Future UK circulation and wind projections and their relevance for the built environment.

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Executive Summary

This EPSRC funded project highlights the uncertainty in future UK winds through analysis of multi model projections. A weather classification methodology has been used to explore how the frequency and characteristics of particular weather types are projected to change into the future. A comparison with ERA40 has highlighted that current Global Circulation Models (GCMs) have too many cyclonically classified days and too few anticyclonic days. In particular the models have too few UK centred intense high pressure days and too few runs of anticyclonic conditions. There are also too many UK centred weak cyclonic days and too many runs of cyclonic days in the models. The present day relationship between different weather types and average wind speeds across the UK has been determined and the specific weather types associated with high and low wind UK wide wind conditions highlighted. A future shift to more anticyclonic and less cyclonic days is seen across both ensemble datasets annually and particularly in summer and autumn. Detailed analysis has highlighted this future shift is from UK centred weak cyclonic days to low wind anticyclonic days, with an increase in consecutive days of anticyclonic conditions. The limited capability of different models to capture the characteristics of blocking anticyclones is well documented and should therefore be taken into account when interpreting the results. An increase in UK wide low wind anticyclonic conditions into the future could have important implications for society. During hot spells in the summer, higher wind speeds help building ventilation; these preliminary results indicate that overheating of buildings could increase into the future. UK wide anticyclonic events have also been seen to reduce wind power production across the UK and consequently the projected future increase in low wind events in summer and autumn, combined with an increasing reliance on wind power could compromise our future energy resilience. This work has demonstrated how weather type analysis can be used to help understand the societal impacts of climate change. Further work is required to fully assess the impacts of future circulation changes on specific societal sectors.

Introduction

PROMETHEUS is an EPSRC funded project led by the University of Exeter to investigate how probabilistic climate change data can be used to make building design standards and decisions more resilient to a changing climate. This multi disciplinary project is concentrating on how to produce hourly climate data sets (reference years) for the UK that can be fed into building models, making use of UKCP09 information. In addition this project is assessing what are the social and practical barriers to new probabilistic reference years being used by the building sector.

The design of buildings has long taken the local climatic conditions into account. The local environment can affect the choice of location, structure material used and design of the surrounding environment. For example location can be chosen to avoid excessive flooding risk from either the sea or a river, the choice of material and ventilation and cooling system to cope with temperature extremes and the choice of drainage system to manage pluvial flood risk. The Greater London Authority (2005) published a qualitative report on how climate change could impact upon buildings, giving advice on how planners and designers could include adaptation within their design and construction. One of the largest consequences of inappropriate building design is for human health. Overheating of buildings during heat wave conditions can lead to human discomfort or illness, for example in Europe during the heat wave of 2003, an additional 40,000 people died (García-Herrera et al., 2010). The presence of the urban heat island further exacerbates the importance of adequate building design standards.

Wind speed extremes and direction can influence various building properties and functions. A windy location would require more robust building construction, while low winds can influence choice of ventilation and cooling system. In the UK high wind speeds are most often associated with low pressure systems, while low wind speeds are often related to high pressure 'blocking' systems. The impact of climate change on the UK wind field is not well understood and is currently an active area of ongoing research. This work further explores this area using global model ensemble datasets. In addition this research examines whether through the use of weather types more can be learnt about future changes in the UK wind conditions which are of relevance to the building industry.

Current day understanding of wind and weather type changes

Skill and understanding of how winds and synoptic-scale processes affecting the UK may change under a warming climate is still limited and is an area of active research. Below is a summary of latest model skill assessment for UK winds, anticyclonic events and mid latitude storms, including future projections and their uncertainty.

The confidence in future changes in the windiness in Europe was classed by the latest Intergovernmental Panel on Climate Change (IPCC) report at relatively low. Different studies have been found to give opposite results and have been attributed to variations in the strength of the large scale north-south pressure gradient between models. It was noted that models have shown a general similarity between the future changes in average and extreme winds. Brown et al. (2009) have completed an assessment of model wind speed skill and analysed future projections from the Hadley Centre regional climate model (RCM) and HadCM3. They found the RCM to have biases when compared to both ERA40 and observations and have attributed this to orography and surface roughness related parameterisations in the RCM, rather than from the driving GCM. However the RCM was found to compare better with the wind speed observations than the GCM and was recommended for use in climate change anomaly studies. Mean ensemble future wind speed changes were found to be small in both the RCM and GCM, reflecting the lack of a coherent signal between members, with seasonal changes at individual locations across the mainland UK between +10% and -15%. However the ensemble mean wind speed changes did show a future reduction in the westerly flows over the southern half of the UK in summer and an increase in the north, and also an increase in southerly flow over the UK in winter.

The latest IPCC report highlighted that GCMs tend to better simulate the location of northern hemisphere blocking than their frequency or duration and that blocking events seen in GCMs are generally shorter and rarer than observed (Pelly and Hoskings (2003), Ringer et al., 2006). There is considerable interannual and interdecadal variability in blocking frequency in observations and therefore care must be taken in looking at changes into the future. Matseuda et al., (2009) found that only with a high resolution GCM could Euro-Atlantic winter blocking events be accurately represented. For the UK, James et al., (2009) found that the location and strength of blocking events within HadCM3 when compared to observations was diagnostic dependent, however HadCM3 was found to be competitive with other GCMs. Projections for future changes in frequency and strength of blocking events were found to be small and again diagnostic dependent, leading to the conclusion that across the different ensembles there was not a consistent signal of change and the evidence for substantial changes appears to be small (James et al., 2009). Ringer et al. (2006) documented an improvement in modelling atmospheric blocks in HadGEM1 over previous Hadley Centre models associated with an increase in transient eddy kinetic energy and improved physical parameterizations.

IPCC concluded that GCMs when run with observed sea surface temperatures produce storm tracks in approximately the correct locations but that many have problems with the level of cyclone activity and distribution. James et al. (2009) found that the HadCM3 ensemble mean cyclone activity track was too far south compared to observations and that too few storms in each season were simulated, however that HadCM3 was more realistic than many other GCMs. The IPCC concluded that in the future models suggested a reduction in the number of mid-latitude storms averaged over each hemisphere and a poleward shift of the storm tracks. James et al, when concentrating on the N. Atlantic storm track found that HadCM3 suggested a more southerly future storm track position with a small weakening in storm strength, while a multi model ensemble suggested little change in the N. Atlantic storm track location and generally increasing storm strength. James et al. concluded that simulated future changes in the frequency, position and strength of N. Atlantic storms were modest and that subtle shifts in the storm track position were possible although were inconsistent between models.

Methodology

An analysis of future wind speeds and frequency characteristics of synoptic scale variability has been assessed using two ensemble data sets. The first dataset is the Met Office perturbed parameter ensemble (QUMP – Quantifying Uncertainty in Model Predictions, see Collins et al 2006) using the coupled ocean-atmosphere circulation model, HadCM3. This ensemble has 17 members which sample the uncertainty in key atmospheric processes, through the systematic variation of key parameter values. A full description of the experiment design is given in the UKCP09 Climate Change Projections report (James et al., 2009). The second dataset is a 15 member multi-model ensemble (MME) and represents a subset of global modelling experiments which contributed to the IPCC Fourth Assessment report (Meehl et al., 2007). A list of modelling results used can be seen in Annex A and represents the models for which daily wind speed information is available. This ensemble should therefore not be confused with the full MDD ensemble of Meehl et al., 2007. The same models have been used for both the wind and weather type analysis. For each ensemble modelling results have been extracted for a past (1960-1989) and future (2080-2099) period, the exact thirty year period depending on the availability of data. The SRES A1B emissions scenario has forced the climate in the future modelling results. The QUMP ensemble is available from the British Atmospheric Data Centre (BADC – http://badc.nerc.ac.uk/data/link) and the MME data available from the Program for Climate Model Diagnosis and Intercomparison (PCMDI – http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php).

Daily mean wind speed is not available from the MME and consequently the wind speed results shown have been calculated from daily mean u and v wind components for each ensemble. Ensemble mean future wind speed anomalies have been calculated and their variance explored.

To investigate how synoptic-scale variability may change into the future, daily objective Lamb weather types (LWT) have been calculated following the methodology of Jones et al (1992) for each ensemble member. Each day the mean sea-level pressure field (MSLP) over the wider UK region (25ºW-15ºE, 40ºN-70ºN, see Jones et al., 1992) is analysed and characterised into one of 27 LWTs, based on the relationship between the geostrophic flow (F) and total shear vorticity (TSV). The MME, QUMP and ERA40 daily pressure fields are initially regridded onto the NCEP GCM grid prior to the LWT classification step. The NCEP grid has a resolution of 5º north-south and 10º east-west, leading to approximately 20 grid points over the UK domain. The impact of model resolution on the LWT classification has not been investigated here. The TSV is composed of the southerly and westerly shear vorticity components, and are calculated by analysing the variation in pressure gradient from east to west and from south to north respectively. The flow strength is calculated through analysis of pressure gradients with latitude and longitude. The unit of TSV is hPa per 10º latitude at 55ºN, where 100 units are equivalent to 0.46 times the Coriolis parameter at 55ºN. The flow unit is also hPa per 10º latitude at 55ºN, where 1hPa equates to 1.2 knots respectively. A full description of the technique is described in Jones et al. (1992).

The 27 individual LWTs can be grouped into three main circulation types, cyclonic (C), anticyclonic (A) and unbiased (U). A cyclonic LWT has positive TSV, an anticyclonic LWT negative TSV and an unbiased (i.e. uni-directional flow) LWT results from the TSV being less than F. Purely directional LWTs (purely cyclonic (PC) and purely anticyclonic (PA)) result from the TSV being greater than 2F. If the TSV lies between F and 2F then the day is characterised as a hybrid day, given both a type (A, C or U) and a flow direction over the UK (one of eight compass directions), resulting in LWTs such as unbiased south-easterly (USE), anticyclonic northerly (AN) or cyclonic south-westerly (CSW). The LWT methodology has been applied to both the post and future climate model ensemble datasets and also the ERA40 reanalysis dataset. ERA40 (Uppala et al., 2005) is a long term consistent record of past global climate through the incorporation of past observations into a modern forecast model and is available from 1957 to 2002 with a 1 degree resolution. The average pressure pattern for all days within the ERA40 dataset with the same LWT are shown in Figure 1a and b with their corresponding name. These figures demonstrate how the technique is capable of splitting the daily pressure fields into recognisable patterns with the low and high pressure centres (shown in blue and red respectively) centred in different locations around the UK.

For each ensemble member the change in the frequency of three measures has been assessed; the individual LWTs; the generic type (A, C or U) where all the individual LWTs of the same generic type are considered together; and by direction, where all the individual LWTs of the same direction are considered together. The mean frequency change across each of the ensembles has been calculated and also the level of agreement across the ensemble in the direction of change. The future change is defined to be ‘robust’ if 75% or more of the ensemble members agree on the direction of change. Results are only described where changes are robust, unless otherwise stated.

Wind speed analysis

The higher mean annual and seasonal wind speeds over the sea compared to land areas can be clearly seen in the ensemble means (Figure 2 and Figure 3). Over the UK in both ensembles the mean wind speeds vary with season, the winter the most windy and the summer the least. Scotland can be seen to have higher winds in many seasons than other parts of the UK. On the whole the UK has higher winds than many inland European regions especially in autumn and winter.

