

METEOROLOGY

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ensemble prediction systems



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# Prediction of extratropical cyclones by the TIGGE ensemble prediction systems

Lizzie S. R. Froude

Environmental Systems Science Centre, University of Reading, UK

Extratropical cyclones are fundamental to the everyday weather in the mid-latitudes, but they can also be extremely hazardous. The accurate prediction of these weather systems is therefore of key importance. A cyclone tracking technique has been developed for analysing the prediction of extratropical cyclones by numerical weather prediction. This technique has been used to compare the prediction of extratropical cyclones by nine different Ensemble Prediction Systems (EPSs). These will be identified by just the name of the production centre (see Box A). These EPS data are freely available to researchers via the THORPEX Interactive Grand Global Ensemble (TIGGE) archives (see *Bougeault et al.*, 2010).

Results show large differences in cyclone predictive skill between the different EPSs. Key findings include:

- ECMWF has the highest level of skill in predicting cyclone position, intensity and propagation speed.
- The Japan Meteorological Agency (JMA), the National Centers for Environmental Prediction (NCEP), the Met Office (UKMO), and the Canadian Meteorological Centre (CMC) have the next highest level of skill.
- NCEP, the Centro de Previsão de Tempo e Estudos Climáticos (CPTEC), and the Australian Bureau of Meteorology (BoM) significantly underpredict cyclone intensity. They also have faster intensity error growth in the earlier part of the forecast and are very underdispersive in cyclone intensity.
- Cyclone propagation speed is underpredicted (i.e. the forecast cyclones propagate slower than the analysed cyclones) by the perturbed members and control forecasts of all nine EPSs.
- For all nine EPSs, the ensemble mean provides very little advantage over the control forecast for cyclone position, but for cyclone intensity the ensemble mean does provide a significant improvement.
- ECMWF and JMA have an excellent spread-skill relationship for cyclone position in the northern hemisphere and ECMWF also does in the southern hemisphere. The other EPSs are underdispersive.
- All the EPSs are much more underdispersive for cyclone intensity. ECMWF and CMC have the smallest difference between ensemble spread and ensemble mean error.

This article briefly describes the methodology used to analyse the TIGGE data and discusses some of the results. For further details the reader is referred to *Froude (2010a,b)*.

## The nine centres whose EPSs have been used in this study

**A**

- |   |   |
|---|---|
| <ul style="list-style-type: none"> <li>• Bureau of Meteorology (BoM)</li> <li>• Canadian Meteorological Centre (CMC)</li> <li>• Centro de Previsão de Tempo e Estudos Climáticos (CPTEC)</li> <li>• China Meteorological Administration (CMA)</li> <li>• European Centre for Medium-Range Weather Forecasts (ECMWF)</li> <li>• Japan Meteorological Agency (JMA)</li> </ul> | <ul style="list-style-type: none"> <li>• Korea Meteorological Administration (KMA)</li> <li>• National Centers for Environmental Prediction (NCEP)</li> <li>• UK Met Office (UKMO)</li> </ul> <p>Note that Météo-France is excluded from the analysis because its forecasts are only integrated out to three days, which is not long enough to include the full life cycle of a large number of cyclones.</p> |
|---|---|

### TIGGE data and storm tracking methodology

Medium-range ensemble forecasts are now routinely produced at numerous operational weather centres around the world. The EPSs of these centres differ in many ways, using different models, resolutions, perturbation methodologies and so on. It is important to assess and compare the performance of the different EPSs to determine the impact the different configurations have on forecast performance and to determine how the EPSs could be improved.

TIGGE is a major component of the World Weather Research Programme. One of its main objectives is to enhance collaboration on the development of ensemble prediction between operational centres and universities by increasing the availability of EPS data for research. Since 1 February 2008 ten operational weather forecasting centres have been delivering near-real-time ensemble forecast data to three TIGGE data archives located at ECMWF, the National Center for Atmospheric Research (NCAR) and the China Meteorological Administration (CMA). For further details of TIGGE see *Bougeault et al. (2010)*.

The prediction of extratropical cyclones by nine of the EPSs contained in the TIGGE archives has been assessed. Table 1 lists these EPSs and summarises their main characteristics.

Extratropical cyclones are identified and tracked using 850 hPa relative vorticity field separately in the northern (20°–90°N) and southern (20°–90°S) hemispheres for all perturbed members and control forecasts. This identification and tracking is also performed with the ECMWF analysis. Cyclones predicted by the different EPSs are compared with those in the ECMWF analysis, and forecast verification diagnostics are generated for cyclone position, intensity and propagation speed. Since the cyclones are verified against the ECMWF analysis, there may be some positive bias towards ECMWF in the results. However, previous work suggests this will only be significant in the earlier part of the forecast. Further details of the cyclone identification and tracking methodology are provided in Box B.

