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RESEARCH ARTICLE

Multi-model ensemble predictions of aviation turbulence

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Turbulence remains one of the leading causes of aviation incidents. Climate change is predicted to increase the occurrence of clear-air turbulence and therefore forecasting turbulence will become more important in the future. Currently, the two World Area Forecast Centres (WAFCs) use deterministic numerical weather prediction models to predict clear-air turbulence operationally; it has been shown that ensemble forecasts improve the forecast skill of traditional meteorological variables. This study applies multi-model ensemble forecasting to aviation turbulence for the first time. It is shown in a 12-month global trial from May 2016 to April 2017 that combining two different ensembles yields a similar forecast skill to a single model ensemble and yields an improvement in forecast value at low cost/loss ratios. This finding is consistent with previous work showing that the use of ensembles in turbulence forecasting is beneficial. Using a multi-model approach is an effective way to improve the forecast skill and provide pilots and flight planners with more information about the forecast confidence, allowing them to make a more informed decision about what action needs to be taken, such as diverting around the turbulence or requiring passengers and flight attendants to fasten their seatbelts. The multi-model ensemble approach is intended to be made operational by both WAFCs in the near future and this study lays the foundations to make this possible.

KEYWORDS
aviation, ensemble, forecast, multi-model, turbulence

1 | INTRODUCTION

Aviation turbulence is experienced by most people who fly. It is a major hazard, with tens of millions of dollars paid out annually by airline companies to passengers and crew who are injured, and over 7,000 person-days of lost time for cabin crew related injuries (Sharman and Lane, 2016). Therefore, forecasting turbulence is vital in maintaining the safety of passengers and crew. Turbulence affecting aviation comes in different forms including clear-air turbulence (CAT), which is particularly hazardous because it cannot be remotely detected by pilots. CAT is defined as high-altitude in-flight bumps in airspace devoid of significant cloudiness and away from thunderstorm activity (Chambers, 1955). Turbulence can be formed by mountain wave turbulence (MWT) (Lilly, 1978), convectively induced turbulence (CIT) (Uccellini and Koch, 1987; Koch and Dorian, 1988) and shear-induced turbulence (Endlich, 1964; Atlas *et al.,* 1970). Our ability to forecast turbulence has improved recently, because of advances in our mechanistic understanding (Williams *et al.,* 2003, 2005, 2008; Knox *et al.,* 2008; McCann *et al.,* 2012) and new measurement techniques (Marlton *et al.,* 2015). An extensive overview of aviation turbulence can be found in Sharman and Lane (2016).

There are two World Area Forecast Centres (WAFCs)—London (Met Office) and Washington (National Oceanic and Atmospheric Administration, NOAA)—that create the turbulence forecasts used operationally by pilots and flight planners around the world. Currently, the two centres produce turbulence forecasts by creating a turbulence product with a horizontal resolution of 1.25° from a single output deterministic model. Turbulence cannot be explicitly

simulated by numerical weather prediction models because the turbulence scales impacting aviation are between 100 m and 1 km, which is smaller than a grid box of an operational global forecast system (Sharman *et al.,* 2006). The WAFCs therefore use a diagnostic indicator to predict areas of the atmosphere likely to contain turbulence. Both WAFCs use the Ellrod and Knapp (1992) Turbulence Index 1 (Ellrod TI1) (ICAO, 2012), which predicts shear-induced turbulence that is dominated by strong deformation regions associated with the jet stream. It is important to note that the Ellrod TI1 is not able to capture all shear turbulence generation mechanisms. However, the jet stream is a current of fast-flowing air that is constantly evolving and difficult to predict. Therefore, a deterministic model arguably does not fully capture the uncertainty of the parameters of the jet stream and the location of turbulence (Gill and Buchanan, 2014). Also the Ellrod TI1 is unable to detect convective events or MWT unless in areas of strong wind shear. Gill (2014) demonstrates this by showing that the skill of the TI1 is reduced in the Tropics where shear turbulence is less important and convection is the main cause of turbulence. Ellrod and Knox (2010) developed an improvement for the Ellrod TI1 turbulence index by including a divergence trend. This resulted in the Ellrod3 turbulence diagnostic which Sharman and Pearson (2017) showed to have a higher area under the curve than other turbulence diagnostics. The Ellrod TI1 was chosen in this study to be consistent with the current operational forecast system; however, this shows there is potential to further increase forecast skill by using the updated turbulence index.

To help include jet stream uncertainty in the forecasts, Gill and Buchanan (2014) and Buchanan (2016) showed that using an ensemble of simulations improved the forecast skill. An ensemble forecast is a collection of many simulations of the same event with each outcome equally likely. By combining all the possible results, a probability field showing the likelihood of exceeding a turbulence threshold and therefore experiencing turbulence can be created. Having a probabilistic forecast can help pilots, flight planners and air traffic control manage their response accordingly. An example of this would be if 1 out of 10 ensemble members predict turbulence (i.e. there is a 10% probability of turbulence), in which case pilots might continue their route because the chances are still small. If, on the other hand, all 10 models predict that the threshold will be exceeded, then a pilot may divert around that region (expensive), change flight level (less expensive) or put the seatbelt sign on (free) to avoid injury to passengers and crew. Choosing the appropriate action can reduce injuries and save costs. For example, if the turbulence is expected to be light or moderate or there is a low probability of the turbulence, then putting the seatbelt sign on is a cost-free response but can impact passenger comfort. If the turbulence predicted is severe or there is a high probability, then the pilot might choose to change the flight level, which might cost money in terms of fuel usage but this cost would be less than a full diversion. If the turbulence predicted is on multiple flight levels, then a full diversion might be appropriate, which would be more expensive by increasing flight time and fuel usage, but this would be cheaper than damaging the aircraft or injuring passengers and crew.

Having a probabilistic forecast with more information allows pilots and flight planners to choose the appropriate action to reduce the costs of preventative action whilst maintaining the safety of passengers and crew. If more ensemble members are used, the ensemble spread is larger and the understanding of the certainty of the forecast is improved. This approach therefore provides more information to pilots and flight planners about where turbulence is likely to be and, therefore, which regions they should avoid. However, increasing the forecast spread could capture more turbulence events but also could increase the number of false alarms, and this trade-off is one that needs to be managed to maximize forecast skill. This study further expands on the use of an ensemble forecast, and follows other areas of meteorology such as the TIGGE project (Swinbank *et al.,* 2016) which looks at combining ensembles from different centres around the world. A particular research area using multi-model ensembles is tropical cyclone forecasting (Krishnamurti *et al.,* 2000; Vitart, 2006; Titley and Stretton, 2016). All of these studies show that using multi-model ensembles improves the overall skill of the forecasts, and they therefore show a useful application that is investigated for turbulence in this study. By using at least two ensembles, not only is the spread increased by increasing the number of forecasts, but also a different numerical model is used, assimilating a differing set of observations that will have different strengths and weaknesses. These strengths and weaknesses can come from how the ensembles are perturbed. An example is the European Centre for Medium-Range Weather Forecasts (ECMWF) Ensemble Prediction System (EPS), which starts each model run with the same initial conditions but adds dynamically defined perturbations to create the model spread (Molteni *et al.,* 1996). In contrast, the Met Office Global and Regional Ensemble Prediction System (MOGREPS-G) uses different initial conditions and model perturbations to provide the ensemble spread (Bowler *et al.,* 2008). The initial conditions are perturbed using the ensemble transform Kalman filter (Bishop *et al.,* 2001) and the model perturbations are driven by two stochastic physics schemes. These two schemes are the random parameter scheme and the stochastic convective vorticity scheme. Bowler *et al*. (2008) showed as an example that the screen temperature Brier Skill Score was higher for ECMWF EPS compared to MOGREPS-G, but that for wind speed the MOGREPS-G ensemble was more skilful than the ECMWF EPS. Thus, each ensemble has its own strengths and weaknesses that it is hoped will increase the forecast spread and

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therefore increase the forecast skill. This study is the first time multi-model ensemble forecasting has been applied to turbulence. Both WAFCs plan to use a multi-model ensemble in the near future, and therefore this study lays the foundations to make this possible.

