

A Novel Algorithm for Detecting and Characterizing Lake-Breeze Fronts at Lake Victoria

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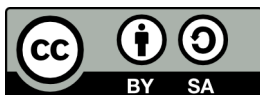
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Abstract

Lake Victoria (LV), located in East Africa, is the world's largest tropical freshwater body and supports the livelihoods of over 40 million people. Due to its vast size, LV strongly influences regional climate through diurnally varying lake-land breeze (LLB) circulations driven by thermal contrasts between the lake and surrounding land. A key feature of this circulation is the lake-breeze front (LBF), which represents its leading edge. LBFs frequently trigger cloud formation, deep convection, and heavy precipitation, often leading to weather-related hazards. Given the important role of LLBs in controlling the timing and location of convection over the Lake Victoria basin (LVB), improved understanding of these systems is essential. A practical first step to study LLBs is through identification of their associated LBFs. However, no objective methodology for detecting LBF currently exists in the region. This gap motivates the present study, whose primary aim is to develop an algorithm that can objectively and systematically identify LBFs.

Accordingly, in the first step, an Objective Lake Breeze Detection Algorithm (OLBDA) was developed using 15-minute data from an unprecedentedly dense network of 45 automatic weather stations (AWSs) across Uganda's extended coastal region over six years (2017-2022). Focusing on daytime (0900-1900 LT; LT = UTC + 3) during the dry months of December-February (DJF) and June-August (JJA), the algorithm applies thresholds based on the lowest (highest) 30% of temperature drops (dew point and wind speed increases), enabling detection of subtle meteorological changes associated with LBF passages. Performance was assessed against manually identified lake-breeze (LB) and non-LB cases from visible satellite imagery. The algorithm demonstrates strong skill, with high accuracy ($ACC = 0.76$) and probability of detection ($POD > 0.7$), and a low false alarm rate ($POFA = 0.2$).

Next, the OLBDA was applied to all 45 AWSs to derive key LB characteristics across the region. The results show that LBFs predominantly occur from early afternoon to evening, peaking around 1300 LT near the coast and shifting inland with distance. LBFs were observed on 48% of days, with December-February and January having the highest seasonal and monthly frequencies, respectively. Spatial variability is evident, with the northern sector of the lake experiencing more LB days (90.8%) than the western sector (81.7%). LBF propagation speeds vary in relation to background wind across different

hinterland sectors, reaching $\sim 8 \text{ m s}^{-1}$ westward and as low as 5.8 m s^{-1} northward. LBFs were found to penetrate up to $\sim 130 \text{ km}$ inland. These results provide a baseline climatology, which was subsequently used to evaluate the ability of the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS) 9 km operational analyses to represent the lake-breeze system (LBS) over the LVB.

To evaluate its robustness, the OLBDA was applied to hourly station data and IFS surface data to identify LBF passages, and subsequently validated against the same manually identified satellite LB and non-LB events. The OLBDA was found to be robust across both datasets, achieving a POD of 0.71 and POFA of 0.25 for IFS, comparable to AWS (POD = 0.74, POFA = 0.20). LBFs were detected on 48% of days in IFS, and 38% in hourly AWS data, with near-even distribution of LB days between western and northern lake sectors. Mean arrival times exhibit clear inland progression, occurring earlier (1200-1400 LT) near the lakeshore and later (1600-1700 LT) farther inland, consistent with expected daytime LBF propagation. However, despite reproducing the overall temporal evolution of LBFs from early to late afternoon, IFS exhibits systematic biases, including an overprediction of LBF occurrence by approximately 26% and an early arrival of 1-2 hours at most stations. These discrepancies highlight limitations in representation of surface heterogeneity and boundary-layer processes in IFS.

In the final step, three commonly used parameters for delineating LBFs, i.e., surface convergence, and gradients of surface specific humidity and boundary-layer height (BLH), were evaluated against the station-based baseline climatology. The latter two emerged as the most reliable indicators of LBF structure and evolution in the IFS over the LV region. Composite and vertical cross-section analyses reveal physically consistent three-dimensional lake-breeze features in IFS, although notable differences exist between western and northern transects. The Northwest-Southeast (NW-SE) transect shows stronger vertical motion and deeper inland penetration compared to the North-South transect, likely due to the influence of the mean easterly low-level flow over the lake. In the late afternoon, BLH depth reaches up to 3 km. These findings suggest that ECMWF IFS operational analyses can reliably support lake-breeze studies in both observational and modeling contexts, while highlighting model behavior and biases, particularly in data-sparse regions reliant on global model outputs.

This thesis represents one of the first integrated efforts to develop and validate an objective LBF detection over LV using an unprecedentedly dense station network, while also assessing IFS representation of the lake-breeze circulation system over the region. The findings offer valuable insights with potential applications in disaster preparedness and climate mitigation. Furthermore, the methodologies and analysis presented here lay a strong foundation for improving monitoring, modeling, and forecasting of lake-breeze systems, thereby supporting enhanced weather prediction and hazard mitigation efforts in the LVB.

Zusammenfassung

Der Viktoriasee (LV) in Ostafrika ist der weltweit größte tropische Süßwasserkörper und bildet die Lebensgrundlage für über 40 Millionen Menschen. Aufgrund seiner enormen Ausdehnung beeinflusst der LV das regionale Klima maßgeblich durch tageszeitlich variierende Land-See-Winde (LLB), die durch thermische Kontraste zwischen dem See und der umliegenden Landoberfläche angetrieben werden. Ein wesentliches Merkmal dieser Zirkulation ist die Seewindfront (LBF), die deren Vorderkante darstellt. LBFs lösen häufig Wolkenbildung, hochreichende Konvektion und starke Niederschläge aus, was oft zu wetterbedingten Gefahren führt. Angesichts der wichtigen Rolle der LLBs bei der raum-zeitlichen Auslösung der Konvektion über der Viktoriaseeregion ist ein besseres Verständnis dieser Systeme unerlässlich. Ein praktischer erster Schritt zur Untersuchung von LLBs ist die Identifizierung der damit verbundenen LBFs. Derzeit gibt es in der Region jedoch keine objektive Methodik zur Detektion von LBFs. Diese Lücke ist der Anlass für die vorliegende Studie, deren primäres Ziel die Entwicklung eines Algorithmus ist, der LBFs objektiv und systematisch identifizieren kann.

Dementsprechend wurde im ersten Schritt ein Algorithmus zur Detektion von Seewindfronten ("Objective Lake Breeze Detection Algorithm", OLBDA) entwickelt, wobei 15-Minuten-Daten aus einem für die Region einzigartig dichten Netzwerk von 45 automatischen Wetterstationen (AWS) entlang der ausgedehnten Küstenregion Ugandas über einen Zeitraum von sechs Jahren (2017–2022) herangezogen wurden. Der Algorithmus konzentriert sich auf den Zeitraum bei Tag (09:00–19:00 LT; LT = UTC + 3) während der Trockenmonate Dezember–Februar (DJF) und Juni–August (JJA) und wendet Schwellwerte an, die auf den untersten (obersten) 30 % der Temperaturabnahmen (Taupunkt- und Windgeschwindigkeitszunahmen) basieren, wodurch sich subtile meteorologische Veränderungen im Zusammenhang mit dem Durchzug einer Seewindfront erkennen lassen. Die Leistungsfähigkeit wurde anhand von manuell identifizierten Fällen mit Seewindenfronten (LB) und ohne (Non-LB) aus sichtbaren Satellitenbildern bewertet. Der Algorithmus zeigt eine hohe Güte mit hoher Genauigkeit ($ACC = 0,76$) und Erkennungswahrscheinlichkeit ($POD > 0,7$) sowie einer niedrigen Fehlalarmrate ($POFA = 0,2$).

Anschließend wurde das OLBDA-Modell auf alle 45 AWS-Stationen angewendet, um wichtige LB-Merkmale für die gesamte Region abzuleiten. Die Ergebnisse zeigen, dass

LBFs vorwiegend vom frühen Nachmittag bis zum Abend auftreten, ihren Höhepunkt um 13:00 Uhr Ortszeit in Küstennähe erreichen und sich mit zunehmender Entfernung landeinwärts verlagern. LBFs wurden an 48 % der Tage beobachtet, wobei die Monate Dezember bis Februar bzw. der Januar die höchsten saisonalen bzw. monatlichen Häufigkeiten aufwiesen. Es zeigt sich eine deutliche räumliche Variabilität: Im nördlichen Sektor (90,8 %) des LV gab es mehr LB-Tage als im westlichen Sektor (81,7 %). Die Ausbreitungsgeschwindigkeiten der LBFs variieren in Abhängigkeit vom Hintergrundwind in den verschiedenen Hinterlandsektoren und erreichen in westlicher Richtung $\sim 8 \text{ m s}^{-1}$, während sie in nördlicher Richtung nur $5,8 \text{ m s}^{-1}$ betragen. Es wurde festgestellt, dass die LBFs bis zu $\sim 130 \text{ km}$ landeinwärts vordringen. Diese Ergebnisse liefern eine klimatologische Basis, die anschließend zur Bewertung der Fähigkeit der operationellen Analysen des Integrierten Vorhersagesystems (IFS) des Europäischen Zentrums für mittelfristige Wettervorhersagen (ECMWF) mit einer Gitterweite von 9 km herangezogen wurde, das Seewind-System (LBS) über dem LVB abzubilden.

Um die Robustheit des OLBDA zu bewerten, wurde das Modell auf stündliche Stationsdaten und IFS-Oberflächendaten angewendet, um LBF-Durchgänge zu identifizieren, und anschließend anhand derselben manuell identifizierten LB- und Nicht-LB-Ereignisse aus Satellitendaten validiert. Es zeigte sich, dass das OLBDA in beiden Datensätzen robust war und für IFS einen POD von 0,71 sowie einen POFA von 0,25 erreichte, was mit den Ergebnissen von AWS (POD = 0,74, POFA = 0,20) vergleichbar ist. LBFs wurden an 48 % der Tage in den IFS-Daten und an 38 % der Tage in den stündlichen AWS-Daten erkannt, wobei sich die LB-Tage nahezu gleichmäßig auf den westlichen und nördlichen Seeabschnitt verteilten. Die mittleren Ankunftszeiten zeigten eine deutliche Ausbreitung landeinwärts: Sie traten in Ufernähe früher (12:00-14:00 LT) und weiter landeinwärts später (16:00-17:00 LT) auf, was mit der erwarteten Propagation von LBFs tagsüber übereinstimmt. Obwohl das IFS den allgemeinen zeitlichen Verlauf der LBFs vom frühen bis zum späten Nachmittag wiedergibt, weist es systematische Fehler auf, darunter eine Überschätzung des LBF-Auftretens um etwa 26 % und ein um 1-2 Stunden verfrühtes Eintreffen an den meisten Stationen. Diese Diskrepanzen verdeutlichen die Defizite bei der Darstellung der Oberflächenheterogenität und der Grenzschichtprozesse im IFS.

Im letzten Schritt wurden drei häufig verwendete Parameter zur Abgrenzung von LBFs - nämlich die bodennahe Windkonvergenz sowie die Gradienten der spezifischen Oberflächenfeuchte und der Grenzschichthöhe (BLH) - anhand der stationsbasierten Referenzklimatologie ausgewertet. Die beiden letztgenannten erwiesen sich als die zuverlässigsten Indikatoren für die Struktur und Entwicklung von LBFs im IFS über dem LVB. Analysen von Kompositen und Vertikalschnitten zeigen physikalisch konsistente dreidimensionale Merkmale von Seewindfronten im IFS, obwohl zwischen den westlichen und nördlichen Transekten deutliche Unterschiede bestehen. Der Nordwest-Südost-Transekt

(NW-SE) weist im Vergleich zum Nord-Süd-Transekt stärkere vertikale Bewegungen und ein tieferes Eindringen ins Landesinnere auf, was wahrscheinlich auf den Einfluss der mittleren östlichen Strömung in den unteren Schichten über dem See zurückzuführen ist. Am späten Nachmittag erreicht die Grenzschichthöhe bis zu 3 km. Diese Ergebnisse deuten darauf hin, dass die operationellen IFS-Analysen des ECMWF Studien zur Seewinden sowohl im Beobachtungs- als auch im Modellierungskontext zuverlässig unterstützen können, während sie gleichzeitig Modellverhalten und Modellfehler hervorheben, insbesondere in datenarmen Regionen, die auf globale Modellausgaben angewiesen sind.

Diese Arbeit stellt einen der ersten ganzheitlichen Ansätze dar, eine objektive Detektion von LBF im LVB mithilfe eines einmalig dichten Stations-Netzwerks zu entwickeln und zu validieren und gleichzeitig die Darstellung des Seewind-Zirkulationssystems in der Region durch das IFS zu bewerten. Die Ergebnisse liefern wertvolle Erkenntnisse mit potenziellen Anwendungsmöglichkeiten in den Bereichen Katastrophenvorsorge und Klimaschutz. Darüber hinaus bilden die hier vorgestellten Methoden und Analysen eine solide Grundlage für die Verbesserung der Überwachung, Modellierung und Vorhersage von Seewind-Systemen und unterstützen damit eine verbesserte Wettervorhersage sowie Maßnahmen zur Gefahrenminderung im LVB.

Preface

The PhD candidate confirms that the research presented in this thesis contains significant scientific contributions by himself. This thesis reuses material from the following publications:

Ssemujju, M., Maranan, M., Fink, A. H., and Ageet, S. (2026a): A Novel Algorithm for Detecting Lake-Breeze Fronts at Lake Victoria Using Station Observations. *Journal of Applied Meteorology and Climatology*, **65**, 941-960, 10.1175/JAMC-D-25-0253.1

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Microsoft Copilot¹, an artificial intelligence (AI) tool, was employed during the preparation of this thesis to support the grammar, style, and clarity of the text. In particular, Copilot was used extensively in Chapter 2 to assist with grammar correction, and paraphrasing of selected sentences to improve clarity, coherence, and conciseness. All AI-generated suggestions were carefully reviewed, edited where necessary, and approved by the author before being incorporated into the thesis. Furthermore, DeepL² was used to translate the abstract into German. The author remains fully responsible for the content, interpretation, and conclusions presented in this work.

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¹<https://m365.cloud.microsoft/chat> (Access Date: 2026-06-15)

²<https://www.scc.kit.edu/dienste/deepl.php> (Access Date: 2026-06-20)

[Ssemujju et al. \(2026a,b\)](#) were solely performed by the candidate, who also wrote the text with advice from Andreas H. Fink, Marlon Maranan and Simon Ageet.

The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the publications of others. This copy has been supplied on the understanding that this is copyright material and that no quotation from the thesis may be published without proper acknowledgement.

List of Acronyms

3-D	Three Dimensional
ACC	Accuracy
AGL	Above Ground Level
AWS	Automatic Weather Station
BID	Bias in Detection
BLH	Boundary Layer Height
COSMO	Consortium for Small-Scale Modeling
CSI	Critical Success Index
CP	Convection Permitting
DAAD	Deutscher Akademischer Austauschdienst / German Academic Exchange Service
DJF	December-January-February
DWD	Deutscher Wetterdienst
ECMWF	European Centre for Medium-range Weather Forecasting
EOSDIS	Earth Observing System Data and Information System
GLOBE	Global Land One-Km Base Elevation project
GPM	Global Precipitation Measurement
H	High Pressure Center
HSS	Heidke Skill Score
HyVic	Hydrometeorology project for Lake Victoria basin
ICON	ICOsahedral Nonhydrostatic
IFS	Integrated Forecasting System
IMERG	Integrated Multi-satellite Retrieval for GPM

IPCC Intergovernmental Panel on Climate Change

ITCZ Inter-Tropical Convergence Zone

JJA June-July-August

L Low Pressure Center

LB Lake Breeze

LBC Lake Breeze Circulation

LBF Lake Breeze Front

LBI Lake Breeze Index

LCL Lifting Condensation Level

LES Large Eddy Simulations

LLB Lake-Land Breeze

LSB Land-Sea Breeze

LT Local Time

LV Lake Victoria

LVB Lake Victoria Basin

LWST Lake Water Surface Temperature

MAM March-April-May

MetUM Met Office Unified Model

ML Machine Learning

MODIS Moderate Resolution Imaging Spectroradiometer

N North/Northern

NASA National Air Space Agency

NMHS National Meteorological and Hydrological Service

N-NE North-Northeast

NOAA National Oceanic and Atmospheric Administration

NW Northwest

NWP Numerical Weather Prediction

NW-SE Northwest-Southeast

OLBDA Objective Lake Breeze Detection Algorithm

OSTIA Operational Sea Surface Temperature and Ice Analysis

POD Probability of Detection

POFA Probability of False Alarm

SBC Sea Breeze Circulation

SBF Sea Breeze Front

SE Southeast

SON September-October-November

SR Success Ratio

SST Sea Surface Temperature

TAHMO Trans-African Hydro-Meteorological Observatory

TIBL Thermal Internal Boundary Layer

U Horizontal Wind

UDMS Uganda Department of Meteorological Services

UKMO United Kingdom Meteorological Office

USA United States of America

UTC Universal Coordinate Time

VIIRS Visible Infrared Imaging Radiometer Suite

W West/Western

WD Wind Direction

WRF Weather research and Forecasting

WMO World Meteorological Organisation

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1. Introduction

A large and growing proportion of the global population lives within 150 km of the ocean and lake coastlines, where many mega cities are located (Small and Cohen, 2004; Cosby et al., 2024). These regions are particularly susceptible to land-sea and land-lake breeze (LSB/LLB) circulations, which greatly impact cloud development (van der Linden et al., 2015; Viner et al., 2021; Wermter et al., 2022), deep convective initiation and related (extreme) rainfall events (Mapes et al., 2003b,a; Warner et al., 2003; Miller et al., 2003; Birch et al., 2015; Fu et al., 2022). The LSBs and LLBs also impact air quality through pollutants transport and dispersion (Zhang et al., 2007; Loughner et al., 2011; Stauffer et al., 2015; Deroubaix et al., 2019), and shaping local climate patterns (e.g. Dai et al., 1999). Despite their importance, LSBs and LLBs and their associated impacts remain poorly understood and inadequately represented in most global climate models (Hannak et al., 2017), partly due to the coarse resolution and insufficient and/or inadequate observational data for assimilation. These model deficiencies contribute to substantial uncertainties in projections of future coastal climate and rainfall patterns. This “global” problem is also relevant to Lake Victoria (LV), the second largest lake on Earth (Encyclopaedia Britannica, 2025). The region surrounding LV is already experiencing devastating extreme rainfall and urban flooding events (Wainwright et al., 2021; Pietroiusti et al., 2024), exacerbated by rapid population growth, and escalating pollution levels, which contribute to clogged drainage systems and degradation of natural water management systems. Climate change is expected to aggravate these impacts through even more extreme rainfall events (IPCC, 2023; WMO, 2025).

Lake Victoria, located in East Africa, is the largest tropical freshwater body in the world, with a surface area of 69,000 km² (Semazzi, 2011). The lake straddles the equator and is shared by three countries namely, Uganda, Kenya, and Tanzania (Figure 1.1). The lake holds immense economic and social importance for East Africa. It supports the livelihood of over 40 million people in eastern Africa through its productive fishery, one of the largest freshwater fisheries globally, provides water for domestic and industrial use, facilitates transport, and sustains agriculture and tourism in the region (Ntiba et al., 2001; Song et al., 2004; Semazzi, 2011; Chamberlain et al., 2014; Nyamweya et al., 2023). The region surrounding LV including the Kamapala metropolitan area along its

northern shores in Uganda is usually termed as the Lake Victoria basin (LVB). Because of its vast size, the lake exerts a profound influence on the local and regional climate of East Africa, driving strong, diurnally varying lake-land breeze (LLB) circulations that shape weather patterns and significantly affect the timing, location, and intensity of convective precipitation across the LVB (Woodhams et al., 2019; Nicholson et al., 2021b). Furthermore, this local LLB system generates diurnal wind patterns, enhances moisture convergence, impacts air quality through pollutant transport and dispersion, and plays a key role in the development of intense nocturnal thunderstorms and convective rainfall over the lake and its surroundings (Thiery et al., 2015; Woodhams et al., 2019).

The LLB circulations are thermally driven mesoscale (local) systems formed due to pressure gradients between the air over a warmer land surface and cooler adjacent water body during the day and vice-versa at night. These circulations are favoured in weak synoptic flow (Miller et al., 2003; Wentworth et al., 2015), and can be triggered by a temperature gradient as low as 1°C (Watts, 1955). Larger temperature gradients, which are often common in dry months, induce stronger sea- or lake-breeze fronts (SBF/LBF), the leading edge of the sea/lake breeze, with greater propagation velocity and deeper inland penetration. For instance, sea-breezes have been observed to penetrate over 200 km inland in Australia (Simpson, 1994; Barry and Chorley, 2010) and over 100 km in Brazil, India, and southeastern United States (Planchon et al., 2006; Muppa et al., 2012; Noble et al., 2024), while Guedje et al. (2019) reported SBFs reaching 185 km inland over West Africa, driven by strong temperature and pressure gradients. In the LVB, Woodhams et al. (2019) reported LBF propagation up to ~240 km during the dry season when the temperature contrasts were strongest in the afternoon.

Lake breezes have been extensively studied worldwide, particularly around large lakes such as the Great Lakes of North America and Lake Geneva, where both observational campaigns and high-resolution numerical models have highlighted their role in local weather, convection, and air quality. Various methods have been employed to detect SBFs/LBFs, with many studies relying on time series from at least two meteorological stations (e.g. Papanastasiou and Melas, 2009; Laird et al., 2001; Azorin-Molina et al., 2011; Stauffer et al., 2015; Hughes and Veron, 2018; Guedje et al., 2019; Mazzuca et al., 2019; Viner et al., 2021). Typically, data from coastal and inland stations are used to track the inland progression of the breeze front. Efforts to automate SBF/LBF detections using either station data or satellite images have led to the development of various algorithms, with most of them being developed in extra-tropical regions (e.g. Berri and Dezzutti, 2020; Viner et al., 2021; Hughes and Veron, 2018; Wentworth et al., 2015; El-Geziry et al., 2021; McCabe and Freedman, 2023), and only fewer studies in tropical regions (e.g. Guedje et al., 2019; Ferdiansyah et al., 2020; Abatan et al., 2014; Planchon et al., 2006). A key challenge remains in ensuring that the observed changes in the meteorological variables are solely caused by the SBF/LBF passages (Ryznar

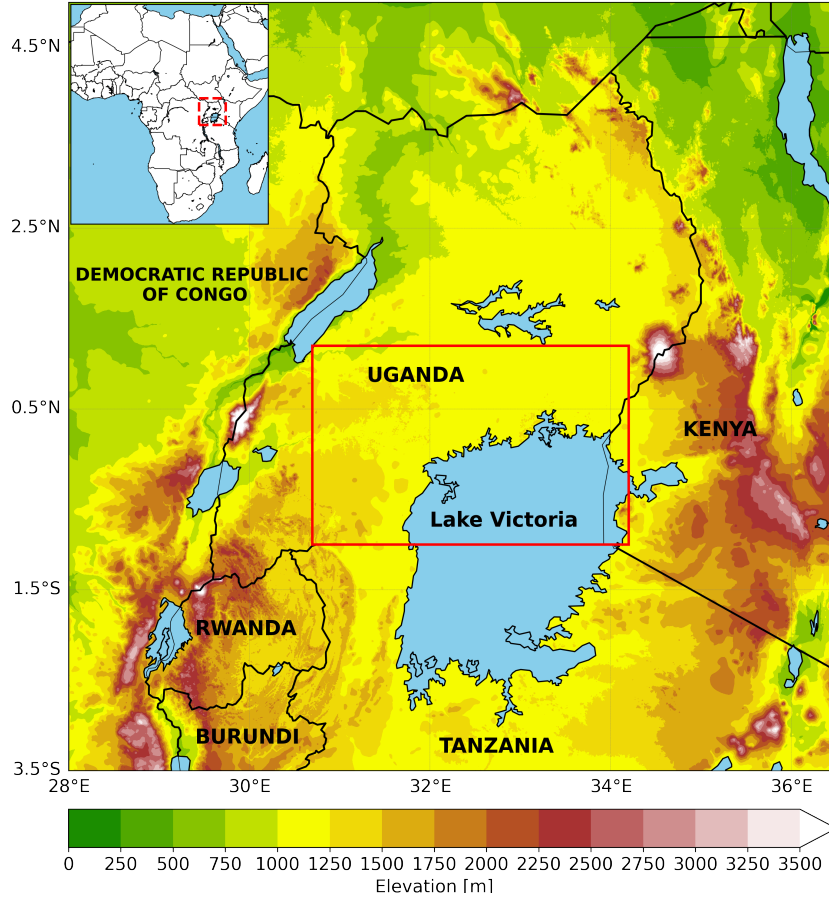


Figure 1.1: Map of study area showing the Lake Victoria region (red rectangle). The shading show the highly varying elevation of the study area as given by the Global Land One-Km Base Elevation project (GLOBE; [Hastings and Coauthors, 1999](#)). The map inset shows the location of Uganda (red rectangle) in Africa.

and Touma, 1981). Nonetheless, these algorithms have proven effective, largely due to their objective criteria, reliance on standard meteorological observations, and ease of application to long-term datasets. However, over the LVB, observational approaches, including surface station data, satellite imagery, and reanalysis products, have been used to document LLB impacts associated wind patterns, cloud development, and precipitation variability (e.g. [Fraedrich, 1968, 1972](#); [Lumb, 1970](#); [Datta, 1981](#)). However, persistent convection over the lake complicates the clear attribution of cloud and rainfall patterns to LLB dynamics alone (e.g. [Datta, 1981](#); [Chamberlain et al., 2014](#)). Pioneering regional climate modeling studies (e.g. [Song et al., 2004](#); [Anyah and Semazzi, 2006](#)) and more recent convection-permitting (CP) simulations (e.g. [Woodhams et al., 2019, 2022](#); [Finney et al., 2020](#)) have demonstrated the critical role of LLB circulations in driving nocturnal convection and rainfall. Despite these advances, important limitations remain that earlier modeling studies often relied on coarse resolutions and convection parameterization schemes that introduce uncertainties and limit the realism of simulated frontal structures and precipitation patterns (e.g. [Song et al., 2004](#); [Anyah and Semazzi,](#)

2006). Although CP models provide more detailed insights, they are typically restricted to case studies and lack systematic evaluation. Observational efforts are similarly constrained by sparse in-situ measurements, particularly over the lake, limited vertical profiling, and operational challenges affecting radar data continuity (e.g. Waniha et al., 2019; Wilson and Roberts, 2022). Consequently, a major bottleneck in advancing the understanding and detection of lake-breeze-related features, including the development of robust ground-based LBF detection algorithms, remains the lack of a dense and reliable observational network capable of resolving their spatial coherence and variability under different synoptic conditions.

From the above discussions, it is clear that despite the enormous role of LLBs over LVB and the obvious usefulness of detection algorithms, yet to the best of my knowledge, no algorithm currently exists for detecting and tracking LBFs using observational data from a dense station network. This gap is largely due to the scarcity of publicly available data around LV, making it hard to develop an automated algorithm in the first place. Furthermore, global models such as the European Center for Medium-range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS), a state-of-the-art system used in operational forecasting, can, in principle, reproduce mesoscale features such as LBFs. However, their ability to represent these features has not been systematically evaluated and remains largely unquantified in the existing literature. This is particularly important because IFS-based forecasts and reanalyses underpin many coastal climate and weather applications. To address this gap, this thesis develops and evaluates an automated observation-based lake breeze detection algorithm (OLBDA) using data from an unprecedented dense network of stations, primarily concentrated along the northern shore in Uganda. Beyond the development of the detection algorithm, a baseline climatology of LBFs in the region based on algorithm-detected events was developed. Additionally, the ability of IFS operational forecasts to represent LLBs over Lake Victoria was evaluated. This work represents only a small step towards solving this global problem of systematic evaluation of how LBFs are represented in a global modeling system over LV, focusing on their timing, propagation speed, and thermodynamic structure. The goals of this thesis are to:

1. Develop and validate a station-observation-based algorithm for detecting lake-breeze fronts (LBFs) over a large low-latitude lake.
2. Construct climatologies of LBFs across the lake basin.
3. Evaluate the capability of high-resolution operational analyses to represent the key characteristics of LBFs.

The rest of this thesis is structured as follows: Chapter 2 provides the theory and literature review on the LLB and LSB, with particular focus on LLB over Lake Victoria.

Focus is put on the observation and detection mechanisms over the lake. Chapter 3 elaborates on the principal research objectives and the research questions designed to address and achieve these objectives. Next, Chapter 4 presents the results starting with the development of a novel algorithm to detect LBFs using station data and then its application to derive various LBF characteristics. In Chapter 5, the results obtained from applying the algorithm to the ECMWF IFS operational analysis, as well as to suitable IFS-based proxies, are presented. To finalise the thesis, Chapters 6 and 7 present the conclusions and outlook of this thesis, respectively.

2. Theory, Background and Literature Review

2.1 Sea/Lake breeze and Land breeze Systems: Fundamentals

Sea-, lake-, and land-breeze circulations are among the most common thermally driven mesoscale atmospheric systems that develop in coastal and lacustrine environments as a result of differential heating and cooling between land surfaces and adjacent water bodies ([Figure 2.1](#)). Because land has a lower heat capacity than water, it responds more rapidly to solar heating during the day, leading to warmer surface and air temperatures over land than over the water. The resulting horizontal temperature contrast generates a pressure gradient that drives cooler, denser marine or lake air inland, forming a sea or lake breeze (Onshore flow in [Figure 2.1](#)) near the surface ([Simpson, 1994](#)). As warm air (red arrow pointing up in [Figure 2.1](#)) rises over the heated land, mass continuity is maintained through a compensating return flow aloft directed toward the water body (blue arrow pointing down), thereby establishing a closed circulation cell ([Anthes et al., 1987](#); [Arritt, 1993](#); [Miller et al., 2003](#)). Typically, the onshore inflow is confined to the lowest several hundred metres to approximately 1 km above ground level, while the return flow may extend to heights of several kilometres depending on atmospheric stability and the strength of surface heating ([Barry and Chorley, 2010](#)). After sunset, the thermal contrast reverses as land cools more rapidly than water, producing relatively higher pressure over land (blue H) and initiating an offshore-directed land breeze with an opposite circulation pattern. Together, these coupled daytime and nighttime circulations constitute a diurnal land-water breeze system that plays an important role in regulating boundary-layer structure, moisture transport, cloud development, convection, and local weather conditions in coastal and lakeshore regions ([Simpson, 1994](#)).

Although sea and lake breezes share the same fundamental physical mechanisms, important differences arise due to variations in water-body size, shoreline geometry, surrounding topography, atmospheric stability, and regional meteorological conditions. For example, [Zhang et al. \(2024\)](#) using large-eddy simulations (LES) over Tibetan Plateau showed that on sufficiently large lakes, breeze systems from opposite coasts can interact or merge over the interior, generating mesoscale convergence features that depend on basin geometry, a behavior less typical in open ocean settings where coastlines

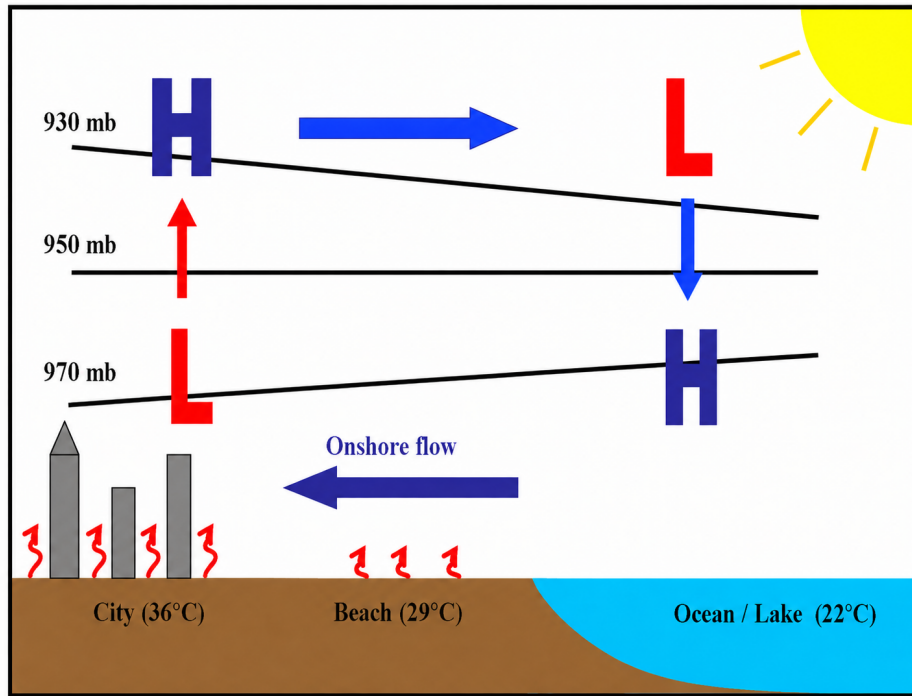


Figure 2.1: A schematic illustration of how formation of Sea/Lake-breeze circulation. A sea breeze circulation is formed due to temperature differences between air over land and air over water. During daytime, the air over water is kept cooler due to the high specific heat of water. This causes a horizontal temperature and pressure gradient. An onshore flow develops from the ocean to the land. A return flow is caused by uplifting air over the land. This can lead to sinking air over the ocean. Modified figure from [Hughes \(2011\)](#).

are far apart or absent. In this thesis, sea and lake breezes are therefore treated within a unified conceptual framework, and the terms are used interchangeably, except where distinctions between oceanic and lake environments are explicitly required.

These circulations are of particular importance in regions surrounding large tropical lakes such as Lake Victoria, where lake-breeze dynamics play a key role in boundary-layer evolution, convective initiation, and regional rainfall patterns. A thorough understanding of these processes is therefore essential for interpreting local climate variability and associated weather hazards. This section reviews the historical development of sea- and lake-breeze research, the physical mechanisms governing their formation and evolution, and the theoretical and numerical models used to describe these circulations.

2.1.1 Historical Background

Sea and land breezes are among the earliest atmospheric circulations to attract scientific attention. Their regular diurnal occurrence in coastal regions has been recognized for centuries, with early explanations dating back to ancient Greece (see [Simpson, 1994](#); [Miller et al., 2003](#)). Aristotle discussed the origin of sea-breeze winds more than two

thousand years ago, although the physical mechanisms responsible for their formation were not yet understood at the time (Simpson, 1994). Systematic scientific investigation began in the nineteenth century, when observational studies started to document the timing, inland penetration, and spatial extent of sea-breeze circulations (SBCs). One of the earliest organized field campaigns was conducted near Boston, USA, where Davis et al. (1890) employed a dense network of observers to track the inland propagation of the sea-breeze front. Early studies like this one, marked a transition from qualitative descriptions to more structured observational analysis.

During the twentieth century, advances in meteorological instrumentation, theory, and numerical modeling led to substantial progress in understanding thermally driven coastal circulations. Research increasingly focused on the physical mechanisms, structure and evolution of sea-breeze systems, leading to the development of conceptual, analytical, and numerical models (e.g., Simpson, 1994; Crosman and Horel, 2010). This period established the theoretical framework that still underpins modern studies of mesoscale circulations.

Research on lake breezes followed a similar trajectory, though it developed somewhat later. While lake-induced circulations had been noted in earlier meteorological observations, detailed investigations became more common during the second half of the twentieth century, particularly in the North American Great Lakes region (e.g., Biggs and Graves, 1962; Moroz, 1967; Lyons, 1972; Estoque et al., 1976). These studies demonstrated that lake breezes are driven by the same fundamental mechanism as sea breezes, namely differential heating between land and water surfaces, while also exhibiting distinct characteristics influenced by lake size, shoreline geometry, and regional meteorological conditions (Moroz, 1967; Lyons, 1972). In recent decades, research has expanded beyond mid-latitude environments to include large tropical lakes, most notably Lake Victoria (e.g. Datta, 1981; Anyah and Semazzi, 2006; Woodhams et al., 2019, 2022; Odongo et al., 2022; Glazer et al., 2025).

2.1.2 Formation and Physical Mechanisms

(a) Differential heating between land and water

The fundamental driving mechanism of lake- and sea-breeze circulations (LBCs/SBCs) is the differential heating and cooling of land and water surfaces as illustrated in **Figure 2.1**. Because land has a lower heat capacity and smaller effective thermal depth than water, it responds more rapidly to incoming solar radiation. During daytime, land surfaces warm more quickly than adjacent water bodies, establishing a horizontal temperature gradient directed from the cooler water toward the warmer land. At night, this gradient reverses as land cools more rapidly than the water surface (e.g., Simpson, 1994; Crosman and Horel, 2010). In addition to heat capacity differences, surface energy balance processes such as sensible and latent heat fluxes play a crucial role in modulating the strength

of these temperature contrasts. Over water bodies, a larger proportion of incoming energy is partitioned into latent heat flux and mixed over a greater depth, reducing near-surface temperature variations. In contrast, over land, heating is concentrated near the surface, enhancing near-surface temperature gradients. Recent studies have further highlighted the importance of lake depth, thermal stratification, and surface flux exchanges in controlling the intensity and timing of breeze circulations (e.g., [Xu et al., 2021](#); [Wang and Zhuo, 2022](#)).

(b) Pressure gradient development

The temperature contrasts established between land and water give rise to horizontal pressure gradients that drive the circulation. As shown in [Figure 2.1](#), daytime heating of the land causes the overlying air column to expand hydrostatically, leading to lower surface pressure relative to the cooler air over the water. This pressure gradient induces an onshore-directed flow known as the lake or sea breeze. Then at night, warmer air over the water and cooler air over land reverse this pressure gradient, producing an offshore-directed land breeze. These pressure gradients are fundamentally linked to baroclinicity within the boundary layer and are modulated by both local thermal forcing and larger-scale atmospheric conditions as documented in [Atkinson \(1981\)](#) and [Miller et al. \(2003\)](#). Furthermore, recent theoretical studies (e.g., [Shokurov and Kraevskaya, 2024](#)) and numerical investigations by [Arrillaga et al. \(2020\)](#) at the CESAR site near the North Sea demonstrate that breeze circulation can be interpreted as a response to buoyancy-driven pressure perturbations, with its structure influenced by stratification and background winds.

[Figure 2.2](#) further illustrates the fundamental role of differential heating and pressure-gradient development in driving lake-breeze circulation over the course of a day. [Moore \(2019\)](#) showed that in the morning hours, solar radiation heats the land surface more efficiently than the adjacent water body due to its lower heat capacity, producing stronger turbulent mixing and a comparatively shallow terrestrial boundary layer, while mixing over the lake remains weak under light synoptic flow. Studies by [Sills et al. \(2011\)](#) and [Xu et al. \(2021\)](#) show that as heating intensifies into the afternoon, the boundary layer over land deepens significantly, increasing the temperature contrast between land and water. This contrast generates a horizontal pressure gradient through hydrostatic adjustment, which, under weak background winds, induces an onshore flow from the lake toward the warmer land, thereby establishing the lake-breeze circulation. The process persists as long as the land–water thermal contrast is maintained, typically weakening toward sunset. As documented in several studies (e.g., [Segal et al., 1997](#); [Crosman and Horel, 2010](#); [Moore, 2019](#)), the development of this circulation is therefore strongly dependent on sufficient solar heating, minimal synoptic forcing, and clear or partly cloudy conditions that allow differential heating to maximize, explaining why

lake breezes are most common during summer when warm land surfaces coexist with relatively cooler water bodies.

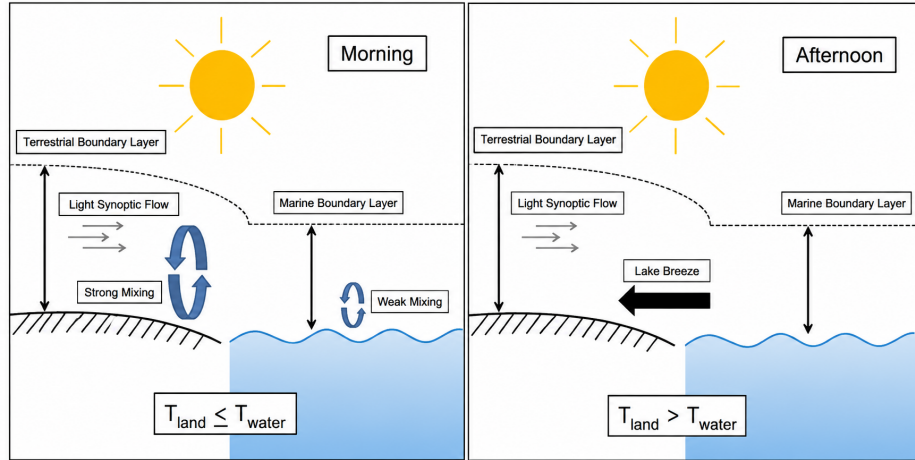


Figure 2.2: A schematic of the typical meteorological conditions prior to and during lake-breeze system development. In the morning, land temperatures are similar to or slightly cooler than those over the water. However, incoming solar radiation heats the land surface more efficiently, causing stronger warming and a deeper mixed terrestrial layer in the air above it. As the day progresses, the land becomes significantly warmer than the adjacent water. Under conditions of weak large-scale winds, this temperature difference creates a pressure gradient that initiates a lake breeze circulation. Adapted from [Stauffer \(2012\)](#).

