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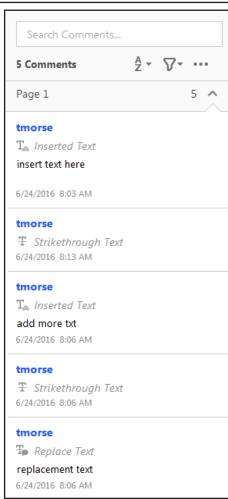
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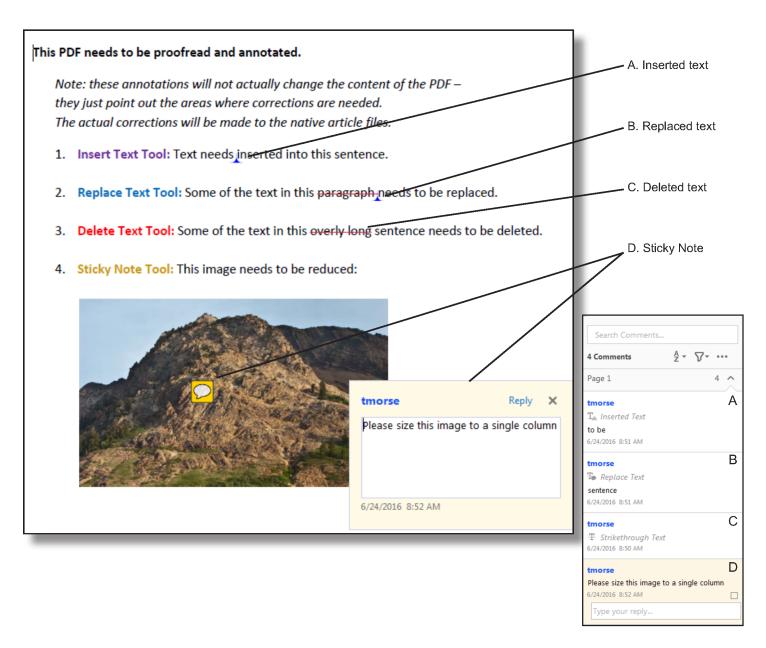
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F1

# On the Diurnal Cycle of Rainfall and Convection over Lake Victoria and Its Catchment. Part II: Meteorological Factors in the Diurnal and Seasonal Cycles

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ABSTRACT: The purpose of this article is to determine the meteorological factors controlling the lake-effect rains over Lake Victoria. Winds, divergence, vertical motion, specific humidity, convective available potential energy (CAPE), and convective inhibition (CIN) were examined. The local wind regime and associated divergence/convergence are the major factors determining the diurnal cycle of rainfall over the lake and catchment. The major contrast between overlake rainfall in the wet- and dry-season months is the vertical profile of omega. This appears to be a result of seasonal contrasts in CAPE, CIN, and specific humidity, parameters that play a critical role in vertical motion and convective development.

SIGNIFICANCE STATEMENT: The results of this study suggest that local factors (the anabatic–katabatic flow and lake–land breezes) do not play a role in the seasonal contrast in the lake-effect rains. The major contrast between the dry and wet seasons is evident in the vertical profile of omega, which is stronger and extends higher in the atmosphere during the wet season. Atmospheric humidity is higher during the wet season, modifying the values of CAPE and CIN. By modulating omega, these determine the seasonal cycle of lake-effect rains. These results have implications for predicting changes in the lake that will occur under global warming.

KEYWORDS: Africa; Inland seas/lakes; Instability; Lake effects; Precipitation; Seasonal cycle

#### 1. Introduction

Lake Victoria, lying in a basin between the eastern and western branches of the East African Rift (Fig. 1), is by area the largest lake in Africa and the largest tropical lake in the world. Its surface area is 68 870 km<sup>2</sup>, and from year to year its depth fluctuates between 80 and 84 m. The lake provides the livelihood of 30 million people in Kenya, Uganda, and Tanzania (Semazzi 2011). It sustains the fishing industry and agriculture and it also provides hydroelectric power (Chamberlain et al. 2014). Its levels control the flow of the White Nile, which sustains the populations of Sudan, South Sudan, and Egypt (Sene 2000; di Baldassarre et al. 2011). Thus, its natural resources support the lives of 300 million people in the Nile basin. It is also a dangerous lake. Thunderstorms result in some 3000-5000 deaths over the lake as a result of outflow winds, waves, and lightning (Virts and Goodman 2020). These thunderstorms are particularly hazardous because they occur primarily at night, when most fisherman operate on the lake.

Regional topography and lake-land breezes (Lumb 1970) enhance overlake rainfall compared to rainfall in the surrounding catchment (e.g., Flohn and Fraedrich 1966; Ba and Nicholson 1998; Yin and Nicholson 1998). The enhancement is apparent in every month, ranging from 20% to 60% in individual months (Nicholson et al. 2021a). Significant rainfall occurs over the lake even in months when catchment rainfall averages only 30–40 mm. Annually, the enhancement is on the order of 43%. Overlake rainfall represents over 80% of the input to Lake Victoria (Yin and Nicholson 1998) and in some

years it is nearly twice as great as rainfall over the surrounding basin. Thus, overlake rainfall is a critical determinant of lake level, which in turn plays a major role in determining the flow of the White Nile. Sene (2000) calculated that a 1-m rise of Lake Victoria can increase flow throughout the White Nile system by 70%–80%. It also affects rainfall in the catchment surrounding the lake (Fraedrich 1972; Okeyo 1986; Anyah et al. 2006; Nicholson et al. 2021b, hereafter Part I; Mahony et al. 2020).

