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INVESTIGATION OF PREDICTABILITY DURING THE EXTRATROPICAL TRANSITION OF TROPICAL CYCLONES USING TIGGE

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1. INTRODUCTION

The extratropical transition (ET) of a tropical cyclone may have a significant influence on the synoptic situation around the transforming storm as well as in regions further downstream. Because of an amplified wave pattern, the tropical cyclone may reintensify or the development of a new extratropical cyclone further downstream will be triggered. These systems may cause severe weather events in the regions downstream of the transforming storm, like for example western Europe or Northern America. The interaction between the transforming storm and the midlatitude wave pattern depends strongly on the phasing between these two structures, and is thus very sensitive to forecast errors. Even weak differences in the forecast position and acceleration of the storm or the wave pattern may lead to totally different synoptic developments. Thus, the ET of a tropical cyclone often leads to a reduction in predictability.

Recent studies have used the variability among the NCEP and ECMWF ensemble prediction systems (EPS) to investigate the predictability during ET events (Harr et al. (2008), Anwender et al. (2008)). They found a strong increase in the standard deviation of the geopotential height at 200 and 500 hPa shortly after the tropical cyclone was classified as an extratropical system. This increase was independent of the forecast interval prior to the ET (Anwender, 2007). Furthermore, the differences between the several EPS members formed typical variability patterns in the trough-ridge structure which could be associated with the ET event. Experiments with the ECMWF EPS showed that disturbances, introduced during the ET process might affect the forecast for regions further downstream.

The new THORPEX Interactive Grand Global Ensemble (Bougeault et al., 2010) provides an opportunity to extend the previous studies and to compare predictability during ET events in a number of different EPS. TIGGE is a multi-model EPS, which combines the EPS from ten different weather services with different initial perturbation methods, size and characteristics. Using this new EPS and the analysis methods of Harr et al. (2008) we investigate the predictability during the ET of tropical cyclones which underwent ET in 2008 or later. Our main interest is to find out if we gain more spread and therefore more possible development scenarios using TIGGE instead of a single EPS, like the ECMWF EPS. Here we present a case study of Hurricane Ike which underwent ET in 2008. In the following we use the notation T̈IGGE ensemble" for one of the individual EPS of TIGGE and refer to a single member of any TIGGE ensemble as an “ensemble member” or “TIGGE member”.

2. METHODOLOGY

The technique we use to analyse the TIGGE data is based on an Empirical Orthogonal Function- (EOF-) Analysis of the EPS runs, followed by a fuzzy clustering of the Pricnipal Components (PCs) of each member (Harr et al. 2008). This analysis is applied to the geopotential height (gph) at 200 hPa. The EOFs, calculated for the variance-covariance matrix of the data, describe the regions of highest variability between all ensemble members. Using the PCs of these EOFs, the fuzzy clustering algorithm allows us to group ensemble members that have a related contribution to the patterns of uncertainty, as they are expected to show related synoptic patterns at the investigation time. Thus we extract the predominant scenarios out of the huge amount of information furnished by the TIGGE ensemble. At the same time we learn about the probability of these scenarios, as the number of members contributing to one scenario is related to the probability of this scenario occuring (Harr et al., 2008). This procedure was applied to all TIGGE ensembles except the MeteoFrance-EPS, which was not included because of the short forecast time (2.5 days only), and the Korean EPS. The Korean EPS was not used as it turned out to differ strongly from the other EPS. This led to one highly separated cluster and decreased the spread between the other groups, as the clustering process depends to some extent on the EPS instead of the physical situation. Thus, our dataset overall contains 231 ensemble members from eight different EPS.

