the Integrated Multi-satellitE Retrievals for GPM (IMERG) V06B (Huffman et al. 2019) satellite product, showed that both the intensity and timing of the nocturnal rainfall maximum vary with the season. The maximum is most intense during the March-to-May season, peaking at roughly 03 to 06 local standard time (LST). It is weakest in June-to-August, peaking later at roughly 09 LST. Nicholson et al. (2021b) obtained similar results with the Tropical Rainfall Measuring Mission (TRMM) 3B42 V7 (Huffman et al. 2007, Huffman and Bolvin 2014) and also highlighted the strong minimum over the catchment between 15 LST and 21 LST and the maximum over the catchment between 15 LST and 18 LST. The did not find an afternoon maximum over the eastern-most lake area, in contrast to Onyango et al. (2020) and Yin et al. (2000). The diurnal cycle over the lake was clearly paralleled by the diurnal cycle of Mesoscale Convective Systems, as was its contrast between the two rainy seasons. Nicholson et al. (2021c) concluded that the relative stability of the diurnal cycle is the control by stationary factors, e.g., the lake/land breezes and topographic effects, while large-scale atmospheric factor determine the seasonal changes in the diurnal cycle.

The most extensive study of the diurnal cycle over the lakes of eastern Africa is that of Camberlin et al. (2018). Also using TRMM 3B42 V7, they produced an annual average diurnal cycle over 14 Rift Valley lakes. They distinguished four type of diurnal regimes. Over the largest lakes nocturnal rainfall prevailed, with a maximum around 09 LST for Lakes Victoria and Tanganyika and around 03 LST for Lakes Malawi, Rukwa, and Albert. A late afternoon/early evening maximum prevailed over all other lakes in the study. It occurred at 18 LST in seven of those lakes, most of which experienced a second maximum at 06 LST or 09 LST. Over Lakes Tana and Kyoga a single maximum around 21 LST prevailed.

The purpose of this article is to establish to the extent currently feasible the amount of rainfall of the Rift Valley lakes and compare this with rainfall over the surrounding area. This goes beyond the work of Camberlin et al. (2018) in several ways. For one, 17 additional lakes are examined. Secondly, that work considered primarily the timing of the diurnal cycle and did not consider individual months. Here we emphasize its magnitude as well, examine rainfall in each month, and make calculations both over the lake and over its catchment or surrounding land area. Comparison of over-lake to catchment rainfall is an indicator of the rainfall enhancement via lake effects (lake and land breezes and/or moisture availability) or a combination of lake and topographical effects (e.g., mountain/valley winds or slope winds). Section 2 of this article describes the data used and the approach taken. Section 3 presents the analysis results for annual and monthly rainfall. Section 4 covers the comparison between lake rainfall and rainfall in the catchment or surrounding area. The diurnal cycle is considered in Section 5. A summary and conclusions are presented in Section 6.

2. METHODS

Satellite rainfall estimates are used to evaluate the annual, seasonal, and diurnal cycles for the 27 lakes shown in Fig. 1. At the annual and seasonal scale, maps are presented for five sectors of eastern Africa. The lakes included in these are indicated in Table 1, along with their surface area. Note that some lakes, such as Rukwa, change in size over time. All of the lakes except Victoria and the Kyoga Reservoir fall into four geographical sectors of the Rift Valley. Lakes

Abaya, Chamo Koka, Tana, Ziway, Shala, Abiyata and Langano are in the Ethiopian Rift Valley. Lakes Albert, Edward, Kivu and Tanganyika are in the Western or Albertine Rift. Lakes Baringo, Naivasha, Turkana, Kitangiri, Eyasi, Manyara and Natron lie in the Eastern Rift Valley. The Southern Rift Valley lakes include Rukwa, Malawi, Malombe, Chilwa, Mweru, and Mweru Wantipa. The annual cycle of rainfall shifts from north to south, so that the northern most lakes in the Ethiopian Rift have rainy season in the boreal summer. The rest in that group, plus all in the Western Rift except Tanganyika, have the bimodal equatorial rainfall regime with maxima in the two transition seasons. Most of the lakes in the Eastern Rift do also, but the southern-most tend towards a single maximum in the boreal winter. Lake Tanganyika and those in the Southern Rift (except Chilwa) have a single maximum in the boreal winter.

For the analysis of lake versus catchment rainfall, the actual catchment is considered for the larger lakes and for Lake Tana. For the smaller lakes, for which maps of the catchment could not be found, a "pseudo-catchment" is defined using satellite grid boxes surrounding the lake. This area is selected heuristically by examining the monthly maps in Figs. 3 through 6 and delineating the area around the lake with lower rainfall. These are shown in Fig. 1S in the electronic supplementary material. For the sake of simplicity, the term catchment is used in all cases. For each lake the ratio of lake to catchment rainfall is derived for nocturnal and diurnal rainfall and for each month.

Lake Turkana is a special case. Its catchment includes high-rainfall regions, such as the Ethiopian highlands. However, the lake itself lies in an extremely arid channel. The enhancement over the lake is calculated with respect to this arid region, rather than with respect to the actual catchment.

The accuracy of satellite estimates of precipitation varies as a result of climate, topography, and seasonal rainfall patterns (e.g., Dinku et al. 2018). Consequently, a single product might not be the best product for every lake evaluated. Determining that for each lake is beyond the scope of this study. However, the excellent performance of CHIRPS and TRMM products has been shown in many studies of African rainfall (e.g., Nicholson et al. 2019, Camberlin et al. 2019). Nicholson et al. (2021a) compared six products in the Lake Victoria region. All products produced similar values for catchment rainfall, but estimates were very diverse for over-lake rainfall. However, the best performance was that of CHIRPS2 (Funk et al. 2015) and TRMM 3B43

(Huffman et al. 2007, Huffman and Bolvin 2014) and these appeared to perform exceedingly well over the lake.

A preliminary analysis of all lakes in the current study was performed using CHIRPS2 and TRMM 3B43, as well as the relatively new, high-resolution IMERG Final product (IMERG-F) (Huffman et al. 2019). CHIRPS2 is heavily dependent on gauge data while TRMM 3B43 is primarily dependent on space-born radar data and to a lesser extent passive microwave (PMW) data. IMERG-F is more heavily dependent on PMW data. As was the case with Lake Victoria (Nicholson et al. 2021a), IMERG-F tended to over-estimate rainfall over the large lakes (see also Guilloteau et al. 2017, Petrović and Kummerow 2017). It also appeared to underestimate over the very small lakes. CHIRPS2, with its heavier reliance on gauge data, failed to detect rainfall over many of the small lakes. Thus, consistent with the studies of Camberlin et al. (2018) and Onyango et al. (2020), the current study relies on TRMM 3B42 for evaluating the diurnal cycle and TRMM 3B43 for examining monthly and annual rainfall.

Both TRMM products have a spatial resolution of 0.25 degrees and are available from 1998 through 2019. However, 2019 is not used in this analysis as some questionable data was found over some lakes. TRMM 3B43 has monthly resolution while TRMM 3B42 has three-hourly resolution.

3. RESULTS

3.1 MONTHLY RAINFALL

Figs. 3 through 6 show mean rainfall in each month. The clearest enhancement is evident over Lake Victoria (Fig. 3) and is seen in all months. Several other lakes in this region appear to receive more rainfall than the surrounding area. This is strongly apparent for several lakes in Tanzania, but most notably for Lakes Eyasi and Manyara, where rainfall is higher than in the surroundings in every month. Less pronounced is the enhancement over Lakes Natron and Kitangiri. The lakes in central Kenya, to the east of Lake Victoria, are notably smaller. Because of the relatively low resolution of TRMM 3B43, evaluation of rainfall over the lake itself is difficult. Some degree of enhancement is noted over Lake Naivasha in most months and over Lake

Baringo in the drier months. No enhancement is evident over other small lakes in this region. However, because of the relatively low resolution of TRMM 3B43, it cannot be ruled out.

Fig. 3 also shows four lakes to the west and north of Lake Victoria: Albert, Edward, and Kivu along the western Rift Valley and the Kyoga Reservoir north of Lake Victoria. In some months there appears to be higher rainfall over the lake than over the surroundings, but the effect is not strong. This is later examined further, when rainfall over the lake and catchment is quantified.

Fig. 4 show Lakes Tanganyika, Rukwa, Mweru and Mweru Wantipa. Rainfall enhancement compared to the surrounding area is clear over Lake Tanganyika during the wet season months of October through May and it is particularly strong in the middle and southern sections of the lake. It is not apparent in the dry season. In contrast, rainfall is clearly higher over Lakes Rukwa and Mweru Wantipa during the dry season, when the surrounding region is essentially rainless. The effect over Lake Mweru Wantipa is particularly clear and this might be a consequence of its peculiar characteristics. These include its shallow depth and swampy conditions in some areas, which result in warmer water temperatures than over the larger and deeper lakes, and also the hot springs nearby (Brelsford 1954). This would promote vertical motion over the lake and vertical transport of water vapor. For Lake Mweru over-lake rainfall is not clearly greater than rainfall in the surrounding, although some evidence of a lake-effect is seen in its southern-most region in some months.

Lake Malawi (Fig. 5) appears to enhance rainfall particularly in its central and northern areas. The impact is seen in all months but is most pronounced during the rainy season months of December through April but also in May and June. Lake-effect rains are also strongly evident over Lakes Chilwa and Malombe, especially during the dry season from May through October.

