SPECIAL PROJECT PROGRESS REPORT

Reporting year	2010
Project Title:	The impact of tropical cyclones on extratropical predictability
Computer Project Account:	spdeet
Principal Investigator(s):	Prof. Sarah Jones
Affiliation:	Institut für Meteorologie und Klimaforschung - KIT
Name of ECMWF scientist(s) collaborating to the project (if applicable)	Dr. Martin Leutbecher, Dr. Carla Cardinali
Start date of the project:	July 2004
Expected end date:	2012

Computer resources allocated/used for the current year and the previous one
(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	350000	284121.39	350000	91923.53
Data storage capacity	(Gbytes)				

Summary of project objectives

The aim of this project is to quantify the impact of tropical cyclones undergoing extratropical transition (ET) on the predictability of the midlatitude flow. A particular emphasis is placed on the predictability of developments downstream of an ET event. Here for we conduct case studies in which principal component / cluster analysis is applied to ET cases using the TIGGE dataset. We investigate the sensitivity of singular vectors (SVs) targeted on tropical cyclones and the global tropical band to spatial resolution and diabatic processes and perform experiments to assess their impact on the EPS. By studying the evolution of the singular vectors within the optimisation interval we identify the dominant processes that lead to large error growth. Furthermore we assess the impact of different perturbation methods (perturbations to the initial conditions and stochastic physics perturbations) on tropical cyclone ensemble forecasts.

Summary of problems encountered (if any)

none

Summary of results of the current year (from July of previous year to June of current year)

The report of the results can be found below

List of publications/reports from the project with complete references

Peer reviewed:

Keller, J. H., S. C. Jones, J. L. Evans, and P. A.Harr (2011): Characteristics of the TIGGE multimodel ensemble prediction system in representing forecast variability associated with extratropical transition, Geophys. Res. Lett., 38, L12802

Lang, S. T. K., S. C. Jones, M. Leutbecher, M. S. Peng, and C. A. Reynolds, 2011: Sensitivity, structure and dynamics of singular vectors associated with hurricane Helene (2006). submitted to J. Atmos. Sci.

Other:

J. H. Keller et al.: Investigation of predictability during the Extratropical Transition of Tropical Cyclones using the THORPEX Interactive Grand Global Ensemble (TIGGE). Oral presentation. Annual Meeting of the European Meteorological Society (EMS) 13 - 17 September 2010 Zuerich, Switzerland

J. H. Keller et al.: Investigation of predictability during the extratropical transition of tropical cyclones. Oral presentation. Third THORPEX International Science Symposium (TTISS) 14 – 18 September 2009 Monterey, California, USA

J. H. Keller et al.: Studien zur Umwandlung von Hurrikanen in außertropische Tiefdruckgebiete unter Verwendung des neuen THORPEX Interactive Grand Global Ensemble (TIGGE). Oral presentation. Symposium „Klimasystem Nordatlantik“ 5 – 6 November 2009 Hamburg, Germany

J.H. Keller: Investigation of predictability during the extratropical transition of tropical cyclones using the THORPEX Interactive Grand Global Ensemble (TIGGE). Oral presentation. 29th Conference on Hurricanes and Tropical Meteorology 10 – 14 May 2010 Tucson, Arizona, USA

S. T. K. Lang et al.: The structure of singular vectors associated with extratropical transition of tropical cyclones. Oral presentation. Third THORPEX International Science Symposium (TTISS) 14 – 18 September 2009 Monterey, California, USA

S. T. K. Lang et al .: Die Struktur singula¨rer Vektoren im Falle der Umwandlung eines tropischen Wirbelsturms in ein Tiefdruckgebiet der mittleren Breiten. Oral presentation. Symposium „Klimasystem Nordatlantik“ 5 – 6 November 2009 Hamburg, Germany

S.T. K. Lang: The structure of singular vectors associated with extratropical transition of tropical cyclones. Oral presentation. 29th Conference on Hurricanes and Tropical Meteorology 10 – 14 May 2010 Tucson, Arizona, USA

S.T. K. Lang et al.: The structure and sensitivity of singular vectors associated with extratropical transition of tropical cyclones. Poster presentation. Annual Meeting of the European Meteorological Society (EMS) 13 – 17 September 2010 Zuerich, Switzerland

Summary of plans for the continuation of the project

This special project ends this year. Dr. Doris Anwender from this group has submitted a proposal entitled "Impact of blocking and tropical-extratropical interactions on predictability in the Atlantic-European Sector". The project will (i) use medium range and seasonal EPS to investigate the dynamical processes involved in the onset and for the intensity, the scale, the lifetime, the track, the predictability and the impact of blocking, and (ii) use THORPEX Pacific Asian Regional Campaign (T-PARC) observations, YOTC data, data denial experiments and analysis of ECMWF EPS to quantify the mechanisms that determine the structural changes of a tropical cyclone during ET and their relation to the downstream impact and to investigate impact of tropical convection on midlatitude predictability.