3. CASE STUDY: ET OF HURRICANE IKE (2008)

Hurricane Ike formed out of a tropical wave near the west coast of Africa around the 30th of August 2008 and underwent a strong intensification, reaching category 4 on the Saffir-Simpson scale around 06 UTC 4 September, while it moved towards Haiti. Ike made landfall in Texas around 07 UTC 13 September 2008 as a category 2 hurricane. Thereafter the system started to recurve and underwent its ET, which was completed around 12 UTC 14 September (Fig.1a). The extratropical system moved towards the north east and led to hurricane force wind gusts in north-

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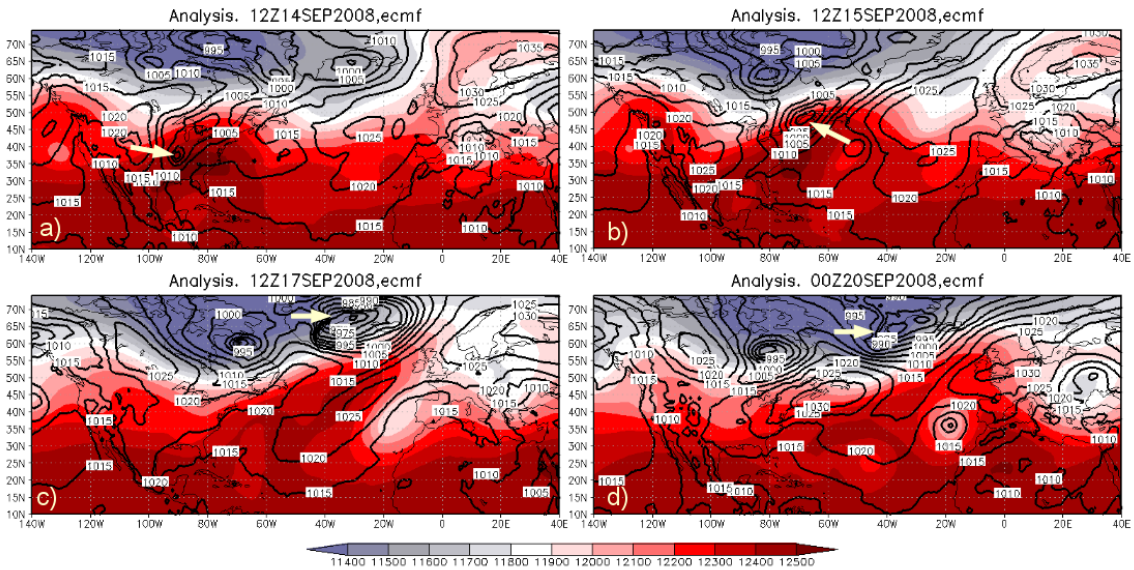

FIG. 1: ECMWF-Analysis for the ET of Hurricane Ike. Geopotential height at 200 hPa (shaded) and mean sea level pressure (contour). Arrows mark position of Ike-remnants. a) 14 Sep 08, 12 UTC (ET completed),b) 15 Sep 08, 12 UTC, c) 17 Sep 08,12 UTC, d) 20 Sep 08, 00 UTC.

