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Estimating areal rainfall over Lake Victoria and its basin using ground-based and satellite data

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ABSTRACT

A gridded monthly rainfall dataset having a spatial resolution of 2 km and covering the period 1960–2004 was derived for the Lake Victoria basin. The lake and its basin support more than 30 million people and also contribute substantially to the River Nile flow. The major challenge in the estimation of the Lake Victoria water balance is the estimation of the rainfall over the lake, which is further complicated by the varying quality and spatial coverage of rain-gauge data in the basin. In this study, these problems were addressed by using rain-gauge data for 315 stations around the basin and satellite-derived precipitation data from two products to derive a monthly precipitation dataset for the entire basin, including the lake. First, the rain-gauge data were quality controlled. Thereafter short gaps were filled in the daily data series which resulted in 9429 additional months of data. Two spatial interpolation methods were used for generating the gridded rainfall dataset and the universal kriging method performed slightly better than the inverse distance weighting method. The enhancement of rainfall over the lake surface was addressed by estimating a relationship between rain-gauge and satellite data. Two satellite rainfall products, TRMM 3B43 and PERSIANN were compared to the interpolated monthly rain-gauge data for the land part of the basin. The bias in the TRMM 3B43 rainfall estimates was higher than the bias for PERSIANN but its correlation was higher with a better representation of the intra-annual variability. The TRMM 3B43 product showed an enhancement of lake rainfall over basin rainfall of 33% while the PERSIANN product gave a much higher enhancement of up to 85%.

1. Introduction

With a surface area of 68,800 km^2, Lake Victoria is the largest freshwater lake in the tropics and the second largest in the world. The lake and its basin support over 30 million people, who directly or indirectly depend on it for their livelihoods, drawing on services like fishing, transport, agriculture, water supply, tourism and hydropower (Ntiba et al., 2001). The lake system, including the wetland and the rivers that flow into it, is the largest inland water sanctuary in East Africa. Being one of the sources of the Nile, the lake is a major supplier for the water needs of Sudan and Egypt (Sutcliffe and Parks, 1999). About 80% of the input into the lake is rainfall over its surface, leading some researchers to describe it as 'atmosphere controlled' (Flohn and Burkhardt, 1985; Tate et al., 2004; Yin and Nicholson, 2002). This essentially means that the variability of rainfall over the lake plays a key role in the fluctuation of the lake levels. Evaporation, which is the largest output, is considered to have less inter-annual variation and, therefore, a smaller effect on lake level fluctuations (Sutcliffe and Parks, 1999). In addition, evaporation is difficult to estimate as available data are usually fragmented and unreliable. Historically, the lake levels have exhibited large and rapid changes in response to rainfall anomalies over the last century (Conway, 2002; Fraedrich, 1972; Mistry and Conway, 2003; Yin and Nicholson, 2002).

There are three major problems related to the assessment of spatial variability of rainfall in the Lake Victoria basin. The first is the differences in the spatial distribution of rainfall stations around the lake (Fig. 1). The second is that the data quality varies considerably depending on data source and period analysed, with frequent gaps in the series varying from days to several years. The third problem is that there are hardly any long-term rainfall stations on the lake surface which makes the estimation of the lake areal rainfall based only on rain-gauges impossible.

The earliest data collection expeditions in the basin were carried out at the turn of the 20th century, but more regular collection

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of rainfall and other hydro-meteorological data started in the mid-1920s as part of the preparations for the construction of the Owen Falls dam. Following the sudden rise in water level between 1961 and 1964, the hydrometerological survey project was set up under WMO and intensified the collection of data in the lake and its basin (de Baulny and Baker, 1970; WMO, 1982). This monitoring network was later handed over to the respective countries to manage. As a result there have been more than 1000 documented rainfall gauging stations in the Lake Victoria basin over time. While the distribution of the stations is not uniform in time and space around the basin, they, nonetheless, provide a sample that is representative for analysing the spatial rainfall variability within most parts of the basin.