The chain of lakes in Ethiopia and Lake Tana (Fig. 6) show clear evidence of lake-effect rains, especially during the dry months of November through February. The strongest influence appears to be over Lakes Tana, Ziway, and Abaya. Further south, on the Ethiopian/Kenyan border Lake Turkana also exhibits enhanced rainfall compared to its very dry surroundings, particularly during the dry seasons from June through September and December through February (Fig. 6). The overall aridity in this region is related to the presence of the low-level Turkana Jet (Nicholson 2016). The rainfall over the lake stands in stark contrast to that over the dry surroundings.

3.2 RAINFALL ENHANCEMENT OVER THE LAKES

Fig. 7 quantifies the annual average lake effect by presenting the ratio between rainfall over the lake and over its surroundings. For the larger lakes the comparison is with rainfall over the catchment. This is the case for Lakes Victoria, Tanganyika, Malawi and Tana. For the other lakes the comparison is with the "pseudo-catchment", as defined in section 2. In this figure, the three lakes Shala, Abiyata and Langano are grouped together as they are too close to look at the lakes individually. This group is identified in the figure as S/A/L. Some degree of enhancement over the lake is evident for all lakes except Lake Mweru. The enhancement ranges from roughly 1% for the Kyoga Reservoir to near or over 100% for Lakes Chamo, Chilwa, Manyara, and Ziway. The enhancement over the largest Lakes Victoria, Tanganyika, and Malawi is given as 40%, 20% and 30%, respectively. For Lakes Victoria and Tanganyika this is consistent with past estimates of 43% (Nicholson et al. 2021a) and 20% (Nicholson and Yin 2002), respectively. However, the only prior estimate for Lake Malawi (Nicholson and Yin 2002) suggested little net enhancement.

The lake/catchment rainfall ratio for each month is shown in Table 2. Values less than or equal to 1 (no enhancement) are shown in yellow. Ratios exceeding 2 are shown in blue. The second column in the table also indicates if the dry season is predominantly the boreal winter (W) or the boreal summer (S). The table suggests that the enhancement is greatest during the dry season. For example, it is greatest during the boreal winter for the Ethiopian Lakes Abaya, Chamo, Koka, the S/A/L group, Tana, Ziway and also Lake Turkana. The generally greater enhancement during the dry season is confirmed by Fig. 8, which presents over-lake and catchment rainfall for each lake. The exceptions are the largest lakes, Victoria, Tanganyika and Malawi. For several of the Ethiopian lakes there is enhancement year-round.

3.2 THE DIURNAL CYCLE

To examine the diurnal cycle of rainfall, graphs were made of monthly rainfall over each lake and its "catchment". The results are too voluminous to include here in their entirety. However, typical examples are shown in Fig. 9 and characteristic maxima are given in Table 3. The discussion here is based on similar diagrams for all of the lakes. Several things became apparent in surveying these results. One was that in almost every case, a major shift in the ratio of lake to catchment rainfall occurred at 15 LST. This observation led to defining daytime rainfall as 15 LST to 24 LST and nocturnal rainfall as 03 LST to 12 LST.

The second observation was that four patterns of diurnal cycle of the lakes could be broadly distinguished. The examples shown in Fig. 9 illustrate these. The first type is a nocturnal maximum in all months. It is illustrated using Lake Victoria, but Lakes Tanganyika and Malawi (Table 3) also fall into this category. The second type is a daytime maximum in all months. It is exemplified by Lake Kivu but Lake Kyoga also falls into this category. The most common pattern, illustrated in Fig. 9 with Lake Ziway, is a bimodal cycle, with a morning and an afternoon maximum. Thirteen lakes were subjectively assigned to this category (Table 3). In most cases the two maxima are about equal in magnitude. However, for Abaya the afternoon maximum is the greater and for Lake Rukwa the morning maximum is greater. Camberlin et al. (2018) also noted this bimodal pattern for Lakes Abaya, Eyasi, Manyara and Ziway. The fourth pattern is a "hybrid", with a single maximum in the wet season and a double maximum in the dry season. It is illustrated using Lake Chilwa. The single wet season maximum occurs during the daytime.

The diurnal cycles over the lake catchments are more difficult to generalize. For those in category 1, with a strong nocturnal maximum over the lake, catchment rainfall generally has an afternoon maximum, but a secondary nocturnal maximum appears in some months. That is most often the case in the wet months and this may be a spillover from the rainfall generated over the lake (Nicholson et al. 2021b). For lakes in category two (two maxima) and four (wet season/dry season contrast) there is a single maximum over the catchment and it occurs in the afternoon, usually at 18 LST but at 15 or 21 LST in some months. For the numerous lakes in category 3, with two rainfall maxima over the lake, the diurnal cycles over the catchments are more complex. Over roughly half of the catchments there is a single rainfall maximum, usually around 18 LST, but in some cases around 15 LST. Others have a double maximum, the strongest occurring around 15 LST or 18 LST and the secondary maximum occurring around 03 or 06 LST. For Lakes Rukwa, Manyara and Koka maximum rainfall over the catchment occurs at night or in the early morning in some months.

Fig. 10 shows the ratio of nocturnal to daytime rainfall over each of the lakes and over the catchments. The percentage of nocturnal rainfall is almost universally greater over the lakes than over the catchment. The exceptions are a handful of individual months. However, in only a few cases is the ratio greater than one, indicating a nocturnal maximum. The most striking nocturnal regime is that over Lake Victoria. Nocturnal rainfall is roughly four to five times greater than daytime rainfall in all months and catchment rainfall has a daytime maximum (ratio below one) in all months. Tanganyika and Malawi also have a strong nocturnal maximum in all or nearly all months. Over Lakes Albert and Rukwa notable nocturnal maxima occur in some rainy season months. Over Lakes Turkana, Koka, and Kitangiri nocturnal maxima are apparent in some dry season months. Over the last two lakes the nocturnal maxima are strong and occur during several months of the boreal summer. Except for Lake Koka, catchment rainfall has a clear daytime maximum in nearly all months. In a few individual months for Lakes Turkana, Rukwa, Ziway and Kitangiri the catchment maxima roughly equals or slightly exceeds the nocturnal maximum.

The third observation made in surveying the graphs of the diurnal cycle is that there tends to be some uniformity in the times of maximum and minimum rainfall over the lakes and catchments. To examine this, histograms were derived for the mean times of minimum and maximum rainfall over each lake and catchment and in all months. The histograms are shown in Fig. 11. The uniformity is striking as is the similarity between lake and catchment. The time of minimum rainfall is overwhelmingly at 12 LST, with an earlier minimum over the catchment in a few cases. The time of maximum rainfall is overwhelmingly at 18 LST, which is consistent with the fact that for nearly all lakes and catchments there is primarily daytime rainfall (Fig. 10). Not a single maximum occurs at 12 LST, the preferred time of minimum rainfall. Some early morning maxima are evident over the lakes and these are linked to the nocturnal rainfall over Lakes Victoria, Tanganyika and Malawi. A large number of cases show a maximum over the catchment at 15 LST.

3.3 RAINFALL ENHANCEMENT BY NIGHT AND DAY

The greater nocturnal rainfall over the lakes than over the catchments suggests that the degree of enhancement of rainfall over the lakes might differ between day and night. This is examined in Fig. 12, which shows the ratio of over-lake to "catchment" rainfall during the hours of 03 LST to 12 LST versus 15 LST to 24 LST.

For virtually every lake and month, the ratio of lake to catchment rainfall exceeds 1 for the nocturnal period. This indicates at least some degree of rainfall enhancement over the lake at night in all months. Its magnitude clearly varies from month to month. In every case the enhancement is greater during the dry season, to some extent because of the extreme low catchment rainfall during the dry season.

In many cases, there is also an enhancement during the day. This is particularly true for the Ethiopian Rift Valley lakes and Lake Turkana during the dry season. Lakes Eyasi, Manyara, Natron, Chilwa, Malombe, Mweru Wantipa, and Rukwa also showed daytime enhancement, in several cases nearly as large as the enhancement at night. The Western Rift Valley lakes Albert, Edward and Kivu and also the Kyoga Reservoir showed no enhancement during the day and only modest enhancement at night. Lakes Baringo and Naivasha showed no enhancement during the day but substantial enhancement at night. The largest lakes Tanganyika, Victoria and Malawi showed a high degree of enhancement at night but lower rainfall over the lake than over the catchment during the day in most or all months. Rainfall was also reduced over Lake Albert during the day in most months.

4. DISCUSSION

Enhancement of rainfall over a lake compared to its surrounding is generally assumed to have two possible origins. One is the lake/land breeze. The other is topographic: slope winds and/or mountain/valley breezes. The lake/land breeze system requires a temperature contrast between the lake and the land. Because of local mixing of air, this contrast would generally be lacking for the smallest lakes and would be likely be small in the case of shallow marshy lakes. Superimposed upon the local wind systems is the prevailing large-scale wind, which tends to be easterly over eastern Africa.

In the case of a lake/land breeze, the wind blows away from the lake during the day and towards the lake at night. The impact would be wind convergence during the night, which promotes uplift and rainfall, and divergence during the day, which would tend to suppress rainfall.

Since most of the Rift Valley lakes lie in a basin, some topographic effect is likely around most of the lakes in this study. The air tends to flow upslope during the day and downslope at night. This would tend to enhance any existing lake/land breeze effect. Both effects would tend to enhance rainfall and night and suppress rainfall during the day. A combination of these effects produces the nighttime or early morning maxima over the largest lakes, Tanganyika, Victoria and Malawa (Camberlin et al. 2018).

The vast majority of lakes in this study have an early evening maximum, as evidenced also by Camberlin et al. (2018) for the smaller lakes in their study. They concluded that this maximum is associated with the drift of convective systems generated over the nearby land areas. Although the lower lake surface temperatures, compared to the land, would tend to suppress convection at this time, this effect appears then to be minimal over the smaller lakes. An explanation is evident in the findings of Camberlin et al. (2018) and Haile et al. (2009) that the effect of the lake increases with distance from the shoreline. Thus, for small lakes, the influence can be minimal.