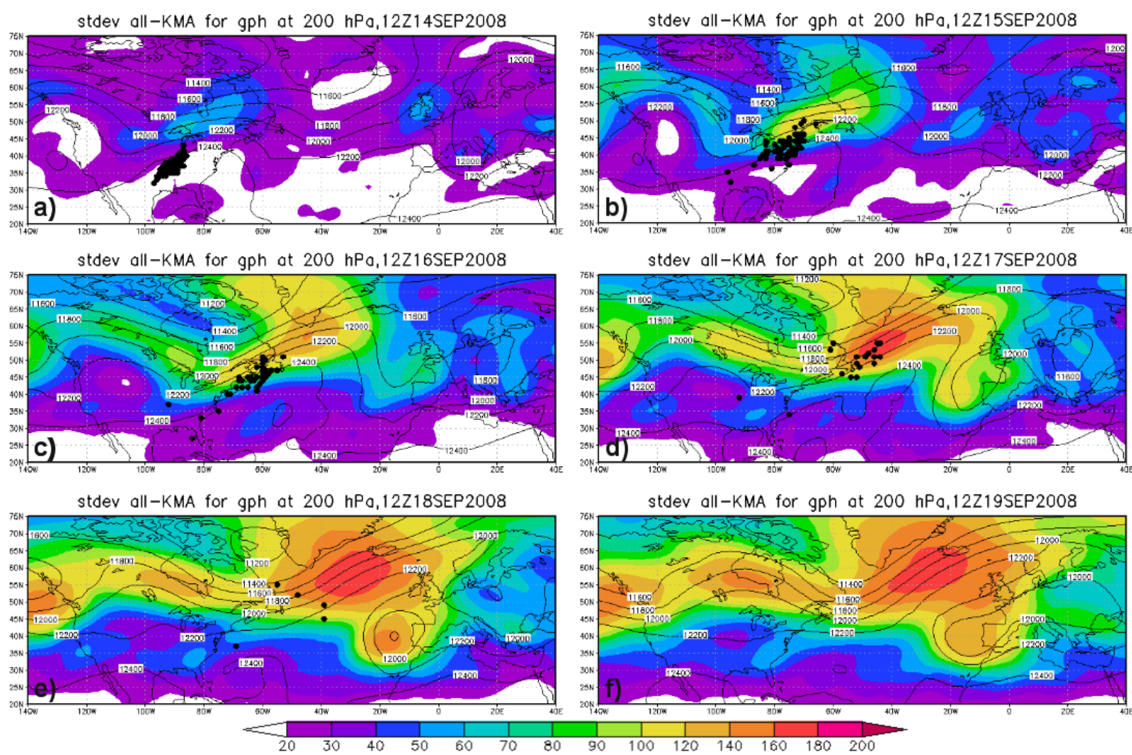

FIG. 2: Standard deviation of 200 hPa geopotential height (in gpdm) between the TIGGE members for the forecast, IT: 12 UTC, 12 Sep 08 (shaded), and forecasted position of Ike or its remnants, based on the minimum in mean sea level pressure. a) 12 UTC 14 Sep 08, b) 12 UTC 15 Sep 08, c) 12 UTC 16 Sep 08, d) 12 UTC 17 Sep 08, e) 12 UTC 18 Sep 08, f) 12 UTC 19 Sep 08.

eastern parts of the US (Berg, 2009). The remnants of Ike interacted with a midlatitude ridge, which amplified strongly thereafter. Ike moved through the ridge structure towards the Denmark Strait (Fig.1b) where it finally decayed. A short-wave trough formed directly downstream of the ridge to the west of Portugal and developed into a cut-off low with a surface system during the next days (Fig.1c). For this case study we selected a forecast which was initialized at 12 UTC 12 Sep 08 and therefore 48 hrs prior to the ET of Ike. This forecast showed a clear increase in standard deviation for the 200 hPa geopotential height after Ike had completed its ET.

3.1 *Forecast Uncertainty*

The differences between the TIGGE members are illustrated using the evolution with time of the the spatial distribution of the standard deviation, together with the forecast position of the remnants of Ike in every ensemble member. Around the ET time (12 UTC 14 Sep 08) a slightly increased standard deviation can be identified northward of the recurving Ike, whose forecast position in the different TIGGE members is spread over 10 degrees in each direction (Fig.2a). After a further 24 hrs the uncertainty in the position and ahead of the trough structure, which was interacting with the transforming storm, had increased further (Fig.2b). Around 12 UTC, 16 Sep 08, the uncertainty has started to propagate further downstream, with maximum value south of Greenland, while its western boundary is still linked to the forecast position of Ike in some TIGGE members. (Fig.2c). During the next 24 hrs, until 12 UTC, 17 Sep 08, the maxima of increased uncertainty moved towards the south of Greenland. Furthermore, a stronger increase in standard deviation could be found in the downstream trough at this time. During the following 48 hrs, the increased standard deviation, related to the rear flank of the ridge has propagated further downstream towards the central Atlantic. The uncertainty associated with the development of the downstream trough and the cut-off low has increased (Fig.2e,f).

The strongest increase in standard deviation occurs in the vicinity of Ike after 00 UTC, 17 September, as illustrated in the Hovmoeller diagram (Fig.3). The uncertainty plume indicates two peaks, related to the ridge close to Ike and to the short-wave structure forming downstream. Thus it is obvious, that the strongest differences between the TIGGE members of the forecast in question could be found in the vicinity and directly downstream of Ike. The forecast position of Ike also varies strongly between the TIGGE members, it spread up with some members remaining to the west, while most members show eastward moving remnants of Ike. The 17th of September 12 UTC was selected as investigation time for the following EOF-Analysis. This time is 72 hrs after the defined ET time for Ike and shortly after the onset of the stronger increase in standard deviation.