Annual and seasonal mean wind speed anomalies (future- past) meaned over the individual ensembles can also be seen in Figure 2 and Figure 3 . The mean change in future wind speed over the region of +/- 1m/s (5-10% of mean wind speed) is small across both ensembles and seasons. Greater mean future wind speed changes are seen in the QUMP ensemble and across the region can be double the magnitude of the MME changes (reaching +1m/s compared to 0.5m/s).

If 75% of models within each ensemble agree on the future sign of the change in wind speed, the grid box is annotated with a star. Across the year and for individual seasons over the entire region, there is a better agreement in the direction of future wind speed changes in the QUMP ensemble than the MME. Much of the region covered has robust future wind speed changes in the QUMP ensemble, while for the MME there is generally only agreement over Iceland, Southern Europe, the Mediterranean and North Africa. The QUMP ensemble shows more agreement over the UK across the seasons and annually than the MME.

The variation in mean seasonal future wind speed anomalies across the individual ensembles is also shown in Figure 2 and Figure 3. This highlights the better agreement for future wind speed changes in the QUMP ensemble than the MME across the different seasons and both within the UK and across the wider region. A greater difference in standard deviation between the models occurs in regions with higher wind speed anomalies but also in regions of disagreement such as to the west of the UK in winter in the MME.

Considering the wind speed anomalies between the two ensembles highlights there is some similarity in patterns although significant variations exist for individual locations. For example in winter and autumn, there is an agreement across both ensembles for robust reductions in wind speed over the Mediterranean and North Africa or an increase in future winds in Scandinavia in autumn. However there are many occurrences of opposite mean changes, such as over Scandinavia in spring. The MME for all seasons except summer shows a future reduction in winds in S. Europe, over the Mediterranean and over Iceland, with increases in wind speed over the UK and N. Europe and Scandinavia. While the QUMP ensemble shows a mixed picture for seasonal changes over most of mainland Europe and the Mediterranean and N. Africa, with future reductions in wind speed for a south-west, north-east band over the UK reaching into Scandinavia and to the south-west of the UK over the N. Atlantic.

There is therefore great uncertainty in future UK winds, with the two ensembles disagreeing in the mean change across the year and seasons with the exception of summer. For example in Scotland in winter the QUMP ensemble suggests a reduction in future winds with an ensemble mean reduction of approximately 3% (0.2m/s), while the MME shows an increase of approximately the same amount (Figure 4). Both ensembles do have members that have both increasing and decreasing future winds that cross the zero line. One area where agreement on robust changes in both ensembles is seen stretches from the UK to the SW over the Atlantic in summer. Both ensembles show two bands with future decreasing wind speeds to the north (including the UK) and future increasing winds to the south (including Spain).

Figure 4 also shows the wind speed changes for N. England for individual ensemble members in summer. Both ensembles show a future mean reduction in wind speed of 1%-2% in summer, although they range from -10% (-0.5m/s) to +7% (0.3m/s). Therefore even where there is consensus of mean direction of future wind speed change at a location, a range of magnitudes and signs of change is seen across the ensembles.

Weather type and wind speeds analysis

When the ERA40 daily MSLP is categorised into objective LWTs, 38% of days are of type unbiased, 35% anticyclonic and 24% cyclonic (3% unclassified). South westerly and westerly flow directions dominate with on average 51 and 55 days per year respectively, followed by north westerly and southerly flow types the next most frequent (on average 35 and 31 days respectively, Figure 5). The most frequently observed individual LWTs are purely anticyclonic (PA) (79/yr), purely cyclonic (PC) (47/yr), followed by UW (35/yr) and USW (31/yr).

There is little variation in the frequency of cyclonic weather types across the seasons (Figure 6), although slightly higher frequencies are found in spring, associated with more PC days. There is however greater variation in frequencies of anticyclonic and unbiased flow types with season. Anticyclonic events are most common in summer and least common in winter, while the reverse is true for unbiased LWTs. For example there are on average 8 more PA days in summer than winter, while approximately 3 more days of USE, US, and USW in winter than summer. All of the seasons show the predominance of westerly (SW, W, NW) wind directions, however for each direction the highest frequency occurs in different seasons. N and NE flow are most common in spring (associated with unbiased flow, UN and UNE), SW and W in autumn and winter (associated with unbiased flow, USW and UW), NW in summer (associated with anticyclonic flow, ANW) and S flow in winter (associated with unbiased flow, US).

The average wind speed anomaly per LWT throughout the ERA40 period is shown in Figure 7a and b and highlights the relationship between LWT and wind speed across the UK. As expected higher wind speed anomalies (red) over the UK are found when strong pressure gradients (see Figure 1) are seen, for example associated with a CSW flow. Lowest wind speeds (blue) occur around the centre of high pressure systems, for example PA leads to lower than average winds over the whole of the UK. The unclassified LWT also gives an average wind speed anomaly that is very low. A summary of the LWTs responsible for high and low winds over the majority of the UK are shown in Table 1.

Table 1: A summary of LWTs that produce high and low wind conditions over the majority of the UK

	Associated weather types
High UK winds	USW, UW, UNW, CSW, CW, CNW
Low UK winds	PA, AS, CE, N

The skill of both the MME and QUMP ensemble for generating realistic LWT climatologies can be assessed through comparison with ERA40. Both ensembles overestimate the frequency of PC, while underestimate the frequency of PA during the end of the 20th century (Figure 5and Figure 8). Some models are under and over predicting the frequencies by up to 50% and 100% respectively. For the other LWTs, both ensemble members have more realistic frequencies, although NE and E flow directions are overestimated in the QUMP ensemble. In general the spread of the QUMP model LWT frequencies are smaller than the MME as would be expected due to the QUMP ensemble all having the same underlying model, with parameter perturbations.

The seasonal model ensemble biases with respect to ERA40 are very similar to those for the annual LWT frequencies (not shown). In the QUMP ensemble there are too many SW and W flow types in winter (too many CSW, CW), while too few in summer (USW, UW). The former is also seen in the MME. The insufficient number of westerly days is also seen in Autumn (UW) in the QUMP ensemble. In general unbiased flow types occur too frequently in the QUMP ensemble in summer.

The application of LWTs to future climate data highlights there is a clear split in future frequency changes between the different type categories (Figure 9 and Figure 10). Into the future both ensembles suggest an increase in anticyclonic LWTs and a reduction in cyclonic LWTs. However for the unbiased LWTs, the MME gives an increase in the frequency (11 out of 16 models) while the QUMP ensemble a reduction in frequency into the future. When looking at the direction of flow, the MME shows a reduction in NE, E, SE and S flow, while an increase in SW, W and NW flow. In comparison the QUMP ensemble doesn't show any robust future changes, except for a reduction in easterly flow. The future changes in flow directions for the MME can clearly be seen in Figure 9 by the sinusoidal percentages frequency changes. For the MME robust frequency changes are seen for 2/3rds of LWTs, with an increase in westerly (SW, W, NW) anticyclonic and unbiased LWTs and a reduction in unbiased and cyclonic easterly (NE, E, SE) LWTs. For the QUMP ensemble, similar frequency direction changes are seen with nine LWTs moving in agreement with the MME. In particular there is agreement across the two ensembles on the most frequent LWTs, with PA days increasing in frequency by 10%-20% and PC days reducing by 10%-20% also.

Table 2: The number of individual, categories and directions of LWTs that agree within each ensemble on the sign of future change at the 75% level.

	Individual LWTs (out of 26)		**Types (out of 3)**		**Directions (out of 8)**	
	MME	QUMP	MME	QUMP	MME	QUMP
Annual	16	12	2	3	6	1
Winter	8	6	0	0	2	3
Spring	5	7	0	2	4	0
Summer	15	15	2	3	4	4
Autumn	17	6	3	2	6	3

Table 2 highlights there is more agreement across both ensembles for a future change in LWT frequency in summer and autumn than winter or spring. The annual increase in anticyclonic LWTs and the reduction in cyclonic LWTs projected in both ensembles occur during these seasons (Figure 11 and Figure 12). For example in summer both ensembles show a robust increase in PA, ANW and AN, while in autumn an increase in PA and UW. This finding is in agreement with both Giorgi and Coppola (2007) and James (2006). In contrast in summer both ensembles show a robust reduction of frequency of PC, CE, CSW, CSE, CE along with USE and US and in autumn there is agreement over a reduction in PC and UE. In spring there is agreement for an increase in AW and a reduction in CE and CSE. Although there is little agreement across the year on how future wind directions could change across both ensembles, there is better agreement in summer and autumn, associated with robust LWT frequency changes described when all directional LWTs are considered together. In summer there is an increase in mean frequency of northerly flows of between 10-20%, with a reduction in south-easterly and southerly flow of 20%-40%. In autumn there is agreement on a reduction in mean easterly frequency by 15%-30% and an increase in mean westerly flow frequency of 10%-30%.

PA and PC are the most commonly observed LWTs and show robust frequency changes into the future and therefore merit further investigation.

Purely Anticyclonic case study

There is an interest to understand how the frequency and length of anticyclonic weather conditions will change into the future as they are often associated with heat wave conditions in the summer and very cold conditions in the winter. Both impacts have implications for building design and human comfort, especially in conjunction with low wind speeds (see Figure 7a). To summarise the results from the previous section, PA flow is the most frequent individual LWT per year and occurs most often in summer and least often in winter. Both model ensembles underestimate the frequency of PA flow compared to ERA40 by up to 50% and this is seen in all seasons. A robust signal for an annual increase in the frequency of PA into the future is found across both ensembles (see Table 3). Both ensembles agree with an increase in the future frequency of PA in the autumn and summer, with the QUMP ensemble also projecting an increase in spring.

Table 3: The ensemble mean percentage frequency change in PA LWT for annual and different seasons. Only robust changes are shown.

	MME	QUMP
Annual	+12%	+26%
Winter	+2%	
Spring		+18%
Summer	+22%	+46%
Autumn	+18%	+18%

The strength of the anticyclone can be assessed using the total shear vorticity (TSV). The distribution to TSV across all PA days for ERA40 and both ensembles is seen in Figure 13. The majority of days have a TSV of -20hPa to -50hPa in the ERA40 analyses. Both ensembles marginally overestimate the frequency of less intense high pressures, and underestimate the frequency of the more intense anticyclones (TSV more intense than -40hPa). QUMP compares more favourably with the ERA40 analyses than the MME.

The increase in the future frequency of PA days seen can be attributed to a robust increase in anticyclones over the UK with a TSV in the range of -15hPa to -50hPa in the QUMP ensemble and -22 to -40 in the MME (Figure 14). The QUMP ensemble has robust changes for a wider spread of TSV values and has percentage increases over twice as large as for the MME, with a doubling of the frequency into the future. This signal is seen robustly in both ensembles in summer and autumn (Figure 15), where increases of between 100%-200% are seen for PA days with mid range TSV. Robust future changes are not seen for PA days with a TSV of over 50hPa, which represent days with a small centred anticyclone, leading to intense circulation and very high relative pressure over the UK.

The wind conditions across the UK during PA conditions can be seen in Figure 16. The total flow over the UK can range between 0 and over 20hPa (approximately 0 to 12m/s) on different PA days, seen in ERA40. The majority of days have a total flow of approximately 3hPa-8hPa, with few days above 13hPa and below 1hPa. The majority of models within both ensembles underestimate the frequency of PAs across the range of total flows. This is especially true for PA days with a total flow above 10hPa. Many of the MME members underestimate the yearly frequency of PA days across the different total flow values by 50%.

