SUMMARY
This paper provides a progress report on what steps have been taken by the WAFCs to harmonize and verify the forecasts of CB clouds, icing and turbulence in grid point format. Verification of the icing forecasts is presented in a separate paper.

1. INTRODUCTION

1.1 The sixth meeting of the World Area Forecast System Operations Group (WAFSOPSG/6) further reviewed the development of the gridded forecasts of cumulonimbus (CB) clouds, icing and turbulence and formulated the following conclusion:

Conclusion 6/15 — Development and use of WAFS gridded forecasts

That, WAFC Provider States be invited to:

a) pursue further improvement and harmonization of the WAFS gridded forecasts for turbulence, icing and CB cloud; and

b) conduct routine verification of the WAFS gridded forecasts using extensive datasets to establish to the extent possible the quality of the products in different parts of the world and report back to WAFSOPSG/7.
2. **DISCUSSION**

2.1 The attached report describes in detail a process that has been implemented by both WAFCs to improve the harmonization of the gridded forecasts of CB clouds, icing and turbulence. The rationale behind the harmonization process was described in WAFSOPSG/6-IP/12 and the world area forecast centres (WAFCs) were invited to pursue the harmonization as per the conclusion above.

2.2 The attached report describes the algorithms used by the WAFCs to produce the gridded forecasts of CB clouds, icing and turbulence. It then describes the harmonization methodology and the harmonization system as implemented by both WAFCs. It then presents verification results of the CB and turbulence forecasts which have been verified by WAFC London. Icing verification is presented in a separate paper presented to the meeting.

2.3 The algorithms used by the WAFCs continue to evolve and several changes to the algorithms have been implemented over the past 18 months following a rigorous testing and verification period. Further changes are likely to the algorithms in the coming years leading to further improvements in skill.

2.4 Each WAFC performs the harmonization process in parallel. The harmonization system has performed well at both WAFCs since its implementation in November 2011, with only a limited number of ‘failures to harmonize since inception. A ‘failover’ system is deployed such that if the other centre’s data is not received by the agreed cut-off time, the raw (or unharmonized) data is transmitted instead.

2.5 Verification results for the harmonized turbulence forecasts show skill at all latitude bands for derived vertical gust of >2 m/s (light turbulence or greater). For the higher threshold of >4.5 m/s there are insufficient reports at some of the latitude bands to generate reliable results. Using data from the Relative Operating Characteristic (ROC) curves, it is possible to determine the Probability of Detection (POD) and False Alarm Rate (FAR) for any level of turbulence that an operator may wish to choose.

2.6 Verification results for the harmonized CB forecasts of horizontal extent show skill in both winter and summer seasons. The skill of the harmonized forecasts is superior to either the individual gridded forecasts or the traditional SIGWX forecasts of CB. However, it should be noted that not all CB is included in the traditional SIGWX forecasts, so comparisons should be made with care. It should also be noted that the CB verification covers less than half the globe, approximately 80N to 40S and 100W to 80E.

3. **CONCLUSION**

3.1 The harmonized forecast system has proved a reliable, resilient system capable of producing global harmonized forecasts of CB clouds, icing and turbulence that meet the operational requirements.

3.2 The verification results exhibit skill in different climatic zones that are at least equivalent to or exceed the accuracy of the traditional SIGWX forecasts.

3.3 The verification results should be published on the WAFCs websites. Consideration should be given to extending the verification systems globally where suitable observational datasets exist.
3.4 The group is invited to consider the following draft conclusion:

**Conclusion 7/xx — Operational Implementation of harmonized WAFS Gridded Products**

That,

a) the WAFSOPSG endorse the gridded, harmonized forecast of CB cloud, icing and turbulence as meeting operational requirements;

b) ICAO update the relevant Annex 3 provisions accordingly; and

c) WAFCs be invited to publish the CB, icing and turbulence verification results on the WAFCs website; and to extend the verification systems globally and report back to the WAFSOPSG/8 Meeting.

4. **ACTION BY THE WAFSOPSG**

4.1 The WAFSOPSG is invited to:

a) note the information contained in this working paper; and

b) decide on a draft conclusion/decision for the group’s consideration.
Operational implementation of harmonised WAFS gridded products

11th June 2012
Paul Maisey
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Summary

As the accuracy of numerical weather prediction (NWP) models has increased in recent years the potential to use model output directly, even for critical applications such as aviation hazard forecasts, is becoming a reality. The international aviation community has expressed the desire for forecasts of icing, turbulence and cumulonimbus (CB) clouds, which are crucial to the safe and efficient operation of global aviation, to be generated from gridded NWP output. In response the World Area Forecast Centres (WAFC London and WAFC Washington) have developed systems to produce forecasts of these hazards in the GRIB2 data format. Responding to concerns relating to consistency and interoperability, the forecast products were harmonised by generating mean and maximum forecast fields from the two centres' original 'raw' data outputs. A successful service is now in operation to provide harmonised forecasts from both WAFCs. This report describes the scientific and technical attributes of the system and its implementation at WAFC London, and reviews the consistency and quality of the harmonised aviation hazard products.