Centre	Horizontal resolution	Number of levels	Number of members	Initial perturbations	Perturbation of model physics	Forecast length (days)	Forecast base times (UTC)	Data assimilation
BoM (Australia)	TL119 (1.5°)	19	32	SVs (NH, SH)	No	10	00, 12	GenSI
CMA (China)	T213 (0.5625°)	31	14	BVs (Globe)	No	10	00, 12	GSI
CMC (Canada)	TL149 (1.2°)	28	20	EnKF (Globe)	Yes	16	00, 12	4D-Var
ECMWF (Europe)	TL399 (0.45°) TL255 (0.7°)	62	50	SV (Globe)	Yes	0–10 10–15	00, 12	4D-Var
JMA (Japan)	TL319 (0.5625°)	60	50	SVs (NH, TR)	No	9	12	4D-Var
KMA (Korea)	T213 (0.5625°)	40	16	BVs (NH)	No	10	00, 12	3D-Var
NCEP (USA)	T126 (0.9474°)	28	20	ET (Globe)	No	16	00, 06, 12, 18	GSI
UKMO (UK)	1.25°×0.83°	38	23	ETKF (Globe)	Yes	15	00, 12	4D-Var
CPTEC (Brazil)	T126 (0.9474°)	28	14	EOF (45°S–30°N)	No	15	00, 12	NCEP Anal

**Table 1** Characteristics of the nine EPS used in this study. The abbreviations used in the table are as follows; SV (Singular Vector), BV (Bred Vector), ET (Ensemble Transform), EnKF (Ensemble Kalman Filter), ETKF (Ensemble Transform Kalman Filter), EOF (Empirical Orthogonal Functions), NH (Northern Hemisphere), SH (Southern Hemisphere), TR (Tropics), GenSI (Generalised Multivariate Statistical Interpolation), 3/4D-Var (3/4 Dimensional Variational Analysis), GSI (Gridded Statistical Interpolation), Tx (spectral triangular truncation at total wave number x) and TLx (spectral triangular truncation at total wave number x with linear grid). (From *Froude, 2010a*).

### Cyclone tracking methodology

B

The cyclones are identified and tracked along the 6-hourly forecast trajectories of each of the perturbed ensemble members, the control forecasts and analysis data using the method of Hodges (1995, 1999). The cyclones are identified in the 850-hPa relative vorticity field. In order that only synoptic-scale extratropical cyclones are identified, the data is first reduced to a resolution of T42. The planetary scales with total wave numbers less than or equal to 5 are also removed as in Hoskins & Hodges (2002). Once the cyclones are identified the tracking is performed by the minimisation of a cost function. Only those cyclone tracks that last at least 2 days and travel further than 1000 km are retained for the statistical analysis.

A matching methodology is used to objectively determine which forecast tracks correspond to which analysis tracks. A forecast cyclone track was considered to be the same system as an analysis cyclone track (i.e. matched) if the two tracks met certain predefined spatial and temporal criteria (see Froude, 2010a for details). The forecast tracks that matched with analysis tracks are then used to compute diagnostics for cyclone position, intensity and propagation speed.

As with any analysis methodology there may be biases and shortcomings that have some impact on the results. For further details and discussion of this please see Froude *et al.* (2007).