Turbulence forecasting will become more important in the future, because climate change is predicted to increase the frequency of CAT globally (Storer *et al.,* 2017). The turbulence increases arise because of changes to the jet streams, which are also predicted to modify flight routes and journey times (Williams, 2016). Storer *et al*. (2017) showed that flights all around the world will have an increase in turbulence for all strength categories from light to severe. Therefore, improved turbulence forecasts will be a vital tool to limit the increase in injuries to passengers and crew as well as aircraft damage arising from the increase in turbulence events. Not only will this improve passenger comfort and safety, it will also reduce the loss of money paid out for compensation.

The paper is set out as follows. Section 2 introduces the observational data, Section 3 explains the forecasting system, Section 4 discusses the verification method, Section 5 presents the results and Section 6 summarizes the results and outlines future work.

2 | OBSERVATIONS

In order to verify the forecasts, a "truth" dataset is needed. Previous work used pilot reports (PIREPS) (Tebaldi *et al.,* 2002; Kim and Chun, 2011), but these can be unreliable (Schwartz, 1996; Kane *et al.,* 1998; Sharman *et al.,* 2014). PIREPS are subjective and are also aircraft dependent, so a smaller aircraft will experience more severe turbulence than a larger aircraft in the same volume of turbulent air. PIREPS also have poor spatial reliability as they tend to be located in turbulence, so null turbulence events are rarely recorded as there is no specified frequency (Kane *et al.,* 1998). The location and time of PIREPS may also not be correct as they are manually reported after the event and for more severe events where action is required this may be some time later. To avoid these problems, in this study aircraft data recorded on a fleet of Boeing 747 and 777 aircraft are used. These data have been used in other meteorological studies (Tenenbaum, 1991; Gill, 2014). High-resolution automated aircraft data, available at 4 s intervals, giving over 76,000,000 data points, are used to calculate an aircraft-independent turbulence measure known as the derived equivalent vertical gust (DEVG), defined as:

$$\mathrm{DEVG} = \frac{Am \mid \Delta n \mid}{V} \tag{1}$$

where Δn is the peak modulus value of the deviation of aircraft acceleration from 1 g in units of g, m is the total mass of the aircraft (metric tonnes), V is the calibrated airspeed at the time of the observation (knots) and A is an aircraft specific parameter which varies with flight conditions and is defined as:

$$A = \bar{A} + c_4(\bar{A} - c_5)\left(\frac{m}{\bar{m} - 1}\right) \tag{2}$$

$$\bar{A} = c_1 + \frac{c_2}{c_3 + H(\mathrm{kft})} \tag{3}$$

where H is the altitude (thousands of feet), $\bar{m}$ is the reference mass of the aircraft (metric tonnes) and parameters c_1 to c_5 depend on the aircraft's flight profile as outlined in Truscott (2000).

DEVG is one of the World Meteorological Organization (WMO) recommended turbulence indicators and has a typical uncertainty of around 3–4% (WMO, 2003). DEVG is aircraft independent so values from all aircraft can be combined to create an observational database. Table 1 compares DEVG to the eddy dissipation rate (EDR) which is another aircraft independent measure that can be used in turbulence verification (Storer *et al.,* 2018). There are limitations to using this dataset because aircraft manoeuvres and active control techniques can enhance or dampen vertical accelerations of aircraft leading to over- or under-representation of the vertical gusts (WMO, 2003). One of the other main issues with this dataset is the typical spatial coverage. Figure 1 is a plot of aircraft data for May 2016 and shows the spatial coverage of our observations. It has very good coverage over the North Atlantic and Europe but poorer coverage over Asia and the Pacific. Despite the uneven spatial coverage, this dataset is still the best available source of truth data for verification, which is why it has been chosen here. The Ellrod TI1 turbulence predictor used in this study only forecasts shear-induced turbulence and is not able to predict convective turbulence. This study will therefore use a satellite-based convective product to filter out convective turbulence events (Francis and Batstone, 2013). A better representation of the forecast skill should be obtained by removing events that will not be forecast in this study and only looking at the non-convective events.

3 | FORECAST DATA

This project uses an entire year of global ensemble data between May 2016 and April 2017 from two forecast

TABLE 1 Turbulence severity for values of derived equivalent vertical gust (DEVG) (Truscott, 2000) and eddy dissipation rate (EDR) (Sharman *et al.,* 2014)

Turbulence severity	DEVG (m/s)	EDR ($m^{2/3}/s$)
None	DEVG ≤ 2	EDR ≤ 0.07
Light	2 ≤ DEVG ≤ 4.5	0.07 ≤ EDR ≤ 0.27
Moderate	4.5 ≤ DEVG ≤ 9	0.27 ≤ EDR ≤ 0.61
Severe	9 ≤ DEVG	0.61 ≤ EDR

Note. For severe turbulence to be observed the DEVG value must be greater than or equal to 9 m/s and therefore 9 ≤ DEVG.

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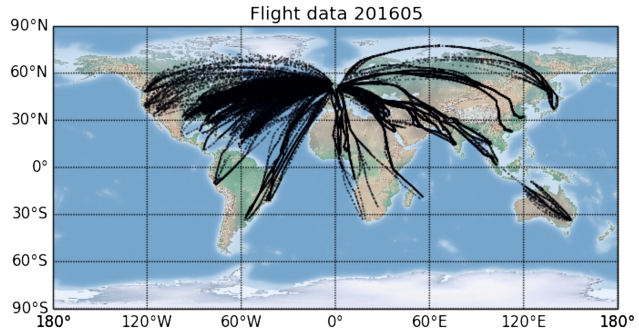

FIGURE 1 Plot of the spatial coverage of flight data from the fleet of Boeing 747 and 777 aircraft in May 2016 [Colour figure can be viewed at wileyonlinelibrary.com]

centres: MOGREPS-G (Bowler *et al.,* 2008) and the ECMWF EPS (Molteni *et al.,* 1996). The forecast data are available with 3 hr intervals, and at the time of this study the MOGREPS-G ensemble had 12 members with forecasts every 6 hr, with 33 km resolution and 70 vertical levels, 10 of which are between 150 and 350 hPa. The ECMWF forecast had 51 ensemble members with 18 km resolution and 91 vertical levels, 14 of which are between 150 and 350 hPa. To use the ECMWF EPS system operationally the forecast range would have to be extended by approximately 12 hr due to a delay in accessing the forecast data. This is important to note because it means that the results of the ECMWF EPS will be theoretical and in practice the skill will be reduced as longer lead times have to be used. This is shown by the WAFC verification website demonstrating how the forecast skill is reduced with forecast lead time (Met Office, 2018). The longer lead times have not been used in this study but understanding the impact this will have on the forecast skill would be an interesting area of further study. Also, for both ensembles this study only had access to the 0000 UTC model run between May 1, 2016 and August 7, 2016, which means that for that period only half of the day was forecast. Between August 7, 2016 and April 30, 2017 both the 0000 UTC and 1200 UTC model runs were available. The forecast lead time used throughout is T + 24, T + 27, T + 30, T + 33 hr.