In the future, robust increases in the frequency of PA days with total flows below 7hPa are found for both ensembles (Figure 17). The QUMP ensemble shows almost double the percentage increase seen in the MME ensemble. Robust increases in frequency of lower end flows is seen in spring, summer and autumn in the QUMP ensembles, particularly in summer where over a 150% increase in days with flow between 2.5-5hPa is found and a 100% increase in days with flow between 0hPa and 2.5hPa (Figure 18). In the MME, similar but less robust and smaller changes are found.

The above analyses have not distinguished between one day and multiple day PA events. The longer the number of days with consecutive PA weather conditions, the less frequent the event, as seen in the ERA40 analyses in Figure 19. For example on average there are every year, 19 single PA days, four 3-day events and one 5-day event. Once every three years a block (here defined as consecutive days with PA conditions) of 8 days occurs and once every 10 yrs a block of 10 days. The MME underestimates the yearly frequency of all different length blocks, with a greater disparity to the ERA40 frequency than the QUMP ensemble average. The QUMP ensemble only underestimates the frequency of blocks of length 7 days or more.

For blocks of length 1-2 days or greater, both ensembles show a robust increase in their frequency in the future (Figure 20). For blocks of length 3 days and longer, the MME and QUMP ensembles respectively show on average a 11% and 29% increase in future frequency. For blocks of length 5 days of more, the QUMP ensemble shows a robust mean increase in future frequency of 45%, while for the MME a mean increase of 18% is seen however only 10 out of 17 models project an increase (Figure 21).

Purely Cyclonic case study

There is an interest to understand how cyclonic weather conditions will change as they are often associated with high wind speeds causing damage to buildings, and play a role in cooling buildings. Purely cyclonic flow is associated with higher than average wind speeds over the southern half of Britain and lower than average winds over Scotland, however it is not associated with the most extreme wind conditions, such as associated with a CSW. To summarise the results from the previous section, PC flow is the second most frequent individual LWT per year and its frequency is evenly split across the seasons, although spring has a marginally higher occurrence. Both model ensembles overestimate the frequency of PC flow compared to ERA40 by up to 100% and this is seen is all seasons. A robust signal for an annual reduction in the frequency of PC into the future is found across both ensembles (see Table 4). Both ensembles agree with a decrease in the future of PC in the summer and autumn. The robust seasonal changes in PC frequency agree with those for PA, but show a decrease rather than an increase.

Table 4: The ensemble average percentage frequency change in PC LWT for annual and different seasons. Only robust changes are shown.

	MME	QUMP
Annual	-15%	-15%
Winter		
Spring		-13%
Summer	-26%	-41%
Autumn	-22%	-9%

The strength of the cyclone can be assessed using the total shear vorticity (TSV). The distribution to TSV across all PC days for ERA40 and both ensembles is seen in Figure 13. The majority of days have a TSV of 10 to 50hPa in the ERA40 analyses, with few days with a TSV of greater than 60hPa or lower than 10hPa.

The wind conditions across the UK during PC conditions can be seen in Figure 16. The total flow over the UK on PC days can range between 0 and approximately 40hPa (approximately 0 to 24m/s), seen in ERA40. The majority of days have a total flow in the region of 9hPa, with few days above 30hPa and below 2hPa. The overestimation of PC days in both models occurs for low pressure systems with low TSV (20-40hPa) and low total flows (3-10hPa). The frequency distribution at the higher TSV and total flow values is closer to ERA40, although many models marginally underestimate their frequency.

The robust decrease in the future frequency of PC days can be attributed to a robust decrease (20%-50%) in cyclones over the UK with a TSV in the range of 5hPa to 60hPa in both ensembles (Figure 14). Although there is considerable inter model variability in frequency reduction. Robust future changes are not seen for PC days with a TSV of over 60hPa, which represent the more intense low pressure systems. As previously this signal is mainly seen in summer and autumn (Figure 22). In the future, robust reductions in the frequency of flows below 12hPa are found for both ensembles (Figure 17), in the order of 50% per 3hPa bin. Robust decreases in frequency of lower end flows (0-15hPa bins) is seen in summer in both ensembles (of the order of 100-200%) and in addition in autumn in the MME (50-100%), see Figure 23.

The number of consecutive days with a PC LWT can give an idea of either slow moving low pressure systems or fast moving consecutive low pressure systems. As with the PA, the longer the run of PC days, the less frequent the event, as seen in the ERA40 analyses in Figure 24. On average, every year there are 19 days of single PC events, three 2-day events and every 2 years there is a 5 day run of PC weather conditions. Both ensembles can be seen to overestimate the yearly frequency of consecutive days of PC conditions, with the average MME model showing a greater disparity to the ERA40 frequency than the QUMP ensemble average.

For runs of PC weather conditions of length 3 days and longer, the MME and QUMP ensembles show an approximate 20% reduction in future frequency (Figure 20). For runs of length 5 days of more, both ensembles show a mean reduction of the order of 28% (Figure 21).

Conclusions

There is little agreement on how future UK winds will change under a warming climate. Ensemble mean wind speed anomalies show disagreement about the sign of change into the future for three out of four seasons, with only summer showing a consistent reduction in future wind speeds in N. England and Scotland. The percentage changes in wind speed are small, with mean changes of +/- 0:1m/s (5%-10% of mean wind speed), although individual models show a larger range of wind speed anomalies, with occasional outliers. Consistent future wind speed changes are found for certain regions within the European domain covered, although agreement can be seasonally dependent. In general the QUMP ensemble has better internal agreement on the sign and magnitude of the anomalies than the MME, as would be expected when comparing results from different variants of the same model with those from different models. At the European scale higher magnitude wind speed changes into the future are seen in the QUMP ensemble. These results tie in with the previous studies highlighting the uncertainty in future UK winds.

Application of the LWT classification methodology to ERA40 has resulted in an approximately even split between anticyclonic and unbiased LWTs over the past period, with one third less cyclonic LWTs. South-westerly and westerly directions dominate the ERA40 distribution and specifically PA and PC occur most frequently. Both ensembles greatly overestimate both the annual and seasonal occurrence of PC days and underestimate the occurrence of PA days when compared to ERA40. Most other individual LWT frequencies are reasonably well captured in the model past periods. Both ensembles robustly project an annual increase in anticyclonic LWTs (particularly PA) and an annual reduction in cyclonic LWTs (particularly PC) into the future and exploration has shown these frequency changes are projected to occur in summer and autumn and are of the order of 10% - 40%. This projected future change is in agreement with previous studies. Agreement across the two ensembles for robust changes in winter LWT frequency is not found with only a few robust changes projected in spring. The MME does suggest robust annual directional changes into the future with more westerly type flows and a decrease in easterly type flows, although such robust changes are not found in the QUMP ensemble. However in summer and autumn there is some agreement across both ensembles in wind directional frequency changes when LWTs are considered together (not shown), including an increase in northerly flows in summer and westerly flow in autumn and a reduction in south easterly and southerly flows in summer and easterly flows in autumn. The spread of the magnitude of LWT frequency changes is greater in the MME than the QUMP ensemble.

The frequency changes in PA and PC LWTs have been studied in more detail as they are the most frequent LWT and show robust future frequency changes. A measure of the total shear vorticity and total flow (calculated to classify days into LWTs), has been investigated to better understand how the strength and associated atmospheric flow of these important LWTs may change.

The underestimation of the frequency of PA days in the models when compared to ERA40 particularly occurs for stronger anticyclones (greater negative vorticity) and also for all flow strengths. The MME underestimates the frequency of blocks of all durations, while the QUMP ensemble is more realistic for blocks of length less than 7 days. For these three measures the QUMP ensemble has a smaller bias when compared to ERA40 than the MME. Both ensembles agree with an annual increase in PA days, seen in summer and autumn of the order of 20%-45%. In the future an increase in PA days with medium vorticity strength and low total flow is seen in both ensembles, particularly in summer and autumn. The QUMP ensemble shows a greater frequency increase (approximately double) than those of the MME. Blocking events of duration 1-2 days or greater and equal to 3 days are projected to robustly increase in both ensembles, while for blocks of length 5 days or more a mean increase in frequency is projected in both ensembles, although only the QUMP ensemble has robust internal agreement of the sign of change.

The annual and seasonal PC frequencies in both ensemble past periods are too high when compared to ERA40. This frequency overestimation occurs for weak PC days with both low TSV and total flow. The frequency of consecutive PC days of any duration is also over estimated when compared to ERA40. For all three measures the QUMP ensemble is closer to ERA40 than the MME. The annual frequency of PC days in the future is projected to reduce by 15% in both ensembles; in the summer and autumn larger reductions are seen. A similar frequency reduction is seen in spring in the QUMP ensemble. Both ensembles project a reduction in annual and summer frequency of PC days into the future with low flow strength and a range of circulation strengths. For the PC days with the highest vorticity or flow values the projections do not show a robust frequency change. For consecutive days of PC conditions of length 1-2 days, greater or equal to 3 days or greater or equal to 5 days, both ensembles show a robust reduction in their frequency, the longer durations by approximately 20%. Numerous studies have documented the limited ability of GCMs to accurately capture the position, frequency and duration of blocking events across the globe. Although the future changes described here are seen in the majority of models, it is important to take this uncertainty into account when interpreting the results.

To conclude, into the future a shift from UK centred weak cyclonic days to low wind speed anticyclonic days is projected in summer and autumn. More frequent consecutive high pressure days with low wind speeds into the future could indicate an increased frequency of overheating of buildings and resultant human health issues. This analysis has demonstrated how LWT classification techniques can be used to examine how climate change may impact upon specific society relevant weather events. To fully explore what climate change could mean for building design a full analysis of all the different LWTs responsible for specific impacts should be ascertained and studied together. For example to better understand the future risk of overheating of buildings all LWTs responsible for both high temperature and low winds could be investigated looking at both their future frequency and characteristics.

References

Brown S., P. Boorman, R., McDonald and J. Murphy. Interpretation for use of surface wind speed projections from the 11-member Met Office Regional Climate Model ensemble. Post-launch technical documentation for UKCP09

Collins, M., Booth, B. B. B., Harris, G., Murphy, J. M., Sexton, D. M. H. & Webb, M. J. (2006). Towards quantifying uncertainty in transient climate change. *Climate Dynamics*, **27**, 127-147.

García-Herrera, R., J. Díaz; R. M. Trigo, J. Luterbacher, E. M. Fischer (2010). A Review of the European Summer Heat Wave of 2003. *Critical Reviews in Environmental Science and Technology*, 1547-6537, Volume 40, Issue 4, 2010, Pages 267 – 306

Giorgi and Coppola 2007. *Geophysical Research Letters* dx.doi.org/10.1029/2007GL031223

James, P.M., 2006. An assessment of European synoptic variability in Hadley Centre Global Environmental Models based on an objective classification of weather regimes. *Climate Dynamics* DOI 10.1007/s00382-006-0133-9

Jones P.D, M. Hulme and K.R. Briffa, 1992, 'A comparison of Lamb Circulation types with an objective classification scheme', *Int. Journal of Climate*, **13**, 655-663

Matsueda, M., Mizuta, R. and S. Kusunoki, 2009. Future change in wintertime atmospheric blocking simulated using a 20-km-mesh atmospheric global circulation model. *Jour. Geophys. Res.*, **114**, D12114, doi:10.1029/2009JD011919.

Meehl, G.A. et al. (2007) Global Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Murphy, J. M., Sexton, D. M. H., Jenkins, G. J., Booth, B. B. B., Brown, C. C., Clark, R. T., Collins, M., Harris, G. R., Kendon, E. J., Betts, R. A., Brown, S. J., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R., and Wood, R. A., 2009: UK climate projections science report: Climate change projections. Met Office Hadley Centre, Exeter, UK.

