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Forecasting storms over Lake Victoria using a high resolution model

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ABSTRACT: Lake Victoria in East Africa is one of the world's largest freshwater lakes and is used on a daily basis by thousands of fishermen. Each year, severe storms on the lake cause multiple boating accidents which often result in fatalities. Recent initiatives have seen an effort to reduce accidents by issuing storm warnings when severe weather is expected. Here the Met Office global Unified Model is evaluated along with a 4 km limited-area model which has been set up to assist forecasters in the region to issue these warnings. Findings indicate the 4 km model is capable of producing more realistic strong wind speeds and rain rates than the global model. Case studies relating to fatal boating accidents on 1 March and 4 March 2012, showed improved warning signals of severe storms in the 4 km model compared to the global model. Objective comparisons between model and observations were conducted on 2 months of data. An objective method was used to determine 'storm'/'no storm' in the model forecasts. These were then compared against cloud top temperature from IR satellite and lightning data from the arrival time difference (ATD) radio ground network to determine whether each model was successful at forecasting storm/calm events. The 4 km model was able to capture more storm hits (thus had fewer storm misses), but also gained more false alarm events. Overall, the objective analysis showed that both models had some predictive skill and both were an improvement on a persistence forecast.

KEY WORDS forecasting; tropical thunderstorms; Lake Victoria; Uganda; limited area model; Met Office

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1. Introduction

Lake Victoria is the largest lake in Africa, with a surface area of approximately 68 000 km^2. The lake extends into Uganda, Kenya and Tanzania and provides fresh water to a large population enabling agriculture, fishing and some local supply of hydroelectric energy. The fishing industry on the lake contributes more than 30% of the food supply for the region surrounding the lake (Song *et al.*, 2004).

The lake is located between the eastern and western branches of the East Africa Rift System more than 1100 m above sea level. The seasonal climate of this region of East Africa is controlled largely by the passage of the Inter-Tropical Convergence Zone (ITCZ). The region experiences two main rainfall seasons as the ITCZ transitions between its northern most and southern most locations (Nicholson, 1996). Figure 1 shows the average daily rainfall over the lake between 1997 and 2007 from the Global Precipitation Climatology Project (GPCP) dataset. GPCP is a blend of microwave data from polar orbiting satellites, infrared (IR) data from geostationary satellites and rain gauge observations (Huffman *et al.*, 1997). Rainfall occurs over the lake throughout the year with peaks in March to May (long rains) and October to December (short rains).

Lake/land breezes driven by the thermal gradient between the lake and land surface dominate the diurnal cycle over the lake and surrounding area. During the day the land warms more than the lake surface, setting up a lake breeze that results in convection over the land east of the lake (see Figure 2). Anyah *et al.* (2006) found that this process is enhanced by the terrain east of the lake when anabatic (upslope) winds are generated. These winds are caused by mountain tops heating faster than their surroundings, drawing the lake breeze front further east. Conditions over the lake are not conducive to thunderstorm development when a daytime lake breeze is in effect as it results in divergent flow over the lake and subsidence that suppresses vertical development of storms.

The lake breeze process is reversed at night, when the lake surface is warmer than the land surface, leading to convergence over the lake that is enhanced by both katabatic (downslope) winds from the terrain to the east (Anyah *et al.*, 2006) and thermal instability resulting from air temperatures being $\sim$3 °C cooler than the lake surface (Ba and Nicholson, 1998). This night-time land breeze circulation leads to a peak in convection over the lake between 0000 and 0600 UTC (Ba and Nicholson, 1998; Song *et al.*, 2004; Anyah *et al.*, 2006). Figure 2 shows the fraction of time very cold cloud ($<$ 210 K) is present over the lake in local time (UTC + 3 h) and the strong diurnal cycle can be seen with a peak in convection present between 0300 LT (0000 UTC) and 0900 LT (0600 UTC). Results from Yin *et al.* (2000) indicate an east–west split in the diurnal cycle over the lake with the early morning peak in convection occurring in the west (particularly north-west) and a late afternoon peak over the eastern part of the lake. Figure 2 appears to corroborate this finding.

The nocturnal circulation that leads to convection over the lake in the early hours of the morning is present roughly 175 days *per* year, lasting for around 6 h *per* day (Flohn and Burkhardt, 1985). In addition to this, severe storms can form over nearby land regions and advect over the lake at any time of day.

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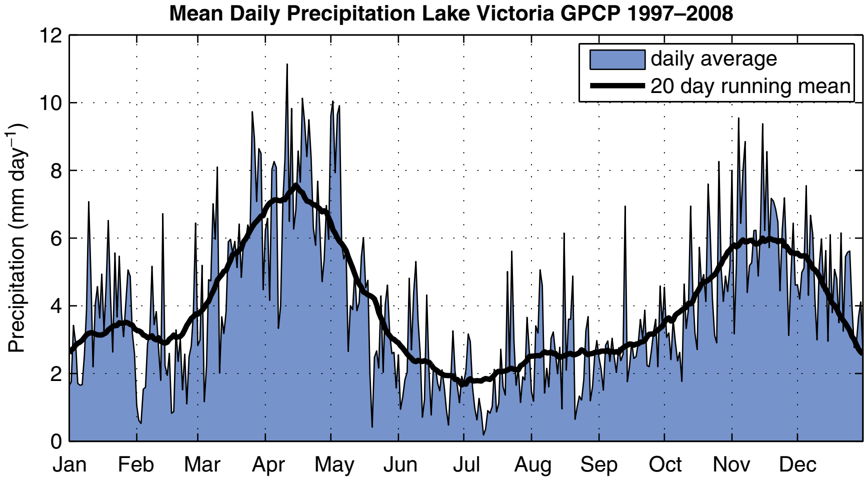

Figure 1. Annual cycle of precipitation over Lake Victoria from GPCP satellite and gauge observations. The shaded region shows the mean precipitation each day for 1997–2008. The black line is a smoothed 20 days running mean. This figure is available in colour online at wileyonlinelibrary.com/journal/met

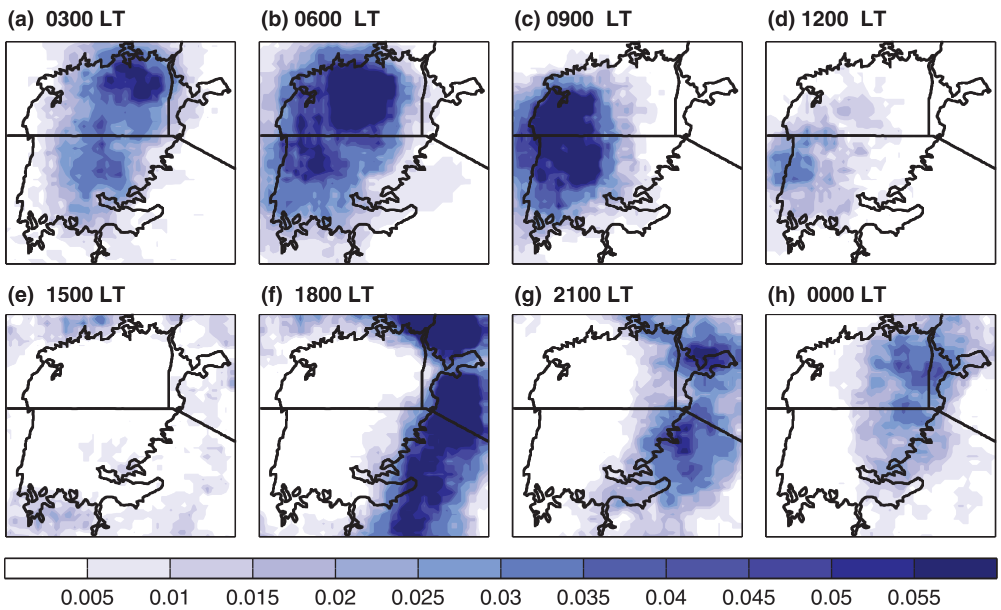

Figure 2. Diurnal cycle of fraction of cold cloud < 210 K at 3 h intervals from (a) 0000 UTC to (h) 2100 UTC from IR satellite taken from the GridSat database (Knapp *et al.*, 2011). The shading represents a mean from January to December 2009. Figures labelled in local time (UTC + 3 h). This figure is available in colour online at wileyonlinelibrary.com/journal/met