While this can explain the presence of an early evening maximum over the lakes, it cannot explain the enhancement of rainfall over the lakes compared to the catchment during the early evening, as found in this study. It may be that the inherent afternoon thermal instability is enhanced over the lakes because of the presence of moisture. The higher moisture levels over Lake Victoria contribute to the lake-effect rains (Nicholson et al. 2021c, Woodhams et al. 2019). The fact that the early evening maximum is more prevalent during the dry season provides some evidence for this.

A puzzling finding in this study is the uniformity of the times of rainfall maxima and minima over the lakes and the catchments or surrounding areas. As shown in Fig. 11, the maxima over the lakes and catchments are overwhelming at 18 LST and the minima are overwhelming at 12 LST over the lakes and catchments or surrounding areas. The uniformity of the early evening maximum can be readily understood in terms of the thermal instability and the seasonal constancy of the diurnal cycle in the tropics. As noted also by Camberlin et al. (2018), there is a very sharp transition from minimum rainfall over the lakes and catchments at 12 LST and high rainfall commencing at 15 LST. Further investigation is needed to provide an explanation for the rapidity of this transition.

Of the 27 lakes in this study 19 have a bimodal diurnal cycle of over-lake rainfall. In 13 of them, the diurnal maximum is evident in all months. In 6, it is evident primarily in the dry season months. There are strong peaks at 18 and 21 LST and 06 and 09 LST. The main exceptions to this are the large lakes with a nocturnal rainfall maximum. In nearly all cases with a bimodal maximum in over-lake rainfall, there is also a bimodal maximum in catchment rainfall. However, for both maxima, there is higher rainfall over the lake. The explanation is not clear, but this could be indicative of storms formed over the lakes drifting over the land. Such an effect is effect over the western portion of Lake Victoria's catchment (Nicholson et al. 2021a).

5. CONCLUSIONS

For the 27 lakes studied, average over-lake rainfall exceeds that in the surrounding land area or catchment. The annual enhancement is minimal over Lake Mweru and the Kyoga Reservoir and small over Lakes Baringo, Edward, Kivu, and Albert (10 % or less). For the remaining lakes annual rainfall over the lake exceeds that of the catchment/surrounding land by roughly 20% to over 100%. The enhancement is greatest over the small lakes Ziway, Eyasi, Chamo, and Manyara and over Lake Chilwa.

With few exceptions rainfall is greater over the lake than in the surrounding land or catchment in every month. The difference tends to be greatest during the driest months. The ratio of lake to catchment rainfall is, in nearly all cases, considerably greater at night than during the day. For some lakes, enhancement is limited to the nocturnal hours but for most lakes rainfall is enhanced over the lake also during the daytime. The exceptions are the largest lakes (Victoria, Tanganyika, Malawi), over which rainfall is suppressed during the day. During the dry seasons there is often rainfall over the lake when none occurs over the catchment.

Several aspects of the diurnal cycle over the lakes and catchment became clear through the analyses. One is that over the majority of lakes there is a bimodal diurnal cycle, which rainfall peaks both in the early evening and in the morning hours. Another is that nocturnal rainfall is common over both the lakes and the catchments. Further, there is a consistency between lakes and catchment in the time of maximum and minimum rainfall. The time of maximum is overwhelmingly at 18 LST for both and the time of minimum is overwhelmingly at 12 LST for both.

The exceptions to this are four of the five the largest lakes and Lake Koka. Lake Koka has a maximum at 06 LST during the three rainy season months of the boreal summer. For Lakes Malawi, Victoria and Tanganyika the maximum is 06 or 09 LST.

These results have strong implications for water balance calculations. Typically, stations near the shore are used to estimate rainfall over the lake (Yin and Nicholson 1998). Clearly, this is inadequate. Further the diurnal regime must be considered in calculating evaporation from the lake because of the diurnal cycle of cloudiness, which presumably roughly matches that of rainfall.

The impact of considering the day/night partitioning of cloudiness affects evaporation calculations by roughly 10% (Nicholson and Yin 2002).

In view of the sensitivity of this region to climatic change, the longer-term response of the lakes to global warming is a serious concern (Akurut et al. 2014, di Baldassarre et al. 2011). An understanding of the impact of lakes on the rainfall regime is critical to estimating this longer-term response.

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TABLES

Table 1. Lakes in the study and their surface area.

LAKE	AREA (KM^2)
VICTORIA	59,947
TANGANYIKA	32,900
MALAWI	30,000
TURKANA	6,405
RUKWA	5,670
ALBERT	5,300
MWERU	5,120
TANA	3,200
EDWARD	2,325
KIVU	2,220
CHILWA	1,750
KYOGA	1,720
MWERU WANTIPA	1,500
ABAYA	1,162
EYASI	1,050
NATRON	1,041
CHAMO	551
ZIWAY	485
MANYARA	470
MALOMBE	450
SHALA	329
KOKA RESERVOIR	250
LANGANO	230
NAIVASHA	160
BARINGO	130
AWASA	129
KITANGIRI	?

TABLE 2. Ratio of over-lake to catchment rainfall by month. Values of 2 or greater are highlighted in green. Values of one or lower (indicating over-lake rainfall equal to or lower than catchment rainfall) are highlighted in yellow.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
ABAYA	W	3.4	2.9	1.6	1.0	1.1	1.0	1.1	1.2	1.2	1.1	1.5	2.7	1.3
ALBERT	S	1.4	1.2	1.0	1.0	1.1	1.1	1.1	1.0	1.0	1.1	1.1	1.3	1.1
BARINGO	S	1.5	1.2	1.1	1.0	1.0	1.1	1.0	1.0	1.1	1.0	1.0	1.2	1.1
CHAMO	W	3.8	3.1	2.0	1.3	1.3	1.4	1.4	1.5	1.4	1.4	2.2	3.7	1.7
CHILWA	S	1.0	1.0	1.1	2.5	9.6	8.6	8.8	7.4	8.5	3.9	1.4	1.0	1.9
EDWARD	S	1.2	1.1	1.0	1.0	1.0	1.1	1.2	1.1	1.0	1.0	1.0	1.0	1.0
EYASI	S	1.5	1.6	1.3	1.4	3.3	6.3	7.8	6.6	5.4	2.7	1.4	1.3	1.9
KITANGIRI	S	.9	1.1	1.0	1.1	1.5	5.9	4.5	5.6	4.0	1.9	1.2	1.0	1.2
KIVU	S	1.0	1.1	1.1	1.1	1.2	1.2	1.5	1.2	1.1	1.1	1.0	1.1	1.1
KOKA	W	2.3	1.8	1.7	1.4	1.2	1.1	1.1	1.1	1.3	2.6	4.2	4.0	1.4
KYOGA	S	1.3	1.2	1.0	1.0	.9	.9	1.0	1.0	1.0	1.1	1.0	1.2	1.0
MALAWI	S	1.2	1.3	1.4	1.6	2.3	2.4	2.2	1.8	1.6	1.3	1.1	1.2	1.3
MALOMBE	S	1.0	.9	1.0	1.3	5.8	5.3	5.9	3.2	3.1	2.2	1.1	1.0	1.3
MANYARA	S	1.7	1.4	1.2	1.2	2.3	7.3	15.5	10.4	9.2	3.4	1.8	1.4	1.9
MWERU	S	.9	1.0	1.0	1.1	1.1	1.8	2.3	1.9	1.5	1.0	.9	1.0	1.0
MWERU WANTIPA	S	.9	1.0	1.0	1.2	6.0	14.7	22.6	16.2	8.2	2.3	1.0	1.0	1.4
NAIVASHA	S	1.5	1.4	1.3	1.1	1.2	1.5	1.6	1.6	1.6	1.5	1.3	1.5	1.4
NATRON	S	1.3	1.2	1.1	1.0	1.2	2.8	2.9	2.9	2.8	1.4	1.1	1.1	1.2
RUKWA	S	1.1	1.1	1.0	1.1	2.4	7.8	10.1	13.0	8.9	3.5	1.2	1.1	1.2
SAL	W	2.6	2.0	1.7	1.3	1.3	1.2	1.1	1.1	1.1	1.8	2.7	3.3	1.4
TANA	W	10.6	7.3	4.4	2.7	1.5	1.2	1.1	1.0	1.0	1.4	2.7	7.4	1.4
TANGANYIKA	S	1.1	1.1	1.1	1.1	1.5	1.8	2.1	1.3	1.4	1.4	1.4	1.2	1.2
TURKANA	W	3.5	3.7	1.7	1.0	1.1	1.3	1.2	1.4	2.4	1.2	1.5	2.4	1.6
VICTORIA	S	1.4	1.2	1.4	1.5	1.6	1.5	1.3	1.3	1.3	1.5	1.4	1.6	1.4
ZIWAY	W	4.1	3.0	2.4	1.9	2.1	1.7	1.2	1.3	1.7	3.4	4.5	6.0	2.1

Table 3. Categorization of the diurnal cycle for the 27 lakes surveyed. Three lakes did not fit into any of the categories. Indicated on the right is the time of maximum rainfall. For the lakes with two maxima, the time of the secondary maximum is indicated in parentheses. For the lakes with two maxima in the dry season and one in the wet season, only the wet season maximum is given.