1. INTRODUCTION

Predicting the extratropical transition of tropical cyclones (ET) poses a considerable challenge for numerical weather forecast systems as the interaction between the tropical cyclone and the midlatitude flow covers a large range of scales from the convective inner-core of a tropical cyclone to the synoptic-to-planetary-scale Rossby waves. Reduced predictability may be associated with the direct impact of an ET event, if the ex-tropical cyclone is predicted to reach a continent as an extratropical storm. Arguably the larger impact on predictability, however, occurs due to the excitation of a Rossby wave packet that can initiate explosive development downstream of the ET system itself. This may initiate extratropical cyclogenesis in the eastern ocean basin, or modify existent flow patterns enhancing the risk of severe precipitation events. Due to its influence on the downstream flow an ET event can lead to significantly reduced predictability over an entire ocean basin.

2. REPRESENTATION OF INITIAL CONDITION UNCERTAINTY AND MODEL ERROR ASSOCIATED WITH TROPICAL CYCLONES AND ET

Different methods are used within the ensemble prediction system (EPS) of the European Centre for Medium-range Weather Forecasts (ECMWF) to represent uncertainty associated with the initial conditions and model physics. To account for the uncertainty of the analysis, perturbations generated from an ensemble of analyses (EDA) and singular vectors (SVs) are used (Buizza et al., 2008). Two stochastic schemes aim to mimic the effects of errors in the model formulation, the stochastically perturbed tendencies scheme and the stochastic kinetic energy backscatter scheme (Palmer et al., 2009). In the first part of this study (Section 2.1) we investigate the value of high resolution SVs for ensemble forecasting in case of tropical cyclones. In the second part the impact of the different perturbation methods on TC ensemble forecasts is assessed (Section 2.2).

2.1 SINGULAR VECTORS

At ECMWF diabatic SVs targeted at tropical cyclones are calculated operationally (Barkmeijer et al., 2001). These extra sets of SVs are included in the EPS whenever a TC is reported. The calculations are performed at rather low spatial resolution (T42 ~ 320 km), which is too low to represent the TCs properly (Lang et al. 2011). In our study we calculate SVs with a resolution up to TL255 (~ 80 km) targeted on Hurricane Helene (2006) and on the global tropical band. The SVs are optimized over the depth of the troposphere and are calculated with a dry total energy norm (Leutbecher and Palmer, 2008). We calculate SVs targeted on Helene for nine initialization dates (16 September 12 UTC to 24 September 12 UTC). Furthermore we test the tangent linear approximation in case of SVs targeted at TCs and assess the potential impact on the EPS of high resolution SVs associated with TCs.

At T42 resolution the SVs are not able to isolate TCs as major sources of error growth within the tropics (Puri et al., 2001). Figure 1a shows the vertically integrated total energy of the leading 20 T42 SVs targeted on the global tropical band from 17 September 2006 12 UTC. At this time Hurricane Helene (2006) is located within the Atlantic around 20°N and 60°W and no signal of the leading 20 SVs T42 is associated with Helene. If the resolution of the SV calculation is increased to TL255 the SV formalism identifies Helene as one of the most uncertain systems within the tropics (Fig. 1b). Now some of the leading SVs are associated with Helene. This is potentially useful for the EPS since it opens the possibility to include the whole tropical band as a target region instead of targeting each TC individually.