2.1.3 Horizontal and Vertical Structure of the LLB Circulation

This section gives an overview of the detailed structure and dynamics of the lake-land breeze circulation (LBC) system. The mature lake-breeze circulation exhibits a well-defined horizontal and vertical structure characterized by a shallow onshore inflow layer near the surface, a zone of ascent along the advancing breeze front, a region of strong turbulent mixing usually behind the head, thermal internal boundary layer (TIBL), and a compensating offshore return flow aloft as shown in [Figure 2.3](#). Together, these components form a closed, thermally direct circulation cell that redistributes heat, moisture, and momentum within the coastal environment. To study the horizontal and vertical structure of the LBC, [Sills et al. \(2011\)](#) designed an idealized model ([Figure 2.3](#)) basing on previous studies (e.g., [Stull, 1988](#); [Simpson, 1994](#)). This model was later adapted by [Wentworth et al. \(2015\)](#) to study lake breeze impacts on ozone and nitrogen oxide over the Greater Toronto area.

[Figure 2.3](#) illustrates a vertical cross-section of an idealized lake-breeze circulation occurring under weak large-scale winds as designed by [Sills et al. \(2011\)](#). After sunrise, the land surface warms more rapidly than the adjacent water, leading to warmer air over the land compared to the cooler air above the lake. This temperature difference

creates a pressure gradient, causing denser, cooler air from over the lake to move inland. As this air travels inland, it gradually warms and forms a shallow TIBL that increases in depth. According to [Shokurov and Kraevskaya \(2024\)](#), this TIBL is formed inside the body of the cold gravity current. At the leading edge of this advancing air mass, a narrow uplift zone known as the LBF develops and continues moving inland throughout the day. The circulation is completed by descending air in the return flow aloft, which also produces a shallow capping inversion layer over the lake. In [Segal et al. \(1997\)](#), it is shown that this inversion tends to inhibit cloud formation behind the LBF, while the rising motion along the front can generate a narrow band of clouds.

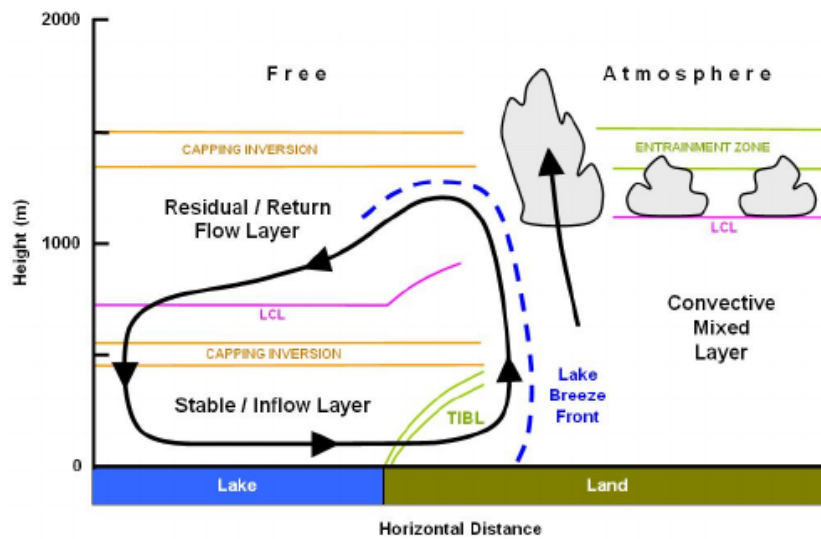


Figure 2.3: Vertical cross-section diagram showing an idealized lake-breeze circulation penetrating inland in a calm synoptic wind regime. Arrows show air motions within and adjacent to the lake-breeze circulation. A thermal internal boundary layer (TIBL) is shown growing in vertical extent with distance inland behind the lake-breeze front (blue dashed line). Magenta lines indicate the lifting condensation level (LCL), green outlines indicate entrainment zones, and orange outlines indicate capping inversions. Taken from [Sills et al. \(2011\)](#), Figure 2, © 2011 Copernicus Publications on behalf of the European Geosciences Union

The horizontal extent and inland penetration of the circulation depend on the strength of the land-lake thermal contrast, background winds, and lake dimensions, with penetration distances ranging from several to tens of kilometres under favourable conditions ([Atkinson, 1981](#); [Simpson, 1994](#); [Crosman and Horel, 2010](#)). In their study over the southern Great Lakes region, [Sills et al. \(2011\)](#) using observational data and high-resolution numerical simulations showed that in some cases, LBFs can extend up to approximately 200 km inland, though they more commonly remain within several tens of kilometres from the shoreline. Over large lakes, opposing breeze systems may interact, producing

convergence zones over land or subsidence over the lake interior (Physick, 1976; Comer and McKendry, 1993). Vertically, the circulation is characterized by a relatively shallow near-surface inflow layer overlain by a deeper return-flow layer. Observational studies indicate that the onshore inflow is typically confined to the lowest few hundred metres of the atmosphere (~ 1 km above ground level), while the compensating return flow may extend to heights of approximately 1-3 km, depending on atmospheric stability, boundary-layer depth and forcing conditions (Lyons, 1972; Keen and Lyons, 1978; Atkinson, 1981; Miller et al., 2003; Barry and Chorley, 2010). Using high-resolution observations and numerical simulations over the Lake Victoria region, (Woodhams et al., 2022) found the onshore flow was confined to the lowest ~ 300 m of the atmosphere, while the return flow extended up to 1-4 km above ground level. This vertical structure plays a crucial role in redistributing heat, moisture, momentum, and atmospheric constituents such as aerosols and pollutants (e.g., Woodhams et al., 2019, 2022; Wagner et al., 2022).

2.1.4 Factors controlling strength and inland penetration

The intensity, timing, and inland extent of lake-breeze circulations are controlled by a combination of local, mesoscale, and synoptic-scale factors. Several factors including background synoptic flow, atmospheric stability, surface friction, sensible heat flux, coastline orientation and curvature, magnitude of the land-water temperature contrast, size of the water body, topography, Coriolis force, and turbulence are summarized in Figure 2.4. However, not all of these factors apply to our study region. For example, owing to the region of LV along the equator, Coriolis force has no effect on LLBs. Hence, this section only extensively reviews key factors that are applicable to LVB.

(a) Background synoptic wind

Although lake breezes are fundamentally thermally driven, their development, strength, and inland penetration are strongly influenced by the prevailing synoptic-scale wind. The magnitude and direction of the background flow relative to the shoreline determine whether the thermally induced circulation is enhanced or suppressed (Estoque, 1962; Arritt, 1993; Crosman and Horel, 2010). As illustrated in Figure 2.4, when the background flow is offshore (blowing from land toward the water body), it opposes the onshore sea/lake breeze circulation, which in turn slows down the LBF and weakens convergences at the front. For example, Bechtold et al. (1991) showed that under calm or weak synoptic conditions, strong thermal contrasts dominate, allowing well-organised LBCs to form around much of the lake perimeter. In such cases, a clear pressure gradient develops between land and water, supporting a well-defined LBF and promoting significant inland penetration (Simpson, 1994; Miller et al., 2003).

Offshore-directed background winds can initially enhance lake-breeze development by increasing low-level convergence where the thermally driven onshore flow meets the

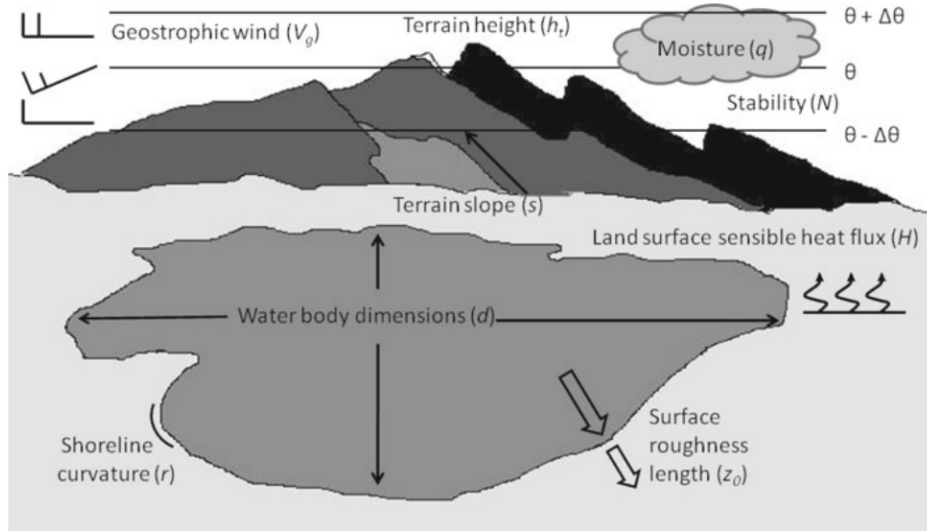


Figure 2.4: Geophysical variable that control sea and lake breezes (Coriolis parameter f is not shown). The important factors in LVB are: N, H, d, r, q, s , and Z_0 . Taken from [Crosman and Horel \(2010\)](#), Figure 1.

opposing synoptic wind. This interaction often sharpens the LBF and strengthens upward motion along it. However, if offshore winds become sufficiently strong, they can overwhelm the thermally driven circulation, suppressing its development or preventing inland progression altogether. Observational studies (e.g. [Atkinson, 1981](#)) indicate that opposing winds exceeding roughly $7\text{--}10 \text{ m s}^{-1}$ typically inhibit lake breezes, while modeling studies suggest similar thresholds of $6\text{--}11 \text{ m s}^{-1}$ (e.g. [Arritt, 1993](#); [Porson et al., 2007](#)).

In contrast, onshore synoptic winds tend to weaken LBCs by reducing the land–lake thermal contrast and diminishing the associated pressure gradients. As a result, the LBF may become diffuse, less distinct, or displaced farther inland ([Biggs and Graves, 1962](#); [Simpson, 1994](#)). Earlier studies by [Estoque \(1962\)](#) and [Bechtold et al. \(1991\)](#) documented that winds parallel to the shoreline exert a more limited influence, mainly through frictionally induced modifications to the pressure field, and are generally less important than cross-shore flows. Overall, weak background winds favour well-developed lake breezes, whereas stronger synoptic forcing especially in opposition, can delay, distort, or suppress their formation, highlighting the sensitivity of lake-breeze systems to multiscale atmospheric interactions.

(b) Atmospheric stability

The influence of atmospheric stability on the structure, strength and evolution of LBCs is better illustrated in [Figure 2.3](#). As the LBF propagates inland, it separates two distinct turbulence regimes. Ahead of the front, continued surface heating sustains a deep, unstable boundary layer with strong mixing, whereas behind the front, the influx

of cooler lake air produces a shallower and more stable layer with reduced turbulence. This sharp gradient in stability and turbulent kinetic energy across the frontal zone strengthens low-level convergence and enhances upward motion, contributing to the maintenance of a well-defined LBF (Segal et al., 1997; Crosman and Horel, 2010). Greater turbulent mixing within the continental boundary layer also facilitates entrainment and increases the vertical extent of the circulation, allowing the lake breeze to penetrate farther inland. Arrillaga et al. (2020) and Wagner et al. (2022) showed that under more unstable atmospheric conditions, buoyancy-driven turbulence enhances vertical mixing, deepens the inland boundary layer, and promotes a more vigorous and vertically developed lake-breeze system. In contrast, Arritt (1993) found that strongly stable conditions suppress vertical motions, reduce circulation depth, and ultimately limit the intensity and inland reach of the system. More generally, a weakly stable or near-neutral atmosphere provides the most favourable conditions for lake-breeze development, whereas strong stability tends to dampen the circulation. Several studies (e.g., Wentworth et al. (2015)) have shown that increasing atmospheric stability primarily reduces the vertical extent and intensity of the breeze, with only minor effects on its horizontal extent and speed.

(c) Turbulence

As shown in many previous studies (e.g. Pielke and Segal, 1986; Abbs and Physick, 1992; Arritt, 1993; Miller et al., 2003; Crosman and Horel, 2010; Arrillaga et al., 2020), turbulence plays a fundamental role in controlling the intensity, vertical structure, and inland penetration of LBCs. By governing the transport of heat, momentum, and moisture within the boundary layer, it directly influences the thermally driven pressure gradients that sustain the circulation. Over land, daytime heating generates strong buoyancy-driven turbulence, enhancing vertical mixing, deepening the convective boundary layer, and strengthening the thermal low, thereby increasing the vertical extent of the circulation (Pielke and Segal, 1986; Arritt, 1993; Miller et al., 2003). In contrast, studies by Abbs and Physick (1992), Miller et al. (2003), and Crosman and Horel (2010) showed that weaker turbulence over the cooler lake surface promotes stable stratification and suppresses mixing, helping to maintain the land–water thermal contrast that drives the breeze circulation.

Turbulence also shapes the structure and evolution of the LBF (Crosman and Horel, 2010; Arrillaga et al., 2020). As the front advances inland (cf. Figure 2.3), it separates a well-mixed turbulent air mass ahead from a cooler, more stable layer behind, creating sharp gradients in temperature, momentum, and turbulent kinetic energy that enhance convergence and upward motion (Segal et al., 1997; Crosman and Horel, 2010). Additionally, turbulent entrainment at the top of the boundary layer further deepens the circulation and supports inland penetration (Wood et al., 1999; Ogawa et al., 2003). For example, Ogawa et al. (2003) showed that inland progression can slow

in the early afternoon due to turbulent frontolysis before accelerating later as turbulence weakens. More broadly, several studies (e.g. [Crosman and Horel, 2010](#); [Jiang et al., 2017](#); [Wagner et al., 2022](#)) have shown that stronger turbulence tends to produce deeper, more vigorous LBFs, whereas weak turbulence is often associated with stable conditions that lead to shallower, less organized circulations with reduced inland extent. Overall, turbulence acts as a key intermediary linking surface forcing to the dynamical response of lake-breeze systems.

(d) Atmospheric moisture

Atmospheric moisture plays a key role in modulating LBC development and impacts through its influence on boundary-layer processes and convection ([Moon, 1988](#); [Nicholls et al., 1991](#); [Shepherd et al., 2001](#); [Fovell, 2005](#); [Woodhams et al., 2022](#)). As illustrated in [Figure 2.4](#), near-surface moisture can increase rapidly due to evaporation from moist soils and water bodies, enriching the LB inflow. This enhanced low-level humidity promotes moist convection along LBFs, where converging air is forced to rise, often interacting with other mesoscale or synoptic features to further enhance convective development ([Nicholls et al., 1991](#); [Shepherd et al., 2001](#); [Fovell, 2005](#)). In addition, feedback from convection can in turn strengthen LBCs. Idealized studies (e.g. [Song, 1986](#); [Moon, 1988](#)) show that deep convection enhances vertical development and intensifies winds, while observational and high-resolution modeling studies in northern Australia (e.g. [Nicholls et al., 1991](#); [Fovell, 2005](#)) and the LVB ([Woodhams et al., 2022](#)) demonstrate that latent heat release reinforces uplift and convergence, producing deeper, more vigorous circulations.

Moisture also indirectly affects circulation strength through cloud–radiation interactions. Increased moisture promotes cloud formation, reducing solar radiation and weakening the land–lake thermal contrast ([Pielke and Segal, 1986](#)), whereas clearer conditions enhance heating and favour stronger breeze development. In tropical regions such as the LVB, moisture plays an even more critical role due to its strong coupling with deep convection ([Anyah and Semazzi, 2006](#); [Thiery et al., 2015](#); [Nicholson et al., 2021a](#)). [Nicholson et al. \(2021b\)](#) and [Thiery et al. \(2016\)](#) show that high ambient humidity and strong diurnal heating promote frequent convection linked to LLBs, while nighttime land-breeze convergence can trigger and organize mesoscale convective systems over the lake. This highlights the dual role of moisture in shaping LBC dynamics and amplifying their weather impacts.

(g) Water body dimensions and shoreline curvature

The size of a water body and shoreline geometry ([Figure 2.4](#)) strongly govern the development, structure, and inland penetration of LBCs. Over large systems such as the North American Great Lakes, lake breezes typically extend 20-50 km inland,

though they can penetrate farther under weak synoptic forcing (Lyons, 1972; Ryznar and Touma, 1981; King et al., 2003). Under favourable thermal and synoptic conditions, penetration may exceed 100 km, approaching classical sea-breeze scales (Simpson, 1994; Sills et al., 2011). Using observations from the southern Great Lakes, Sills et al. (2011) and Curry et al. (2017) documented inland penetration of 100-200 km, demonstrating that sufficiently large lakes can dynamically resemble ocean coastlines and support well-developed mesoscale circulations. This scaling is evident when comparing large and small systems: lakes wider than 100 km tend to produce sea-breeze-like circulations with stronger onshore flow, deeper boundary layers, and enhanced vertical motion. Both numerical and observational studies show that increasing lake size strengthens updrafts, enhances vertical velocities, and promotes more organized, deeper circulations (e.g., Crosman and Horel, 2012; Zhang et al., 2024). Ma et al. (2026) further showed that large lakes deepen the surrounding boundary layer and enhance land-lake coupling through sustained thermal forcing, particularly during warm seasons when land-water contrasts are strongest. In contrast, smaller and medium-sized lakes exhibit weaker, more nonlinear circulations, with limited horizontal extent and vertical development due to reduced thermal contrast, a smaller reservoir of cool air, and stronger interaction with the continental boundary layer (Crosman and Horel, 2012). Observations indicate that such circulations are less frequent, more irregular, and highly sensitive to terrain and background winds; for example, Staver et al. (2022) found that LLB events over a small elongated lake in Croatia were intermittent and strongly constrained by topography and atmospheric conditions, producing weaker, less organized flows.

Additionally, shoreline curvature modifies the structure and intensity of LBCs, particularly for circular or semi-enclosed basins. As illustrated in Figure 2.4, in such geometries, flows from different parts of the shoreline can converge toward the interior, enhancing uplift and occasionally strengthening localized circulation features. However, for small or highly curved water bodies, competing “mirror” circulations may limit the availability of cool inflow air, thereby weakening the overall system. As a result, both the depth and inland extent of the circulation tend to decrease with decreasing lake size, while the spatial structure becomes more complex due to curvature-induced interactions. These effects highlight the importance of water body dimensions and geometry as key controls on lake-breeze dynamics, in addition to thermal forcing in governing lake-breeze dynamics.

Other factors such as land-use characteristics further influence breeze dynamics. For example, urbanization can modify surface roughness and enhance thermal gradients through the urban heat island effect, thereby altering breeze strength and penetration. Similarly, in complex terrain, studies by Xu et al. (2021), Viner et al. (2021), and Cheng et al. (2025) has shown that interactions with mountain-valley circulations can produce hybrid or “extended” breeze systems that exhibit distinct temporal and

spatial characteristics. Moreover, Observational and modeling studies over LVB (e.g., [Woodhams et al., 2022](#)) have shown that LBFs exhibit strong low-level convergence and upward vertical velocities, often exceeding $1\text{--}2\text{ m s}^{-1}$, which can trigger cloud formation and deep convection. The inland penetration of the LBF varies widely, but under favourable conditions, such as weak synoptic winds and unstable atmospheric stratification, it can extend more than 100 km from the shoreline. The front typically advances inland throughout the afternoon before weakening in the evening as the land-water temperature contrast diminishes ([Wang et al., 2019](#); [Viner et al., 2021](#)).

2.1.5 Theoretical and Numerical Models used to study LLBs

The study of lake- and sea-breeze circulations has progressed from early conceptual descriptions to sophisticated analytical and numerical modeling frameworks. These approaches have been essential for understanding the underlying physical processes, quantifying circulation characteristics, and predicting their impacts on local weather and climate.

(a) Conceptual and Analytical Models

Early theoretical understanding of breeze circulations was based on simplified conceptual models. One of the most influential was proposed by [Defant \(1951\)](#), who described the sea-breeze as a closed thermally driven circulation arising from differential heating between land and water surfaces. In this framework, daytime heating over land produces a horizontal pressure gradient that drives onshore flow near the surface and a compensating return flow aloft (cf. [Figure 2.1](#)). Despite its simplicity, the Defant model provides a fundamental conceptual basis for interpreting the structure and evolution of lake- and sea-breeze systems.

Building on this conceptual foundation, [Estoque \(1962\)](#) developed one of the first analytical models of the sea-breeze circulation by solving simplified forms of the governing momentum and thermodynamic equations. This work provided quantitative insight into key aspects of the circulation, including its intensity, vertical structure, and inland penetration. The Estoque model demonstrated the importance of factors such as horizontal temperature gradients, friction, and atmospheric stability in determining the evolution of the breeze, marking a transition from purely descriptive to predictive theoretical frameworks.

Subsequent theoretical developments introduced scaling analyses and a deeper dynamical interpretation of thermally driven circulations. [Rotunno \(1983\)](#) formulated scaling relationships based on the balance between buoyancy forcing and pressure-gradient responses, providing estimates of circulation depth, propagation speed, and intensity. This work emphasized the nonlinear nature of breeze systems and their sensitivity to environmental conditions such as background wind shear and stratification. More recent

theoretical perspectives have further interpreted sea-breeze circulations as internal gravity-wave-like responses to diurnal heating, highlighting the role of atmospheric stratification and rotational effects in governing their structure and evolution ([Shokurov and Kraevskaya, 2024](#)).

(b) Idealized Numerical Models

With the advancement of computational methods, idealized numerical models became an essential tool for investigating breeze dynamics under controlled conditions. These models typically employ simplified geometries and prescribed surface forcing to isolate key processes such as thermal contrasts, boundary-layer mixing, and the influence of background winds. Idealized simulations have demonstrated that LBFs and SBFs behave as density currents, with propagation speed and depth determined by the strength of buoyancy forcing and ambient stratification ([Wang and Kirshbaum, 2017](#)). They have also shown that interactions between thermal forcing and background wind can produce a wide range of circulation regimes, from well-defined frontal systems to suppressed or asymmetric flows. Furthermore, such studies have highlighted the importance of nonlinearity in breeze evolution, including the development of sharp fronts, enhanced convergence zones, and gravity-current-like structures ([Shokurov and Kraevskaya, 2024](#)).

These simplified modeling approaches remain valuable for developing physical intuition and testing theoretical predictions, particularly in understanding sensitivity to individual parameters such as heating intensity, Coriolis force, and terrain effects.

(c) Mesoscale and High-Resolution Atmospheric Models

Modern research on lake- and sea-breeze circulations relies heavily on three-dimensional mesoscale atmospheric models. For example, [Haupt \(2024\)](#) used ICON-LAM at a resolution of 0.06° to study sea-breezes over the Gulf of Guinea, while [Woodhams et al. \(2022\)](#) used a sub-kilometer resolution with Met Office Unified Model (MetUM) to study lake-land breezes at LV during the dry period. Widely used modeling systems such as the Weather Research and Forecasting (WRF) model, COSMO/ICON, and the ECMWF Integrated Forecasting System (IFS) enable detailed simulation of atmospheric processes across a range of spatial and temporal scales. These models incorporate advanced representations of boundary-layer turbulence, land-surface interactions, and lake thermodynamics, allowing for realistic simulation of breeze initiation, frontal propagation, and vertical structure. High-resolution simulations, particularly those with grid spacing of a few kilometres or less, have been shown to significantly improve the representation of lake-breeze fronts, convergence zones, and associated convection. For example, convection-permitting simulations can explicitly resolve deep convection triggered by breeze circulations, providing improved insight into cloud formation and precipitation processes ([Woodhams et al., 2019](#)).

In other examples, mesoscale models have been used extensively to investigate interactions between lake breezes and larger-scale atmospheric processes. These include the influence of synoptic winds on breeze initiation and propagation, as well as feedbacks between breeze-induced convergence and convective development. Multiscale modelling studies demonstrate that realistic simulation of these interactions requires careful coupling between local thermal forcing and regional atmospheric dynamics ([Arrillaga et al., 2020](#)).

(d) Global Models and Reanalysis Systems

In addition to regional and mesoscale models, global numerical weather prediction and reanalysis systems such as the ECMWF IFS provide a broader framework for studying lake-breeze dynamics within the context of large-scale atmospheric circulation. These models are valuable for examining climatological patterns, seasonal variability, and interactions between lake breezes and synoptic-scale processes as shown in [Brown et al. \(2026\)](#) over Australia. However, due to their coarser spatial resolution, global models often struggle to resolve fine-scale shoreline gradients, sharp frontal boundaries, and localized convection associated with breeze circulations. As a result, they may underestimate the intensity and spatial variability of lake-breeze systems, particularly in regions with complex coastlines or heterogeneous land surfaces ([Crosman and Horel, 2010](#); [Dehghan et al., 2018](#); [Brown et al., 2026](#)). Ongoing developments in model resolution and parameterization are gradually improving their ability to represent such mesoscale phenomena.

2.2 Lake Victoria Region

2.2.1 Climatology

The climate of the LVB varies significantly in both space and time, with Koppen-Geiger climate classification based on [Beck et al. \(2018\)](#) showing at most three different climates, including the Equatorial (Af), Monsoon (Am), and tropical Savanna (Aw) types ([Figure 2.5](#)). According to [Nicholson \(2017\)](#), these different climates are as a result of (a) local topographical features (e.g., East African highlands, and Lake Victoria), and (b) regional circulation features (e.g., tropical easterly jet, low-level westerlies and easterlies, and localized convergence). On average, the region receives between 1100-2400 mm of rainfall annually, most areas receiving between 800-1200 mm ([Nicholson, 2017](#); [Olaka et al., 2019](#)). The northwestern portions of the LVB receives the heaviest precipitation, peaking up to 2400 mm annually, while some western areas over the lake can see localized highs reaching up to 3000 mm ([Olaka et al., 2019](#)). Over the lake, rainfall ranges between 1400-1500 mm per year, accounting for ~80% of the lake's total water input ([Flohn and Burkhardt, 1985](#); [Olaka et al., 2019](#)).

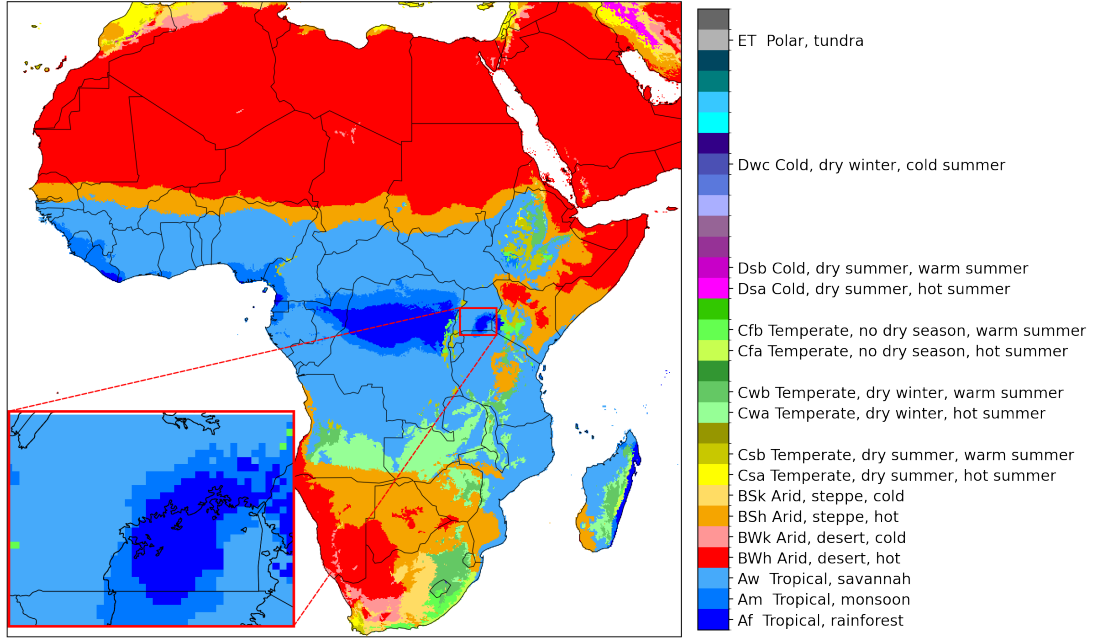


Figure 2.5: The climate over Africa according to the Koppen-Geiger classification. The inset (red box) shows the study area with clearly three distinct Tropical climate classes of Rainforest (Af), Monsoon (Am) and Savannah (Aw). Figure drawn using data from [Beck et al. \(2018\)](#).

As demonstrated in [Figure 2.6](#) and past studies, the LVB region is characterized by two distinct rainfall seasons; March to May (MAM), commonly termed as the ‘long rains’ with its peak in April, and September to November (SON), commonly known as the ‘short rains’ with its peak in October ([Nicholson, 2017](#); [Diem et al., 2019](#); [Nicholson et al., 2021b](#)). June to August (JJA) and December to February (DJF) are typically designated as the dry seasons within the region. The major systems controlling the rainfall over the Lake Victoria region include the intertropical convergence zone (ITCZ), the subtropical anticyclones, the northeast and southeast trade winds, and the moist westerlies from the Congo air mass ([Ba and Nicholson, 1998](#)). The streamlines in [Figure 2.6](#), show that the prevailing surface winds are mostly easterlies, with some seasonal variability due to the apparent movement of the ITCZ ([Flohn and Fraedrich, 1966](#); [Nicholson, 1996](#)). Over the lake, the primary maximum convection occurs during morning hours between 0500 and 0800 LT, and a second maxima in the afternoon ([Nicholson et al., 2021b](#)). In contrast, over surrounding land, the maximum occurs generally in late afternoon and during the evening ([Ba and Nicholson, 1998](#); [Nicholson et al., 2021b](#)). This contrast reflects different heating and cooling rates between land and water surfaces.

Furthermore, the region receives significant rainfall amounts even during the dry months of JJA and DJF. These rains are the result of the local effect of Lake Victoria, particularly, the LLB circulation system which result in nocturnal and afternoon rainfall regimes in the western and eastern side of the lake, respectively ([Nicholson, 2017](#); [Nicholson et al.,](#)

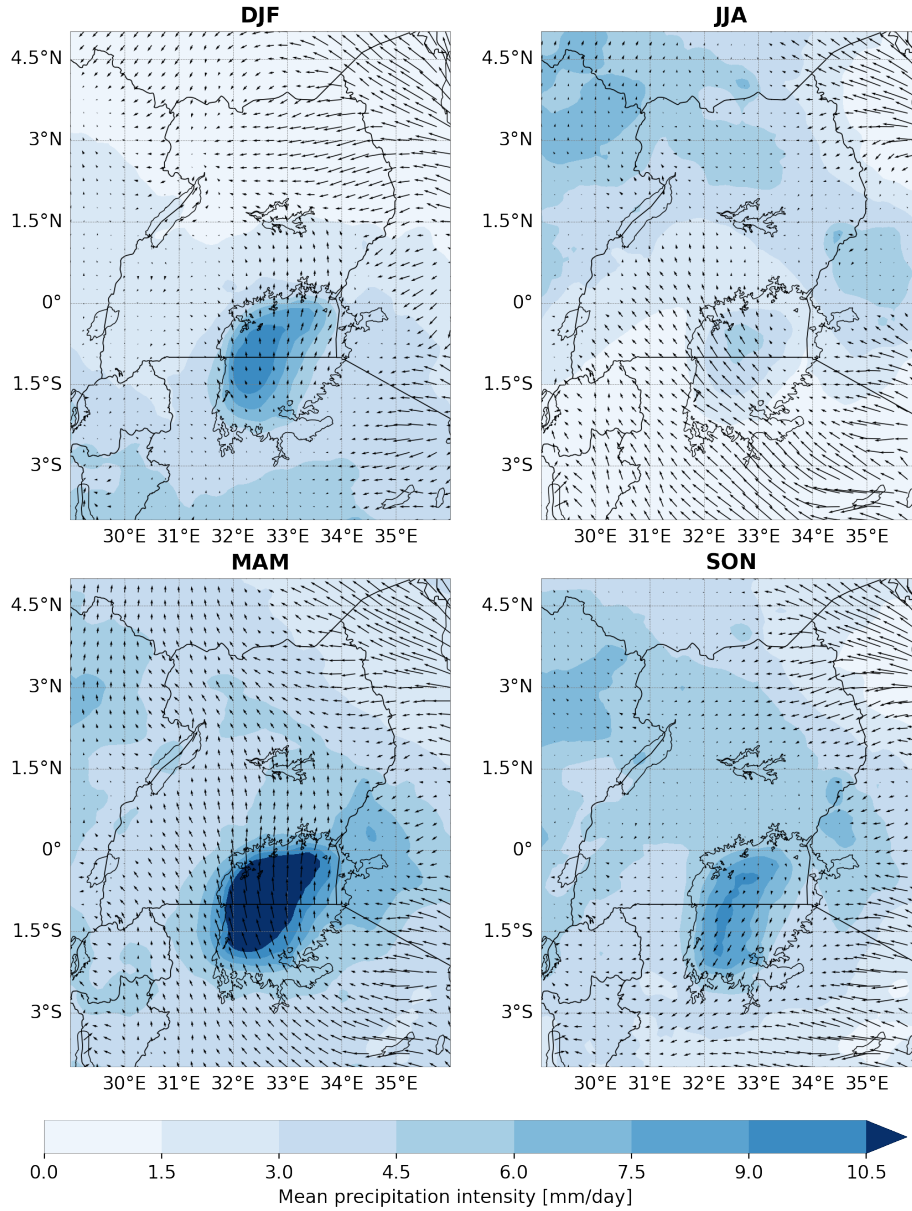


Figure 2.6: Mean daily precipitation in each season of the year over Uganda based on IMERG-F v7, [Huffman et al. \(2023\)](#) for the period 2001-2020. The 10 wind (vectors) are based on ERA5, [Hersbach et al. \(2020\)](#) for the period 1991-2020.

[2021b](#)). The LLB circulation system, driven by the land-lake temperature contrast and governed by diurnal heating, has been identified in several studies over the region as the dominant feature that controls storm initiation, location, timing, intensity, and propagation, especially during the dry seasons of DJF and JJA (e.g. [Flohn and Fraedrich, 1966](#); [Anyah and Semazzi, 2006](#); [Thiery et al., 2015](#); [Woodhams et al., 2019](#); [Van de Walle et al., 2020](#); [Virts and Goodman, 2020](#); [Nicholson et al., 2021c](#)). Owing to the fact that Lake Victoria's surface temperature is almost stable ($\sim 25^{\circ}\text{C}$) throughout the day ([Lumb, 1970](#)), lake-breezes are expected to form only in the afternoon when land-lake thermal contrasts are high. Due to strong insolation, low cloudiness, and weak synoptic

winds (Ngoma et al., 2021) during the dry months, these periods are ideal for studying lake-breezes in the region. Moreover, the plethora of above studies on LLB corroborate that even though the temperature gradient between the lake and surrounding land is relatively small, it is still sufficient to drive daytime LLBs during the relatively cloud-free dry seasons.

2.2.2 Lake-Land Breeze Characteristics over Tropical Africa

Although LLB circulations are well documented in mid-latitude coastal regions (e.g. Sills et al., 2011; Hawbecker and Knievel, 2022), their behavior in the tropical environment, particularly over large inland water bodies, exhibits distinct characteristics. In the African tropics, strong solar insolation, weak seasonal temperature variability, and relatively small diurnal temperature differences over large lakes create a unique environment where even modest land–lake thermal contrasts can drive persistent LLB systems (e.g. Lumb, 1970; Thiery et al., 2015). Unlike mid-latitudes, where synoptic forcing may dominate, tropical LLBs can remain active throughout the year and often interact with large-scale circulation features such as the ITCZ and regional trade winds (Nicholson, 1996, 2017; Ramotubei et al., 2025). These interactions enhance low-level convergence and contribute significantly to convective processes (Nicholson, 1996; Anyah et al., 2006; Woodhams et al., 2019; Finney et al., 2020; Nicholson et al., 2021a). Furthermore, additional factors such as seasonal variations in cloud cover, moisture availability, and large-scale circulation patterns can modulate lake-breeze development and associated convective activity (Anyah and Semazzi, 2006; Thiery et al., 2015). In this context, seasonal variability in LLB systems is less directly controlled by solar radiation and more strongly influenced by large-scale atmospheric circulation. For example, studies by Anyah and Semazzi (2006) and Thiery et al. (2015) show that lake-breeze activity is strongly modulated by the migration of the ITCZ, variations in cloud cover, and changes in regional wind fields. Despite the persistence of land-lake temperature contrasts throughout much of the year, these seasonal shifts in atmospheric circulation ultimately govern the timing, intensity, and spatial distribution of lake-breeze systems.

LLB systems in the tropics are primarily identified through a combination of dynamical and observable features, with the LBF representing the most prominent and diagnostically important signature. The LBF is a low-level convergence boundary separating relatively cool, moist air advected inland from the lake from the warmer ambient air over land, and it is typically characterized by sharp gradients in wind direction, temperature, and moisture (Sills et al., 2011; Guedje et al., 2019; Woodhams et al., 2022). In tropical regions, especially over large inland water bodies such as the African Great Lakes (e.g., Lake Victoria), these convergence zones frequently manifest as distinct cloud lines aligned with the leading edge of the breeze front, making them readily detectable in satellite imagery (Waniha et al., 2019; Wilson and Roberts, 2022). These cloud bands mark zones of enhanced low-level convergence and upward vertical motion, which

often act as triggers for deep moist convection (van der Linden et al., 2015; Virts and Goodman, 2020). As a result, LLB systems play a critical role in modulating the diurnal cycle of rainfall in tropical lacustrine environments, with convection frequently initiating along LBFs and propagating inland or downstream (Flohn and Fraedrich, 1966; Anyah et al., 2006; Virts and Goodman, 2020; Van de Walle et al., 2020; Guedje et al., 2019). These observable features such as cloud lines, convergence bands, and localized precipitation maxima, serve as key indicators for identifying LLB systems in the tropics and underscore their importance in regional weather and climate dynamics.

Over LVB, the LLB system exhibits some of the most pronounced and impactful characteristics observed in the tropics. Due to the lake’s large size and relatively stable surface temperature ($\sim 25^{\circ}\text{C}$) (Lumb, 1970), strong diurnal heating of the surrounding land produces consistent lake-land temperature gradients that drive daily LLB cycles. As a result, daytime lake breezes promote convergence over land, leading to afternoon convection and rainfall, while nocturnal land breezes focus convergence over the lake, triggering nighttime thunderstorms (Thiery et al., 2015; Woodhams et al., 2019; Virts and Goodman, 2020; Finney et al., 2020; Glazer et al., 2025). This diurnal reversal leads to a distinct spatial and temporal redistribution of rainfall, with early morning rainfall maxima over the lake, and late afternoon and evening rainfall maxima over land (Thiery et al., 2016; Virts and Goodman, 2020; Glazer et al., 2025; Vizzy et al., 2026). Furthermore, these circulations are strongly linked to intense thunderstorms and high lightning frequency, making the LVB one of the most electrically active regions globally (Virts and Goodman, 2020; Wilson and Roberts, 2022). The interaction between LLBs and regional features such as easterly winds and orographic flows (e.g., from the East African Highlands) further enhances convergence and convective intensity (Lumb, 1970; Ba and Nicholson, 1998; Anyah et al., 2006; Chamberlain et al., 2014; Finney et al., 2019; Woodhams et al., 2019, 2022). Thus, within the tropical African context, and particularly over Lake Victoria, LLB systems are not merely secondary mesoscale phenomena but represent a dominant mechanism controlling convection, rainfall distribution, and storm evolution.

2.2.3 Importance of Lake-land breezes over LVB

LLBs exert wide-ranging influences on coastal and lacustrine environments through their control of boundary-layer structure, wind fields, and mesoscale convergence. Although LLBs are relatively shallow compared to synoptic systems, their regular diurnal occurrence makes them a key component of local climatology, particularly over large inland water bodies such as Lake Victoria.