Pelly, J.L., and B.J. Hoskins, 2003: How well does the ECMWF Ensemble Prediction System predict blocking? *Q. J. R. Meteorol. Soc.*, 129, 1683–1702.

Ringer M A, Martin G, Greeves C, Hinton T, James P, Pope V, Scaife A, Stratton R, Inness P, Slingo J, Yang G-Y (2006) The physical properties of the atmosphere in the new Hadley Centre Global Environmental Model (HadGEM1). Part II: Aspects of variability and regional climate. *J Clim* **19**:1302-1326

Uppala, S.M., Kållberg, P.W., Simmons, A.J., Andrae, U., da Costa Bechtold, V., Fiorino, M., Gibson, J.K., Haseler, J., Hernandez, A., Kelly, G.A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R.P., Andersson, E., Arpe, K., Balmaseda, M.A., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B.J., Isaksen, L., Janssen, P.A.E.M., Jenne, R., McNally, A.P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N.A., Saunders, R.W., Simon, P., Sterl, A., Trenberth, K.E., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J. 2005: The ERA-40 re-analysis. *Quart. J. R. Meteorol. Soc*., 131, 2961-3012.doi:10.1256/qj.04.176

The Greater London Authority, 2005. Adapting to climate change: a checklist for development. Guidance on designing developments in a changing climate. Published by The Greater London Authority, London Climate Change Partnership.

Annex A:

The multi model ensemble (MME) used in this study consists of the models below. This is a sub set of models used in the AR4 modelling studies seen in the IPCC AR4 WG1 Ch11, 'MMD-A1B simulations' and represents those where daily wind speed information where available. This same set were used for both the wind and weather type work.

- Bjerknes Centre for Climate Research (bccr_bcm2_0)
- Canadian Centre for Climate Modelling & Analysis (cccma_cgcm3_1)
- Canadian Centre for Climate Modelling & Analysis (cccma_cgcm3_1_t63)
- Météo-France / Centre National de Recherches Météorologiques (cnrm_cm3)
- CSIRO Atmospheric Research (csiro_mk3_0)
- CSIRO Atmospheric Research (csiro_mk3_5)
- US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory (gfdl_cm2_0)
- NASA / Goddard Institute for Space Studies (giss_aom)
- NASA / Goddard Institute for Space Studies (giss_model_e_r)
- LASG / Institute of Atmospheric Physics (iap_fgoals1_0)
- Institute for Numerical Mathematics (inmcm3_0)
- Institut Pierre Simon Laplace (ipsl_cm4)
- Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (miroc3_2_medres)
- Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group (miub_echo_g)
- Meteorological Research Institute (mri_cgcm2_3_2a)

Figures

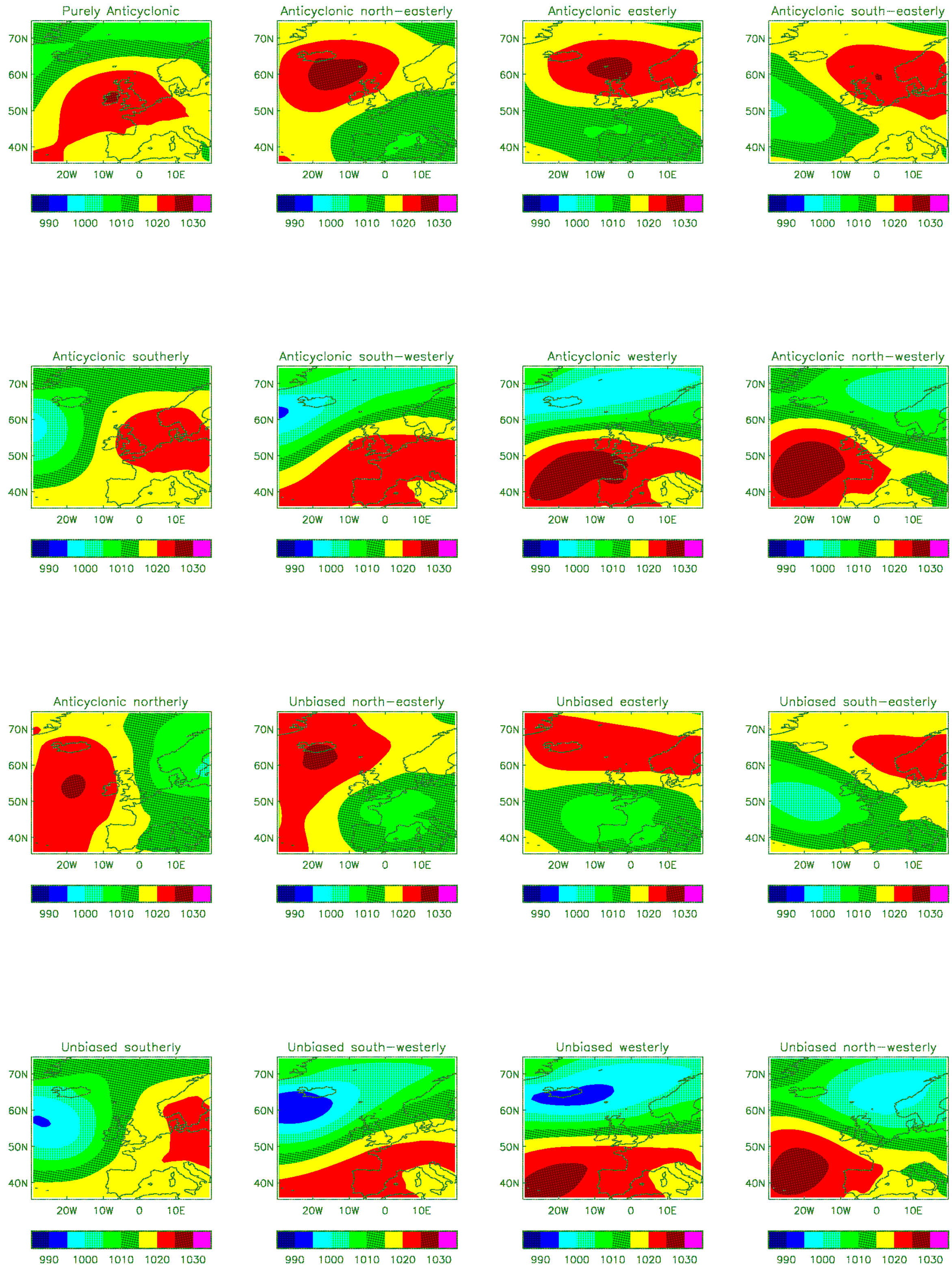

Figure 1a: The average pressure pattern per LWT over the ERA40 dataset (hPa).

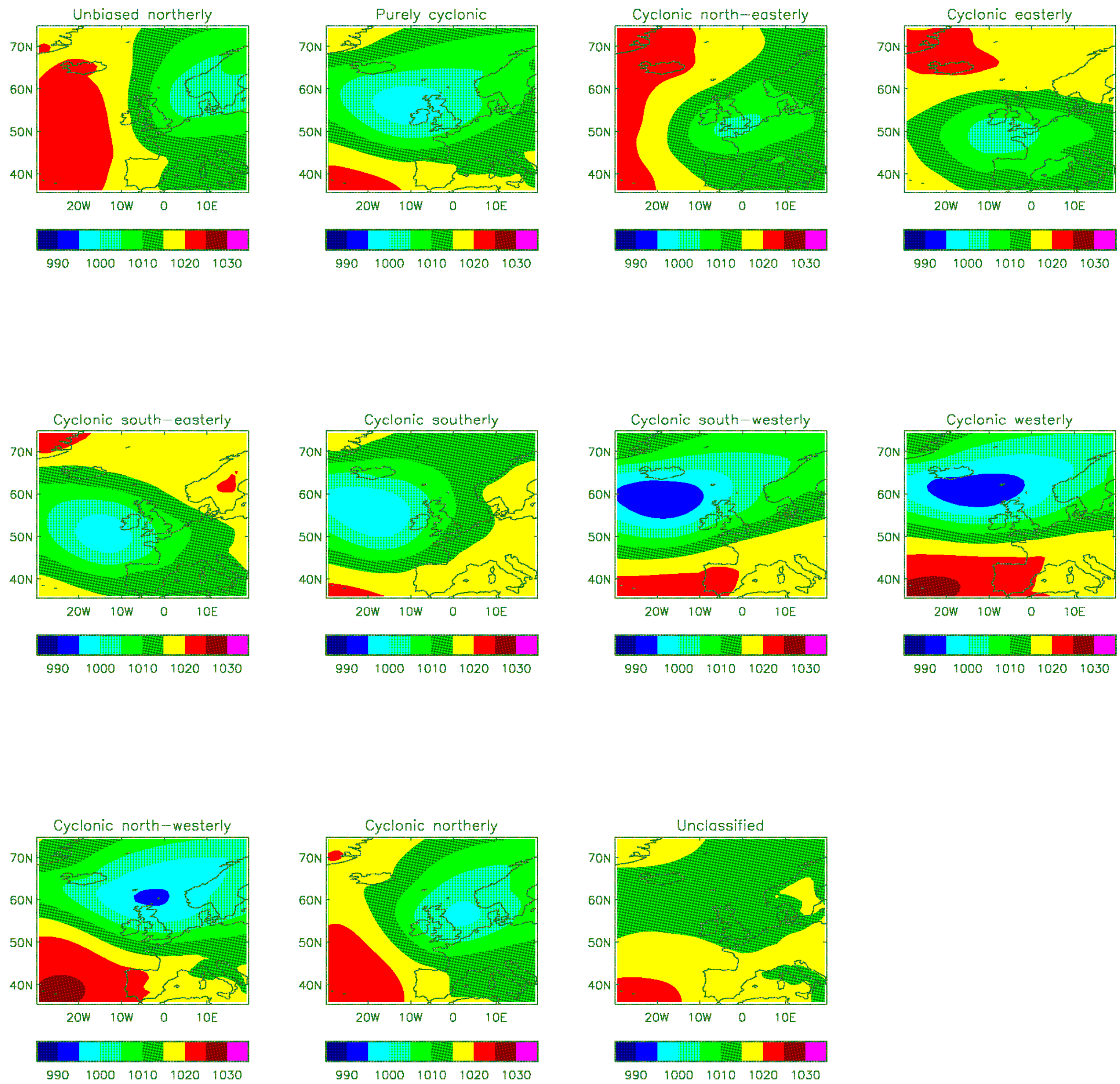

Figure 1b: The average pressure pattern per LWT over the ERA40 dataset (hPa) - continued.