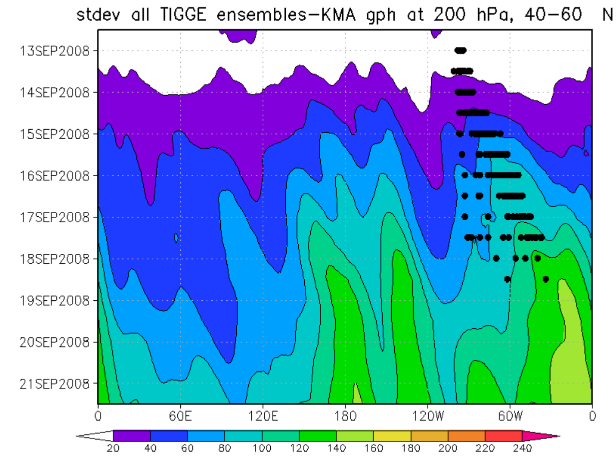

FIG. 3: Hovmoeller Diagram for the standard deviation of the 200 hPa geopotential height (in gpdm) between the TIGGE members for the forecast, IT: 12 UTC, 12 Sep 08 (shaded), averaged between 40-60° N, and forecasted position of Ike or its remnants, based on the minimum in mean sea level pressure.

3.2 *Regions Of Uncertainty, Identified Using The EOF-Analysis Method*

The first step in the applied analysis method, we use to extract the main differences in the forecast in question is to calculate the EOF of the variance-covariance matrix for the whole forecast field at the time of investigation. The distributions of the EOFs depict the regions of uncertainty between the TIGGE members. These distributions are expected to roughly resemble the distribution of standard deviation, presented in Fig.2. The EOF-distributions are displayed together with the TIGGE-mean for the 200 hPa geopotential height to identify the synoptical structures, the strong uncertainties belong to. In this analysis, we examined the first two EOF only, as they normally capture the largest amount of uncertainty. The strongest uncertainty between the TIGGE members, depicted by EOF 1 (Fig.4a), can be found close to the flanks of the tilted ridge over the central Atlantic. The distribution of the potential temperature at the 2 PVU surface (not shown) indicates low PV air, moving into this ridge due to Ike. This EOF 1 distribution resembles the so called shift-pattern (Anwender et al., 2008). Secondary regions with strongest differences are located in the rear flank of a broad and weak trough structure in the upstream region over northern America, as well as between the apex and the front flank of the short-wave trough, forming close to western Europe. EOF1 captures around 26% of the total variability, contained in this forecast. The second strongest differences between the TIGGE members, captured by EOF2, can be found at the rear flank of the tilted ridge, elongating into its apex, and at the rear flank of the weak short-wave ridge, forming over western Europe. Thus this distribution partially resembles an amplitude pattern (Anwender et al., 2008).

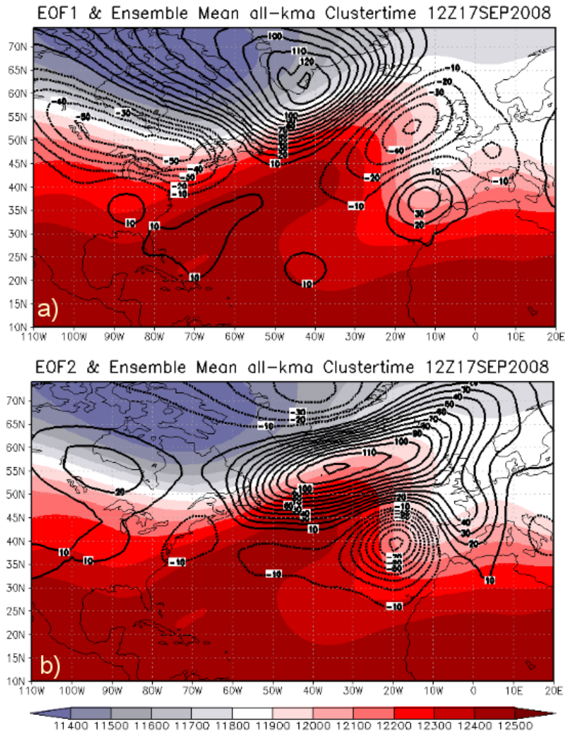

FIG. 4: Distribution of uncertainty, depicted by the first two EOFs (contours) and ensemble mean of the 200hPa geopotential height (shaded) at investigation time (12 UTC 17 Sep 08). a) EOF 1, which captures 26% of the total uncertainty. b)EOF 2, which captures 18% of the total variability.