(a) Effects on Coastal Climatology

LLB systems are a fundamental component of coastal climatology, as they significantly modify near-surface temperature, humidity, wind patterns, boundary-layer structure,

and convective activity. By transporting relatively cool and moist air inland during the daytime, lake breezes moderate near-surface temperatures and increase humidity in shoreline regions compared with inland locations. Conversely, nighttime land-breezes transport relatively cooler continental air over the lake, thereby modifying near-shore temperature and humidity fields. These effects are most pronounced during periods of strong solar heating, when land-water temperature contrasts are largest ([Simpson, 1994](#); [Laird et al., 2001](#); [Sills et al., 2011](#)).

In the LVB, LLBs play a central role in regional climatology. Observational and modeling studies indicate that these circulations influence the timing, location, and intensity of convective rainfall, contributing to the well-documented diurnal cycle of precipitation over and around the lake ([Anyah and Semazzi, 2006](#); [Thiery et al., 2015, 2016](#); [Woodhams et al., 2019](#)). They also regulate boundary-layer development and moisture transport, thereby shaping local climatic conditions in surrounding coastal communities ([Anyah et al., 2006](#)). Together, LLB systems represent an important source of mesoscale climatic variability, influencing both short-term weather patterns and longer-term coastal climate characteristics.

(b) Convective Initiation and Rainfall

LLB systems play a fundamental role in convective initiation and rainfall variability over the Lake Victoria basin by modulating boundary-layer processes, moisture transport, and mesoscale convergence. Arising from differential heating between the lake surface and surrounding land, these thermally driven circulations generate pronounced contrasts in stability and humidity that can either suppress or enhance convection depending on environmental conditions. In particular, the convergence zone along the lake-breeze front acts as an effective trigger for deep convection by forcing low-level air to ascend, especially when sufficient moisture and atmospheric instability are present ([Anyah and Semazzi, 2006](#); [Thiery et al., 2015](#)). These locally generated convergence zones frequently interact with regional-scale circulations, including easterlies and upslope flows from adjacent highlands, as well as with outflow boundaries from pre-existing storms, thereby intensifying convective development and increasing rainfall production ([Thiery et al., 2015, 2016](#); [Woodhams et al., 2019](#)).

The diurnal reversal of LLBs further exerts strong control on the timing and spatial distribution of convection across the basin. During daytime, lake breezes transport relatively cool and stable air inland, favoring the development of afternoon and evening thunderstorms over surrounding land areas ([Virts and Goodman, 2020](#); [Nicholson et al., 2021a](#)). At night, land-breeze circulations converge over the warmer lake surface, promoting organized convection and enhanced rainfall during the late night and early morning hours ([Anyah and Semazzi, 2006](#); [Thiery et al., 2015](#); [Woodhams et al., 2019](#); [Nicholson et al., 2021a](#)). This dynamic leads to a characteristic land–lake contrast in

precipitation patterns and contributes to the highly heterogeneous distribution of rainfall observed across the region. Moreover, sustained moisture convergence and organized convective structures associated with LLB systems can prolong storm lifetimes, increasing the likelihood of heavy precipitation and localized extremes (Virts and Goodman, 2020). Consequently, lake-induced circulations are a dominant control on the hydroclimate of the LVB, shaping both the intensity and variability of rainfall and underscoring the critical importance of accurately representing lake–atmosphere interactions in weather and climate models.

Apart from influencing coastal climatology and convective initiation, other impacts of LBCs span air quality, wind energy, and socioeconomic activities. LBCs modulate the transport, dispersion, and redistribution of atmospheric pollutants, with convergence along LBFs concentrating pollutants and associated vertical motions redistributing them within the boundary layer (Lyons, 1972; Simpson, 1994); in rapidly urbanizing regions such as the LVB, this has important implications for emissions from industry, transport, and biomass burning, and hence for human and ecosystem health. They also play a key role in shaping the regional wind climate, introducing pronounced spatio-temporal variability that directly affects wind energy potential, turbine siting, and operational efficiency. Daytime lake-breeze-driven flows can enhance nearshore wind speeds and energy yield, whereas weaker nighttime winds, along sudden wind shifts and increased shear, complicate forecasting and reduce reliability (e.g. Lundquist, 2022; Liu et al., 2025; Brown and Vincent, 2026). For instance, Ssenyimba et al. (2020) showed that diurnally varying LLB winds strongly control power availability in hybrid energy systems in the Ssesse Islands. More broadly, LBCs exert substantial socioeconomic impacts across LVB, where dense populations depend on weather-sensitive sectors such as fishing, transport, and shoreline commerce (Semazzi, 2011; Semazzi et al., 2014; Cannon et al., 2014). Their diurnal modulation of winds affects navigation and vessel stability, while abrupt shifts associated with LBFs create hazardous conditions, especially for small-scale fishers (Song et al., 2004; Thiery et al., 2015; Woodhams et al., 2019, 2022). From a hazards perspective, convergence along LBC boundaries frequently triggers intense convection in this lightning-active region, producing storms with heavy rainfall, strong winds, and frequent lightning that threaten infrastructure and lives. For example, studies by Semazzi (2011), Cannon et al. (2014), Thiery et al. (2016), Van de Walle et al. (2020), and Nicholson et al. (2021c) have shown that nocturnal LLB events over LV are particularly dangerous, contributing to thousands of fatalities on the lake annually.

Overall, the combined influence of lake-breeze dynamics, convective hazards, and limited forecasting capacity underscores the need for improved high-resolution observational and modeling systems in the LV region. Enhanced representation of lake-atmosphere processes is critical not only for advancing meteorological understanding but also for

strengthening early warning systems, improving risk management, and supporting climate resilience in this highly vulnerable and densely populated basin.

2.3 Lake-breeze observational datasets and their potential LBF indicators

Observational studies have been fundamental to advancing the understanding of lake- and sea-breeze circulations. From early surface-based measurements to modern multi-platform observing systems, these techniques have provided key insights into the structure, evolution, and variability of thermally driven mesoscale circulations. Observations are particularly important for validating theoretical frameworks and numerical models, as well as for identifying fine-scale features such as breeze fronts, convergence zones, and convective initiation. Here, I review the most commonly used observational datasets for detection of lake breezes, highlighting the most viable LBF indicators in each.

2.3.1 Surface-based observations

Early investigations of lake- and sea-breeze systems relied heavily on surface meteorological observations (e.g. [Watts, 1955](#); [Biggs and Graves, 1962](#)). Networks of weather stations located along coastlines and inland regions have long been used to document diurnal variations in wind, temperature, humidity, and pressure, forming the backbone of observational studies of these mesoscale circulations (e.g. [Miller et al., 2003](#); [Guedje et al., 2019](#)). These measurements provide fundamental information on breeze onset, inland penetration, and temporal evolution. For instance, the passage of a sea- or lake-breeze front at a surface station is typically identified by a distinct wind shift, a drop in temperature, and changes in humidity and pressure ([Simpson, 1994](#); [Crosman and Horel, 2010](#)), which together provide a clear signature of frontal arrival as illustrated in [Figure 2.7](#).

High-density observational networks are particularly valuable for resolving the spatial variability of lake-breeze systems and tracking the propagation of breeze fronts across heterogeneous terrain. In addition to standard meteorological measurements, in situ instruments such as flux towers and eddy covariance systems provide detailed observations of surface energy exchanges, including sensible and latent heat fluxes. These measurements are essential for understanding the processes that control the development and variability of thermal gradients driving the circulation. For example, the Hydrometeorology Project for Lake Victoria Basin (HyVic) campaign provided high-resolution data that was used by [Woodhams et al. \(2022\)](#) to study the lake-land breezes over Lake victoria.

Over large lakes, buoy-based observations and offshore platforms provide important complementary measurements of near-surface atmospheric conditions over the water. Such observations are often underrepresented in conventional monitoring networks but

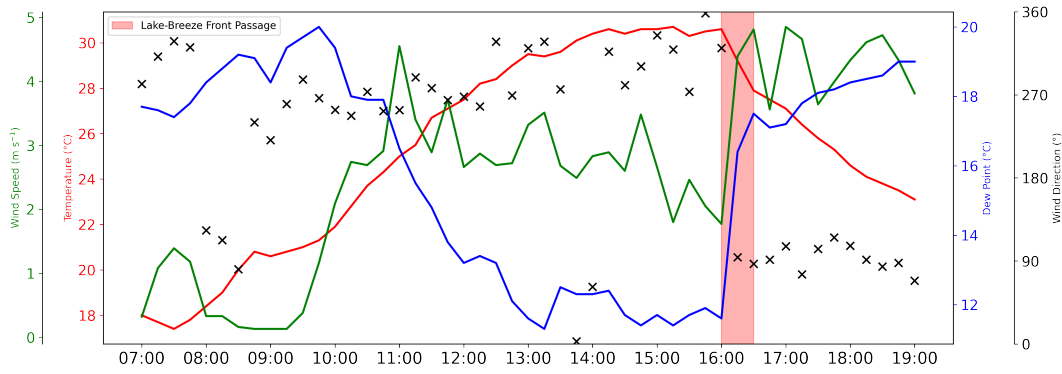


Figure 2.7: Illustration of the changes in meteorological parameters during the passage of the LBF. Case study from 30 January 2018 portraying the meteorological effects of a LBF passage at Kamenyamigo station on the western shore of Lake Victoria. The temperature (red), dewpoint (blue), wind speed (green) and wind direction (black x) before and after LBF passage are shown. The red shading indicates Lake-breeze frontal passage.

are critical for capturing land-water contrasts and improving the characterization of lake-atmosphere interactions. Moored and drifting buoys routinely measure variables such as wind speed and direction, air and water temperature, wave height, and pressure, providing continuous datasets over otherwise data-sparse regions. For example, recently in 2022, the Uganda Meteorological department in partnership with the Ministry of Works and Transport installed a network of nine buoys on Ugandan lakes, with 6 on Lake Victoria to monitor meteorological and hydrodynamic conditions (Waiswa, 2023), enabling improved understanding and modeling of lake-breeze processes and their impacts.

Recent studies have also demonstrated that high-frequency surface observations can be used for the objective identification of lake-breeze fronts (e.g. Stauffer et al., 2015; Hughes and Veron, 2018; Guedje et al., 2019; Noble et al., 2024; Ssemujju et al., 2026a). For example, Hughes and Veron (2018) used 5-minute station data and applied threshold-based approaches on station data changes in temperature, humidity (dew point), and wind to detect sea-breeze frontal passage over Delaware in the United States of America. Similarly, Guedje et al. (2019) used 3-hourly station data to study land and sea breezes over The Guinea Coast in West Africa. While the methods to detect lake- and sea-breezes are discussed in more detail in Section 2.4, they highlight the continued importance of surface observations for both qualitative and quantitative analysis of lake-breeze systems. Therefore, surface observations remain the primary means of identifying and characterizing LBCs.

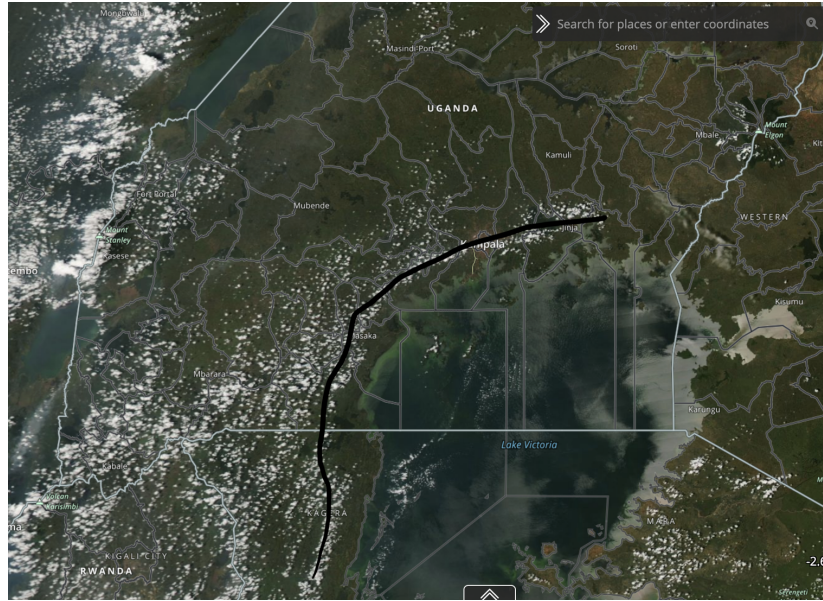


Figure 2.8: An example of cumulus clouds associated with the lake breeze occurrence at 13:30 LT over the western and northern shores of LV as observed by NASA’s Aqua-MODIS visible channel. The black line indicates the separation the cumulus clouds from a cloud-free belt (cloud lines) near the shoreline and propagating inland, which is a typical signature feature of the lake breezes.

2.3.2 Remote Sensing and Satellite Observations

Remote sensing and satellite techniques have greatly expanded the spatial and temporal coverage of lake- and sea-breeze observations, complementing in situ measurements through continuous, large-area monitoring. Studies across diverse regions, including West Africa (Schrage and Fink, 2012; van der Linden et al., 2015), Brazil (Planchon et al., 2006), Indonesia (Ferdiansyah et al., 2020), and the LVB (Van de Walle et al., 2020; Virts and Goodman, 2020; Vizy et al., 2026), demonstrate that satellite data are particularly effective for identifying land–water temperature contrasts, cloud structures, atmospheric moisture, and precipitation patterns associated with breeze circulations. Although satellite observations provide indirect detection of breeze fronts, they offer useful indicators of their structure and location. For instance, linear cloud bands or cumulus lines along convergence zones are often visible in high-resolution imagery, particularly under convectively active conditions (e.g., Figure 2.8; Miller et al. 2003). However, according to (Planchon et al., 2006), LBF detection can be more challenging in cloud-free or weakly convective environments. Nonetheless, these datasets are especially valuable in tropical regions such as the LVB, where ground-based observations are sparse. For example, Van de Walle et al. (2020) and Virts and Goodman (2020) used satellite observations to document the diurnal cycle of convection, including the frequent occurrence of nighttime thunderstorms over the lake linked to land-breeze convergence.

Such observations provide critical insights into regional rainfall patterns and support the evaluation of numerical weather prediction models.

Although not used in this study, other lake-breeze observational data and their indicators provide valuable insight into the structure and evolution of LBCs, particularly through upper-air profiling, radar, and targeted field campaigns. Upper-air observations, traditionally from radiosondes and pilot balloons, reveal the vertical structure of breeze circulations and their interaction with larger-scale flows; for example, [Fraedrich \(1968\)](#) showed that Lake Victoria LLB signatures are largely confined below ~ 2 km, with synoptic winds dominating aloft. More recent ground-based remote sensing systems, including Doppler lidar, sodar, microwave radiometers, and wind profilers, now enable continuous high-resolution monitoring of boundary-layer structure, demonstrating features such as shallow (~ 200 m) lake-breeze inflow layers despite deeper dynamical signatures ([Wagner et al., 2022](#)). In addition, weather radars offer complementary high spatio-temporal resolution, making them especially effective for identifying convergence lines, breeze fronts, and convective initiation. As illustrated in [Figure 2.9](#), in clear-air mode on weather radars, LBFs often appear as thin reflectivity lines formed by concentrated aerosols or insects, allowing near-real-time tracking of their formation and inland progression (e.g. [Wilson et al., 1994](#); [Atkins and Wakimoto, 1997](#); [Waniha et al., 2019](#); [Wilson and Roberts, 2022](#)). Radar observations from campaigns such as the HIGHWAY project ([Roberts et al., 2022](#)) have further demonstrated how these convergence boundaries organize diurnal convection over LV ([Wilson and Roberts, 2022](#); [Méndez et al., 2023](#)). Additionally, aircraft and intensive field campaigns provide detailed three-dimensional measurements of breeze circulations that are not captured by routine networks, resolving sharp gradients in temperature, moisture, and wind across fronts, as well as vertical transport pathways. For instance, during the HyVic campaign, [Woodhams et al. \(2022\)](#) used aircraft and dropsondes to document fine-scale features such as wind reversals, strong moisture gradients, and low-level convergence zones, offering unprecedented detail on the structure and dynamics of LLB systems.

2.3.3 Integrated Observational Approaches

Modern investigations of lake- and sea-breeze systems increasingly rely on integrated observational approaches that combine multiple data sources, including surface meteorological networks, upper-air profiling instruments, radar systems, satellite observations, and field campaign measurements (e.g. [Sills et al., 2011](#); [Wentworth et al., 2015](#); [van der Linden et al., 2015](#); [Guedje et al., 2019](#); [Berri and Dezzutti, 2020](#); [Woodhams et al., 2022](#)). This multi-platform strategy enables comprehensive analysis of these circulations across a wide range of spatial and temporal scales. The integration of observational datasets with numerical modeling has further advanced understanding of breeze dynamics (e.g. [Woodhams et al., 2022](#)). [Woodhams et al. \(2022\)](#) used both aircraft and satellite observations plus a sub-kilometer modeling to study lake-land breeze circulation

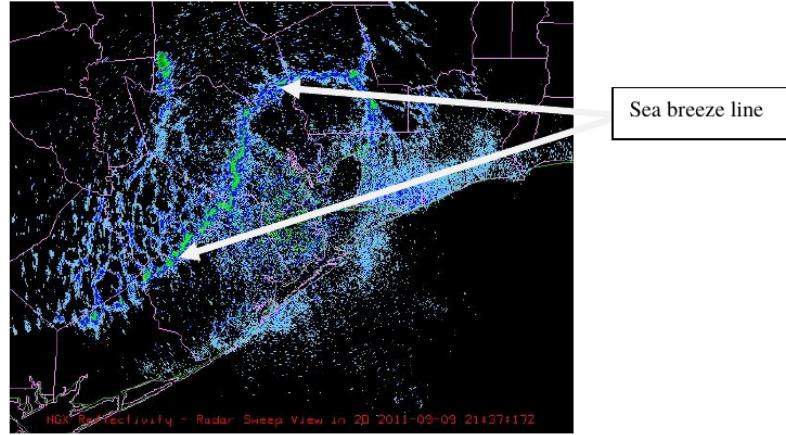


Figure 2.9: An example of a sea- or lake-breeze front as observed on radar. The thin reflectivity line shows an sea breeze front propagating inland. Taken from [Kocen \(2013\)](#).

over LV. Their results provided an unprecedented detail on the vertical and horizontal structure of the lake-land breeze system.

Despite these advances, challenges remain in achieving consistent, high-resolution observational coverage, particularly in regions with sparse monitoring infrastructure. Continued development of coordinated observational networks and multi-instrument field campaigns is therefore essential for improving the representation of lake-atmosphere interactions and their associated mesoscale processes.

2.4 LBF Detection Methods

The identification and tracking of LBFs are central to understanding mesoscale circulation dynamics, convective initiation, and associated impacts. Because lake-breeze systems are often shallow and transient, their detection requires the integration of multiple observational variables and analytical approaches. Over the years, both qualitative and objective methods have been developed in different parts of the world to identify these fronts using surface observations (e.g. [Borne et al., 1998](#); [Laird et al., 2001](#); [Papanastasiou and Melas, 2009](#); [Azorin-Molina et al., 2011](#); [Hughes and Veron, 2018](#); [Guedje et al., 2019](#); [Viner et al., 2021](#)), satellite and remote sensing data (e.g. [Planchon et al., 2006](#); [Schrage and Fink, 2012](#); [van der Linden et al., 2015](#); [Berri and Dezzutti, 2020](#)), and numerical model output (e.g. [Anyah et al., 2006](#); [Van de Walle et al., 2020](#); [Woodhams et al., 2019, 2022](#)). The detection of LBFs generally relies on a combination of thermodynamic and kinematic variables that exhibit characteristic changes during frontal passage as discussed in the previous section. No single variable is sufficient in all cases; instead, robust identification is typically based on a multi-parameter approach (e.g. [Simpson, 1994](#); [Borne et al., 1998](#); [Hughes and Veron, 2018](#); [Noble et al.,](#)

2024). Accordingly, several objective detection algorithms have been developed for LBF identification.

2.4.1 Detection Algorithms

Given the complexity and variability of lake-breeze systems, numerous objective detection methods have been developed worldwide to automate front identification using either station data or satellite images. Most of these algorithms have been developed in extra-tropical regions (e.g. Wentworth et al., 2015; Stauffer and Thompson, 2015; Hughes and Veron, 2018; Berri and Dezzutti, 2020; Viner et al., 2021; El-Geziry et al., 2021; McCabe and Freedman, 2023), with fewer studies in tropical regions (e.g. Planchon et al., 2006; Abatan et al., 2014; Guedje et al., 2019; Ferdiansyah et al., 2020). These algorithms are grounded in the characteristic signatures associated with density current-like behavior. For example, frontal passage is typically characterized by a shift in wind direction from offshore (or weak background flow) to onshore flow, often accompanied by an increase in wind speed due to a strengthening horizontal pressure gradient (Lyons, 1972; Simpson, 1994). This transition is frequently associated with a drop in air temperature and a rise in moisture (e.g., dew point or humidity), reflecting the contrast between the interacting air masses. Together, these simultaneous changes form the basis for commonly used detection criteria in surface observations (Simpson, 1994; Crosman and Horel, 2010). As a result, wind direction reversal is commonly used as the primary criterion for identifying sea/lake-breeze days in most of these algorithms, though not all SBF/LBF passages exhibit this feature (Guedje et al., 2019). Some are better identified through increases in wind speed, temperature drops, and humidity rises, often using fixed thresholds (e.g. Mazzuca et al., 2019; Sikora et al., 2010; Stauffer et al., 2015; Hughes and Veron, 2018; Noble et al., 2024). The detection methods range from simple threshold-based techniques to advanced machine learning approaches as discussed below with relevant examples.

(a) Threshold-Based Algorithms

Threshold-based detection remains one of the most widely used approaches for identifying LBFs due to its simplicity and applicability to surface station data. These methods rely on predefined criteria applied to key meteorological variables, typically identifying frontal passage when one or more variables exceed specified thresholds within a short time interval. Early studies by Watts (1955) and Biggs and Graves (1962) demonstrated the usefulness of such criteria for identifying sea-breeze events. For example, Biggs and Graves (1962) developed a lake-breeze forecasting index (LBI) based on background wind speed and the land-sea temperature contrast (Equation 2.1).

$$LBI = \frac{|U|^2}{C_p \Delta T} \quad (2.1)$$

where; $|U|$ is the near-surface wind speed [m s^{-1}], C_p is the specific heat capacity of dry air at constant pressure ($1.004 \text{ J g}^{-1} \text{ K}^{-1}$), and ΔT is the difference between inland air temperature and the temperature of the water surface ($T_{\text{land}} - T_{\text{sea}}$) [$^{\circ}\text{C}$].

Both the wind speed $|U|$ and temperature difference ΔT were calculated from observations at locations sufficiently inland to remain unaffected by the sea breeze. Large values of the LBI indicate that a lake/sea breeze is unlikely to form, whereas small values suggest favorable conditions for its development and inland penetration. They identified a critical LBI value of 3.0, with a threshold range of 2.7-3.2, within which the method correctly predicted the occurrence or non-occurrence of lake-breeze events in approximately 97% of cases. This index has since been widely adapted for different regions by recalibrating the threshold values (e.g. Lyons, 1972; Simpson, 1994; Brown et al., 2026).

Subsequent observational studies showed that the associated meteorological variables do not change independently, but instead evolve as a coherent signal linked to the advancing front (Atkinson, 1981; Simpson, 1994). As a result, most threshold-based methods now apply combined criteria, such as requiring both a wind shift and a temperature decrease within a defined temporal window, to reduce false detections caused by unrelated mesoscale variability.

Building on this foundation, more recent developments have focused on refining these approaches using high-frequency observations and more objective, data-driven criteria to improve detection accuracy and temporal resolution (e.g. Sills et al., 2011; Hughes and Veron, 2018; Berri and Dezzutti, 2020). Hughes and Veron (2018) used 5-minute data station data of air temperature, wind direction and speed, and precipitation to develop an automatic algorithm for detecting the occurrence of sea-breezes at Delaware Bay in the USA. Their objective algorithm looked for hourly changes in the meteorological conditions using a sliding window through steps of 5 minute intervals from 0800-2000 local time during the summer months of June-August. For example, the first comparison is between 0800 and 0700 LT and then it is incremented to 0805 and compared to observations at 0705LT. They suggested that the 1-hour window was reasonable enough to expect differences due to a sea breeze. In their study, they had two categories of sea-breezes (i.e., Classic and Weak sea-breezes). Hence, they set different fixed thresholds for the hourly changes in air temperature, wind direction and speed. For example, classic sea-breezes were categorized by rapid change in wind direction ($\Delta WD > 45^{\circ}$) from offshore/calm to onshore, with at least a 2°C drop in air temperature (i.e., $\Delta T < -2^{\circ}\text{C}$) over 1 hour, while weak sea-breezes were categorized by wind staying onshore and have a wind direction gradient of at least 45° between the test station and the reference station. However, both sea-breeze categories shared four detection criteria in common. That is, both detection categories required wind at a test station to have onshore flow with wind speed greater than 1 m s^{-1} . Furthermore, both classes required wind at the reference

station to be offshore or calm at the same time to prevent false detection of sea-breeze due to onshore synoptic flow. Similarly, both categories required dry conditions (<0.1 mm) for 3 hours prior to frontal passage, such that false detections of sea-breeze-like conditions caused by precipitation-induced drop in temperature and wind direction shifts are prevented. This entire process is summarized in [Table 2.1](#) below.

Table 2.1: Sea-breeze detection algorithm criteria applied to station observations (Adapted from [Hughes and Veron \(2018\)](#)).

	Direction	Direction (1 h ago)	Synoptic direction	1 h Δ direction	Direction grad	Wind speed	1 h Δ temp	3 h precip
CSB	Onshore	Offshore/calm	Offshore/calm	$>45^\circ$	–	>1.0	$<-2^\circ\text{C}$	<0.1 mm
WSB	Onshore	Onshore	Offshore/calm	–	$>45^\circ$	>1.0	–	<0.1 mm

Over tropical Africa, only [Abatan et al. \(2014\)](#), [Coulibaly et al. \(2019\)](#), and [Guedje et al. \(2019\)](#) describe methods for detecting sea-breezes from station data, all focusing on the West African coast. [Abatan et al. \(2014\)](#) identified sea-breeze onset over the Nigerian coast using hourly surface data and a clear wind reversal from offshore (night) to onshore (day). Their method relied on three criteria: (1) predominantly offshore or calm winds from sunrise -6 h to sunrise $+2$ h; (2) onshore winds for at least two consecutive hours between sunrise $+2$ h and sunset $+2$ h; and (3) a positive daytime land–sea temperature contrast ($\Delta T = [T_{land} - T_{sea}] > 0$). [Coulibaly et al. \(2019\)](#) applied essentially the same approach but added a sunshine-duration criterion to better characterize coastal breezes along the Guinea Coast. In contrast, [Guedje et al. \(2019\)](#) used a different approach based on flexible filters applied to 3-hourly data, without explicitly requiring wind reversal. Their criteria included: (1) a daytime increase in wind speed (06–12 UTC) followed by a decrease toward evening, with a fixed threshold of 2 m s^{-1} ; (2) onshore wind direction (100° – 260°) after sunrise; and (3) a positive daytime land–sea temperature contrast ($\Delta T = [T_{land} - T_{sea}] > 0$). Despite methodological differences, all studies share a common requirement which is a positive daytime temperature contrast between land and sea ($\Delta T = [T_{land} - T_{sea}] > 0$), and they were all able to detect sea breezes in their respective study areas.

Despite their advantages, threshold-based methods have several limitations. Their performance is sensitive to the choice of thresholds, which may vary with local climatology, station density, and background synoptic conditions. Furthermore, they may struggle to distinguish LBFs from other mesoscale boundaries, such as outflow boundaries or synoptic fronts, which can produce similar signatures in individual variables. Nonetheless, due to their transparency, low computational cost, and direct physical interpretability, threshold-based techniques continue to serve as a foundational approach for LBF detection and often provide the baseline against which more advanced methods are evaluated.

(b) Gradient-Based Methods

Gradient-based methods constitute an important class of objective techniques for detecting lake-breeze fronts, particularly when high-resolution spatial data (e.g., radar, satellite imagery, dense station networks, or model output) are available. As noted by [Atkins and Wakimoto \(1997\)](#) and [Crosman and Horel \(2010\)](#), these methods identify fronts as zones of strong spatial or temporal gradients in meteorological variables such as temperature, moisture, or wind convergence, thereby capturing the boundary between contrasting air masses in a physically consistent way. Unlike threshold-based approaches that rely on discrete local changes, gradient-based techniques focus on spatial discontinuities, offering a more realistic representation of frontal structure, although their effectiveness depends on the availability of dense datasets ([Crosman and Horel, 2010](#); [Brown et al., 2026](#)). This approach is supported by early observational studies (e.g. [Simpson, 1994](#); [Atkins and Wakimoto, 1997](#)), which describe the sea-breeze front as a density current with a well-defined leading edge where gradients are maximized. Exploiting this property, gradient-based methods locate regions of maximum spatial change to infer frontal position; for example, [Viner et al. \(2021\)](#) used radar data over the southeastern USA to detect fine-line reflectivity boundaries associated with convergence along the front.

Using gridded datasets such as numerical model output or reanalysis, gradient-based detection is typically implemented through numerical derivatives or edge-detection operators applied to scalar fields (e.g., temperature or equivalent potential temperature) (e.g. [Haupt, 2024](#)). The resulting gradient-magnitude fields are then analyzed to identify coherent linear features associated with the front, and in some cases, multi-variable gradients (e.g., temperature and moisture) are combined to improve robustness by better capturing thermodynamic contrasts. A clear example is provided by [Brown et al. \(2026\)](#), who applied a gradient-based moisture frontogenesis diagnostic to model datasets over Australia. After computing moisture gradients at each grid point, they used a percentile-based threshold (99.5th percentile) adapted to each dataset to isolate strong gradient zones, successfully identifying sea-breeze fronts across different model configurations.

Similarly, over tropical Africa, [Haupt \(2024\)](#) applied gradient-based methods to ICON model outputs of boundary-layer depth (BLH) and horizontal wind speed (U) along the Guinea coast. By combining the two-dimensional gradients of BLH and wind speed and applying threshold criteria (e.g., $|\nabla BLH| \geq 250$ m and $|\nabla U| \geq 0.4$ m s⁻¹) as shown in [Equation \(2.2\)](#) and [Equation \(2.3\)](#), she was able to clearly delineate the sea-breeze front position, demonstrating how gradient-based diagnostics can be adapted to different variables and regions while retaining a physically consistent representation of the boundary.

$$\frac{|\nabla BLH|}{0.06^\circ} \geq 250 \text{ m} \quad (2.2)$$

$$\frac{|\nabla U|}{0.06^\circ} \geq 0.4 \text{ m s}^{-1} \quad (2.3)$$

Despite their advantages, gradient-based methods also present challenges, as their performance depends strongly on data resolution and quality; coarse grids can smooth gradients and obscure frontal signatures, while similar gradients may arise from other mesoscale features (e.g., outflow boundaries or synoptic fronts), requiring additional constraints such as wind convergence for reliable identification. Nevertheless, because they provide a physically consistent framework for detecting LBFs as spatially coherent boundaries, complementing threshold-based approaches that emphasize temporal changes at individual locations, both methods were integrated in this study. Specifically, gradient- and threshold-based techniques were applied to IFS operational analysis data in Chapter 5 to identify LBF passages and develop suitable LBF proxies over LVB.

(c) Machine Learning Approaches

Machine learning (ML) approaches are increasingly being applied to the detection of LBFs, offering a flexible alternative to traditional threshold-based methods by learning complex, nonlinear relationships among atmospheric variables and defining adaptive decision boundaries (Biard and Kunkel, 2019; Hill et al., 2020; Dagon et al., 2022; Justin et al., 2023). These methods can integrate diverse data sources, such as surface observations, radar, satellite imagery, and model outputs, and, in some cases, perform adaptive feature fusion by dynamically weighting variables depending on environmental conditions (e.g. Hill et al., 2020; Bochenek et al., 2021). For example, a random forest (RF) classifier can be trained on labeled LBF events using predictors such as temperature gradients, wind direction shifts, humidity changes, and convergence signatures; during training, the model learns the combinations of these variables that best distinguish frontal boundaries from non-frontal conditions, enabling reliable detection even when individual signals are weak or ambiguous (e.g. Biard and Kunkel, 2019; Bochenek et al., 2021; Justin et al., 2023). In Biard and Kunkel (2019), a deep learning model trained on multiple atmospheric variables was able to successfully detect frontal boundaries (90%) by learning coherent patterns in temperature, wind, and moisture fields. This shows that a model may correctly identify a front despite weak temperature contrasts by recognizing consistent signals in wind convergence and humidity gradients, capabilities that conventional fixed-threshold methods often miss. While these approaches require large, high-quality labeled datasets and careful validation to avoid overfitting, especially in data-sparse regions like the LVB, they ultimately provide robust, scalable, and adaptive solutions. Overall, machine learning methods offer a promising pathway to

improve LBF detection in complex atmospheric environments (Biard and Kunkel, 2019; Bochenek et al., 2021; Justin et al., 2023).

2.4.2 Observation and Detection Challenges

Despite notable progress in observational techniques, studying LBFs in the LVB remains challenging due to significant data limitations. A major constraint is the lack of comprehensive spatial coverage, particularly over the lake itself, where in situ observations are extremely sparse. Most routine measurements are confined to shoreline stations, limiting the ability to directly observe critical processes such as offshore convergence, land-breeze propagation, and moisture transport across the lake. Furthermore, advanced observational systems are not widely available in the region; radar coverage is limited, long-term continuous datasets are scarce, and radiosonde or atmospheric profiling observations are infrequent. As a result, capturing the vertical structure of the boundary layer and validating numerical simulations of LBF dynamics remain difficult.

Although satellite observations help to partially bridge these gaps, they also have important limitations, especially in resolving shallow boundary-layer processes that are crucial for breeze development. The detection of LBFs is further complicated by factors such as variable cloud cover, background synoptic conditions, and interactions with other mesoscale phenomena, including convective outflows and topographically driven circulations. Compared to well-instrumented mid-latitude regions, the LVB remains under-observed, particularly over water, restricting accurate representation of land-lake contrasts and offshore breeze evolution. Consequently, robust LBF detection in this region relies on integrating multiple data sources, such as surface observations, radar, satellite products, and model outputs, while highlighting the urgent need for expanded observational infrastructure and sustained measurement campaigns.

On the other hand, detecting LBFs in the LVB is hindered by methodological limitations and the absence of standardized approaches. Several studies in the region have relied on expert judgment to manually identify lake-breeze events, making the process inherently subjective and difficult to reproduce without the original analyst. This lack of reproducibility is compounded by the absence of a unified, standalone detection framework tailored to the region, resulting in inconsistencies across studies. Furthermore, limited access to state-of-the-art high-performance computing infrastructure restricts the use of advanced modeling approaches such as large-eddy simulations (LES), which could otherwise provide detailed insights into LBF dynamics. Although some efforts have employed CP models to study related processes (e.g. Woodhams et al., 2019, 2022; Finney et al., 2020), these approaches remain computationally demanding and are not routinely applicable in the region.

Additional challenges arise from the inherent ambiguity in detection criteria and environmental complexity. For example, common observational indicators such as temperature

changes, wind shifts, or convergence signatures can also be produced by unrelated processes, including synoptic-scale fronts, convective outflows, or topographically induced circulations, increasing the risk of misidentification. The temporal variability of LBFs further necessitates high-frequency observations, which are often unavailable in the LVB, while the shallow nature of these fronts limits their detectability in satellite products. Although multi-variable and algorithm-based methods have the potential to improve detection reliability, they depend on high-quality, high-resolution datasets that are still sparse in the region. Consequently, these combined limitations continue to pose significant barriers to consistent, accurate, and scalable LBF detection in the LVB.

Although numerous approaches have been proposed for identifying LBFs, most existing methods rely either on manual interpretation of multiple datasets or on threshold-based criteria applied to individual meteorological variables. Such approaches are often difficult to implement in regions with sparse observations and highly heterogeneous frontal structures, where signals may be subtle or obscured. These limitations highlight the need for objective, reproducible, and transferable detection algorithms capable of identifying frontal passages using routinely available surface observations. Therefore, the methodology developed in this thesis builds upon existing approaches while leveraging the high spatial density of the Lake Victoria AWS network to establish a robust, consistent, and automated framework for LBF detection.

3. Research questions

Based on the previous chapters, LBCs are commonly identified through the passage of their leading edge, the LBF, which is typically associated with abrupt changes in meteorological conditions, including shifts in wind direction, decreases in temperature, increases in humidity, and enhanced vertical motion ([Simpson, 1994](#); [Sikora et al., 2010](#)). Accurate identification of LBF passages is therefore fundamental for investigating lake-breeze dynamics, quantifying their spatial and temporal variability, and assessing their influence on local weather and climate.

Following this general principle, several approaches have been employed to identify and monitor LBFs. Traditional methods rely on manual examination of surface meteorological observations, whereby analysts identify characteristic signatures in temperature, humidity, and wind fields (e.g. [Sikora et al., 2010](#); [Azorin-Molina et al., 2011](#); [Stauffer and Thompson, 2015](#); [Guedje et al., 2019](#); [Viner et al., 2021](#)). Other studies have utilized radar observations, satellite imagery, numerical weather prediction models, or high-resolution reanalysis products to detect and track LBCs (e.g. [Miller et al., 2003](#); [Crosman and Horel, 2010](#); [Sills et al., 2011](#); [Berri and Dezzutti, 2020](#)). While these mostly subjective approaches have significantly advanced understanding of lake-breeze processes, they often require specialized datasets, extensive manual analysis, or computationally intensive modeling systems that may not be readily available for long-term climatological investigations, particularly in data-sparse regions like in tropical Africa.

To overcome these limitations, several objective detection algorithms have been developed for sea-breeze and lake-breeze identification (e.g. [Azorin-Molina et al., 2011](#); [Wentworth et al., 2015](#)). These algorithms generally employ threshold-based criteria involving changes in temperature, humidity, wind speed, and wind direction measured at surface stations. Such objective methods offer important advantages, including consistency, reproducibility, and the ability to process large observational datasets efficiently ([Wentworth et al., 2015](#); [Hughes and Veron, 2018](#)). However, most existing algorithms have been developed and tested in coastal environments, particularly for sea-breeze detection, and their applicability to large tropical lake systems remains uncertain. Furthermore, relatively few studies (e.g. [Hawbecker and Knievel, 2022](#)) have evaluated

the robustness of these algorithms across stations characterized by different shoreline orientations, land-use characteristics, and exposure to local circulations.

Despite the recognized importance of lake-breeze circulations over the LVB, there remains no widely adopted objective methodology for detecting LBF passages using routine surface meteorological observations alone. The absence of an objective, observationally based detection framework represents a significant gap in the current understanding of lake-breeze dynamics over the LVB. Without a reliable and automated method for identifying LBF passages, it is difficult to establish long-term climatologies of lake-breeze occurrence, evaluate spatial variability across the basin, or provide a consistent basis for future studies of mesoscale weather processes. Addressing this gap requires the development of a robust algorithm capable of identifying LBF passages using readily available ground-based meteorological observations. Such a framework would facilitate systematic analysis of lake-breeze occurrence, enable the development of baseline climatologies, and support future investigations of the role of lake breezes in regional weather and climate.

Accordingly, the first objective of this research is to develop an objective algorithm based solely on ground-station meteorological observations to detect LBFs and evaluate its ability to accurately identify LBF passages across the study domain. This objective is addressed in Chapter 4 through the following research questions:

- RQ 1a** Which meteorological variables and thresholds are optimal for identifying LBF passages using surface observations in the hinterland of Lake Victoria?
- RQ 1b** How well does the algorithm perform compared to manually identified satellite lake-breeze and non-lake-breeze days?
- RQ 1c** Does the algorithm maintain consistent detection skill across different stations in the study domain?

Having developed and assessed the algorithm's ability to objectively detect LBFs, the next aim was to use it to analyse the spatio-temporal characteristics of LBFs and to develop a baseline climatology of LBFs in the region based on algorithm-detected events. Previous research over the region (e.g. [Chamberlain et al., 2014](#); [Thiery et al., 2016](#); [Woodhams et al., 2019](#); [Finney et al., 2020](#)) has consistently reported that precipitation extremes and severe thunderstorms are linked to LLB circulations and their associated LBFs, particularly during the dry seasons of DJF and JJA. However, there is no existing literature on the frequency of occurrence of these LLBs. Furthermore, no baseline climatology of these LBFs and their associated characteristics has been established for the region, despite their significant role in modulating regional weather and climate patterns.

This gap is partly due to the fact that most research on LLBs in the region is based on case studies and is limited by sparse in situ observational data, making it difficult to construct a climatology. In this study, this problem is addressed by utilising an unprecedentedly dense network of automatic weather stations to identify LBFs over a six-year period. Consequently, their spatio-temporal characteristics can be analysed to construct a baseline climatology, which constitutes the second aim of this thesis. To achieve this, the following research questions were posed:

RQ 2a How frequently do LBFs occur within the northern part of the LVB in Uganda?