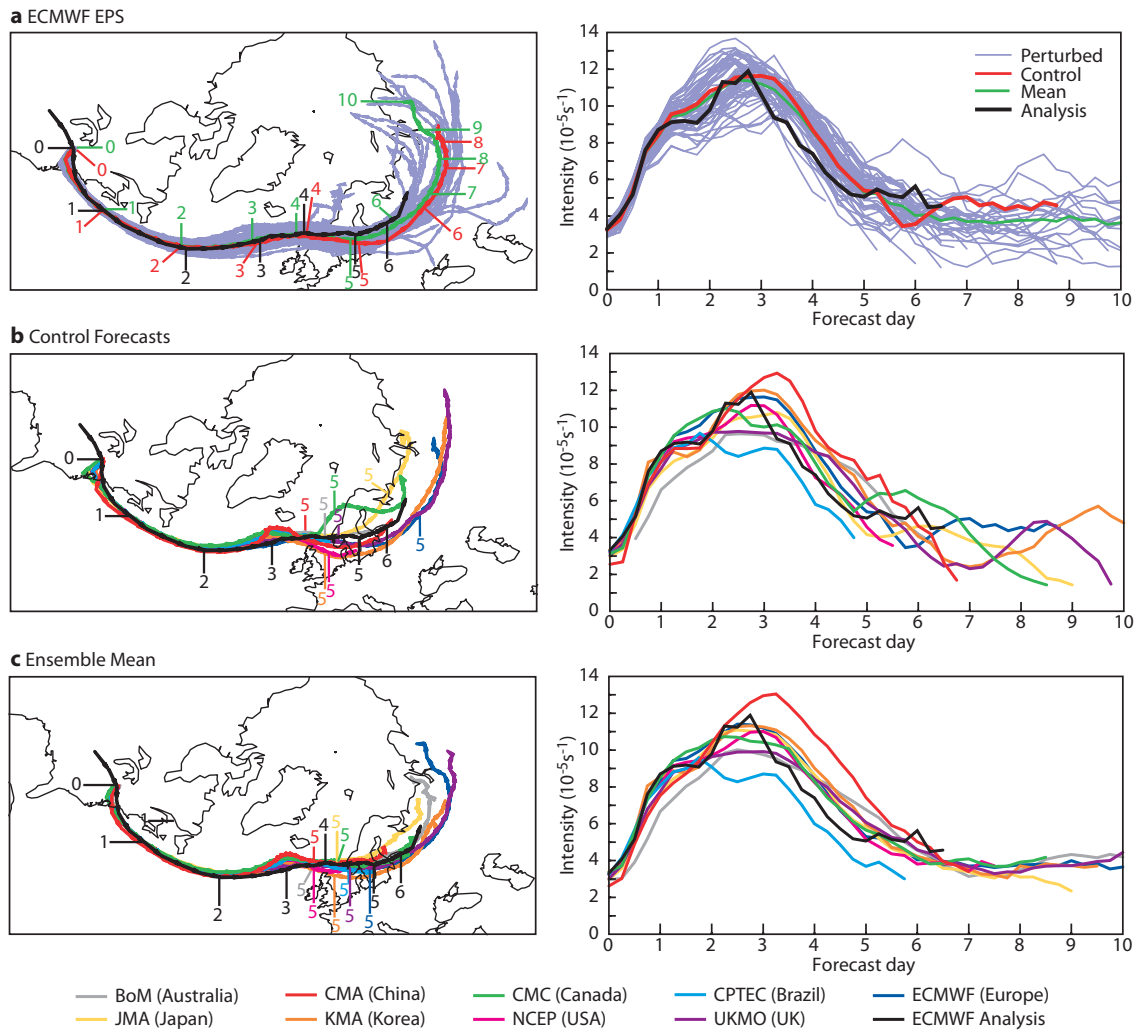
### An Atlantic cyclone

Figure 1a shows an example of the tracks and intensities of an Atlantic cyclone predicted by ECMWF. The analyzed Atlantic cyclone (shown in black) formed over North America at 00 UTC on 22 February 2008. It then travelled across the Atlantic, intensifying rapidly over the next three days before reaching its maximum relative vorticity amplitude of  $11.9 \times 10^{-5} \text{ s}^{-1}$  at 06 UTC on 25 February. The cyclone then moved north of the British Isles, over Scandinavia, and just into Russia while decaying over the next 3.5 days.

The ensemble member tracks are tightly spaced around the analysis track indicating that this particular cyclone is highly predictable. The mean track (calculated by averaging all the ensemble member tracks) and the control track lie virtually on top of each other until day 4 of the forecast. From this point the control track is slightly too far to the south and the mean is closer to the analysis. The spread in the intensity for this cyclone is also small, particularly during the initial growth phase in the first day of the forecast. From this point the ensemble members are more dispersed. Both the ECMWF control and ensemble mean exhibit high levels of predictive skill for this cyclone.

Figures 1b and 1c show the control tracks/intensities and mean tracks/intensities respectively for each of the nine EPSs. The track of the cyclone is predicted very well by all the centres until about day 4, when (as with ECMWF) the forecast tracks begin to diverge from the analyzed track. Some of the forecast cyclones travel considerably farther into Russia than the analyzed cyclone. There is a larger difference in performance between the centres for the cyclone's intensity than track. Overall ECMWF and Korea Meteorological Administration (KMA) have the highest level of performance. The CMA mean and control overpredict the maximum intensity of the cyclone and the other centres have an underprediction.

For this particular cyclone there is only a small difference in skill between the control and ensemble mean. However, for other cyclones, there can be a larger difference. The relative performance of the different EPSs can also vary considerably for different cyclones (see Froude, 2010a). This highlights the importance of performing a statistical analysis of a large number of cyclones to assess the skill and determine the strengths and weaknesses of the different EPSs.



**Figure 1** Tracks and intensities of an Atlantic cyclone predicted by the (a) ECMWF EPS, (b) control forecasts of each EPS and (c) ensemble mean (calculated by averaging all the ensemble member tracks/intensities) of each EPS. The ECMWF analysis is also shown in all the plots. Units of intensity are  $10^{-5} \text{ s}^{-1}$  (relative to background field removal) and the numbers along the tracks correspond to the forecast lead-time in days. The forecast start time (day 0) is 12 UTC on 22 February 2008. (Figure partly from Froude, 2010a).