Introduction

Since 1984, WAFC London and WAFC Washington have been required to provide global aviation forecasting services that include “global forecasts of significant weather phenomena” (ICAO, 2007) as part of the World Area Forecast System (WAFS).

Operation of the two WAFCs is overseen by the WAFS Operations Group (WAFSOPSG). At the inaugural WAFSOPSG meeting it was proposed that improvements in the spatial resolution and physical parametrizations of NWP models would make it “feasible to provide new WAFS output products for turbulence and icing in grid point format” (ICAO, 2003). From inception, WAFS output identifying aviation hazards has been provided in the form of manually-produced SIGWX charts. The expectation of the WAFSOPSG was that gridded model hazard forecasts might “replace WAFS SIGWX forecasts for medium levels” (ICAO, 2006).

Work commenced on gridded hazard forecasts in 2006. Initial WAFS user feedback highlighted the potential benefits from gridded forecasts as supplementary input to flight planning optimisation software, enabling aviation hazard avoidance to be integrated with existing efficient route selection (ICAO, 2008).
Further informal evaluation of the gridded hazard products from WAFC London and WAFC Washington identified some inconsistencies. Consequently it was decided to “pursue further…harmonisation of the WAFS gridded forecasts for turbulence, icing and CB cloud” (ICAO, 2011d). The rationale behind harmonisation (occasionally known as ‘blending’) was outlined at WAFSOPSG/6 (ICAO, 2011e).

This report describes the progress that has been made towards operational implementation of harmonised WAFS gridded products for aviation hazards. Section 2 describes aviation meteorological hazards and the current aviation hazard product set. In section 3, the harmonisation methodology and system set up are described. Section 4 assesses operational product availability and summarises the subjective and objective verification of the harmonised hazard forecasts. The report concludes with some options for further development in section 5.

**Aviation hazards**

**Meteorological hazards to aviation**

Icing, turbulence and cumulonimbus (CB) clouds are amongst the main meteorological hazards to en-route air traffic.

Airframe icing is caused by the impact of super-cooled water droplets on the aircraft, which can adhere at rates of up to 1 inch (2.5 cm) in 2 minutes. The worst effects are experienced between 0 and -15°C (Wickson, 1997). Icing can affect the weight distribution and impact the aerodynamic properties of the airframe. Ice accretion can block air intakes and affect instrumentation (e.g. blocked pitot tubes). Engine performance can also be impaired by in-cloud icing.

Turbulence at high levels mainly results from wind shear in association with jetstreams, mountain waves and deep convection. Mountain wave turbulence (MWT) originates as orographically-induced surface stress that is transported via gravity waves, resulting in momentum deposition aloft when the waves overturn or break. This wave breaking results in turbulence that can occur up to 100 km downwind of the associated terrain (Turner, 1999). A distinction is made between the shear- and terrain-induced clear-air turbulence (CAT) and the convectively-generated in-cloud turbulence (ICT). Turbulence impacts on
aircraft range from ‘bumpiness’ for passengers caused by light turbulence to structural damage in severe cases (Appendix A for further categorisation of impacts).

CB cloud presents an environment that includes the risks of turbulence and icing (possibly severe) already identified along with additional hazards to aviation such as electrical activity. Updraughts associated with CB clouds can typically reach 4000 ft/min (1220 m/min) and the impacts can extend to the tropopause (Wickson, 1997).

**Aviation hazard products**

The aviation hazard forecasts form part of the WAFS Upper Air Forecast GRIB2 dataset (ICAO, 2011f). Table 1 lists the forecast fields that are provided as a harmonised output.