RQ 2b How do LBF occurrence rates vary spatially across the LVB?

RQ 2c To what extent do LBF occurrences vary on monthly, seasonal, and inter-annual scales?

RQ 2d At what times of day do LBFs most frequently develop and propagate inland?

From the previous chapter, it is clear that the biggest bottleneck to LLB studies over the LVB is the paucity in observational data and limited detection techniques. Thus, having constructed the baseline climatology of LBF characteristics over the region, I now have a foundation to evaluate the skill of the ECMWF Integrated Forecasting System (IFS) operational analysis (hereafter, IFS) in representing the LLB system over LVB. In this step, the developed algorithm is applied, with only minor modification to the temporal resolution, to gridded model outputs of the same variables used in the observational dataset. Previous studies in other regions (e.g. [Hawbecker and Knievel, 2022](#)) have shown that observation-based detection algorithms often underperform when applied to model outputs. Therefore, this part of the thesis focuses on evaluating how accurately the IFS represents the timing, occurrence, structure, and spatial evolution of LBFs. Since model outputs provide a wider range of variables than observational datasets, this thesis part also seeks to identify the most suitable proxy variables in IFS for detecting LBFs over LVB. To achieve these aims, the following research questions are addressed:

- RQ 3a** How well does IFS capture the occurrence and timing of the LBF onset as compared observational datasets?
- RQ 3b** How well does the IFS represent the 3-dimensional structure and intensity of LBFs over the northern shores of Lake Victoria?
- RQ 3c** How accurately does the IFS represent the inland propagation speed and overall spatial evolution of LBFs?
- RQ 3d** Which proxy variables within the IFS framework provide the most reliable detection of LBFs over the LVB?

4. Detection of lake-breeze fronts from station observations

This chapter presents the novel algorithm developed to detect lake-breeze fronts at Lake Victoria using a dense network of station observations. First, the study domain and datasets are presented in [Section 4.1](#). The methods including the development of the detection algorithm and verification of the detected lake-breeze days are explained in [Section 4.2](#). Then the results of the validation of algorithm performance and sensitivity tests to identify the best threshold configuration are presented in [Section 4.3](#). The results of the application of the algorithm including extracting several lake-breeze features are also presented in this section. This chapter ends with [Section 4.4](#) where the discussion and conclusion of the results herein were put in broad perspective and compared with previous studies.

4.1 Study area and datasets description

4.1.1 Study domain

The study focuses on the areas surrounding the northern shores of Lake Victoria including the Kampala metropolitan area in Uganda ([Figure 4.1](#)). Lake Victoria, located in East Africa, is the largest tropical freshwater body in the world, with a surface area of 69,000 square kilometers ([Semazzi, 2011](#)). Straddling the Equator, the lake is shared by three East African countries (Uganda, Kenya, and Tanzania), and supports the livelihood of approximately 40 million people in eastern Africa ([Semazzi, 2011](#); [Nyamweya et al., 2023](#)). The study area is characterized by two distinct rainfall seasons: MAM, commonly termed as the ‘long rains’ with its peak in April, and SON, commonly known as the ‘short rains’ with its peak in October ([Nicholson, 2017](#); [Diem et al., 2019](#)). However, the region receives significant rainfall amounts even during the dry months of JJA and DJF. These rains are the result of the local effect of Lake Victoria, particularly, the LLB circulation system which result in nocturnal and afternoon rainfall regimes in the western and eastern side of the lake, respectively ([Nicholson, 2017](#); [Nicholson et al., 2021b](#)). In addition, the prevailing surface winds are mostly easterlies, with some seasonal variability due to the movement of the ITCZ ([Flohn and Fraedrich,](#)

1966; Nicholson, 1996). Topographically, the area is relatively flat which favours inland penetration of the lake-breezes (LBs).

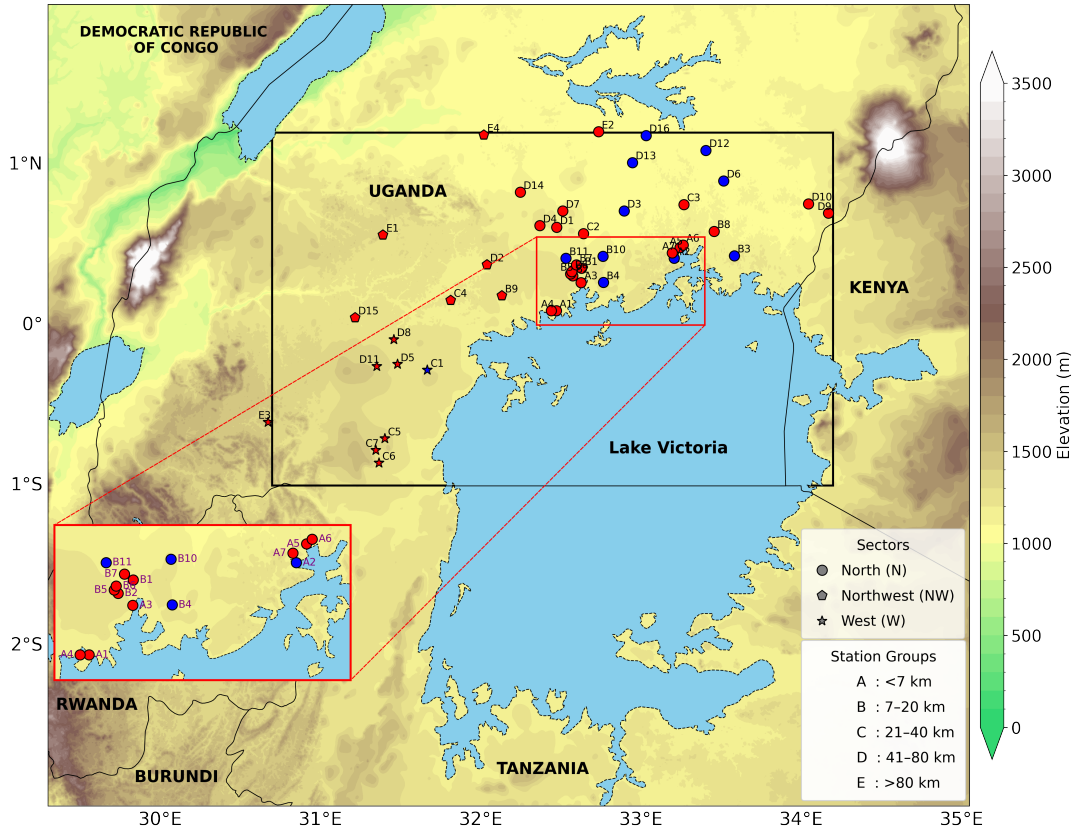


Figure 4.1: Map showing the location of Lake Victoria and the surrounding topography. The study area is shown by the black box together with the distribution of the automatic weather stations (AWSs); TAHMO (red) and UNMS (blue). Stations are classified according to (a) their relative distances from the coastline (letters A-E), and coastal sector location (markers) (see Table A.1 for further information). The colour shading shows the elevation from Global Land One-km Base Elevation Project (GLOBE; Hastings and Coauthors, 1999). The inset highlights the location of stations around Kampala and Jinja within the study area (red box). Taken from Ssemujju et al. (2026a). © American Meteorological Society. Used with permission.

4.1.2 Observational Datasets

4.1.2.1 In situ station data

High-quality ground-based observations are often essential in any scientific research due to their accuracy and reliability. In this study, in-situ data from 45 automatic weather stations (AWSs) located along the northern shores of LV in Uganda within a radius of 100 km from the lake shore are utilized (Figure 4.1). Of these, 34 stations are operated by the Trans-African Hydro-Meteorological Observatory (TAHMO, <https://tahmo.org>,

Van de Giesen et al. (2014), while the remaining 11 are managed by the Uganda Department of Meteorological Services (UDMS).

The AWSs record several meteorological parameters, including precipitation, air temperature, solar radiation, relative humidity, atmospheric pressure, and wind speed and direction at 15-minute intervals. TAHMO data, which has been widely used in previous studies across Africa (e.g. Macharia et al., 2022; Hoeller et al., 2024), was downloaded from the TAHMO data portal (<https://portal.tahmo.org/login>), while UDMS station data were obtained from UDMS. It is important to note that both TAHMO and UDMS data used in this study are recorded at 2-meter height above ground level.

Given that some of the UDMS AWS datasets had not previously been used in scientific research, a comprehensive quality control process was undertaken prior to analysis. This included checks for timestamp consistency, range and step tests to flag values outside known climatological bounds, and internal consistency checks for parameters such as wind and temperature. TAHMO applies quality control processes that include cross-calibration between sensors, comparisons between nearby stations, and qualitative intercomparisons with satellite observations (Van de Giesen et al., 2014; Macharia et al., 2022).

Considering the tropical climate of the study area, which is characterized by alternating wet and dry seasons, LB circulations are more pronounced during dry, sunny periods (Planchon et al., 2006). Therefore, the analysis concentrates on the dry seasons (DJF and JJA) to identify LB events during the six-year study period from 2017 to 2022. Since not all AWSs were operational throughout the entire period, we limit our analysis for each station to days with more than 80% of wind or temperature data records. Therefore, data availability varies amongst stations depending on installation date, with 42 (36) of the 45 stations having more than 60% (80%) sub-daily data availability (see Figure 4.2 and Table A.1). Additionally, the stations are classified relative to their distance from LV as follows: A (<7 km); B (7-20 km); C (21-40 km); D (41-80 km); and E (>80 km) (see Figure 4.1 and Figure 4.2).

4.1.2.2 Satellite images

In addition to ground-based station data, this study incorporates visible satellite imagery from NASA’s Earth Observing System Data and Information System (EOSDIS) Worldview platform (NASA EOSDIS Worldview) ¹ to identify LBFs during the DJF and JJA seasons over the 2017-2022 period. The analysis utilizes visible spectrum channels from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA’s Terra and Aqua satellites, as well as the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi NPP and NOAA-20 satellites. These satellites provide twice-daily overpasses (nominal equatorial overpass times) over the study region at the

¹<https://worldview.earthdata.nasa.gov>

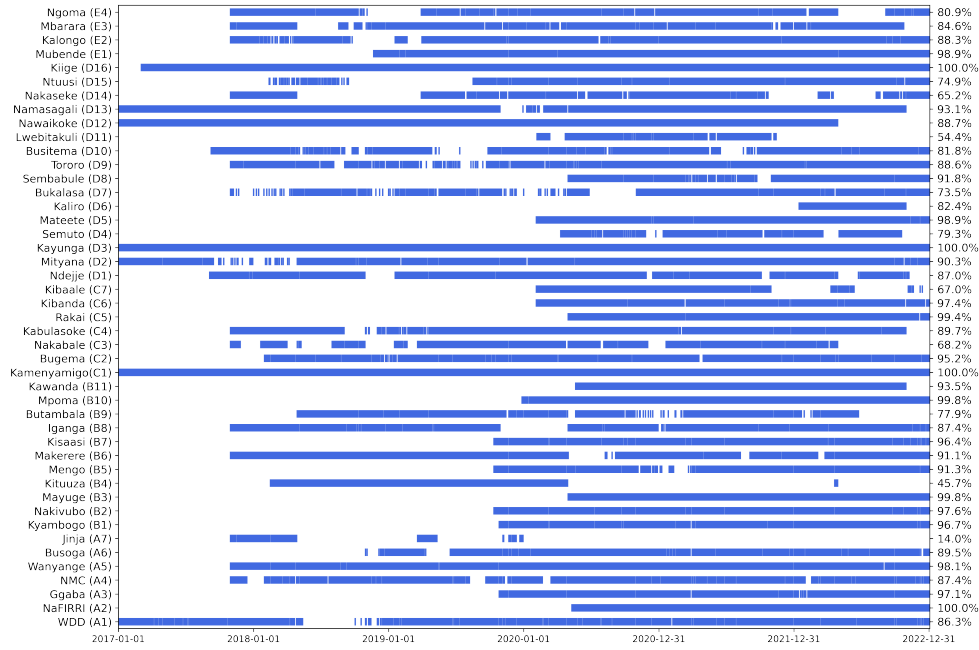


Figure 4.2: Temporal availability of the 45 AWS data used in the study for the period 2017-2022. The number string in the bracket after the station name indicates the station’s distance in kilometers from the coast (see [Figure 4.1](#)). The blue-strip shading shows >80% sub-daily data availability based on the 41-timesteps from 0900-1900LT (15-minute intervals) expressed as percentage (numbers on the right) for each station during the dry seasons of DJF and JJA in the period 2017-2022. Taken from [Ssemujju et al. \(2026a\)](#). © American Meteorological Society. Used with permission.

following local times: 10:30 and 22:30 for Terra-MODIS; 12:20 and 00:20 for NOAA-20/VIIRS; and 13:30 and 01:30 for both Aqua-MODIS and Suomi NPP/VIIRS. The thermal band spatial resolution is ~ 250 meters per pixel for MODIS and 375 meters per pixel for VIIRS, enabling detailed observation of mesoscale atmospheric features.

4.2 Methods

4.2.1 Sampling potential lake-breeze candidates from satellite images

Using visible-spectrum satellite imagery, LBFs are often identified by the presence of cumuli-form cloud lines aligned parallel to the shoreline and moving inland under the influence of LB circulation ([Simpson, 1994](#)). However, not all LB circulations result in visible cloud lines; particularly in conditions of low atmospheric humidity, cloud development may be suppressed, rendering the LBF undetectable in visible imagery. Thus, the absence of visible cloud lines does not necessarily indicate the absence of a lake breeze.

To effectively identify LB events in our study area, the northern shores of Lake Victoria were partitioned into three coastal sectors based on coastline orientation and complexity: Western (W: 30°E - 32°E , 1°S - 0°); Northwestern (NW: 31°E - 32°E , 0° - 1°N); and Northern

(N: 32°E-34°E, 0°-1.3°N) ([Figure 4.2](#)). Then, visible-spectrum satellite images from NASA EOSDIS Worldview were visually inspected for the dry seasons of DJF and JJA over the period 2017-2022. Days such as those shown in [Figure 4.3](#), exhibiting clear cloud lines aligned parallel to the coast were catalogued as LB days, while days with no discernible LB features were recorded as non-LB days in this study. Furthermore, days characterized by (i) strong synoptic disturbances with extensive cloud cover or (ii) entirely cloud-free conditions across the study area were considered as non-LB days following the screening methodology of [Planchon et al. \(2006\)](#) and [Damato et al. \(2003\)](#).

In addition to using linear, coherent cloud bands as the primary indicator of LB activity, the visual inspection also considered other supporting mesoscale cloud structures (e.g., horizontal convective rolls and cloud streets) when their orientation and timing were consistent with expected LB evolution. These combined qualitative indicators formed the basis of the satellite-derived reference dataset. For each of the 1,093 dry-season days examined, 2-3 visible-spectrum satellite images (depending on overpass times) were reviewed to ensure consistency in identifying LB-related cloud signatures. Of these days, 578 were classified as LB days and 210 as non-LB days. Days for which the satellite scene did not allow for a confident classification were designated as “uncertain” and excluded from the analysis to minimize potential misclassification and to maintain a robust comparison between clear LB and non-LB cases. These resulting LB and non-LB samples serve as the “reference” dataset for validating the LBF detection algorithm for ground-based station data, as described in the next section.

4.2.2 Description of the objective Observation-based Lake Breeze Detection Algorithm (OLBDA)

4.2.2.1 General overview of the algorithm

The algorithm is developed using key characteristic features of SBF/LBF passage at an observing station, with all its main components described in more detail in the next section. The algorithm begins by checking for onshore winds at a test station, a compulsory flag based on the definition of sea-/lake-breeze circulation that must be satisfied before proceeding to the next step. If this is passed, then it checks for a change in environmental conditions at that station as a result of the marine air mass from the lake replacing the air over land. For example, when an LBF passes over a test station, there is a rapid increase in onshore wind speed usually accompanied by a sharp decrease in temperature and an increase in humidity or dew point ([Sills et al., 2011](#); [Miller et al., 2003](#)). Finally, the algorithm checks whether the above changes were not a result of cold pools of convective systems. By doing this, the algorithm ensures that all the changes in the measured meteorological parameters are exclusively produced by the LBF passages. If all these criteria flags are passed sequentially, then the LBF passage at that station is

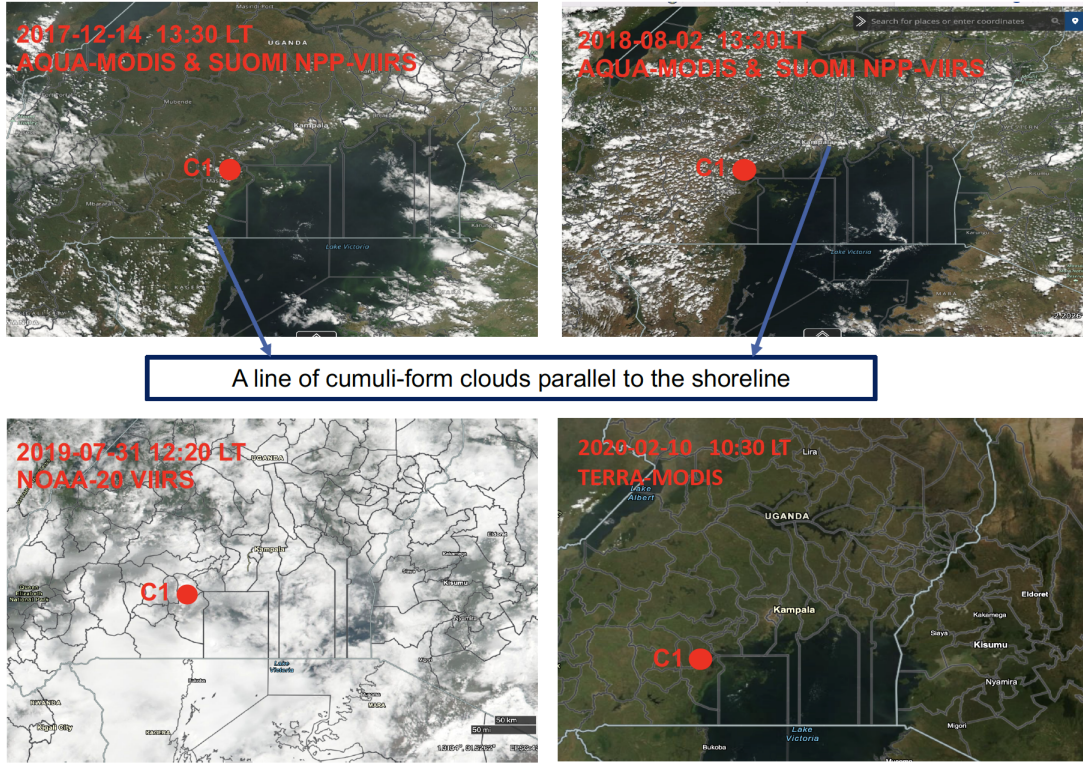


Figure 4.3: Top panel: Examples of the manually identified satellite LB days where lake breeze fronts (LBFs) were visible around Lake Victoria from NASA EOSDIS Worldview Visible spectrum images. A line of cumuli-form clouds aligned parallel to Lake Victoria’s shoreline advecting inland shows the presence of the LBF on these days. Bottom Panel: Examples of satellite non-LB days: a cloudy day and a completely cloud-free day image. The red-shaded circle in all panels indicates the location of Kamenyamigo station (C1), which is also passed by the LBF in the top panel subfigures. Taken from [Ssemujju et al. \(2026a\)](#). © American Meteorological Society. Used with permission.

counted. The complete sequence of procedures employed to automatically identify LBF occurrences at a station is outlined in the OLBDA flowchart ([Figure 4.4](#)).

4.2.2.2 Detailed description of the algorithm

The OLBDA shown in [Figure 4.4](#) processes 15-minute instantaneous observations of 2 m temperature, dew point, and wind at each station, iterating through the time series and comparing each observation with the one from 15 minutes earlier to detect 15-minute changes. For example, at 0915LT, the algorithm compares the observations from 0915LT to those recorded at 0900LT. Then it is incremented to 0930LT and compared to the observations from 0915LT. This 15-minute window was chosen because it was the highest temporal resolution available across all stations and is sufficient to capture changes due to LBF passage.

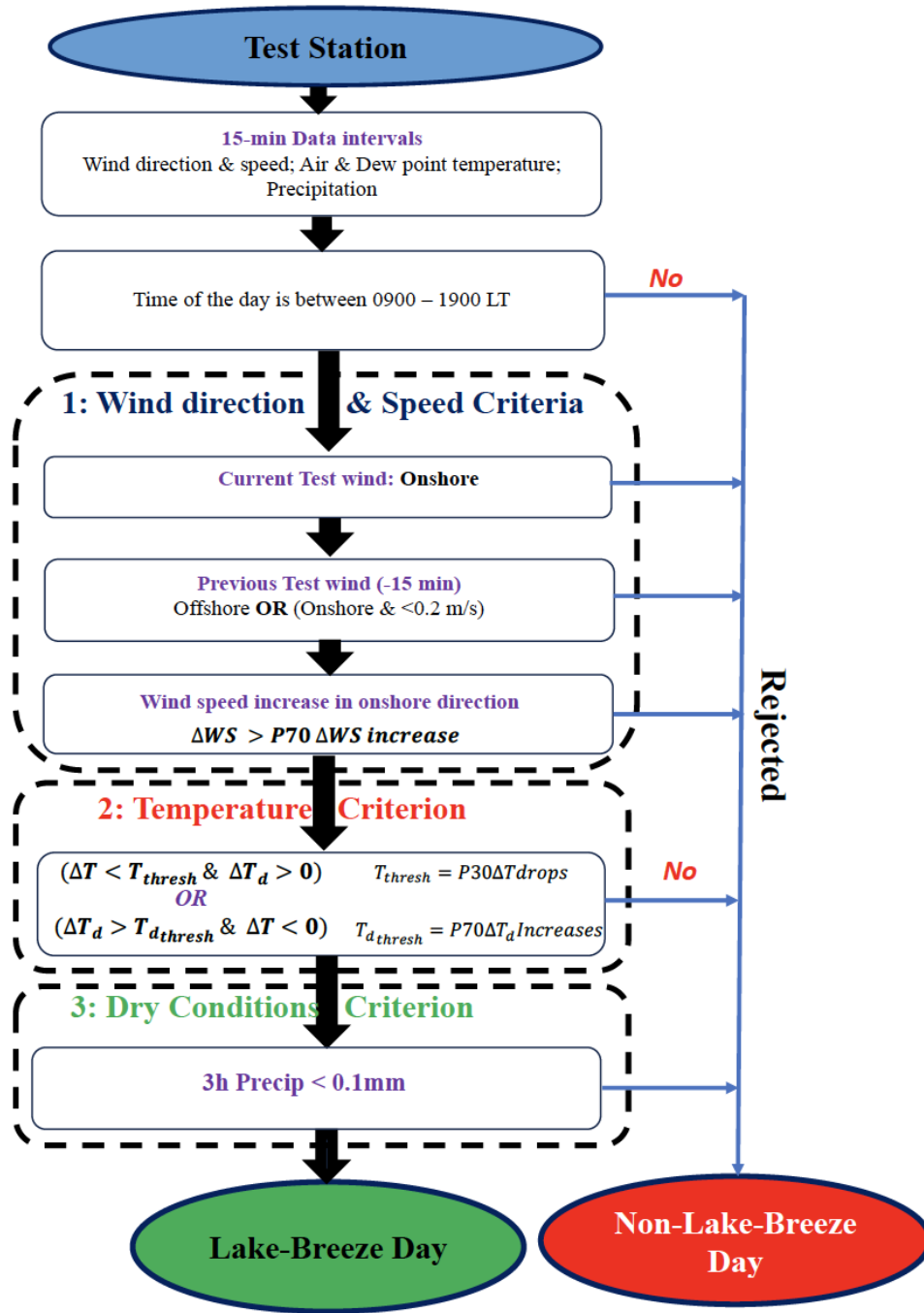


Figure 4.4: Flow diagram illustrating the three criteria used by the Objective Lake-Breeze Detection Algorithm (OLBDA) to identify lake-breeze front (LBF) passage at a station using meteorological observations of temperature, dew point temperature, wind, and precipitation. A day is classified as a lake-breeze day only when all three criteria are satisfied; otherwise, it is classified as a non-lake-breeze day. Here, ΔT , ΔT_d , and ΔWS denote 15-minute changes in air temperature, dew point temperature, and wind speed, respectively, while P30 and P70 represent the 30th and 70th percentile values of these changes. Adapted from Ssemujju et al. (2026a). © American Meteorological Society. Reproduced with permission.

Like in [Hughes and Veron \(2018\)](#) and [Hawbecker and Knievel \(2022\)](#), we identify LBs by focusing on daytime periods when the coastal land-lake temperature contrast is assumed to be strong. Specifically, the algorithm searching times are limited to 0900-1900 LT, during the dry months (i.e., DJF and JJA). The three different criteria employed to detect lake-breeze episodes from station observational data are described in the following.

(i) Wind shift and wind speed increase criteria

Based on the definition of the sea/lake breeze circulation, winds are expected to be onshore winds as described in [Azorin-Molina et al. \(2011\)](#) and [Hughes and Veron \(2018\)](#). Hence, the algorithm starts by defining an onshore wind direction for each station. That is, for each station, we define the onshore angle range such that it encompasses the extent/shoreline of LV as illustrated in [Figure 4.5](#). If the recorded wind direction at this station falls within this range, it is classified as onshore; otherwise, it is classified as offshore.

A potential LBF passage is detected at any given station and time if one of the following wind conditions are met; either there is a rapid shift in wind direction from offshore to onshore (i.e., wind direction reversal), or there is a rapid increase in wind speed in the onshore direction within a 15-minute period at the onset of the lake-breeze. Owing to the complex shape of LV's shoreline, wind shifts at individual stations are defined relative to the orthogonal of the nearest shoreline.

Although a shift from offshore to onshore often accompanies LBF passage, this is not typical in our study area due to its location and prevailing large-scale synoptic flow, which is predominantly easterly at low levels (northeasterly in DJF and southeasterly in JJA). In such cases, LBF passages can be associated with increases in wind speed driven by a positive land-lake temperature contrast ([Azorin-Molina et al., 2011](#)). Consequently, our algorithm is designed to detect LBFs without explicitly requiring wind reversal, but onshore wind remains a mandatory condition to exclude signals from other phenomena such as synoptic fronts ([Borne et al., 1998](#)) and must be satisfied before the algorithm proceeds to identify an LBF passage.

(ii) Temperature criterion

Once the wind direction and speed criteria are met, the data are tested for a drop in air temperature or an increase in dew point temperature, which are often associated with the influx of cooler moist air coming from the lake.

Given the variability in temperature drops and dew point increases across stations ([Figure 4.1](#)), applying a single fixed threshold was not feasible. For example, [Figure 4.6a](#) illustrates that a fixed 0.5°C temperature drop (black dashed line) in 15 minutes would miss many LBF passages at stations A1, A3, A4, B5, B7, and D9, since this value

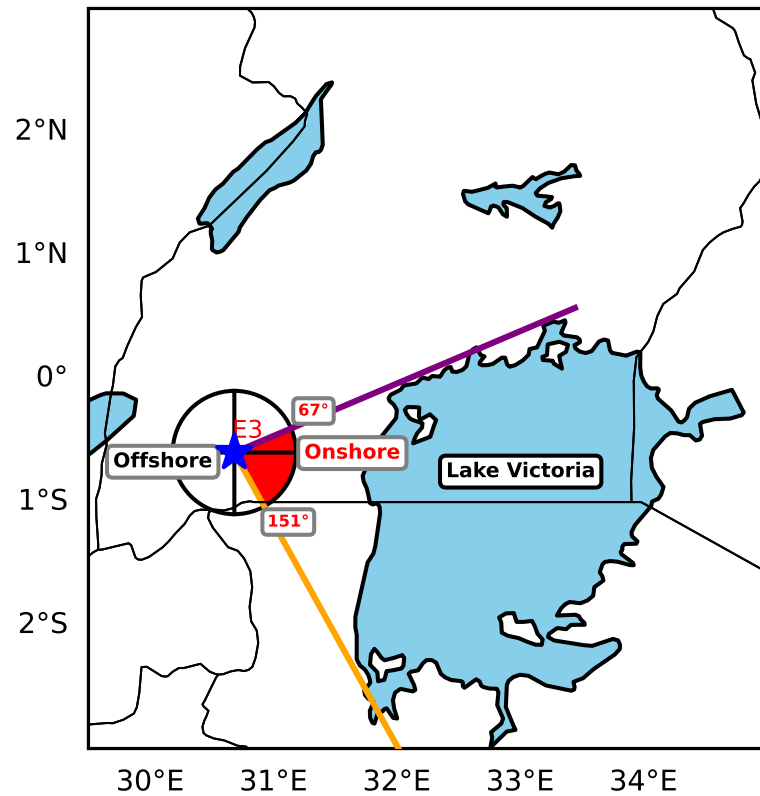


Figure 4.5: An illustration of how onshore angle ranges were determined at any station. Onshore angle range (red shading) is defined based on the minimum and maximum radial line from the point of interest towards LV in a clockwise sense and intersecting with it. In this example, the blue star represents the station of interest (Mbarara, E3) for which the onshore minimum (67°; purple line) and maximum (151°; orange line) angles are determined. If the wind direction at this station lies in-between these two angle values, then it is characterized as an onshore wind, otherwise, it is offshore (no shading). Adapted from [Ssemujju et al. \(2026a\)](#). © American Meteorological Society. Reproduced with permission.

exceeds the interquartile range at these stations. Similarly, [Figure 4.6b](#) shows that a fixed 0.5°C dew point increase would underestimate LBF occurrences at most stations.

As a result, percentile-based thresholds for temperature and dew point criteria are applied to account for regional variabilities. Here, the lowest (highest) 30% of the air (dew point) temperature decreases (increases) in the dry seasons are used, making temperature change thresholds station-dependent. These percentile thresholds stem from a performance test of OLBDA that is presented later in [Section 4.3.2](#).

(iii) Exclusion of cold pool passages

A day is not counted as a lake-breeze day if there is significant precipitation within 3 hours prior to the potential LBF passage detection, including the time of arrival at the

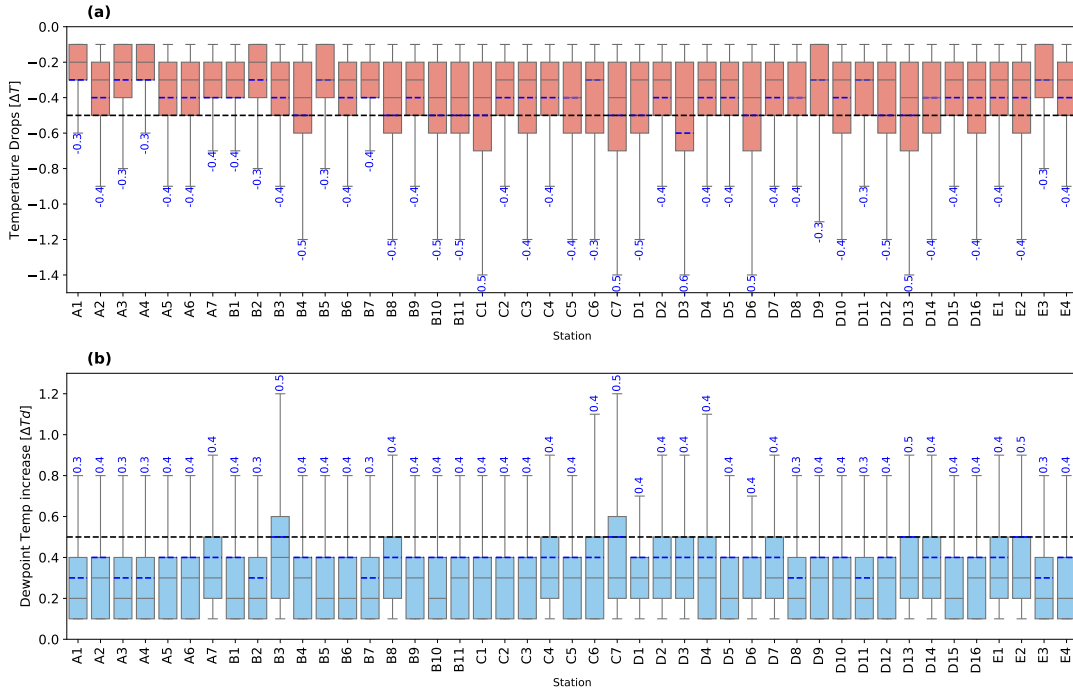


Figure 4.6: Box and Whisker plot showing the distribution of 15-minute temperature drops (a), and dew point increase (b), at every station within the study area during the dry seasons of DJF and JJA, and within 0900-1900 LT. On each box, the black central mark is the median, the top and bottom of the box are the upper and lower quartiles, respectively. The black-dashed line exemplarily represents the -0.5°C (0.5°C) temperature (dewpoint) change, respectively across the different stations. The blue-dashed line in each box indicates the percentile-based threshold value (also annotated at the top of each whisker) for each station. Adapted from [Ssemujju et al. \(2026a\)](#). © American Meteorological Society. Reproduced with permission.

station. This filter was introduced to minimize misclassification, since precipitation-related convective cold pools can generate temperature, dewpoint, and wind changes similar to those associated with LBF passages. Accordingly, this algorithm requires that in case of any precipitation at a station in the preceding 3-hour period inclusive of arrival time, it should not exceed 0.1mm prior to the LBF passage. The filter therefore removes any candidate LBF event coinciding with antecedent precipitation at the station above this threshold. By contrast, cases in which precipitation develops after LBF detection are retained.

If in any 15-minute interval, all the three specified criteria are satisfied at a given station, then the entire day is classified as an LB day for that station. The timing of the LBF passage can be used to examine the expected changes in the meteorological variables resulting from the front's passage over a particular station as shown later in the results section.

4.2.3 Verification of OLBDA detected lake-breeze days

To test the performance, the OLBDA-detected LB days at a given station were compared with the manually identified satellite LB and non-LB days (“reference dataset”) in the same geographical area. The number of identified lake-breeze days in both OLBDA and satellite gives the hits (H), while the number of OLBDA-detected LB days common in the satellite non-LB days gives the false alarms (F). The number of satellite LB days that were not detected by the OLBDA gives the misses (M), while the number of non-LB days in both OLBDA and satellite gives correct negatives (N). From this, a 2x2 contingency table (Table 4.1) was formed and the evaluation of the OLBDA was carried out using the performance metrics, namely, probability of detection (POD), probability of false alarm (POFA), success ratio (SR), critical success index (CSI), bias in detection (BID), accuracy (ACC), and Heidke skill score (HSS). The description and calculation of each statistic are summarized in Table 4.2.

Table 4.1: A 2x2 contingency table for comparing algorithm lake-breeze (LB) detected days and satellite identified LB and non-LB days. Taken from Ssemujju et al. (2026a).

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	Satellite LB day	Satellite non-LB day
OLBDA LB day	Hit (H)	False alarm (F)
OLBDA non-LB day	Miss (M)	Correct rejection (R)

4.2.4 Deriving lake-breeze characteristics

After the LBF passage is detected at a station, that day is classified as a lake-breeze day at that station. Then, LBF occurrences are analyzed for LB frequency and onset (arrival) time statistics. Additionally, the LBF occurrences are analyzed for diurnal, seasonal, and inter-annual variability. To assess the meteorological conditions surrounding the passage of the LBF, each LB day is aligned such that time, t_0 ($t=0$), corresponds to the LBF’s arrival time. This alignment enables a comparative analysis of atmospheric variables within a 3-hour window before and after the event, offering insights into the directional persistence of the LB and associated meteorological changes. Furthermore, inland penetration characteristics such as LBF speed and depth are investigated using transects in different directions. For example, when the LBF moves through two of the stations along the transect, then the difference in the frontal arrival time is used to calculate the LBF speed between those two stations. Finally, a snapshot climatology of lake-breeze characteristics is developed.

Table 4.2: A summary of the different performance metrics used in this study to validate the algorithm. The terms H , F , M and R denote hits, false alarms, misses and correct negatives, respectively. The range and best possible score of each statistic is added in the first column in square brackets and bold numbers, respectively. Taken from [Ssemujju et al. \(2026a\)](#). © American Meteorological Society. Used with permission.

Statistic	Formula	Description
POD, [0,1], 1	$POD = \frac{H}{H + M} \quad (4.1)$	Quantifies the ability of the OLBDA to correctly detect LB days
POFA, [0,1], 0	$POFA = \frac{F}{H + F} \quad (4.2)$	Proportion of OLBDA detected lake-breeze days that were non-LB days in the satellite
SR, [0,1], 1	$SR = \frac{H}{H + F} \quad (4.3)$	Compares the number of correctly detected LB days with the total number of OLBDA detected LB days
CSI, [0,1], 1	$CSI = \frac{H}{H + F + M} \quad (4.4)$	Ratio of all LB days detected and observed which are correctly detected
BID, $[-\infty, +\infty]$, 1	$BID = \frac{H + F}{H + M} \quad (4.5)$	Assesses whether the OLBDA overestimates or underestimates LB days frequency
ACC, [0,1], 1	$ACC = \frac{H + N}{H + N + F + M} \quad (4.6)$	Quantifies the ability of the OLBDA to correctly detect LB and non-LB days
HSS, $[-\infty, 1]$, 1	$HSS = \frac{2(HR - FM)}{(H + M)(M + R) + (H + F)(F + R)} \quad (4.7)$	Accesses the skill of the OLBDA compared to random chance

4.3 Results

4.3.1 Example of lake-breeze front passage detected by the OLBDA

This section presents an example of the LBF passage detected by OLBDA on 14 December 2017 at Kamenyamigo station (C1), located 28 km from LV along the western coast. The algorithm detected the LBF passage at approximately 1600 LT, coinciding with notable changes in atmospheric variables ([Figure 4.7](#)). Specifically, air temperature dropped by 1.4°C and 1.3°C over two consecutive 15-minute intervals, while dew point temperature increased by 4°C and 2°C, respectively. These abrupt

changes exceeded the thresholds defined by the lowest (highest) 30% of the air (dew point) temperature decreases (increases) at Kamenyamigo by more than 0.8°C (1.6°C). Concurrently, wind direction shifted from northerly (offshore) to easterly (onshore), accompanied by a marked increase in wind speed. These changes are characteristic of the LBF passage. The passage time (i.e., 1600 LT) is defined as the moment when a sharp temperature drop and a simultaneous rise in humidity are observed, marking the arrival of the thermodynamic front. This OLBDA-detected LB day was also confirmed by the satellite image in [Figure 4.3](#) (top left panel).

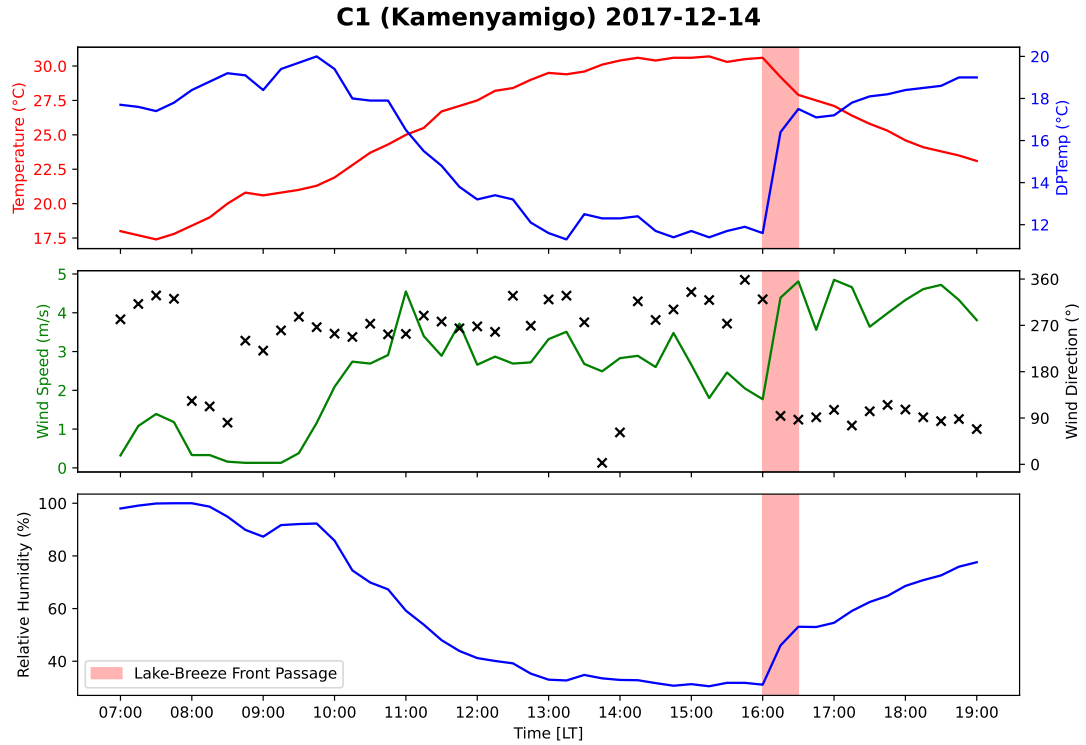


Figure 4.7: Case study from 14 December 2017 portraying the meteorological effects of a lake breeze frontal passage at station C1 (Kamenyamigo) as detected by the OLBDA. The temperature (top panel), wind speed and direction (middle panel), and relative humidity (bottom panel) before and after LBF passage are shown. The red shading indicates LBF passage. This same day was captured by the satellite images (see [Figure 4.3](#); Top left panel). Adapted from [Ssemujju et al. \(2026a\)](#). © American Meteorological Society. Reproduced with permission.