The lake is used daily by a large number of boats for transportation and fishing. High winds and waves associated with storm downdrafts can pose a serious hazard for lake users. Local news reports indicate that hundreds of people lose their lives on the lake each year, with a proportion of these related to storm conditions on the lake, and others attributed to poorly maintained boats, a lack of health and safety awareness/equipment, swimming ability, or a combination of these factors.

The Met Office, through the UK contribution to the World Meteorological Organisation Voluntary Cooperation Programme (VCP), has a long-standing commitment to help developing countries improve their meteorological services. In May 2011 the Met Office became involved with a new Mobile Weather Alert Service in Uganda, a project coordinated by the World Meteorological Organisation (WMO). Ugandan forecasters from the Department of Meteorology use model information from a range of available sources, including from the Met Office global Unified Model (UM) at 40 km resolution and a 4 km limited area version of the UM centred over Lake Victoria. The forecasters use the model information along with satellite and other indicators to produce colour-coded hazard warnings which are disseminated directly to local fishermen *via* SMS text message, alerting them of potential storm risks. The pilot study has recruited over 1000 people to take part in the alert system with the aim of expansion in future.

Met Office model performance over Lake Victoria is assessed during spring 2012 with the aim of quantifying the forecast skill of the operational global UM *versus* the 4 km limited area UM in the prediction of dangerous weather events. It should not be assumed that higher resolution models will always improve all meteorological representation, or that it should lead to increased skill in the forecast. Improving skill depends on the relative influence of data assimilation and representation and interaction of meteorological processes, not all of these always improve with resolution in every geographic location. Hence, this study aims to assess if and where improvements to forecasts are made with the 4 km model in comparison to the global model. It is hoped that these results may be useful to forecasters and will provide guidance on the skill of models at predicting storm events in the Lake Victoria region.

The paper is set out as follows: Section 2 introduces the data. Section 3 verifies the models against surface station data. Section 4 looks at two case study storm events from March 2012. Section 5 shows statistical comparisons of objective forecasts using the global and 4 km models. Section 6 is discussion and conclusions.

2. Data

The study is split into three parts: point to point verification, case studies and an objective statistical comparison. The period of study is primarily February to March 2012.

2.1. Met Office Unified Model (UM)

Two operational configurations of the UM are used in this study: the global model and a 4 km limited-area model centred over Lake Victoria. Both models were operational in spring 2012.

The global model had a horizontal resolution of 25 km at mid-latitudes but, due to nature of the latitude-longitude model grid, the resolution at the equator was approximately 40 km. It had 70 vertical levels with a model lid of 80 km. Forecasts were run out to 7 days, with a time-step of 10 min. The atmospheric scientific configuration in spring 2012 was GA3.1 (Walters *et al.*, 2011) and analyses were produced using 4D-Var data assimilation. There were four main forecast runs *per* day (nominally at 0000, 0600, 1200 and 1800 UTC).

In spring 2012 the 4 km Lake Victoria model was run out to 2 days operationally. It had a time-step of 100 s and was driven by three hourly boundary conditions from global model fields. Initial conditions were interpolated to 4 km from the $T + 3$ h forecast fields of the most recent main global run, e.g. the 1200 UTC run of 4 km Lake Victoria model was initialized from the 3 h forecast of the earlier global 0600 UTC model run. The 4 km Lake Victoria model then ran a 3 h forecast to allow time for spin-up, before its first forecast dissemination. The atmospheric science configuration matched the operational UK4e configuration of the UM from spring 2012. The 4 km Lake Victoria model was run twice *per* day (0000 and 1200 UTC). It had 70 vertical levels but the model lid was only 40 km high, providing greater resolution in the boundary layer. The model can be thought of as a 'downscaler', in that it was driven by the global initial conditions and boundary data and there was no data assimilation. Soil moisture content was interpolated from an earlier global run and lake surface temperatures were based on ARCLake monthly night-time climatologies from the University of Edinburgh (MacCallum and Merchant, 2011).

Hourly and three-hourly forecast data for a large number of model fields from the operational global and Lake Victoria models are stored in the Met Office MASS-R archive. To determine useful identifiers of severe weather on and around the lake, a number of forecast fields were considered. Five indicators were selected to assess model storm activity: cloud top temperature (derived from outgoing longwave radiation field), surface gusts, wind shear between 250 and 700 hPa, accumulated precipitation and winds at 850 hPa. This parameter set was selected following consultation with forecasters from the Hazard Centre at the Met Office and the Uganda Department of Meteorology.

Information from a WMO report on the Mobile Weather Alert Service that was released prior to the pilot starting in Uganda was considered in the selection of model fields. Table 1 shows the thresholds for dangerous events and business as usual (BAU), i.e. calm days, that were selected as guidelines for Ugandan forecasters issuing alerts.

2.2. Observations

A number of sources of observational data were considered for use in verification: Station data were used for point to point verification; Information from forecasters and news reports were used to identify potential case studies; Satellite and lightning data were used to verify the model over the lake for the objective comparisons where a continuous data source was required, as no surface observations were available over the lake itself.

Automatic Weather Station (AWS) data were received from the Uganda Department of Meteorology for four Ugandan stations on or close to the lake shoreline for May to September 2011. These included hourly wind speed and direction and daily precipitation. The data is highly useful for verification as the wind data were recorded hourly. However, observations were limited to 0400–1500 UTC (0700–1800 LT) so all information on late evening/early morning storms was missing. Since the early morning was expected to be the peak time for convection over the lake, it was decided that these data could not be used to determine whether a storm occurred on any given day. In addition, the stations were all located on the lake shore, thus they were not necessarily indicative of conditions over the lake. This became apparent when attempting to use the station data to verify some of the storm dates provided by Ugandan forecasters.

It was therefore decided that station data were inappropriate for verification of the model over the lake and remotely sensed observations became the only option. Hourly geostationary satellite images were converted to brightness temperatures (BT) in Kelvin using:

$$BT = \left(\frac{BT_{\max} - BT_{\min}}{DN_{\max} - DN_{\min}}\right) \times (DN - DN_{\max}) + BT_{\max} \quad (1)$$

where DN is the digital number in the IR satellite image. This equation linearly maps brightness temperatures to the digital satellite image. The 10.8 µm IR channel from the Meteosat second generation satellite was used. The brightness temperature range given in the product metadata was 198–308 K. The digital image colours ranged from 0 (black) to 255 (white). Some colours were reserved for annotations – coastline, latitude, longitude, legend etc., so only levels 4–254 were used for the image (i.e. $DN_{\max}$ and $DN_{\min}$). Putting in the known values allowed the equation to be rearranged to:

$$BT = -0.44 \times (DN - 4) + 308 \quad (2)$$

The number of grid points with a value equal to or less than −60 °C (213 K) was used to indicate storm activity. This threshold was chosen to be indicative of tall cumulonimbus (i.e. deep convection). To reduce the chance of cold cirrus producing false positives, remotely sensed lightning from the

Table 1. Hazard thresholds to trigger storm warning alerts.