This study focuses on non-convective turbulence and uses the Ellrod TI1 predictor, which is defined as:

$$\mathrm{TI1} = \mathrm{DEF} \times \mathrm{VWS} = \left\{ \left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 \right\}^{1/2} \times \left\{ \left(\frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial v}{\partial z} \right)^2 \right\}^{1/2} \quad (4)$$

where u is the horizontal wind velocity in the east–west direction, v is the horizontal wind velocity in the north–south direction, x is distance in the east–west direction, y is distance in the north–south direction and z is distance in the vertical. This is the same index as that used in previous studies and is the turbulence diagnostic currently used by the WAFCs. The Ellrod TI1 combines deformation and vertical wind shear as shown in Equation (4) and is a well-established shear turbulence diagnostic. Previous research has shown it predicts up to 65% of CAT events (Sharman *et al.,* 2006), although it is typically only useful in the mid to high latitudes. Also the Ellrod TI1 was not developed to predict CIT or MWT, which are both prominent turbulence sources.

To create a probability forecast, the ensemble data from both WAFCs were used and thresholds were set based on the literature (ICAO, 2012). The turbulence threshold used in this project for the Ellrod TI1 is 3×10^{-7} s^{-2} which is equivalent to moderate or greater (MoG) turbulence. However, additional thresholds that range from light or greater to severe or greater turbulence were also calculated. Using multiple thresholds to predict different turbulence strength categories is similar to the approach used by Williams (2017) and Storer *et al*. (2017). Ellrod and Knapp (1992) also discuss the use of higher thresholds for moderate and severe turbulence with the actual values used being model specific. These additional thresholds are used to optimize the turbulence forecast as a lower threshold will capture more MoG turbulence events but also more false alarms, and a higher threshold will forecast fewer MoG events but also fewer false alarms. The additional thresholds used are 8×10^{-8} s^{-2}, 1×10^{-7} s^{-2}, 5×10^{-7} s^{-2}, 8×10^{-7} s^{-2}, 1.1×10^{-6} s^{-2} and 2×10^{-6} s^{-2}. Above these thresholds, it is classed as an area of the atmosphere containing turbulence. Combining all the ensemble results gives the probability for a grid point containing MoG turbulence. The more ensemble forecasts that predict the occurrence of turbulence, the higher the probability forecast will be. It is then possible to combine both the ensemble forecasts, which can be done in two ways. The first is a standard equally weighted multi-model super ensemble and the other is a weighted multi-model ensemble. This study uses the simple super ensemble by combining the two equally weighted ensembles. This was created by first calculating the probability field of turbulence for both the single model ensembles based on exceeding a threshold of 3×10^{-7} s^{-2}. The mean of the probability for both ensembles then created the multi-model ensemble. This therefore means that, although the ECMWF EPS ensemble has more ensemble members, it does not have any more weight in the multi-model ensemble.

4 | VERIFICATION METHOD

The verification method used in this study is outlined in Gill (2014, 2016). Aircraft observations are processed into 10 min segments, which equate to approximately 100 km of flight. On analysing the DEVG values in each segment, if the maximum value exceeds a given threshold it is classed as a turbulence event. The aircraft data are constrained to

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±1.5 hr of the forecast time to ensure the aircraft observations reflect the forecast. Therefore each 10 min segment (observation) within the 3 hr time window is used for verification as beyond this the observations are not valid for the forecast. It is then possible to compare the turbulence observations to the forecast and a 2 × 2 contingency table can be set up as shown in Table 2. One of the best ways to visualize these results is to use a relative operating characteristic (ROC) plot (Jolliffe and Stephenson, 2012; Gill, 2016), which plots the hit rate against the false alarm rate, defined as:

$$\text{hit rate } (H) = \frac{A}{A + C} \tag{5}$$

$$\text{false alarm rate } (F) = \frac{B}{B + D} \tag{6}$$

where A is a hit; B is a false alarm; C is a miss; and D is a correct rejection. To create the ROC curve, thresholds are applied to the probabilities that then create binary yes/no forecasts with corresponding 2 × 2 contingency tables yielding the hit rate and false alarm rate which are plotted together. This produces a curve where, the larger the area under the curve, the more skilful the forecast is at discriminating between events and non-events.

The reliability of the forecasts can be assessed visually by using a reliability diagram (Jolliffe and Stephenson, 2012; Gill, 2016), where each probability is binned and the frequency of the event is calculated. The forecast probability should equal the observed frequency. For example, if the probability is 30% then turbulence in that region should be observed 30% of the time. Therefore, a perfect forecast would result in a straight line; however, in practice this is not the case and forecast probabilities tend to over-forecast the turbulence (below the line) or under-predict turbulence (above the line). Understanding these biases allows a linear calibration to be implemented which should bring the forecast probability more in line with the observed frequency. Calibrating the forecast will not compromise the forecast skill, since the ROC area discriminatory skill and reliability are independent (Gill, 2016).

A more practical analysis of the results for stakeholders would be to assess the relative economic value (V) of the forecast, which is defined as:

$$V = \frac{\min(\alpha,\ \bar{o}) - F\alpha(1-\bar{o}) + H\bar{o}(1-\alpha) - \bar{o}}{\min(\alpha, \bar{o}) - \bar{o}\alpha} \tag{7}$$

where α = cost/loss, $\bar{o}$ is the fraction of occasions where the event occurred, F is the false alarm rate and H is the hit rate (Richardson, 2000; Jolliffe and Stephenson, 2012). This assigns a cost and loss for the elements in a contingency table (Table 3) where different outcomes depend on whether action was taken and if the event occurred or not. For a given model, the hit rate (H), false alarm rate (F) and fraction $\bar{o}$ of occasions the event occurred can be calculated using a 2 × 2 contingency table, and therefore varying the cost/loss ratio gives a different value which can be plotted. The more skilful the model, the higher the maximum value will be (but the actual value will depend on the cost/loss ratio of the user), and if the value is higher for all cost/loss ratios then that model will be the most useful for any consumer (as the cost/loss ratio may vary depending on the consumer); this is known as sufficiency (Ehrendorfer and Murphy, 1988). Gill and Buchanan (2014) and Buchanan (2016) showed that probability turbulence forecasts have greater value than deterministic forecasts, so this project will aim to show by combining ensembles that the value can be further increased.