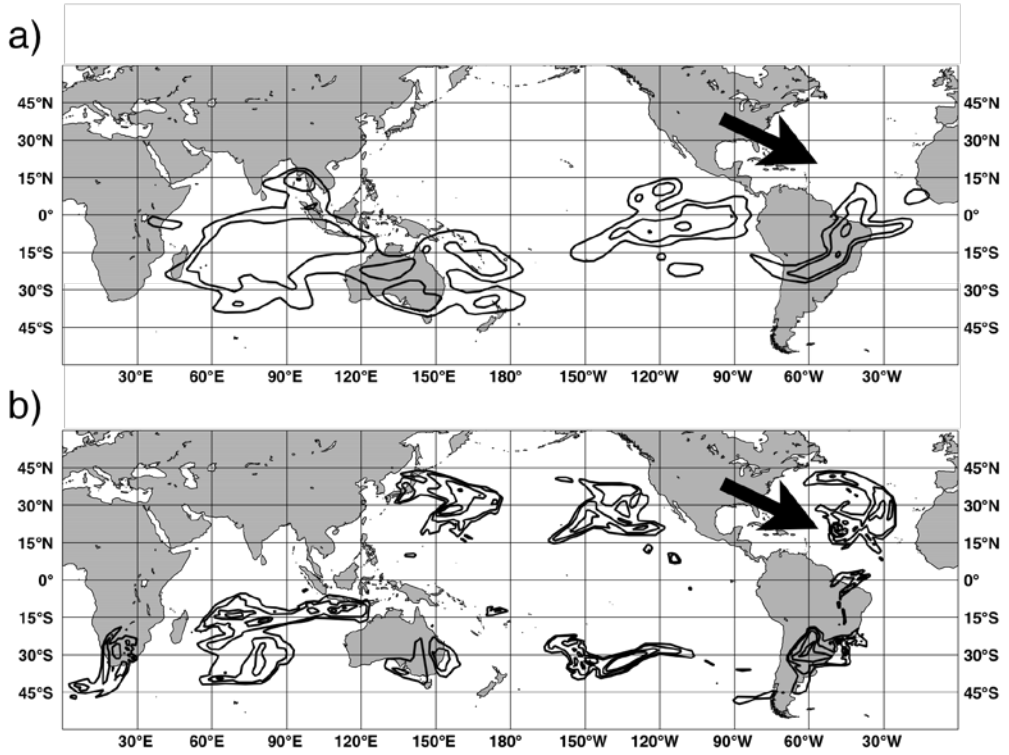

Figure 1: Vertically integrated total energy (black contours) of the leading 20 initial SVs from 17 September 2006 12 UTC optimized for the tropical belt (30°N to 30°S). a) T42 SVs and b) TL255 SVs. Contour lines are drawn at 5, 10, 25 and 50 J kg−1. The position of Helene is indicated by the arrow (from Lang et al., 2011).

To assess the impact of high resolution SVs on the EPS we perform idealized ensemble experiments with the integrated forecasting system (IFS) of ECMWF for which only SVs targeted at TCs are included as initial perturbations. The stochastic physics schemes are deactivated for these experiments. The ensembles consist of 1 control and 10 perturbed forecasts with a resolution of TL255. On average the high resolution (TL255) moist (diabatic) SVs have a stronger impact on the track and intensity spread of Helene after 48 hours than their dry and lower resolution counter parts (Fig. 2a and b). The dry TL255 SVs impact the track of Helene more strongly Only during the early tropical phase. However, the intensity spread of the experiment initialized with most SVs is larger at this time.

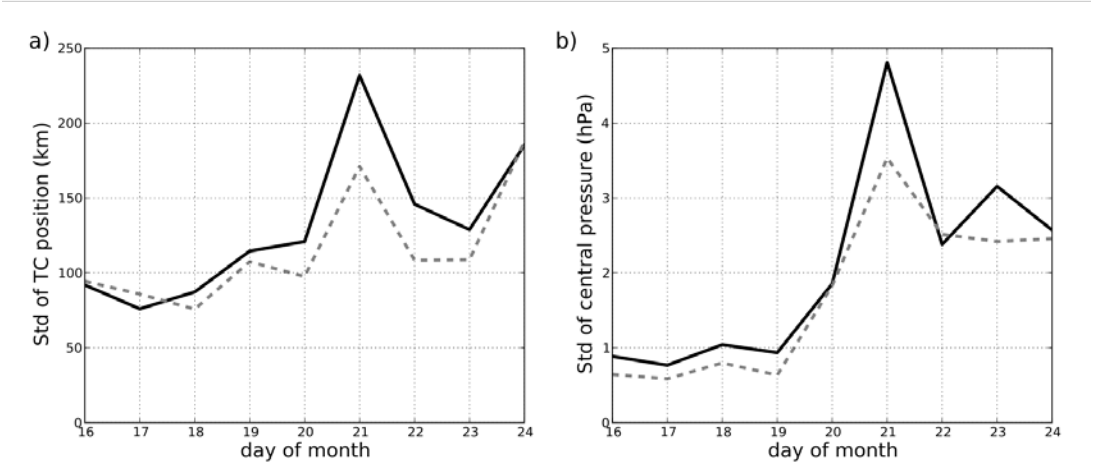

Figure 2: Spread (standard deviation) of Helene's position (a) and of minimum pressure (b) at 48 hours forecast time for the EPS experiment with TL255 moist SVs (solid black line) and TL255 dry SVs (dashed grey line) (from Lang et al., 2011).