*Table 1: Harmonised forecast fields and pressure levels (*for icing and ICT, the forecast values at a specific level represents a layer of 100hPa depth centred on the level; for CAT, the forecast values apply to a 50hPa layer centred on the forecast level)*

<table>
<thead>
<tr>
<th>Hazard forecast parameter</th>
<th>Levels*, hPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean icing potential</td>
<td>800, 700, 600, 500, 400, 300</td>
</tr>
<tr>
<td>Maximum icing potential</td>
<td>800, 700, 600, 500, 400, 300</td>
</tr>
<tr>
<td>Mean in-cloud turbulence potential</td>
<td>700, 600, 500, 400, 300</td>
</tr>
<tr>
<td>Maximum in-cloud turbulence potential</td>
<td>700, 600, 500, 400, 300</td>
</tr>
<tr>
<td>Mean clear-air turbulence potential</td>
<td>400, 350, 300, 250, 200, 150</td>
</tr>
<tr>
<td>Maximum clear-air turbulence potential</td>
<td>400, 350, 300, 250, 200, 150</td>
</tr>
<tr>
<td>CB horizontal extent</td>
<td>n/a</td>
</tr>
<tr>
<td>CB top pressure altitude, m</td>
<td>n/a</td>
</tr>
<tr>
<td>CB base pressure altitude, m</td>
<td>n/a</td>
</tr>
</tbody>
</table>

The expected ranges and units of the hazard parameters are available in the appendix of the guidance document (ICAO, 2011b).

The WAFC London harmonised hazard products contain data for the period T+6 to T+36 at 3-hourly time intervals (T+6, T+9, T+12, etc), issued 4 times per day based on model run times of 00, 06, 12 and 18 UTC (ICAO, 2008). Output is issued on a 1.25 x 1.25 degree regular grid (up to 288 by 145 points; ~140 km spatial resolution at the equator).
Hazard algorithms

1.1.1 Icing

The WAFC gridded icing parameter is formulated to give an indicator of “the confidence that any given atmospheric location, represented by a three-dimensional model grid box, would contain super-cooled liquid water that is likely to form ice on an aircraft” (ICAO, 2011d). It is best described as an icing ‘potential’ parameter.

The WAFC London algorithm calculates relative humidity (RH) from model forecasts of specific humidity (q), pressure (p) and temperature (T):

$$RH = \frac{w}{ws} \times 100\% = \frac{q}{1-q} \times 100\%$$

where the saturated mixing ratio, $ws$, is defined as:

$$ws = \frac{0.622 \times e_s}{p - e_s}$$

and the saturated vapour pressure, $e_s$, is defined as:

$$e_s = 6.11 \times 10^{\frac{7.5 \times T}{237.7 + T}}$$

The subsequent RH field is compared to temperature and layer cloud masks to identify regions where cloud is present for temperature between -20°C to 0°C. At points where these criteria are met, RH is used as an icing potential indicator (Turp et al., 2006). Null values are assigned to grid boxes occupied by model orography.

WAFC Washington use model forecasts of cloud condensate (total water and ice) and RH to calculate non-convective cloud cover and combine this with convective precipitation to identify all cloudy areas. Fuzzy membership functions, a form of probability distribution determined experimentally (Bernstein et al., 2004), of temperature, cloud top temperature, cloud cover and vertical velocity are used to calculate icing potential (Trojan, 2007).
An icing threshold of 0.1 equates to ‘trace’ icing (ICAO, 2011c) as is the same as a 10% icing potential. Values of icing potential are in the range 0 to 1 (ICAO, 2011b).

1.1.2 Clear-air Turbulence

The CAT potential parameter derived by WAFC London combines two elements: shear-induced turbulence and terrain-induced turbulence. Shear-induced turbulence is based on the Ellrod TII index (Ellrod and Knapp, 1992), which combines deformation (Def) and vertical wind shear (VWS) terms derived from model wind fields:

$$Ellrod\ TII = VWS \times Def$$

$$VWS = \left( \left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial z} \right)^2 \right)^{1/2}$$

$$Def = \left\{ \left( \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 \right\}^{1/2}$$

where u and v are the zonal and meridional components of the wind, respectively.

Terrain-induced or mountain wave turbulence uses model forecasts of gravity wave stress that are calculated in order to balance the global momentum budget within NWP models. The spatial scale of gravity waves necessitates parametrization at current global NWP spatial resolution. Upper level winds are used to advect MWT downstream for values above a set threshold (Turner, 1999). The magnitude of MWT as originally implementated was reduced by a factor of 10 as a result of subsequent investigation of ‘hot spots’ (Wells, 2011).

The turbulence components are converted into percentages using linear mappings between each component and the CAT Index (indicates the probability of encountering CAT) based on empirical study (Turner, 1999; Turp et al, 2006):

For MWT ≥ 0.0625 Pa:  
$$MWT \text{ probability} = \left( \frac{8.0}{0.1875 \times MWT} \right) + 1.83333$$

For MWT < 0.0625 Pa:  
$$MWT \text{ probability} = 0$$
The Ellrod TI1 probability is then defined as:  
\[ \text{prob} = (1383149.3 \times TI1) + 2.7258455 \]

Ellrod TI1 probability is set to zero for values below 3.5%.