NOCTURNAL MAXIMUM	
VICTORIA	06 or 09
TANGANYIKA	06 or 09
MALAWI	03 or 06
DAYTIME MAXIMUM	
KIVU	18 or 21
KYOGA	21 or 24
TWO MAXIMA	
EYASI	18 (06 or 09)
RUKWA	03 (18)
SHALA, ABIYATA, LANGANO (S/A/L)	18 (03 or 06)
ZIWAY	18 (06 or 09)
TURKANA	18 (06 or 09)
MANYARA	18 (03 or 06)
MWERU WANTIPA	18 (06 or 09)
NAIVASHA	15 or 18 (06)
ABAYA	18 (03 or 06)
ALBERT	18 (00, 03 or 06)
CHAMO	18 (03 or 06)
TWO MAXIMA IN DRY SEASON, ONE IN WET SEASON	
CHILWA	18
TANA	18
MALOMBE	18

NATRON	18
BARINGO	18
EDWARD	18 or 21
OTHERS	
KITANGIRI	15
MWERU	18
KOKA	06

FIGURES

1. Map of the lakes of eastern Africa.

2. Mean April rainfall (mm/hour) over Lake Victoria and in the surrounding area at 06 LST and 18 LST, based on TRMM 3B42 for the period 1998 to 2020.

3. Mean monthly rainfall (mm/mo) for the Lake Victoria region.

4. Mean monthly rainfall (mm/mo) for the Lake Tanganyika region.

5. Mean monthly rainfall (mm/mo) for the Lake Malawi region.

6. Mean monthly rainfall (mm/mo) over Ethiopia and northern Kenya.

7. Ratio of annual over-lake rainfall to catchment rainfall. S/A/L stands for the combined area of Lakes Shala, Abiyata, and Langano.

8. Monthly mean over-lake and catchment rainfall (mm/mo). S/A/L stands for the combined area of Lakes Shala, Abiyata, and Langano. The lakes are arranged geographically, with the top to bottom rows indicating Ethiopian, Western, Eastern and Southern Rift Valley lakes, respectively.

9. The mean diurnal cycle over four lakes and the surrounding catchment. The maximum height of the bar indicates mean rainfall in mm/hour for the lake (gray) and catchment (black).

10. Ratio of nocturnal to daytime rain over the 27 lakes and catchments. Otherwise as in Fig. 8.

11. Histograms of the times of maximum and minimum rainfall calculated from the average diurnal cycle in each month over each lake.

12. Ratio of lake to catchment rainfall by day and at night. The dashed line represents a value of 1, so that points below that indicate greater rainfall over the catchment than over the lake. The bottom graph is mean monthly rainfall (mm/mo). Otherwise as in Fig. 8.

Figure 1

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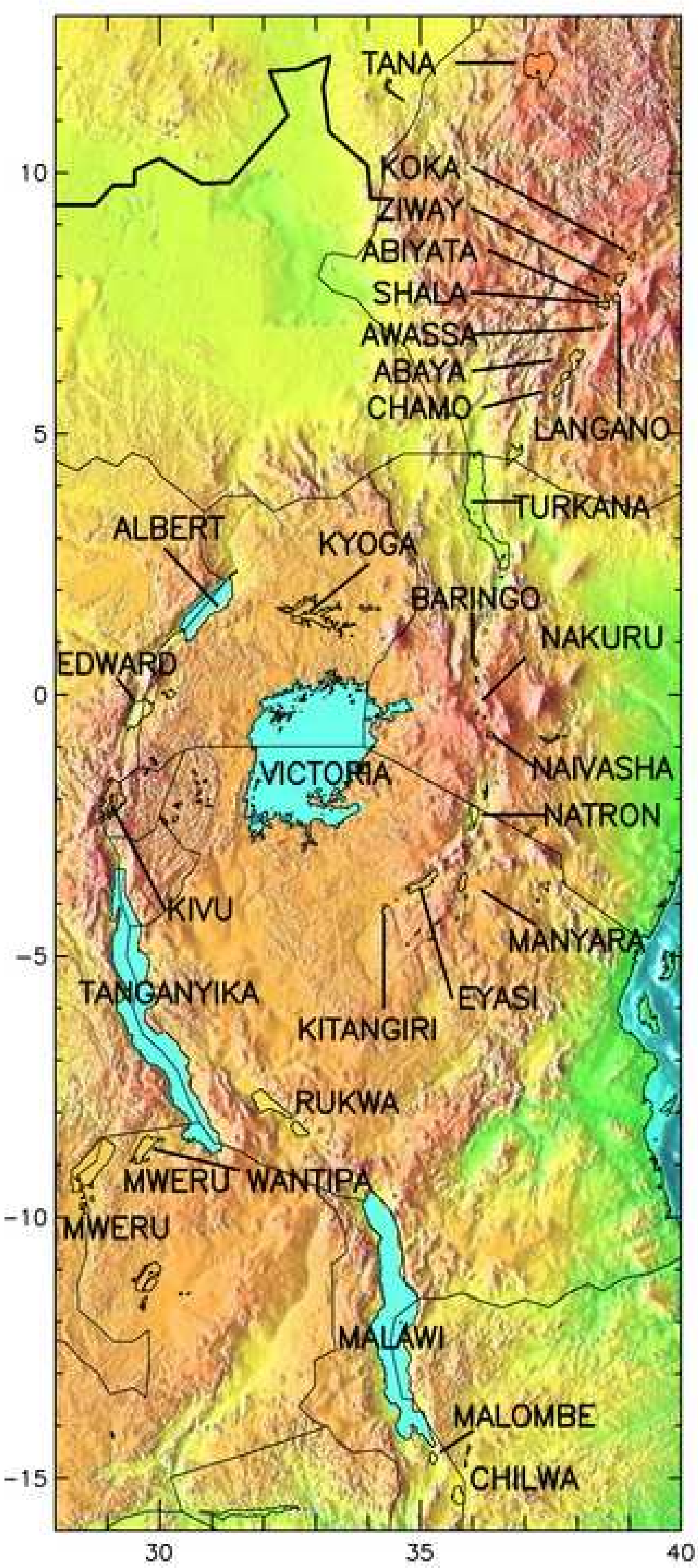

Figure 2

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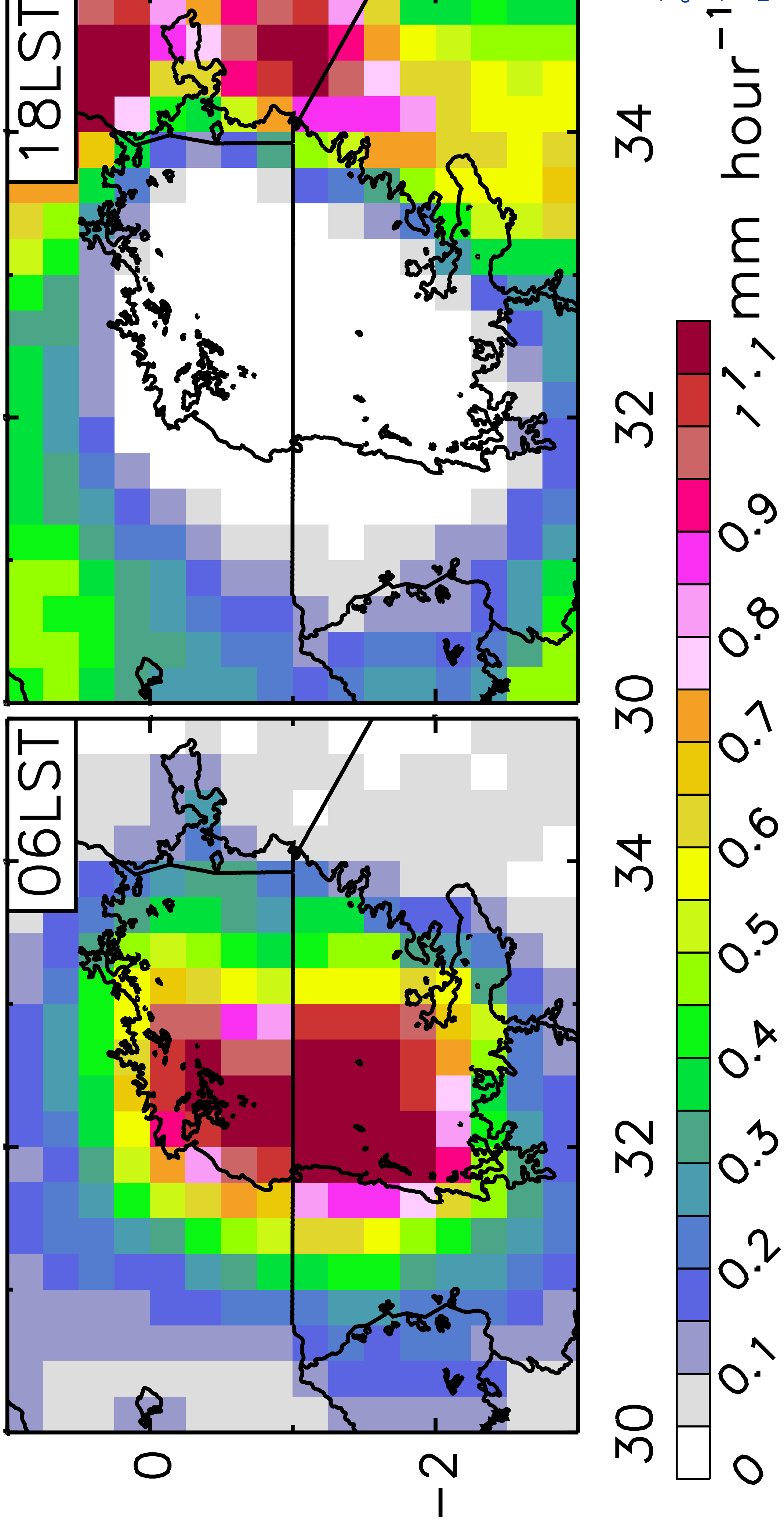