4.3.2 Sensitivity test: Identification of the best configuration

To optimize the algorithm, multiple configuration setups were tested to identify the most effective threshold combination for detecting LBF passages at near coastal stations. We only selected coastal stations based on the certainty that the LBF passed them as visually seen from the satellite images in [Figure 4.3](#). The algorithm operates on absolute 15-minute changes in air temperature, dewpoint, and wind speed rather than percentage

changes. Accordingly, all percentile thresholds used in the sensitivity analysis were derived from the empirical distributions of these absolute changes and are independent of the baseline meteorological conditions at each station. This approach ensures that the thresholds represent characteristic magnitudes of short-term variability rather than proportional departures from background state.

The algorithm’s sensitivity was evaluated by systematically varying percentile thresholds for air temperature drop, dewpoint, and wind speed increase. In this framework, each percentile corresponds to a defined portion of the observed distribution at each station (e.g., a combination of P30, P70 and P70 means the lowest 30% of temperature drops, the highest 70% of dewpoint increases and the highest 70% of wind speed increases), allowing us to evaluate how increasingly stringent or permissive criteria affect detection performance. The resulting impacts on POD, POFA, SR, CSI, and BID are summarized in the performance diagram in [Figure 4.8](#).

A total of 58 configuration setups were assessed, including two configurations with fixed thresholds for temperature, dew point, and wind speed changes. Each configuration yielded varying LBF detection counts, confirming the algorithm’s sensitivity to threshold values. To identify the most effective setup, performance metrics were calculated for the identified LBF events with each configuration and then averaged across stations. The station ensemble mean position of each configuration was then plotted on the performance diagram for easy comparison. As shown in Fig. 8, the “ $P40 - P60_ΔWS > 0$ ” configuration had the highest POD but also the highest POFA and BID, indicating over-detection, while the “ $ΔT_ΔT_d = 0.5_ΔWS = 0.2$ ” configuration showed the highest SR (0.81) but a lower POD (0.57) and CSI (0.50). Conversely, the “P40-P60-P60” was unbiased (BID = 1), but had a lower SR (0.75). The most balanced configuration for identifying LBFs was “P30-P70-P70”, with POD = 0.74, SR = 0.79, CSI = 0.62, and BID = 0.95. Thus, the “P30-P70-P70” configuration (see highlighted marker in [Figure 4.8](#)), representing the lowest 30% air temperature drops and highest 70% dew point and wind speed increases in the dry seasons, was adopted as the optimal threshold for these parameters in the algorithm.

4.3.3 Station-based performance evaluation

To evaluate performance, OLBDA-detected LB days obtained using the most suitable configuration from [Section 4.3.2](#) are compared with the manually identified satellite lake-breeze days during the study period.

The OLBDA algorithm demonstrates robust performance in detecting LB events, particularly at coastal stations. It achieves a high probability of detection (POD > 0.7), low false alarm ratio (POFA = 0.2), and good overall accuracy of 0.76, although it slightly underestimates LB frequency (BID = 0.95) (see [Figure 4.8](#)). The spatial distribution of performance metrics is shown in [Figure 4.9](#). [Figure 4.9a](#) shows that POD values in

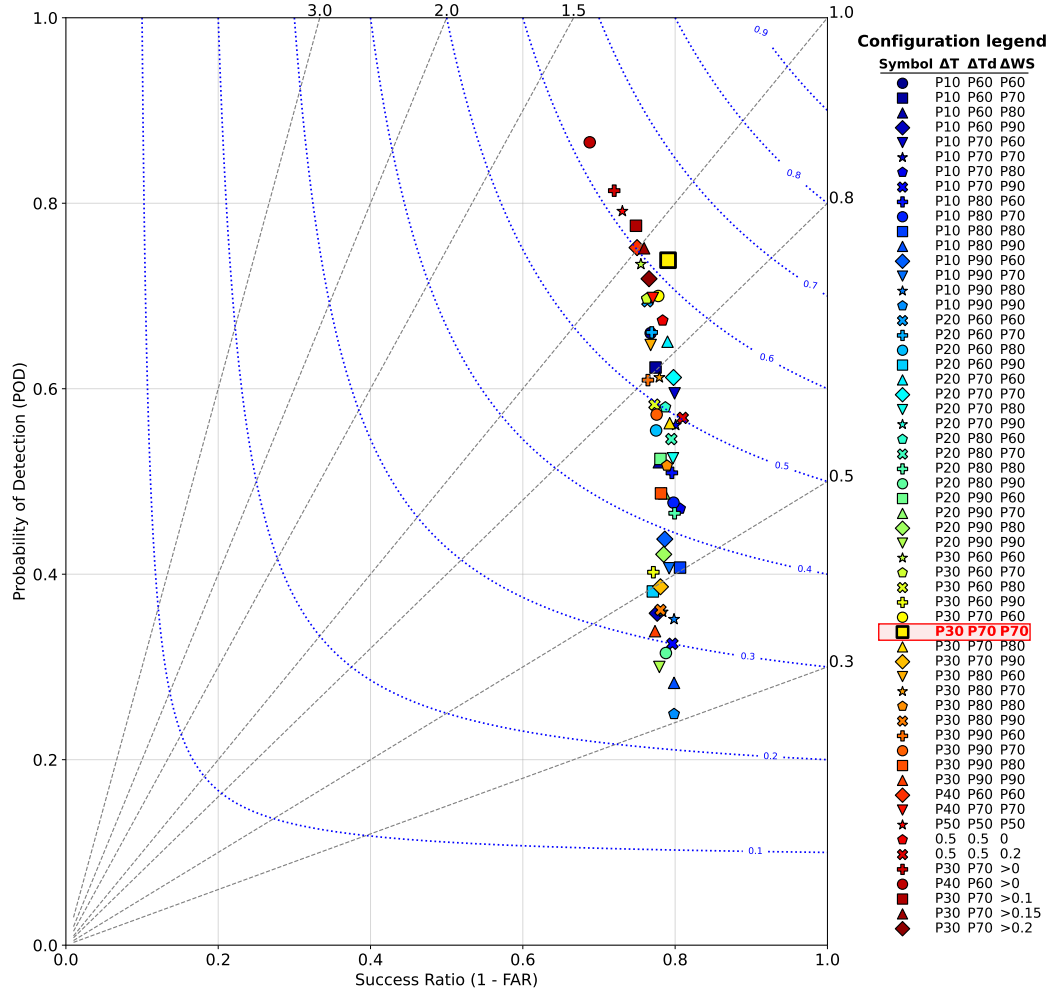


Figure 4.8: Performance diagram for near-coastal stations showing the probability of detection (POD; horizontal lines), success ratio (SR; vertical lines), critical success index (CSI; blue dotted lines), and bias (BID; gray dashed lines). The diagram summarizes sensitivity tests based on varying temperature and wind thresholds used in algorithm tuning. In the legend, the leading “P” denotes percentiles of air-temperature decrease (ΔT), dew-point increase (ΔT_d), and wind speed increase (ΔWS) applied in the different configurations. Markers indicate the ensemble mean position for each sensitivity test. The red, bolded configuration (P30-P70-P70), highlighted with a black-edged yellow square marker, represents the eventual configuration used. Adapted from Ssemujju et al. (2026a). © American Meteorological Society. Reproduced with permission.

the western sector and within 20 km of the shoreline are higher than 0.6, while beyond 70 km they are less than 0.40. This indicates that the algorithm correctly captures the majority of the LB days identified by the satellite, especially near the coast, likely because the changes in wind and temperature are stronger. About 93% of the stations have POFA values below 0.25, with an average value of 0.19 (Figure 4.9b), implying that 19% of detected LB events at these stations are false alarms. The CSI, SR, and ACC patterns (Figure 4.9c-e), align closely with those of POD, indicating consistent

detection reliability. The majority of stations exhibit $\text{CSI} > 0.4$ (73%), $\text{SR} > 0.7$ (98%), and $\text{ACC} > 0.6$ (93%), with coastal stations having the highest values across all three metrics. The mean CSI value of 0.49 across all stations implies that the algorithm correctly detects nearly half of the LB events (observed and/or detected). As with other metrics, the HSS in Figure 4.9f highlights greater detection skill near the coast, diminishing inland. With a mean HSS value of 0.37, OLBDA demonstrates a higher ability to detect LBF passages compared to random chance at most stations. Overall, OLBDA effectively captures most satellite-identified LB days, underscoring its high suitability for LB detection, particularly along the coast. The diminishing detection skill further inland is related to the fact that not all LBFs actually reach the inland stations as some may weaken or stagnate while moving inland due to the weak onshore flow, potentially leading to an overestimation in the number of misses at these stations.

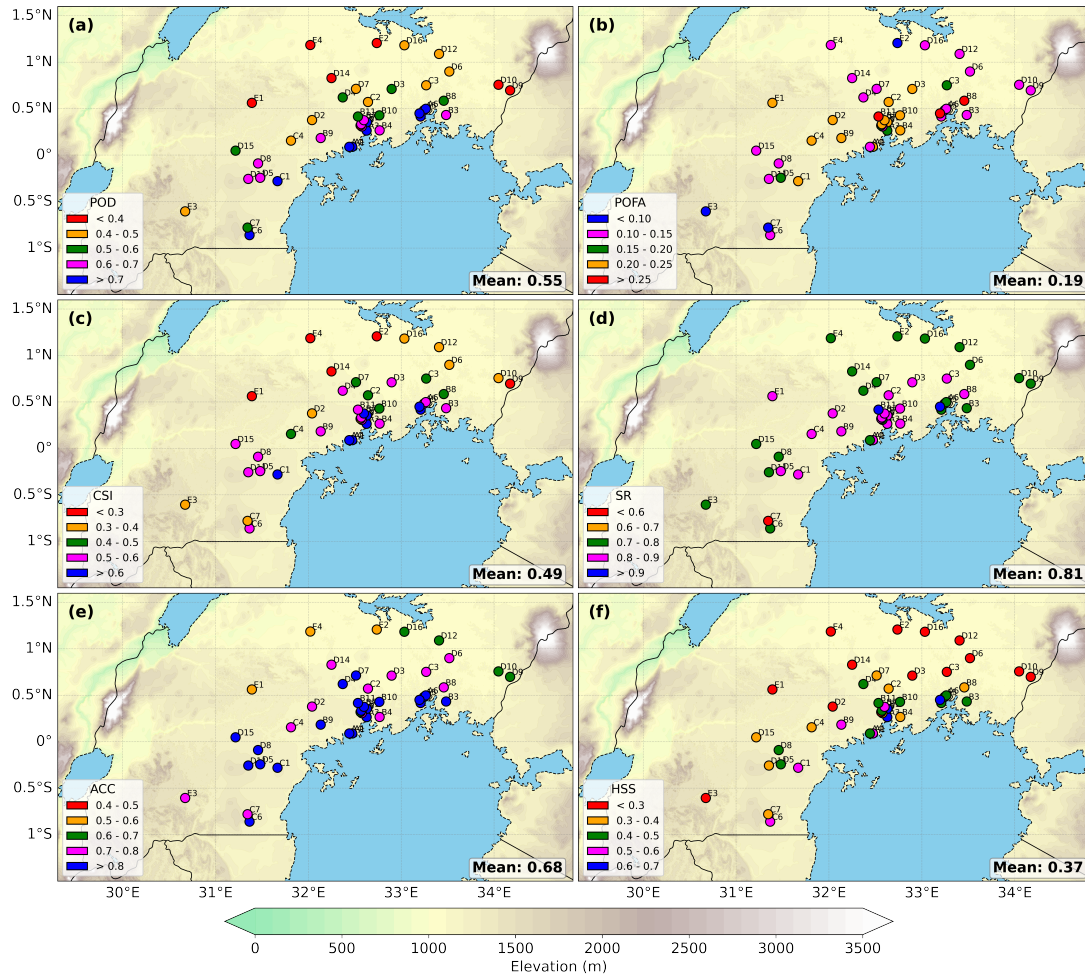


Figure 4.9: Spatial distribution of (a) POD, (b) POFA, (c) CSI, (d) SR, (e) Accuracy (ACC), and (f) HSS for the algorithm's performance at different stations in the study area. The mean value for each metric is indicated in the bottom right corner of each subpanel. The background shading shows the elevation from GLOBE (Hastings and Coauthors, 1999). Adapted from Ssemujju et al. (2026a). © American Meteorological Society. Reproduced with permission.

Table 4.3: Total number of lake-breeze (LB) days detected in December - February and June-August (DJF-JJA), Western coast (W), and Northern coast (N)

Year	Number of days (DJF-JJA)	Detected LB days	LB days (W)	LB days (N)
2017	182	72	53	72
2018	182	58	48	54
2019	182	83	63	77
2020	183	99	82	85
2021	182	111	93	98
2022	182	101	89	90
Total	1093	524	428	476

4.3.4 Application of Algorithm

After evaluating the algorithm's performance, it was applied to extract several LB features as discussed in the following subsections.

4.3.4.1 Observed lake-breeze frequency and variability

(a) Overall observed frequency

Using results from the algorithm, a day is considered as an LB day in this study if OLBDA detects LBF passage in at least three arbitrary coastal stations on that day. Based on this definition, a total of 524 LB days were identified out of 1093 days in DJF and JJA considered (Table 4.3), representing 48% (i.e., one LB event every 2.1 days). Of these LBs, 428 (81.7%) were detected on the western sector and 476 (90.8%) on the northern sector of LV. The variation in frequency is partly due to the availability and location of coastal stations used on either side of the lake. For instance, the closest station to the coast on the western side is 27 km away, while on the northern side it is only 0.2 km (see Figure 4.1, Table A.1). Consequently, the observed LB frequency on the western side is likely underestimated, as weaker LBs that cannot penetrate far enough inland go undetected. Table 4.3 also reveals that the number of LB days per year is not evenly distributed, with 2021 (2018) having the most (least) LB days of 111 (58), respectively, out of the 182 available days. This indicates inter-annual variability in the frequency of LB occurrence.

Figure 4.10 shows the spatial distribution of LB days during the dry months (December-February and June-August) throughout the entire study period. During daylight hours (0900-1900 LT), LBF passages are observed at most stations on 12%-54% of the days (Figure 4.10; Table A.2). Furthermore, Figure 4.10 and Table A.2 reveal substantial spatio-temporal variability in the frequency of LB days across the entire study region. For instance, the proportion of detected LB days varies by sector: 4%-54% in the northern (N), 3%-33% in the northwestern (NW), and 10%-44% in the western (W)

sectors. Like seen in section 4c, station proximity to the coastline plays a significant role, with coastal stations consistently recording higher LB day frequencies ([Figure 4.10](#)). As explained previously, not all LBFs propagate deeply inland. This results in fewer detections inland as most LBFs dissipate before reaching inland stations. Consequently, the misses are potentially overestimated at these stations.

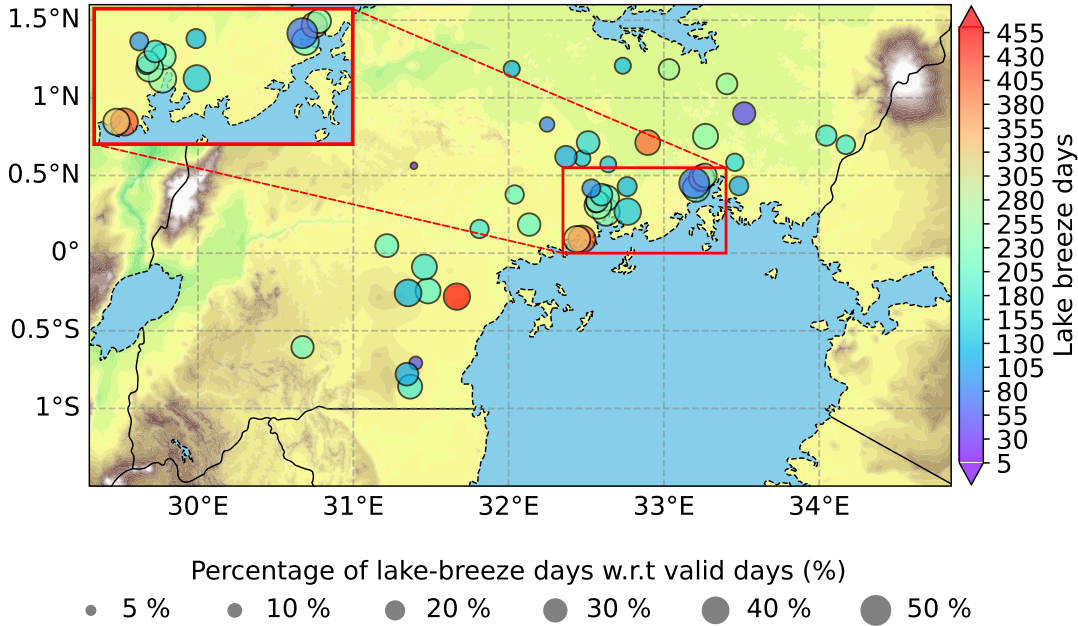


Figure 4.10: Spatial distribution of lake-breeze days at each station (see [Figure 4.1](#)) for the period 2017-2022 during the dry months of DJF and JJA. The colour represents the number of lake-breeze days recorded at each station while the size of the circle represents the percentage of lake-breeze days relative to the total number of valid days at that station. Adapted from [Ssemujju et al. \(2026a\)](#). © American Meteorological Society. Reproduced with permission.

A case of A1 (Entebbe WDD) and C1 (Kamenyamigo) stations

[Figure 4.11](#) demonstrates distinct differences in the frequency and diurnal timing of LB occurrences at two stations close to the coast with the most complete dataset (2017-2022): Entebbe WDD (A1, N) and Kamenyamigo (C1, W). As expected, A1, located just 0.2 km from the coast, experiences lake-breeze conditions earlier in the day than C1, which lies farther inland ([Figure 4.11a](#)). Typically, LBFs arrive between 0900 and 1900LT, peaking at 1200 LT for A1 and 1500LT for C1, indicating a systematic shift with increasing distance from the coastline. This pattern underscores the strong influence of coastal proximity on LBF timing, consistent with findings by [Odongo et al. \(2022\)](#), who used ERA-5 data to study lake-breezes at these stations.

[Figure 4.11b](#) reveals that LB occurrences peak in January and August and are lowest in June at both stations. The highest LB occurrences in January and August can be attributed to being the hottest months of the year in the area, whereas the lowest

occurrences in June are partly due to the transition from the long March-May rain season. Comparing the two dry seasons, DJF records more LBs than JJA, with A1 and C1 registering 226 and 255 events in DJF, against 188 and 197 in JJA, respectively. This is supported by an auxiliary temperature analysis (not shown), which shows slightly higher temperature gradients in DJF than JJA on average.

Frequency of lake-breezes at any given station also vary interannually. [Table 4.4](#) and [Figure 4.11c](#) demonstrate the variability for A1 and C1 stations. At these stations, lake-breezes were detected on 35%-52% and 26%-59% of dry season days depending on the year for A1 and C1, respectively ([Table 4.4](#)). The annual LBF frequency at these stations shows a year-to-year variability, typical of what is seen across the study region. These results corroborate with findings in the previous subsection.

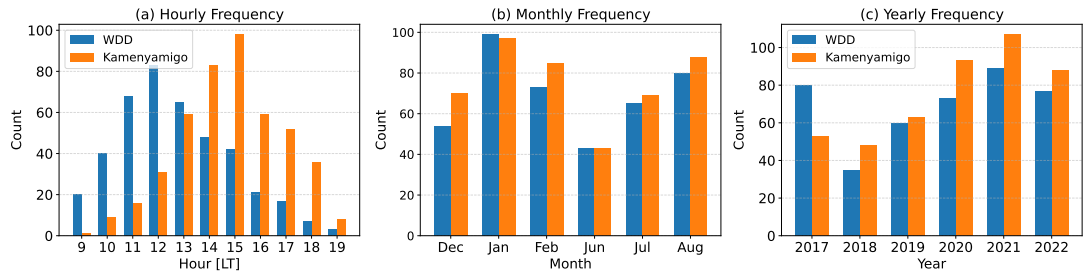


Figure 4.11: Bar graphs showing the occurrence of lake-breeze events detected using the algorithm at Entebbe WDD (A1, N) and Kamenyamigo (C1, W) stations during the dry seasons (DJF and JJA) between 2017 and 2022 in terms of number of detected events by: (a) hour, (b) month, and (c) year. These stations are the closest to the coastline in each sector, with the most complete dataset during the period 2017-2022. Adapted from [Ssemujju et al. \(2026a\)](#). © American Meteorological Society. Reproduced with permission.

Table 4.4: Lake-breeze front (LBF) occurrences at Entebbe WDD (A1, N) and Kamenyamigo (C1, W) stations showing interannual variability. Taken from [Ssemujju et al. \(2026a\)](#). © American Meteorological Society. Used with permission.

Year	Entebbe WDD (A1)			Kamenyamigo (C1)		
	DJF–JJA	LB	LB days	DJF–JJA	LB	LB days
	valid days	days	percentage (%)	valid days	days	percentage (%)
2017	170	80	47.1	182	53	29.1
2018	84	35	41.7	182	48	26.4
2019	172	60	34.9	182	63	34.6
2020	172	73	42.4	183	93	50.8
2021	172	89	51.7	182	107	58.8
2022	173	77	44.5	182	88	48.4

4.3.4.2 Observed lake-breeze characteristics

(a) Mean observed conditions before and after LBF passage

To illustrate the spatial variation in the atmospheric conditions introduced as the LBF propagates through different directions, the changes in the observed meteorological variables 3-hours before and after the detected LBF passage are averaged and aligned with respect to the frontal passage as presented in [Figure 4.12](#). On average, the mean air temperature sharply drops by over 0.75°C in response to the passing of the front and continues to decrease steadily for the next 3-hours on all sides of the lake after the LBF passage ([Figure 4.12a](#)). This is probably due to the late arrival of the front mostly in late afternoon coinciding with a decrease in incoming solar radiation as suggested by [Hughes and Veron \(2018\)](#). Also, the small temperature change is most likely related to the weak temperature gradient between the lake and the land. Notably, the temperature drop remains consistent in western and northwestern sectors even after the front passage. The mean dew point shows a similar trend across all sectors, increasing by over 0.7°C ahead of the frontal passage and continues to increase briefly after the passage, peaking within 15 minutes ([Figure 4.12b](#)). Thereafter, the dewpoint starts to drop slightly in all sectors. The northern sector shows the greatest increase ($\sim 0.9^{\circ}\text{C}$), while the western sector records the lowest (0.7°C), indicating a westward reduction in moisture influx during the LBF passage. The slight drop in dewpoint after the peak may be attributed to the mixing of incoming cooler marine air with warmer air over land within the convective internal boundary layer.

On the other hand, the mean relative humidity exhibits a reverse pattern to that of mean temperature, increasing by over 5% ahead of the LBF passage and even after the frontal passage for all sectors ([Figure 4.12c](#)). Like for dewpoint, the greatest increase in relative humidity is experienced on the northern sector while the lowest increase occurs on western side of the lake. Lastly, the winds weaken after the frontal passage in all directions except for the northern sector where they remain steady for 15-minutes before decreasing ([Figure 4.12d](#)). However, during the frontal passage, wind speed increases sharply in all sectors with a rise of over 0.6 m s^{-1} within 15 minutes, with western (northwestern) sector showing the greatest (least) increase of 0.85 (0.65) m s^{-1} .

(b) LBF arrival times

To assess the influence of coastal proximity on LBF arrival time characteristics, stations were clustered into five groups based on their relative distance from the coastline and their coastal sector (see [Fig. Figure 4.1](#)). [Figure 4.13](#) presents the spatio-temporal LBF characteristics across these groups. Lake-breeze conditions occur earlier in the day, starting at 0900 LT for stations within 40 km across all sectors ([Figure 4.13a-c](#)). The median LBF arrival time for stations within 7 km from coast coincides with the peak arrival time of 1400 LT ([Figure 4.13a](#)). For stations 7-20 km inland, both median and

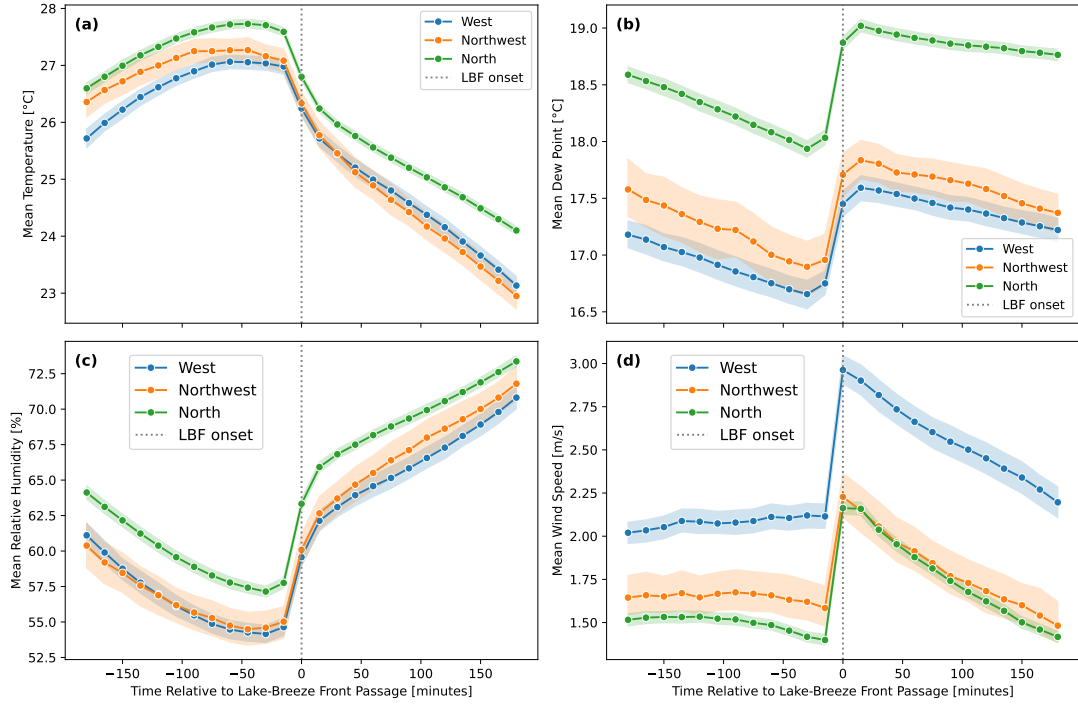


Figure 4.12: Mean observed atmospheric conditions before and after lake-breeze frontal (LBF) passage on the western (W: Blue), northwestern (NW: Orange), and northern (N: Green) sides of the lake, for (a) mean temperature; (b) mean dew point; (c) mean relative humidity; and (d) mean wind speed. The vertical dotted gray line indicates the first timestep that fulfilled the LBF criteria, t_0 . The shading indicates 95% confidence interval. Adapted from [Ssemujju et al. \(2026a\)](#). © American Meteorological Society. Reproduced with permission.

peak arrival times shift to 1500 LT in all sectors ([Figure 4.13b](#)). This timing remains consistent for the 21-40 km group, except in the NW sector where the peak shifts to 1600 LT ([Figure 4.13c](#)). In the 41-80 km range ([Figure 4.13d](#)), the median arrival time is 1500 LT in W and NW sectors, and 1600 LT for N, indicating a clockwise delay pattern. However, the peak arrival time in this group is 1600 LT across all sectors.

For stations beyond 80 km, both the median and peak arrival times are further delayed to 1600 LT in the N and NW sectors, and 1700 LT in the W ([Figure 4.13e](#)). This marks a drastic 2 hr delay in median arrival time between the 41-80 km and >80 km groups in the W sector, with the peak also delayed by 1 hr. Notably, no LBFs are detected before 1100 LT in any sector for stations beyond 40 km. Overall, LBFs occur from early afternoon to evening in all sectors, peaking between 1400-1500 LT within 40 km of the coast, and between 1600-1700 LT beyond 80 km. These findings align with those of [Datta \(1981\)](#), who observed maximum LBF strength at 1500 LT using coastal station observations. Furthermore, these results support the strong influence of coastal proximity on LBF timing.

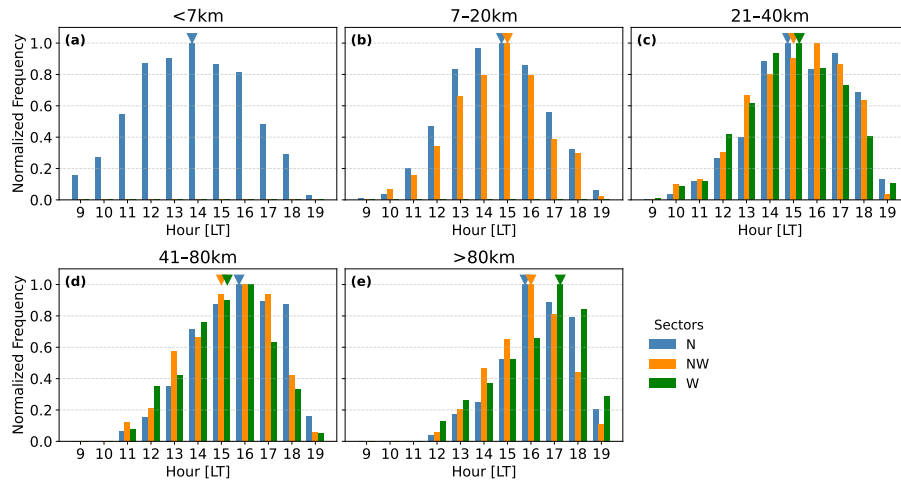


Figure 4.13: Bargraphs showing the arrival time of lake-breeze fronts (LBF) initially detected at different station classes from the coast: (a) A (<7km), (b) B (7-20 km), (c) C (21-40 km), (d) D (41-80km), and (e) E (>80km) in the three different coastal sectors; Northern (N: Blue); Northwestern (NW: Orange); and Western (W: Green). The triangle marker on top of the bars indicated the median arrival time. Note: The hour bin plotted here contains all LBF passages in that hour (e.g., 10 LT contains all passages between 1000 and 1059 LT). Adapted from [Ssemujju et al. \(2026a\)](#). © American Meteorological Society. Reproduced with permission.

(c) LBF propagation characteristics and climatology

To assess LBF propagation and develop its climatology over the northern and western shores of LV, station data along seven transects (T1-T7) in three coastal sectors were analyzed. Isochrones of mean LBF arrival times ([Figure 4.14](#)) interpolated using cubic polynomial method were used to visualize spatio-temporal inland propagation of the front, with wider spacing indicating faster movement and closer spacing reflecting slower progression. Propagation speed along each transect was estimated using time differences between LBF arrivals at successive stations, representing a relative forward propagation speed. In estimating propagation speed, we explicitly assumed that the LBF travels along a straight-line path between station pairs, consistent with previous station-based tracking methods (e.g. [Hughes and Veron, 2018](#)). For each successive station pair, the propagation speed was calculated from the inter-station distance and the difference in detected arrival times. When multiple station pairs were available, the transect-scale propagation speed was computed from the total distance and travel time. Although this approach provides a practical estimate of LBF propagation, the resulting speeds should be interpreted in light of inherent uncertainties due to the straight-line assumption, interstation spacing, and the potential curvature or spatial heterogeneity of the front.

The analysis presented in [Figure 4.14](#) reveals that coastal stations typically experience LBFs between 1300 and 1400 LT, while far inland stations such as E4 (~132 km from

the shoreline) record arrivals between 1700 and 1730 LT. Most stations (75%) register mean arrival times between 1400 and 1600 LT, with cessation occurring around 1730 LT. The relatively late onset at coastal stations suggests a weak initial thermal contrast between lake and land, which intensifies in the afternoon after substantial solar heating. These patterns indicate steady inland propagation of the front with the timing and inland extent being controlled by regional climatology and modified by local topography, consistent with previous findings of Woodhams et al. (2019). The maximum inland extent of ~ 132 km confirms the findings of Woodhams et al. (2019), who reported propagation up to ~ 240 km during the dry season.

LBF propagation speeds vary by sector: in the western sector, speeds along transects T1 and T2 averaged ~ 8 m s $^{-1}$ northwestward; in the northwestern sector, speeds range from 5.2 m s $^{-1}$ to 7.6 m s $^{-1}$ for transects T3 and T4, averaging 6.5 m s $^{-1}$; and in the northern sector, frontal speeds along T5, T6, and T7 average 5.8 m s $^{-1}$ northward. These propagation speeds are consistent with Woodhams et al. (2019) and indicate that LBFs propagate fastest westward and slowest northward of the lake. This directional variation suggests a clockwise decrease in inland speed from west to east, likely driven by alignment with prevailing easterly winds (Figure B.1), as supported by Baker et al. (2001). Additionally, although not shown here, LBFs tend to move slowly within the first few kilometers from the shoreline before accelerating further inland. This is likely due to increased land friction and urban effects from coastal cities as observed by other studies (e.g. Thompson et al., 2007).

4.4 Discussion and conclusions

Using an unprecedented dense network of AWS, we developed and tested a novel observation-based lake-land breeze detection algorithm (OLBDA) and inferred climatological LLB characteristics for 2017-2022. The OLBDA analyses 15-minute temperature, wind speed and direction, and precipitation to objectively identify and detect LBF passages over a range of stations across LVB. It employs three sequential detection criteria: (i) wind-based criterion (wind shift and speed increase); (ii) temperature-based criterion (air temperature drop and dewpoint increase); and (iii) dry-condition criterion that filters out cold-pool passages. Detection is based on station-specific percentile thresholds, defined using the lowest (highest) 30% of temperature (dewpoint and wind speed) decreases (increases), to ensure sensitivity to the subtle signals typical of LBFs in this region. A day is classified as an LB day based on the first daytime LBF passage at a station. Verification against manually identified satellite-based LB and non-LB days shows that OLBDA reliably captures LBF events, especially at coastal stations, demonstrating high detection probability, low false-alarm rates, and good overall accuracy. These results confirm that the algorithm effectively detects the small temperature, humidity, and wind speed changes associated with LBFs over LVB.

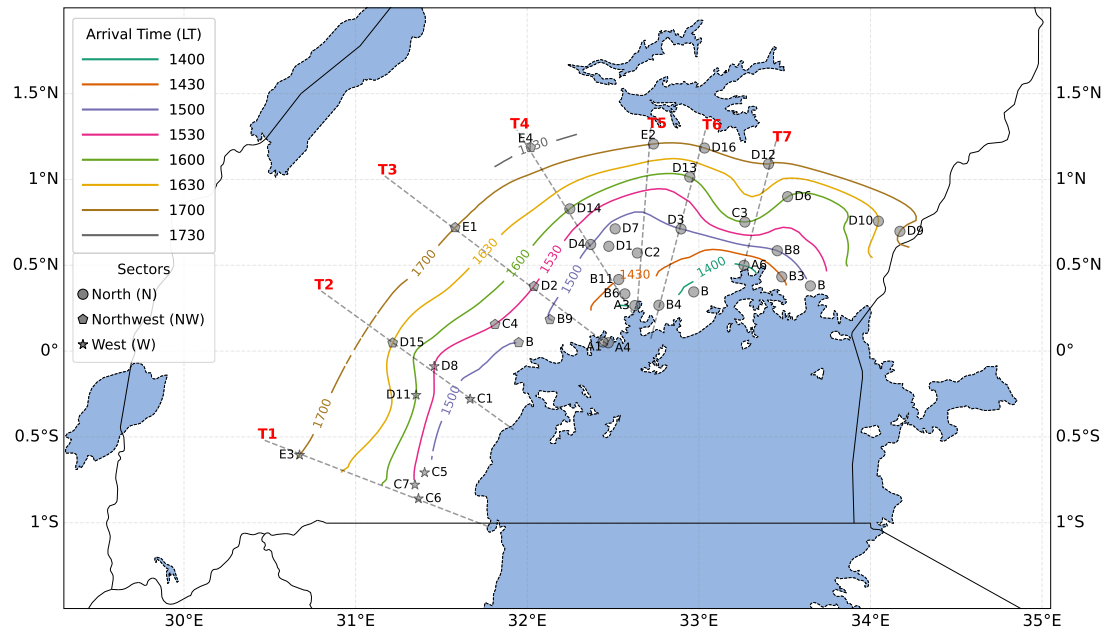


Figure 4.14: Spatio-temporal evolution of the LBF being shown by the 30-minute isochrones of LBF mean arrival times across stations along the northern and western parts of Lake Victoria. The dashed gray lines labelled in red bold-face (T1-T7) represent transects in different sectors of the lake. Adapted from [Ssemujju et al. \(2026a\)](#). © American Meteorological Society. Reproduced with permission.

Applying the OLBDA to all the 45 stations in the study area, and analysing all detected lake-breeze days to determine the LBF characteristics over the northern edge of Lake Victoria in Uganda revealed the following key results:

1. Nearly half (48%) of all DJF and JJA days during 2017-2022 featured an LB event (524 of 1093 days), implying one LB event about every two days.
2. LBF passages occur on 12%-54% of dry-season days (DJF and JJA) between 0900 and 1900 LT across most stations, with slightly more frequencies in DJF season due to slightly higher temperature gradients. The LB occurrences also exhibit interannual variability in frequency.
3. Station proximity to the LV shoreline significantly influences LBF frequency, with coastal stations consistently recording more events than inland stations. This is partly because LBFs may dissipate before reaching distant stations, leading to potential underestimation. Additionally, some LBFs may pass through inland stations undetected by the algorithm as noted by [Hughes and Veron \(2018\)](#), especially when they move slowly and warm over land, thereby failing to meet the algorithm's temperature criteria. Besides proximity, LBF frequency also

varies by coastal sector, reflecting localized influences on breeze development and propagation.

4. Most LBFs occur from early afternoon at coastal stations to late evening at the furthest stations. The relatively late onset at coastal stations suggests a weak thermal contrast between the lake and surrounding land. Peak arrival times range between 1200 and 1300 LT for coastal stations, shifting with increasing distance inland, and averaging between 1400-1500 LT across most stations. Dissipation typically occurs around 1730 LT at the furthest stations. These timing patterns align with the findings of [Datta \(1981\)](#) over the region, confirming that proximity to the coastline strongly influences LBF timing.
5. LBFs propagate fastest westward of LV at 8 m s^{-1} and slowest northward at an average speed of 5.7 m s^{-1} , indicating a directional variation in inland movement. This variation, which decreases progressively in a clockwise direction from west to east, highlights the influence of the prevailing easterly background flow on frontal speed. Similar patterns have been observed elsewhere (e.g. [Baker et al., 2001](#)), where LBs propagate inland faster when synoptic winds align with the low-level breeze flow.

Despite these directional differences in speed, LBFs can penetrate up to $\sim 132 \text{ km}$ inland in all directions, consistent with findings of [Woodhams et al. \(2019\)](#).

6. The LB exhibits weak frontal properties, with mean temperature drops of 0.75° - 0.80°C , dewpoint increases of 0.7° - 0.85°C , relative humidity increases of 5%-8%, and wind speed increases of 0.65 - 0.85 m s^{-1} , depending on the direction of propagation.

The development of the OLBDA presented in this article represents a significant advancement in the analysis of LBFs and other local meteorological phenomena over the LVB, with potential applications in disaster response and recovery. Unlike region-specific developed algorithms (e.g. [Hughes and Veron, 2018](#); [Ferdiansyah et al., 2020](#); [Viner et al., 2021](#)), OLBDA uses percentile-based thresholds in its detection criteria, making it adaptable across regions. Additionally, the algorithm can be applied to various gridded datasets with minor tuning. However, like other algorithms, its sensitivity to wind direction signals may lead to its underperformance in capturing the total LBF occurrences at some stations. In addition, the use of 2-m wind measurements from the AWSs instead of the standard 10-m height, introduces uncertainty in the wind-based criterion and may significantly affect the number of LBF passages detected. A further limitation arises from exclusion of cold pool passages by relying solely on precipitation at a station, which is not optimal since rainfall may have occurred away from the station.