The region is considered to be a "hot spot" for climatic change, so that the longer-term response of the lake to global warming is a serious concern (Vanderkelen et al. 2018; Akurut et al. 2014; di Baldassarre et al. 2011). It is very likely that precipitation will be strongly affected (Kent et al. 2015; Otieno and Anyah 2013; Souverijns et al. 2016). Farmers living in the Victoria basin are extremely vulnerable to climatic change (Gabrielsson et al. 2013). The countries of the Nile basin require sufficient water resources for their future development and wellbeing, considering the population growth and economic development (Deconinck 2009; Taye et al. 2011). Projected changes over Lake Victoria include not only total rainfall, but also hydrological extremes (Taye et al. 2011; Thiery et al. 2016), the seasonal cycle (Olaka et al. 2019; Gudoshava and Semazzi 2019; Onyutha et al. 2016), AU2 and temperature (Otieno and Anyah 2013; Olaka et al. 2019). Projected changes within the lake include fundamental and rapid changes in the fish community composition and abundance, eutrophication, oxygen content and algal growth (Hecky et al. 2010). These will presumably affect the intensity of the lake-effect rains (Olaka et al. 2019) and lake levels (Vanderkelen et al. 2018), which in turn affect rainfall in the Lake Victoria catchment and the flow of the Nile. Thus, a

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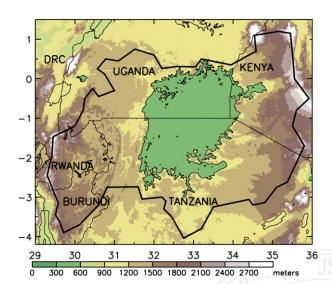


FIG. 1. Image of Lake Victoria and surrounding topography.

The solid black line shows the lake catchment.

thorough understanding of the lake-effect rains is critical in evaluating these responses and in projecting future water resources.

In Part I of this study, we described the diurnal cycle of rainfall over the lake and its catchment during wet and dry seasons, by contrasting conditions over the eastern and western portions of the catchment, and by examining the diurnal cycle and spatial distribution of mesoscale convective systems (MCSs) over the lake and surrounding regions. Here in Part II we advance the understanding of the lake-effect rains over Lake Victoria by examining the meteorological actors governing the diurnal cycle. Only a few papers have considered meteorological factors, and they are focused mainly on wind (see section 2). An exception is Woodhams et al. (2019), who demonstrated the importance of convective available potential energy (CAPE) and convective inhibition (CIN) in individual storm formation over Lake Victoria. Here we advance the understanding of the meteorological aspects of lake effect rains by examining on a seasonal basis specific humidity, CAPE, and CIN, in addition to

wind and circulation. These factors are compared for wet- and dry-season months. Section 3 describes the methodology and the data utilized. Section 4 examines the meteorological factors. A summary and conclusions are presented in sections 5 and 6.

#### 2. Prior research on the diurnal cycle over Lake Victoria

#### a. Rainfall and storms

The background literature on the diurnal cycle of rainfall and storms over Lake Victoria was reviewed in detail in Part I. The presence of a nocturnal rainfall maximum over Lake Victoria has long been known (e.g., Flohn and Fraedrich 1966; Datta 1981). Satellite data allowed for more detailed analysis of the diurnal cycle. The contrast between the nocturnal maximum over the lake and the afternoon/early evening maximum over its catchment (Fig. 2) was highlighted in several studies (e.g., Ba and Nicholson 1998; Yin et al. 2000; Nicholson and Yin 2002; Haile et al. 2013; Camberlin et al. 2018; Tan et al. 2019; Part I). Holle and Murphy (2017), Virts and Goodman (2020), and Thiery et al. (2016) considered the diurnal cycle of lightning and storms, demonstrating a nocturnal maximum over the lake as well.

#### b. Associated meteorological factors

Most of the studies that considered meteorological factors related to Lake Victoria's lake-effect rains examined only wind and circulation. Fraedrich (1972), using a model of the dynamics and energetics of the nocturnal circulation, showed that this circulation is a result of a three-way interaction among the diurnal land-lake breeze, the mountain-valley winds, and the prevailing "monsoon" flow. Camberlin et al. (2018) came to a similar conclusion, but suggested that the convergence of the katabatic winds and easterly flow was the primary driver. They did not examine the circulation directly, drawing their conclusions on the spatial distribution of the time of maximum and minimum rainfall.

Finney et al. (2019) and Van de Walle et al. (2020) both used convection-permitting models to study the diurnal cycle over Lake Victoria. The latter, in agreement with Camberlin et al. (2018) emphasized the importance of orographic effects and

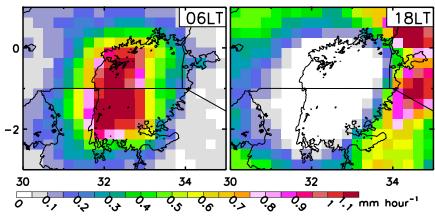


FIG. 2. Mean rainfall (mm h<sup>-1</sup>) in April at 0600 and 1800 LST.

easterly trade winds. Onyango et al. (2020) compared composites of wet and dry days during the March-May (MAM) season. They concluded that over the area of the basin, wet days occurred when convergence over the lake at night was anomalously weak; divergence during the day was stronger during dry days than during wet days. Mahony et al. (2020) focused on rainfall over the Serengeti, to the southeast of Lake Victoria. However, their analyses included the lake region. They showed prevailing easterlies over the lake during both rainy seasons but strong northerly or southerly components to the flow during the two dry seasons. They also showed that daytime divergence over the lake was much greater during the dry season of the boreal summer (June-September), but that the divergence during the boreal winter (January-February) was only marginally greater than during the wetseason months. They further demonstrated the presence of a daytime circulation cell between the lake and land with return flow at about 700-750 hPa during March but considerably lower in August.