**Comparison of ensemble mean skill**

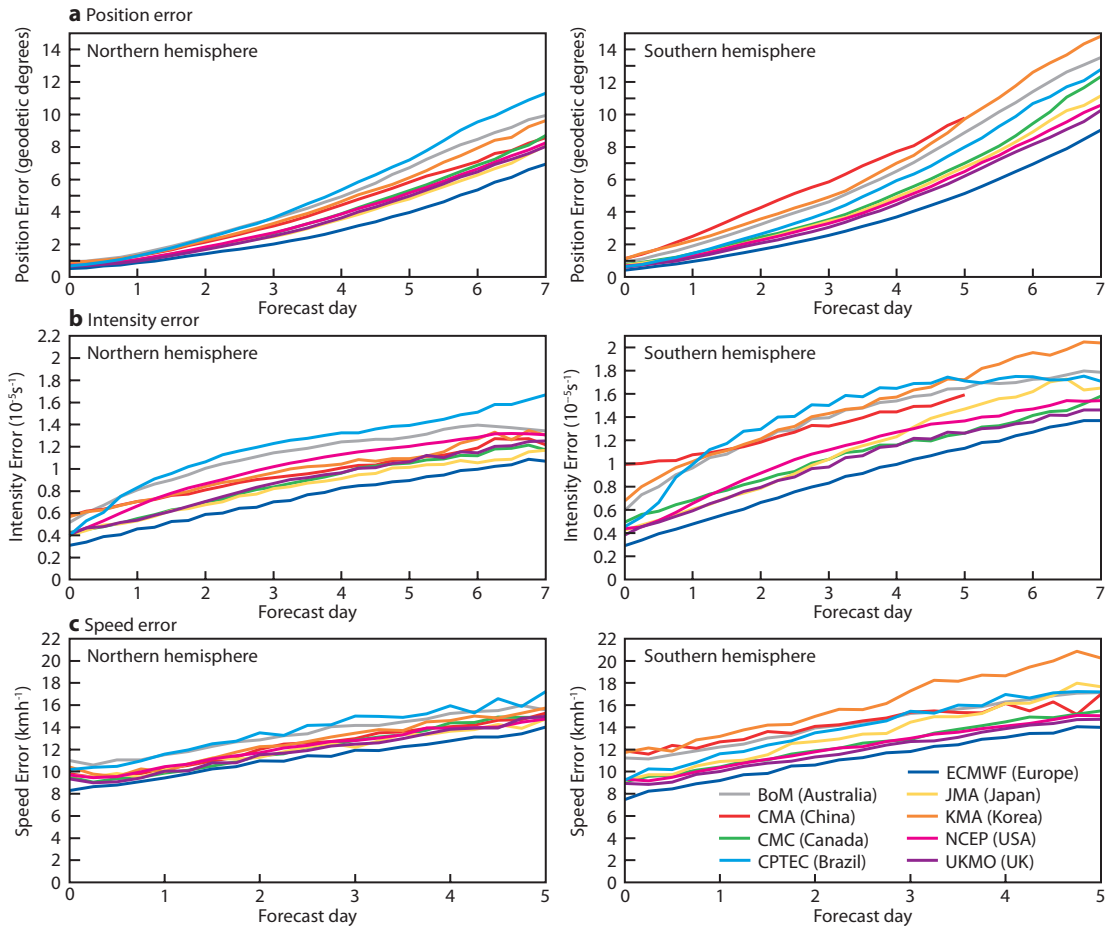
Figure 2 shows the ensemble mean error in cyclone position, intensity and propagation speed for each EPS in the northern and southern hemispheres for the 6-month period from 1 February to 31 July 2008. For details of how the ensemble mean error is calculated see Box C. There is a large difference in forecast skill between the different EPSs. ECMWF has the highest level of skill for all cyclone properties, with NCEP, JMA, UKMO and CMC having the next highest level of performance.

NCEP, CPTEC and BoM have faster initial error growth in cyclone intensity than the other EPSs (Figure 2b). This is perhaps because these EPSs have comparatively low resolutions and are not able to accurately capture the cyclones’ growth and decay. CMC is also integrated at a comparatively low resolution and does not exhibit this rapid intensity error growth. However, unlike NCEP, CPTEC and BoM, CMC has a 4D-Var data assimilation system. Perhaps this is compensating for the low resolution by providing a better initial state.

The errors in the southern hemisphere are larger than in the northern hemisphere for all the EPSs, but CMA and KMA have significantly larger errors in the southern hemisphere compared to the northern hemisphere. This is perhaps to be expected for KMA since it does not apply perturbations in the southern hemisphere. For CMA (which does apply perturbations in both hemispheres) the difference in the error between hemispheres is particularly noticeable. The reason for this difference for CMA is less clear,

but it is suspected that it is caused by large errors in the initial state, which are related to the observations used in this hemisphere and how they are assimilated (see *Froude, 2010b* for details).

The mean error in cyclone propagation speed is large throughout the forecast range for all EPSs (Figure 2c). It should be noted that the speed error is different in nature to the position or intensity error in that it would not necessarily be expected to grow with lead time (see Box C). However, there will be a cumulative effect of a consistent error in speed on the position of the cyclone with increasing lead-time.