5 | RESULTS

Throughout this analysis the focus is on shear turbulence; however, MWT and CIT will be present in the observational truth data. To identify the source of turbulence, this study plots the aircraft data over a plot of orography, convection and shear turbulence. The orography plot uses a surface map that indicates terrain height and therefore mountain ranges. The orography map shows the height of the terrain, and any event that occurs near high terrain could be caused by MWT, whereas the CIT plot uses a satellite product that indicates areas of deep convection (Francis and Batstone, 2013). The satellite product identifies regions of overshooting tops which indicate the regions of the strongest updraft, above the smooth anvil of a typical thunderstorm. To identify these regions they use two methods: the first is the water vapour infrared window brightness temperature difference method (Schmetz *et al.,* 1997) and the second is the infrared window texture method (Bedka *et al.,* 2010). The infrared channel can be used in both day and night which is

TABLE 2 A 2 × 2 contingency table showing the possible results of a turbulence forecast or event

	Turbulence observed	Turbulence not observed
Turbulence forecast	A (hit)	B (false alarm)
Turbulence not forecast	C (miss)	D (correct rejection)

Note. The four possible outcomes include a hit, miss, false alarm and correct rejection.

TABLE 3 A 2 × 2 contingency table assigning a cost to the possible results of a turbulence forecast or event

	Turbulence observed	Turbulence not observed
Turbulence forecast Action taken	Hit Cost	False alarm Loss
Turbulence not forecast No action taken	Miss Loss	Correct rejection

Note. The four possible outcomes include a hit (with a subsequent cost), miss (with a subsequent cost), false alarm (with a subsequent cost) and correct rejection (with no cost as no action was taken).

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important for aviation. Full global coverage was not available for the satellite product, and therefore only CIT events within that spatial coverage could be removed. For shear turbulence both ensemble probability fields are plotted so it will be clear if shear turbulence is a likely cause and if both ensemble products predict turbulence. The plots have aircraft data ±1.5 hr which will help identify the likely source of turbulence.

Figure 2 is a plot of a shear turbulence case study that was forecast by both the MOGREPS-G and ECMWF EPS ensembles. The plot clearly shows that the MoG turbulence event was over the North Atlantic so MWT is not a factor, and the satellite product shows there is no deep convection in the area, although there is some convection much further south. Thus, the turbulence event was well forecasted by the ensemble products. There is also a light turbulence event further south, and this is not forecast by either ensemble. This is to be expected as the threshold used for this figure is typical for MoG turbulence and therefore not expected for this event. There is some convection just to the south; however, it seems too far away to cause this light turbulence event.

Looking at Figure 3 there is no CIT in the area; however, this could be MWT, as this event is over some smaller mountains, or shear turbulence as it is forecast by the MOGREPS-G ensemble. This is a case that shows the benefit of using the multi-model ensemble approach. If only the ECMWF EPS ensemble were available then the event would not be forecast and as a result people could be injured. However, since both ensembles are available, the event is forecast and therefore preventative action can take place, increasing passenger and crew comfort and safety.

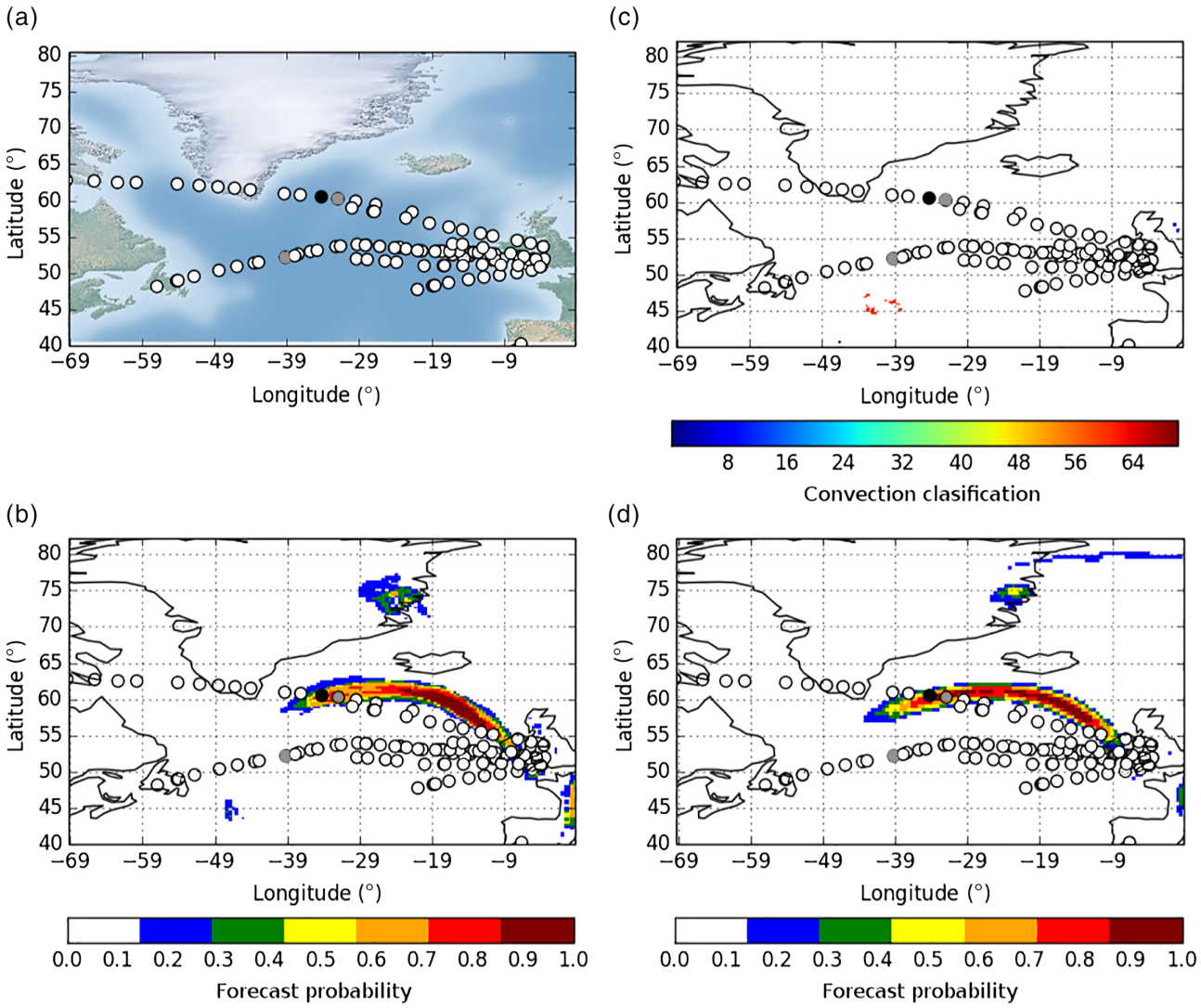

FIGURE 2 Plot of a moderate or greater turbulence event over the possible sources of turbulence: (a) orography, shear turbulence ((b) Met Office Global and Regional Ensemble Prediction System [MOGREPS-G] and (d) European Centre for Medium-Range Weather Forecasts Ensemble Prediction System [ECMWF EPS] probability forecast) and (c) convection from satellite data. Both the MOGREPS-G and ECMWF EPS ensembles forecast the shear turbulence event. The circles indicate turbulence observations with white indicating no turbulence, grey indicating light turbulence and black indicating moderate or greater turbulence. The convective classification can be found in Francis and Batstone (2013) [Colour figure can be viewed at wileyonlinelibrary.com]