The role of atmospheric moisture was considered by Mahony et al. (2020), Anyah and Semazzi (2004), and Anyah et al. (2006). The specific humidity at 825 hPa is low over the lake during the July-September dry season, but the contrasts between the wet-season months and the January-March dry season are relatively weak. Song et al. (2002, 2004) described the development of a coupled regional climate model for the Lake Victoria Basin. Anyah and Semazzi (2004) and Anyah et al. (2006) used that model to study processes associated with climatic variability over the basin and concluded that both lake temperature and moisture advection are important.

The only detailed study of meteorological conditions other than wind and circulation is that of Woodhams et al. (2019). Concluding that the mean diurnal cycle is insufficient to understand the processes responsible for individual storm formation, they conducted three case studies: a wet-season storm, a dry-season storm, and a 3-day dry period during the dry season. They concluded that the lake-land breeze circulation provided a major control on the initiation, location, timing and propagation of convection over Lake Victoria. The found that during the wet-season storm (in May of 2015) an atmosphere high in CAPE and low in CIN is an important factor in triggering a storm. The dry-season storm demonstrated the importance of convection from the previous day in altering the local atmosphere. This result supports a study of Thiery et al. (2016), which notes a strong correlation between intense storms over land during the afternoon and intense nocturnal storms over the lake.

#### 3. Data and methodology

Most of the Lake Victoria region has a bimodal seasonal distribution of rainfall. The two rainy seasons occur during the two transition seasons. Rainfall is greatest during the "long rains" season, March-May. The secondary rainy season, the "short rains," occurs in October, November, and early December (Nicholson 2015). The characteristics and large-scale forcing of the two rainy seasons are very different (Nicholson 2017). June, July, and August are the

driest months. A second dry season occurs in January and February.

The diurnal cycle is examined in the wettest month of each wet season, April and November. It is also examined in the driest month of each dry season, February and July. During February the tropical rainbelt lies to the south of Lake Victoria. In July it lies to the north. By examining these four months, the lake effect is put into the context of highly contrasting large-scale meteorological conditions.

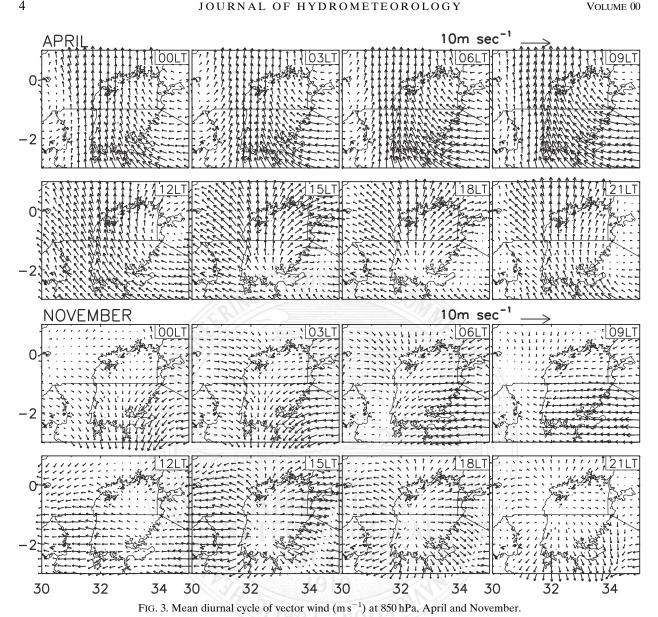
For meteorological variables ERA5 reanalysis is utilized. It replaces ERA-Interim and commences in 1979. It provides hourly coverage at roughly 31-km global resolution on 137 vertical levels (Hersbach and Dee 2016). It includes atmospheric circulation variables that are used to assess low-level winds, divergence, and vertical motion (omega), as well as specific humidity, CAPE, and CIN. Each of these variables is evaluated for the two wet-season months and the two dryseason months.

#### 4. The diurnal cycle of associated meteorological conditions

a. Surface wind

Wind is examined at 850 hPa, which is the approximate level of the surface of Lake Victoria. The 850-hPa winds, like rainfall, show a strong diurnal cycle (Figs. 3 and 4). The **F3 F4** diurnal cycle is best developed in the central and eastern portions of the lake and is relatively weak in the lake's western fringe, except in November. This spatial contrast is most likely a consequence of the topographical contrasts on the eastern and western sides of the lake (Fig. 1). Over the East African highlands to the east, the elevation exceeds 1800 m over large areas and the highest topography is only about 100 km from the lake, creating a very strong topographic gradient (Anyah et al. 2006). To the west in the Ruwenzori Mountains the elevation exceeds 1800 m in a very limited area and the topographic gradient is much smaller, with the highest elevations lying some 150-200 km from the lake. The result is a stronger mountain-valley wind system in the east.

In April the anabatic wind commences around 1500 local standard time (LST) in the east and possibly around 1200 LST in the west. It is difficult to identify the start in the west because the large-scale wind is in a similar direction. The katabatic flow starts in the east around 2100 LST. In the west the katabatic component is extremely weak and appears only between 0000 and 0900 LST. It does not extend to the lake because the katabatic component in the east is so strong that it appears to cover the entire lake between 0000 and 0600 LST. Flow from the southeast is particularly strong at 0600 and 0900 LST. This timing probably reflects a combination of katabatic winds from highlands and the prevailing large-scale easterlies, which cannot be readily distinguished. At 1200 LST southeasterly flow is ubiquitous over the lake but it may be a combination of katabatic wind from the east and anabatic wind in the west. The anabatic component is well developed in the east and the west at 1500 and 1800 LST, creating divergence over the lake.