When verifying the skill of OLBDA, it is important to clarify what we defined as ‘truth’ in this study. We defined ‘truth’ as LB and non-LB days identified visually from

satellite imagery as described in Section 3a. Because the satellite-based reference dataset relied on only a limited number of daily overpasses, this temporal sampling limitation may have affected the representativeness of both the LB and non-LB classifications. Since only a few overpasses were available, with at most three overpasses a day, LB events that occurred outside these times may have been missed, leading to some true LB days to be categorized as non-LB days, and thereby inflating the number of false alarms. This means that we would expect even a much better performance of the OLBDA. Additionally, because days with either clear skies or extensive cloud cover were classified as non-LB days in this study, the number of false alarms is most likely further overestimated. Nevertheless, it was the only feasible option available for constructing a reference dataset. We therefore consider the verification of OLBDA using visually identified LB days to be reasonable, though not perfect, and this limitation should be kept in mind when interpreting the algorithm’s performance.

Our analysis provides refined insights into LBF behaviour over LV and reinforces earlier findings. The observed peak arrival times of 1200-1300 LT at coastal stations and 1500-1600 LT inland, reflect the weak lake-land temperature gradient, a well-known peculiarity of the LLB system in this region. These timings are broadly consistent with previous studies reporting predominantly afternoon lake breezes (e.g. [Flohn and Fraedrich, 1966](#); [Datta, 1981](#); [Woodhams et al., 2019](#); [Van de Walle et al., 2020](#); [Odongo et al., 2022](#)). The observed LBF penetration of up to ~ 132 km inland at speeds of $5.7\text{--}8.0\text{ m s}^{-1}$ also agrees with simulation results of [Woodhams et al. \(2019\)](#). Overall, the weak thermal contrast explains the generally weak frontal properties and modest temperature drops ($\sim 0.75^\circ\text{C}$), underscoring the complexity of identifying LBs in this region and the tropics compared to mid-latitudes, where drops often exceed 3°C .

Although this study does not focus exclusively on precipitation-producing events, LBFs are fundamental components of the mesoscale circulation system over Lake Victoria, shaping boundary-layer structure, local wind regimes, humidity gradients, and the thermodynamic environment that can favour convective initiation, even on non-precipitating days. Their objective identification therefore contributes to a more comprehensive understanding of regional mesoscale dynamics and offers a physically grounded benchmark for evaluating numerical weather prediction and climate models. In addition, because LBFs modulate conditions relevant to air quality, heat stress, and the preconditioning of the atmosphere for subsequent convection, their detection provides broader utility beyond rainfall-focused applications.

5. Representation of the 3-D lake-land breeze circulation of Lake Victoria in ECMWF IFS operational analyses

In this chapter, an analysis of how the ECMWF IFS operational system represents the LLB circulation over Lake Victoria is presented. As in the previous chapter, the datasets and methods are briefly introduced in the first section. [Section 5.2](#) presents results on the assessment of the skill of OLBDA relative to IFS, as well as the capability of IFS to represent the LLB. This analysis also includes the identification of the most suitable IFS variables that can serve as proxies for delineating the LBF over the LVB. In addition, [Section 5.2](#) examines the representation of the three-dimensional vertical structure of the LBF across the northern shores of Lake Victoria. Finally, [Section 5.3](#) provides the discussion and conclusions.

5.1 Data and Methods

5.1.1 Data

This study uses hourly output from the ECMWF IFS Cycles 43-47 operational forecast dataset (ECMWF, 2017, 2019, 2020, 2022). The data are provided at 9 km horizontal resolution and are available at the surface and across 137 model levels, enabling a consistent analysis of surface and boundary-layer processes relevant to lake-breeze dynamics. The analysis is conducted over the northern shores of Lake Victoria, Uganda, during the dry seasons of DJF and JJA over the period 2017-2022, consistent with [Chapter 4](#).

We utilize surface variables including 2-m temperature, 2-m dewpoint temperature, 10-m wind components, surface pressure, as well as boundary-layer height. Specific humidity is computed from 2-m dewpoint temperature and surface pressure using the MetPy Python package ([May et al., 2020](#), v1.7). Additionally, hourly vertical velocity, temperature, and horizontal wind components are extracted for the lowest 38 model levels, extending to ~ 5 km above ground level (AGL).

For validation of LBFs detected in IFS analyses, we use hourly surface observations obtained from a network of 45 automatic weather stations (AWSs; [Figure 5.1](#)) operated by the Trans-African Hydrometeorological Observatory (TAHMO; [Van de Giesen et al., 2014](#)) and the Uganda Department of Meteorological Services (UDMS). In addition, satellite visible imagery from NASA’s Earth Observing System Data and Information System (EOSDIS) Worldview platform is used. Here, lake-breeze and non-lake-breeze days identified from satellite visible imagery serve as the reference dataset for validating IFS-detected lake-breeze days, following the methodology in [Chapter 4](#).

5.1.2 Methods

5.1.2.1 LBF Identification using OLBDA

LBF passages are objectively identified using the OLBDA, which detects characteristic thermodynamic and kinematic signatures of the lake breeze at individual stations or grid points within the study domain. The algorithm is applied to hourly grid point values of wind and temperature between 09:00 and 19:00 LT (daylight hours) to determine frontal location and occurrence. The OLBDA algorithm identifies LBF passage by applying thresholds based on the lowest 30% of temperature drops and the highest 30% of dewpoint and wind speed increases, enabling detection of subtle meteorological changes associated with LBF passages. For full methodological details on OLBDA, the reader is referred to [Section 4.2.2](#).

5.1.2.2 Definition of a Lake-Breeze Day and Performance of OLBDA

Following [Chapter 4](#), and accounting for the limited number of coastal AWSs, a lake-breeze (LB) day in the station dataset is defined as a day on which the OLBDA detects LBF passage in at least three coastal stations. I apply a similar approach to IFS by treating the nearest IFS grid points as stations and then checking whether at least three of these pseudo-coastal stations recorded a passage. This ensures a consistent and fair comparison of LB day detection between the AWS and IFS datasets. The performance of the OLBDA is then evaluated using the same methodology and reference dataset of the manually identified satellite LB and non-LB days as in [Chapter 4](#).

5.1.2.3 Identifying LBFs Using Proxy Fields in IFS

Global reanalysis and forecast systems such as the IFS provide spatially continuous, three-dimensional fields of winds, moisture, and boundary-layer structure beyond the capabilities of surface stations. If the OLBDA framework can robustly identify LBFs from gridded IFS output using near-surface wind, temperature, and dewpoint, then the full model state can be exploited to evaluate additional physically motivated diagnostics of LBF activity. To assess the suitability of such diagnostics, I evaluate three commonly used proxies between 09:00 and 19:00 LT: the horizontal gradient of boundary-layer

height (∇BLH ; Antonelli and Rotunno, 2007; Kalthoff et al., 2020), low-level horizontal wind convergence ($-\nabla \cdot \mathbf{U}$; Miller et al., 2003; Drobinski et al., 2006; Crosman and Horel, 2010; Brown et al., 2026), and the horizontal gradient of specific humidity ($\nabla_h q$; Borne et al., 1998; Laird et al., 2001; Zhu and Atkinson, 2004; Brown et al., 2026). Together, these diagnostics leverage the spatial and vertical structure of IFS fields to assess whether the model captures robust mesoscale signatures of LBFs. The diagnostics are defined and computed as shown below.

(a) Gradient of Boundary Layer Height (∇BLH)

The gradient magnitude is defined in accordance with Equation (5.1) below:

$$|\nabla BLH| = \sqrt{\left(\frac{\partial BLH}{\partial x}\right)^2 + \left(\frac{\partial BLH}{\partial y}\right)^2} \quad (5.1)$$

Here the frontal zones correspond to sharp discontinuities in BLH. It is a proxy for boundary-layer transitions induced by lake-cooled air.

(b) Horizontal Wind Convergence ($\nabla \cdot \mathbf{U}$)

Horizontal wind convergence is defined according to Equation (5.2) below:

$$\nabla \cdot \mathbf{U} = \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) < 0 \quad (5.2)$$

The front is often characterized by surface divergence over the water and convergence at the front over land. Hence, here convergence indicates mesoscale frontal lifting, i.e., strong negative values indicate boundary-layer convergence typical of LBF lifting zones.

(c) Horizontal Gradient of Specific Humidity ($\nabla_h q$)

Moisture gradients often mark maritime-continental air-mass contrasts. It highlights moisture contrasts arising from shallow lake-modified air masses. the horizontal gradient of moisture, in this case specific humidity is calculated according to Equation (5.3) below:

$$|\nabla_h q| = \sqrt{\left(\frac{\partial q}{\partial x}\right)^2 + \left(\frac{\partial q}{\partial y}\right)^2} \quad (5.3)$$

Therefore, a diagnostic combining the spatial gradient of moisture and the horizontal divergence of the wind field is a robust identifier for LBFs, even in lower-resolution models.

5.2 Results and Discussion

5.2.1 LBF Occurrence Frequency

Using the LB day definition in Section 2.3, the OLBDA identifies 526 and 417 LB days in the IFS and AWS datasets, respectively, out of 1,093 DJF and JJA days, corresponding to 48% and 38% (Table 5.1; Figure 5.1). Of these, 400 are common to both datasets, representing 76% of IFS-detected and 96% of AWS-detected LB days. When applied to IFS, the OLBDA achieves a probability of detection (POD) of 0.71 and a false-alarm ratio (FAR) of 0.25, comparable to the AWS POD (0.74) and FAR (0.20), indicating robust performance of the algorithm across model and observational data. In IFS, LB days are nearly evenly distributed between the western and northern sectors, whereas AWS observations show higher frequency in the northern sector. Interannual variability is consistent across datasets, with 2021 (2018) recording the highest (lowest) LB days (Table 5.1).

Spatially, both datasets exhibit a coherent gradient, with highest LBF occurrences along the Lake Victoria shoreline and progressively decreasing inland (Figure 5.1a). This pattern is consistent with the expected spatial footprint of LBFs, frequent near the lake where the circulation forms, and diminishing inland as the temperature-driven pressure gradient weakens.

The IFS reproduces this large-scale pattern but exhibits a systematic positive bias in LBF frequency. Across all stations, 30 of 45 ($\sim 67\%$) show higher LBF frequencies in the IFS than in the AWS, suggesting that the model overestimates LBF occurrence. This positive bias is typically $\sim 5\%$ and spatially consistent, with 10 of 15 ($\sim 67\%$) stations in the western and 20 of 30 ($\sim 67\%$) in the northern sector. The overestimation is most pronounced within ~ 20 km of the shoreline, where occurrence frequencies reach $\sim 50\%$ in both datasets, but decline more slowly inland in the IFS than in the AWSs. On average, LBF frequency in IFS decreases by $\sim 4\%$ every 20 km inland, compared to a steeper decline of $\sim 6\%$ in AWS data.

The positive bias in occurrence frequency in IFS extends even to the most distant stations, with 4 of 7 showing higher LBF frequencies than in AWS. This suggests that the LBF in the IFS model propagates farther and more frequently inland than observed. This behavior may reflect an excessively smooth or overly persistent representation of the lake-land temperature contrast in the IFS, which can effectively strengthen or sustain the thermal gradient that drives LBF initiation and inland penetration. It may also stem from unresolved sub-grid processes such as shoreline roughness transitions, small-scale topographic variations, local land-use heterogeneity, or shallow boundary-layer mixing that in reality inhibit inland penetration of the breeze. However, along portions of the northern coast, the IFS closely matches observed coastal frequencies and reproduces

the inland decline to $\sim 20\%$ within ~ 40 km. Overall, the IFS captures the regional-scale spatial gradient of LBF occurrence but systematically overestimates event frequency.

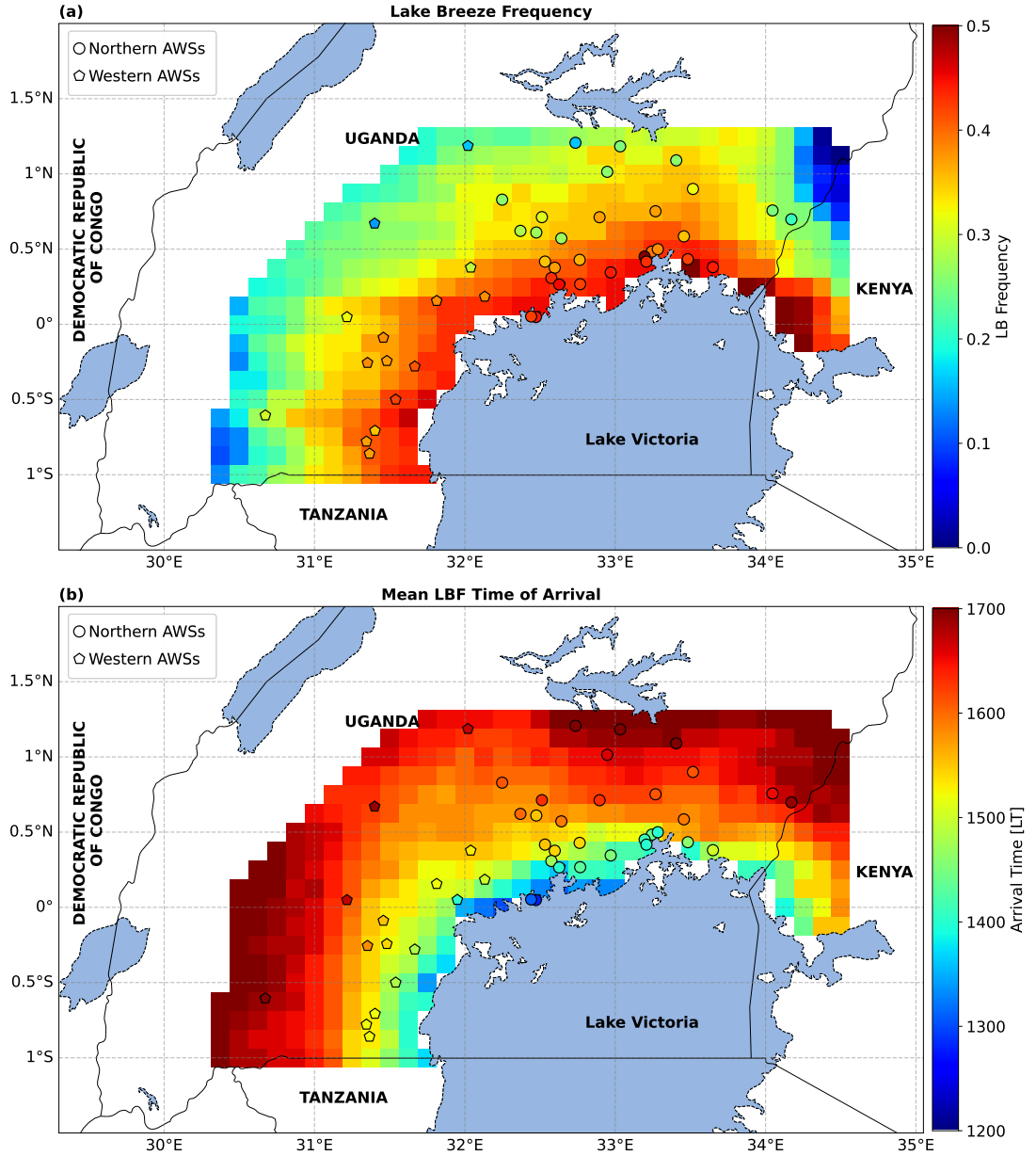


Figure 5.1: A comparison of IFS (grids) and AWSs (scatters) regarding (a) lake-breeze frequency and (b) mean time of arrival (LT) for the dry months of DJF and JJA during 2017-2022. The colored pixels show the study region. Northern and western AWSs are denoted by circle and pentagon markers, respectively. Taken from [Ssemujju et al. \(2026b\)](#). © 2026 The Author(s), John Wiley & Sons Ltd. Used with permission.

5.2.2 Mean Time of LBF Arrival

Figure 5.1b presents the mean LBF arrival time from AWSs and IFS grid points. The mean arrival times show a clear and coherent inland progression, with earlier arrivals

Table 5.1: Summary of lake-breeze days (LBDs) statistics, including total number of LBDs detected in December-February and June-August (DJF-JJA) during 2017-2022 for IFS (collocated grid points) and AWS (values in parenthesis). W and N represent western and northern sectors of the lake, respectively.

Year	Number of days (DJF-JJA)	Detected LB days	LB days (W)	LB days (N)
2017	182	89 (70)	69 (50)	70 (62)
2018	182	68 (52)	66 (42)	55 (41)
2019	182	75 (59)	71 (55)	62 (56)
2020	183	86 (72)	80 (72)	70 (70)
2021	182	112 (84)	84 (84)	105 (88)
2022	182	96 (80)	83 (75)	92 (75)
Total	1093	526 (417)	453 (378)	454 (392)

(12:00-14:00 LT) near the lakeshore and later arrivals (16:00-17:00 LT) farther inland, consistent with the expected daytime propagation of the LBF seen in previous work (e.g., Anyah and Semazzi, 2006; Chamberlain et al., 2014; Woodhams et al., 2019; Ssemujju et al., 2026a). Both datasets capture this distance-dependent delay, indicating realistic representation of inland progression.

The IFS, however, exhibits a systematic early-arrival bias. Across the network, 27 of 45 stations (~60%) record LBF arrivals at least 1 hour earlier than observed. Of the remaining stations, 11 (~24%) show delayed arrivals, while the rest agree closely. The bias is strongest in the western sector, where 12 of 15 stations (80%) record earlier arrival, compared to 15 of 30 (50%) in the northern sector. On average, the model leads observations by ~1 hour, with local leads of 1-2 hours depending on the station.

Despite this bias, spatial patterns are consistent across datasets. In the IFS, LBFs typically arrive first along the northern coast (~12:00 LT) and then along the western coast (~13:00 LT), slightly earlier than observed but following the same sequence. The reasons for the earlier onset and the faster and deeper inland propagation of the LBF remain elusive, but are likely related to the representation of boundary layer and land-surface processes in the IFS model.

5.2.3 Performance of diagnostic proxy variables from IFS: Case study of 26 January 2022

To evaluate the proxy variables described in Section 2.4, we examine a representative lake-breeze case on 26 January 2022. This day was consistently identified as a LB day by satellite imagery and the OLBDA across most AWS stations and IFS grid points, with clearly defined frontal progression. Figure 5.2 compares the diurnal evolution of the LBF inferred from these proxies with OLBDA- and satellite-inferred frontal positions at 12, 15, and 18 LT. All three LBF metrics exhibit coherent inland propagation. At

12 LT, a clear signal delineating the shoreline appears in all three fields, indicating the initial development of a lake-driven circulation (Figure 5.2a,d,g). By 15 LT, this signal intensifies and extends inland, consistent with the daytime progression of a developing lake-breeze system (Figure 5.2b,e,h), while by 18 LT (Figure 5.2c,f,i) the signal becomes more diffuse and further displaced inland.

However, among the three diagnostics, ∇BLH provides the most continuous and well-defined frontal signature throughout the day (Figure 5.2a-c). At 12 LT, strong land-lake contrasts in boundary-layer depth produce a pronounced ∇BLH signal that becomes more organized by 15 LT and remains identifiable, though weaker, by 18 LT. The resulting narrow and spatially coherent band allows the front to be tracked from initiation through inland propagation. The $\nabla_h q$ also delineates the LBF clearly, particularly during the early-to-mid afternoon (Figure 5.2d-f). A sharp $\nabla_h q$ band forms along the shoreline at 12 LT, intensifies and advances inland by 15 LT, and remains detectable at 18 LT, albeit broader and less sharply defined than ∇BLH . Overall, $\nabla_h q$ appears a suitable diagnostic, but tends to develop other strong gradient structures between the LBF and the shoreline (Figure 5.2e,f). In contrast, horizontal convergence exhibits weaker and more fragmented signatures as shown in Figure 5.2g-i, with broader and less spatially consistent bands near the shoreline than those identified by ∇BLH and $\nabla_h q$.

As a quantitative validation of the frontal locations, satellite imagery from Terra-MODIS (10:30 LT), NOAA-20 (12:20 LT) and Suomi-NPP (13:30 LT) are shown in Figure 5.2j-l. In both scenes, cloud lines or sharp surface reflectance contrasts align closely with fronts identified by ∇BLH and $\nabla_h q$, providing independent confirmation of these diagnostics in this region. This visual agreement supports both diagnostics as physically consistent indicators of LBF position and morphology. Thus, LBF climatologies from IFS ∇BLH and $\nabla_h q$ will be henceforth considered.

5.2.4 Composite of LBF propagation within ∇BLH and $\nabla_h q$

To further assess the robustness of the two best-performing diagnostics, Figure 5.3 presents composites of ∇BLH and $\nabla_h q$ for 400 common lake-breeze days, providing a generalized view of how well these fields capture the typical evolution of the observed LBF. Before noon, developing lake-land thermal contrasts produce weak, spatially incoherent gradients in both ∇BLH and $\nabla_h q$. Consistent with surface observations, no shoreline-anchored front is evident, as a coherent LBF forms only after ~ 12 LT. We therefore focus our analysis from 12 LT onward.

At 12 LT, both ∇BLH and $\nabla_h q$ show gradient maxima closely aligned with the OLBDA-derived front along most shoreline sectors (Figure 5.3a,d). The close agreement in frontal position, curvature and shoreline-parallel orientation indicates that both proxies reliably capture the early-stage LBF structure despite substantial event-to-event

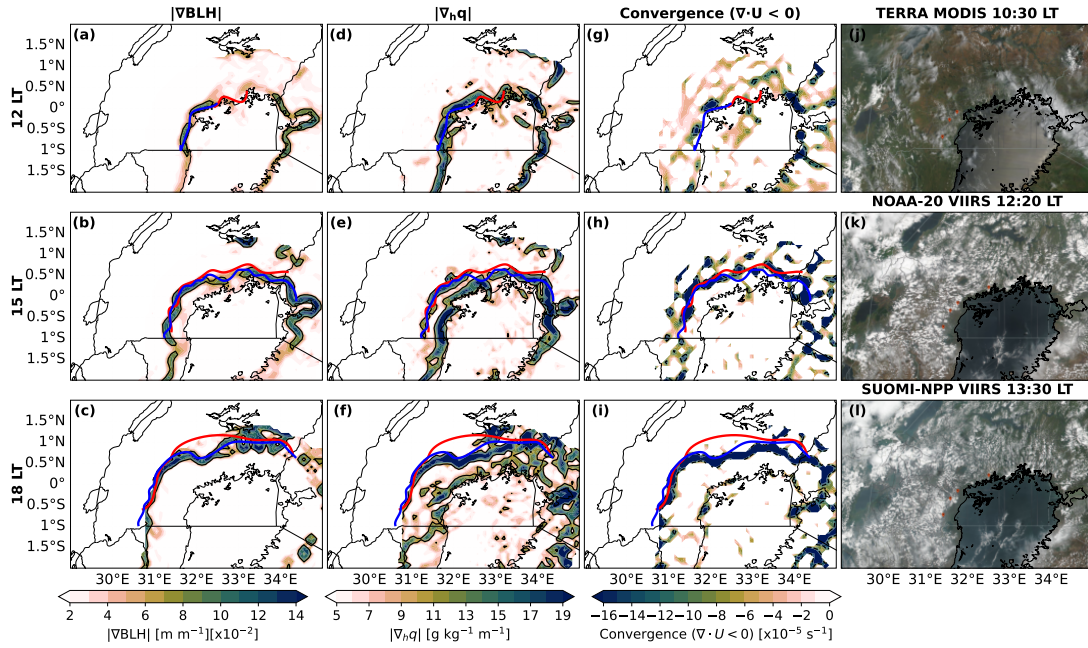


Figure 5.2: Comparison of three proxy diagnostics for identifying the lake-breeze front (LBF) in the IFS on 26 January 2022 at 12, 15, and 18 LT. Shown are (a-c) boundary-layer height gradient (∇BLH), (d-f) horizontal gradient of specific humidity ($\nabla_h q$), and (g-i) low-level horizontal convergence. Panels (j-l) show corresponding satellite imagery from MODIS Terra (10:30 LT), VIIRS NOAA-20 (12:20 LT), and VIIRS Suomi-NPP (13:30 LT), respectively, for visual comparison of observed frontal position. Red and blue contours denote OLBDA-identified LBF position from AWS and IFS data, respectively, for this case study. The black contours delineate areas where the threshold values applied to the proxy-variable fields are exceeded: $\nabla BLH > 0.07 \text{ m m}^{-1}$, $\nabla_h q > 10 \text{ g kg}^{-1} \text{ m}^{-1}$, and convergence $< -12 \times 10^{-5} \text{ s}^{-1}$. Adapted from Ssemujju et al. (2026b). © 2026 The Author(s), John Wiley & Sons Ltd.

variability. From 12 to 18 LT, both fields track the observed inland propagation of the breeze but differ structurally. The ∇BLH field provides the most intuitive correspondence, with gradient bands advancing inland in parallel with the OLBDA-detected front and retaining a compact structure that closely matches the observed frontal geometry (Figure 5.3a-c). In contrast, $\nabla_h q$ signal expands inland rather than forming a single sharp boundary, especially in the western sector, where coherent, narrow contours are less prominent (Figure 5.3d-f). Here, agreement with observations is better reflected in the inland extent and spatial footprint of enhanced $\nabla_h q$ than in a discrete moving front.

Despite these structural differences, both diagnostics retain strong spatial correspondence with the observed front throughout the afternoon. The $\nabla_h q$ reliably highlights the moisture discontinuity associated with the breeze, while ∇BLH more clearly delineates a migrating frontal boundary. This consistency relative to the OLBDA-identified front demonstrates that ∇BLH and $\nabla_h q$ are reliable and complementary proxies for diagnosing LBF structure and propagation in the IFS.

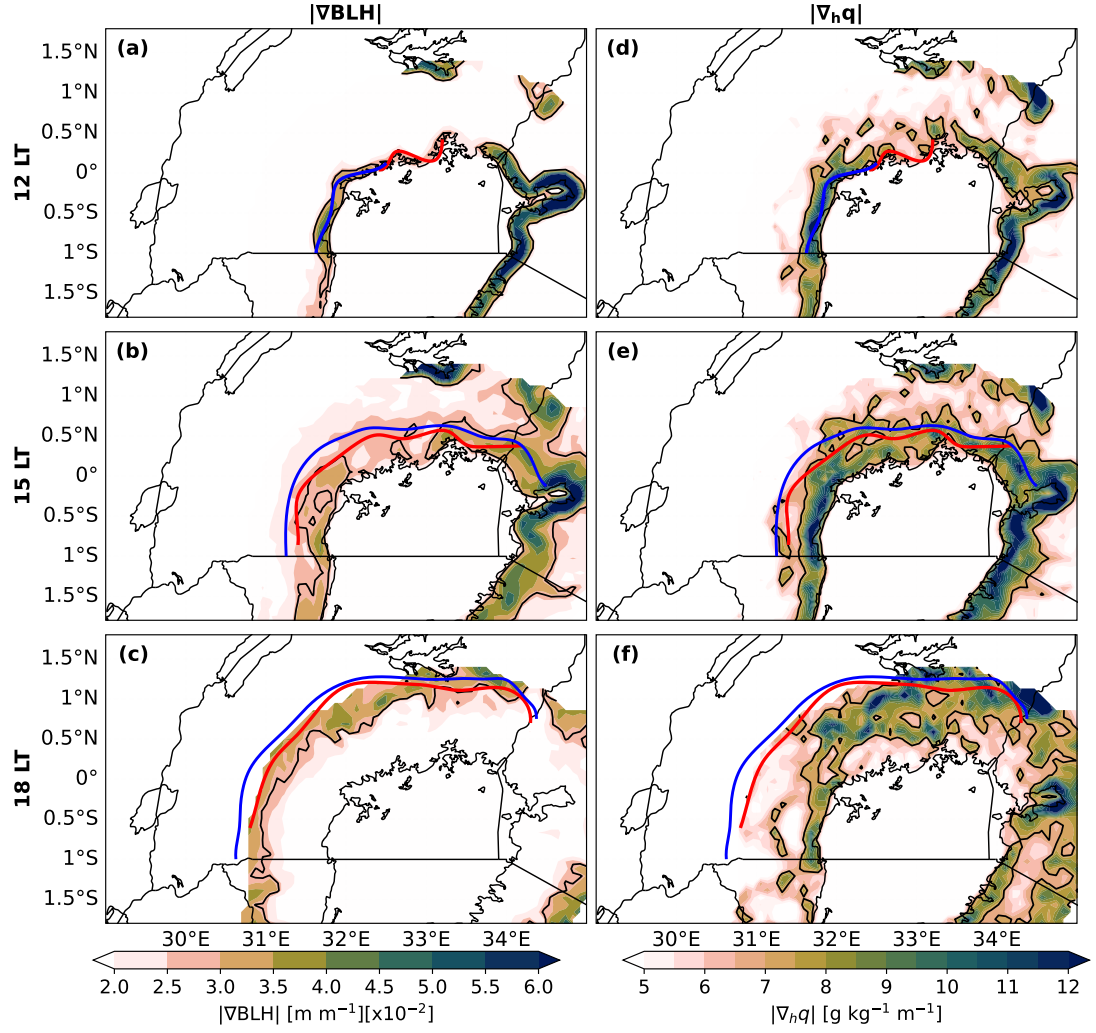


Figure 5.3: Composite lake-breeze structure derived from all satellite-identified lake-breeze days, shown for the two best performing proxies. Panels show (a-c) boundary-layer height gradient (∇_{BLH}), and (d-f) horizontal gradient of specific humidity (∇_{hq}) at 12, 15, and 18 LT. Red and blue contours denote OLBDA-identified composite LBF position from AWS and IFS data, respectively. The black contours delineate areas where the threshold values applied to the proxy-variable fields are exceeded: $\nabla_{BLH} > 0.028 \text{ m m}^{-1}$, and $\nabla_{hq} > 7 \text{ g kg}^{-1} \text{ m}^{-1}$. Reproduced from [Ssemujju et al. \(2026b\)](#). © 2026 The Author(s), John Wiley & Sons Ltd. Used with permission.

5.2.5 Vertical Structure and Evolution of the Lake-Breeze Circulation (LBC)

The almost complete lack of upper-air observations inhibits any in-situ studies on the vertical structure of the LBF during the course of the day. Based on the reasonable delineation of the LBF by IFS, we created daytime composite cross-sections of vertical velocity (w), BLH, and virtual potential temperature (θ_v) along transects perpendicular

to the western and northern shores (Figure 5.4a) to examine the diurnal vertical structure.

The vertical cross-sections reveal a well-defined thermally-driven LBC evolving systematically from 12 to 18 LT (Figure 5.4b-g). At 12 LT, a shallow ascent zone (blue shading) forms near the shoreline along both transects, indicating the lake-breeze initiation (Figure 5.4b,e). Over the lake, stable stratification maintains a shallow boundary layer (black line), while inland heating drives boundary-layer growth. A modest cross-shore θ_v gradient (green contours) establishes the thermal contrast required for circulation development, and weak low-level onshore flow emerges but remains confined near the coast. This structure is consistent with the initial adjustment phase of thermally-forced breezes described in classical conceptual models (Simpson, 1994).

By 15 LT, the circulation peaks (Figure 5.4c,f). A pronounced ascent zone develops tens of kilometers inland, collocated with the inland-most extent of onshore flow, representing the LBF. The strongest ascent coincides with a sharp BLH gradient, indicating low-level convergence, intrusion of cooler lake-modified air, and frontal lifting characteristic of a density-current head. Ahead of the front, strong surface heating rapidly deepens the boundary-layer, leading to enhanced mixed-layer growth inland. The inland, weakly stratified and well-mixed boundary-layer reaches a maximum depth of ~ 3 km AGL, consistent with previous studies over Lake Victoria (e.g. Fraedrich, 1968; Woodhams et al., 2019), and within the typical 2-3 km depth of vigorously convective boundary layers under strong surface heating (e.g. Stull, 1988; Miller et al., 2003). Streamlines indicate a fully developed closed circulation cell with well-defined onshore flow feeding the frontal ascent and a distinct return branch aloft, while weakened vertical θ_v gradients inland indicate increased instability and continued deepening of the mixed layer relative to the cooler, more stably stratified lake-modified air.

By 18 LT, the circulation weakens as surface heating diminishes (Figure 5.4d,g). Frontal ascent becomes shallower and less coherent, the onshore flow retracts toward the shoreline, and thermal gradients relax. The inland BLH decreases and the frontal gradient becomes less distinct, marking a transition to the decay phase. Residual ascent persists longer along the western transect, but overall vertical motion diminishes, consistent with the canonical diurnal cycle of thermally-driven breezes.

Despite similar evolution, the two transects differ systematically. Along the western transect (Figure 5.4e-g), ascent is deeper and stronger, boundary-layer growth is more rapid, and the LBF penetrates farther inland (~ 200 km), with a clearer return flow aloft. Along the northern transect shown in Figure 5.4b-d, ascent is weaker, boundary-layer development is more gradual, and inland penetration is limited (~ 130 km). These contrasts reflect shoreline orientation relative to the prevailing easterlies (see Figure B.1). Along the western shore, the easterlies impinge more perpendicular to the coast, enhancing low-level convergence and strengthening frontal lifting, whereas along the northern shore,

more parallel flow weakens convergence and yields a weaker LBF. Similar sensitivities to synoptic wind alignment have been documented in previous lake- and sea-breeze studies (e.g., Simpson, 1994; Miller et al., 2003; Markowski and Richardson, 2011).

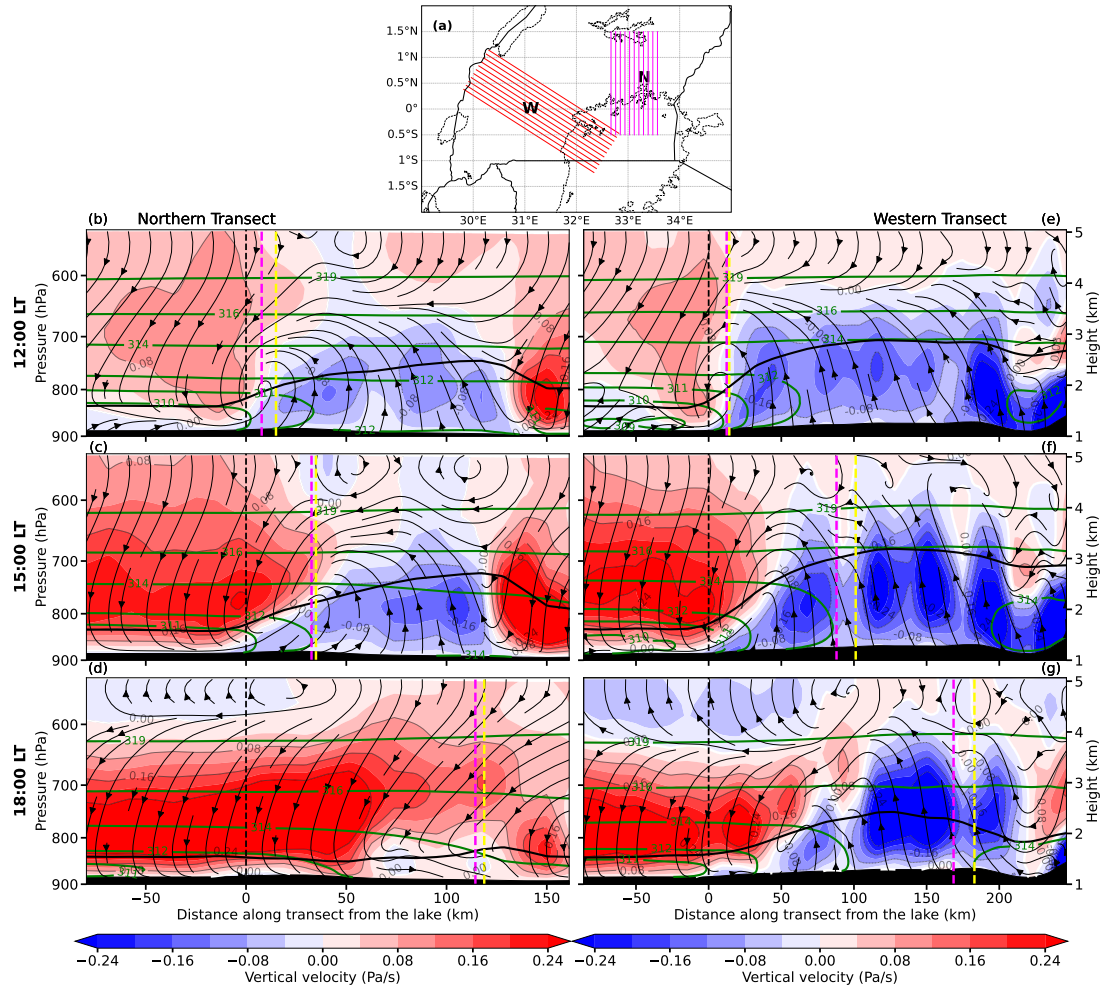


Figure 5.4: (a) Study domain showing red and magenta lines (transects) oriented perpendicular to the western (W) and northern (N) shores of Lake Victoria, respectively, used to compute the mean cross-sections. (b)-(d) and (e)-(g) Composite vertical cross-sections of vertical motion along the northern and western transects at 12:00, 15:00, and 18:00 LT, respectively. Shading denotes vertical velocity (blue = ascent, red = descent). The black solid line shows the boundary layer height, green contours represent virtual potential temperature, and arrows indicate 2-D streamline flow. The magenta and yellow dashed vertical lines in (b)-(g) roughly mark the composited LBF location from AWS and IFS, respectively, along the averaged northern and western transects. Distance in km is measured from the lake shoreline (vertical dashed black line) with positive (negative) values showing distance away from (into) the lake. Reproduced from Ssemujju et al. (2026b). © 2026 The Author(s), John Wiley & Sons Ltd.

Overall, the coupled evolution of w , BLH, and θ_v demonstrates a classic thermally-driven mesoscale circulation whose strength, vertical extent, and inland propagation are

strongly governed by surface heating and modulated by synoptic flow orientation. This three-dimensional analysis further highlights the advantage of the IFS data by revealing aspects of the LBF that cannot be resolved from a two-dimensional perspective, including the vertical thermodynamic structure of the front, the return flow aloft, the pronounced BLH gradient marking the frontal boundary, and variations in boundary-layer depth throughout the evolution of the lake breeze. These results reinforce established LBC theory while providing new insight into its vertical structure and asymmetry over Lake Victoria.

5.3 Summary and Conclusions

This study evaluates how well lake-breeze fronts (LBFs) are represented in ECMWF IFS operational forecasts over the Lake Victoria region. Applying the OLBDA developed in [Chapter 4](#) directly to the IFS data allowed grid point detection of LBF passages and direct comparison with the passage at a large network of weather observations. The main findings are:

1. The results demonstrate that the IFS provides a realistic representation of the regional-scale lake-breeze circulation, although systematic biases in LBF occurrence and arrival time remain.
2. Evaluation of three commonly used proxy diagnostics against OLBDA-identified LBFs (based on wind, temperature, and dew point, as shown in [Figure 5.2](#)) indicates that the BLH gradient provides the most consistent and physically interpretable representation of LBF structure. The specific humidity gradient performs nearly as well, particularly during the early-to-mid afternoon, while horizontal convergence alone is weaker and less consistent.
3. Vertical cross-sections show a well-defined LBC along both western and northern transects, with marked differences in strength and depth. The western transect, favorably aligned with the prevailing easterly synoptic-flow, exhibits stronger low-level convergence, deeper ascent, and greater inland penetration (~ 200 km), whereas the northern transect shows a weaker, shallower circulation. Furthermore, the results show that inland regions often develop a deep (~ 3 km) convective boundary layer prior to frontal passage, with a distinct BLH gradient marking the ascent zone, consistent with density-current-like LBF structure.

This chapter provided insights into how well the LBFs are represented in IFS operational forecasts over Lake Victoria region. By applying the OLBDA developed in [Chapter 4](#) to the IFS data, with only minor modifications to the temporal resolution, LBF passages were successfully detected at every grid point. In addition, the performance of the OLBDA when applied to IFS gridded model data was assessed, demonstrating robust skill, with a POD of 0.71 and a FAR of 0.25. The identified LBF passages were further

used to derive various LBF characteristics across the region, which were subsequently compared with those previously obtained from AWS data. The results suggest that ECMWF IFS 9-km operational analyses provide a realistic and coherent picture of daytime evolution of the three-dimensional land-lake circulation at the western and northern shores of Lake Victoria during the dry seasons. Some deficiencies are noted regarding the overestimation of the frequency and swifter inland propagation. The tendency of the IFS to predict more LBFs and earlier frontal arrival times may be due to biases in the representation of land-lake thermal contrasts, surface heat fluxes, boundary-layer evolution, shoreline roughness transitions, and limitations in the representation of turbulent mixing, which require further investigation.