A region of second strongest uncertainty with opposite sign is located close to the apex of the short-wave trough west of Europe, where the cut-off low forms during the following hours. EOF2 accounts for 18% of the total variability.

3.3 *Grouping Of The Ensemble Members, Different Development Scenarios*

It is not immediately evident how many groups (i.e. clusters) are necessary to capture all the important information, contained in the TIGGE forecast in question. Therefore, we execute the clustering algorithm with an increasing number of clusters (6-15). After each clustering process, the results were compared to find out if a development scenario occurs that differ strongly from the former ones. If such a new scenario exists, the number of clusters is increased further, otherwise the clustering process is finished by using the former cluster number (Harr et al., 2008). In the case presented here we found 10 different development scenarios. Out of the ten different scenarios, we extracted four main development scenarios (Fig.5), whose differences could be explained in terms of their contribution to the EOF distribution. The other six scenarios, which are not presented here, are combinations of these scenarios or resemble them to a lesser extent.

The clusters with a negative contribution to EOF 1 but a positive contribution to EOF 2 (Fig.5a) are characterized by a strong and amplified ridge (positive EOF2), strongly tilted to the east (negative EOF1) as well as a moderate short wave ridge over western Europe (positive EOF2). The short-wave trough in between these two ridge structures is also strongly amplified, forming a cut-off low (positive EOF2). These development scenarios show a rather strongly developed extratropical cyclone, containing remnants of Ike, on a rather eastward position, close to the Denmark Strait. Furthermore, they resemble the analysis most closely (Fig.1c).

The group of clusters with an overall positive contribution (positive EOF1 and EOF2) mainly differ from the development, described before, by showing a weaker tiled ridge over the central Atlantic (positive EOF1), as well as in the weaker ridge over Europe (Fig.5b). Due to the different ridge flanks the short-wave trough to the west of Europe has a broader, less amplified structure (positive EOF1) as in the former mentioned development, a cut-off low does not develop. Here only a weak remnant of Ike can be identified at a western position.

The third group of clusters are those clusters with an overall negative contribution (negative EOF1 and EOF2). They are characterized by a less amplified and rather weak tilted ridge (Fig.5c) structure over the central Atlantic (negative EOF1 and EOF2), but a moderately amplified short-wave ridge over western Europe (negative EOF1). The trough structure in between those ridges is rather broad and weak, compared to the former cases, also without the formation of a cut-off cyclone. The remnants of Ike have reintensified strongly, but are located more to the southwest, close to the southern tip of Greenland.

The fourth main possible development scenario is stated by those clusters, having a positive EOF1- and a negative EOF2-contribution (Fig.5d). They are characterized by a moderately amplified (negative EOF1), but weakly tilted ridge at a rather western position (positive EOF1), and a very weak ridge structure over Europe (positive EOF1). Due to the small tilt ridge over the central Atlantic and the weak ridge over Europe, only a broad and weak short-wave trough develops to the west of Europe. These clusters show only weak remnants of Ike close to the southern tip of Greenland.

3.4 *Contributions from the several TIGGE EPS*

To investigate whether we obtain some new possible development scenarios by using the TIGGE multi model EPS instead of a single EPS, such as the ECMWF