**Figure 2** EPS mean error in (a) position, (b) intensity and (c) propagation speed in the northern (left) and southern (right) hemispheres for 1 February to 31 July 2008. The curves are only plotted to day 5 for the CMA EPS in the southern hemisphere due to insufficient matches between forecast and analysis tracks (see *Froude, 2010b*). The intensity is assessed relative to background field removal. (Figure from *Froude, 2010b*).

**C**

**Calculating the ensemble mean error**

The ensemble mean error is calculated by computing the mean track, mean intensity, and mean propagation speed of the matching ensemble member tracks (including the control) for each cyclone in each ensemble forecast at each forecast lead time.

The mean error in position is calculated as the mean geodetic separation distance between the mean tracks and the corresponding ECMWF analysis tracks. Also the mean intensity error was calculated similarly, from the filtered vorticity value (see Box A) at the cyclone centres, using the absolute intensity difference as the measure of error.

The propagation speeds of the analysis and ensemble member cyclones were calculated at each point on their tracks by comparing the position of consecutive points on the tracks. Since the points on the tracks are 6 hours apart, the speed calculated at each point corresponds to the average propagation speed of the cyclone in the next 6 hours.

**Bias**

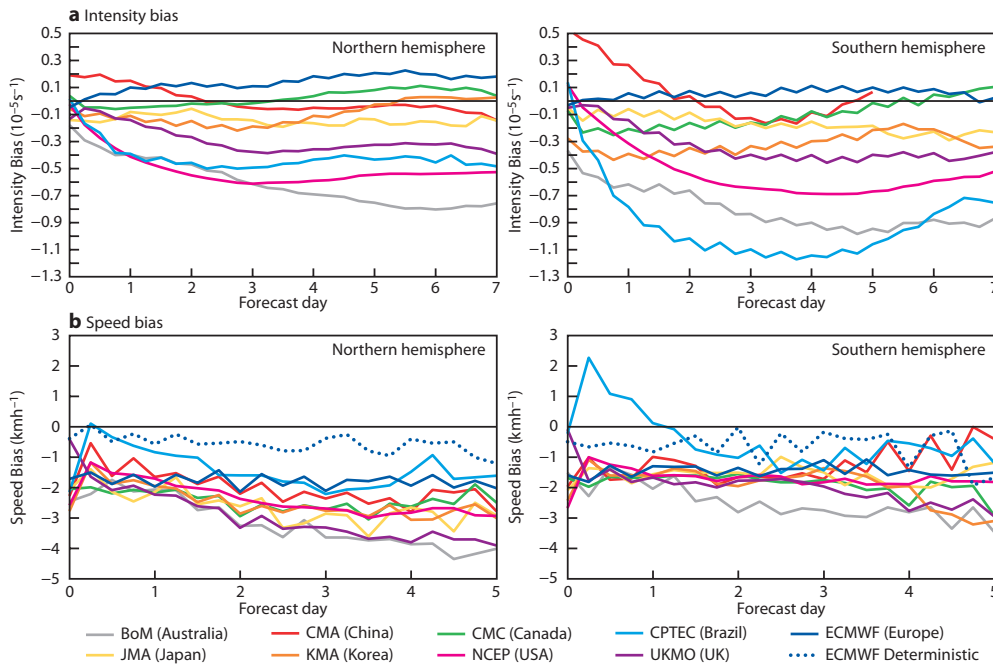
Figure 3a shows the bias in the intensity error given in Figure 2b. CMC, ECMWF and JMA all have small biases, with ECMWF being the only one to consistently overpredict cyclone intensity. The magnitude of the ECMWF bias is slightly smaller in the southern hemisphere compared to the northern hemisphere. This is perhaps to be expected given the simpler more symmetric structure of this hemisphere in terms of land and sea, making cyclone development easier to model. It is apparent that CMA has a significantly larger positive bias at day 0 in the southern hemisphere compared to the northern hemisphere, but this bias becomes negative from day 2.5. As discussed above, this suggests a problem in the initial state of the CMA system.

BoM, NCEP, CPTEC and UKMO all significantly underpredict cyclone intensity. BoM, NCEP, and CPTEC in particular show a dramatic increase in negative bias in the earlier part of the forecast. This corresponds to the rapid error growth exhibited by these systems in the initial period (Figure 2b).

CPTEC has a significantly larger intensity bias in the southern hemisphere compared to the northern hemisphere. In particular there is a dramatic increase in negative bias in the first day of the forecast. This is most probably due to inconsistency between the initial state and forecast model since CPTEC use NCEP’s analysis as their initial state and run their own forecast model (see Froude, 2010b for further discussion).

Figure 3b shows the bias in the propagation speed error given in Figure 2c. Interestingly all the EPSs underpredict propagation speed (i.e. the predicted cyclone arrives too late). The magnitude of this bias is small, but the cumulative effect will result in the 5-day forecast being approximately 200–400 km behind the analysed cyclone, which would be of importance to many forecast users. CPTEC has a large jump in speed bias at the beginning of the forecast, which is again probably related to some type of adjustment of the model from the initial state.