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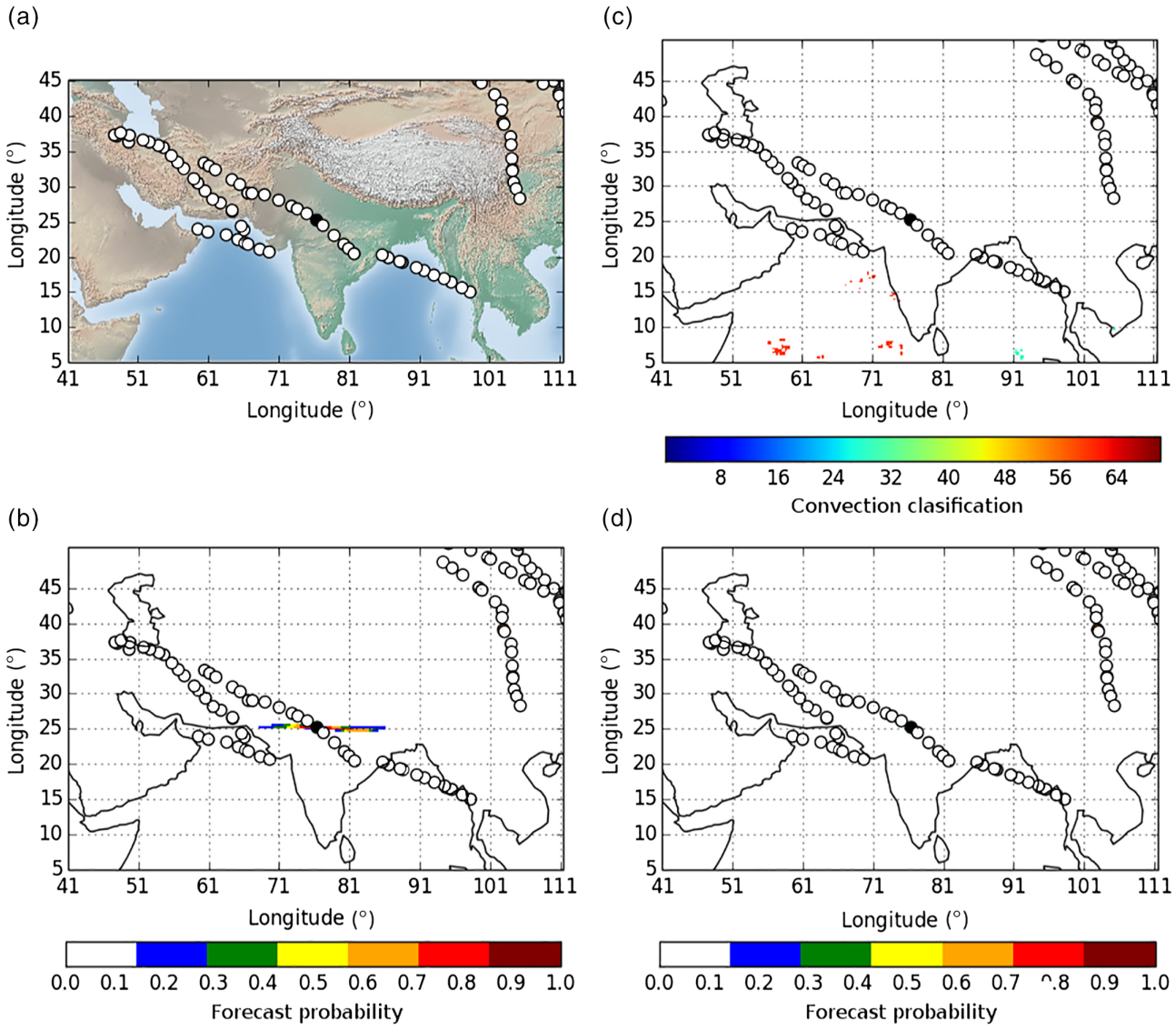

FIGURE 3 Plot of a moderate or greater turbulence event over the possible sources of turbulence: (a) orography, shear turbulence ((b) Met Office Global and Regional Ensemble Prediction System [MOGREPS-G] and (d) European Centre for Medium-Range Weather Forecasts Ensemble Prediction System probability forecast) and (c) convection from satellite data. Only the MOGREPS-G ensemble forecasts the shear turbulence event. The circles indicate turbulence observations with white indicating no turbulence, grey indicating light turbulence and black indicating moderate or greater turbulence. The convective classification can be found in Francis and Batstone (2013) [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 4 shows another example where the multi-model ensemble approach is better, as the MOGREPS-G ensemble does not forecast the shear turbulence event but the ECMWF EPS ensemble does. This case study is interesting, however, because the turbulence event is over the Rocky Mountains, so this could be MWT. It is probably a combination of shear and MWT and again shows the multi-model ensemble approach is a benefit, as if only the MOGREPS-G ensemble was available this event would not be forecasted. This case also reinforces the need to have a MWT diagnostic, as the severe turbulence observations spread further than the forecast indicated. Figure 4 also shows some of the problems with turbulence forecasting, as what could be a false alarm event over Canada is seen. Both the ECMWF and MOGREPS-G ensemble predict turbulence; however, no turbulence is observed. This shows the benefit of using a probabilistic forecast because different end users can select the probability threshold of when they would take action. For example, if the probability forecast for turbulence is 20%, then there is a 1 in 5 chance of turbulence being observed. However, if the end user sets their threshold for action at 10%, then this event would be classed as a false alarm because it was forecasted (as it was above the 10% threshold) and the event did not occur. If the threshold they used was 30%, however, this would be a correct rejection as turbulence would not be forecast as the threshold was not exceeded and turbulence did not occur.