Figure 3

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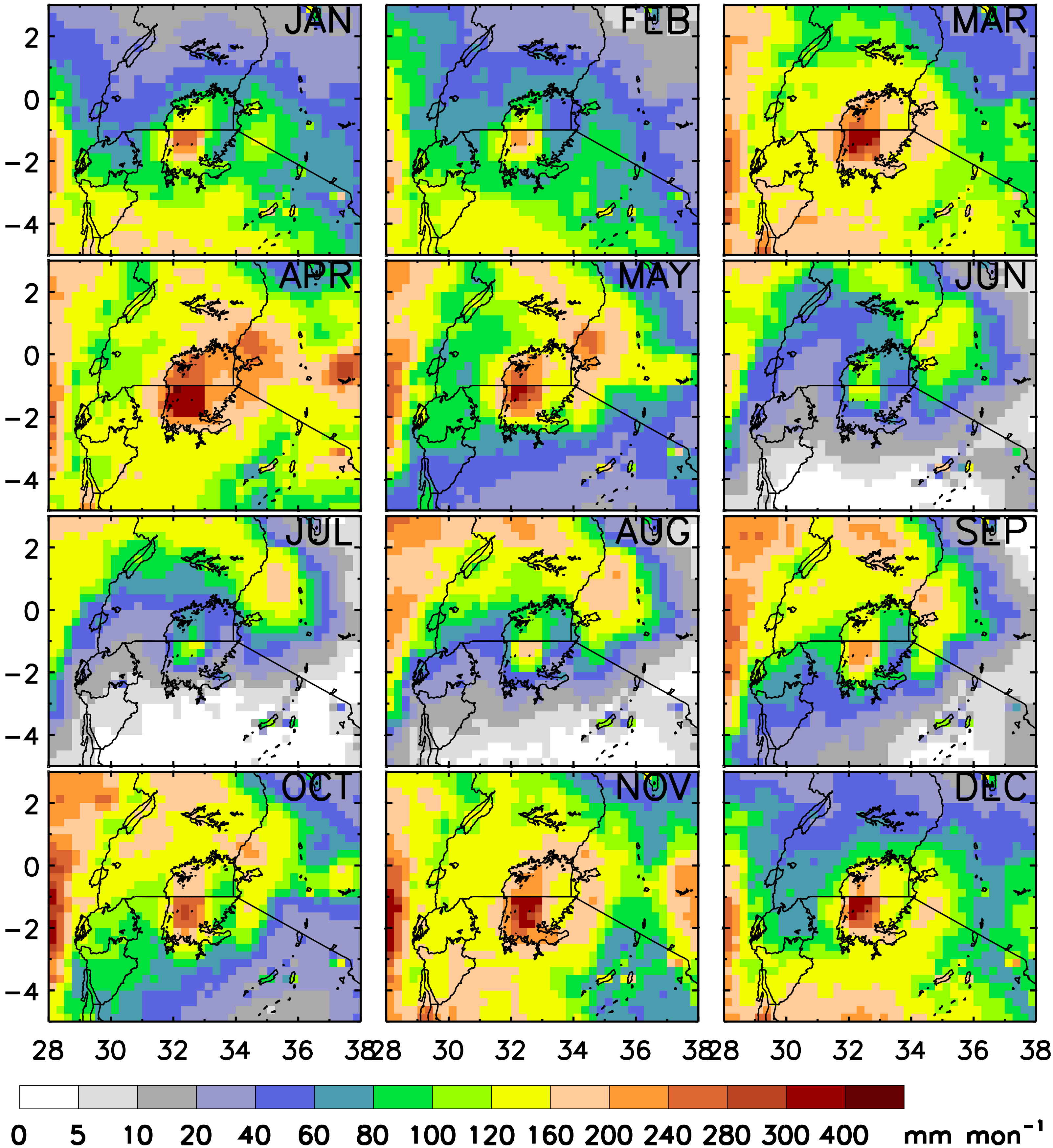

Figure 4

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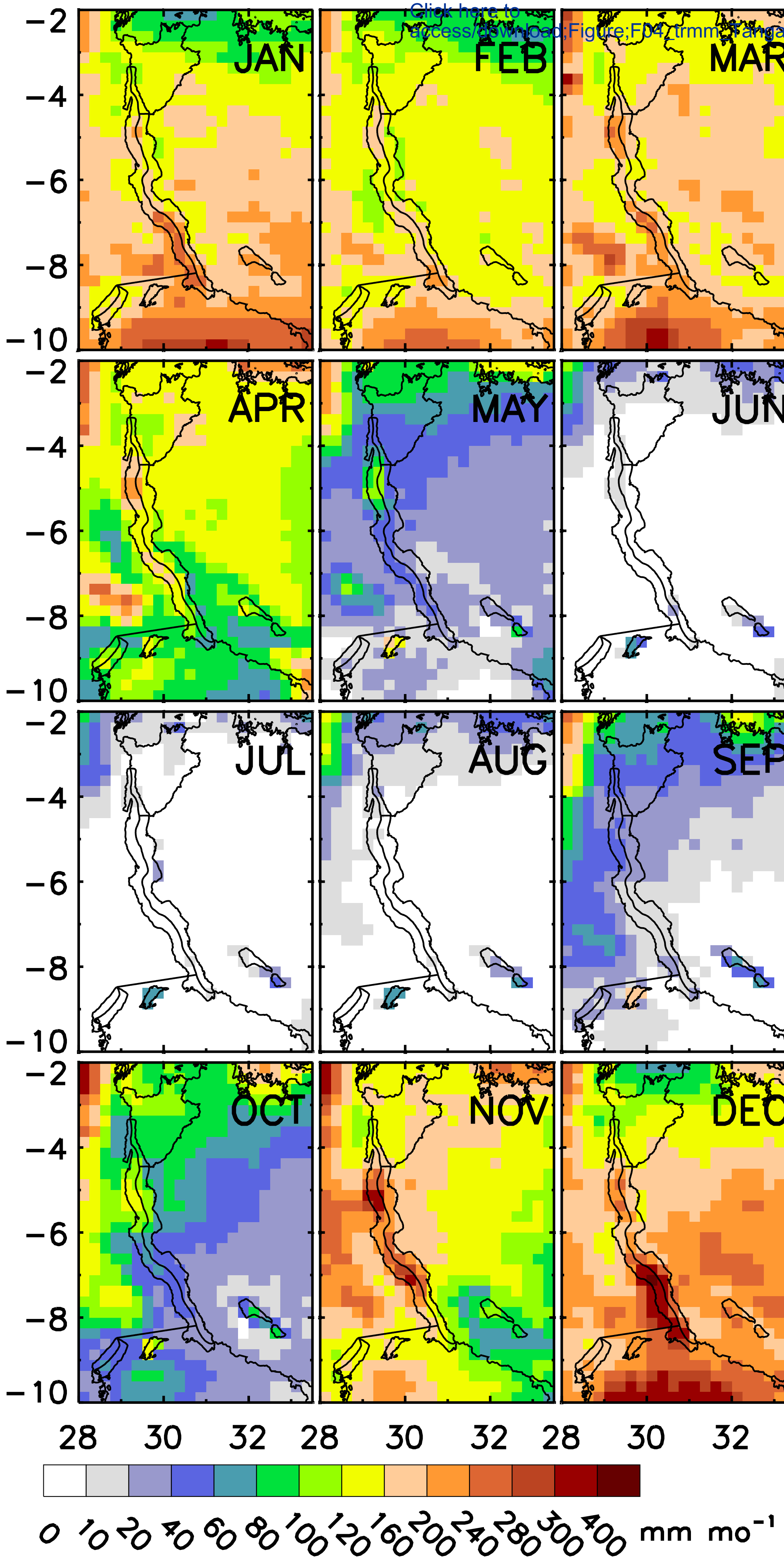