Since all the EPSs have a negative bias in propagation speed and this bias was also found for the control forecasts (not shown) it must be related to the forecast models rather than the ensemble setup. To investigate this further, the propagation speed bias was also computed for ECMWF’s deterministic (high resolution) forecast during the same period and is also shown in Figure 3b. During this time period the ECMWF deterministic forecast was run at a spectral resolution of T799 as opposed to T399 for the ECMWF EPS (see Table 1). The deterministic forecast has a smaller bias than the EPS. It appears that increasing the resolution of the forecast model decreases the bias. This is perhaps related to the temporal resolution of the ECMWF model, which is lower for the EPS (30 minutes) than the deterministic forecast (12 minutes).



**Figure 3** EPS mean bias in (a) intensity and (b) propagation speed in the northern (left) and southern (right) hemispheres for 1 February to 31 July 2008. The propagation speed bias is also shown for the ECMWF high-resolution deterministic forecast in (b). The intensity is assessed relative to background field removal. (Figure from Froude, 2010b).

### Mean error, control error and spread

Figures 4 and 5 show the ensemble mean error, control forecast error and ensemble spread, for cyclone position and intensity respectively, for each EPS and each hemisphere. Spread is calculated as the average distance of the ensemble member position/intensity from the analysis position/intensity. One of the aims of an EPS is for the ensemble mean to provide a forecast of higher skill than the control forecast.

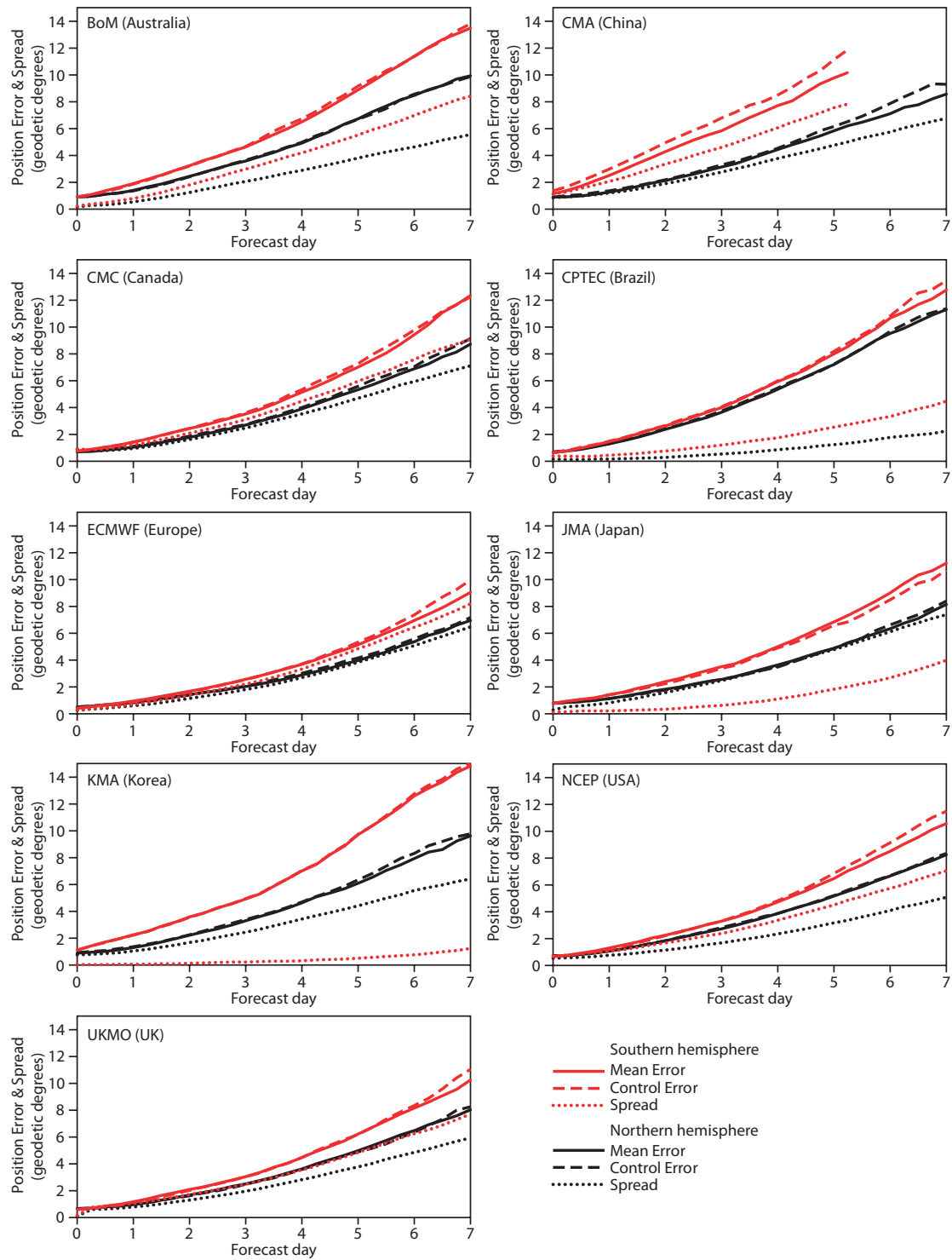
It is clear that the ensemble mean provides very little advantage over the control forecast in predicting the position of cyclones for all EPSs (Figure 4). It is noted that a small difference can be seen for CMA in the southern hemisphere, but this is likely to be caused by insufficient data (see Froude, 2010b).