A single CAT potential is created by taking the maximum value of the shear-induced and terrain-induced turbulence probabilities (Turp et al., 2006). MWT values are not available beyond T+24 and at certain pressure levels, thus CAT is determined using the shear-induced value alone for these forecast times. The parameter represents the likelihood of encountering CAT and is typically in the range 0 to 30 (ICAO, 2011b).

WAFC Washington uses the Ellrod TI1 algorithm for CAT without the addition of MWT (Trojan, 2007).

Users are advised to develop their own threshold, taking into account the exposure to turbulence of different aircraft by weight, speed and aerodynamic characteristics (ICAO, 2011b).

1.1.3 **In-cloud Turbulence**

The current ICT indicator used by WAFC London is based on the degree of convective turbulence within large-scale layer cloud. Specifically, the algorithm uses negative vertical gradients of equivalent potential temperature (-d\(\theta_e\)/dz) as an indicator of convective instability within cloud for each WAFS-defined pressure level (Turp et al., 2006). The calculation of equivalent potential temperature, \(\theta_e\), is based on model forecast temperature and pressure fields, where \(\theta_e\) is defined as:
\[ \theta_e = \theta \times \exp \left[ \frac{L \times w_s}{C_p \times T} \right] \]

where \( \theta = T \times \left[ \frac{P_0}{P} \right]^{0.286} \)

\[ w_s = 0.622 \times \left( \frac{e_s}{p-e_s} \right) \]

\[ e_s = e_{s0} \times \exp \left[ \frac{L}{R_v} \times \left( \frac{1}{T_0} - \frac{1}{T} \right) \right] \]

<table>
<thead>
<tr>
<th>L</th>
<th>Latent heat of condensation</th>
<th>(2.5 \times 10^6) J/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_p)</td>
<td>Specific heat at constant pressure</td>
<td>1004.0 J</td>
</tr>
<tr>
<td>(R_v)</td>
<td>Gas constant for water vapour</td>
<td>461.5 J/kgK</td>
</tr>
<tr>
<td>(e_{s0})</td>
<td>Saturation vapour pressure at reference temperature (T_0)</td>
<td>611.0 Pa</td>
</tr>
<tr>
<td>(T_0)</td>
<td>Reference temperature</td>
<td>273.0 K</td>
</tr>
<tr>
<td>(p_0)</td>
<td>Reference pressure</td>
<td>100000.0 Pa</td>
</tr>
</tbody>
</table>

Turbulence related explicitly to CB clouds is not represented by ICT. Values of the ICT predictor are in the range 0 to 1. Null values are assigned to grid boxes occupied by model orography.

For consistency, the WAFC Washington ICT indicator also uses equivalent potential temperature \((\theta_e)\) to identify convective instability (Trojan, 2007). For regions where model cloud amount (the maximum of total and convective cloud cover) is greater than 0.1, the Brunt-Vaisala frequency is calculated from the vertical gradient of \(\theta_e\):

\[ N^2 = \frac{g}{\theta_e} \times \frac{\partial \theta_e}{\partial z} \]

### 1.1.4 CB clouds

The CB product comprises three components:

- convective cloud horizontal extent;
- height of convective cloud base;
- height of convective cloud top.
WAFC London output assigns CB cloud to model grid boxes for which model convective cloud is present and the model convective precipitation rate is above a set threshold, currently 0.00025 kgm$^{-2}$s$^{-1}$. Convective cloud base and top are determined by comparing the CB field with model fields of convective cloud base and top pressures. The final CB field is smoothed to fill in gaps and remove ‘speckling’.

CB horizontal extent is calculated as the maximum fraction of the model grid box that is covered by CB clouds for all the levels between the CB base and top. Initially, CB horizontal extent was assigned to an index value of 0, 1, 2 or 3 corresponding to cloud fractions of 0, 0.01, 0.5 and 0.75, respectively. More recently this has been changed to a linear range of 0 to 1 to be consistent with WAFC Washington output.

CB base height and top height are calculated for all grid boxes showing CB clouds and given in pressure altitude, expressed in metres using the International Standard Atmosphere (ICAO, 1993). The height of the CB base is calculated by taking the minimum pressure altitude at the base of any CB clouds in the grid box. The height of the CB top is similarly calculated by taking the maximum pressure altitude at the top of any CB clouds for each grid box.

CB implicitly includes the icing and turbulence potential associated with convective clouds that has not been identified by either the icing potential in layer cloud or the shear-induced and terrain-induced turbulence parameters.