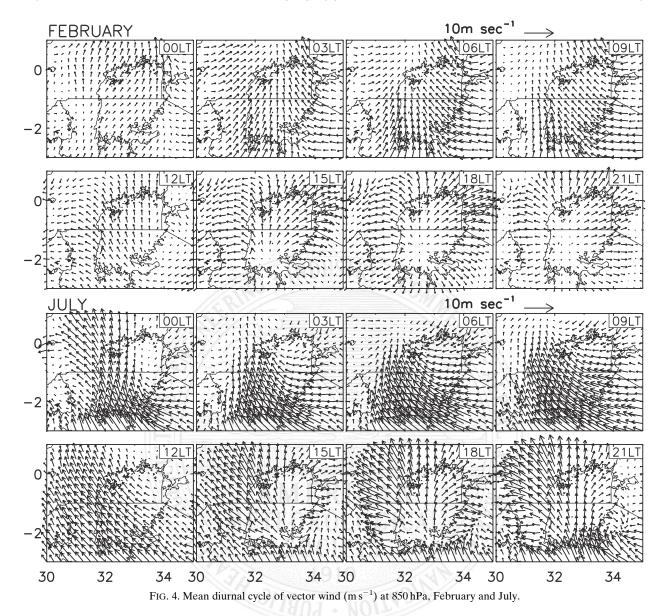
In November the mountain-valley breeze system and the large-scale winds are much weaker. The anabatic wind commences around 1200 LST in west and 1500 LST in the east. It is strongest around 1500 LST. Katabatic flow begins around 2100 LST in the east and 0000 LST in the west, but is markedly stronger in the east. It displaces the nocturnal convergence toward the western part of the lake. Katabatic flow continues in

the west until 0600 LST but until 0900 LST in the east.

July is the driest month. The large-scale wind is very strong and generally from the east or southeast throughout most of the analysis sector. The diurnal cycle of wind is markedly similar to that of April at most times, although the wind magnitude is generally greater in July. The contrasts are evident at 2100 and 0000 LST. At 2100 LST in July anabatic flow prevails in the east and the west, but in April katabatic flow is evident at that time in the east. In April, katabatic flow

begins in the west at 0000 LST. In contrast to April, weak anabatic flow is still evident in the west at 0000 LST in July.

February, another dry-season month, also shows much similarity to April, although the winds are generally weaker. There is a general tendency for strong southerly, southwesterly or southeasterly flow over the lake at night and early morning. In the afternoon, commencing around 1500 LST, there is clearly divergent flow over the lake and it continues through 2100 LST. The switch from anabatic to katabatic flow in the east and west tends to occur between 2100 and 0000 LST. The katabatic flow becomes very strong at 0300 and 0600 LST. As with July, the contrasts with April are most apparent at 2100 and 0000 LST. The strong divergence at 2100 LST is not apparent in April. At 0000 LST winds tend to be southwesterly over the lake and strongest in the north in February, but southeasterly and strongest in the south in April.



Note that at this scale, it is impossible to distinguish between lake-land breezes and anabatic-katabatic flow. The land breeze in the east is in the same direction as the katabatic flow, so that it likely enhances the latter (Mahony et al. 2020).

#### b. Divergence

Despite the contrasts in the surface winds, the spatial pattern and diurnal cycle of surface divergence is fairly similar in all four months, so that only April and July are shown. In April (Fig. 5) divergence is evident over the eastern and western highlands and the northern fringe of the lake at 0000 LST, while convergence prevails over the rest of the lake. By 0300 LST convergence is evident over the western highlands and the entire lake, being especially strong in the south. Divergence continues over the eastern highlands. This pattern continues

through 0900 LST. There is a striking reversal of the pattern at 1200 LST, with strong divergence over the lake and some areas to the west, but convergence over the eastern highlands. Peak divergence over the lake and peak convergence over the eastern highlands occur at 1500 LST. This pattern continues through 2100 LST, with the area of convergence in the east becoming more extensive but weakening.

The pattern is similar in November (not shown) and in the two dry-season months (only July is shown): divergence over the lake between 1200 and 2100 LST and convergence from 0300 to 0900 LST. However, convergence over the lake at night is somewhat weaker in November than in April. The main contrast with April is apparent in July (Fig. 5). Divergence over the lake during the day and convergence at night are both stronger in July than in April, despite the very weak lake-effect rains. These results suggest that the local

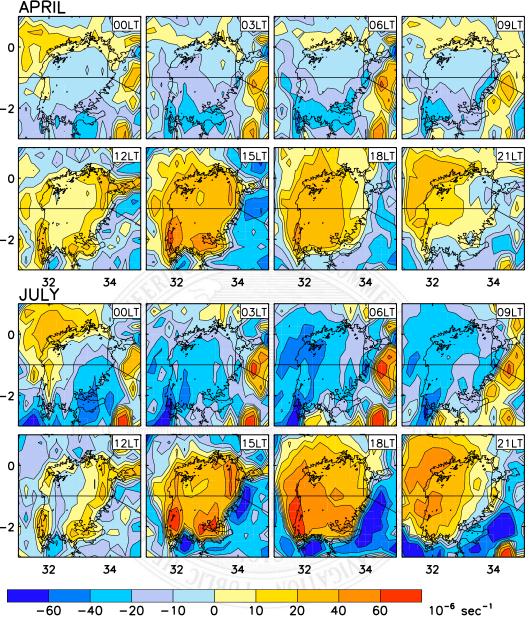


FIG. 5. Mean diurnal cycle of divergence  $(10^{-4} \, \text{s}^{-1})$  at 850 hPa, April and July.

winds around the lake do not control the intensity of the lake-effect rains.