For the intensity of the cyclones, much more of a difference can be seen between the control and the ensemble mean (Figure 5). In the northern hemisphere the ensemble mean begins to provide an advantage over the control forecast for all the EPSs except CPTEC from around day 2. The results are similar in the southern hemisphere, except for JMA and KMA which do not apply perturbations in the southern hemisphere (see Table 1). The ensemble mean of these EPSs therefore provides no advantage over the control forecast.

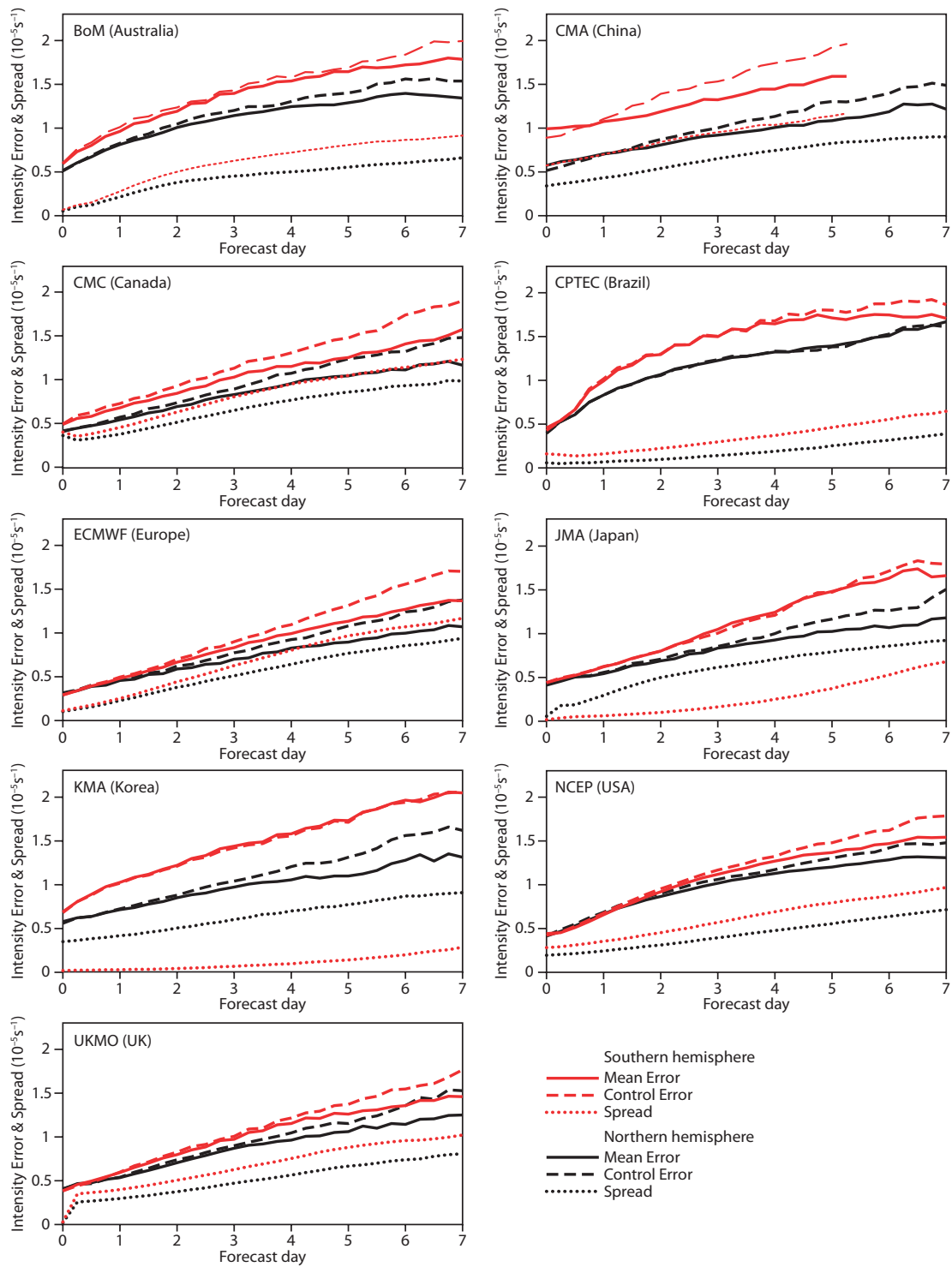
For an EPS to be statistically reliable the spread should be equal to the ensemble mean error on average so that the spread can be used as a measure of the current predictability of the atmosphere, providing an estimate of the error in the ensemble mean forecast. In the northern hemisphere, ECMWF and JMA both have an excellent spread-skill relationship for cyclone position (Figure 4). This is interesting since the two systems have very similar characteristics in the northern hemisphere (see Table 1): both EPSs use 50 members, singular vector perturbations and 4D-Var, and have similar horizontal and vertical resolutions. There is however one major difference between the two systems in this hemisphere. ECMWF does include model perturbations whereas JMA does not, but this appears to have no impact on the spread-skill relationship for cyclone position. The other EPSs are all underdispersive to varying degrees. In the southern hemisphere, ECMWF also has an excellent spread-skill relationship for cyclone position. However, JMA and KMA are very underdispersive in the southern hemisphere, since they do not apply perturbations in this hemisphere.