To investigate how linear the growth of the SVs is in case of a TC, we calculate two linearity indices. These indices are the relative nonlinearity (Gilmour et al., 2001) and the anticorrelation of

the perturbations (Buizza, 1995). Low values of the anticorrelation and high values of the relative nonlinearity indicate the existence of strong nonlinearities. With higher resolution the linearity of the SVs within the nonlinear model is reduced (Tab. 1). If diabatic effects are accounted for within the SV calculations the linearity is reduced also. This effect is small at low resolution (T42), but becomes large at high resolution (TL255). At high resolution a reduction of the initial amplitude of the SVs is needed to stay close to the linear regime. However, even with reduced linearity in comparison to lower resolution or dry SVs the TL255 moist SVs produce stronger growth and a larger spread. Therefore it is clear that they identify faster-growing structures.

Resolution	moist / dry	SVs	$\bar{l}$	$l\uparrow$	$l\downarrow$	$\overline{\Theta}$	$\Theta\uparrow$	$\Theta\downarrow$
T42	moist	1-5	0.85	0.98	0.31	0.53	1.19	0.22
TL95	moist	1-5	0.80	0.97	-0.16	0.63	1.52	0.24
TL159	moist	1-5	0.70	0.94	-0.80	0.75	1.91	0.34
TL255	moist	1-5	0.60	0.92	-0.80	0.86	1.91	0.42
T42	dry	1-5	0.87	0.97	0.64	0.52	0.85	0.24
TL255	dry	1-5	0.78	0.95	0.42	0.67	1.18	0.31
TL255*	moist	1-5	0.71	0.97	-0.71	0.72	1.89	0.29
TL255*	dry	1-5	0.82	0.96	0.17	0.58	1.29	0.28
TL255*	moist	1	0.83	0.91	0.58	0.60	0.92	0.46
TL255*	dry	1	0.87	0.95	0.69	0.51	0.79	0.32

Table 1: Relative nonlinearity Θ and anticorrelation l of the linearity experiments after 48 hours forecast time. An overbar denotes the mean over all SVs and all initialisation dates. ↑ denotes the upper bound and ↓ denotes the lower bound of the linearity indices. The * marks experiments with a reduced scaling of the initial amplitude of the SVs. The column labeled with "SVs" indicates the SVs that are considered for calculating the linearity measures (from Lang et al., 2011).

2.2 IMPACT OF DIFFERENT PERTURBATION METHODS ON TC FORECASTS

To quantify the impact on TC forecasts of the different methods used at ECMWF to generate perturbations for the EPS we set up ensemble experiments with only one of the methods activated. In addition we set up one experiment with all methods activated, which corresponds to the new operational configuration. The experiments were run from 1 August to 5 October 2008. For this study we consider 14 TCs in total. First results indicate that the perturbations of both the stochastic schemes have a large impact on the track and intensity of the TCs. While in general the mean track spread of the ensemble with all methods activated is somewhat larger than its mean error, probability ellipses indicate that the ensemble has some problems capturing the best track positions of the TCs for longer lead times.

2.3 OUTLOOK

We will calculate high resolution SVs for more TC cases. In addition we will continue to investigate the impact on TC track and intensity of the perturbations generated by the different methods. Furthermore we will analyse the spatial structure and growth mechanisms of the different perturbations.

3 CLUSTER ANALYSIS OF THE TIGGE DATA SET

The extratropical transition of tropical cyclones often leads to a reduction of predictability which can propagate into regions further downstream. Ensemble forecasts provide a means to investigate predictability and the range of possible development scenarios during ET events. The TIGGE multi

model EPS facilitates exploration of differences and uncertainties in the forecasts that are caused by distinct model approaches, physics and parametrisations. In this study we have examined forecast variability, related to ET events in the TIGGE data set. Our focus was put on the characterisation of this multi model EPS in forecasting ET events. We investigate whether TIGGE provides enhanced forecast variability and thus more possible development scenarios during ET events, compared to a single model EPS. Furthermore, we consider if characteristic behaviour of the individual constituent EPS exists within the multi model combination, i.e. related forecast variability and development scenarios.