#### c. Vertical motion

F6

The diurnal cycle of near-surface omega is also similar in both April and November, so that only April is shown in Fig. 6. Values are given for 800 hPa, as omega must go to zero at the surface and hence becomes very small at 850 hPa. The omega field is very consistent with the divergence field. Between 0000 and 0900 LST ascent is strong over the lake but subsidence is apparent over the highlands to the east and west. A reversal occurs at 1200 LST, with subsidence limited to the lake area and with ascent in surrounding areas. The

area where subsidence prevails expands until 1800 LST, when it is relatively weak. It is strongest over the lake at 1500 and 1800 LST. Ascent continues to prevail over the highlands until 1800 LST; it peaks at 1500 LST. The only notable contrast with November (not shown) is that the ascent over the eastern highlands is considerably greater than during April.

The near-surface patterns of omega during the dry-season months are surprising. The pattern in February (not shown) is similar to that of April, but with stronger ascent over the lake at night and stronger subsidence during the day. That for July is considerably different (Fig. 7). Ascent at night is F7 markedly stronger than during April and it evident well beyond the lake. Between 0000 and 0900 LST the maximum

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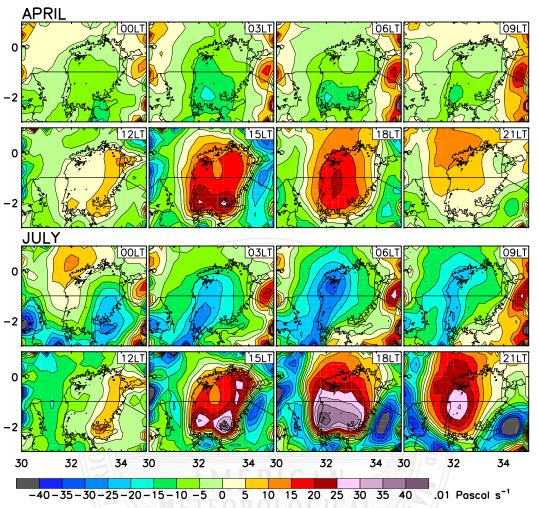


FIG. 6. Mean diurnal cycle of omega (0.1 Pa s<sup>-1</sup>) at 800 hPa, April and July.

progressively shifts from the eastern side of the lake to the western. A major change occurs at 1500 LST when subsidence prevails over the lake and continues until 2100 LST.

Thus, the analysis of omega just above the lake indicates stronger nocturnal ascent during the dry-season months, when the lake-effect rains are weak. This is consistent with the pattern of divergence in the various months. The omega fields further indicate that surface forcing of the lake-effect rains is actually strongest during months when the lake-effect rains are weakest. The explanation becomes apparent from the vertical profiles of omega. In April (Fig. 7), the wettest month and the month of the strongest lake-effect rainfall, ascent develops over the center of the lake starting at 2100 LST but it is only evident above 700 hPa. By 0300 LST an intense and deep column of ascent extends over the lake from roughly 900 hPa through to the upper troposphere. The ascent is strongest at 0300 LST but the column is still very strong at 0900 LST. Maximum ascent is at roughly 400-500 hPa. Starting at 1200 LST subsidence is evident over the lake, with a maximum at 700-800 hPa. Columns of ascent extending to at least 700 hPa are evident over the highlands both to the east and west of the

lake. Peak subsidence over the lake and peak ascent over the highlands occur at 1500 LST, when both the subsidence and the ascent reach into the upper troposphere. By 2100 LST both the subsidence and the ascent are considerably weaker.

The omega profiles in November are similar to those of April. The major contrasts are in ascent over the lake. It is stronger at 2400 and 0300 LST in April but at 1200 LST in November, when it is restricted to western portions of the lake.

The contrast with the dry-season months is stark, especially with respect to the nocturnal updraft over the lake (Fig. 8). In F8 July strong convergence extends to the upper troposphere only at 0600 and 0900 LST and it is very weak above 600 hPa. It is markedly weaker than during the wet-season months and maximum ascent is at about 800 hPa, compared to around 500 hPa in the wet months. In February the column also extends to the upper troposphere at 0300 LST but is also markedly weaker than during the wet-season months. During the daytime the main contrast is that the subsidence over the lake is stronger in both February and July than during the wet-season months.

Contrasts are also apparent over the land (Figs. 7 and 8), particularly with respect to the ascent over the highlands. In

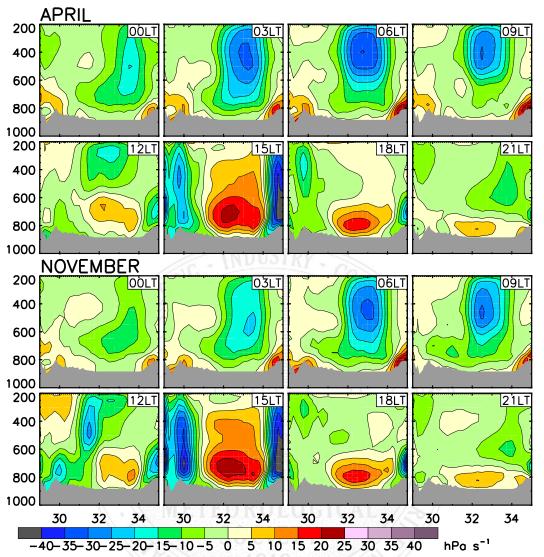


FIG. 7. Mean diurnal cycle of the vertical profile of omega ( $hPas^{-1}$ ), April and November.

some cases, such as 1800 LST in February, it is actually stronger than during the wet months. However, the column of ascent is vertically limited in both February and July. It generally lies below about 600 hPa, and the maximum is around 700 hPa or lower.