Colour coding		Green	Yellow	Orange	Red
Hazard thresholds	Mean wind	0–5 kt	6–10 kt	11–20 kt	Over 20 kt
	Wind gusts	5–10 kt	11–20 kt	21–30 kt	Over 30 kt
	Thunderstorms	Light	Moderate	Strong	Severe
	Visibility	>1 km	500–1000 m	100–500 m	<50 m
Response level		Appropriate individual response under BAU	Some multi-agency response but mostly BAU	Multi-agency response needed	Multi-agency strategic response needed, mutual aid necessary perhaps national co-ordination
Implications for users of Lake Victoria		Business as usual (BAU)	Forecast weather may lead to hazardous conditions. Be aware	Weather conditions are likely to lead to hazardous conditions. Be prepared should the situation worsen	Weather conditions will lead to life threatening conditions on the lake. Take action
Public advice		None	Be aware	Be prepared	Take action

Thresholds are given for dangerous events and business as usual (BAU), i.e. calm days.

Arrival Time Difference (ATD) radio ground network data were also consulted.

ATD Lightning data were available at high temporal resolution for the whole study period. The technique triangulates very low-frequency radio signals received at four or more ATD masts to identify the location and timing of a lightning strike. The main type of lightning detected is cloud to ground lightning. Some cloud to cloud lightning may also be detected, but verification of detection rates is difficult. Spatial accuracy over Africa may be low due to its large land mass and fewer receiving masts, thus errors can be as large as 40–50 km.

Both of the remotely sensed data sources have some disadvantages, but combining them should lead to more confidence in diagnosing storm events.

3. Verification

Observations from 28 ground stations in the Lake Victoria domain were compared against model output valid at the same locations from 15 August 2011 to 31 March 2012.

Normalized frequency distributions of accumulated precipitation and wind speed for observations, the global model and the 4 km Lake Victoria model were analysed. Figure 3(a) shows the distribution of precipitation. The global dataset is larger than that of the 4 km due to it running four times each day rather than twice, so normalized frequencies have been used for easy comparison.

The operational global model is known to generate too much light rainfall, too frequently when compared with observations (Stephens *et al.*, 2010) and is poor at capturing high intensity events. The plot of the whole distribution (Figure 3(a)) shows that the 4 km Lake Victoria model also produces light rainfall too often. However, there is a reduction in light rainfall in the 4 km model compared to the global model. When considering the less frequent but high intensity events (Figure 3(b)), the global model generates no rainfall events with accumulations greater than 30 mm 6 h^{-1}. The 4 km Lake Victoria model is capable of forecasting more intense rainfall; this demonstrates an improvement in the representation of rainfall in the 4 km model over that of the global – although further work is required to reduce the amount of light rainfall events in both models.

Wind speed observations from the ground stations near Lake Victoria (Figure 3(c)) suggest a non-uniform distribution and 30% of the time, no wind is recorded at all. When wind is recorded, the most frequent speed is approximately 3 m s^{-1}. There is a secondary peak in the observed wind distribution at 6 m s^{-1}. This could be due to local effects of orography, nocturnal low level jets or lake breezes at some stations. The surface wind speeds in the models peak near 2 m s^{-1} and have greater frequencies in this lower part of the wind field spectrum.

Neither of the model forecasts capture the secondary peak in wind speed at 6 m s^{-1}. The 4 km model does show an increased distribution of wind speeds greater than 3 m s^{-1}, which is an improvement over the global model. The global model does not forecast winds greater than 10 m s^{-1} (~20 kts) as shown in Figure 3(d) whereas the 4 km model does display the capability to produce wind speeds over 15 m s^{-1}. Both models still have room for improvement in the representation and distribution of wind speed.

4. Case studies

The case studies were suggested by forecasters in the Met Office Hazards Centre and the Uganda Department of Meteorology. Both cases concerned fatal boating accidents on the lake that were attributed (at least in part) to severe weather.

4.1. Case study 1 1200 UTC, 1 March 2012

On 1 March 2012 some time after 1930 LT (1630 UTC), a boat carrying 17 passengers and crew capsized in the Buvuma region, northern Lake Victoria, in poor weather conditions and high waves. Local news reports suggested that only two people survived the incident (http://www.allafrica.com/stories/201203120163.html).

Satellite images (Figure 4) showed the storm developing north of Lake Victoria between 1200 UTC and 1500 UTC on 1 March and propagating westwards. It appeared to dissipate by 1800 UTC although there were signs of new convective activity south of the original storm.

The global model $T+12$ h forecast for 1200 UTC on 1 March 2012 is shown in Figure 5. To gain insight into typical model values, the forecast fields are compared to the mean value of each field for the whole of February 2012 and also to a day when conditions were calm at the same time, in this case 1200 UTC on 7 March 2012.

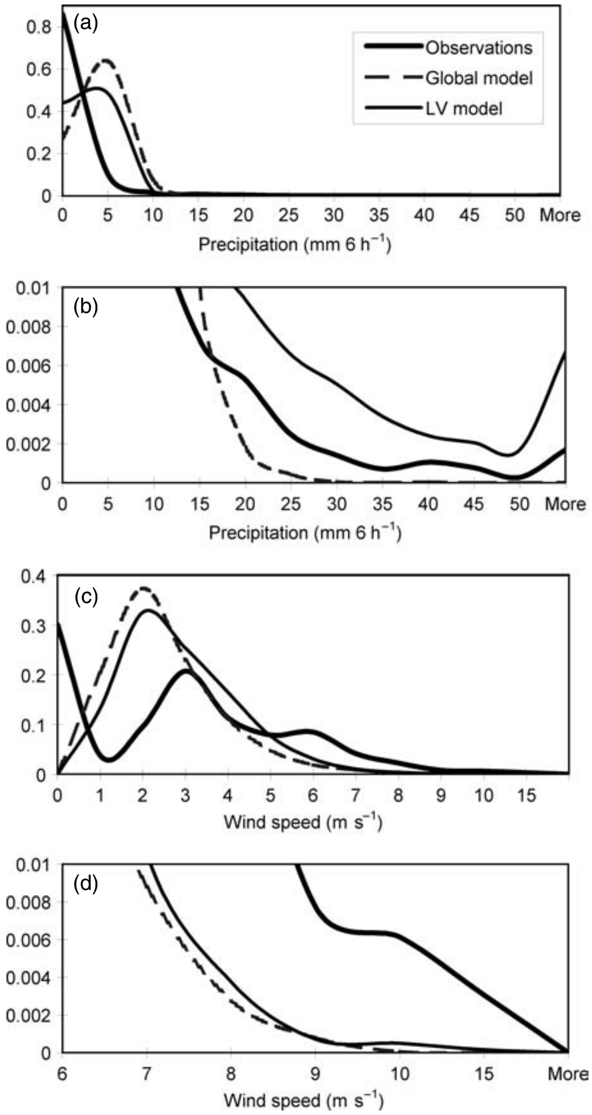

Figure 3. Normalized frequency distribution of accumulated precipitation and wind speed for observations, the global model and the 4 km Lake Victoria model. (a) The whole distribution of precipitation values (b) Zoom on less frequent precipitation events ($< 1\%$) to capture the changes in high levels of rainfall (c) The whole distribution of wind speed values (b) Zoom on less frequent wind events to capture the changes in high wind speeds.