3.1 METHODOLOGY AND DATA BASE

To investigate forecast variability and extract the main possible development scenarios out of the ensemble forecast in question, we employed an Empirical Orthogonal Function (EOF)-Analysis of the EPS runs and a subsequent fuzzy clustering of the Principal Components (PCs) of the individual members (Harr et al., 2008, Keller et al., 2011) . The analysis was applied on to one specific forecast time, typically the first 12 hr forecast interval after which the strongest increase in forecast uncertainty for the considered variable could be observed. The EOFs indicate where the several ensemble members show strongest differences. How each member contributes to this variability is stated by its PCs. Members with related contributions (related PCs) exhibit similar possible development scenarios. This characteristic was used in the subsequent fuzzy clustering, which grouped members with related contributions and thus extracted the main possible development scenarios. We examined forecast variability for the 500 hPa geopotential height field. This variable nicely captures the interaction between the transitioning storm and the midlatitude flow and is available for all TIGGE EPS.

To characterise the behaviour of TIGGE and compare it with a single model EPS, three different data sets were investigated: TIGGE as a whole multi model EPS, the ECMWF EPS as a single model EPS and TIGGE without ECMWF, referred to as TI-EC in the remainder of this report. The multi model EPS was formed from eight of the ten available EPS. The MeteoFrance EPS and the EPS from the Korean Meteorological Administration were not included, due to the short forecast range of the former and a potential systematic bias in the upper tropospheric geopotential height in the latter. To gain a broader insight into the characteristics of the TIGGE data set, ten different forecasts, which were initialized prior to the ET of five tropical cyclones in 2008 were examined in this study (Keller et al., 2011).

3.2 RESULTS

The outcome of this study allows us to characterise the behaviour of the multi model EPS in forecasting ET events. Forecast variability in TIGGE often differs from the variability in the ECMWF EPS as do the possible development scenarios. Preferred groupings among members from the individual EPS and typical contributions to the variability can be identified.

3.2.1 Forecast variability and variability captured by EOF fields

During the ET events, the individual EPS, contributing to TIGGE showed distinct representations of forecast variability, expressed as standard deviation of 500 hPa geopotential height field (Figure 3). Two of the three individual EPS and TIGGE show increased forecast uncertainty (shading) downstream of the ET of Hurricane Ike (black dots). The Canadian EPS and TIGGE exhibited a two-peaked uncertainty region, while in the ECMWF the main uncertainty was located further downstream. The Australian EPS did not show enhanced forecast uncertainty related to the storm.