#### d. Specific humidity

The extremely strong development of the column of ascent during the wet-season months, despite weaker surface forcing than during the dry-season months (Fig. 5), suggests that other factors must play a role. The role of instability and atmospheric moisture has been suggested by several papers examining the lake-effect rains or the seasonal cycle (e.g., Yang et al. 2015; Woodhams et al. 2019). To examine these factors, specific humidity is considered here and CAPE and CIN are examined in the following section.

F9 F10 Figures 9 and 10 show the mean vertical profile of specific humidity (grams per kilogram). A notable feature is a "moisture

bulge" over the lake that is particularly pronounced at night. While a specific humidity maximum appears over the lake at all times and in all four months, the "bulge" (with the humidity maximum extending well above the lake) is apparent only in November. It is notably absent during April. These findings are consistent with a study by Woodhams et al. (2019), who were the first to point out this feature. It appeared in two sets of synoptic case studies during the dry season (July), but was absent during their May wet season case study. They attributed its absence to the overall moist atmosphere during the long rains. During the day in April and November (Fig. 9) and during both day and night in February and July (Fig. 10) there is a depression in specific humidity above the humidity maximum just over the lake.

Close examination of Figs. 9 and 10 does suggest that specific humidity is highest in April, when the lake-effect rains are strongest. It becomes progressively lower from November to July. It is extremely low in July, when the lake-effect rains are weakest. As noted earlier, a lack of ascent

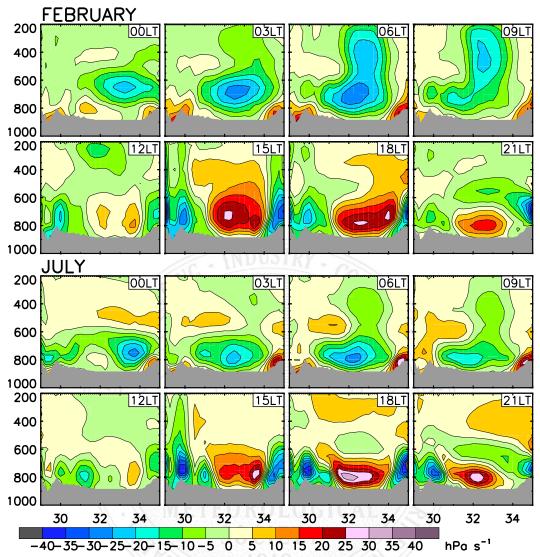


FIG. 8. Mean diurnal cycle of the vertical profile of omega (hPa s<sup>-1</sup>), February and July.

cannot explain the absence of lake-effect rains in February. The analysis of specific humidity suggests that the low moisture content is a limiting factor in convective development in February. Moisture content is associated with the large-scale conditions prevailing in wet and dry seasons. It is also a factor in virtual temperature, which is a term in the calculation of CAPE and CIN.

#### e. CAPE and CIN

CAPE is the integrated amount of work that the upward (positive) buoyancy force would perform on a given mass of air if it rose vertically through the atmosphere under given atmospheric conditions. It reflects vertical profiles of moisture and temperature. We hypothesize that CAPE is very strong during the wet-season months and weak during the dryseason months. In all four months CAPE is greatest over the lake at night (Fig. 11). This is at least partially a consequence of the relative constancy of the lake surface temperature

versus the nocturnal cooling of the overlying air (e.g., Flohn and Fraedrich 1966; Woodhams et al. 2019). CAPE peaks along both the eastern and western shores of the lakes, presumably a result of moisture advection by the lake breezes and anabatic slope winds. The stronger peak in the west is consistent with moisture advection westward by the strong katabatic flow at night off the eastern highlands.

As with specific humidity, there is a strong contrast between CAPE in the two wet-season months and CAPE in July. However, the magnitude of CAPE in February is much stronger than in all other months, although the lake-effect rains are much weaker than in April and November. The strength of CAPE in February suggests that CAPE is not the limiting factor in overlake rainfall development in that month.

While CAPE represents buoyancy, CIN acts against it. It suppresses uplift near the surface. The tendency for convection to develop is strong when CAPE is high but CIN is low. Figure 12 shows CIN eight times per day in April, when the F12

F11

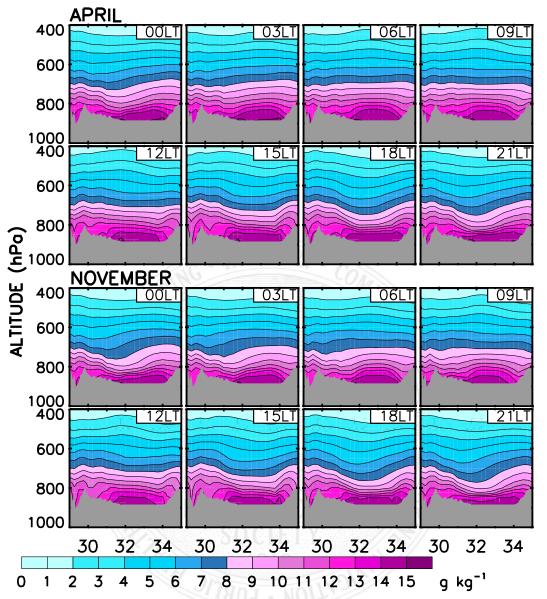


FIG. 9. Mean diurnal cycle of specific humidity (g kg<sup>-1</sup>) in April and November.

lake-effect rains are strongest. November is not shown because the pattern and magnitude of CIN is extremely similar to that of April. CIN is strongest over the lake between 1500 and 2100 LST, the driest periods over the lake. It is lowest at 0300 and 0600 LST, when the lake effect rains are strongest. It continues to be strong at 0900 LST, when the lake-effect rains continue.