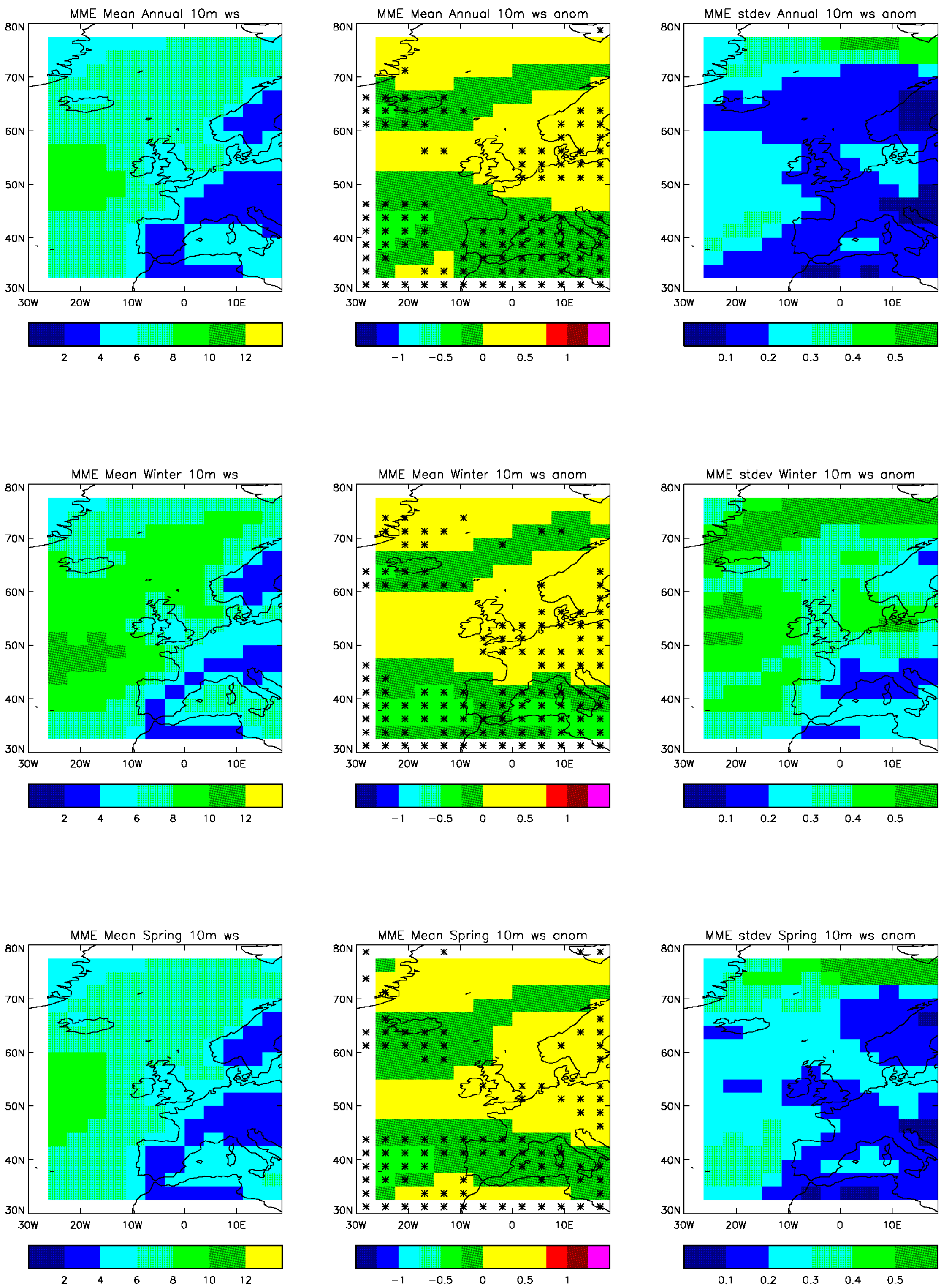

Figure 2a: MME mean wind speed m/s (left), mean wind speed anomaly m/s (middle) and standard deviation of mean wind speed m/s (right) anomaly for annual, winter and spring (top to bottom).

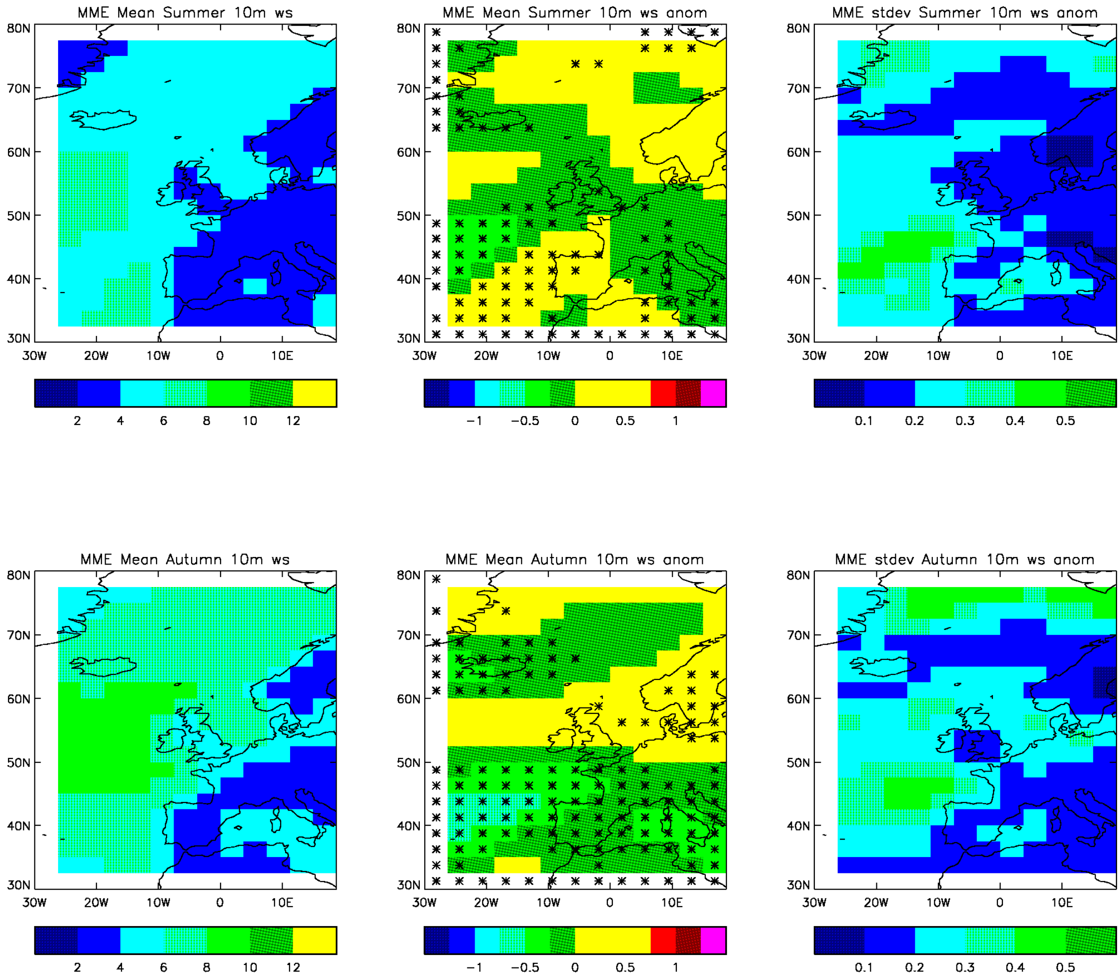

Figure 2b: As for Figure 2a but for summer (top) and autumn (bottom)

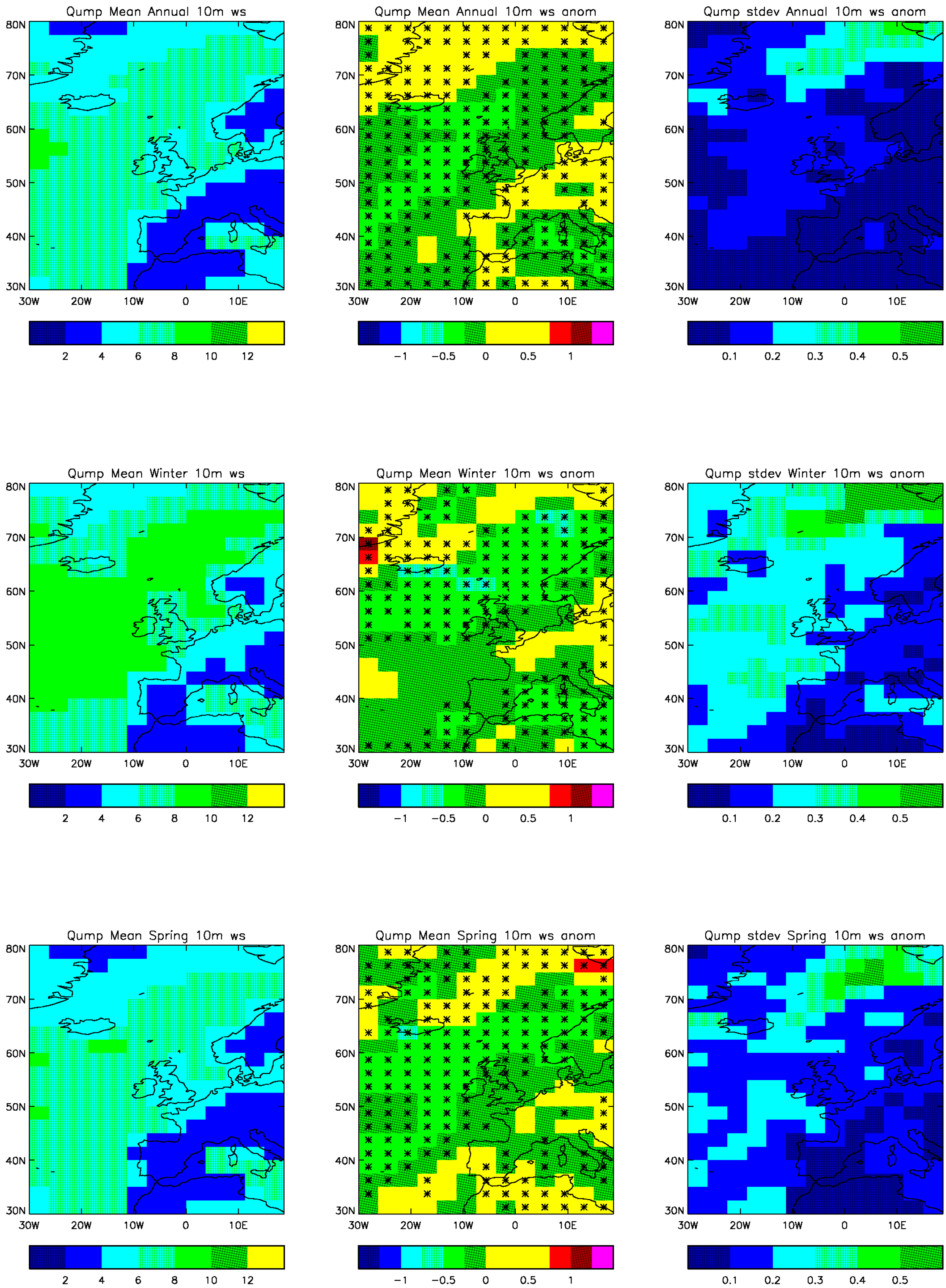

Figure 3a: QUMP ensemble mean wind speed (left), mean wind speed anomaly (middle) and standard deviation of mean wind speed anomaly for annual, winter, spring (top to bottom).