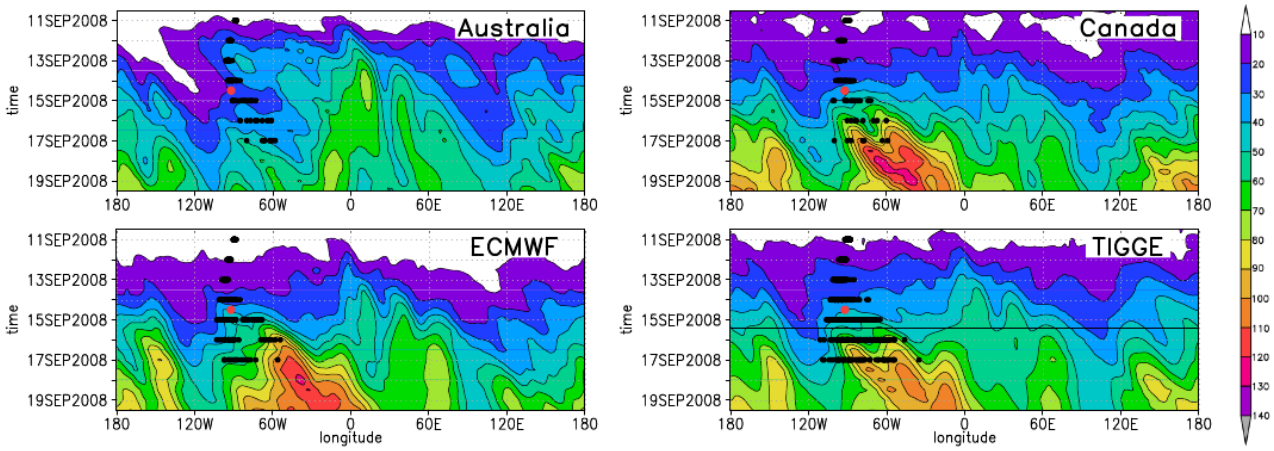

Figure 3: Hovmoeller diagram for the standard deviation of the 500 hPa geopotential height field (in gpm) in three individual EPS and TIGGE for one forecast that was initialized prior to the ET of Hurricane Ike (IT: 10 Sep 2008, 12 UTC). Surface position of Ike in all ensemble members is marked by black dots (from Keller et al., 2011).

As indicated by Figure 3, patterns of variability vary between the individual EPS and TIGGE. This is confirmed by an analysis of the EOF fields for the 500 hPa geopotential height in the three data sets under consideration (not shown). Based on visual comparison and a similarity index the two dominant EOF fields of all three data sets are compared. In one of the ten cases, closely related EOFs were identified in all three data sets, indicateing that TIGGE, TI-EC and ECMWF exhibit dominant variability in the same regions of the geopotential height field. In three cases TIGGE and TI-EC showed related EOF fields, while the variability in ECMWF occurred in distinct regions. Thus, ECMWF did not dominate the first two EOFs in TIGGE, as its exclusion caused no differences. In the remaining six cases, only the strongest variability was found to be related in TIGGE and TI-EC. This indicated the ECMWF EPS to influence the second strongest variability in the TIGGE data set (causing additional variability in other regions), as its inclusion caused differences in the EOF2 field.

3.2.1 Contributions of individual EPS to TIGGE clusters

The variability in TIGGE captured by the EOFs arises due to a superposition of forecast variations of the individual constituent EPS. How each of these EPS contributes to the patterns of variability can be examined using the clustering results. Clustering from the forecast of Hurricane Ike that was initialised prior to the ET of Hurricane Ike (Figure 4) indicated different contributions (number of members, y-axis) of the several EPS (x-Axis) to the six identified clusters (colours). The Australian and Brazilian EPS contributed to only two or even one of the six clusters and thus showed only a narrow range of possible development scenarios. The opposite was found for the ECMWF and JMA EPS, which contributed to five of the six scenarios.

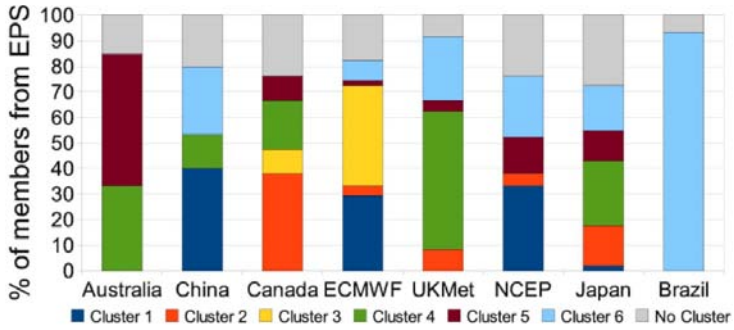

Figure 4: Contribution of members from the individual EPS to the different clusters (in colours) for forecast of Hurricane Ike. Ordinate: % of members from the given EPS, contributing to the cluster in question (colour). Non-assigned members are outlined in grey (taken from Keller et al. 2011).

The investigation of all ten cases corroborated the findings from this sample case (Figure 5). While the Australian and Brazilian EPS showed only weak splitting into different clusters, the JMA EPS turned out to have the broadest variation in possible development scenarios (contributing to most of the extracted clusters). The ECMWF EPS also contributed to a variety of possible development scenarios often, but in several cases seemed to dominate one cluster, which had only weaker contributions from other members (e.g. cluster 3, yellow, in Figure 4) Furthermore, the ECMWF and Canadian EPS tended to share clusters in eight of the ten cases as did the NCEP and JMA EPS (not shown). For the TI-EC data sets the results overall remained the same.