The global model shows an increase in wind intensity over both the mean and the calm day fields on 1 March 2012. However, the strength of the winds does not exceed the highest thresholds given in Table 1 of 20 kts for mean wind speed or 30 kts for wind gusts. There is a lack of spatial accuracy in most of the forecast fields. There may be some indication of spatial skill in the wind shear between 250 and 700 hPa, where the increased shear coincides with the location of the storm. Further case studies would confirm whether this is model skill or coincidence.

In the 4 km model output, most fields showed an increased intensity over the mean state and the calm day state when a storm was present. Figure 6 compares the $T + 12$ h forecast for the five 'best' model fields on 1 March at 1200 UTC with the mean fields for February 2012 and also those at the same time on a calm day (7 March 2012).

The north-east region that produced high winds on 1 March has a slight tendency towards higher wind speeds than other areas of the lake (possibly due to the proximity of mountains to the north-east). However, there is still an increase in wind speed above the mean in the north-east region on the storm day. The spatial accuracy of this forecast appears to be good since the storm was developing in this area at 1200 UTC (Figure 6(a)).

Both models appear to be identifying an increased storm risk 12 h before the storm starts to develop. The high resolution model adds value to the forecast from the global model by capturing the features of the event more keenly, producing higher wind speeds at the surface and aloft and also resolving the location of the storm more accurately than the global model.

4.2. Case study 2 0600 UTC, 4 March 2012

On 4 March 2012, a fishing boat was lost in a storm in the Bukoba region of Tanzania in the western part of the lake. Local news reports suggested that two fishermen died in the event but gave no indication of the time of storm occurrence. Satellite images were used to pinpoint the time of the storm and a selection of images can be seen in Figure 7. The storm grew over Kampala from approximately 0000 UTC (0300 LT) and moved southwards towards the Bukoba region by 0300 UTC (0600 LT). It is assumed the boat experienced dangerous weather conditions around this time.

As in Section 4.1, the model output for the case was compared to the February mean (this time valid at 0600 UTC) and a calm day, such that typical model tendencies are compared against the case study forecast.

Figures 8 and 9 show the global and 4 km model $T + 6$ h forecast fields at 0600 UTC on 4 and 5 March. The 5 March showed no evidence of storm at this time in the satellite images (and is therefore designated as 'calm day'). The global model output (Figure 8) shows some skill in the cloud top temperature and precipitation fields, with an increased risk on the storm day over both the February mean field and those plotted for the calm day. Wind gusts and wind at 850 hPa show an increase in the mean field at 0600 UTC compared to 1200 UTC in case study 1, suggesting the model produces stronger winds at this time routinely. It is difficult to assess skill in these fields subjectively since the storm day fields look very similar to those from the calm day and the mean for February. Wind shear is also similar between stormy and calm days.

The improvement in the 4 km model fields over the global is apparent in Figure 9 as all fields show an increase in intensity over the mean and the calm day fields. The location of the storm risk is variable as is its accuracy across the fields. Wind fields and cloud top temperature place the anomaly slightly too far south, although generally in the correct area. In this case, the 4 km model is giving a clearer signal of severe storm activity although the global model does show some increased level of warning.

5. Objective comparison of model to observed storms

To compare the model to observations over a longer period, an objective method identifying storms in both observations and model was devised. The study was conducted on data from February and March 2012. A reduced area covering just the lake was selected as forecasting storm events over the lake was the prime motivation for the study. Temporal accuracy was tested by evaluating forecasts over 6 h periods (Section 5.2).

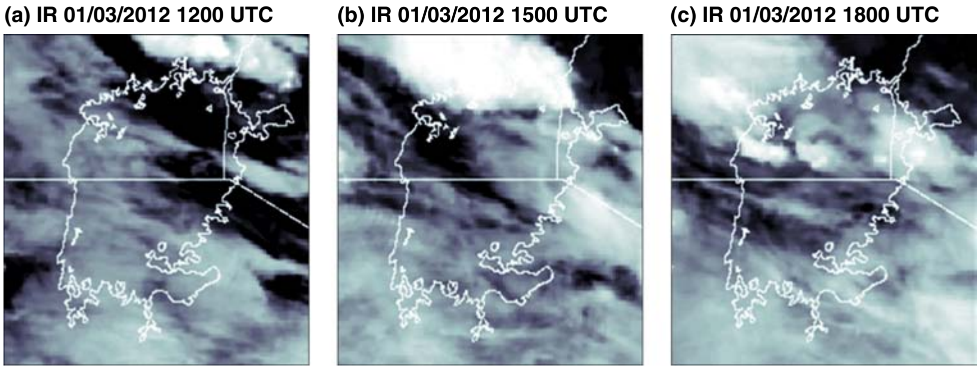

Figure 4. Evolution of the storm 1 March 2012. 10.8 μm IR images taken by Meteosat for (a) 1200 UTC, (b) 1500 UTC and (c) 1800 UTC. This figure is available in colour online at wileyonlinelibrary.com/journal/met

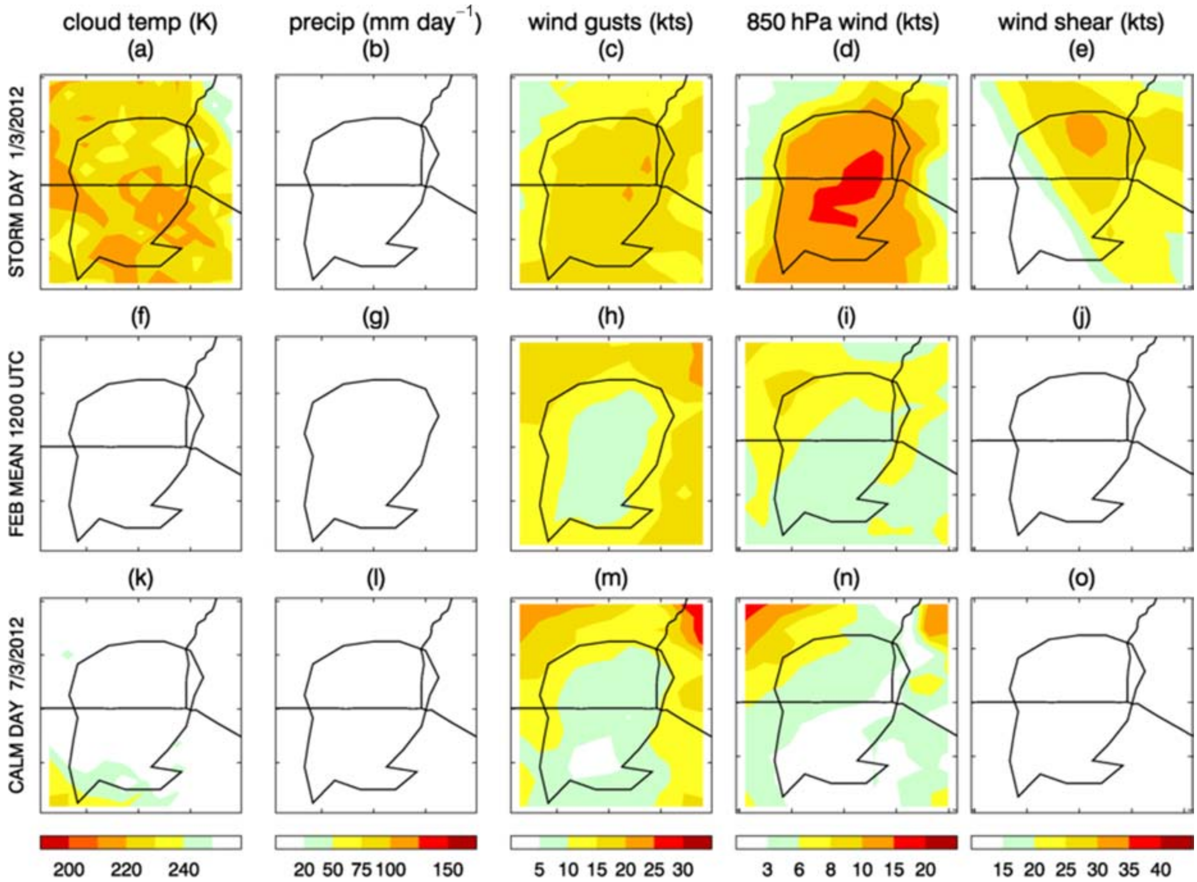

Figure 5. Global UM: (Top row (a–e)): 1200 UTC 1 March 2012 $T + 12$ h forecast for storm day. (Middle row (f–j)): February mean of $T + 12$ h forecasts valid at 1200 UTC. (Bottom row (k–o)): 1200 UTC 7 March 2012 $T + 12$ h forecast for calm day. (a, f, k) Cloud top temperature (K) (b, g, l) Precipitation (mm 6 h^{-1}) (c, h, m) Wind gusts (kts) (d, i, n) 850 hPa wind (kts) (e, j, o) Wind shear 700 to 250 hPa (kts). This figure is available in colour online at wileyonlinelibrary.com/journal/met

In addition, the comparison was made over each 1 day period (Section 5.3) to diagnose whether storms were captured in the model for a particular day even if the timing was not quite correct (i.e. storm was not forecast in the correct 6 h period but was predicted to occur within the day period).

5.1. Objective diagnosis of storms in the observations

There was no *in situ* data over Lake Victoria in spring 2012, so remotely sensed observations were used to find storms. Identifying storms in observation data proved challenging as tall clouds and lightning were regularly present over the lake region. It was decided that only the most severe events were of interest to the study, but determining which storms cause problems at the surface from remotely sensed data remains an outstanding issue.

For evaluating the forecast over 6 h periods, observations were used from 6 h centred on each diagnostic time: 0000, 0600, 1200 and 1800 UTC. This captured the storms used in the case studies (from Section 4) effectively. To diagnose a storm, both

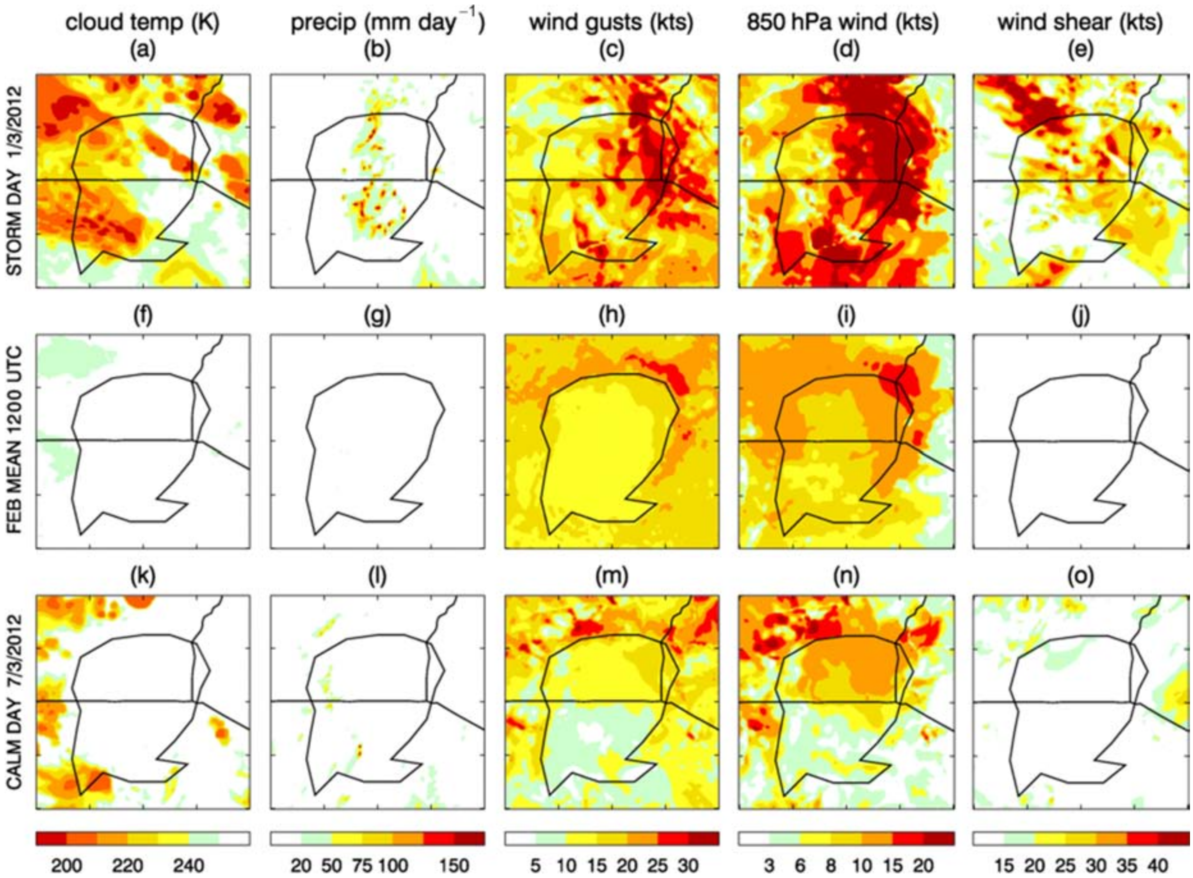

Figure 6. Four kilometres Lake Victoria model 1 March 2012, columns and rows as in Figure 5. This figure is available in colour online at wileyonlinelibrary.com/journal/met

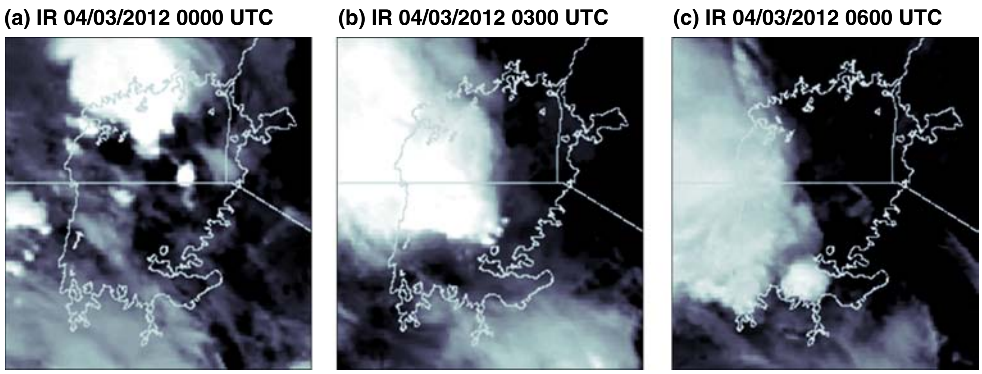

Figure 7. Evolution of the storm on 4 March 2012. 10.8 µm infrared images taken by Meteosat for (a) 0000 UTC, (b) 0300 UTC and (c) 0600 UTC. This figure is available in colour online at wileyonlinelibrary.com/journal/met

the cold cloud amount (no. grid points < 213 K) and the number of lightning strikes had to be at least one standard deviation from their monthly mean and one of these indicators had to be at least two standard deviations from their monthly mean. Storms were identified in 8% of the 6 h time intervals over the 2 month period using this method.

In order to diagnose a storm day (i.e. 24 h period), cold cloud amount and lightning strikes were totalled for each day and then averaged for the month and standard deviations calculated. The criteria for diagnosing storms was relaxed slightly such that any day where either of the two indicators departed than two standard deviations from their monthly mean was designated a ‘storm day’. Storms were diagnosed on 10% of days in the 2 month period (note: some of these lasted more than 6 h).

Since February and March are highly convectively active months, it is likely that this objective method gives an underestimation of severe storms. Therefore it should be considered that this method only identifies the most severe events and that smaller storms, which may still be dangerous, are missed by this type of strict objective analysis.

5.2. Forecasting storms in a 6 h period

An objective method which did not depend on forecaster skill was required to identify storms in the model. The method

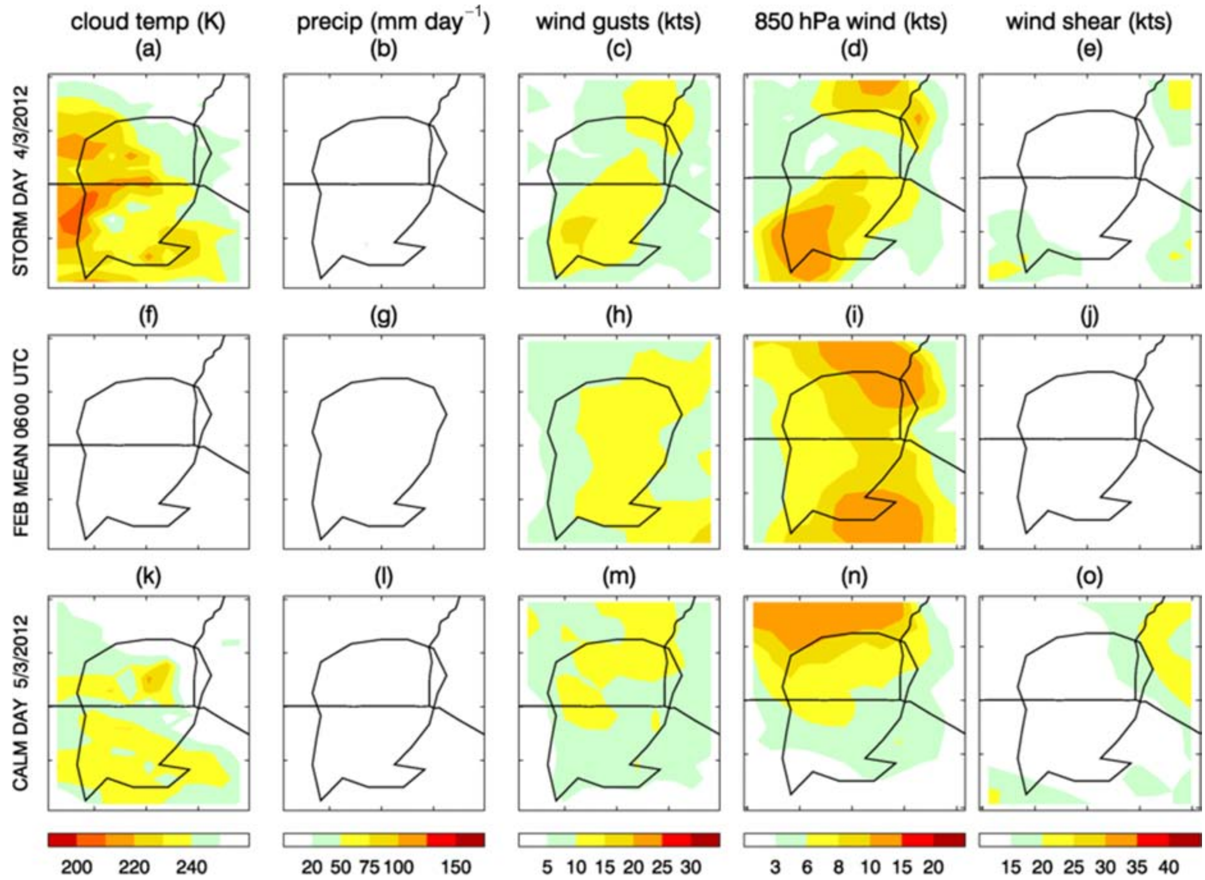

Figure 8. Global UM: (Top row (a–e)): 0600 UTC 4 March 2012 $T+6$ h forecast for storm day. (Middle row (f–j)): February mean of $T+6$ h forecasts valid at 0600 UTC. (Bottom row (k–o)): 0600 UTC 5 March 2012 $T+6$ h forecast for calm day. (a, f, k) cloud top temperature (K) (b, g, l) precipitation (mm 6 h^{-1}) (c, h, m) wind gusts (kts) (d, i, n) 850 hPa wind (kts) (e, j, o) wind shear 700 to 250 hPa (kts). This figure is available in colour online at wileyonlinelibrary.com/journal/met

deployed took into account the behaviour of five different model fields and was designed to capture above-average storm conditions. The fields were assessed on both their average value over the lake and their maximum or minimum value across the lake. This allowed both storms that were widespread and isolated severe storms to be identified. To ensure that small insignificant anomalies in the model fields did not skew the objective forecasts, an additional check of the number of grid points exceeding a 'dangerous' threshold value was included. These thresholds were loosely based on Table 1 but were altered during a series of sensitivity tests in which the ability of the objective method to predict the case studies in Section 4 was considered. The same thresholds were used for both models and it is acknowledged that this may give the global model a disadvantage due to its reduced ability to predict extremes. However, a consistent method across models was required, so this might be seen as a reasonable compromise.

Table 2 shows the warning thresholds for the five model parameters used to objectively determine whether the models were forecasting a storm. The method for objective model 'storm' forecast followed four steps:

Step 1 Forecasts were analysed for February and March 2012 at lead times of $T+6$–24 h over the lake and its coastline to produce values for the following: average value of field over the area, maximum (minimum) value of field, and number of grid points exceeding a 'dangerous' threshold value.

Step 2 For each of the values output in step 1, the monthly mean and standard deviation were calculated for each forecast lead time.

Step 3 Occasions where the step 1 values departed from the monthly mean by more than two standard deviations were highlighted.

Step 4 Storms were diagnosed when two of the five model fields produced a value (average, maximum or points above threshold) exceeding two standard deviations from the mean for that month.

Table 2 shows the values for two standard deviations from the mean for each of the statistics considered for each six hourly forecast lead time out to $T+24$ h for the global model and 4 km Lake Victoria model averaged over February and March 2012.

Some differences between the global and 4 km model are apparent from Table 2. The global model demonstrates an inability to produce strong gusts or shear in this domain as no grid-points broke the 'dangerous' threshold value for wind. The global model also appears to be unable to produce intense rainfall events, as in Section 3. The 4 km Lake Victoria model is able to produce more intense extremes in all model fields for the region. The similarity in the average precipitation fields between the two models coupled with the vast difference between the maximum values produced for the same field, indicate the 4 km model is producing more intense precipitation over a smaller area.

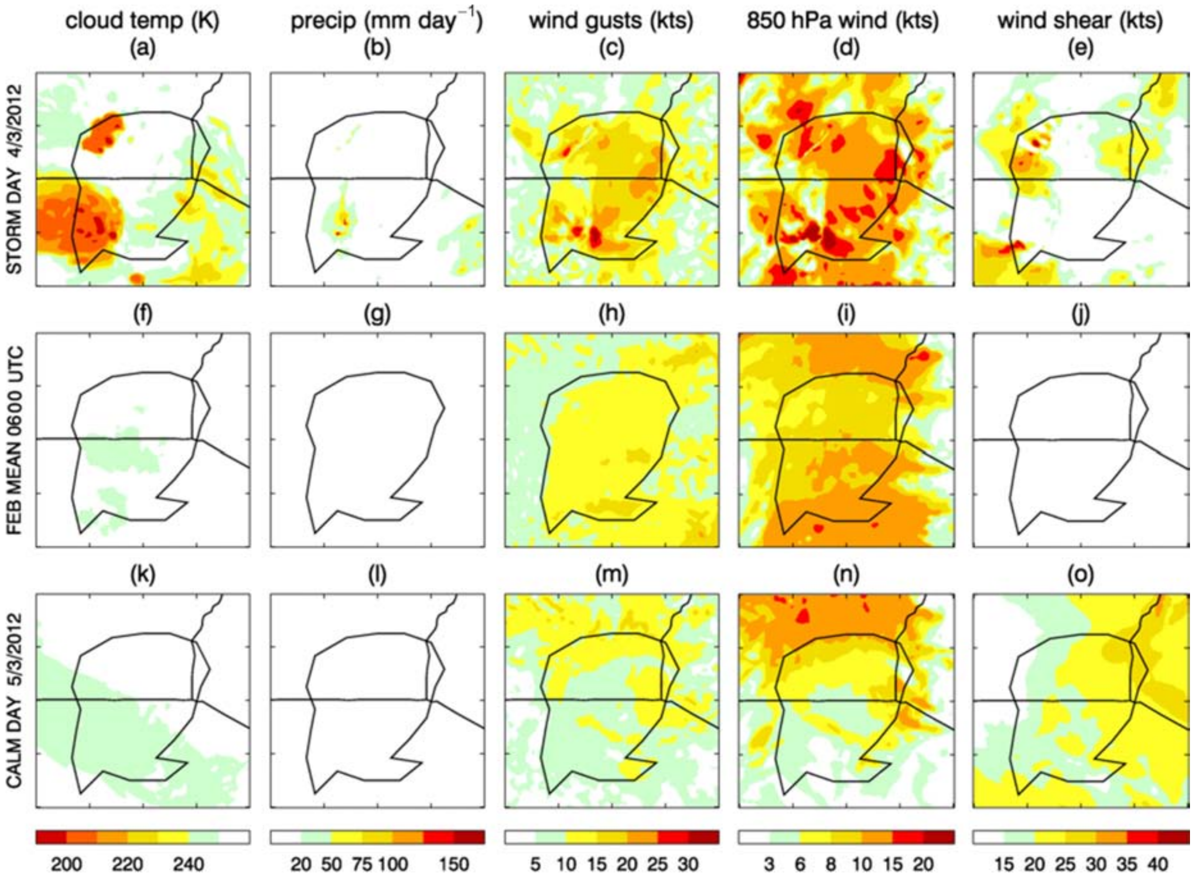

Figure 9. Four kilometre Lake Victoria model 4 March 2012, columns and rows as in Figure 8. This figure is available in colour online at wileyonlinelibrary.com/journal/met

Figure 10 shows the performances of the models as percentages of successful forecasts valid at each six hourly time slot. This technique is strict in its requirement for the model to generate a storm at the correct time of day and the poor results reflect this lack of flexibility.

The global model performed poorly at all times of day when it came to correctly forecasting storms, only identifying 1 out of 18 storms correctly in the 2 month period. The global model did forecast storms, particularly at 0600 UTC, but they were mostly false alarms. The 4 km model performed better, correctly identifying 50% of the storms that occurred at 0600 and 1200 UTC (0900 and 1500 LT).

Both models failed to identify any storms at either 1800 or 0000 UTC (2100 and 0300 LT) when a third of all storms occurred. The ratio of false alarms to missed storms can be used as an indication of the cause of missed storms. Figure 10 shows that the global model at 1200 UTC and the 4 km Lake Victoria model at 1800 UTC have a small proportion of false alarms in relation to the number of missed storms. By contrast, both models produce an excessive number of storms at 0600 UTC, although the 4 km model had increased storm hits compared to the global model.

These results could serve as useful guidance to forecasters using the model operationally so that they can be aware of times the models are more likely to perform poorly. The deficiencies in diurnal cycle of convection in the global model fits in with our understanding of parameterized models where it tends to rain more during the day than the night (e.g. as discussed in Stratton and Stirling, 2012) and brings motivation for future improvements. However, it is not fully explained why this diurnal bias in skill should occur in the 4 km Lake Victoria model which explicitly represents more convective processes. It could be that the study period is not long enough to capture true diurnal skill variability, or it could be that the 4 km is still relying too much on parameterization. Understanding deficiencies in the diurnal cycle does remain an open question.

5.3. Forecasting storms in a 24 h period

Results from the objective analysis valid over 6 h periods showed that there were occasions when the model was forecasting a storm either too early or too late, creating both a missed event and a false alarm for that storm occurrence. In order to capture events where the model timing was imperfect, an evaluation of how well the model performed over a whole day was carried out for short forecast lead times, $T + 6–12$ h and longer lead times, $T + 18–24$ h. A simple method of achieving this was devised by diagnosing a storm in the models on any day where a storm was produced in the six hourly periods shown in the previous section. This was then compared to the daily storm observations derived as in Section 2.2.

The percentage of hits and misses issued by each model for both storm and calm days is shown in Figure 11 for two forecast periods. The skill for forecasting calm conditions remained high for both the global and 4 km Lake Victoria models when using this method. A persistence forecast of ‘today will be the same as yesterday’ produced the highest rate of calm day hits (93% correct), but also absolutely no storm hits at all (0% correct),

Table 2. Warning values for five model fields.

			$T+6$ h	$T+12$ h	$T+18$ h	$T+24$ h	Mean
Global	Cloud top temperature (K)	Mean	238	238	236	239	237
		Minimum	206	208	204	209	207
		Points < 208 K	2	1	2	1	1
	Wind gusts (kts)	Mean	15	14	14	13	14
		Maximum	23	22	22	22	22
		Points > 38 kts	0	0	0	0	0
	Wind shear 250–700 hPa (kts)	Mean	24	23	23	23	23
		Maximum	32	30	31	30	31
		Points > 38 kts	0	0	0	0	0
	Precipitation (mm 6 h^{-1})	Mean	6	8	10	12	9
		Maximum	19	22	27	30	24
		Points > 130 mm 6 h^{-1}	0	0	0	0	0
	Wind speed 850 hPa (kts)	Mean	13	12	12	11	12
		Maximum	23	19	22	18	20
		Points > 20 kts	4	0	3	0	2
4 km	Cloud top temperature (K)	Mean	236	241	242	245	241
		Minimum	176	182	183	192	183
		Points < 208 K	704	270	317	126	354
	Wind gusts (kts)	Mean	16	18	15	16	16
		Maximum	41	40	36	37	38
		Points > 38 kts	22	62	2	2	22
	Wind shear 250–700 hPa (kts)	Mean	23	21	22	21	22
		Maximum	46	39	40	36	40
		Points > 38 kts	5	20	17	0	11
	Precipitation (mm 6 h^{-1})	Mean	10	11	7	5	8
		Maximum	212	267	201	216	224
		Points > 130 mm 6 h^{-1}	15	26	15	6	16
	Wind speed 850 hPa (kts)	Mean	14	14	12	13	14
		Maximum	38	33	31	29	33
		Points > 20 kts	750	621	221	270	465

The mean field value, two standard deviations from the mean (either a minimum or maximum amount) and the number of times the field exceeds a 'dangerous threshold' – loosely based on those given in Table 1 – for February and March 2012. Each of the statistics is rounded to 0 d.p. and have been considered for each six-hourly forecast lead time out to $T+24$ h for the both the global and Lake Victoria model.

meaning that persistence performed worse than the models and would not be useful for predicting storm events.

There is evidence in these results to suggest that the high resolution 4 km Lake Victoria model is adding value to the global model forecasts as the percentage of storms captured in the forecast increases with resolution. The large jump in captured storms in the 4 km model between the T + 6–12 h and the $T+18$–24 h forecasts is balanced by a reduction in the percentage of calm days correctly forecast, suggesting the 4 km Lake Victoria model is generating a larger number of false alarms at longer forecast lead times.

Figure 11 shows that the success rates of each forecast type are very similar and largely dominated by successful forecasts of calm weather. The 4 km Lake Victoria model is more likely to correctly forecast a storm than the global model within 24 h of the storm occurring, however it is worth forecasters noting the increased false alarm rate when considering forecasts at lead times of $T+18$ h or longer. Forecast times of $T+12$–18 h could be particularly useful for the mobile weather alert project, assuming that a weather warning may be sent out in the early hours of the morning for the coming day.

6. Discussion and conclusions

Results from the point-to-point verification, the case studies and the objective analysis over the 2 month period February to March 2012 suggest that forecasts from the 4 km Lake Victoria model are generally an improvement over the global model and that both models have some skill.

In Section 3, point-to-point verification of the models showed improved distributions of wind speed and precipitation in the 4 km model compared to the global model. This was supported by the subjective analysis of two case studies in Section 4. The case studies demonstrated that the 4 km model was capable of generating more intense wind speeds and precipitation than the global model. Both models showed increased warning levels when storm events were present.

For objective forecasting, the five best performing model fields were: Cloud top temperature, surface wind gusts, 700 to 250 hPa wind shear magnitude, 6 h accumulated precipitation and 850 hPa wind speeds. These were used to objectively identify when the model was producing 'storm' or 'no storm' for a statistical comparison. The values used for this objective technique (outlined in Table 2 and Section 5.2) could be used as a guide for forecasters issuing storm alerts from model data.

The 4 km model displayed greater temporal accuracy than the global model when compared to six hourly observations. In general the forecasts from both the global and 4 km were more reliable at 0600 and 1200 UTC (0900 and 1500 LT) than at night. The global model had little temporal accuracy but was more useful when a whole day was considered rather than a 6 h period.

Both the global model and the 4 km model identified the case study days as storm days from the shorter forecast lead times ($T+6$ and $T+12$ h) within the statistical comparison carried

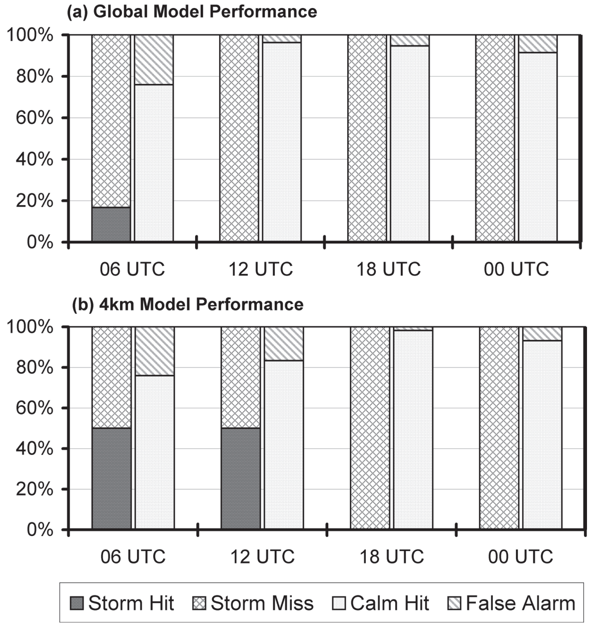

Figure 10. Forecast success rates for six-hourly periods in February and March 2012 for the (a) global and (b) 4 km Lake Victoria models at forecast lead times of $T + (6–24)$ h.

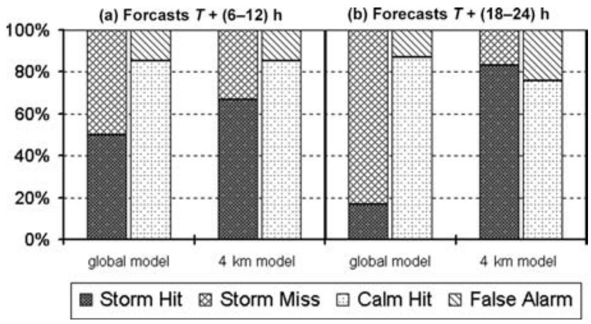

Figure 11. Forecast success rates for daily periods in February and March 2012 for the global and 4 km Lake Victoria models at forecast lead times of $T + (6–12)$ h and also $T + (18–24)$ h.

out in Section 5.3. Both missed the storm on 4 March at longer lead times of $T + 18$ and $T + 24$ h. Neither model was able to identify the case study storms within the correct 6 h period in the results from Section 5.2, instead generating a mixture of false alarms and missed events in the statistics.

This study does have its limitations. The objective analysis had very strict criterion for identifying severe events within the data and using different methods of automated storm identification are likely to yield different results. There is currently little way of knowing the actual thresholds where storms start to cause problems for boats. In addition, other factors such as boat stability and level of overcrowding are likely to play important roles, meaning that even a small storm could potentially cause a boating accident.

Relaxing the criteria for diagnosing storms in the observations would likely reduce the rate of false alarms but would also increase the number of missed storms. It is important to try to find better methods of identifying severe storms over the lake in order to verify future forecasts successfully. *In situ* measurements of weather conditions on the lake itself would make the evaluation task much more robust. Installing buoys or instruments on local boats would be a good addition to the observation network in the region.

It should also be noted that this study only looks at whether there is a storm predicted over the lake and makes no attempt to assess spatial accuracy in detail. There was some indication from the case studies that there might be some spatial accuracy for storm location in the 4 km model. This was not investigated further in this study and remains an avenue for further research.

As with other operational Met Office models, development of the 4 km Lake Victoria model is ongoing and forecast performance should continue to improve in future. Shortly after this study, daily OSTIA lake surface temperature analyses replaced the monthly ArcLake climatological SSTs. These daily analyses provide a much more realistic representation of lake surface temperatures. The observations are currently satellite-derived but a project is underway to obtain *in situ* lake temperatures, which will also be included in the OSTIA analyses. There is also scope for improving the atmospheric configuration of the 4 km model. The model settings in the 4 km Lake Victoria model currently follow those in the UK4e but it is likely that performance can be improved further by 'tuning' the model for tropical meteorology.

Finally, this study comprises an initial evaluation of the UM global and 4 km models over Lake Victoria. Only 2 months of model performance are considered and it should be kept in mind that the models may perform differently at different times of year. It may be that there are times of the year when the models are more skillful than others. This is of interest to both the forecasting community and the model evaluation community. However, ultimately, the greatest benefit of continuing verification research is to the users of the forecast products, the fishermen on the lake itself.

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