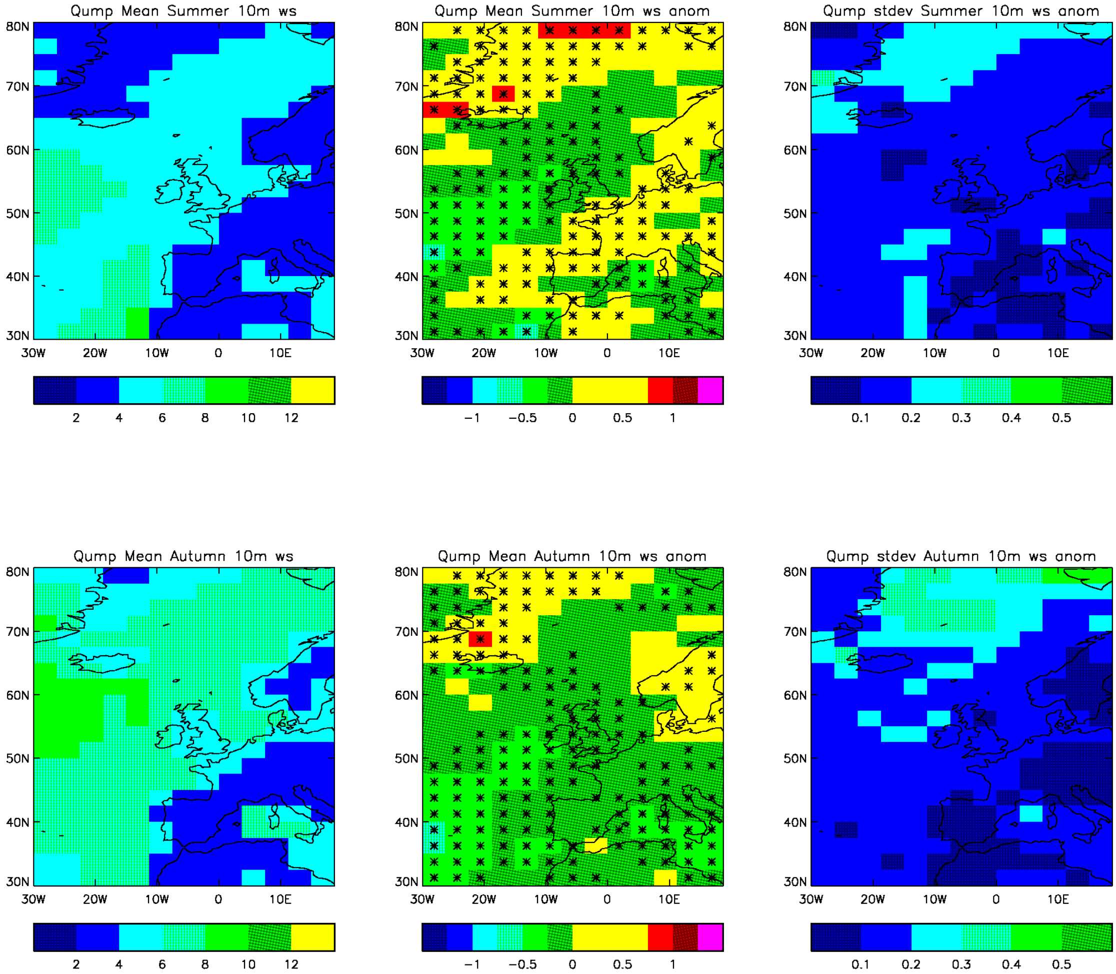

Figure 3b: As for Figure 3a but for summer (top) and autumn (bottom)

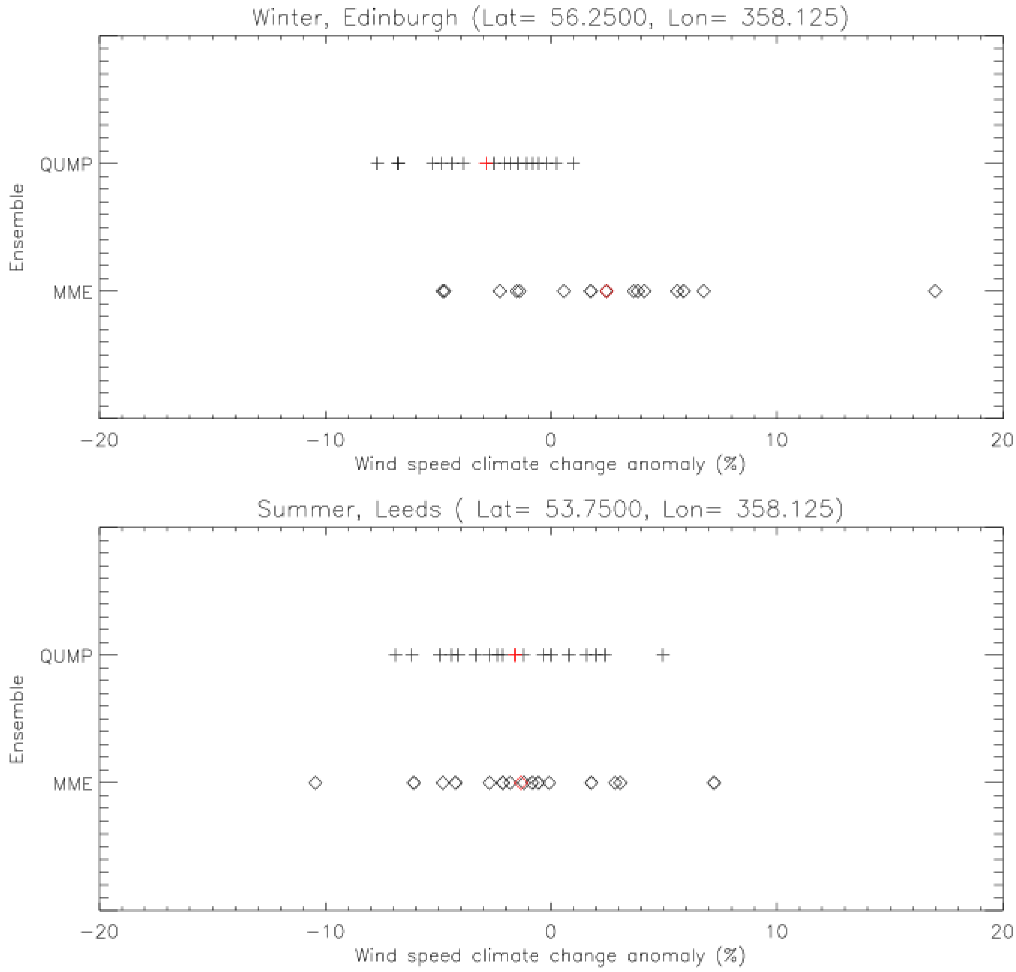

Figure 4: Mean wind speed anomaly (future-past) for both MME (diamond) and QUMP (cross) ensemble members, with the mean of each ensemble in red for two UK grid points (near Edinburgh and Leeds in winter and summer respectively).

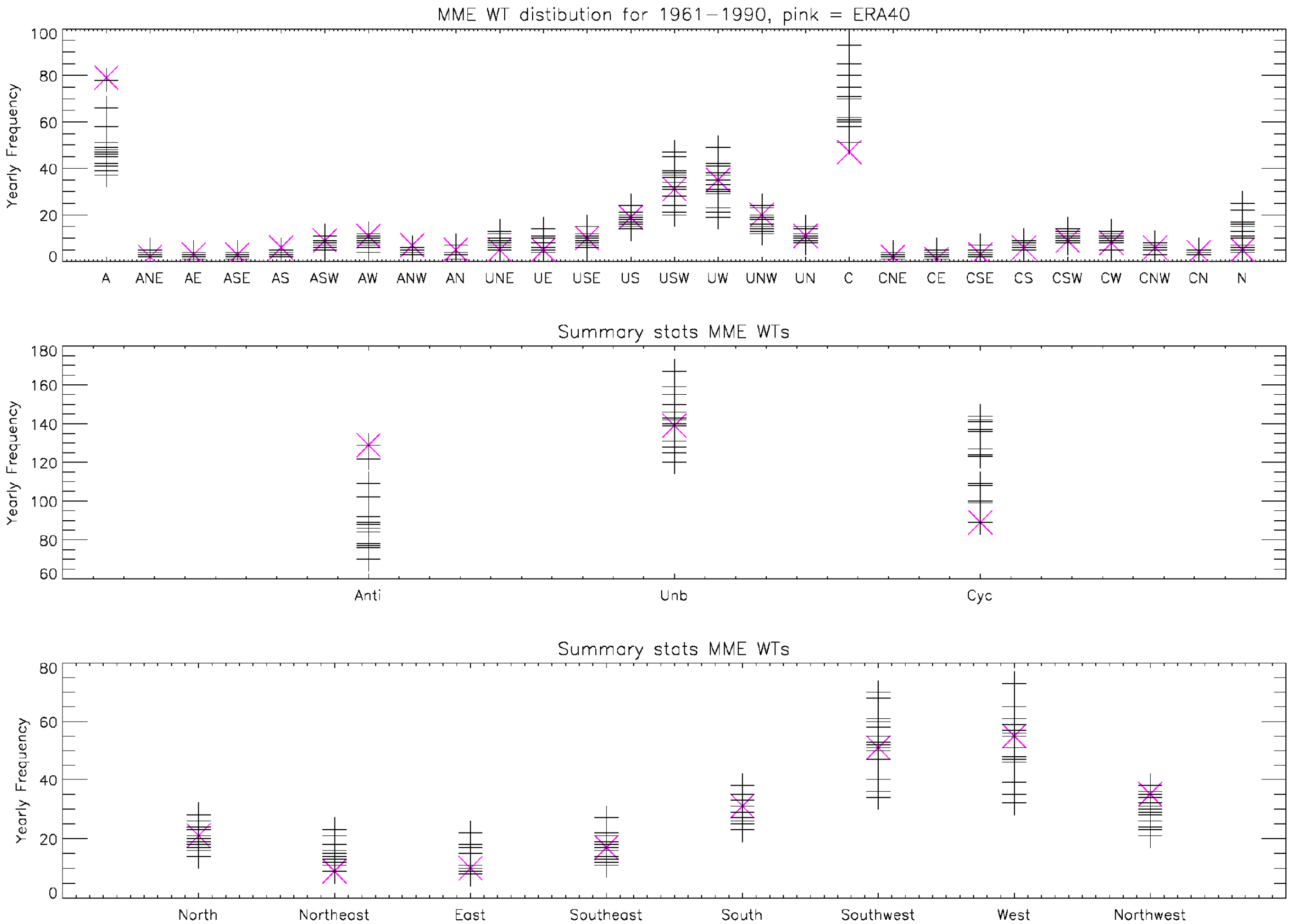

Figure 5 Yearly weather type frequency distribution for each MME member and ERA40 (pink triangle) for all LWTs (top), LWT category (middle) and LWT directions (bottom)