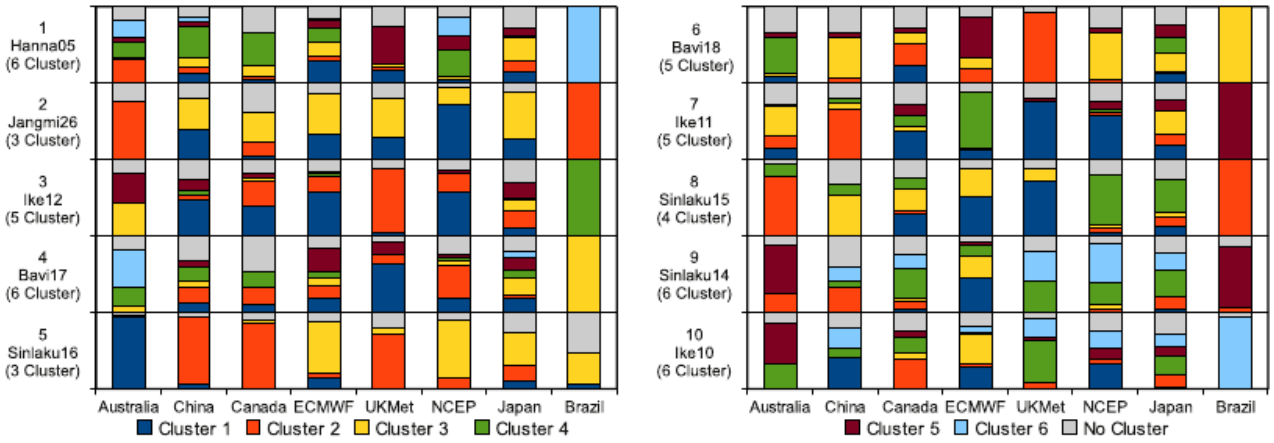

Figure 5: As Figure 4, but for all ten cases, indicated by storm name and day of initialisation (taken from Keller et al., 2011).

3.2.3 Differences in the scenarios

This outcome suggests that the ECMWF EPS capture parts of the development scenarios, contained in the TIGGE data set, but also seem to introduce an additional development scenario. Confirmation therefore is provided by a comparison of the different possible development scenarios (stated by the several clusters) in the TIGGE and TI-EC. Herein, the scenario (cluster) which was dominated by members from the ECMWF EPS was missing in the TI-EC data set. The other scenarios, found in TIGGE occurred with slight or even no modifications in the TI-EC data set as well. A comparison with scenarios of the individual ECMWF EPS indicated that only some of the TIGGE or TI-EC scenarios occur in ECMWF as well, while the other scenarios turned out to be missing.

3.3 SUMMARY AND OUTLOOK

In this study we have characterised the behaviour of the TIGGE multi model EPS in forecasting ET events and investigated the differences in forecast variability, found in the EPS contributing to TIGGE. It was shown that the individual constituent EPS differed in forecast variability and in their contribution to the different development scenarios, found in TIGGE. Our results indicate that TIGGE offers a broader range of forecast variability and thus more possible development scenarios than the single ECMWF EPS. Hence, if the verifying analysis would not be covered by the ECMWF EPS, we might find a verifying scenario in TIGGE (Keller et al., 2011). On the other hand, as the ECMWF EPS was found to introduce an additional scenario in TIGGE, the full range of variability and possible development scenarios would not be obtained by TIGGE without the ECMWF EPS.

In the remained of this project, some of the identified development scenarios will be investigated to get a deeper understanding of the underlying physical processes during an ET event that might cause the forecast uncertainty. Therefore, we will apply an analysis of the eddy kinetic energy (Orlanski and Sheldon, 1995, Harr and Dea, 2009) to the ECMWF EPS forecasts to examine the influence of the transitioning storm on the midlatitude flow. Unfortunately, this method cannot be

applied to the scenarios found in the TIGGE data set, due to the coarse vertical resolution and the non availability of vertical velocity.

4. SUMMARY

In this study we investigated the development scenarios of different ET events within the TIGGE dataset using a fuzzy cluster analysis. This resulted in a characterization of the behaviour of the TIGGE data set in case of an ET event. We assessed the potential value of high resolution SVs for TC ensemble forecasting and the impact of different perturbation methods on the track and intensity spread of ensemble forecast of TCs.

5. ACKNOWLEDGEMENT

We would like to express our sincere gratitude to Carsten Maass and his colleagues from user support for their quick and competent response to all of our questions. Without their support this project could not have been carried out. We thank Martin Leutbecher and Carla Cardinali for their help in setting up the experiments and interpreting the results. This project is supported by the DFG (German Research Council) research group PANDOWAE.

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