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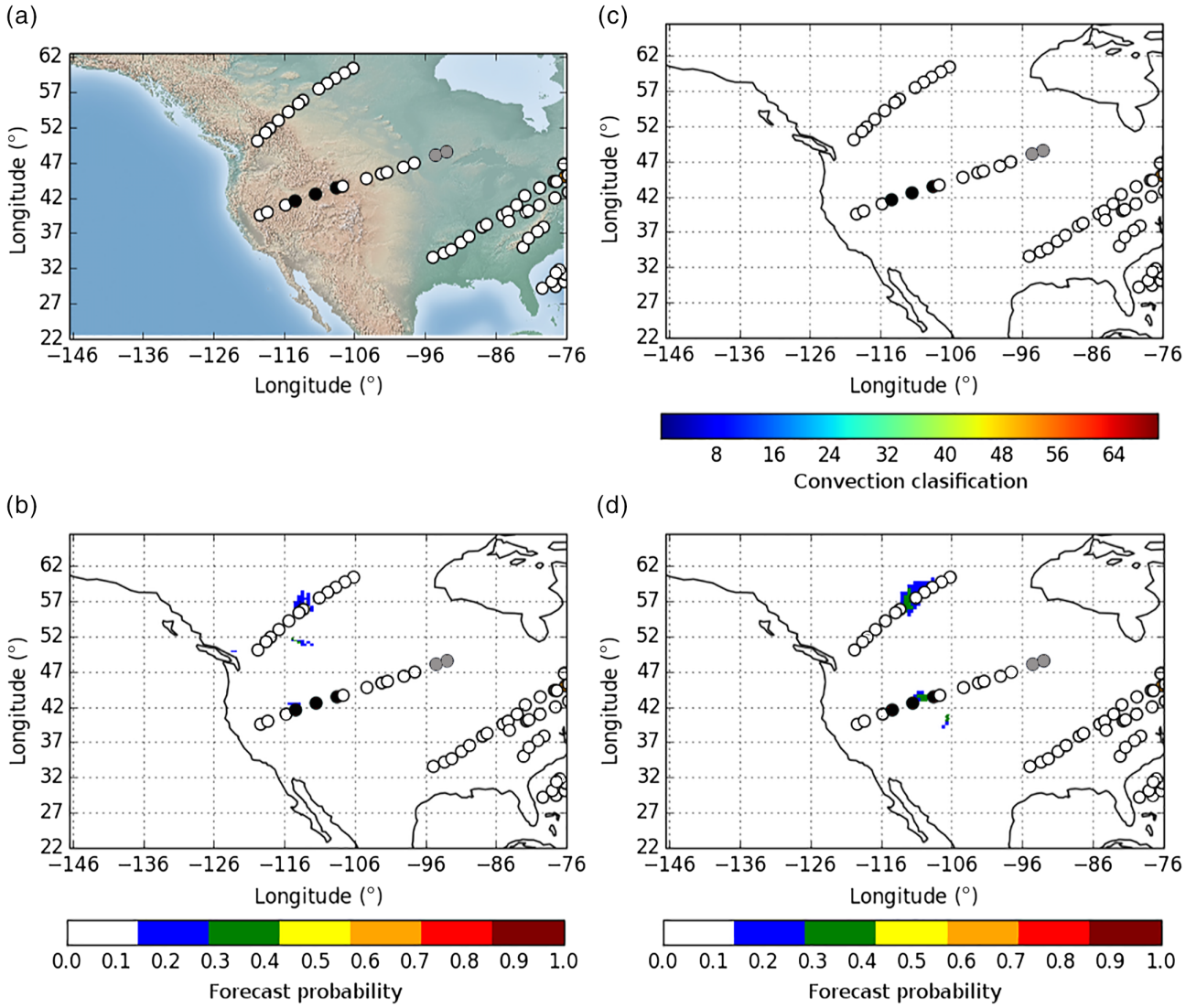

FIGURE 4 Plot of a moderate or greater turbulence event over the possible sources of turbulence: (a) orography, shear turbulence ((b) Met Office Global and Regional Ensemble Prediction System and (d) European Centre for Medium-Range Weather Forecasts Ensemble Prediction System [ECMWF EPS] probability forecast) and (c) convection from satellite data. Only the ECMWF EPS ensemble forecasts the shear turbulence event. The circles indicate turbulence observations with white indicating no turbulence, grey indicating light turbulence and black indicating moderate or greater turbulence. The convective classification can be found in Francis and Batstone (2013) [Colour figure can be viewed at wileyonlinelibrary.com]

This helps to illustrate the trade-off between hits and false alarms and the ability the probability framework gives to its users to fine tune their response to optimize the forecast. So, for this example, a higher threshold would result in a correct rejection, but might also miss the MoG turbulence event over the Rocky Mountains.

After plotting all the 424 MoG turbulence events, 98 cases were identified that are likely to be CIT, which TI1 cannot forecast. To address this issue the CIT events from the rest of our study are removed in order to give the fairest possible test for the multi-model ensemble forecasts. It was decided to keep all other MoG turbulence events in the study because there is no strong evidence that they are not shear related. An example is MWT; although these events can be identified to occur over mountains it is not possible to prove they are not shear turbulence. Using the satellite convection product there is more confidence in the CIT events and therefore more confidence in removing them. If there is uncertainty about whether it is a CIT event, it is kept in the study. What this does highlight, though, is that this study must be extended in the future to include a convective diagnostic and a MWT diagnostic because combined they count for a third of the events in this study.

After removing the events that were categorized as CIT only it was possible to analyse the performance of the multi-model ensemble and the single model ensembles and compare it to previous studies such as that of Gill and Buchanan (2014). Figure 5 is a ROC plot showing the skill for both the single model ensembles and the combined multi-model ensemble. Typically the area under the curve (AUC) is a good measure of discriminatory skill. However, in this study the MOGREPS-G ensemble has a shorter line than both the

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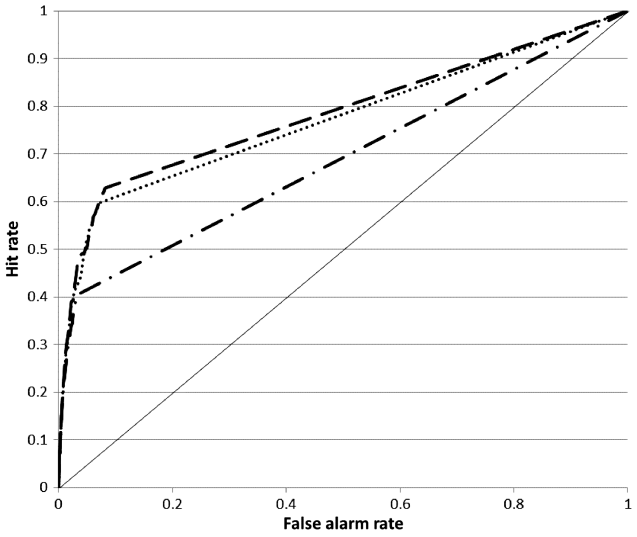

FIGURE 5 Relative operating characteristic plot of the global turbulence forecast performance with the 98 convective turbulence cases removed showing the forecast skill of the Met Office Global and Regional Ensemble Prediction System (dot-dashed) area under the curve (AUC) = 0.6881, the European Centre for Medium-Range Weather Forecasts Ensemble Prediction System (dotted) AUC = 0.772 and the combined multi-model ensemble (dashed) AUC = 0.7842. The data used have a forecast lead time between +24 hr and +33 hr between May 2016 and April 2017

ECMWF and the multi-model ensemble. This is because a 12 member ensemble cannot forecast the same lower probabilities as a larger ensemble. The 12 member ensemble can only predict probabilities as small as 1/12, whereas the ECMWF 51 member ensemble can forecast probabilities as low as 1/51. Therefore, a simple AUC number could be biased towards the ECMWF forecast and multi-model ensemble forecasts as the longer line could (and does in this example) give them a larger AUC. Therefore, it is better to focus on how steep the line is, and therefore on low false alarm rates that are more useful for the aviation industry, although the best method of measuring statistical significance is to use the AUC.