The superior performance of the BLH and specific humidity gradients compared to surface convergence likely reflects the thermodynamic nature of the LBF, which separates relatively cool, moist marine air from warmer continental air and thereby produces sharp horizontal contrasts in moisture and boundary-layer structure that closely delineate the frontal position (e.g., [Simpson, 1994](#); [Miller et al., 2003](#)). As the front propagates inland, strong gradients in specific humidity and BLH remain closely aligned with its leading edge, providing spatially coherent markers of frontal location. By contrast, surface convergence is often diffused or displaced from the thermodynamic boundary and can be modified by local topography and mesoscale circulations, making it a less reliable standalone indicator of LBF position.

According to IFS, the depth of the LLB reaches about 3-4 km ([Figure 5.4](#)). The northern transect in [Figure 5.4](#) covers Entebbe at the lakeshore. [Fraedrich \(1968\)](#) utilized two seasons of PIBAL balloon wind soundings from Entebbe, but only up to 1920 m. His results indicate that in June-August, the depth of the LLB at the coast of Entebbe in the afternoon (12-18 LT) is 1920 m or higher, while it is shallower in December-February. Similar seasonal differences were evident in IFS (not shown). Our NW-SE transect is similar to the one discussed in [Woodhams et al. \(2019\)](#), using Met Office Unified Model convection-permitting simulations at 1.5 km resolution. From comparing our [Figure 5.4f](#) with their [Figure 7n](#), it can be seen that upward motion at the LBF reached around 600 hPa. Unfortunately, no upper-air observations at some distances away from the coast are available to investigate the vertical extent of the LLB.

Furthermore, the results suggest that IFS analyses can be used to study LLBs and to provide boundary conditions for higher-resolution atmospheric models, including those that simulate atmospheric chemistry and pollution. Overall, the findings indicate that synoptic-flow orientation (i.e., the direction of the background synoptic-scale wind relative to the shoreline) and boundary-layer evolution are among the first-order controls of lake-breeze strength, vertical extent, and inland propagation, while the diurnal cycle governs peak timing. This coherent depiction of lake-breeze dynamics provides insight relevant to forecasting, air-quality assessment, and the evaluation of global and regional

models in lake-influenced environments. A caveat for long-term climatological studies is that IFS operational analyses are inhomogeneous, owing to changes in model physics across different model cycles ([ECMWF, 2025](#)).

6. Conclusions

Ocean and lake coastlines areas are strongly influenced by land-sea and land-lake circulations. These thermally driven local circulation systems often play a key role in cloud development, deep convection initiation, extreme rainfall events, wind regimes, and air quality, thereby significantly affecting socio-economic activities. Moreover, a large and growing fraction of the global population resides within a few kilometers of these coastline ([Cosby et al., 2024](#)), making them even more significant. Consequently, a thorough understanding of these processes is essential, particularly over large tropical lakes such as Lake Victoria, where approximately 40 million people depend on the lake for their livelihoods ([Semazzi, 2011](#); [Nyamweya et al., 2023](#)).

Achieving such understanding requires high-resolution observational data and robust detection methods. However, both remain limited in data-sparse regions such as Lake Victoria basin (LVB). Although considerable research has examined convection, thunderstorms, and lightning over the lake, often linking them to lake-land breeze systems (e.g. [Chamberlain et al., 2014](#); [Thiery et al., 2016](#); [Woodhams et al., 2019](#); [Finney et al., 2020](#)), there is currently no unified, objective method for detecting these breezes and their associated fronts. Objective detection approaches offer several advantages, including consistency, reproducibility, and the efficient processing of large datasets. Moreover, they can be applied across different regions and datasets with minimal tuning. Therefore, the development of an objective identification method for lake-land breeze fronts (LBFs) would enhance understanding of regional mesoscale dynamics and provide a physically based benchmark for evaluating numerical weather prediction and climate models over the LVB. In addition, because LBFs influence air quality, heat stress, and the preconditioning of the atmosphere for subsequent convection, their detection has value beyond rainfall-focused applications.

Motivated by these gaps, the primary objective of this thesis was to develop an objective algorithm, based solely on ground-based observations to detect LBFs and to evaluate its performance in identifying their passage across the study domain. Its detection capability was further assessed systematically using manually identified satellite-based lake-breeze and non-lake-breeze events over the LVB. This aim was achieved by answering research

question 1 as asked in Chapter 3 and the answers presented in Chapter 4 are summarized as follows:

RQ 1a Which meteorological variables and thresholds are optimum for identifying LBF passages using surface observations at the hinterland of Lake Victoria?

In this study, the most effective variables were wind direction and speed, air temperature, dewpoint temperature, and relative humidity, with precipitation used as a supporting indicator to distinguish LBF signals from rainfall-induced changes. These variables exhibited clear and immediate changes during LBF passage. Typically, LBFs are characterized by a shift in wind direction, an increase in wind speed, a drop in air temperature, and concurrent increases in dewpoint temperature and relative humidity. These signatures have been widely used in previous studies to identify lake-breeze events (e.g. [Laird et al., 2001](#); [Papanastasiou and Melas, 2009](#); [Hughes and Veron, 2018](#)). Precipitation was not used as a primary detection variable but served as a filter to ensure that observed changes were not associated with rainfall events.

To identify LBF passages objectively, this study applied percentile-based thresholds to account for spatial variability across stations. Fixed thresholds, commonly used in other regions, were found to be unsuitable due to differences in local climatic conditions and station characteristics. Instead, thresholds were derived from the empirical distributions of absolute 15-minute changes in each variable. Specifically, LBF passages were identified using the combination of the lowest 30% of temperature changes (representing significant cooling) and the highest 30% of dewpoint and wind speed increases at each station. This approach ensures that thresholds reflect characteristic short-term variability rather than absolute values, making the method robust and adaptable across different regions. Overall, the combination of dynamically responsive meteorological variables and percentile-based thresholds provided an effective and flexible framework for detecting LBF passages using surface observations over Lake Victoria.

RQ 1b How well does the algorithm perform compared to manually identified satellite lake-breeze and non-lake breeze days?

Overall, the algorithm demonstrates robust performance, particularly at coastal stations. It achieves a high probability of detection ($POD > 0.7$), a relatively low false alarm ratio ($POFA = 0.20$), and a good overall accuracy of 0.76. The bias index ($BID = 0.95$) indicates a slight underestimation of

LB occurrences, suggesting that the algorithm is generally conservative in its detections. Similar hit rates were reported by [Hughes and Veron \(2018\)](#), despite their study being conducted in the temperate climate of Delaware, USA, where they achieved success rates of 70–80% during the JJA season. In contrast, algorithms applied in Europe have generally reported lower hit rates. For example, [Arrillaga et al. \(2020\)](#) achieved a hit rate of 48% over northern Spain during JJA, while [Borne et al. \(1998\)](#) reported success rates of only 17–38% in Sweden during the May–September period.

However, the interpretation of the performance in this study must consider the limitations of the satellite-based reference dataset. The dataset is constrained by a limited number of daily satellite overpasses (typically no more than three), which restricts temporal coverage. As a result, LB events occurring outside these observation times may not be captured, leading to some true LB days being misclassified as non-LB days in the reference dataset. This limitation can artificially inflate the number of apparent false alarms and underestimate the true detection skill of the algorithm. Furthermore, the classification of days with either clear skies or extensive cloud cover as non-LB days introduces additional uncertainty, as such conditions may obscure or mask lake-breeze signatures in satellite imagery. Consequently, some discrepancies between the algorithm and the reference dataset may arise from limitations in the observational data rather than deficiencies in the algorithm itself. Despite these constraints, the comparison provides a reasonable and practical evaluation of the algorithm's performance in the absence of more comprehensive validation data. Overall, the results indicate that the OLBDA is a reliable tool for detecting LBF passages, although the reported performance metrics should be interpreted with caution given the inherent limitations of the reference dataset.

RQ 1c Does the algorithm maintain consistent detection skill across different stations in the study domain?

The detection skill of the OLBDA is not uniform across stations and varies systematically with distance from the lake shoreline. Overall, the algorithm performs significantly better at coastal stations than at inland locations. This spatial variation is most evident in the POD scores, which exceeds 0.6 at stations within 20 km of the shoreline but decreases to below 0.40 at distances greater than 70 km inland. This decline reflects the weakening of lake-breeze signals as they propagate inland, where associated changes in wind and temperature become less pronounced and therefore more difficult to detect. Despite this variability in detection sensitivity, the

algorithm maintains relatively low false alarm rates across most stations. Approximately 93% of stations exhibit POFA values below 0.25, with a mean value of 0.19, indicating that false detections are limited. Other performance metrics including the critical success index (CSI), success ratio (SR), and accuracy (ACC), show patterns consistent with POD, with higher values concentrated at coastal sites. Specifically, 73% of stations have CSI values greater than 0.4, 98% have SR above 0.7, and 93% have ACC exceeding 0.6. The mean CSI value of 0.49 indicates moderate overall event detection skill. The Heidke Skill Score (HSS) further confirms this spatial dependence, with higher values observed near the coastline and reduced skill inland. The average HSS of 0.37 demonstrates that the algorithm performs better than random chance across most stations, although its effectiveness diminishes with increasing distance from the lake. Overall, these results indicate that while the OLBDA provides reliable detection of LBF passages, its performance is strongly influenced by station location, with the highest skill observed near the coast where lake-breeze signals are strongest.

From the above results, it is evident that the developed ground-station-based algorithm, here referred to as OLBDA provides a reliable and objective means of detecting LBF passages across the Lake Victoria basin, based on changes in a set of meteorological parameters. With this reliable detection framework, it became possible to move beyond event identification, and towards a comprehensive characterization of LBF occurrence patterns. This motivated the next stage of the analysis, which focused on quantifying the spatial distribution, temporal variability, and baseline climatological characteristics of LBFs over the Lake Victoria basin. This second aim was also achieved in Chapter 4 as per the following findings:

RQ 2a How frequently do LBFs occur within the northern part of the LVB in Uganda?

Nearly half (48%) of all dry-season (DJF and JJA) days during 2017-2022 featured a lake-breeze front (LBF) event (524 out of 1093 days), corresponding to approximately one event every two days. This indicates that LBFs are a frequent feature of the Lake Victoria basin during the dry seasons. However, this estimate is likely conservative in some areas, as station coverage and distance from the shoreline influence detection. For example, the closest station on the western side is located 27 km inland, whereas on the northern side it is only 0.2 km from the shore. As a result, weaker LBFs that dissipate before reaching inland stations may go undetected, leading to an underestimation of their true frequency.

RQ 2b How do LBF occurrence rates vary spatially across the LVB?

LBF occurrence varies substantially across the study region, with the proportion of detected LBF days ranging from 4%-54% in the northern sector, 3%-33% in the northwestern sector, and 10%-44% in the western sector. Station proximity to the lake shoreline is a primary control, with coastal stations consistently recording higher LBF frequencies than inland stations. This is partly because not all LBFs propagate far inland; many dissipate before reaching distant stations, resulting in fewer detections and a likely underestimation at inland locations. In addition, some LBFs may pass through inland stations undetected by the detection algorithm, particularly when they weaken and warm over land, failing to meet the temperature-based criteria. [Hughes and Veron \(2018\)](#) also found a similar behaviour over Delaware Bay in USA. Beyond proximity effects, variations across coastal sectors suggest that localized factors like coastline geometry and topography also influence breeze development and propagation.

RQ 2c To what extent do LBF occurrences vary on monthly, seasonal, and interannual scales?

LBF occurrences exhibit clear monthly, seasonal, and interannual variability across the study region. On a monthly scale, LBF frequency varies substantially, with peak occurrences in January and minimum in June during the dry seasons (DJF and JJA). This pattern is consistent across stations, as illustrated by Entebbe WDD and Kamenyamigo, where LBF occurrences peak in January (and August) and are lowest in June. The higher frequencies in January and August coincide with the warmest months of the year, while the June minimum is partly linked to the transition from the long March-May rainy season.

Seasonally, DJF records slightly more LBF events than JJA. For example, Entebbe WDD and Kamenyamigo stations register 226 and 255 LBF events in DJF, compared to 188 and 197 events in JJA, respectively. This seasonal difference is supported by auxiliary temperature analysis, which indicate slightly stronger temperature gradients during DJF.

On an interannual scale, LBF frequency also varies from year to year. Between 2017 and 2022, 2021 recorded the highest number of LBF days (111), while 2018 recorded the lowest (58), out of 182 dry-season days per year. At individual stations, LBFs were detected on approximately 35%-52% (Entebbe WDD) and 26%-59% (Kamenyamigo) of dry-season days, depending on the year. This variability is consistent with patterns observed across the study region.

Overall, using the two stations nearest to the lake shores in the northern and western sectors, the results demonstrate that LBF occurrence is modulated by both seasonal thermal contrasts and interannual variability, reinforcing the spatial and temporal consistency of LBF patterns across the study domain.

RQ 2d At what times of day do LBFs most frequently develop and propagate inland?

Most LBFs occur from early afternoon at coastal stations to late evening at the furthest inland stations. Peak arrival times are typically between 1200 and 1400 LT at coastal stations and shift progressively later with increasing distance inland, averaging between 1400 and 1600 LT across most stations. For example, the peak arrival time at Entebbe WDD, located 0.2 km from the lake on the northern side, is 1200 LT, whereas at Kimenyamigo, approximately 27 km inland on the western side, LBFs occur most frequently around 1500 LT. Dissipation generally occurs around 1730 LT at the furthest stations. These timing patterns are consistent with the findings of [Datta \(1981\)](#) and [Odongo et al. \(2022\)](#) over the same region, confirming that proximity to the coastline strongly influences LBF timing.

Given the success of the OLBDA when applied to surface station observations, and with a general picture of the climatology of LBFs across the Lake Victoria basin now established, the next logical step was to apply the algorithm on gridded datasets, particularly numerical model outputs such as reanalysis data. The next question, therefore, was whether the OLBDA could be used to detect LBFs in ECMWF IFS analyses and proxy datasets. The conclusions based on the specific questions are as follows:

RQ 3a How well does the IFS capture the occurrence and timing of LBF onset compared to observational datasets?

The comparison between the IFS and observational datasets indicates that the model successfully captures the overall occurrence patterns and timing characteristics of LBFs, but with systematic biases in both frequency and onset timing. In terms of occurrence frequency, the IFS reproduces the general magnitude and spatial distribution of LBF events reasonably well. The algorithm identifies LBFs on 48% of dry-season days in the IFS compared to 38% in the AWS observations, with a substantial overlap of 400 common events. This represents 76% of IFS-detected and 96% of AWS-detected LBF days, indicating that the model successfully captures the majority of observed events. Performance metrics further support this,

with a probability of detection (POD) of 0.71 and a false alarm ratio (FAR) of 0.25, values that are comparable to those derived from observational data. These results demonstrate that the IFS is capable of representing the occurrence of LBFs at a level broadly consistent with surface observations. Spatially, the IFS accurately reproduces the characteristic inland gradient in LBF occurrence, with higher frequencies near the lake shore and decreasing frequency with distance inland. However, the IFS exhibits a systematic positive bias, overestimating LBF frequency at approximately 67% of stations across both western and northern sectors. This overestimation averages around 5% and is particularly pronounced within the first 20 km of the shoreline, where observed and modeled frequencies are highest. Furthermore, the IFS shows a more gradual decline in frequency with distance inland compared to observations, suggesting that LBFs in the model propagate inland more frequently or persist longer than observed. This bias likely reflects limitations in the representation of near-surface processes, including overly smooth lake-land thermal contrasts, insufficient representation of land-surface heterogeneity, and simplified boundary-layer dynamics.

Regarding the timing of LBF onset, the IFS successfully captures the observed spatial pattern of inland progression, with earlier arrivals near the coast and progressively later arrivals inland. Both datasets show coherent arrival times of approximately 1200-1400 LT at coastal locations and 1600-1700 LT farther inland, demonstrating that the model realistically represents the diurnal evolution and propagation of the breeze. However, the IFS exhibits a consistent early-arrival bias. Approximately 60% of stations record LBF arrival at least one hour earlier in the model than in observations, with average lead times of about one hour and local differences reaching up to two hours. This bias is most pronounced in the western sector, where 80% of stations show earlier arrivals in the IFS, compared to 50% in the northern sector. Despite this timing offset, the sequence of LBF development is well represented, with both datasets indicating initial formation along the northern coast followed by propagation toward the western sector. The systematic early onset in the IFS likely results from an overly rapid development of lake-land thermal contrasts or an over-simplified representation of boundary-layer processes, which may promote premature initiation and faster inland propagation of the LBF.

RQ 3b How well does the IFS represent the 3-dimensional structure and intensity of LBFs over the northern shores of Lake Victoria?

The IFS reproduces the three-dimensional structure and diurnal evolution of the LBC over Lake Victoria with a high degree of realism, capturing the key features of a thermally driven mesoscale system, consistent with the findings of [Woodhams et al. \(2019\)](#). The model simulates a well-defined circulation that develops around midday, intensifies in the afternoon, and weakens toward the evening, consistent with classical lake-breeze theories as explicated in earlier studies (e.g., [Simpson, 1994](#)). The vertical cross-sections showed that the IFS captures the essential dynamical structure of LBFs, including low-level onshore flow, a convergence zone marked by strong frontal ascent, and a return flow aloft forming a closed circulation cell. The model also reproduces the characteristic inland progression of the LBF, with ascent zones extending several tens of kilometers inland and associated with sharp boundary-layer height gradients. Ahead of the front, the IFS realistically simulates strong surface heating and deep convective boundary-layer development, reaching depths of up to ~ 3 km. The boundary-layer heights observed in this study are consistent with earlier findings from the LV region. Using CP simulations MetUM, [Woodhams et al. \(2019\)](#) reported boundary-layer heights of up to 3 km, while [Fraedrich \(1968\)](#), based on upper-air soundings, found comparable values reaching 1920 m.

However, the intensity and depth of the circulation exhibit spatial variability. Over the northern shores, the simulated LBF is relatively weaker and shallower, with reduced vertical motion, slower boundary-layer growth, and more limited inland penetration (~ 130 km) compared to the western sector. This difference is consistent with the influence of prevailing easterly winds, which are more parallel to the northern coastline and therefore produce weaker low-level convergence and frontal lifting. Overall, the IFS provides a realistic representation of the vertical structure and intensity of LBFs, successfully capturing their fundamental dynamics and diurnal evolution, although it tends to simulate a weaker and less vertically developed circulation over the northern shores due to regional flow configuration.

RQ 3c How accurately does the IFS represent the inland propagation speed and overall spatial evolution of LBFs?

The IFS captures the overall spatial evolution and inland propagation characteristics of LBFs as shown in [Ssemujju et al. \(2026a\)](#) reasonably well, however, notable biases remain in propagation speed and inland extent. Spatially, the model reproduces the key feature of LBF evolution, including

a coherent gradient of high occurrence near the shoreline that decreases inland, consistent with observations. It also correctly represents the inland progression of the front, with earlier arrival near the coast and progressively later onset farther inland. This indicates that the IFS realistically simulates the large-scale structure and movement of the lake-breeze system. However, the model tends to propagate LBFs too readily inland. This is evident from the more gradual decline in occurrence frequency with distance compared to observations, suggesting that the model allows the breeze to persist and penetrate farther inland more frequently than observed. This bias is supported by the systematic overestimation of LBF frequency across most stations, including those located at greater distances from the shoreline. Consistent with this behavior, the IFS also exhibits an early-arrival bias of approximately one hour on average, implying that the modeled propagation is faster than observed. This suggests that the model accelerates the development and inland movement of the front, likely due to an overly strong or spatially uniform representation of the lake-land thermal contrast and simplified boundary-layer processes. The vertical structure further supports this interpretation. The IFS simulates a well-organized circulation with strong frontal ascent, deep boundary-layer development, and a closed circulation cell, all of which contribute to sustained inland propagation. In some regions, particularly along the western transect, the model shows deeper ascent and greater inland penetration, consistent with enhanced propagation under favorable wind alignment. Overall, while the IFS successfully reproduces the qualitative spatial evolution of LBFs, including their inland progression and structural characteristics, it tends to overestimate their propagation speed and inland extent. These biases point to limitations in the representation of near-surface heterogeneity and boundary-layer processes, which likely moderate the inland advance of LBFs in reality.

RQ 3d Which proxy variables within the IFS framework provide the most reliable detection of LBFs over the LVB?

Overall, BLH gradient (∇BLH) is the most suitable primary proxy, while the horizontal gradient of specific humidity ($\nabla_h q$) serves as a reliable secondary indicator. Low-level wind convergence is best used as a supplementary diagnostic, particularly when combined with the other fields.

∇BLH is identified as the most effective single proxy, providing a physically interpretable and temporally persistent signature of the LBF. It consistently produces a sharp, narrow, and spatially coherent signal that clearly delineates the frontal boundary from its initiation at the shoreline through its inland propagation. This reflects the strong contrast between the shallow,

stable boundary layer over the lake and the deepening convective boundary layer over land during daytime heating.

The specific humidity gradient ($\nabla_h q$) performs nearly as well and serves as a strong complementary diagnostic. It effectively captures the moisture discontinuity associated with the intrusion of cool, moist lake air over warmer and drier land. While slightly broader and less sharply defined than ∇BLH , particularly later in the day, it reliably tracks the inland extent and spatial footprint of the LBF, especially during the early-to-mid afternoon.

In contrast, low-level horizontal wind convergence is less reliable as a standalone proxy. Although convergence bands are sometimes evident near the shoreline, they tend to be broader, weaker, and less spatially consistent, limiting their usefulness for accurately identifying and tracking the front. However, convergence can still provide supportive information when used alongside ∇BLH and $\nabla_h q$.

These findings are consistent with [Brown et al. \(2026\)](#) over Australia, who showed that moisture-based diagnostics provide a robust basis for sea-breeze identification in model data across different resolutions.

Conclusively, this thesis has demonstrated that an integrated approach combining dense in situ observations, algorithm development, and model evaluation can significantly advance the understanding of lake-land breeze systems over the Lake Victoria basin. The successful development and application of the OLBDA highlights its capability to capture subtle atmospheric signals and provide a robust framework for objectively identifying mesoscale circulations in data-sparse tropical regions. Beyond offering new climatological insights, the work underscores the broader relevance of LBFs in shaping local atmospheric conditions and supporting the evaluation of numerical weather prediction systems. The encouraging performance of the OLBDA when applied to model outputs further emphasizes its value as a diagnostic and validation tool, particularly for assessing the representation of local circulations in global models such as the ECMWF IFS. Ultimately, this study lays a strong foundation for future research and model improvement efforts, contributing to enhanced weather and climate understanding over the Lake Victoria basin and similar environments.

However, despite its overall good performance summarised above, the algorithm has several limitations. Its sensitivity to wind-direction signals may lead to missed LBF occurrences at some stations. The use of 2-m rather than standard 10-m wind measurements introduces uncertainty into the wind-based criterion and may influence the number of detected LBF passages. The exclusion of cold-pool passages based solely on station precipitation may also omit some events. In addition, the satellite imagery used as the reference dataset for verification was subject to temporal sampling limi-

tations, which may also have affected the representativeness of both LB and non-LB classifications. Also, the classification of clear-sky and extensively cloud-covered days as non-LB days may have contributed to an overestimation of false alarms. A further caveat for long-term climatological analyses is the inhomogeneity of IFS operational analyses arising from changes in model cycles over time. Furthermore, although the IFS realistically captures many key aspects of lake-breeze circulation, systematic biases in occurrence frequency, timing, and inland propagation were recorded.

7. Outlook

This thesis has provided a comprehensive framework for detecting and analyzing LBFs over the LVB, combining observational data, algorithm-based detection OLBDA, and model-based diagnostics. Despite these advances, several limitations and open questions remain. Addressing these challenges presents significant opportunities to improve the understanding, detection, and predictability of LBFs, particularly in this data-sparse region. In this context, several key directions for future work emerge, focusing on methodological improvements, enhanced observational capabilities, and the application of advanced modeling and machine learning approaches are suggested below:

The OLBDA algorithm provides a robust framework for detecting LBFs from surface observations. A key strength of the method is its use of station-specific percentile thresholds, which account for local climatological variability and enhance adaptability across the observational network. Nevertheless, the current detection scheme relies primarily on changes in wind direction, wind speed, temperature, and dew point. While these variables are characteristic signatures of LBFs, they are not unique to lake-breeze circulations and may also be associated with other mesoscale and synoptic-scale processes, such as convective outflows or frontal passages. Building on the adaptive framework developed in this study, future work could further improve detection accuracy and robustness by incorporating additional atmospheric variables, such as pressure tendencies, stability indices, and boundary-layer characteristics, within a multi-parameter detection approach. Furthermore, threshold definitions could be refined by explicitly accounting for seasonal variability and prevailing synoptic conditions, rather than relying solely on climatological percentiles. The implementation of temporal and spatial consistency checks would also help reduce false detections caused by short-lived fluctuations and increase confidence in the identification of LBF events.

The OLBDA algorithm demonstrates strong potential for operational forecasting applications. Future work should focus on integrating OLBDA with numerical weather prediction (NWP) outputs to generate real-time likelihood maps of LBF occurrence, which could support short-term forecasting and decision-making. In addition, the development of early warning systems for convection-related hazards associated with LBFs would enhance its practical relevance, particularly in regions vulnerable to severe

weather. Automating the algorithm within existing forecasting workflows would further enable its adoption by regional meteorological services. Beyond operational use, the results of this thesis also indicate that OLBDA can be applied to long-term analyses, including the development of climatologies, retrospective detection of LBF events, and case studies, even in areas with limited observational coverage.

Further advances in understanding lake-breeze dynamics over the LVB would benefit from enhanced spatial and vertical observational coverage, particularly over the lake itself. The observational network used in this study is primarily composed of shoreline stations, which provide valuable insights into the evolution of lake-breeze circulations but offer only limited direct observations of over-lake processes. Expanding observations across the lake would enable a more comprehensive investigation of key features such as offshore convergence, land-breeze propagation, and moisture transport. Similarly, increased radar coverage and the establishment of long-term continuous observing systems would provide new opportunities to examine the variability and evolution of lake-breeze systems across a wide range of temporal scales. At present, many of the available datasets originate from short-term field campaigns rather than sustained operational observing programmes (e.g. [Roberts et al., 2022](#)), highlighting the value of long-term monitoring efforts for future research. Additional progress could be achieved through the expansion of upper-air observations. Routine radiosonde launches and the deployment of advanced profiling systems, such as Doppler lidar and wind profilers, would enable a more detailed characterization of the three-dimensional structure and temporal evolution of lake-breeze circulations. Future observational efforts could therefore focus on the deployment of buoys and offshore measurement platforms, an increased density of shoreline stations, and the establishment of sustained long-term monitoring programmes. Together with enhanced radar coverage and routine vertical profiling observations, these developments would provide a stronger observational foundation for improving process understanding, model evaluation, and the forecasting of mesoscale circulations across the region

With the planned release of the next ECMWF reanalysis, ERA6 ([Copernicus Climate Change Service, 2026](#)), in 2027 at 14 km resolution, i.e. more than double the resolution of ERA5 (32 km), long-term climatologies could be obtained from global models at such a high resolution. Other high-resolution global, like DWD ICON DREAM at 13 km ([Valmassoi et al., 2025](#)), can be used as well to obtain a feeling how differences in data assimilation and model physics impact the LLB. Using these data sets, diurnal, seasonal and interannual variations in the LLB systems of Lake Victoria could be studied. The OBLDA-derived hourly positions of the LLB from weather stations in the period 2017-2022 could also be used to quantitatively assess LLB forecasts that are freely available from both the DWD and ICON model.

The spatial location of lake-breeze initiation plays a crucial role in controlling the intensity and evolution of the circulation, highlighting the need for future investigations

at much finer spatial scales. [Hughes and Veron \(2018\)](#) suggested that studies employing sub-kilometer resolution are essential to adequately resolve the localized processes that govern the formation and inland propagation of LBFs. Moreover, high-resolution numerical experiments would provide a more detailed representation of the underlying dynamics and help capture the inherent variability of this phenomenon. In this context, the application of large-eddy simulations (LES) using state-of-the-art numerical weather prediction models offers a promising pathway. LES frameworks allow for an explicit representation of turbulent motions and boundary-layer processes, thereby providing a physically consistent and highly resolved “model truth.” Such simulations could be used to systematically evaluate the performance of the OLBDA algorithm against well-resolved reference fields, enabling a more rigorous assessment of its detection capabilities. Furthermore, LES-based analyses would facilitate a deeper investigation into the vertical structure, temporal evolution, and three-dimensional characteristics of lake-breeze fronts, which remain insufficiently understood from surface-based observations alone.

Finally, recent advances in machine learning (ML) offer promising opportunities to improve LBF detection, particularly in complex environments such as the LVB. ML techniques such as random forests and convolutional neural networks can capture nonlinear relationships between atmospheric variables, integrate multi-source datasets (e.g., surface observations, satellite data, and model output), and improve detection where traditional threshold-based methods fall short ([Dagon et al., 2022](#); [Justin et al., 2023](#); [Ding et al., 2025](#)). Future work could therefore explore hybrid approaches that combine OLBDA with ML-based classification, as well as the use of ML for feature extraction, such as identifying convergence lines or LBF signatures in satellite imagery. However, these approaches are currently limited by the scarcity of large, high-quality training datasets, the need for well-labeled events (for which OLBDA detections could serve as an initial reference), and the requirement for robust validation strategies to ensure generalization and avoid overfitting.

Bibliography

- Abatan, A. A., Abiodun, B. J., and Omotosho, B. J. (2014). On the characteristics of sea breezes over nigerian coastal region. *Theoretical and applied climatology*, 116(1):93–102.
- Abbs, D. J. and Physick, W. L. (1992). Sea-breeze observations and modelling: a review. *Australian Meteorological Magazine*, 41:7–19.
- Anthes, R. A., Hsie, E.-Y., and Kuo, Y.-H. (1987). Description of the Penn State/NCAR Mesoscale Model Version 4 (MM4). NCAR Tech. Note NCAR/TN-282+STR. <https://doi.org/10.5065/D64B2Z90>.
- Antonelli, M. and Rotunno, R. (2007). Large-eddy simulation of the onset of the sea breeze. *Journal of the Atmospheric Sciences*, 64(12):4445–4457.
- Anyah, R. and Semazzi, F. (2006). Climate variability over the greater horn of africa based on near agcm ensemble. *Theoretical and applied climatology*, 86(1):39–62.
- Anyah, R. O., Semazzi, F. H., and Xie, L. (2006). Simulated physical mechanisms associated with climate variability over lake victoria basin in east africa. *Monthly weather review*, 134(12):3588–3609.
- Arrillaga, J. A., Jiménez, P., Vilà-Guerau de Arellano, J., Jiménez, M. A., Román-Cascón, C., Sastre, M., and Yagüe, C. (2020). Analyzing the synoptic-, meso-and local-scale involved in sea breeze formation and frontal characteristics. *Journal of Geophysical Research: Atmospheres*, 125(4):e2019JD031302.
- Arritt, R. W. (1993). Effects of the large-scale flow on characteristic features of the sea breeze. *Journal of Applied Meteorology and Climatology*, 32(1):116–125.
- Atkins, N. T. and Wakimoto, R. M. (1997). Influence of the synoptic-scale flow on sea breezes observed during cape. *Monthly weather review*, 125(9):2112–2130.
- Atkinson, B. W. (1981). *Meso-scale atmospheric circulations*, volume 495. Academic press London.

- Azorin-Molina, C., Chen, D., Tijn, S., and Baldi, M. (2011). A multi-year study of sea breezes in a mediterranean coastal site: Alicante (spain). *International Journal of climatology*, 31(3):468–486.
- Ba, M. B. and Nicholson, S. E. (1998). Analysis of convective activity and its relationship to the rainfall over the rift valley lakes of east africa during 1983–90 using the meteosat infrared channel. *Journal of Applied Meteorology*, 37(10):1250–1264.
- Baker, R. D., Lynn, B. H., Boone, A., Tao, W.-K., and Simpson, J. (2001). The influence of soil moisture, coastline curvature, and land-breeze circulations on sea-breeze-initiated precipitation. *Journal of Hydrometeorology*, 2(2):193–211.
- Barry, R. G. and Chorley, R. J. (2010). *Atmosphere, weather and climate*. Routledge, 9 edition.
- Bechtold, P., Pinty, J.-P., and Mascart, P. (1991). A numerical investigation of the influence of large-scale winds on sea-breeze and inland-breeze type circulations. *Journal of Applied Meteorology*, 30(9):1268–1279.
- Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., and Wood, E. F. (2018). Present and future köppen-geiger climate classification maps at 1-km resolution. *Scientific data*, 5(1):180214.
- Berri, G. J. and Dezzutti, M. (2020). A sea-breeze case study in the la plata river region using local observations, satellite images, and model simulations. *Boundary-Layer Meteorology*, 177(1):123–147.
- Biard, J. C. and Kunkel, K. E. (2019). Automated detection of weather fronts using a deep learning neural network. *Advances in Statistical Climatology, Meteorology and Oceanography*, 5(2):147–160.
- Biggs, W. G. and Graves, M. E. (1962). A lake breeze index. *Journal of Applied Meteorology (1962-1982)*, pages 474–480.
- Birch, C. E., Roberts, M. J., Garcia-Carreras, L., Ackerley, D., Reeder, M. J., Lock, A. P., and Schiemann, R. (2015). Sea-breeze dynamics and convection initiation: The influence of convective parameterization in weather and climate model biases. *Journal of Climate*, 28(20):8093–8108.
- Bochenek, B., Ustrnul, Z., Wypych, A., and Kubacka, D. (2021). Machine learning-based front detection in central europe. *Atmosphere*, 12(10):1312.
- Borne, K., Chen, D., and Nunez, M. (1998). A method for finding sea breeze days under stable synoptic conditions and its application to the swedish west coast. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 18(8):901–914.

- Brown, A. and Vincent, C. (2026). The impact of sea breezes on offshore wind energy resources in australia. *Wind Energy Science Discussions*, 2026:1–28.
- Brown, A., Vincent, C., and Short, E. (2026). Identifying sea breezes from atmospheric model output (sea_breeze v1. 1). *Geoscientific Model Development*, 19(2):933–953.
- Cannon, T., Krüger, F., Bankoff, G., Schipper, L., and Bamforth, T. (2014). Putting culture at the centre of risk reduction. *World disasters report*, pages 185–209.
- Chamberlain, J., Bain, C., Boyd, D., McCourt, K., Butcher, T., and Palmer, S. (2014). Forecasting storms over lake victoria using a high resolution model. *Meteorological Applications*, 21(2):419–430.
- Cheng, Y., Zhao, W., Nie, X., Zheng, X., Wu, C., Ren, B., Zhou, Y., Liu, C., Wang, X., and Yang, C. (2025). Enhancing or restricting natural ventilation? an investigation into the influence of urban-lake spatial patterns on the penetration of lake breeze fronts in a multi-lake megacity inland setting. *Land*, 14(6):1211.
- Comer, N. T. and McKendry, I. G. (1993). Observations and numerical modelling of lake ontario breezes. *Atmosphere-Ocean*, 31(3):481–499.
- Copernicus Climate Change Service (2026). Copernicus climate’s era6 reanalysis production starts.
- Cosby, A. G., Lebakula, V., Smith, C. N., Wanik, D. W., Bergene, K., Rose, A., Swanson, D., and Bloom, D. E. (2024). Accelerating growth of human coastal populations at the global and continent levels: 2000–2018. *Scientific Reports*, 14(1):22489.
- Coulibaly, A., Omotosho, B. J., Sylla, M. B., Coulibaly, A., and Ballo, A. (2019). Characteristics of land and sea breezes along the guinea coast of west africa: A. coulibaly et al. *Theoretical and Applied Climatology*, 138(1):953–971.
- Crosman, E. T. and Horel, J. D. (2010). Sea and lake breezes: A review of numerical studies. *Boundary-layer meteorology*, 137(1):1–29.
- Crosman, E. T. and Horel, J. D. (2012). Idealized large-eddy simulations of sea and lake breezes: Sensitivity to lake diameter, heat flux and stability. *Boundary-layer meteorology*, 144(3):309–328.
- Curry, M., Hanesiak, J., Kehler, S., Sills, D. M., and Taylor, N. M. (2017). Ground-based observations of the thermodynamic and kinematic properties of lake-breeze fronts in southern manitoba, canada. *Boundary-layer meteorology*, 163(1):143–159.
- Dagon, K., Truesdale, J., Biard, J. C., Kunkel, K. E., Meehl, G. A., and Molina, M. J. (2022). Machine learning-based detection of weather fronts and associated extreme precipitation in historical and future climates. *Journal of Geophysical Research: Atmospheres*, 127(21):e2022JD037038.

- Dai, A., Giorgi, F., and Trenberth, K. E. (1999). Observed and model-simulated diurnal cycles of precipitation over the contiguous united states. *Journal of Geophysical Research: Atmospheres*, 104(D6):6377–6402.
- Damato, F., Planchon, O., and Dubreuil, V. (2003). A remote-sensing study of the inland penetration of sea-breeze fronts from the english channel. *Weather*, 58(6):219–226.
- Datta, R. (1981). Certain aspects of monsoonal precipitation dynamics over lake victoria. *Monsoon Dynamics*, 333:333–350.
- Davis, W. M., Schultz, L., and Ward, R. D. (1890). An investigation of the sea-breeze. *Ann. Harvard College Obs. Cambridge, Mass*, 21:215–265.
- Defant, A. (1951). Windstau und auftrieb an ozeanischen küsten. *Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie A*, 4(1):296–308.
- Dehghan, A., Mariani, Z., Leroyer, S., Sills, D., Bélair, S., and Joe, P. (2018). Evaluation of modeled lake breezes using an enhanced observational network in southern ontario: Case studies. *Journal of Applied Meteorology and Climatology*, 57(7):1511–1534.
- Deroubaix, A., Menut, L., Flamant, C., Brito, J., Denjean, C., Dreiling, V., Fink, A., Jambert, C., Kalthoff, N., Knippertz, P., et al. (2019). Diurnal cycle of coastal anthropogenic pollutant transport over southern west africa during the dacciwa campaign. *Atmospheric Chemistry and Physics*, 19(1):473–497.
- Diem, J. E., Konecky, B. L., Salerno, J., and Hartter, J. (2019). Is equatorial africa getting wetter or drier? insights from an evaluation of long-term, satellite-based rainfall estimates for western uganda. *International Journal of Climatology*, 39(7).
- Ding, X., Peng, X., Xue, Y., Zhang, L., Wang, T., and Zhang, Y. (2025). An adapter and segmentation network-based approach for automated atmospheric front detection. *Applied Sciences*, 15(14):7855.
- Drobinski, P., Bastin, S., Dabas, A., Delville, P., and Reitebuch, O. (2006). Variability of three-dimensional sea breeze structure in southern france: observations and evaluation of empirical scaling laws. In *Annales Geophysicae*, volume 24, pages 1783–1799. Copernicus Publications Göttingen, Germany.
- ECMWF (2025). Integrated forecasting system (ifs) cycles overview. Accessed: 2026-04-23.
- El-Geziry, T. M., Elbessa, M., and Tonbol, K. M. (2021). Climatology of sea-land breezes along the southern coast of the levantine basin. *Pure and Applied Geophysics*, 178(5):1927–1941.