For cyclone intensity (Figure 5) there are much larger differences between the spread and ensemble mean error for all EPSs. In the northern hemisphere the ECMWF and CMC have the highest performance, with JMA not performing quite as well. This is very interesting since ECMWF and CMC both perturb their forecast model physics. It seems that forecast model physics perturbations have more impact on increasing the spread in cyclone intensity than position. This is probably to be expected since cyclone position will be more dependent on the large-scale steering-level flow than on the smaller-scale parametrized processes that are perturbed. Cyclone intensity, on the other hand, will be much more influenced by these smaller-scale processes.





**Figure 4** EPS mean error, control forecast error and spread in cyclone position for each EPS. The curves are only plotted to day 5 for the CMA EPS in the southern hemisphere due to insufficient matches between forecast and analysis tracks (see Froude, 2010b). (Figure from Froude, 2010b).



**Figure 5** EPS mean error, control forecast error and spread in cyclone intensity for each EPS. The curves are only plotted to day 5 for the CMA EPS in the southern hemisphere due to insufficient matches between forecast and analysis tracks (see Froude, 2010b). The intensity is assessed relative to background field removal. (Figure from Froude, 2010b).

## Future work

The cyclone tracking methodology provides useful information about the prediction of extratropical cyclones by EPSs and has revealed large differences in performance between the various systems. The relative performance of the EPSs varies for different measures of ensemble performance (i.e. forecast skill of the ensemble mean or the spread–skill relationship) and for the cyclone property (i.e. position or intensity). This highlights the importance of using a variety of verification measures when assessing the skill of a forecasting system.

Future work in the area of extratropical cyclone predictability will focus on the following key areas.

- **Regional analysis:** The differences in predictive skill of cyclones in different regions by the EPSs will be assessed.
- **Vertical structure:** The vertical structure and tilt of cyclones will be explored to gain a more in-depth understanding of the impacts that different factors, such as resolution, have on the prediction of cyclone growth and evolution.
- **Forecast users:** The results and cyclone-tracking methodology of this article are potentially very useful to a wide range of forecast users. However, further work is required to determine how the results should be interpreted and utilized by each particular user. Forecast tools will be developed to present storm prediction information to users in the marine and insurance sectors.
- **Other types of weather system:** The cyclone identification and tracking methodology is flexible and can be applied to other types of weather systems such as polar lows and tropical cyclones. The predictability of these other types of weather system will be explored.

The author would like to thank Kevin Hodges, Robert Gurney and Lennart Bengtsson for their help and advice on this work and the TIGGE contribution centres and data centres are acknowledged for providing the EPS data.

## Further Reading

**Bougeault, P. & Co-authors**, 2010: The THORPEX Interactive Grand Global Ensemble (TIGGE). *Bull. Am. Meteorol. Soc.*, **91**, 1059–1072.

**Froude, L.S.R.**, 2010a: TIGGE: Comparison of the prediction of northern hemisphere extratropical cyclones by different Ensemble Prediction Systems. *Weather and Forecasting*, **25**, 819–836.

**Froude, L.S.R.**, 2010b: TIGGE: Comparison of the prediction of southern hemisphere extratropical cyclones by different Ensemble Prediction Systems. *Weather and Forecasting*, submitted.

**Froude, L.S.R., L. Bengtsson & K.I. Hodges**, 2007: The Predictability of extratropical storm tracks and the sensitivity of their prediction to the Observing System. *Mon. Wea. Rev.*, **135**, 315–333.

**Hodges, K.I.**, 1995: Feature tracking on the unit sphere. *Mon. Wea. Rev.*, **123**, 3458–3465.

**Hodges, K.I.**, 1999: Adaptive constraints for feature tracking. *Mon. Wea. Rev.*, **127**, 1362–1373.

**Hoskins, B.J. & K.I. Hodges**, 2002: New perspectives on the northern hemisphere winter storm tracks. *J. Atmos. Sci.*, **59**, 1041–1061.

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European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading, RG2 9AX, England

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