In the WAFC Washington output, convective cloud cover is determined from the model convective precipitation rate using the formula of Slingo (1987) modified to produce a better fit to current model data. The definition of CB clouds in this product is restricted to clouds with tops above 400 hPa and more than 300 hPa deep.

1.1.5 Calculation of mean and maximum fields

The horizontal resolution of the NWP model grid is significantly greater than the horizontal resolution of the WAFS GRIB2 gridded products. For WAFC London, model forecast data is output on a horizontal grid with resolution of approximately 40 km at present, while the WAFS products are provided on a grid of no more than 140 km horizontal resolution (section 0). When translating from the model grid to the WAFS GRIB2 grid mean and maximum fields of icing, CAT and ICT are calculated from the mean and
maximum values of the model grid boxes that correspond to each larger WAFS GRIB2 grid box. CB extent, cloud base height and cloud top height are not post-processed in this manner.

**Harmonising WAFC London and WAFC Washington data**

**Harmonisation methodology**

Inconsistencies between the aviation hazard output products of WAFC London and WAFC Washington are caused by several factors. WAFC London forecasts are based on the Met Office Global Unified Model (UM) whilst WAFC Washington forecasts are based on the NOAA/NCEP Global Forecast System (GFS). At any point in time these models can differ in their spatial (horizontal and vertical) and temporal forecast resolution, their dynamical and physical formulations of the atmosphere and their use of observational data sets (e.g. surface observations, satellite data). These factors can all result in a different forecast evolution, which can carry through into variations in the WAFS products issued from the two centres. In order to provide a consistent and reliable set of WAFS products irrespective of the originating centre, it was agreed that an appropriate technique should be applied to combine or ‘harmonise’ the two WAFC forecasts.

The current harmonisation process now being carried out at both WAFCs involves a simple calculation of average and maximum values (ICAO, 2011b) of forecast parameters on all levels and at all forecast times (Table 2).

**Table 2: Harmonisation methodology for each aviation hazard parameter**

<table>
<thead>
<tr>
<th>Hazard forecast parameter</th>
<th>Harmonising method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean icing potential</td>
<td>Arithmetic mean of two WAFC outputs</td>
</tr>
<tr>
<td>Maximum icing potential</td>
<td>Maximum value of two WAFC outputs</td>
</tr>
<tr>
<td>Mean in-cloud turbulence potential</td>
<td>Arithmetic mean of two WAFC outputs</td>
</tr>
<tr>
<td>Maximum in-cloud turbulence potential</td>
<td>Maximum value of two WAFC outputs</td>
</tr>
<tr>
<td>Mean clear-air turbulence potential</td>
<td>Arithmetic mean of two WAFC outputs</td>
</tr>
<tr>
<td>Maximum clear-air turbulence potential</td>
<td>Maximum value of two WAFC outputs</td>
</tr>
<tr>
<td>CB horizontal extent</td>
<td>Maximum value of two WAFC outputs</td>
</tr>
<tr>
<td>CB top pressure altitude, m</td>
<td>Maximum value of two WAFC outputs</td>
</tr>
<tr>
<td>CB base pressure altitude, m</td>
<td>Minimum value of two WAFC outputs</td>
</tr>
</tbody>
</table>
Harmonised mean forecasts of CAT, ICT and icing potential are calculated by taking the arithmetic mean of the mean fields for London and Washington for each grid point.

Harmonised forecasts of maximum CAT, ICT and icing potential are calculated by taking the higher of the maximum values of London and Washington for each grid point.

For CB cloud forecasts, the harmonised forecasts for CB horizontal extent and CB cloud top height are calculated as the higher value of the two forecasts for each grid point, while the harmonised forecast for CB cloud base height is taken as the lower of the two forecasts.

If missing data is indicated in one of the raw WAFC forecasts (e.g. because the model grid point lies below the model surface) then the harmonised output will contain the single value from the other available forecast. If both WAFC London and WAFC Washington indicate missing data for a grid point then the harmonised forecast will contain a missing data indicator.

**Harmonisation system**

Figure 1 shows the technical infrastructure and data flows of the harmonisation system as implemented at WAFC London.

The application software is written in the IDL programming language. The software is hosted on hardware running the Linux operating system within a virtualised environment. Virtualisation offers the benefits of scalability and resilience. In addition to the operational environment of the harmonisation system, two further environments have been created: a formal test environment designed to replicate the operational environment and minimise the risk associated with operational changes; and a development environment designed for trialling new software.