Figure 5

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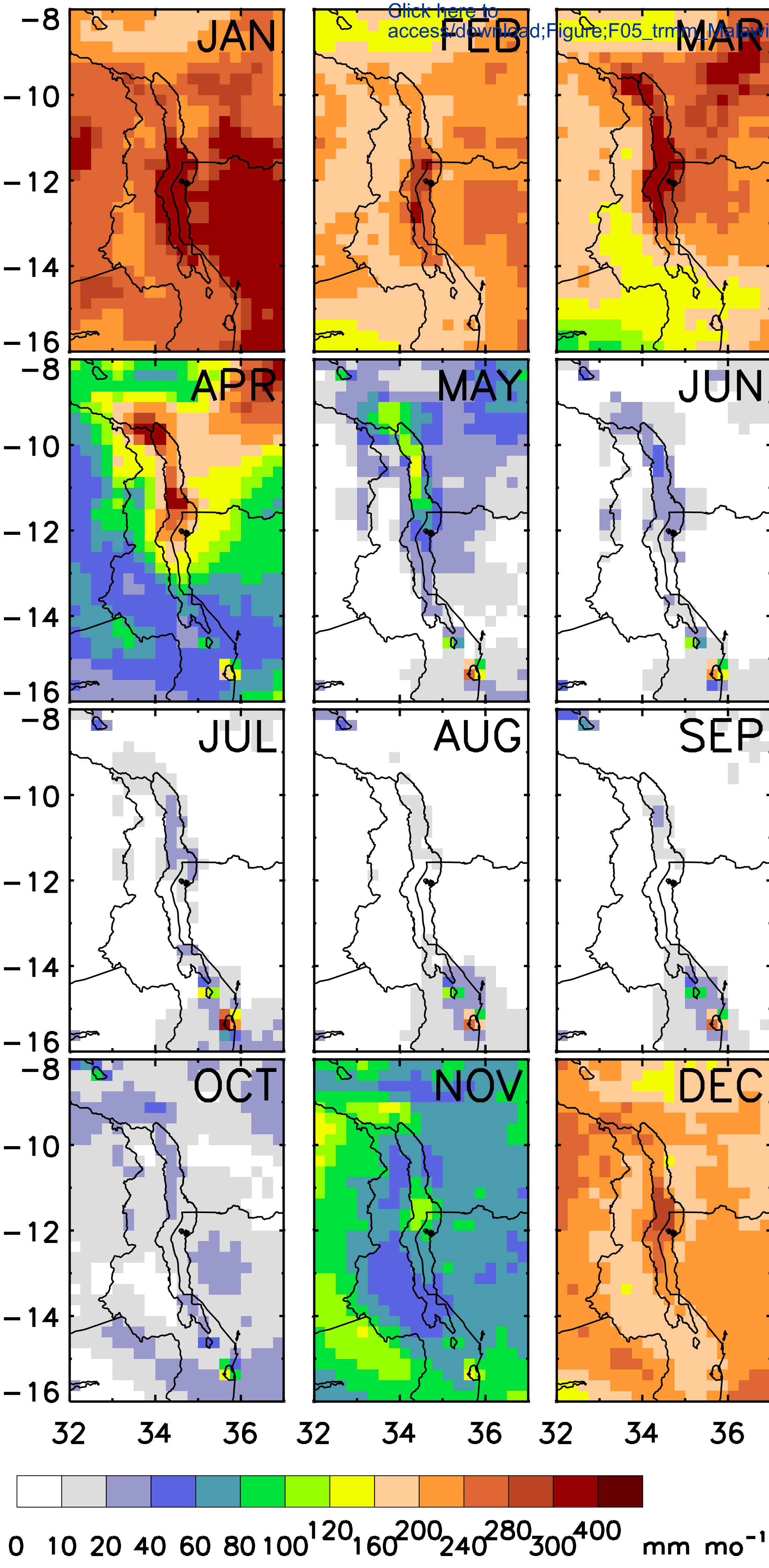

Figure 6

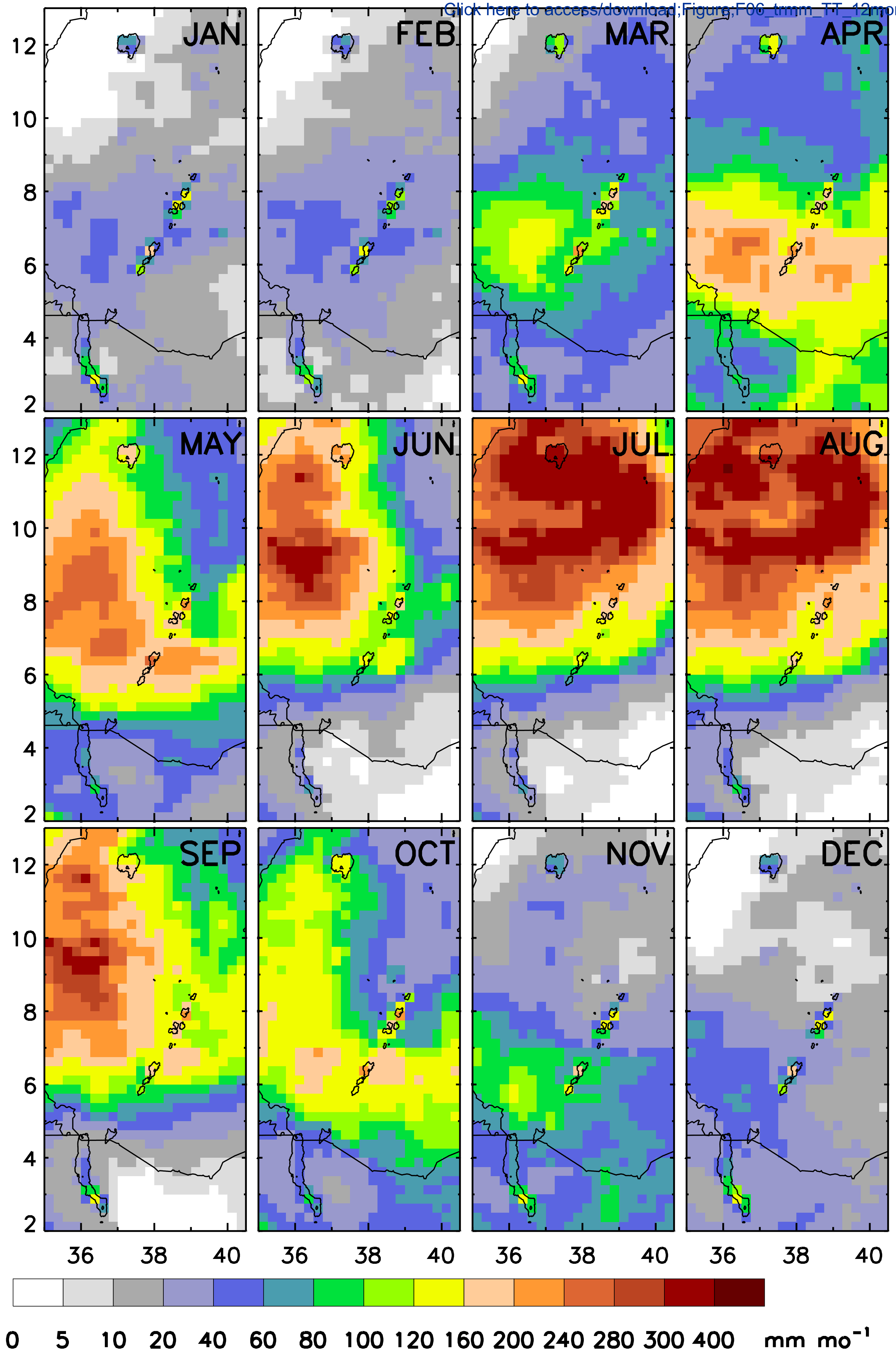

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Figure 7

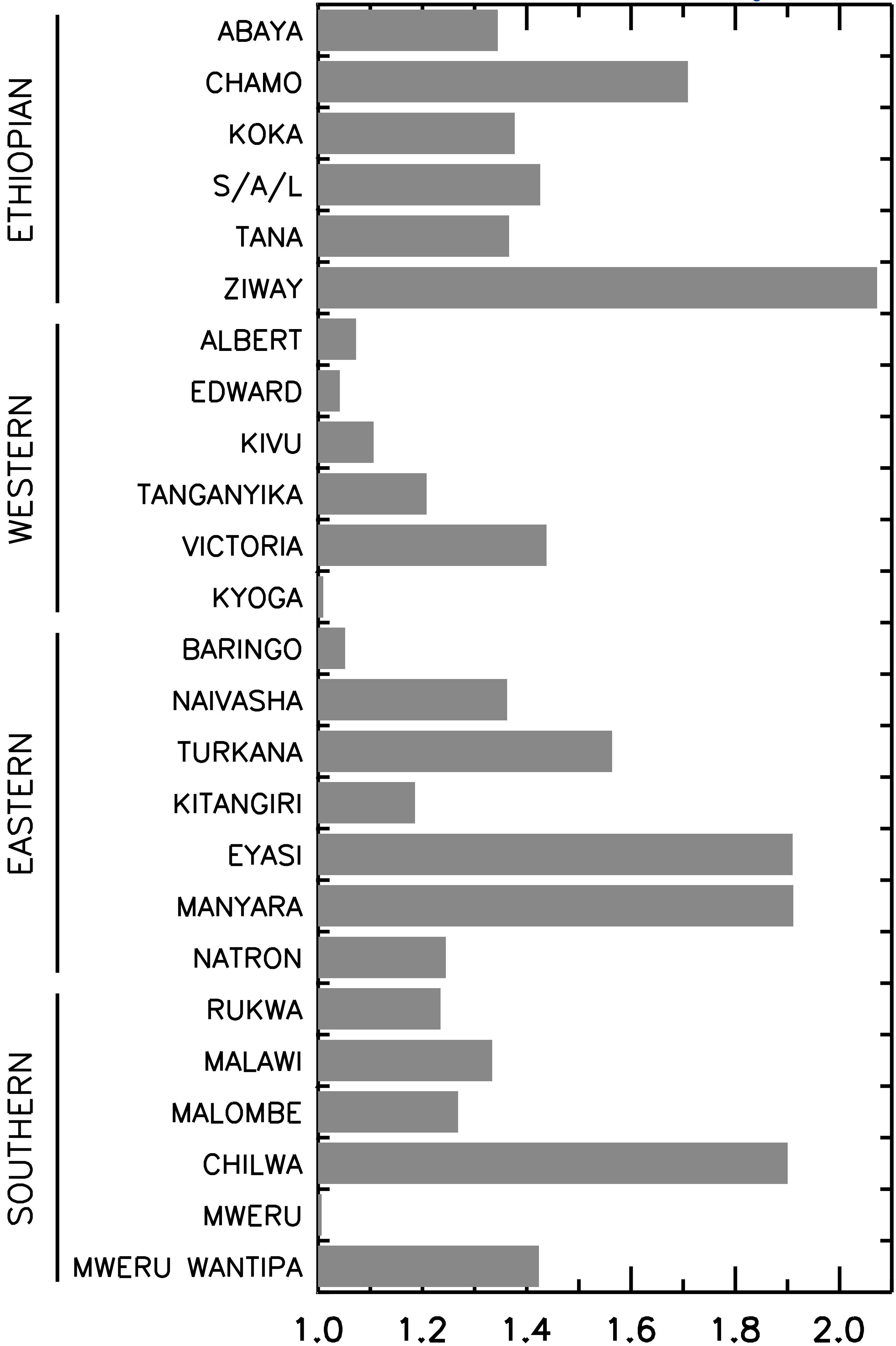
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Figure 8