- Encyclopaedia Britannica (2025). Lake victoria. Accessed 12 June 2026.
- Estoque, M. A. (1962). The sea breeze as a function of the prevailing synoptic situation. *Journal of Atmospheric Sciences*, 19(3):244–250.
- Estoque, M. A., Gross, J., and Lai, H. (1976). A lake breeze over southern lake ontario. *Monthly Weather Review*, 104(4):386–396.
- Ferdiansyah, M. R., Inagaki, A., and Kanda, M. (2020). Detection of sea-breeze inland penetration in the coastal-urban region using geostationary satellite images. *Urban Climate*, 31:100586.
- Finney, D., Marsham, J., Walker, D., Birch, C., Woodhams, B., Jackson, L., and Hardy, S. (2019). The effect of westerlies on East African rainfall and the associated role of tropical cyclones and the Madden-Julian Oscillation. *Quarterly Journal of the Royal Meteorological Society*, 146:647–664.
- Finney, D. L., Marsham, J. H., Rowell, D. P., Kendon, E. J., Tucker, S. O., Stratton, R. A., and Jackson, L. S. (2020). Effects of explicit convection on future projections of mesoscale circulations, rainfall, and rainfall extremes over eastern africa. *Urban Climate*, 33(7):2701–2718.
- Flohn, H. and Burkhardt, T. (1985). Nile runoff at Aswan and Lake Victoria; an example of a discontinuous climate time series. *Z. Gletschkd. Glazialgeol.*, 21:125–130.
- Flohn, H. E. E. M. A. K. N. and Fraedrich, K. (1966). Tagesperiodische zirkulation und niederschlagsverteilung am victoria-see (ostafrika) (the daily periodic circulation and distribution of rainfall over lake victoria). *Meteorologische Rundschau*, 19(6):157–165.
- Fovell, R. G. (2005). Convective initiation ahead of the sea-breeze front. *Monthly Weather Review*, 133(2):264–278.
- Fraedrich, K. (1968). Das land-und seewindsystem des victoria-sees nach aerologischen daten (the land and lake breeze system of lake victoria based on aerological data, in german). *Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie A*, 17(2):186–206.
- Fraedrich, K. (1972). A simple climatological model of the dynamics and energetics of the nocturnal circulation at lake victoria. *Quarterly Journal of the Royal Meteorological Society*, 98(416):322–335.
- Fu, S., Rotunno, R., and Xue, H. (2022). Convective updrafts near sea-breeze fronts. *Atmospheric Chemistry and Physics*, 22(11):7727–7738.

- Glazer, R. H., Coppola, E., and Giorgi, F. (2025). Understanding nocturnally driven extreme precipitation events over lake victoria in a convection-permitting model. *Monthly Weather Review*, 153(6):1085–1103.
- Guedje, F. K., Houeto, A. V., Houngrinou, E. B., Fink, A. H., and Knippertz, P. (2019). Climatology of coastal wind regimes in benin. *Meteorologische Zeitschrift*, 28(1):23–39.
- Hannak, L., Knippertz, P., Fink, A. H., Kniffka, A., and Pante, G. (2017). Why do global climate models struggle to represent low-level clouds in the west african summer monsoon? *Journal of Climate*, 30(5):1665–1687.
- Hastings, D. A. and Coauthors (1999). The global land one-kilometer base elevation (globe) digital elevation model, version 1.0. Accessed 4 June 2025.
- Haupt, J. (2024). *The Land-sea Breeze Along the Guinea Coast and Its Sensitivity to Sea-surface Temperature Variations*. PhD thesis, Karlsruhe Institute of Technology.
- Hawbecker, P. and Knievel, J. C. (2022). An algorithm for detecting the chesapeake bay breeze from mesoscale nwp model output. *Journal of Applied Meteorology and Climatology*, 61(1):61–75.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., et al. (2020). The era5 global reanalysis. *Quarterly journal of the royal meteorological society*, 146(730):1999–2049.
- Hill, A. J., Herman, G. R., and Schumacher, R. S. (2020). Forecasting severe weather with random forests. *Monthly Weather Review*, 148(5):2135–2161.
- Hoeller, J., Haerter, J. O., and Da Silva, N. A. (2024). Characteristics of station-derived convective cold pools over equatorial africa. *Geophysical Research Letters*, 51(6).
- Huffman, G. J., Bolvin, D. T., Nelkin, E. J., and Tan, J. (2023). Integrated multi-satellite retrievals for gpm (imerg) technical documentation. *Nasa/Gsfc Code*, 612(47):2019.
- Hughes, C. P. (2011). *The climatology of the Delaware Bay/sea breeze*. PhD thesis, University of Delaware.
- Hughes, C. P. and Veron, D. E. (2018). A characterization of the delaware sea breeze using observations and modeling. *Journal of Applied Meteorology and Climatology*, 57(7):1405–1421.
- IPCC (2023). *Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

- Jiang, P., Wen, Z., Sha, W., and Chen, G. (2017). Interaction between turbulent flow and sea breeze front over urban-like coast in large-eddy simulation. *Journal of Geophysical Research: Atmospheres*, 122:5298–5315.
- Justin, A. D., Willingham, C., McGovern, A., and Allen, J. T. (2023). Toward operational real-time identification of frontal boundaries using machine learning. *Artificial Intelligence for the Earth Systems*, 2(3):e220052.
- Kalthoff, N., Adler, B., and Bischoff-Gauss, I. (2020). Spatio-temporal structure of the boundary layer under the impact of mountain waves. *Meteorologische Zeitschrift*, 29(5):409–424.
- Keen, C. S. and Lyons, W. A. (1978). Lake/land breeze circulations on the western shore of lake michigan. *Journal of Applied Meteorology*, 17(12):1843–1855.
- King, P. W., Leduc, M. J., Sills, D. M., Donaldson, N. R., Hudak, D. R., Joe, P., and Murphy, B. P. (2003). Lake breezes in southern ontario and their relation to tornado climatology. *Weather and forecasting*, 18(5):795–807.
- Kocen, M. (2013). Observations of sea-breeze fronts along the houston gulf coast.
- Laird, N. F., Kristovich, D. A., Liang, X.-Z., Arritt, R. W., and Labas, K. (2001). Lake michigan lake breezes: Climatology, local forcing, and synoptic environment. *Journal of Applied Meteorology*, 40(3):409–424.
- Liu, Y., Juliano, T. W., Krishnamurthy, R., Gaudet, B. J., and Lee, J. (2025). Linking large-scale weather patterns to observed and modeled turbine hub-height winds offshore of the us west coast. *Wind Energy Science*, 10(2):483–495.
- Loughner, C. P., Allen, D. J., Pickering, K. E., Zhang, D.-L., Shou, Y.-X., and Dickerson, R. R. (2011). Impact of fair-weather cumulus clouds and the chesapeake bay breeze on pollutant transport and transformation. *Atmospheric Environment*, 45(24):4060–4072.
- Lumb, F. E. (1970). Topographic influences on thunderstorm activity near lake victoria. *Weather*, 25(9):404–410.
- Lundquist, J. K. (2022). Wind shear and wind veer effects on wind turbines. In *Handbook of wind energy aerodynamics*, pages 1–22. Springer.
- Lyons, W. A. (1972). The climatology and prediction of the chicago lake breeze. *Journal of Applied Meteorology and Climatology*, 11(8):1259–1270.
- Ma, W., Ma, W., Xie, Z., Wang, B., Shi, H., Woolway, R. I., and Ma, Y. (2026). Unique atmospheric boundary layer structures driven by lake effects. *Communications Earth & Environment*.

- Macharia, D., Fankhauser, K., Selker, J. S., Neff, J. C., and Thomas, E. A. (2022). Validation and intercomparison of satellite-based rainfall products over africa with tahmo in-situ rainfall observations. *Journal of Hydrometeorology*.
- Mapes, B. E., Warner, T. T., and Xu, M. (2003a). Diurnal patterns of rainfall in northwestern south america. part iii: Diurnal gravity waves and nocturnal convection offshore. *Monthly Weather Review*, 131(5):830–844.
- Mapes, B. E., Warner, T. T., Xu, M., and Negri, A. J. (2003b). Diurnal patterns of rainfall in northwestern south america. part i: Observations and context. *Monthly Weather Review*, 131(5):799–812.
- Markowski, P. and Richardson, Y. (2011). *Mesoscale meteorology in midlatitudes*. John Wiley & Sons.
- May, R. M., Arms, S. C., Marsh, P., Bruning, E., Leeman, J. R., Goebbert, K., Thielen, J. E., Bruick, Z. S., and Camron, M. D. (2020). Metpy: A python package for meteorological data. *Version 0.12*, 2.
- Mazzuca, G. M., Pickering, K. E., New, D. A., Dreessen, J., and Dickerson, R. R. (2019). Impact of bay breeze and thunderstorm circulations on surface ozone at a site along the chesapeake bay 2011–2016. *Atmospheric Environment*, 198:351–365.
- McCabe, E. J. and Freedman, J. M. (2023). Development of an objective methodology for identifying the sea-breeze circulation and associated low-level jet in the new york bight. *Weather and Forecasting*, 38(4):571–589.
- Méndez, A., Weckwerth, T. M., Roberts, R. D., and Wilson, J. (2023). Toward improved short-term forecasting for lake victoria basin. part i: a radar-based convective model analysis. *Weather Forec*, 12:2509–2526.
- Miller, S., Keim, B. D., Talbot, R. W., and Mao, H. (2003). Sea breeze: Structure, forecasting, and impacts. *Reviews of geophysics*, 41(3).
- Moon, D. A. (1988). *A Numerical Modeling Investigation of the Effect of Convective-Mesoscale Interactions on the Sea Breeze Circulation*. Ph.d. dissertation, University of Minnesota, Minnesota, USA.
- Moore, D. P. (2019). Detection and analysis of sea breeze and sea breeze enhanced rainfall: A study of the Florida and Delmarva Peninsulas. Master’s thesis, University of Delaware.
- Moroz, W. J. (1967). A lake breeze on the eastern shore of lake michigan: Observations and model. *Journal of Atmospheric Sciences*, 24(4):337–355.

- Muppa, S. K., Anandan, V., Kesarkar, K. A., Rao, S. B., and Reddy, P. N. (2012). Study on deep inland penetration of sea breeze over complex terrain in the tropics. *Atmospheric Research*, 104-105:209–216.
- Ngoma, H., Wen, W., Ojara, M., and Ayugi, B. (2021). Assessing current and future spatiotemporal precipitation variability and trends over uganda, east africa, based on chirps and regional climate model datasets. *Meteorology and Atmospheric Physics*, 133(3):823–843.
- Nicholls, M. E., Pielke, R. A., and Cotton, W. R. (1991). A two-dimensional numerical investigation of the interaction between sea breezes and deep convection over the florida peninsula. *Monthly Weather Review*, 119(2):298–323.
- Nicholson, S., Klotter, D., and Hartman, A. (2021a). Lake-effect rains over Lake Victoria and their association with Mesoscale Convective Systems. *Journal of Hydrometeorology*, pages 1353–1368.
- Nicholson, S. E. (1996). A review of climate dynamics and climate variability in eastern africa. In Johnson, T. C. and Odada, E. O., editors, *The Limnology, Climatology and Paleoclimatology of the East African Lakes*, pages 25–56. Gordon and Breach Publishers.
- Nicholson, S. E. (2017). Climate and climatic variability of rainfall over eastern africa. *Reviews of Geophysics*, 55(3):590–635.
- Nicholson, S. E., Hartman, A. T., and Klotter, D. A. (2021b). On the diurnal cycle of rainfall and convection over lake victoria and its catchment. part i: Rainfall and mesoscale convective systems. *Journal of Hydrometeorology*, 22(11):3037–3047.
- Nicholson, S. E., Hartman, A. T., and Klotter, D. A. (2021c). On the diurnal cycle of rainfall and convection over lake victoria and its catchment. part ii: Meteorological factors in the diurnal and seasonal cycles. *Journal of Hydrometeorology*, 22(11):3049–3064.
- Noble, S., Viner, B., and Wermter, J. (2024). Summary of atmospheric characteristics of days with inland penetrating sea breezes from 2015 to 2021. *Atmospheric Science Letters*, 25(1).
- Ntiba, M. J., Kudoja, W. M., and Mukasa, C. T. (2001). Management issues in the lake victoria watershed. *Lakes & Reservoirs: Research and Management*, 6(3):211–216.
- Nyamweya, C., Lawrence, T. J., Ajode, M. Z., Smith, S., Achieng, A. O., Barasa, J. E., Masese, F. O., Taabu-Munyaho, A., Mahongo, S., Kayanda, R., et al. (2023). Lake victoria: Overview of research needs and the way forward. *Journal of Great Lakes Research*, 49(6):102211.

- Odongo, R. I., Ogwang, B. A., Kisembe, J., and Ngoma, H. N. (2022). An observational study of lake breeze over the victoria basin in uganda. *North American Academic Research*, 5(9):109–123.
- Ogawa, S., Sha, W., and Iwasaki, T. (2003). A numerical study of the interaction of a sea-breeze front with convective cells in the daytime boundary layer. *Journal of the Meteorological Society of Japan*, 81(4):635–651.
- Olaka, L. A., Ogutu, J. O., Said, M. Y., and Oludhe, C. (2019). Projected climatic and hydrologic changes to lake victoria basin rivers under three rcp emission scenarios for 2015–2100 and impacts on the water sector. *Water*, 11(7):1449.
- Papanastasiou, D. and Melas, D. (2009). Climatology and impact on air quality of sea breeze in an urban coastal environment. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 29(2):305–315.
- Physick, W. L. (1976). A numerical model of the sea breeze phenomenon over a lake or gulf. *Journal of the Atmospheric Sciences*, 33(11):2107–2135.
- Pielke, R. A. and Segal, M. (1986). Mesoscale circulations forced by differential terrain heating. In Ray, P. S., editor, *Mesoscale Meteorology and Forecasting*, pages 516–548. American Meteorological Society, Boston, MA.
- Pietroiusti, R., Vanderkelen, I., Otto, F. E. L., Barnes, C., Temple, L., Akurut, M., Bally, P., van Lipzig, N. P. M., and Thiery, W. (2024). Possible role of anthropogenic climate change in the record-breaking 2020 lake victoria levels and floods. *Earth System Dynamics*, 15(2):225–264.
- Planchon, O., Damato, F., Dubreuil, V., and Gouery, P. (2006). A method of identifying and locating sea-breeze fronts in north-eastern brazil by remote sensing. *Meteorological Applications*, 13(3):225–234.
- Porson, A., Steyn, D. G., and Schayes, G. (2007). Formulation of an index for sea breezes in opposing winds. *Journal of Applied Meteorology and Climatology*, 46(8):1257–1263.
- Ramotubei, T. S., Landman, W. A., Mateyisi, M. J., Nangombe, S. S., and Beraki, A. F. (2025). Simulation of the african itcz during austral summer seasons and enso phases: application of an rcm derived from stretched grid esm. *Frontiers in Climate*, 7:1504756.
- Roberts, R. D., Goodman, S. J., Wilson, J. W., Watkiss, P., Powell, R., Petersen, R. A., Bain, C., Faragher, J., Chang’a, L. B., Kapkwomu, J. K., et al. (2022). Taking the highway to save lives on lake victoria. *Bulletin of the American Meteorological Society*, 103(2):E485–E510.

-
- Rotunno, R. (1983). On the linear theory of the land and sea breeze. *Journal of atmospheric sciences*, 40(8):1999–2009.
- Ryznar, E. and Touma, J. S. (1981). Characteristics of true lake breezes along the eastern shore of lake michigan. *Atmospheric Environment (1967)*, 15(7):1201–1205.
- Schrage, J. M. and Fink, A. H. (2012). Nocturnal continental low-level stratus over tropical west africa: Observations and possible mechanisms controlling its onset. *Monthly Weather Review*, 140(6):1794–1809.
- Segal, M., Leuthold, M., Arritt, R. W., Anderson, C., and Shen, J. (1997). Small lake daytime breezes: Some observational and conceptual evaluations. *Bulletin of the American Meteorological Society*, 78(6):1135–1147.
- Semazzi, F. H. M. (2011). Enhancing safety of navigation and efficient exploitation of natural resources over lake victoria and its basin by strengthening meteorological services on the lake. Technical report, North Carolina State University Climate Modeling Laboratory, Raleigh, North Carolina.
- Semazzi, F. H. M., Cornforth, R., Houghton-Carr, H., Bain, C., Anyah, R., Roberts, R., Mutua, F., et al. (2014). Hyvic science plan. Technical report, High Impact Weather Lake System (HyVic) Project.
- Shepherd, J. M., Ferrier, B. S., and Ray, P. S. (2001). Rainfall morphology in florida convergence zones: A numerical study. *Monthly Weather Review*, 129(2):177–197.
- Shokurov, M. V. and Kraevskaya, N. Y. (2024). Sea breeze circulation: Theory and two-dimensional simulation. *Physical oceanography*, 31(4):447–466.
- Sikora, T. D., Young, G. S., and Bettwy, M. J. (2010). Analysis of the western shore chesapeake bay bay-breeze. *National Weather Digest*, 34:55–65.
- Sills, D., Brook, J., Levy, I., Makar, P., Zhang, J., and Taylor, P. (2011). Lake breezes in the southern great lakes region and their influence during baqs-met 2007. *Atmospheric Chemistry and Physics*, 11(15):7955–7973.
- Simpson, J. E. (1994). *Sea breeze and local winds*. cambridge university press.
- Small, C. and Cohen, J. E. (2004). Continental physiography, climate, and the global distribution of human population. *Current Anthropology*, 45(2):269–277.
- Song, J.-L. (1986). *A Numerical Investigation of Florida’s Sea Breeze–Cumulonimbus Interactions*. Ph.d. dissertation, Colorado State University, Fort Collins, Colorado, USA.
- Song, Y., Semazzi, F. H. M., Xie, L., and Ogallo, L. J. (2004). A coupled regional climate model for the lake victoria basin of east africa. *International Journal of Climatology*, 24(1):57–75.
-

- Ssemujju, M., Maranan, M., Fink, A. H., and Ageet, S. (2026a). A novel algorithm for detecting lake-breeze fronts at lake victoria using station observations. *Journal of Applied Meteorology and Climatology*, 65(6):941–960.
- Ssemujju, M., Maranan, M., Fink, H. A., and Ageet, S. (2026b). How well is the lake-land breeze circulation of Lake Victoria captured in ECMWF operational analysis. *Atmospheric Science Letters*.
- Ssenyimba, S., Kiggundu, N., and Banadda, N. (2020). Designing a solar and wind hybrid system for small-scale irrigation: a case study for kalangala district in uganda. *Energy, Sustainability and Society*, 10(1):6.
- Stauffer, R. M. (2012). Bay breeze impact on surface ozone at two coastal sites along the chesapeake bay from 1986-2010.
- Stauffer, R. M. and Thompson, A. M. (2015). Bay breeze climatology at two sites along the chesapeake bay from 1986–2010: Implications for surface ozone. *Journal of Atmospheric Chemistry*, 72(3-4):355–372.
- Stauffer, R. M., Thompson, A. M., Martins, D. K., Clark, R. D., Goldberg, D. L., Loughner, C. P., Delgado, R., Dickerson, R. R., Stehr, J. W., and Tzortziou, M. A. (2015). Bay breeze influence on surface ozone at edgewood, md during july 2011. *Journal of Atmospheric Chemistry*, 72(3-4):335–353.
- Staver, D., Mihanović, H., and Klaić, Z. B. (2022). Lake-land breezes over a small elongated lake (kozjak, plitvice lakes, croatia). *G eofizika*, 39(1):51–70.
- Stull, R. B. (1988). *An introduction to boundary layer meteorology*. Springer Science & Business Media.
- Thiery, W., Davin, E. L., Panitz, H.-J., Demuzere, M., Lhermitte, S., and Van Lipzig, N. (2015). The impact of the african great lakes on the regional climate. *Journal of Climate*, 28(10):4061–4085.
- Thiery, W., Davin, E. L., Seneviratne, S. I., Bedka, K., Lhermitte, S., and van Lipzig, N. P. M. (2016). Hazardous thunderstorm intensification over lake victoria. *Nature Communications*, 7(1).
- Thompson, W. T., Holt, T., and Pullen, J. (2007). Investigation of a sea breeze front in an urban environment. *Quarterly Journal of the Royal Meteorological Society*, 133(624):579–594.
- Valmassoi, A., Anlauf, H., Becker, A., Keller, J., Krebber, S., Zängl, G., Potthast, R., Cress, A., Fundel, F., Hanisch, T., et al. (2025). Icon-dream: Icon-dual resolution reanalysis for emulators, applications and monitoring—the icon-dual resolution reanalysis version v1. 0, deutscher wetterdienst [data set]. *Deutscher Wetterdienst [data set]*, 10.

- Van de Giesen, N., Hut, R., and Selker, J. (2014). The trans-african hydro-meteorological observatory (tahmo). *Wiley Interdisciplinary Reviews (WIREs): Water*, 1(4):341–348.
- Van de Walle, J., Thiery, W., Brousse, O., Souverijns, N., Demuzere, M., and van Lipzig, N. P. M. (2020). A convection-permitting model for the lake victoria basin: evaluation and insight into the mesoscale versus synoptic atmospheric dynamics. *Climate Dynamics*, 54(3-4):1779–1799.
- van der Linden, R., Fink, A. H., and Redl, R. (2015). Satellite-based climatology of low-level continental clouds in southern west africa during the summer monsoon season. *Journal of Geophysical Research: Atmospheres*, 120(3):1186–1201.
- Viner, B., Noble, S., Qian, J.-H., Werth, D., Gayes, P., Pietrafesa, L., and Bao, S. (2021). Frequency and characteristics of inland advecting sea breezes in the southeast united states. *Atmosphere*, 12(8):950.
- Virts, K. S. and Goodman, S. J. (2020). Prolific lightning and thunderstorm initiation over the lake victoria basin in east africa. *Monthly Weather Review*, 148(5):1971–1985.
- Vizy, E. K., Cook, K. H., and Andrews, P. C. (2026). Role of mid-level circulation and moisture accumulation in generating lake victoria’s extreme storms. *Climate Dynamics*, 64(3):81.
- Wagner, T. J., Czarnetzki, A. C., Christiansen, M., Pierce, R. B., Stanier, C. O., Dickens, A. F., and Eloranta, E. W. (2022). Observations of the development and vertical structure of the lake-breeze circulation during the 2017 lake michigan ozone study. *Journal of the Atmospheric Sciences*, 79(4):1005–1020.
- Wainwright, C. M., Finney, D. L., Kilavi, M., Black, E., and Marsham, J. H. (2021). Extreme rainfall in East Africa, October 2019–January 2020 and context under future climate change. *Weather*, 76(1):26–31.
- Waiswa, M. M. (2023). Status of uganda network of buoys. Inspection report, Ministry of Works and Transport (MoWT) and Uganda Department of Meteorological Services (UDMS), Uganda. Prepared by Milton Michael Waiswa, Ag. Director Station Networks and Weather Observations.
- Wang, C.-C. and Kirshbaum, D. J. (2017). Idealized simulations of sea breezes over mountainous islands. *Quarterly Journal of the Royal Meteorological Society*, 143(704):1657–1669.
- Wang, C.-C., Kirshbaum, D. J., and Sills, D. M. (2019). Convection initiation aided by lake-breeze convergence over the niagara peninsula. *Monthly Weather Review*, 147(11):3955–3979.

- Wang, Y. and Zhuo, M. (2022). Modeling investigation of thermal circulations of a large and shallow subtropical lake. *Water*, 14(22):3719.
- Waniha, P. F., Roberts, R. D., Wilson, J. W., Kijazi, A., and Katole, B. (2019). Dual-polarization radar observations of deep convection over lake victoria basin in east africa. *Atmosphere*, 10(11):706.
- Warner, T. T., Mapes, B. E., and Xu, M. (2003). Diurnal patterns of rainfall in northwestern south america. part ii: Model simulations. *Monthly Weather Review*, 131(5):813–829.
- Watts, A. (1955). Sea breeze at thorney island. *Meteorological Magazine*, 84:42–48.
- Wentworth, G., Murphy, J., and Sills, D. (2015). Impact of lake breezes on ozone and nitrogen oxides in the greater toronto area. *Atmospheric Environment*, 109:52–60.
- Wermter, J., Noble, S., and Viner, B. (2022). Impacts of the thermal gradient on inland advecting sea breezes in the southeastern united states. *Atmosphere*, 13(7):1004.
- Wilson, J. and Roberts, R. D. (2022). Lake victoria thunderstorms: Radar-observed initiation and storm evolution modes. *Monthly weather review*, 150(10):2485–2502.
- Wilson, J. W., Weckwerth, T. M., Vivekanandan, J., Wakimoto, R. M., and Russell, R. W. (1994). Boundary layer clear-air radar echoes: Origin of echoes and accuracy of derived winds. *Journal of Atmospheric and Oceanic Technology*, 11(5):1184–1206.
- WMO (2025). *State of the Climate in Africa 2024*. World Meteorological Organization, WMO-No.1370. United Nations.
- Wood, R., Stromberg, I. M., and Jonas, P. R. (1999). Aircraft observations of sea breeze frontal structure. *Quarterly Journal of the Royal Meteorological Society*, 125(558):1959–1995.
- Woodhams, B. J., Barrett, P. A., Marsham, J. H., Birch, C. E., Bain, C. L., Fletcher, J. K., Hartley, A. J., Webster, S., and Mangeni, S. (2022). Aircraft observations and sub-km modelling of the lake–land breeze circulation over lake victoria. *Quarterly Journal of the Royal Meteorological Society*, 148(743):557–580.
- Woodhams, B. J., Birch, C. E., Marsham, J. H., Lane, T. P., Bain, C. L., and Webster, S. (2019). Identifying key controls on storm formation over the lake victoria basin. *Monthly Weather Review*, 147(9):3365–3390.
- Xu, L., Liu, H., Du, Q., Liu, Y., Sun, J., Xu, A., and Meng, X. (2021). Characteristics of lake breezes and their impacts on energy and carbon fluxes in mountainous areas. *Advances in Atmospheric Sciences*, 38(4):603–614.

- Zhang, F., Bei, N., Nielsen-Gammon, J. W., Li, G., Zhang, R., Stuart, A., and Aksoy, A. (2007). Impacts of meteorological uncertainties on ozone pollution predictability estimated through meteorological and photochemical ensemble forecasts. *Journal of Geophysical Research: Atmospheres*, 112(D4).
- Zhang, Y., Han, C., Ma, Y., Fu, S., Zuo, H., and Huang, Q. (2024). Influence of lake breezes on the triggering of moist convection on the tibetan plateau: a large-eddy simulation study. *Journal of the Atmospheric Sciences*, 81(6):983–998.
- Zhu, M. and Atkinson, B. (2004). Observed and modelled climatology of the land–sea breeze circulation over the persian gulf. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 24(7):883–905.

Appendices

Appendix A: Tables

Table A.1: List of meteorological stations with their locations, elevations, and start dates. Stations are classified by distance to the nearest Lake Victoria shoreline (categories A–E) and by coastal sector location (North: N, Northwest: NW, and West: W).

Station Name	Longitude (degree)	Latitude (degree)	Elevation (m)	Distance to shoreline (km)	Station classification	Coastal sector	Start Date
Entebbe WDD	32.47	0.090	1149	0.2	A1	N	01-01-2017
NaFIRRI	32.76	0.430	–	0.2	A2	N	06-06-2020
Ggaba	32.63	0.270	1187	1.0	A3	N	28-08-2019
Entebbe NMC	32.44	0.090	1138	1.1	A4	N	09-09-2017
Wanyange Girls	33.24	0.480	1346	2.6	A5	N	01-11-2017
Busoga College	33.26	0.499	1355	3.3	A6	N	16-11-2018
Jinja Airfield	33.20	0.450	1177	3.4	A7	N	05-09-2017
Kyambogo	32.63	0.355	1241	7.3	B1	N	29-08-2019
Nakivubo Blue	32.58	0.308	1163	7.4	B2	N	22-08-2019
Mayuge-Ikugwe	33.58	0.433	–	7.4	B3	N	30-04-2020
Kituuzi NARO	32.77	0.267	–	8.6	B4	N	23-01-2018
Mengo SS	32.56	0.320	1247	9.2	B5	N	22-08-2019
Makerere University	32.57	0.333	1244	9.3	B6	N	09-09-2017
Kisaasi	32.60	0.376	1218	10.8	B7	N	22-08-2019
Iganga Girls	33.46	0.585	1148	12.9	B8	N	06-09-2017
Butambala	32.13	0.184	1223	17.8	B9	NW	20-04-2018
Mpoma	32.76	0.429	–	18.1	B10	N	30-09-2019
Kawanda	32.53	0.417	–	18.5	B11	N	10-06-2020
Kamenyamigo	31.67	-0.280	–	27.3	C1	W	06-12-2016
Bugema University	32.64	0.572	1167	30.2	C2	N	03-09-2017
Nakabale	33.27	0.752	1114	30.5	C3	N	05-09-2017
Kabulasoke	31.81	0.156	1218	31.2	C4	NW	06-09-2017
Rakai	31.40	-0.708	1267	34.6	C5	W	17-01-2020
Kibanda	31.37	-0.860	1195	36.8	C6	W	17-01-2020
Kibaale	31.35	-0.779	1228	39.2	C7	W	17-01-2020
Ndejje SS	32.48	0.611	1223	40.1	D1	N	01-01-2017
Mityana SS	32.04	0.378	1245	41.4	D2	NW	01-01-2017
Kayunga	32.90	0.712	–	46.4	D3	N	01-01-2016
Semuto	32.37	0.621	1170	47.5	D4	N	19-02-2020
Mateete	31.48	-0.243	1254	47.7	D5	W	18-01-2020
Kaliro	33.52	0.900	–	47.8	D6	N	07-01-2022
Bukalasa	32.51	0.713	1172	48.7	D7	N	06-09-2017
Sembabule	31.46	-0.089	1200	51.6	D8	W	02-03-2020
Tororo	34.17	0.698	1177	52.4	D9	N	06-09-2017
Busitema University	34.05	0.757	1119	54.9	D10	N	22-04-2017
Lwebitakuli	31.35	-0.256	1270	60.4	D11	W	18-01-2020
Nawaikoke	33.41	1.090	–	66.4	D12	N	01-01-2016
Namasagali	32.95	1.014	–	69.9	D13	N	01-01-2016
Nakaseke	32.25	0.829	1090	73.9	D14	N	05-09-2017
Ntuusi	31.22	0.048	1306	81.0	D15	NW	07-09-2017
Kiige	33.03	1.183	–	83.0	D16	N	01-02-2017
Mubende	31.39	0.563	1319	96.3	E1	NW	12-12-2018
Kalongo Seed	32.74	1.207	1047	100.4	E2	N	04-09-2017
Mbarara	30.67	-0.605	1425	120.2	E3	W	08-09-2017
Ngoma SS	32.02	1.186	1069	131.9	E4	NW	05-09-2017

Table A.2: Number of lake-breeze (LB) days recorded at each station and percentage relative to the total number of valid DJF and JJA days (days with >80% of wind or temperature data) during 2017–2022.

Station	Coast sector	Valid days	LB days	LB days (%)
A1	N	943	414	43.9
A2	N	481	206	42.8
A3	N	563	254	45.1
A4	N	786	328	41.7
A5	N	924	358	38.7
A6	N	680	229	33.7
A7	N	131	70	53.4
B1	N	561	217	38.7
B2	N	573	246	42.9
B3	N	486	104	21.4
B4	N	318	133	41.8
B5	N	536	101	18.8
B6	N	857	243	28.4
B7	N	566	160	28.3
B8	N	822	150	18.2
B9	NW	664	201	30.3
B10	N	548	120	21.9
B11	N	446	87	19.5
C1	W	1093	472	43.4
C2	N	847	128	15.1
C3	N	639	238	37.2
C4	NW	823	166	20.2
C5	W	484	48	9.9
C6	W	516	177	34.3
C7	W	355	109	30.7
D1	N	844	130	15.4
D2	NW	987	200	20.3
D3	N	1093	401	36.7
D4	N	394	109	27.7
D5	W	520	193	37.1
D6	N	145	43	29.7
D7	N	485	149	30.7
D8	W	447	166	37.1
D9	N	819	172	21.0
D10	N	679	168	24.7
D11	W	288	122	42.4
D12	N	970	249	25.7
D13	N	954	33	3.5
D14	N	614	78	12.7
D15	NW	643	202	31.4
D16	N	1062	269	25.3
E1	NW	741	20	2.7
E2	N	819	127	15.5
E3	W	735	216	29.4
E4	NW	755	118	15.6

Table A.3: Number of lake-breeze (LB) days recorded at each station, also expressed as a percentage relative to the total number of valid days (days with >80% of wind or temperature data) during the DJF and JJA seasons for 2017-2022 (2020-22).

Station	Coast sector	2017-2022 (2020-22) DJF-JJA Valid Days	2017-2022 (2020-22) LB Days	2017-2022 (2020-22) Percentage LB days (%)
A1	N	943 (517)	414 (239)	43.9 (46.2)
A2	N	481 (481)	206 (206)	42.8 (42.8)
A3	N	563 (531)	254 (243)	45.1 (45.8)
A4	N	786 (499)	328 (207)	41.7 (41.5)
A5	N	924 (539)	358 (197)	38.7 (36.5)
A6	N	680 (523)	229 (169)	33.7 (32.3)
A7	N	131 (0)	70 (0)	53.4 (0)
B1	N	561 (530)	217 (204)	38.7 (38.5)
B2	N	573 (534)	246 (229)	42.9 (42.9)
B3	N	486 (486)	104 (104)	21.4 (21.4)
B4	N	318 (64)	133 (20)	41.8 (31.3)
B5	N	536 (497)	101 (91)	18.8 (18.3)
B6	N	857 (464)	243 (107)	28.4 (23.1)
B7	N	566 (528)	160 (151)	28.3 (28.6)
B8	N	822 (471)	150 (17)	18.2 (3.6)
B9	NW	664 (370)	201 (112)	30.3 (30.3)
B10	N	548 (546)	120 (119)	21.9 (21.8)
B11	N	446 (446)	87 (86)	19.5 (19.3)
C1	W	1093 (547)	452 (268)	41.4 (49.0)
C2	N	847 (528)	128 (51)	15.1 (9.7)
C3	N	639 (385)	238 (125)	37.2 (32.5)
C4	NW	823 (507)	166 (69)	20.2 (13.6)
C5	W	484 (484)	48 (48)	9.9 (9.9)
C6	W	516 (516)	177 (177)	34.3 (34.3)
C7	W	355 (355)	109 (109)	30.7 (30.7)
D1	N	844 (466)	130 (0)	15.4 (0.0)
D2	NW	987 (537)	200 (80)	20.3 (14.9)
D3	N	1093 (547)	401 (186)	36.7 (34.0)
D4	N	394 (394)	109 (109)	27.7 (27.7)
D5	W	520 (520)	193 (193)	37.1 (37.1)
D6	N	145 (145)	43 (43)	29.7 (29.7)
D7	N	485 (425)	149 (135)	30.7 (31.8)
D8	W	447 (447)	166 (166)	37.1 (37.1)
D9	N	819 (530)	172 (54)	21.0 (10.2)
D10	N	679 (483)	168 (128)	24.7 (26.5)
D11	W	288 (288)	122 (122)	42.4 (42.4)
D12	N	970 (424)	249 (103)	25.7 (24.3)
D13	N	954 (504)	33 (28)	3.5 (5.6)
D14	N	614 (394)	78 (41)	12.7 (10.4)
D15	NW	643 (534)	202 (175)	31.4 (32.8)
D16	N	1062 (547)	269 (137)	25.3 (25.0)
E1	NW	741 (542)	20 (17)	2.7 (3.1)
E2	N	819 (536)	127 (89)	15.5 (16.6)
E3	W	735 (481)	216 (89)	29.4 (18.5)
E4	NW	755 (461)	118 (82)	15.6 (17.8)

Appendix B: Figures

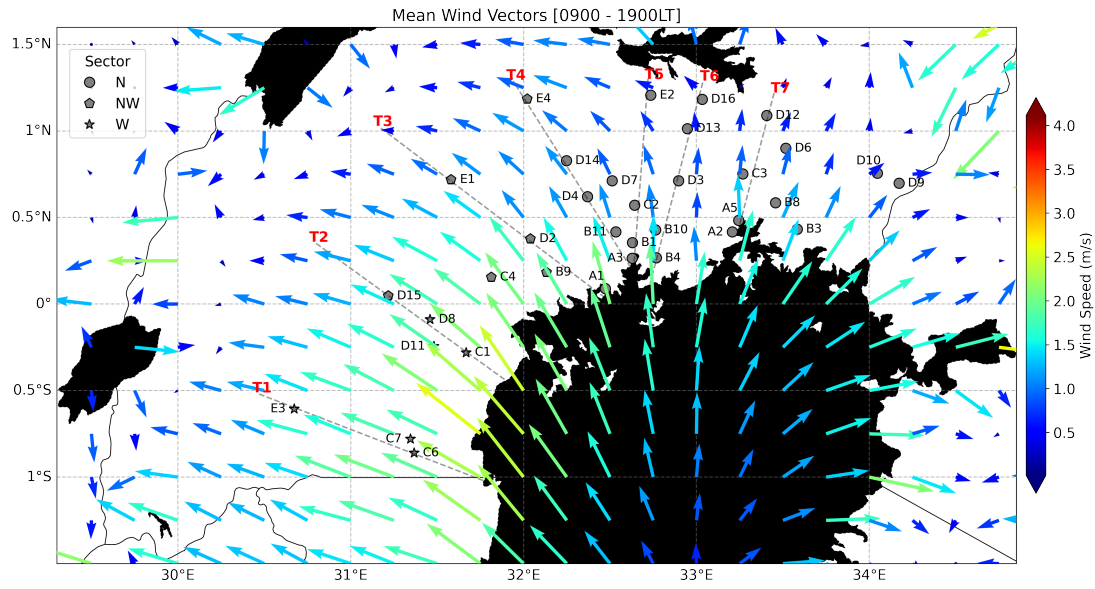


Figure B.1: Daytime mean 10-m wind pattern from IFS during DJF and JJA seasons. Black-dashed and red-dashed lines are transects that represent station pairs used to calculate LBF propagation speeds. The red-dashed line (B4-D16) is projected onto transect B4-E2 to align with the prevailing wind flow. Station symbols indicate sector affiliation: circles (North), pentagons (Northwest), and stars (West; see inset).

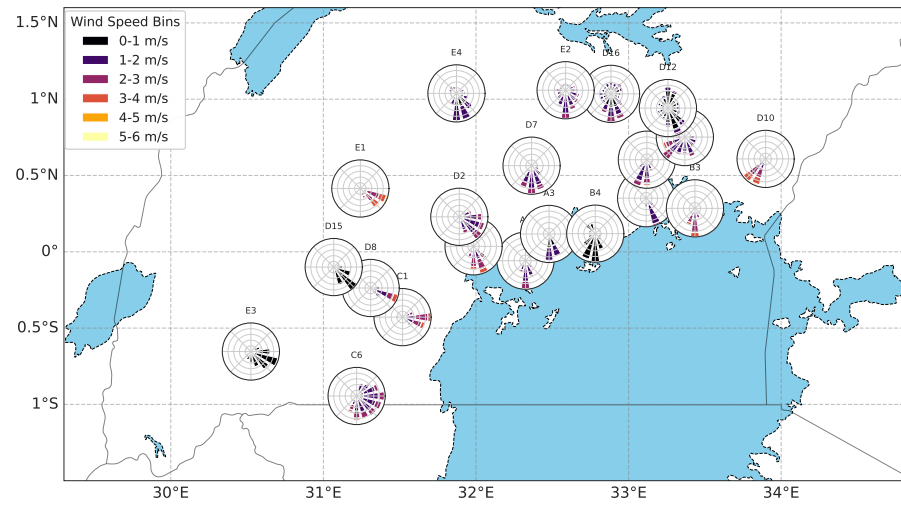


Figure B.2: Composite wind roses of 2-m winds at stations on lake-breeze days.

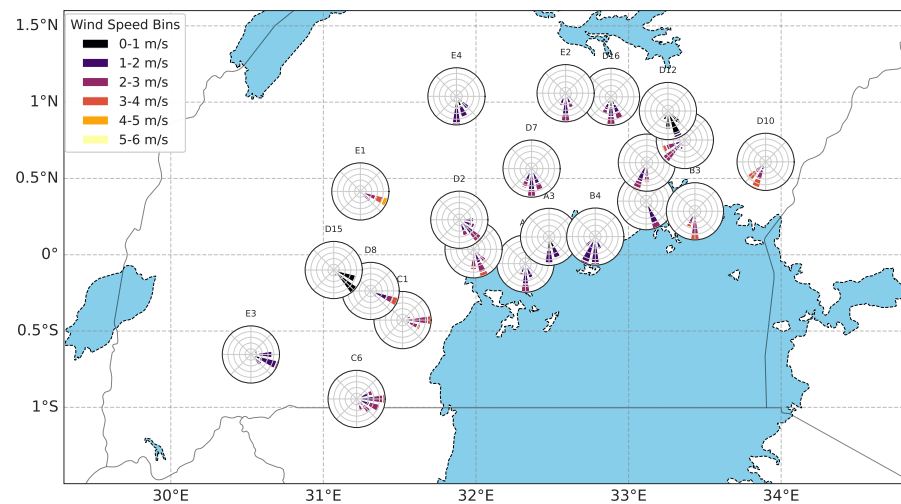


Figure B.3: Composite wind roses of 2-m winds at stations after the lake-breeze front passage.

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