The system is monitored using enterprise monitoring software, which checks operating logs for errors and monitors the timeliness of key software processes. Monitoring information is available through a console in the Met Office’s 24-hour Operations Centre. Staff in the Operations Centre have instructions for remediying a range of common problems. An escalation process is in place for more complex problems, which are referred to a specialist support team for investigation.
The raw WAFC output is comprised of 407 individual files. Harmonised products will only be issued if all of these files have been received and processed correctly within the target time (see section 0). In the event of a failure of the harmonisation process the WAFCs will only issue raw output accompanied by an administration message informing users of the situation.

Figure 1: WAFC London technical infrastructure and data flows
Results

Product availability

London WAFC and Washington WAFC began issuing harmonised hazard products on an operational basis from the 12UTC model run on Tuesday 29th November 2011. From this date forward existing trial forecasts were replaced by harmonised forecasts supported on a 24/7 operational basis. Target availability for the harmonised products is 5 hours and 30 minutes after model run time (ICAO, 2011b). Table 3 shows the mean and maximum completion times of different elements of the harmonisation process, data receipt and product issue for the period 29th November 2011 to 13th February 2012.

Table 3: Operational system timings statistics for the period 29th Nov 2011 to 13th Feb 2012

<table>
<thead>
<tr>
<th>Model run</th>
<th>Measure</th>
<th>UK data received</th>
<th>US data received</th>
<th>Process complete</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>00Z</td>
<td>Mean time</td>
<td>04:11</td>
<td>04:50</td>
<td>05:19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Earliest time</td>
<td>04:10</td>
<td>04:50</td>
<td>05:14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Latest time</td>
<td>04:22</td>
<td>04:51</td>
<td>05:26</td>
<td>05:30</td>
</tr>
<tr>
<td></td>
<td>Range, mins</td>
<td>12</td>
<td>1</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>06Z</td>
<td>Mean time</td>
<td>09:54</td>
<td>10:50</td>
<td>11:18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Earliest time</td>
<td>09:52</td>
<td>10:50</td>
<td>11:11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Latest time</td>
<td>10:01</td>
<td>10:52</td>
<td>11:29</td>
<td>11:30</td>
</tr>
<tr>
<td></td>
<td>Range, mins</td>
<td>9</td>
<td>2</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>12Z</td>
<td>Mean time</td>
<td>16:11</td>
<td>16:50</td>
<td>17:18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Earliest time</td>
<td>16:09</td>
<td>16:50</td>
<td>17:10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Latest time</td>
<td>16:43</td>
<td>16:51</td>
<td>17:23</td>
<td>17:30</td>
</tr>
<tr>
<td></td>
<td>Range, mins</td>
<td>34</td>
<td>1</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>18Z</td>
<td>Mean time</td>
<td>21:57</td>
<td>22:50</td>
<td>23:20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Earliest time</td>
<td>21:54</td>
<td>22:50</td>
<td>23:10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Range, mins</td>
<td>32</td>
<td>20</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

During this period of operation there was no reported down time of the system and harmonised products were issued for all dates and times scheduled.
**Visual monitoring**

Software has been implemented to provide a visual comparison of the harmonised hazard forecasts from the two WAFCs. The graphical output from this process is checked manually on a routine basis.

Figure 2 shows a typical example of the visual comparison for harmonised forecasts of CB cloud base height. The lower panels show WAFC London and Washington harmonised forecasts, with values in the range 1000-15000 m. The top panels show the differences between the two fields, as a continuous field (top right) and in bands (top left). In the top left panel is one centrally-located point, in the band 0.5-1.0, giving an error of 0.01%.

Figure 3 shows a less common example in which the differences between the two harmonised forecasts for CB cloud top height are more widespread, but the magnitude of the rounding errors is comparable with the previous example.
Figure 2: WAFC London and Washington CB cloud base height (bottom panels); continuous difference field (top right); in bands (top left)

Figure 3: As Figure 2, for CB cloud top height fields
Objective verification

1.1.6 Methodology

Objective verification of CAT forecasts was carried out using the GADS database of aircraft observations to calculate Derived Equivalent Vertical Gust (DEVG). DEVG provides a measure of observed aircraft turbulence on near-global coverage for use in verifying WAFC forecasts: DEVG $\geq 2.0\text{ms}^{-1}$ indicates light turbulence and greater; DEVG $\geq 4.5\text{ms}^{-1}$ indicates moderate and severe turbulence only.

Aircraft flight paths are broken down into segments that correspond in distance to the grid length of the WAFC forecast field. Each segment is categorised as turbulent or non-turbulent against a threshold value of DEVG and this is compared to the CAT forecast – bilinearly interpolated from the forecast grid – to populate a 2-by-2 contingency table. DEVG and the method of verification are described in detail in Gill (2012).