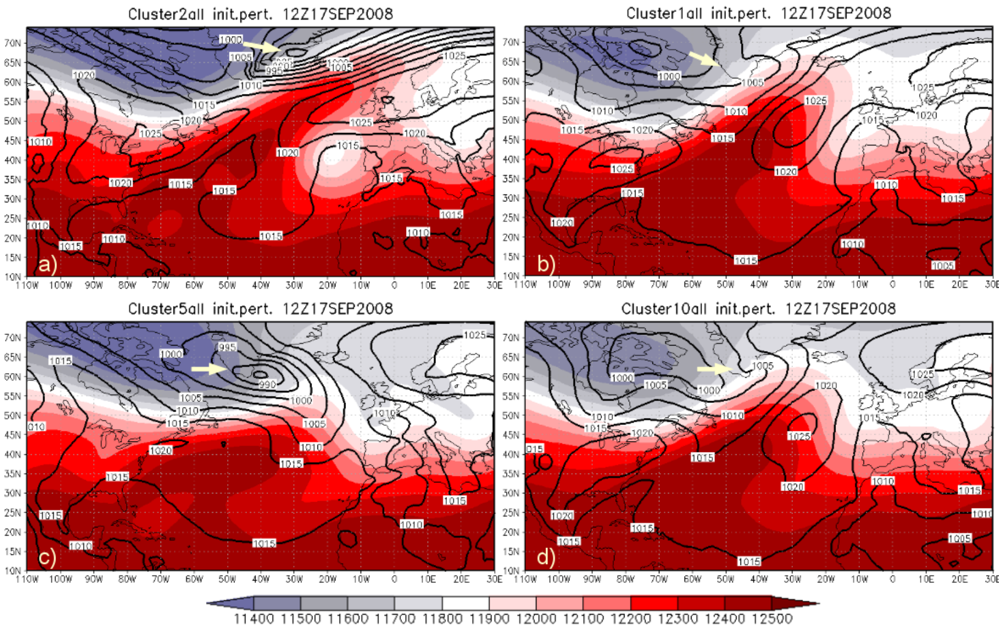

FIG. 5: The four different main development scenarios, found as a result of the EOF- and cluster analysis performed on the TIGGE-forecast, initialized 12 UTC, 12 Sep 08, investigated 12 UTC 17 Sep 08. Cluster mean of 200hPa geopotential height (shaded) and sea level pressure (contours). Arrows mark the positions of the remnants of Ike. Scenarios have different contributions to the EOF distributions. a) -EOF1, +EOF2, b) +EOF1, +EOF2, c) -EOF1, -EOF2, d) +EOF1 , -EOF1

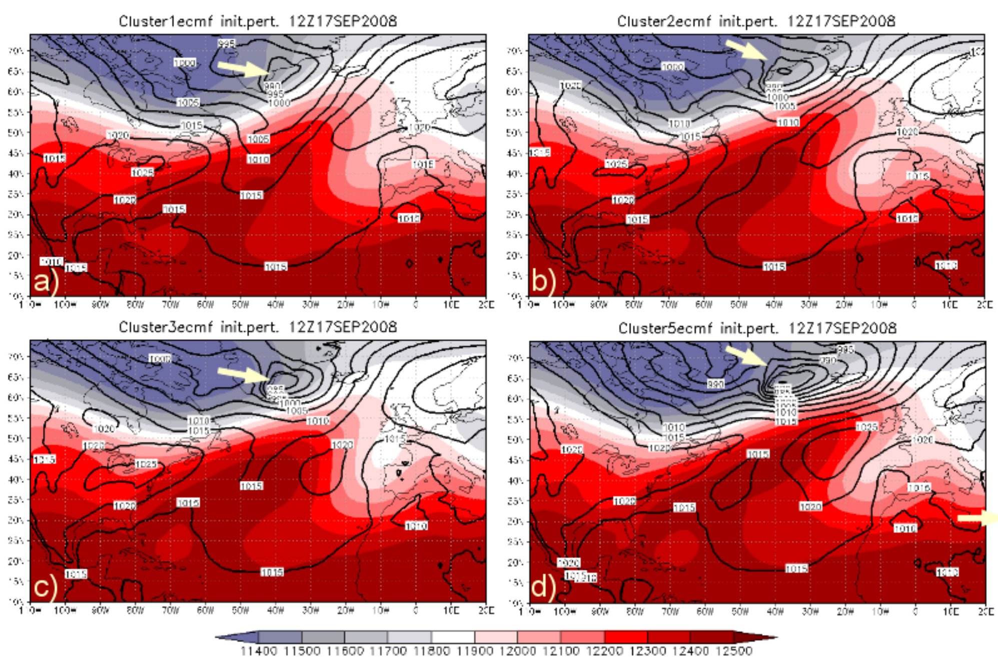

FIG. 6: Four of the five different scenarios, found by investigating the ECMWF EPS. As 5. The fifth scenario combines the scenarios a) and b). Overall, they indicate weaker differences.