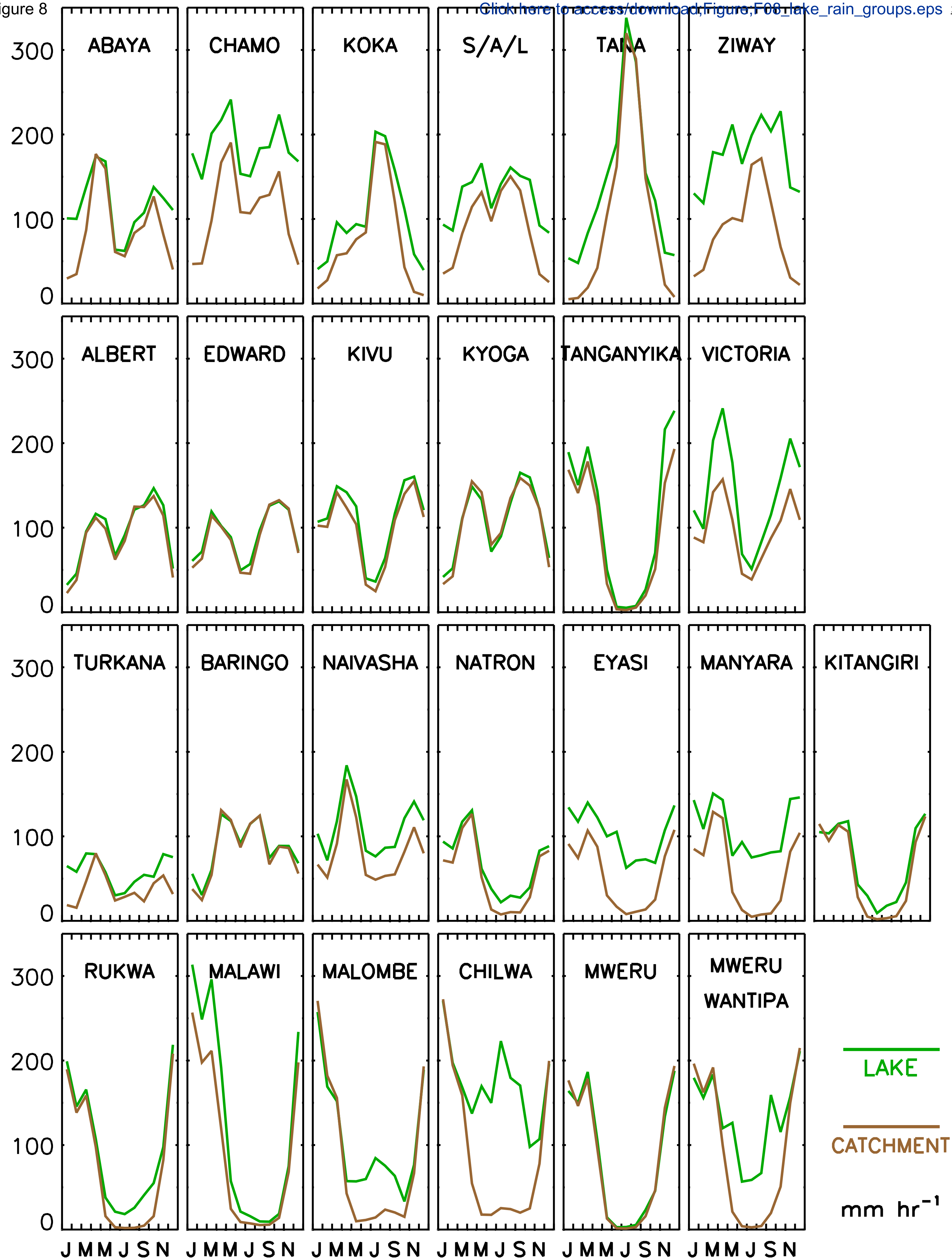
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Figure 9

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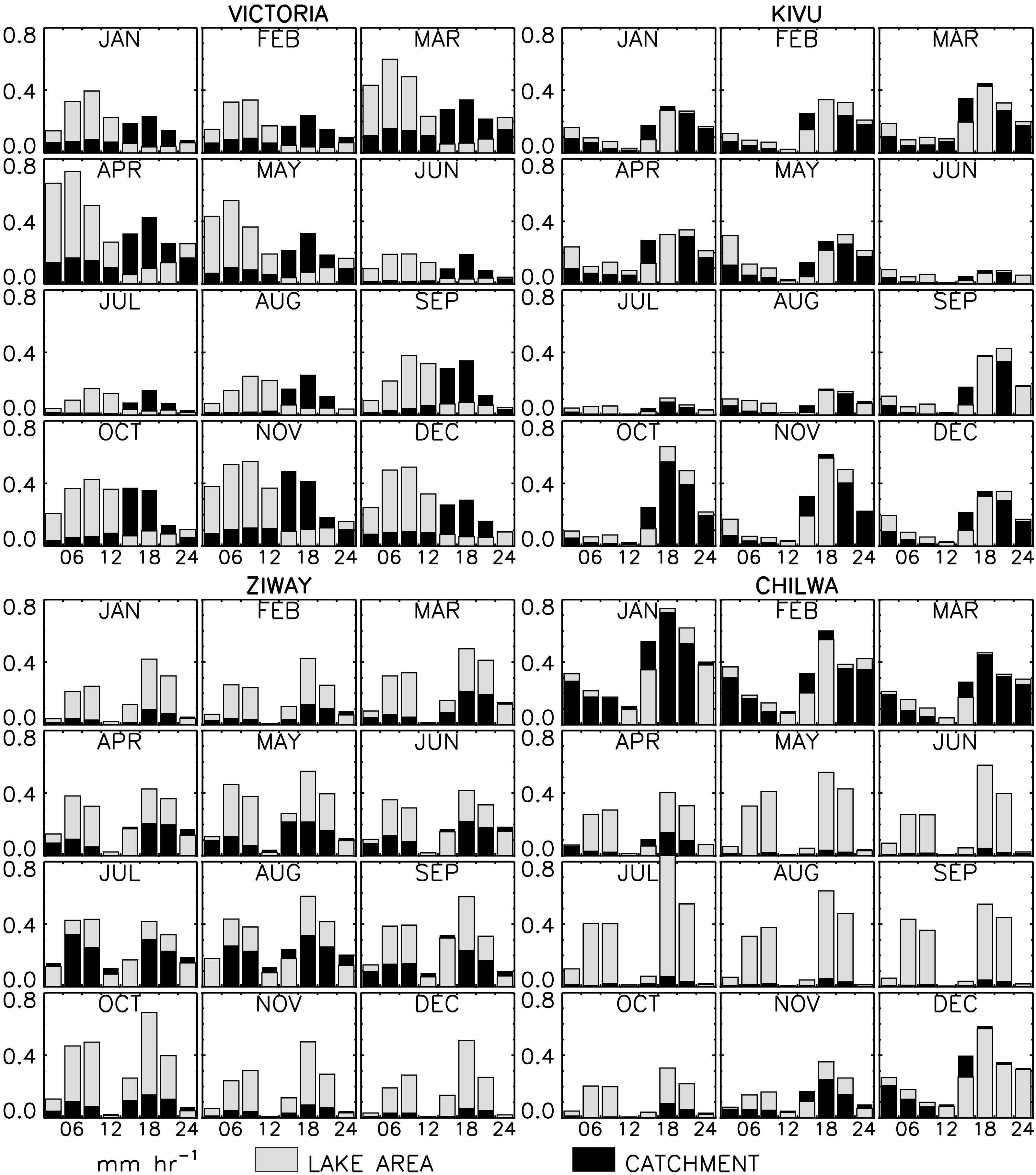