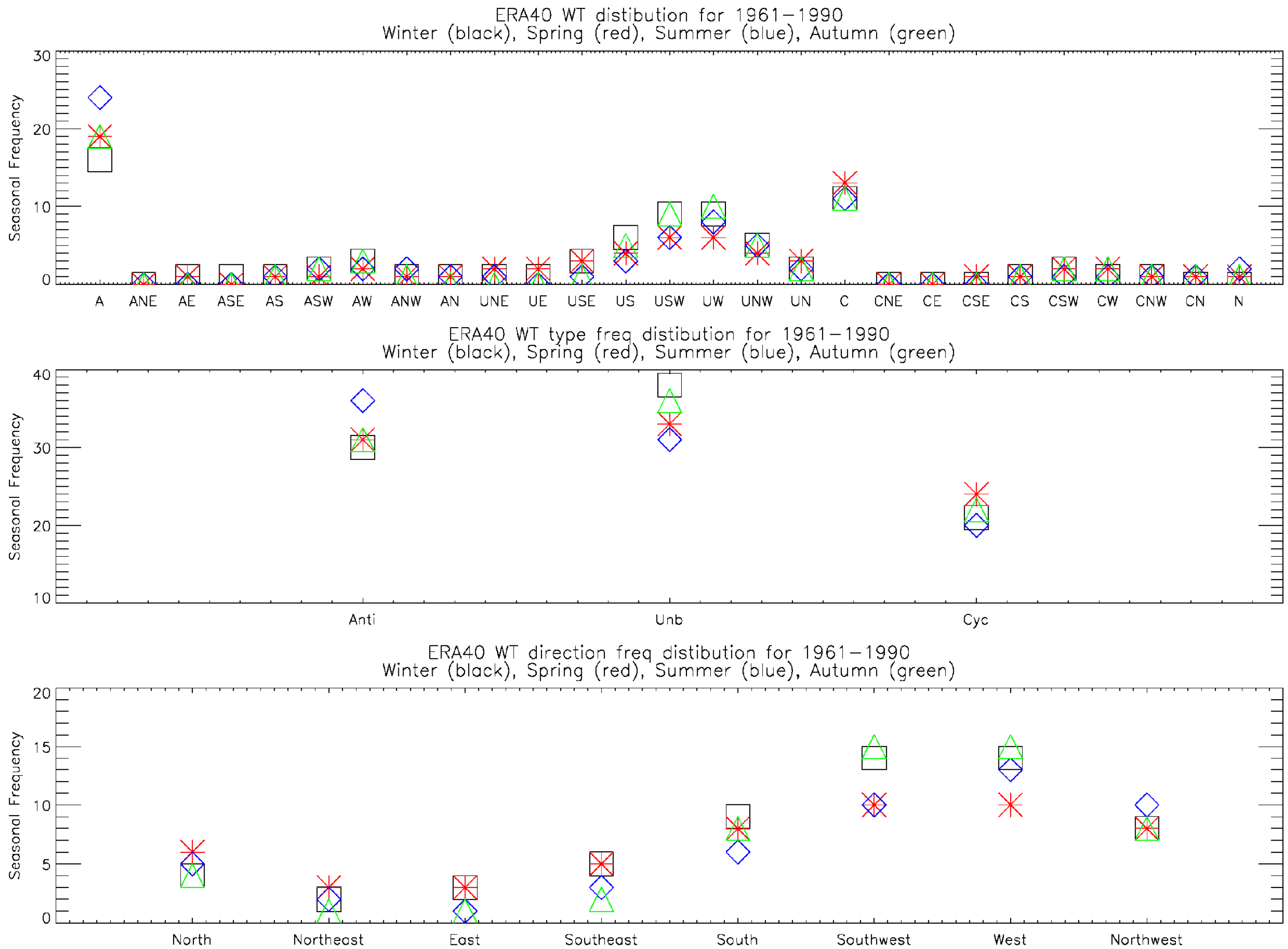

Figure 6: ERA40 seasonal weather type frequency distribution for all LWTs (top), LWT categories (middle) and LWT directions (bottom)

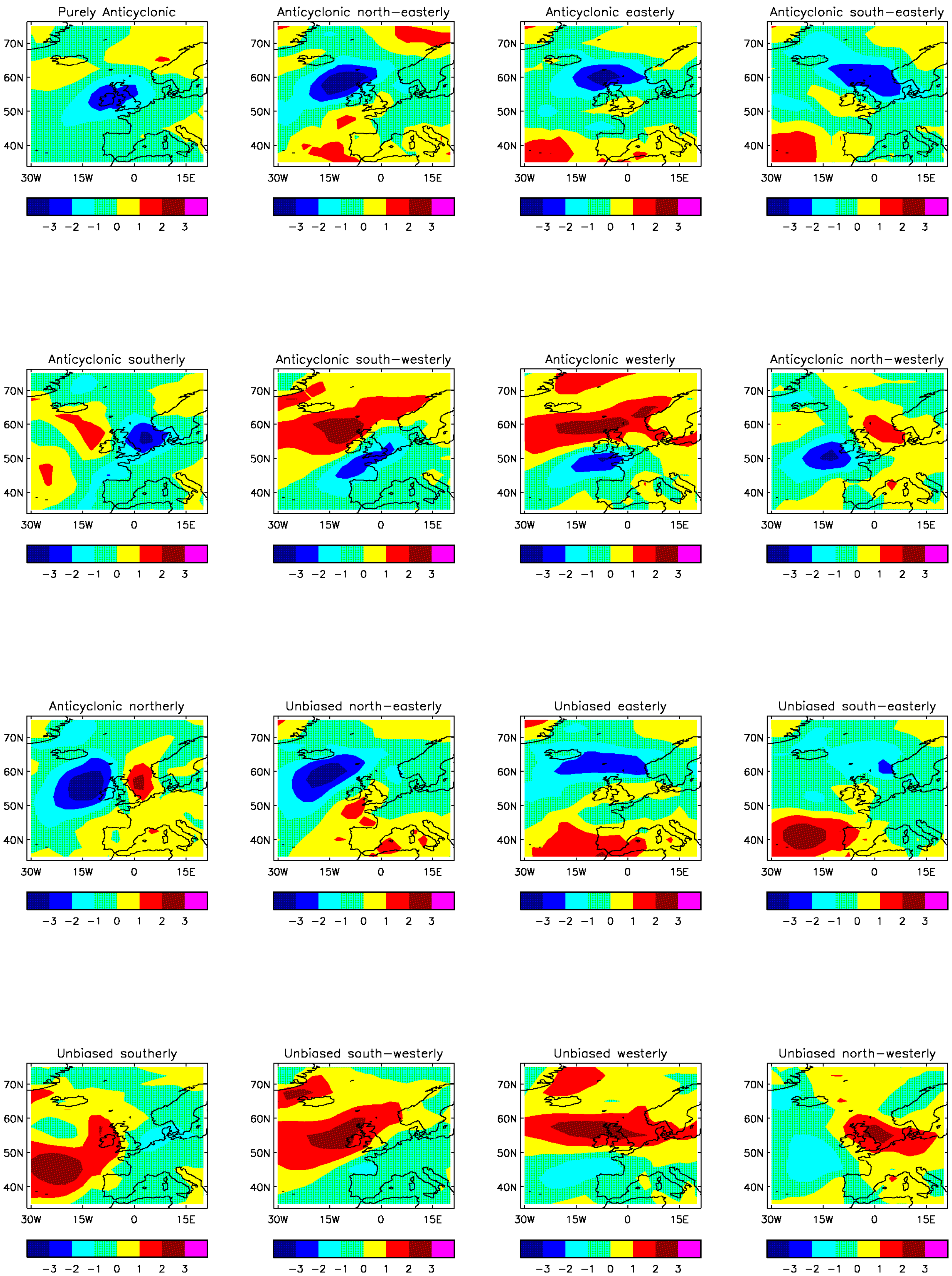

Figure 7a: The average wind speed for each LWT over the ERA40 period relative to the average wind over all weather types (m/s).

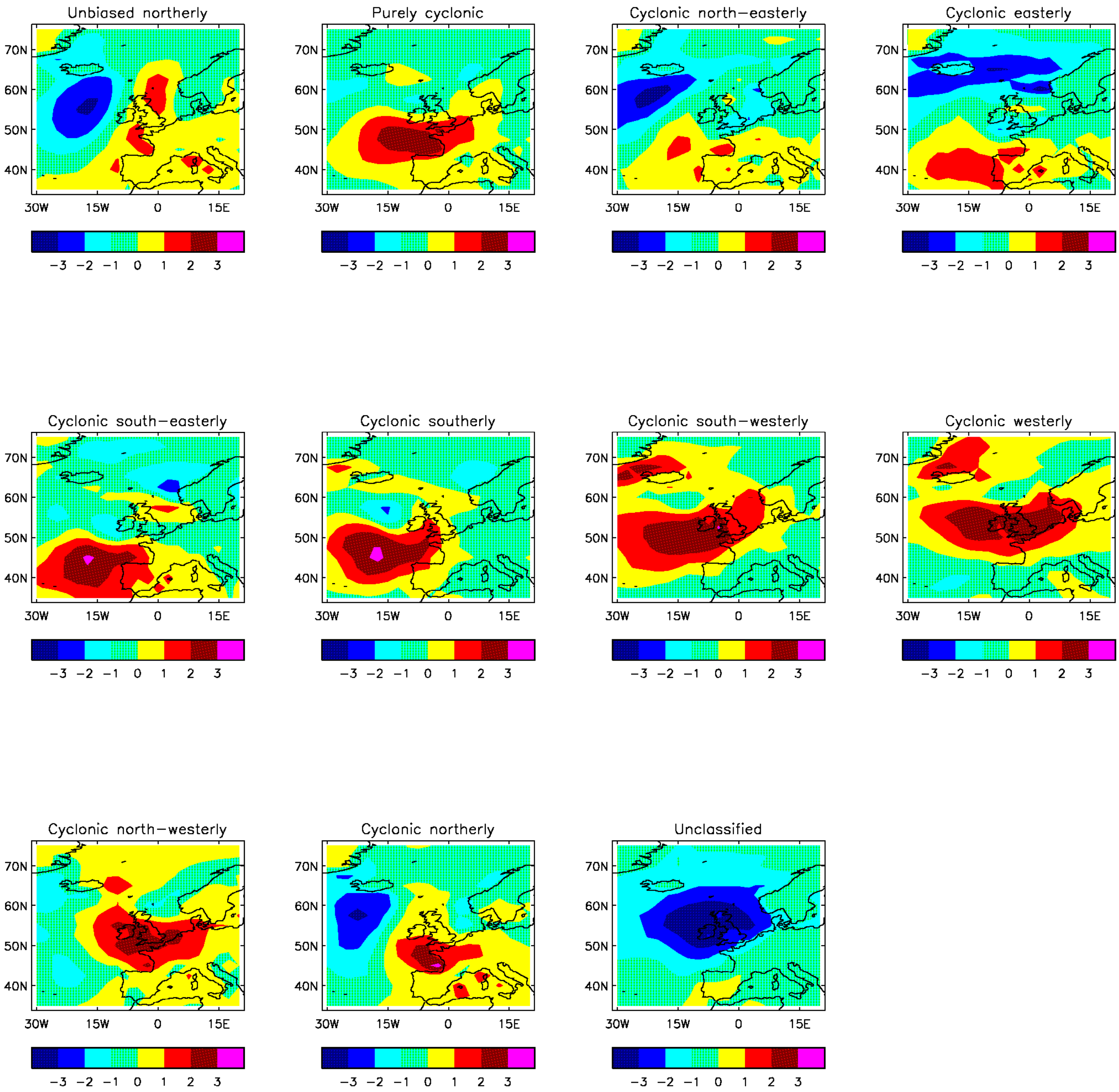

Figure 7b: The average wind speed for each LWT over the ERA40 period relative to the average wind over all weather types (m/s) - continued.