Low false alarm rates are more important for this study because airline companies may have a limit on acceptable hit rates and false alarm rates, and therefore the lower false alarm rates are the ones they would focus on. Figure 5 shows that the ECMWF, MOGREPS-G and simple combined ensemble have almost the same skill. This is surprising because, by combining the two ensembles, the forecast spread has increased and therefore more turbulence events are captured, but consequently more false alarms. Because of this trade-off, no significant increase in skill is seen. The AUC for the two single model ensembles are ECMWF 0.7712 and MOGREPS 0.6881. The multi-model ensemble has an AUC of 0.7842 with the 95% confidence interval lower bound being 0.7538 and the 95% confidence interval upper bound being 0.8102. This therefore shows that at the 95% confidence interval the multi-model ensemble is only significantly better than the MOGREPS single model ensemble but not the ECMWF single model ensemble and this is because the MOGREPS-G line is shorter. To understand the benefit of using a multi-model ensemble Table 4 shows the number of MoG turbulence events where both models agree and, if they disagree, which model forecasted the turbulence event. Out of the 326 MoG turbulence events, the models are in agreement for 243 of them, so they either both forecast the event or both do not forecast the event. That leaves 83 out of 326 MoG turbulence events when the models do not agree. What is found, however, is that this number is not split evenly and ECMWF forecasts 73 times when MOGREPS does not; there are only 10 occasions where MOGREPS forecasts turbulence and ECMWF does not. This suggests that there are only 10 occasions where it is a benefit to have a multi-model ensemble over a single ECMWF ensemble. This could be part of the reason why a large improvement of forecast skill is not seen when combining ensembles. Most of the events are already forecast by one of the models, and therefore there is only a limited benefit in adding the second ensemble.

The relative economic value of the forecast is shown in Figure 6 which shows that the multi-model ensemble has greater value than the single model ensembles but only for low cost/loss ratios. This is important because depending on the relative importance of minimizing misses and maximizing hits for an airline company defines the cost/loss ratio that is focused on. It is also known that the cost of action is likely to be a great deal less than the cost of loss due to injuries or aircraft damage. Therefore, lower cost/loss ratios are likely to be more important for the airline companies, and this study focuses on those here. Thus, the multi-model ensemble is as skilful as the single model ensembles but would be more useful for decision-making in an operational environment. The figure also shows the maximum value for all the thresholds of the combined multi-model ensemble. As mentioned before, the probability fields for many thresholds have been calculated, so this curve takes the highest value threshold for each cost/loss ratio. Since the bold line is above the others, there is more value in some of the other thresholds, and an optimized multi-model ensemble would provide more value and is worth pursuing in future studies. It is important to point out again that the ECMWF EPS value is theoretical and operationally would be lower since the

TABLE 4 Categorizing moderate or greater turbulence events between cases where both the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Met Office Global and Regional Ensemble Prediction System (MOGREPS) models are in agreement (both do/do not forecast turbulence) and where the models are not in agreement (one model does forecast turbulence and the other does not)

	Models not in agreement	
Models in agreement	**ECMWF forecasts turbulence**	**MOGREPS forecasts turbulence**
243	73	10

Note. When the models are not in agreement, the results are put into a subcategory of which ensemble did forecast the turbulence event.

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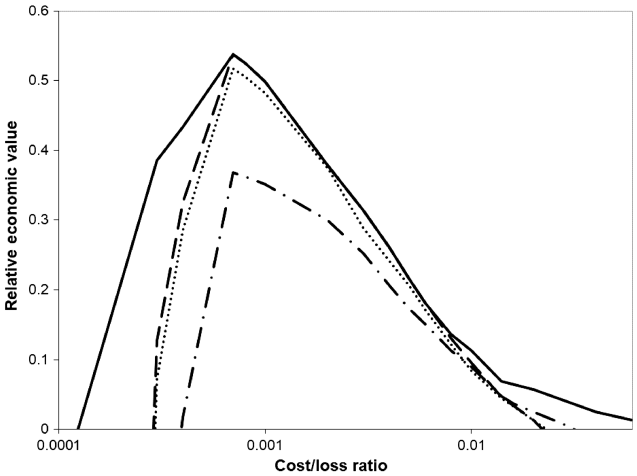

FIGURE 6 Value plot with a log scale *x*-axis of the global turbulence forecast performance with the 98 convective turbulence cases removed showing the forecast value of the Met Office Global and Regional Ensemble Prediction System (dot-dashed), the European Centre for Medium-Range Weather Forecasts Ensemble Prediction System (dotted), the combined multi-model ensemble (dashed) and the maximum value using every threshold of the combined multi-model ensemble (solid line). The data used have a forecast lead time between +24 hr and +33 hr between May 2016 and April 2017

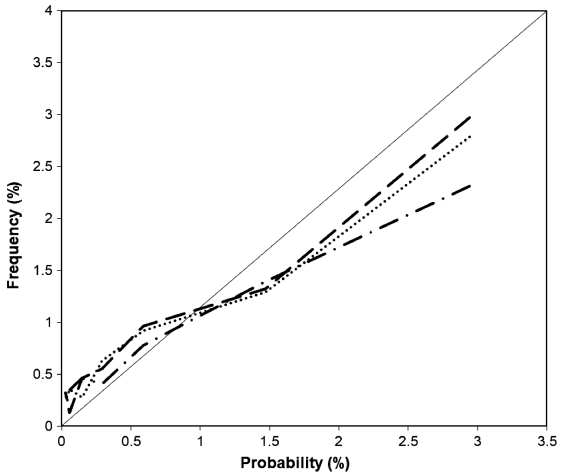

FIGURE 7 Reliability diagram of the Met Office Global and Regional Ensemble Prediction System (dot-dashed), the European Centre for Medium-Range Weather Forecasts Ensemble Prediction System (dotted) and the combined multi-model ensemble (dashed). The data used have a forecast lead time between +24 hr and +33 hr between May 2016 and April 2017

availability of the data forces the use of a longer lead time. Also, when comparing the single model ensembles to the previous study by Gill and Buchanan (2014) an improvement is seen in the relative economic value, showing a significant model improvement over the last few years. This improvement could be because the Met Office introduced the ENDGame (Even Newer Dynamics for General Atmospheric Modelling of the Environment) dynamical core (Walters *et al.,* 2014). This has provided a better forecast and in particular has resulted in a "reduction of the slow bias in tropospheric windspeeds." It is important to note that a direct comparison is not possible because each study looks at two different years, but this study shows a large improvement in the MOGREPS-G value compared to the Gill and Buchanan (2014) result.

Also plotted is a reliability plot shown in Figure 7. This figure shows that the MOGREPS-G, ECMWF EPS and combined multi-model ensembles under-forecast the lower probabilities but over-forecast the higher probabilities. This is shown by each ensemble being above the line of a perfect forecast for the lower probabilities but below the line for higher forecast probabilities. It is important to note that these plots have been calibrated because the forecast percentages from the ensembles are much higher than the observed frequency. This linear calibration is the forecast probability multiplied by a constant, which for this study is 1/17, which brings it more in line with the observed frequency. Although a direct comparison cannot be made, the forecast percentages and observed frequency in this example have increased and the reliability has improved over the last few years compared to Gill and Buchanan (2014). What this again suggests is that the turbulence forecast models have improved over the last few years and the multi-model ensemble is at least as reliable as the individual ensembles.