Estimation of rainfall over Lake Victoria has been a subject of intense investigation due to the lake's abrupt water-level variations and anomalous hydrologic fluctuations (de Baulny and Baker, 1970; Fraedrich, 1972; Mistry and Conway, 2003; Tate et al., 2004; WMO, 1982; Yin and Nicholson, 2002). A standard scheme was proposed by the WMO (1982) hydro-meterological survey project that relied on eight stations around the lake. These stations were used by de Baulny and Baker (1970) to derive a monthly rainfall series for the period 1925–1969. Kite (1981) pointed out that neither the lake's water balance for the 1950s, nor the lake's abrupt rise in the early 1960s could be adequately simulated using a simple water-balance model or a lake-routing model. The discrepancy was particularly large for the 1961–1964 period, when the simulated lake water level rise of 151 mm/year was far smaller than the observed rise of 505 mm/year over the 4-year period. When Kite (1981) increased the lake rainfall values of de Baulny and Baker (1970) by 25–30%, he could accurately reconstruct Lake Victoria's fluctuations prior to the 1970s using a routing model. By increasing the lake rainfall data by 25% in 1977 and 1978 and by 30% in 1979, he could also reproduce the lake's rise during these years. While the selection of the multiplication factors is subjective, later studies also support this idea of an enhancement of rainfall over the lake compared to the surrounding land (Ba and Nicholson, 1998; Datta, 1981; Flohn, 1987; Fraedrich, 1972; Piper et al., 1986). Rainfall enhancement is produced by a nocturnal lake-breeze circulation that produces convergence over the center of the lake (Ba and Nicholson, 1998). The convergence effect is further enhanced by the thermal instability of the boundary layer over the lake, which is a result of air temperatures above the lake being approximately 3 °C lower than the lake surface itself. Consequently, large and intense cumulonimbus clusters develop over the lake at night. The nocturnal circulation produces about 50% of the rainfall over the land and enhances rainfall over the lake considerably, compared to that over its catchment (Fraedrich, 1972). Observations on islands in the lake showed that rainfall amounts can be in excess of 2000 mm/year compared to an average of about 1200 mm/year over the land. There is therefore no doubt that land-based rain gauges are inadequate for direct estimation of lake rainfall. Therefore, to produce reliable areal rainfall estimates over the lake as an input to water-balance studies, it is necessary to account for the rainfall enhancement over the lake. Remotely sensed precipitation data provide a direct means to assess the lake rainfall.

The aim of this study was to derive a spatially detailed gridded monthly rainfall dataset for the lake basin with an improved estimate of the lake surface rainfall through the use of satellite-derived precipitation data. A systematic three-step approach was used to address the three problems identified above; (1) data quality control of rainfall from land gauging stations, (2) spatial interpolation, and (3) estimation of lake rainfall using two remotely sensed precipitation datasets. This dataset is intended as an input to future hydrological studies aimed at water resources management in the basin.

2. Study area and data

2.1. The Lake Victoria basin

Lake Victoria is located between latitudes 0°20′N–3°S and longitudes 31°40′E–34°53′E (Fig. 1). The lake basin area is 194,000 km^2 and the lake surface area is about 68,800 km^2 or 35% of the basin. The lake surface is shared between Kenya (6%), Uganda (43%) and Tanzania (51%) while its basin also includes parts of Burundi and Rwanda. The altitude of the lake surface is about 1,135 m above mean sea level (a.s.l.). The basin consists of a series of stepped plateaus with an average elevation of 2,700 m a.s.l. but rising to 4,000 m a.s.l. or more in the highland areas. The lake is relatively shallow with an average depth of 45 m and maximum depth of 92 m. The main river flowing into the lake is the Kagera which, together with four other tributaries (Nzoia, Yala, and Sondu and Awach-Kaboun) contribute about 50% of the inflow (about 11.5 km^3/year) though there are more than 20 rivers that drain into the lake.

2.2. Rainfall regime

The general climate of the Lake Victoria basin ranges from a modified equatorial type with substantial rainfall occurring throughout the year, particularly over the lake and its vicinity, to a semiarid type characterised by intermittent droughts over some areas located even within short distances from the lake shore (Anyah et al., 2006; Nicholson, 1996). The diurnal, seasonal and interannual variability of the basin climate (and East Africa generally) results from a complex interaction between the Inter-Tropical Convergence Zone (ITCZ), El Nino/Southern Oscillation (ENSO), Quasi-Biennial Oscillation (QBO), large-scale monsoonal winds, meso-scale circulations and extra-tropical weather systems (Mutai et al., 1998; Nicholson and Yin, 2002; Ogallo et al., 1988). The wind and pressure patterns that govern the region's climate include three principal air streams namely; the Congo airstream with westerly and south-westerly winds, the southeast monsoon and the northeast monsoon (Nicholson, 1996; Trewartha, 1981). The Congo air mass is humid, thermally unstable and, therefore associated with rainfall. The monsoons are thermally stable, and associated with subsiding air, and are therefore relatively dry, which partly accounts for the relatively arid conditions in much of East Africa. The three airstreams are separated by two convergence zones; the ITCZ which separates the monsoons and the Congo air boundary which separates the Indian Ocean easterlies and Atlantic Ocean westerlies (Trewartha, 1981). A third convergence zone aloft separates the dry, stable northerly flow from Sahara and the moister southerly flow (Nicholson, 1996).

The seasonal climate patterns follow the seasonal north–south movement of the ITCZ which lags the seasonal migration of the sun by about 1.5 months and results in a bimodal rainfall distribution; the March–May rainfall period (long rains) and the October–December rainfall period (short rains). The northeast (NE) and southeast (SE) monsoon winds also modify the seasonal climate of East Africa (Mukabana and Pielke, 1996). The NE monsoon air stream occurs when the sun is south of the equator (October–March) and, after traversing over Egypt and Sudan, is warm and dry. On the other hand, the SE monsoon air stream occurs when the sun is north of the equator (April–October). It is cool and moist after picking up maritime moisture from the Indian Ocean and is responsible for large-scale precipitation over most of East Africa. The QBO is a quasi-periodic oscillation of the equatorial zonal wind between easterlies and westerlies in the tropical stratosphere with a mean period of 28 months (Indeje and Semazzi, 2000). A strong relationship has been demonstrated between QBO and seasonal