In July, the driest month, CIN it is extremely weak over the lake's catchment area throughout the day (Fig. 12). It is high, nearly as high as during April, over the lake from 1800 to 0000 LST. CIN is lowest between 0600 and 1200 LST, when rainfall is weakly enhanced over the lake, despite low values of CAPE (Fig. 11). However, uplift is confined to low levels over the lake (Fig. 6), consistent with the very poorly developed lake-effect rains.

The situation in February, a month in the first dry season, is very different. CIN over the lake is extremely strong from 1500

to 0000 LST, much stronger than in April or November (12). This coincides with the rainless periods over the lake. During the other four time periods, when lake-effect rains do develop, CIN is notably higher than during the other four months. As noted earlier, CAPE is very high during these periods and ascent is strong (Fig. 11). Despite that, convection develops and lake-effect rains are weak. The explanation appears to be the high values of CIN.

#### 5. Summary

#### a. Winds and divergence

The diurnal cycle of near-surface wind is best developed in central and eastern portions of the lake and is comparatively

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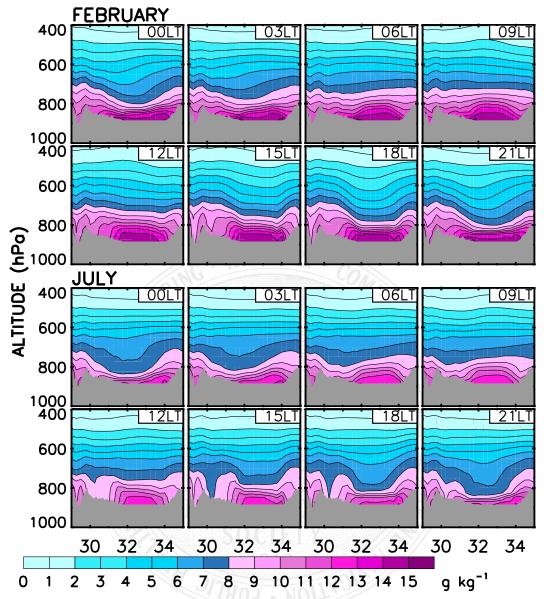


FIG. 10. Mean diurnal cycle of specific humidity (g kg<sup>-1</sup>) in February and July.

weak in the western fringe except in November. This east-west contrast is related to contrasting topography on the two sides of the lake. Katabatic flow from the east is extremely strong, overriding potential katabatic flow in the west. It is strongest in early morning, when it extends over nearly the entire lake and is probably enhanced by the prevailing east-erlies. The result of this wind configuration is that the rainfall maximum is not over center of lake but displaced toward the west and southwest.

Notably, the wind regime is very different in each of the four months evaluated. Surprisingly, however, the pattern of nearsurface wind divergence is very similar in all four months. As expected, convergence prevails over the lake during the night and early morning and divergence prevails during the afternoon and early evening. The opposite is evident in the surrounding catchment: divergence at night and convergence during the day. This is completely consistent with the diurnal cycle of overlake and catchment rainfall. Note that the overlake convergence and divergence are actually greater during the dry-season months than during the wet-season months. So while these surface conditions appear to control the diurnal cycle, they do not account for the seasonal contrasts in the lake-effect rains.

#### b. Vertical motion

Consistent with the near-surface pattern of divergence, there is relatively little contrast between the four months in the near-surface omega fields. This also suggests that local conditions do not control the seasonal changes in lake-effect rains.

However, a very pronounced contrast between the two wetseason and two dry-season months is evident in the vertical

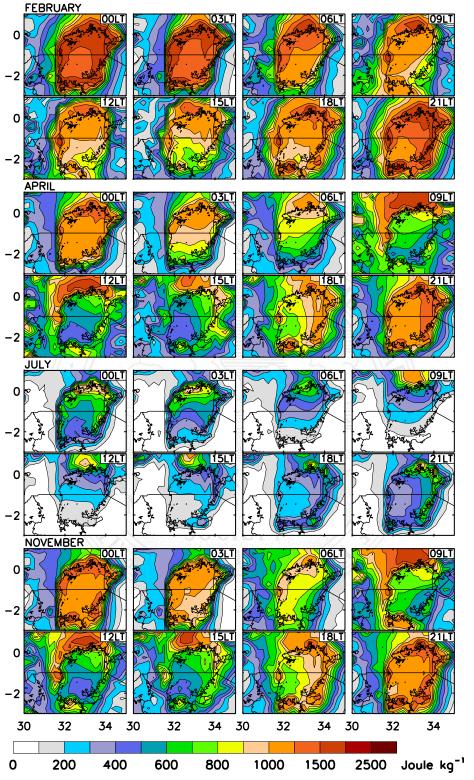


Fig. 11. Diurnal cycle of CAPE (J  $kg^{-1}$ ) in February, April, July, and November.