So far it has been shown that combining two ensembles improves the forecast, but it is also important to understand how the individual ensembles compare with each other. To do this it is first necessary to reduce the ensemble size of the ECMWF forecast to make it a fair comparison. This is because a larger ensemble should give a larger forecast spread, and therefore improve the forecast result, and the ECMWF EPS has 51 members compared to the MOGREPS-G 12 members. To do this the first 12 members of the ECMWF ensemble were chosen. Each of the perturbed members is constructed to be equally likely, and each consecutive member has a "pair-wise anti-symmetric perturbation" (Owens and Hewson, 2018). Therefore, choosing consecutive members is a bias-free method for creating a subsample. This is also how Buizza and Palmer (1998) studied the impact of ensemble size on ensemble skill. They took pairs of perturbed members, so that each ensemble has pairs of members with the same positive and negative perturbations. Figure 8 is the ROC plot with the same ensemble size and it can be seen that both models have almost the same forecast skill. From Figure 9 it is seen that the ECMWF EPS ensemble is more valuable, which is interesting. This would be useful when trying to combine the two ensembles using a weighted scheme to get the best forecast skill. As the ECMWF EPS forecast is more valuable a larger weight would be applied when creating the multi-model ensemble. However, again in an operational system, the ECMWF EPS skill would be reduced as the longer lead time needed due to the time delay of the forecast would reduce the skill. So, before an optimized weighted multi-model ensemble can be created, the performance of the ECMWF ensemble with the

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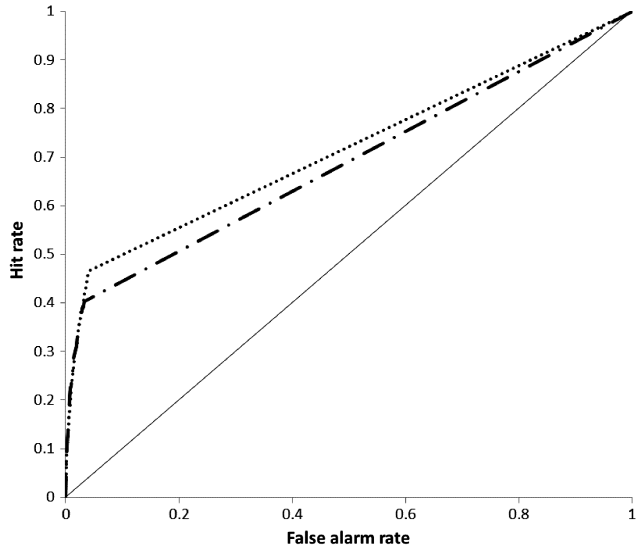

FIGURE 8 Relative operating characteristic plot of the global turbulence forecast performance showing the forecast skill of the Met Office Global and Regional Ensemble Prediction System (dot-dashed) and the European Centre for Medium-Range Weather Forecasts 12 member ensemble (dotted). The data used have a forecast lead time between +24 hr and +33 hr between May 2016 and April 2017

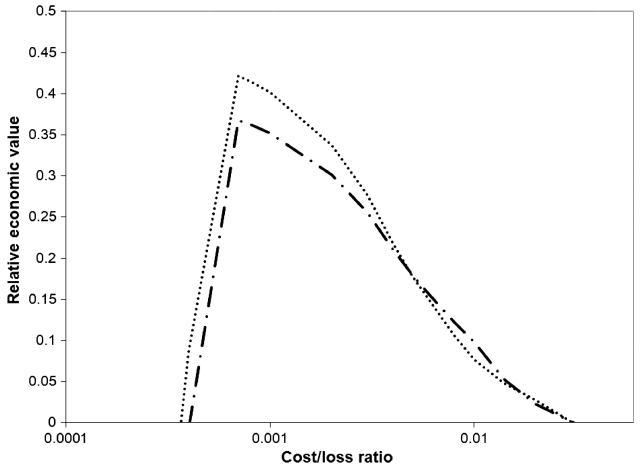

FIGURE 9 Value plot with a log scale *x*-axis of the global turbulence forecast performance showing the forecast value of the Met Office Global and Regional Ensemble Prediction System (dot-dashed) and the European Centre for Medium-Range Weather Forecasts 12 member ensemble (dotted). The data used have a forecast lead time between +24 hr and + 33 hr between May 2016 and April 2017

time delay would have to be analysed. This would then need to be extended to include all turbulence predictors to find the best multi-model ensemble forecast.

6 | CONCLUSIONS AND FURTHER WORK

This study has investigated the role ensemble forecasts have in aviation turbulence. By combining two ensembles to create a simple multi-model ensemble, the aim was to show improved forecast value and skill which could then be implemented operationally. To verify the forecasts, aircraft observations from a fleet of Boeing 747 and 777 aircraft were used and created a contingency table of results. From this the results were analysed to show that the multi-model ensemble system is as skilful as a single model ensemble, which follows on from the work of Gill and Buchanan (2014) and Buchanan (2016).

The results suggest that the forecast skill for the simple equally weighted multi-model ensemble is at least as skilful as the single model ensembles. This lack of significant improvement in the forecast skill was not expected, but could be because, when increasing the forecast spread, more turbulence events are captured and also more false alarms. This trade-off would have to be optimized to maximize the forecast skill, but in this study it was not possible to show a significant improvement. However, the value of the forecast is improved for the multi-model ensemble, particularly at low cost/loss ratios which are more important for operational use. Therefore, to see an improvement in value at low cost/loss ratios it is worth pursuing this multi-model approach as it would be more valuable in an operational setting. Our results also show that the multi-model ensembles are as reliable as the single model ensembles, and therefore overall the multi-model ensembles are an improvement to single model ensembles. Combining two ensembles produces a gain in consistency, gives more operational resilience and creates one authoritative forecast whilst maintaining skill and increasing value, which will be particularly important in operational use in the future by the WAFCs.

Throughout the analysis, it is also found that the Ellrod and Knapp (1992) TI1 predictor is good at forecasting shear turbulence in particular. However, not all the shear-induced turbulence events are forecast and therefore one or more shear turbulence diagnostics would be beneficial, similar to Kim *et al*. (2015). It would also be a good next step to include the Ellrod3 turbulence diagnostic from Sharman and Pearson (2017), as they showed its improved performance over other turbulence diagnostics; this could be an easy step to improving the forecast skill. Also the MOGREPS-G ensemble is designed to be time lagged to create a 24 member ensemble, and this should also be investigated in further work (Met Office, 2017). An alternative method for creating a probabilistic forecast would be a multi-diagnostic approach, rather than the traditional ensemble members approach. Kim *et al*. (2018) showed that a multi-diagnostic approach using two numerical models (NOAA's Global Forecast System and the Met Office's Unified Model) for creating a probability forecast had a far greater statistical performance than the current WAFC forecast and any single CAT diagnostic. This is another example of how probabilistic forecasting can improve forecast skill, but a different method is used to create it. It is also vital to add convective and mountain wave predictors in any further studies. This would then take into account convectively induced turbulence (CIT) and mountain wave turbulence (MWT) that are

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also leading causes of aviation turbulence and account for many injuries to passengers and crew. Also CIT and MWT predictors could benefit more from two ensembles than the Ellrod and Knapp (1992) TI1 forecast. This could be because how the models forecast the predictors could be very different; therefore the forecast spread would be much higher between models, making a multi-model ensemble superior to a single model ensemble.

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