Figure 10

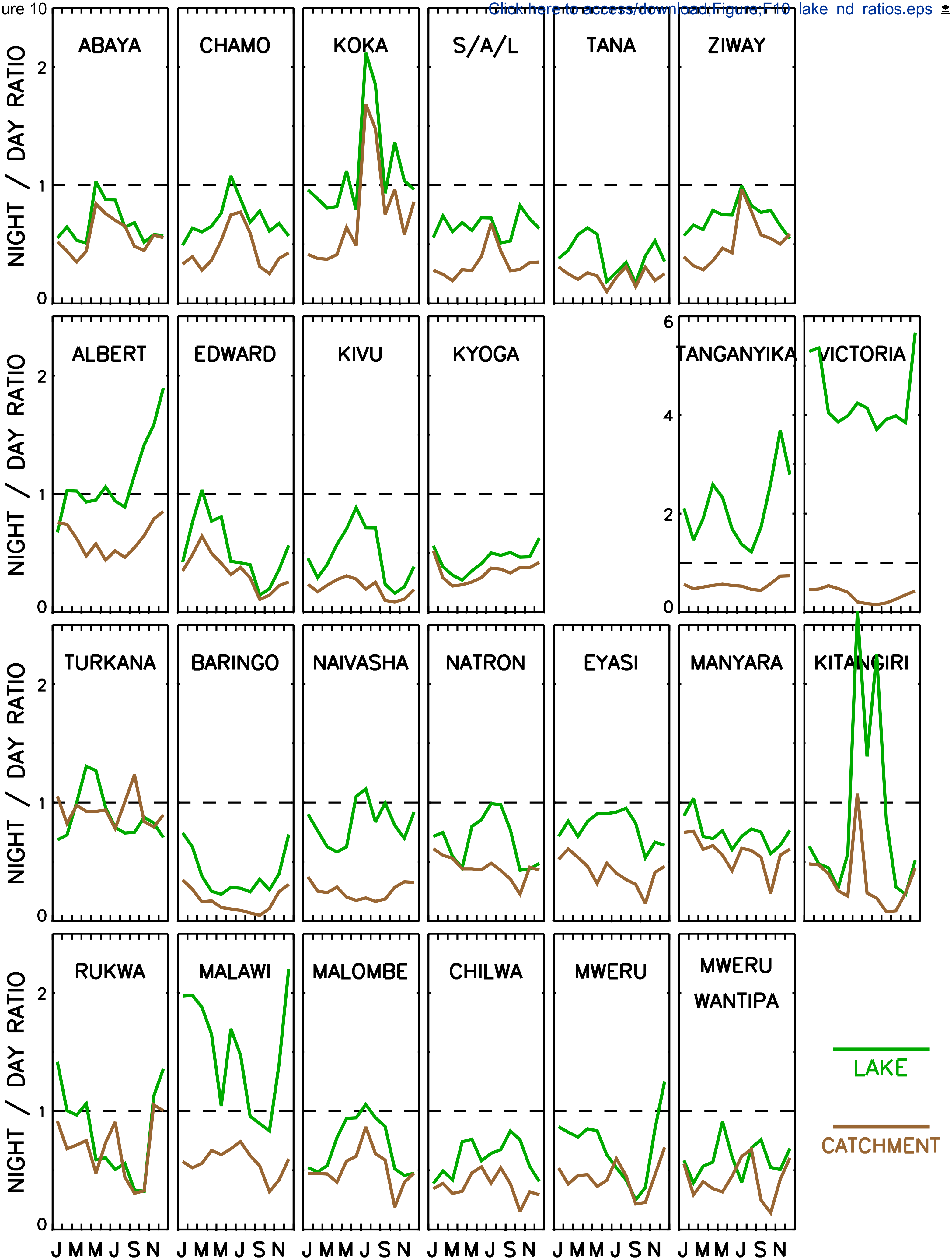
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Figure 11

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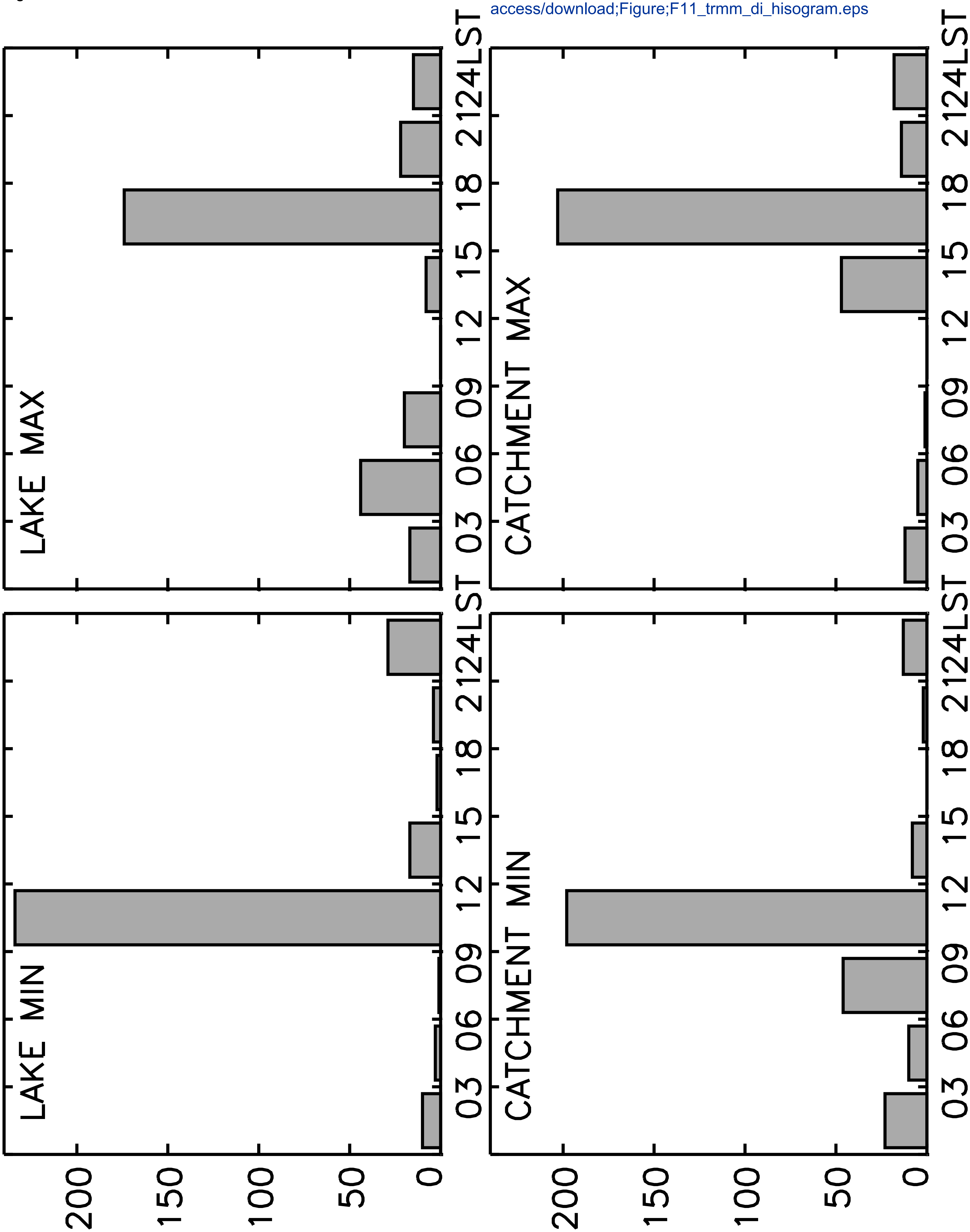
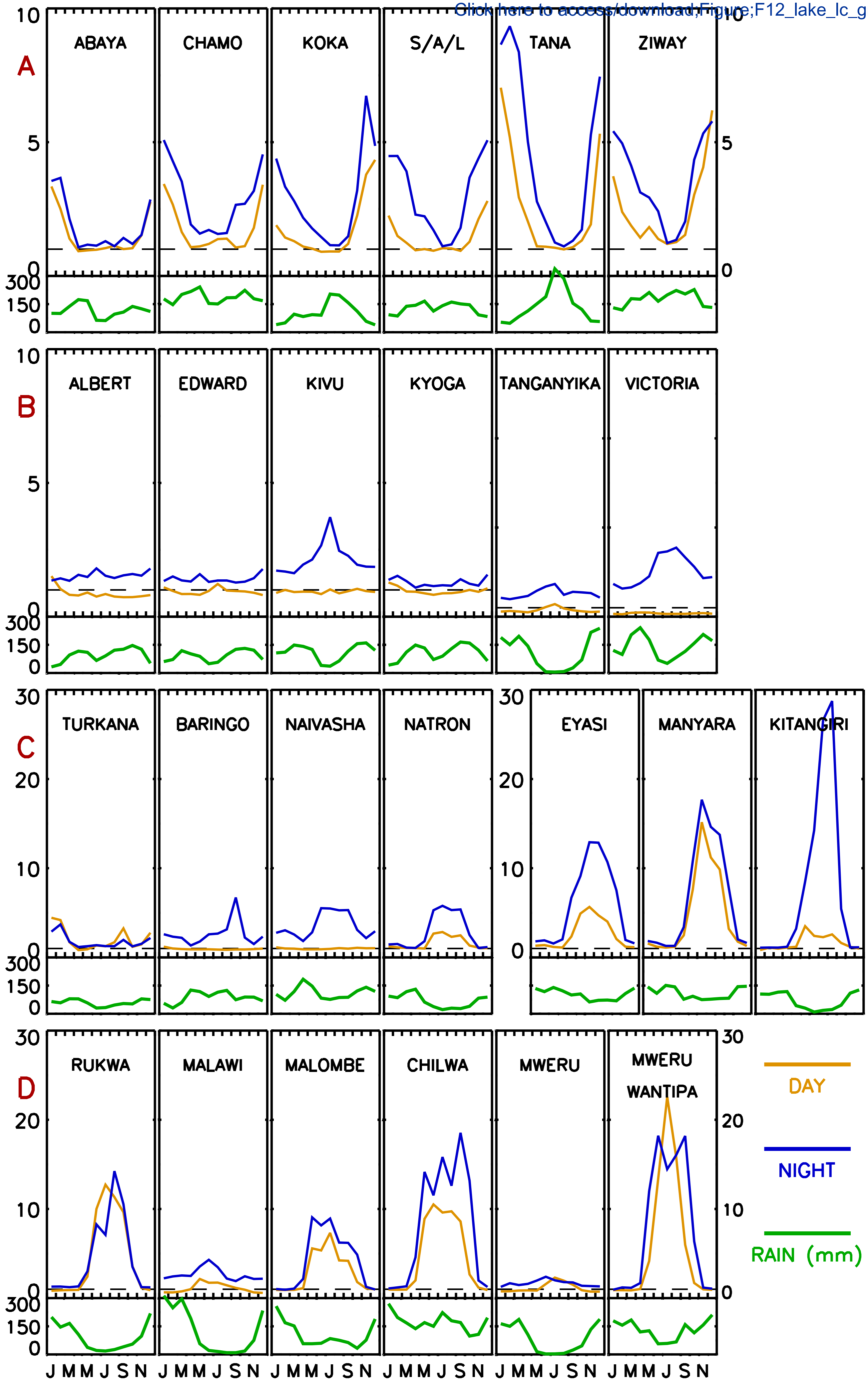


Figure 12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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: