Evaluation of Australian Bureau of Meteorology global numerical weather prediction forecasts of tropical precipitation

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ABSTRACT

The ability of the Australian Bureau of Meteorology’s global numerical weather prediction model to forecast rainfall over the global equatorial tropics between 10°S and 10°N is evaluated by comparing model forecasts with Tropical Rainfall Measuring Mission observations for the period January 2011 to March 2014. Forecast accuracy is assessed using the following objective measures: equitable threat score (ETS), frequency bias (FB), and the ratio of predicted to observed rain volume (RVR). A typical example is provided of an individual daily forecast of rainfall over the maritime continent, indicating that the model produces rainfall that is too widespread and of relatively low intensity (<10 mm) at locations where no rain is observed. While the forecast rain patterns show some approximate agreement with observations at locations where observed rain intensities are above approximately 20 mm, the forecast intensities at these locations are mostly too low. Seasonal mean rain volumes predicted by the model across all longitudes show some general agreement with observed values, but the model produces too much rainfall. The FB metric shows that the rainfall is too widespread, covering a larger area than the observed rainfall. Seasonal ETSs vary between approximately 0.1 and 0.4 across the global tropics. An upgrade of the model from the initial version did not produce an overall improvement in the accuracy of numerical forecasts of equatorial tropical precipitation. Over the maritime continent north of the equator, a seasonal pattern shows lowest ETSs during June to August, and highest during January to March. Over the southern maritime continent, highest ETSs are found during July to October, which is a relatively dry period of the year. Monthly RVRs also show that the model produces too much rainfall. In varying the rain threshold used to compute skill scores to find the optimal value of daily rain rate in sub-domains over the maritime continent, the RVR is found to be generally closest to unity for daily rainfalls less than approximately 15 mm, while FB is closest to unity for daily rainfalls ranging from approximately 12 to 20 mm. Values of the ETS are highest for daily rainfall amounts of approximately 10 mm, although these results vary with location and season.

1. INTRODUCTION

Numerical weather prediction (NWP) models operated at the Australian Bureau of Meteorology (ABOM) produce forecasts several times each day (ABOM 2012, 2013). The accuracy of these forecasts is assessed routinely by comparing them objectively with observed data (Lee 2007; ABOM 2012, 2013; Wu 2013). For example, skill scores such as S1, root mean square error, absolute anomaly correlation and bias are used to assess the agreement between observations and NWP-generated fields, such as mean sea level pressure and 500 hPa geopotential height (ABOM 2012, 2013). Geographical
areas assessed may include the Australian region, the near-Australian tropics and the southern annulus (ABOM 2012).

At the ABOM, NWP-generated forecasts of rainfall have often been assessed by comparing them with datasets based on rain gauge observations (McBride and Ebert 2000; ABOM 2012, 2013). Unlike the skill scores mentioned above which cover various regions of the globe, these assessments of rainfall are generally limited to the Australian continent. Forecasts of precipitation over Australia have been of interest to meteorologists, researchers and the general population, and until recently, rainfall observations consisted largely of gauge observations over the continent. In recent years, observations from the Tropical Rainfall Measuring Mission (TRMM) have been used to provide rainfall estimates over areas where rain gauge observations are not available, such as over the ocean (Jiang and Zipser 2010).

The aim of the current work is to evaluate forecasts of precipitation over the equatorial tropics as produced by the global version of the NWP model operated at the ABOM. This model is based closely on the United Kingdom Meteorological Office’s Unified Model (Cullen 1993; Davies et al. 2005; Rawlins et al. 2007) and is named the Australian Community Climate and Earth System Simulator (ACCESS). The acronym ACCESS-G refers to the global version of the model, which is assessed here. Model and observational data used in the evaluation, along with areas considered, skill scores and an example of a typical forecast, are discussed in the following section. Rain forecasts produced by the model are compared with observations over the global equatorial tropics in Section 3. Model forecasts of tropical rainfall from two different versions of the ACCESS-G model are compared in Section 4. Forecasts of precipitation over areas of the tropics to the north of Australia are examined in Section 5. Variations in skill scores over a range of rain thresholds are considered in Section 6. Findings are summarised in Section 7.

2. DATA AND METHODS

2.1 Model and observed data

Precipitation forecasts produced by the ACCESS-G model are evaluated for the period 1 January 2011 to 30 March 2014. Although the horizontal resolution of the model was increased from N144 (~80 km) to N320 (~40 km) during this period, the forecasts from this 39 month period are considered as a single set. Precipitation forecasts for two 24-hour periods (0-24 and 24-48 hours) are assessed here, each beginning and ending at 00 UTC on successive days. However, after assessing the mean skill of these forecasts, it was found that the 0-24 and 24-48 hour results were very similar, so the presentation here is based only on the 0-24 hour results.
TRMM data (Huffman et al. 2007), available since 1997, allow assessment of tropical rainfall over wide areas including over remote ocean locations where there are no conventional sources of observations, such as rain gauges. There are several products based on TRMM data. The TRMM dataset used here to verify the ACCESS-G rainfall forecasts is known as “3B42”. Estimates of precipitation in this dataset use TRMM observations as a calibrator for microwave estimates from a number of satellites, which are then combined together and corrected using monthly gauge observations where available. Chen et al. (2013a, b) assessed the accuracy of TRMM 3B42 daily estimates of rainfall produced by tropical cyclones over the Pacific Ocean and over Australia. They found that the TRMM 3B42 estimates are most accurate over the ocean, with some limitations identified when tropical cyclone rainfall is enhanced by orography. They also noted that although TRMM data depend on indirect observations of rainfall, rain gauges also have limitations, such as interference from wind and evaporation. Over land, Buarque et al. (2011) and Fleming et al. (2011) found that TRMM data are comparable with rain gauge data over monthly to annual periods of time. Ebert et al. (2007) state that TRMM data are widely considered to provide the most accurate estimates of precipitation from satellite. Therefore, while acknowledging some limitations, the TRMM data are used here to allow assessment of the ACCESS-G model’s performance. Daily observations of rainfall available in the TRMM 3B42 product cover the 24-hour period from 00 UTC, in phase with the start and end time of each 24-hour period of precipitation predicted by the model.

2.2 Areas considered

Equatorial tropical precipitation is evaluated within ±10° latitude of the equator (EQ). A series of areas is defined within this zone to allow assessment of precipitation forecasts at multiple locations. Each area is defined to cover 30° longitude by 10° latitude (greater than 3000 x 1000 km²), with half of these areas lying along the equator in the Southern Hemisphere and the other half in the Northern Hemisphere, as indicated in Fig. 1. A sample of these boxes shown in Fig. 1 illustrates the areas covered by each box between longitudes 60°E to 180°E. These examples include coverage of the maritime continent (MC) and tropical areas to the north of Australia. Selected boxes are numbered 1-4 and labelled north (N) and south (S) of the equator for later reference.

Model predictions of rainfall are evaluated using observations within each of the twenty-four 30° x 10° areas defined over the global equatorial tropics. In each area, a grid is defined with intervals between grid points of 1.0° longitude and 1.0° latitude. To carry out the verification, both model and observed data are interpolated to this common horizontal grid. The skill scores described below are used to compare observed and predicted rainfall for each day of the 39 month period.
2.3 Skill scores

Three measures are used to assess the accuracy of each rainfall prediction. The first two are the equitable threat score (ETS) and frequency bias (FB), as described by Wilks (1995) and Ebert and McBride (1997). These metrics depend on the construction of a contingency table, the cells of which contain aggregates of the number of locations where predicted and observed rain amounts are above or below a selected threshold of rainfall. Consequently, the table contains four cells, as shown by Table 1.

Table 1 Contingency table to assess accuracy of rainfall forecasts, showing the number of Hits (H), False Alarms (F), Misses (M), and correct predictions of rainfall less than the threshold (Z).

<table>
<thead>
<tr>
<th></th>
<th>Predicted: No</th>
<th>Predicted: Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed: No</td>
<td>Z</td>
<td>F</td>
</tr>
<tr>
<td>Observed: Yes</td>
<td>M</td>
<td>H</td>
</tr>
</tbody>
</table>

The formulae used to compute ETS and FB are shown here in Equations 1 and 2, respectively. Although a range of thresholds is considered later, the initial assessment of the rainfall is based on a threshold of 1 mm, which means that points with values of rainfall below this level are considered to be free of rain, in the respective predicted and observed fields. These two scores do not assess rain intensities within areas of rain, but essentially assess the number of matching points between the predicted and observed fields.
$ETS = \frac{ZH-FM}{(F+M)N+(ZH-FM)}$  \hspace{1cm} (1)

$FB = \frac{H+F}{H+M}$  \hspace{1cm} (2)

In Equations 1 and 2, $H$ is the number of Hits or correct forecasts of occurrence of rain, $F$ is the number of False Alarms, $M$ is the number of Missed forecasts, and $Z$ is the number of correct predictions of no rainfall, or rainfall less than the threshold.

Values of the ETS range from a minimum of $-1/3$ to a maximum of 1 for each 24-hour forecast in each of the twenty-four boxes. A value of 1 indicates that the rain was forecast at the correct location with no false alarms. The FB metric assesses the over- and under-prediction of rainfall occurrence, where the ideal value is unity.

To provide some information on the amount of rain produced, the third measure, rain volume (RV), is computed for each forecast period within each area, for both predicted and observed fields. The ratio of model predicted RV to observed RV (RVR) is used to indicate whether the model produced too much rainfall (RVR > 1) or too little (RVR < 1). This ratio is computed based on both daily forecasts and RV totals over longer periods, such as a month or season as applicable.

When computing seasonal values of the ETS and FB, the values of $H$, $F$, $M$, and $Z$ for each day in each box are accumulated in the contingency table over the entire season. These accumulated values are used to compute ETS and FB, rather than computing values of these metrics for each day and subsequently computing mean daily values for the season. Similarly, for the RVR, the observed RV and forecast RV are each accumulated over a season, from which the RVR is computed, rather than computing daily values of RVR from which a mean is computed.

2.4 Example forecast and observed rainfall over the maritime continent

Before proceeding to apply the objective metrics to multiple forecasts of rainfall over the global equatorial tropics, an example is presented to illustrate for a single day the forecast and observed data discussed in Section 2.1, a 30° longitude by 10° latitude area defined in Section 2.2, and the skill scores discussed in Section 2.3. The rainfall forecast for the 24 hours up to 00 UTC on 20130122 is shown in Fig. 2a, with the corresponding observations in Fig. 2b. The location of box 3S is outlined between the equator and 10°S in both diagrams. Skill scores for the rainfall forecast within this box are shown on the second line at the top of Fig. 2. The wider domain surrounding the box provides an overall view of the observed and forecast rainfall over the MC.
In this case, over the wider area there is some good general agreement between the forecast and observed rainfall distributions, particularly for rain amounts above approximately 20 mm, as shown by the locations of the yellow and orange shadings. However, in many of these locations, the forecast rainfall does not exceed 50 mm (yellow), while the observations show peak values above 50 mm (orange). For the region of heavy rainfall in the vicinity of northern Queensland, there is reasonably good agreement.
agreement between forecast and observed fields. An outstanding characteristic of the difference between Figs 2a and 2b is the much more extensive coverage by rain amounts below approximately 5 mm produced by the model relative to the observations, as shown by the blue shadings. The differences between the model forecast and the observed rainfall over the wider area shown in this example are typical of the differences found here for most days examined.

Within the box, however, the comparison between forecast and observed rainfall is less typical. In this case, although differences between the model forecast and observations appear to be generally consistent with the description provided above for the wider area, the skill scores identify the forecast within the box as one that is particularly poor. This is a useful example to consider because it illustrates the ability of the skill metrics, used throughout the remainder of this report, to capture the character of the model forecast relative to observations. In this example, the ETS is low (< 0.1), and the FB is high (> 3), showing that the rainfall is too widespread. The RVR is approximately 2, which means that approximately twice the amount of rain is forecast in the box as was observed.

3. SEASONAL METRICS OF DAILY RAINFALL OVER THE GLOBAL TROPICS

3.1 Rain volumes

Rain volume is used to represent the bulk amount of precipitation produced in each of the 24 boxes around the global tropics. Daily mean RVs predicted by the model are compared with observed values within each box for two 6-month seasons. These seasons are defined based on the occurrence of the wet monsoon season over Indonesia and northern Australia during the November-April period, and the relatively dry May-October season over the southern MC.

The distributions of these RVs across all longitudes are shown in Figs 3a and 3b. Approximate locations of land (Africa, MC, and South America) are shown by the thick horizontal lines along the lower axis of each frame. There are distinct patterns of rainfall across the global tropics. It appears that precipitation is related to the distribution of land and sea, with higher rain volumes over longitudes where land is present. The largest feature evident is the rain volume maximum between 60°-180°E, corresponding approximately to the MC. There is a minimum over the Pacific Ocean around 210°-270°E (90°-150°W). A second maximum is observed in the vicinity of South America. A maximum around 0°-30°E found between EQ-10°N is not evident between 10°S-EQ.
EVALUATION OF AUSTRALIAN BUREAU OF METEOROLOGY GLOBAL NUMERICAL WEATHER PREDICTION FORECASTS OF TROPICAL PRECIPITATION

(Fig. 3b); this may be related to the larger areal coverage of the African continent to the north of the equator compared with the south over these longitudes.

In the north (EQ to 10°N), the RVs during May-Oct are mostly higher than those during Nov-April. In the south, the RVs during May-Oct are less than those during Nov-April. The largest differences in RV between the two seasons are found over Africa (south of the equator), over the MC and over South America. In the south, the smallest differences between seasons are found over the Pacific Ocean.

While the above discussion notes some features related to climatology and geography, there are further points to note in relation to the context of the current work. First, on the large scale, the observations and model data show good agreement (Figs 3a and 3b), with variations occurring in phase over all longitudes. Second, although there are seasonal changes, the general geographic patterns are maintained to a large degree between seasons. Third, the dashed lines representing model-generated precipitation are mostly located above the solid lines (observations) showing that the model is producing too much rain in the tropics. These differences between model data and observations are illustrated more precisely using RVR.

Seasonal RVRs for all longitudes are shown in Figs 3c and 3d. The horizontal dotted lines indicate the ideal forecast (RVR = 1) and an indication of 50% excessive rainfall (RVR = 1.5). Over northern latitudes (Fig. 3c), the RVRs are above unity for most longitudes for both seasons, generally by approximately 20%. Near the eastern edge of the African continent, the RVRs reach maxima of around 1.5 during both seasons, even though there is a minimum in the RV at this location (Fig. 3a). It is possible that these peaks in the RVR result partly from the computation of the ratio; dividing by a particularly small observed RV exaggerates the RVR relative to comparable differences between model and observed values at other locations. In general, the RVR is higher during the May-October season except over the MC and near the western edge of the South American continent.

Over southern latitudes (Fig. 3d), the RVR shows a local maximum above 1.4 during the May-October season near the east coast of Africa. A local maximum is also evident during November-April, with a RVR of approximately 1.25. During both seasons, the RVR is close to unity over the western part of the MC (90°-120°E), increasing eastward to values of approximately 1.5 around 225°-255°E (105°-135°W). A similar but smaller increase in RVR is also evident across these longitudes over the northern latitudes (Fig. 3c). In the south (Fig. 3d), although a local minimum in the RVR is found near the west coast of South America, this RVR is approximately 10% above unity. Values over the
Atlantic are also large, approximately 1.4, during both seasons over the southern latitudes.

Fig. 3  The distribution of observed and model-predicted RVs across all longitudes for two 6-month seasons in the (a) Northern Hemisphere, and (b) Southern hemisphere. Approximate locations of land (Africa, MC, and South America) are shown by the thick horizontal lines along the lower axis of each frame. Corresponding ratios of predicted to observed RVs are shown by (c) and (d).
3.2 Frequency bias

In the previous section, values of the RVR showed that the model produces too much rain over most longitudes of the equatorial tropics. The excessive forecast RVs could manifest in two ways. First, more intense rainfall than observed may occur at locations where rain is falling, and second, rain may fall over a larger area but may not be necessarily more intense than that observed. The seasonal values of FB across all longitudes of the equatorial tropics (Fig. 4) are not only all above unity, but are mostly above 1.5, indicating that the model does forecast rain that is too widespread, consistent with the example shown in Fig. 2. There are some similarities between the distributions of the RVR maxima (Fig. 3) and the FB (Fig. 4), with relatively high values near the east coast of Africa and over the Indian Ocean, over the central to eastern Pacific, and over the Atlantic. Values of the FB over these latter two regions are particularly large over the southern latitudes (Fig. 4b), with values peaking above 2, and even above 3.5 near the west coast of South America during the May-October season. Overall, the data in Fig. 4 show that the model produces areas of rainfall that are too large.

Fig. 4 The distribution of FB across all longitudes for two 6-month seasons in the (a) Northern Hemisphere, and (b) Southern hemisphere. Approximate locations of land (Africa, MC, and South America) are shown by the thick horizontal lines along the lower axis of each frame.
3.3 Equitable Threat Scores

ETSs are shown in Fig. 5. For reference, the dotted line indicates an arbitrary ETS equal to 0.2. For the northern latitudes (Fig. 5a), the lowest ETS for each season occurs over the eastern MC. The highest ETSs are found over the eastern Pacific Ocean. The ETSs during the November-April season are generally higher than those during the May-October season, although this is not the case for the eastern Pacific Ocean and the Atlantic Ocean.

![Fig. 5](image)

Over the southern latitudes (Fig. 5b), the highest ETSs are found from 270°-300°E (60°-90°W) during both seasons. Interestingly, in the box located immediately to the west at 240°-270°E (90°-120°W), the lowest ETS occurs during the May-October season. Figure 3b shows low RVs corresponding to this ETS minimum, while high RVs correspond to the highest ETSs in Fig. 5b. One of the largest differences in ETSs between the two seasons over the southern latitudes occurs over the MC (90°-150°E). The higher ETS, above 0.25, occurs during the dry season, while during the wet season (November to April) the ETS is closer to 0.15. This is a disappointing result because it indicates that the model has less ability to correctly forecast rain during the wet season compared with the dry season at this location. A positive indication is that the model produces values of the RVR and FB that are relatively close to unity over the southern MC during both seasons (Figs 3d and 4b).
4. **DIFFERENCES BETWEEN INITIAL AND UPGRADED VERSIONS OF ACCESS-G**

As the ACCESS-G model was upgraded during the period covered by the data examined here, it may be informative to consider differences between the two versions of the model. One would hope to see an improvement in the performance of the ACCESS-G following the upgrade from the initial Australia Parallel Suite (APS) version 0 (APS0) to APS version 1 (APS1).

To assess differences between each of the three skill scores associated with the respective versions of the model, Equations 3 to 5 were employed. As RVR and FB both have an ideal value of one, the absolute value of the departure from unity is computed for both APS0 and APS1, and the difference between these provides a measure of the relative performance of the two versions. The construction of Equations 3 and 4 means that negative values indicate that the performance of APS1 is superior to that of APS0. For ETS, the difference between the two versions of the model is computed using Equation 5, from which positive values indicate that the performance of APS1 is superior to the performance of APS0.

\[
\Delta RVR = |RV_{APS1} - 1| - |RV_{APS0} - 1| \quad (3)
\]

\[
\Delta FB = |FB_{APS1} - 1| - |FB_{APS0} - 1| \quad (4)
\]

\[
\Delta ETS = ETS_{APS1} - ETS_{APS0} \quad (5)
\]

Figure 6a shows, for the northern equatorial tropics, that APS1 is superior to APS0 in terms of RVR for both seasons over most longitudes, with a prominent improvement over the central Pacific Ocean. Locations where the performance has degraded are over Africa during both seasons, and over the eastern Pacific during the November-April season. For the southern latitudes (Fig. 6b), the change from APS0 to APS1 is less encouraging, although similar general patterns are found with an improvement during November-April over the central Pacific Ocean, but a loss of accuracy during May-October over the eastern Pacific and during both seasons over Africa.

Figure 6c shows that there is a general reduction in accuracy in terms of FB from APS0 to APS1 during both seasons over most longitudes between the equator and 10°N. Over the southern latitudes (Fig. 6d), the differences are relatively larger and positive over many longitudes, showing in general that APS0 performs better than APS1 in terms of FB.

Based on the ETS, APS1 shows an improvement over APS0 during the May-October season over most longitudes of the northern equatorial tropics (Fig. 6e).
Fig. 6  Changes in the accuracy of model forecasts of rainfall between model versions APS0 and APS1, for the northern equatorial tropics based on (a) RVR, (c) FB, (e) ETS, and for the southern equatorial tropics based on (b) RVR, (d) FB, (f) ETS.
During November-April, APS0 is superior to APS1 except over the maritime continent. Over the southern latitudes (Fig. 6f) during May-October, APS0 generally performs better than APS1, except over the western maritime continent and near the west coast of South America. During November-April, the performance of APS1, in terms of ETS, is superior to that of APS0 over longitudes from Africa eastwards to the maritime continent.

5. **MONTHLY METRICS OF DAILY RAIN FORECASTS OVER THE MARITIME CONTINENT**

Monthly metrics of daily rain forecasts are considered for the eight boxes labelled in Fig. 1, including coverage of the area to the north of Australia and the MC. Observed rain volumes and corresponding RVRs are shown in Figs 7a and 7b, respectively, for the northern four boxes. The lowest observed RVs are found in box 1N (thick solid line, Fig. 7a). However, during June to September, this location also exhibits the highest RVR of approximately 1.5 (Fig. 7b). Conversely, box 3N has relatively very high observed RVs during June to August (Fig. 7a), yet RVRs are around 1.0, which is a positive result. Overall, RVRs range from around 1.0 to 1.2 (Fig. 7b). Although there are variations between months, and very different seasonal observed rainfall patterns between the four boxes, these results, consistent with those in previous sections, show that the model is producing too much rain.

For boxes 2N, 3N, and 4N, values of FB are approximately 1.5 throughout the twelve months. The exception is box 1N, where the FB is close to 2.0 from January to May, closer to 2.5 from June to September, and near 1.7 from October to December. These results show that the model produces rain patterns that are too widespread over the northern equatorial tropics of the MC, with even more widespread rainfall over box 1N to the west of the MC near the southern tip of India. A seasonal pattern appears to be displayed by the ETSs for the northern boxes (Fig. 7d), with lowest scores generally during June to August, and highest values during January to March.

For observed monthly RVs in the southern four boxes 1S-4S (Fig. 8a), there are very different seasonal patterns between locations, even though these boxes cover the same latitude and are neighbours. The seasonal pattern of observed RV in 2S is consistent, as expected, with Indonesian and northern Australian rainfall consisting of a wet season (approximately November to April) and a dry season (approximately May to October). There are some similarities between the patterns in 2S and 3S, but greater differences to the west (1S) and east (4S). The RVRs in Fig. 8b, mostly above 1.0, again show that the model produces too much rain. In 2S, however, the RVRs are relatively low, near 1.0 and even less than 1.0 from June to December. Although Fig. 3d shows that model
forecasts of mean RVRs at this location are closer to 1.0 than at other locations in the southern equatorial tropics (equator to 10°S), which is a positive result, the monthly values in Fig. 8b show that model forecasts of RV in 2S are too low from June to December, particularly during August.

In box 3S, the ratios are higher, around 1.1 to 1.2. Although this error of 10-20% might not be considered as small, this is a relatively good result in the context of the generally
poor results in the southern equatorial tropics. The highest overall ratios of approximately 1.1 to 1.3 are found in 4S (Fig. 8b, thin solid line).

In box 1S (Fig. 8b, thick solid line), there is a large seasonal variation with a minimum RVR during July. From June to August there is a deficit of model rainfall at this location. A seasonal variation in the FB is also evident for this box, with largest values during May to August (Fig. 8c). Together, these results suggest that although the model
is not producing enough rain during these months, when it does produce rain it is too widespread.

The FB at location 2S also shows a seasonal variation, with highest values during August and September (Fig. 8c, dashed line), corresponding to the driest period of the year (Fig. 8a). There is also some correspondence between the highest monthly FB in box 3S and the driest month of the year.

For location 1S, ETSs are consistently below 0.2, while in 4S the ETS is very low in April but rises above 0.2 in January, February, October and November. During the months of the wet season, the ETSs in 2S are approximately 0.15, but rise above 0.25 during July to October, the dry season. The same seasonal pattern is found in 3S, although the highest monthly ETSs exceed 0.3 during August and September. In the southern equatorial tropics of the MC, the highest skill scores for rainfall prediction occur during the period of the year when there is least rain, which is an unfortunate result.

6. SKILL SCORE VARIATIONS WITH RAIN THRESHOLDS

Up to this point, skill scores have been based on assessing rain amounts above a threshold of 1 mm. In this section, skill scores are recomputed for a range of model forecast rain thresholds to find the value at which the model forecast is optimised. Figs 9 and 10 contain a range of results for the eight boxes, two seasons, and three metrics (RVR, FB, and ETS). Although the results vary between locations and seasons, the model forecasts produce RVRs closest to unity for rain thresholds below approximately 12 mm (Figs 9a, 9b, 10a, 10b). Above this value, RVRs approach values of approximately 0.5. Values of FB show that the model forecast rainfall is too widespread for thresholds less than approximately 10 mm (Figs 9c, 9d, 10c, 10d). The FB is closest to unity for rain thresholds ranging from approximately 10 to 20 mm. These distributions of FB also show that the model does not produce enough locations with rain amounts greater than 20 mm. In general, the highest ETSs are produced for rain thresholds in the range from approximately 8 to 12 mm, with lowest ETSs occurring for rain thresholds above approximately 30 to 40 mm.

The forecast example shown in Fig. 2, discussed in Section 2.4, is consistent with the FB data (Figs 9c, 9d, 10c, 10d). All of these data show that the model produces too much light rainfall (less than approximately 5-10 mm,) while forecast rain amounts above approximately 20 mm are underestimated by the model. This result is in general agreement with one of the findings by Nguyen et al. (2015), who compared radar observations with a higher resolution version of the ACCESS model over Darwin, and
noted that the model underestimated intensity and overestimated frequency of precipitation.

Fig. 9  (a) RVR, (c) FB, (e) ETS during the November-April season, (b) RVR, (d) FB, (f) ETS during the May-October season, for a range of rain thresholds, for four areas (1N to 4N) in the Northern Hemisphere.
Fig. 10 (a) RVR, (c) FB, (e) ETS during the November-April season, (b) RVR, (d) FB, (f) ETS during the May-October season, for a range of rain thresholds, for four areas (1S to 4S) in the Southern Hemisphere.
7. SUMMARY

Predictions of equatorial tropical rainfall produced by the global version of the NWP model operated by the ABOM have been compared with TRMM 3B42 observations using objective skill scores (RVR, FB, ETS). A period covering 39 months was considered (January 2011 to March 2014).

Observations and model forecasts of RV show some agreement over the global equatorial tropics, with variations occurring in phase over all longitudes during the two 6-month seasons considered. However, the analysis indicates that the model produces too much rainfall over the equatorial tropics. Over both the northern and southern equatorial latitudes, the RVRs are above unity, generally by approximately 10-30%.

In addition to producing too much rainfall, as shown by RVRs, the corresponding values of FB are above unity, generally ranging from approximately 1.5 to 2, showing that the forecast rainfall is too widespread. In general, the highest values of FB are found over oceanic areas. ETSs computed for the southern MC indicate that the model has less ability to correctly forecast rain during the wet season compared with the dry season.

A comparison has been made between mean skill scores based on forecasts produced by the APS0 (ABOM 2010) and APS1 (ABOM 2012) versions of the model. Although the periods covered by these two versions of the model do not coincide, the mean seasonal results provide some indication of the relative ability of the two versions of the model to forecast precipitation over the equatorial tropics. Although a consistent difference between forecasts produced by APS0 and APS1 has not been found, with results varying between the two 6-month seasons considered, across longitudes, and between hemispheres, the upgrade from APS0 to APS1 has not produced an improvement in the ability of the model to forecast tropical precipitation. Overall, it appears that APS1 may perform less well than APS0 in forecasting rainfall in the equatorial tropics.

In addition to seasonal forecasts, monthly metrics of daily rain forecasts were considered for eight boxes spread across the MC. Although there are variations between months, and very different observed seasonal rainfall patterns between the boxes, these results, consistent with those noted above, show that the model often produces too much rain. The most notable exceptions are box 2N during July, box 1S from June to August, and box 2S from June to December. Consistent with the general finding based on seasonal values, monthly values of FB show that rainfall predicted by the model is too widespread. Values of FB are particularly large from June to September in box 1N.
Monthly ETSs display seasonal variations for the four northern boxes, with lowest scores generally during June to August, and highest values during January to March. This pattern is approximately reversed in the southern equatorial tropics of the MC, as represented by boxes 2S and 3S. This is an unfortunate result because the highest skill scores for rainfall prediction occur during the period of the year when there is least rain.

Considering a range of rain thresholds for the 6-month seasonal values for the eight boxes, RVRs are closest to unity for rain thresholds below approximately 12 mm, while above this value, RVRs approach values of approximately 0.5. Values of FB are closest to unity for rain thresholds ranging from approximately 10 to 20 mm. Below this threshold, rainfall is too widespread, while the model under-predicts areas covered by rain amounts above this range. ETSs are highest for rain thresholds in the range from approximately 8 to 12 mm, with lowest ETSs occurring for rain thresholds above approximately 30 to 40 mm.

The overall finding of this work is that the model produces rainfall that is too widespread, often of relatively low intensity (<10 mm), at locations where no rain has been observed. While a forecast rain pattern may show some approximate, or even good, agreement with observations at locations where rain intensities are above about 20 mm, the forecast intensities at these locations are often too low.

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