EPS, we investigate the contribution from members of the several TIGGE EPS to the four development scenarios shown in Fig.5. Therefore, the number of members of each EPS contributing to each of the four scenarios is summarized (Fig.7). Furthermore, this summary contains information about the probability of these main scenarios in each TIGGE EPS, as well as in the TIGGE as a whole, as the number of members, having a related development scenario can be seen as a measure of probability. Thus, for the whole TIGGE EPS, a scenario with negative contribution to EOF1 and positive contribution to EOF2 (Fig.5a) is more likely than a scenario with a positive contribution to EOF1 and a negative to EOF2 (Fig.5d), as the former occurs in 70 of the 231 total members (30% probability), while the other one occurs in less than 30 members (12% probability).

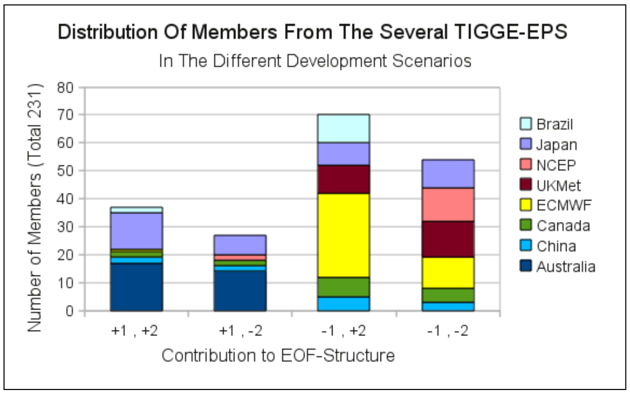

FIG. 7: Contribution of the members of the several TIGGE-EPS to the main EOF-combinations (i.e. development scenarios).

Clear differences can be found in the contribution of the several EPS to the different development scenarios. While the Japanese, Chinese and Canadian EPS contribute to a related amount to all four scenarios, the UKMet, the Australian and the ECMWF EPS contribute mainly to only two of the cases presented here. This leads to the assumption, that the other development scenarios are unlikely to occur in these EPS forecasts. To test the assumption, we applied the same EOF- and clustering analysis to the ECMWF-EPS alone, using the same initialisation- and investigation time. This analysis resulted in five different development scenarios (Fig.6), which are, as expected, related qualitatively to the two TIGGE scenarios with the strong ECMWF contribution (Fig.5a,c).

4. SUMMARY AND OUTLOOK

Eight of the ten EPS, contained in the TIGGE multi-model ensemble were used to investigate the predictability and possible development scenarios during the ET of Hurricane Ike in 2008. First, the spatial distribution of the standard deviation for the 200 hPa geopotential height was investigated during the whole forecast period. Even after a short forecast interval a growth of differences between the ensemble members could be seen north of the transforming storm. This uncertainty grew further during the investigated time period and propagated further downstream as could also be observed and pointed out in a Hovmoeller diagram. An EOF-Analysis, followed by a fuzzy-clustering process was executed on the whole TIGGE dataset, as well as on the single ECMWF EPS, to find the regions of strongest uncertainty and to extract the main possible development scenarios. In the case of the TIGGE analysis, ten different scenarios were found, which could be grouped into four main scenarios, depending on their contribution to the uncertainty patterns. The several EPS, contained in TIGGE showed different contributions to the several development scenarios. Only three of the eight EPS resemble all four different scenarios, while in the other EPS at least one of the four scenarios was not likely to occur. This assumption could be verified for this case study by a qualitative comparison with the five different scenarios, which were the result of the analysis applied to the ECMWF EPS.

By performing more related case studies, we want to investigate the predictability and performance of the TIGGE multi-model ensemble. One of the main questions to address is, whether we get a larger range of possible scenarios. This would be of particular interest if the analysis is not contained in the scenarios, we found by investigating a single TIGGE EPS. e.g. the ECMWF EPS. Thereafter we want to apply an analysis of the eddy-kinetic energy distribution (Orlanski and Sheldon, 1995; Harr and Dea, 2009) and a PV-inversion (Davis and Emanuel, 1991) to analyse the physical processes and the interaction between the storm and the midlatitude flow in several interesting development scenarios.

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