For CB horizontal extent, Sferics (lightning location) data from the Met Office ATDnet system have been shown to be an effective proxy for the location of areas of convection (Mirza, 2011). Observed lightning strikes are mapped to grid boxes for a grid of 640 x 481 points to correspond to the Global UM. As with CAT verification, the occurrence or non-occurrence of forecast and observed events are used to populate a contingency table.

The contingency tables indicate the frequency of correct and incorrect forecasts for observed turbulent and non-turbulent events and thus can be used to calculate hit rate and false alarm rate. This information is represented here using Relative Operating Characteristic (ROC) curves (Gill, 2012). The diagonal line bisecting each plot indicates a line of no-skill. Curves above and to the left of this line demonstrate forecast skill. The area under the curve (AUC) between the curve and the no-skill line provides a quantitative assessment of skill.
1.1.7 Global UM changes

The Global UM model is subject to regular scientific and technical changes on a scheduled basis. Relevant changes that occurred during the verification period are:

- July 2010: Introduction of the PC2 prognostic cloud fraction and condensation scheme to better simulate cloud processes. The overall result was a slight increase in model cloud amounts (including convective cloud) that verified better against SYNOPs.
- November 2010 and July 2011: Changes in the data assimilation methodology to use ensemble model data, leading to improvements particularly in tropical upper level wind forecasts.

Changes to the calculation of aviation hazard outputs already noted are the scaling change to MWT in March 2011 (section 1.1.2) and the change to CB horizontal extent in November 2011 (section 1.1.4). In addition, a correction to remove spurious values of icing potential above 1.0 was implemented in March 2011.

1.1.8 Clear-air turbulence

Figure 4 shows the verification of global mean CAT at T+24 for the DEVG≥ 2.0 intensity threshold for the period November 2011 to February 2012 inclusive. The AUC value for the global mean CAT harmonised forecast of 0.701 indicates skill in identifying observed turbulent events against the threshold DEVG≥ 2.0. The harmonised forecast sits between the more skilful WAFC Washington forecast (0.718) and the slightly less skilful WAFC London forecast (0.669) (Table 4).

In the sample of 641,783 observations 11,690 turbulent events were identified, a frequency of 1.8% of all observations.
Figure 4: ROC curve comparing global WAFC mean CAT forecasts for DEVG ≥ 2.0 between Nov 2011 and Feb 2012 for London (red), Washington (green) and harmonised (blended) WAFC (blue).

Figure 5 shows the same comparison for the moderate and severe turbulence threshold (DEVG ≥ 4.5). AUC values (Table 4) show that skill is comparable for this forecasting turbulence events above this higher threshold. Significantly fewer turbulent events (392) were observed for this threshold giving a frequency of occurrence of 0.1%.
Figure 5: ROC curve comparing global WAFC mean CAT forecasts for $\text{DEVG} \geq 4.5$ between Nov 2011 and Feb 2012 for London (red), Washington (green) and harmonised (blended) WAFC (blue).

Figures 6 and 7 show the same plots for the maximum forecast CAT for both turbulence thresholds. In all instances the AUC values indicate that forecasts of maximum CAT were more skilful than mean CAT (Table 4).
Table 4: AUC values for all three forecasts for both turbulence thresholds for mean and max CAT

<table>
<thead>
<tr>
<th></th>
<th>DEVG≥2.0</th>
<th>DEVG≥4.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Max</td>
</tr>
<tr>
<td>WAFC London</td>
<td>0.669</td>
<td>0.673</td>
</tr>
<tr>
<td>WAFC Washington</td>
<td>0.718</td>
<td>0.721</td>
</tr>
<tr>
<td>Harmonised (Blended)</td>
<td>0.701</td>
<td>0.713</td>
</tr>
</tbody>
</table>

Figure 6: ROC curve comparing global WAFC max CAT forecasts for DEVG≥ 2.0 between Nov 2011 and Feb 2012 for London (red), Washington (green) and harmonised (blended) WAFC (blue)
Figure 7: ROC curve comparing global WAFC max CAT forecasts for DEVG≥ 4.5 between Nov 2011 and Feb 2012 for London (red), Washington (green) and harmonised (blended) WAFC (blue)
1.1.9 **CB horizontal extent**

Figure 8 shows the ROC curve for verification of CB horizontal extent forecasts at T+24 for the 2011 northern hemisphere summer season (June-August). The forecasts have been verified against Sferics data over the whole ATDnet domain from 80N to 40S and 100W to 80E (Mirza, 2011). The ROC curves also include the value for the forecaster-generated SIGWX CB forecast.