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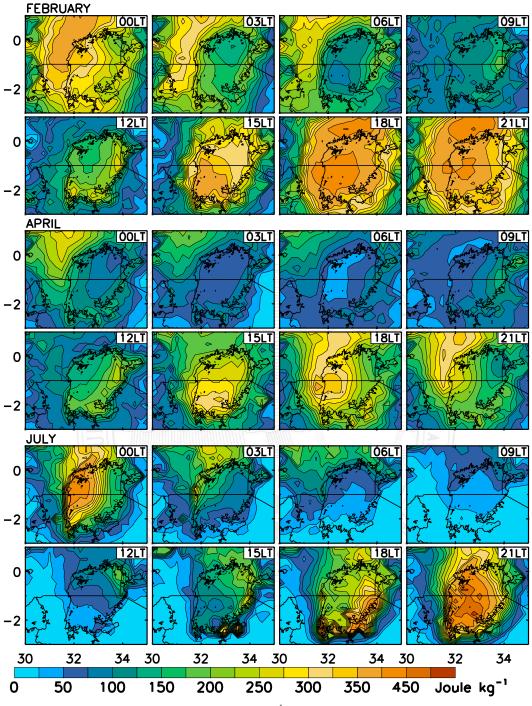


FIG. 12. Diurnal cycle of CIN (J kg<sup>-1</sup>) in February, April, and July.

profile of omega. During April the vertical motion field shows strong updrafts over the lake at night, with maximum speed at around 400-500 hPa. The updrafts are strongest from 0300 to 0900 LST, when the lake-effect rains as indicated by TRMM 3B42 V7 are most pronounced. The updraft is also evident but much weaker at 0000 and 1200 LST, when lake-effect rains are occurring but relatively weak. Low-level subsidence prevails from 1500 to 2100 LST, when rain is nearly absent over the lake. It is strongest at 1500 LST, when divergence is strongest. That is the time of strongest ascent over the catchment. The omega maximum over the catchment precedes the extremely strong catchment rainfall at 1800 LST. The diurnal cycle of omega is very similar in November, but omega is generally weaker than in April.

During the two dry-season months the vertical motion is much weaker than during April and November, consistent with the weaker lake-effect rains. Strong updrafts are evident in February from 0300 to 1200 LST, the periods when lake-effect rains develop. However, the speed maximum is at around 800 hPa, thus much lower than in the wet months. The limited vertical development of the updrafts suggests limited convective development. In July a vertically extensive updraft is evident over the lake only at 0600 and 0900 LST, but its magnitude is extremely weak above around 800 hPa. This is also consistent with the rainfall contrast between February and July.

These results strongly indicate that vertical motion exerts major control on the development of overlake rainfall, both within the diurnal cycle and in wet- versus dry-season months. This conclusion is in itself not surprising. However, it is inconsistent with the lack of contrast in near-surface divergence and omega in the four different months. The lack of contrast suggests that an additional factor controls the atmospheric buoyancy and development of updrafts.

#### c. Moisture, CAPE, and CIN

Three potential factors that impact instability and buoyancy were examined. Specific humidity appears to play some role, as it is greatest during April, when the lake-effect rains are strongest, somewhat lower in November, and lowest in July, when the lake-effect rains are weakest. Thus, it probably plays some role in the intensity of the lake-effect rainfall.

CAPE and CIN are both dependent on atmospheric moisture, because virtual temperature is a term in the calculation of both parameters. CAPE in very strong over the lake from 2100 to 0600 LST in April and November and extremely weak in July. This is consistent with the very weak lake-effect rains in July. However, it is much stronger in February than in April or November, so it is not a limiting factor in overlake rainfall development in February.

The contrast in CIN between April, February, and July is much different. In February, CIN is very high over the lake at night, much higher than in either April or July. The combination of high CAPE and high CIN is consistent with the vertical motion regime in February. Strong updrafts are apparent in the mean at 0600 and 0900 LST, but the maximum vertical motion is generally below 600 hPa.

#### 6. Conclusions

The asymmetry between the topography on the eastern and western sides of the lake plays an important role in the diurnal cycle and spatial configuration of rainfall. This asymmetry, in conjunction with the prevailing easterlies, creates contrasts in convection and the diurnal cycle across the east—west extent of the lake. The nocturnal katabatic flow in the east is so strong that it essentially precludes the possibility of strong katabatic flow off the western highlands. A consequence appears to be the second rainfall maximum over the western portion of the catchment. As this maximum occurs around 0600–0900 LST, coincident with the rainfall maximum over the lake, it probably results from storms initiated over the lake. The second maximum over the western catchment suggests that the lake-effect

rains have an influence on catchment rainfall, at least in the west.

Notable also is the contrast in winds during the four months evaluated but the relative constancy of the near-surface divergence and omega fields. This suggests that local factors, i.e., the anabatic–katabatic flow and lake–land breezes, do not play a role in the seasonal contrast in the lake-effect rains. Consistent with this suggestion, convergence over the lake at night is actually greater during the dry season than during the wet season, as is vertical motion near the surface.

The major contrast between the dry- and wet-season months is evident in the vertical profile of omega. It is much stronger and extends higher in the atmosphere during the wet-season months than during the dry-season months. Consistent with the stronger vertical motion, atmospheric specific humidity is higher during the wet season, contributing to higher values of CAPE. Weak vertical motion appears to be a limiting factor in lake-effect rains in July. In February, when CAPE is large and CIN is very strong, CIN probably plays a greater role in inhibiting overlake rainfall in. Overall these factors play a greater role than local winds in the seasonal cycle of overlake rainfall.

One limitation of this study is that only four representative months were considered. Further research should evaluate the remaining months. In addition, CAPE and CIN are parameters usually considered on the synoptic scale. For that reason, individual case studies within the various months should be carried out. Also, the analysis was unable to distinguish between the role of lake–land breezes versus topographic effects.

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