Based on AUC figures (Table 5), all three forecasts show greater skill than the forecaster-generated CB horizontal extent forecast for this period. The WAFC London forecast (0.739) is slightly more skilful than WAFC Washington (0.713). The harmonised forecast (0.778) is the most skilful of the products verified. This is likely to be a result of the harmonisation method, which takes the value of CB horizontal extent from only one forecast if there is no CB cloud in the other, thus smoothing and expanding the CB field. This increases both the hit rate and false alarm rate, as can be seen by the extension of the harmonised forecast ROC curve being above and slightly to the right of the other curves in Figure 8. Other periods display similar behaviour.

<table>
<thead>
<tr>
<th>Season</th>
<th>WAFC London</th>
<th>WAFC Washington</th>
<th>Harmonised WAFC</th>
<th>London SIGWX</th>
<th>Washington SIGWX</th>
</tr>
</thead>
<tbody>
<tr>
<td>DJF 2011-12</td>
<td>0.782</td>
<td>0.759</td>
<td>0.843</td>
<td>0.710</td>
<td>0.716</td>
</tr>
<tr>
<td>JJA 2011</td>
<td>0.739</td>
<td>0.713</td>
<td>0.778</td>
<td>0.635</td>
<td>0.664</td>
</tr>
<tr>
<td>JJA 2010</td>
<td>0.764</td>
<td>0.655</td>
<td>0.782</td>
<td>0.611</td>
<td>0.657</td>
</tr>
</tbody>
</table>

The results are comparable with those from the previous northern hemisphere summer season (Figure 9) and the latest northern hemisphere winter season (Figure 10). All the forecasts verified show higher skill in forecasting CB horizontal extent in the northern hemisphere winter season relative to the two summer seasons.
Figure 8: ROC curve comparing global WAFC CB horizontal extent forecasts between June and August 2011: London (red); Washington (green); harmonised (blended) (blue); London SIGWX (cyan); Washington SIGWX (pink)
Figure 9: ROC curve comparing global WAFC CB horizontal extent forecasts between June and August 2010: London (red); Washington (green); harmonised (blended) (blue); London SIGWX (cyan); Washington SIGWX (pink)
Concluding remarks

A system for harmonising the gridded WAFS aviation hazard forecasts was implemented in November 2011 at WAFC London and WAFC Washington. This system is robustly monitored and resilient, as demonstrated by the timely and successful dissemination of products in the intervening period.

Visual monitoring of the harmonised products from the two WAFCs shows them to be almost entirely consistent and interoperable to the level of rounding errors.

The harmonisation algorithms as implemented (Table 2) provide a simple and effective method of creating a consistent WAFS output for users. Objective verification of the mean and maximum CAT and CB horizontal extent fields shows that the harmonised product displays forecast skill comparable to the level of skill demonstrated by the WAFC London and WAFC Washington forecasts.
shows slightly greater skill in forecasting CB horizontal extent whilst WAFC Washington shows slightly greater skill in forecasting CAT. The verification of maximum CAT shows slightly greater skill than mean CAT for all three forecasts (the two raw and the harmonised), which suggests that the maximum CAT field is capturing more extreme turbulent events (slightly lower false alarm rate).

Future research activities are likely to feed into improving the quality of the raw WAFS hazard forecasts, which will also benefit the harmonised products. Gill and Buchanan (2012) have trialled the use of ensemble model forecasts to generate ensemble aviation hazard forecasts, an approach that could integrate with, or potentially supersede, the current harmonisation methodology. Planned research into turbulence, icing and convection hazard algorithms all offer potential for improved aviation hazard forecasting.

**Acknowledgements**

The author wishes to thank Helen Wells for directing and reviewing this work. The author would also like to thank Andrew Mirza, Rob Coulson and Phil Gill for providing the objective verification results included within this report.
Appendix

References


Appendix A: Meteorological hazard categorisations

Icing

Index: light (>1 hour exposure for problems); moderate (> short encounters hazardous, anti-icing needed); severe (anti-icing inadequate control method, divert) (ICAO: Wickson, 1997).

Turbulence

Index: light; moderate (can change altitude and speed, 0.5-1.0g accelerometer readings); severe (abrupt change in altitude and speed, momentary loss of control, >1.0g); extreme.

CAT: occurs at medium to high level, in marked wind shear related to jet stream boundaries and upper troughs/ridges.
Index: moderate (20kt/deg lat, 6kt/1000ft), severe (30kt/deg lat, 9kt/1000ft).

— END —