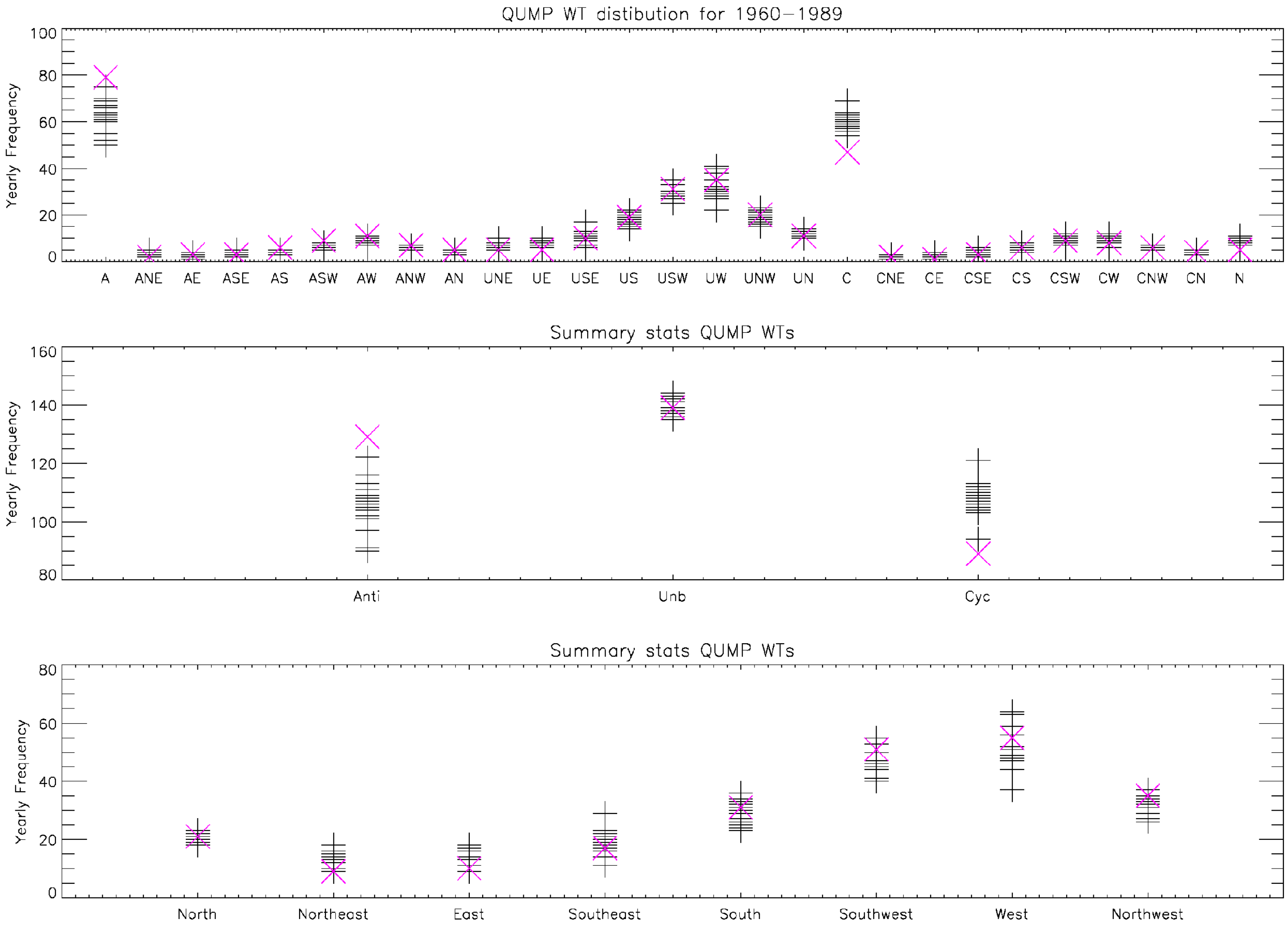

Figure 8: Yearly weather type frequency distribution for each QUMP member and ERA40 (pink crosses) for all LWTs (top), LWT categories (middle) and LWT directions (bottom)

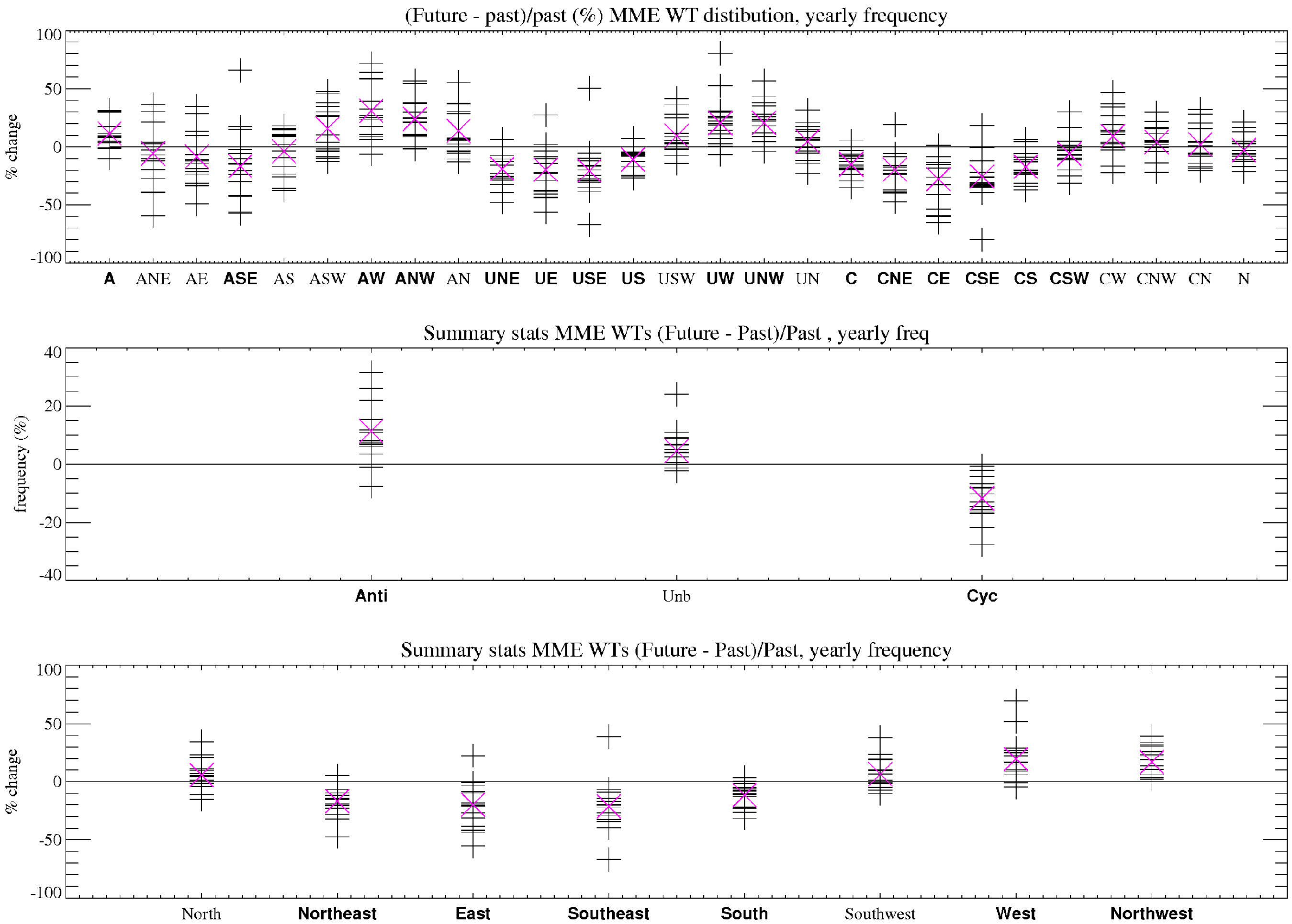

Figure 9: MME future LWT percentage frequency anomalies (Future-Past)/Past for all LWTs (top), LWT categories (middle) and LWT directions (bottom). Mean ensemble anomaly changes are shown in pink. Bold and starred x-axis labels indicates that 75% of models within ensemble agree on the sign of change.

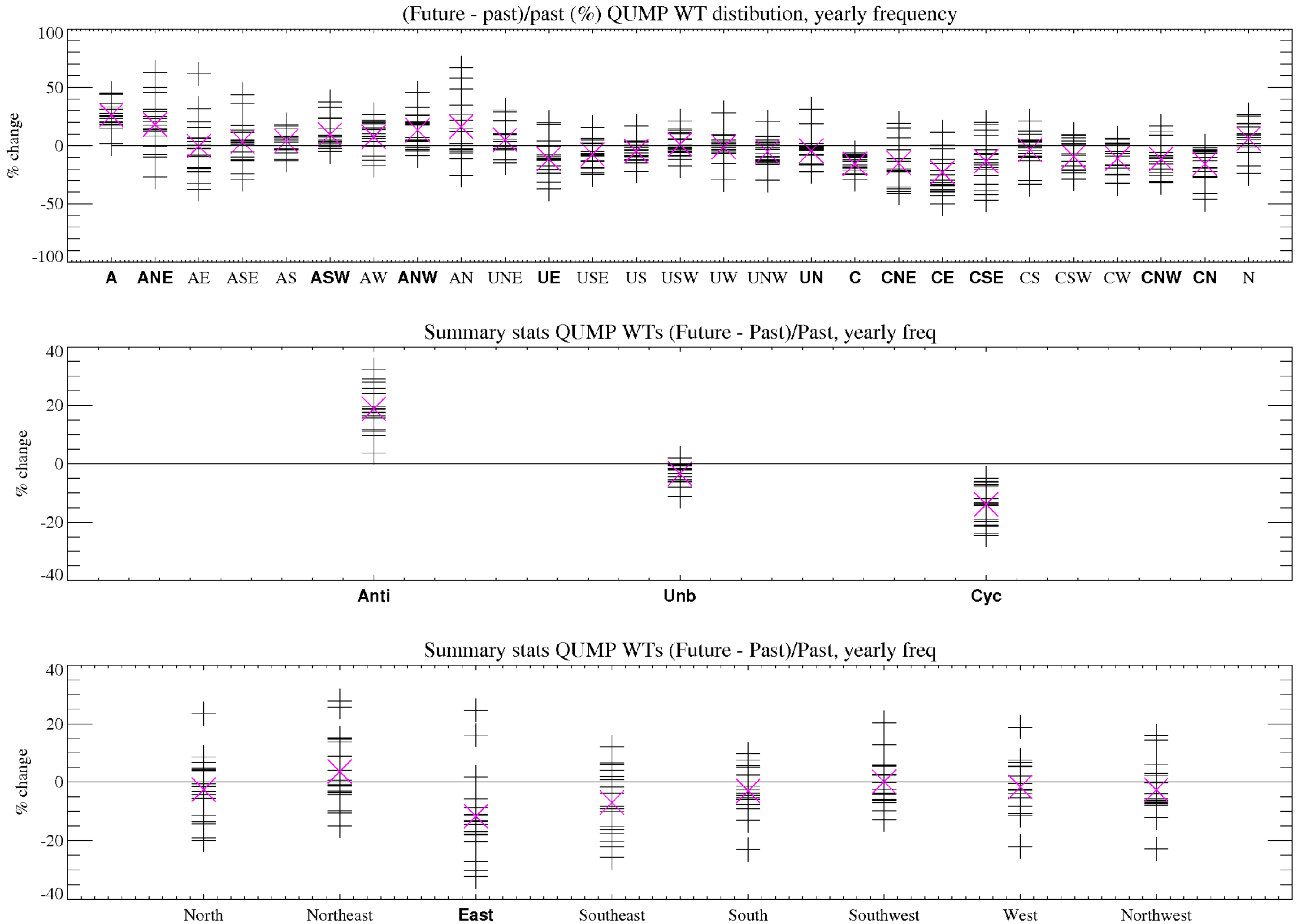

Figure 10: QUMP ensemble future LWT percentage frequency anomalies (Future-Past)/Past for all LWTs (top), LWT categories (middle) and LWT directions (bottom). Mean ensemble anomaly changes are shown in pink. Bold and starred x-axis labels indicates that 75% of models

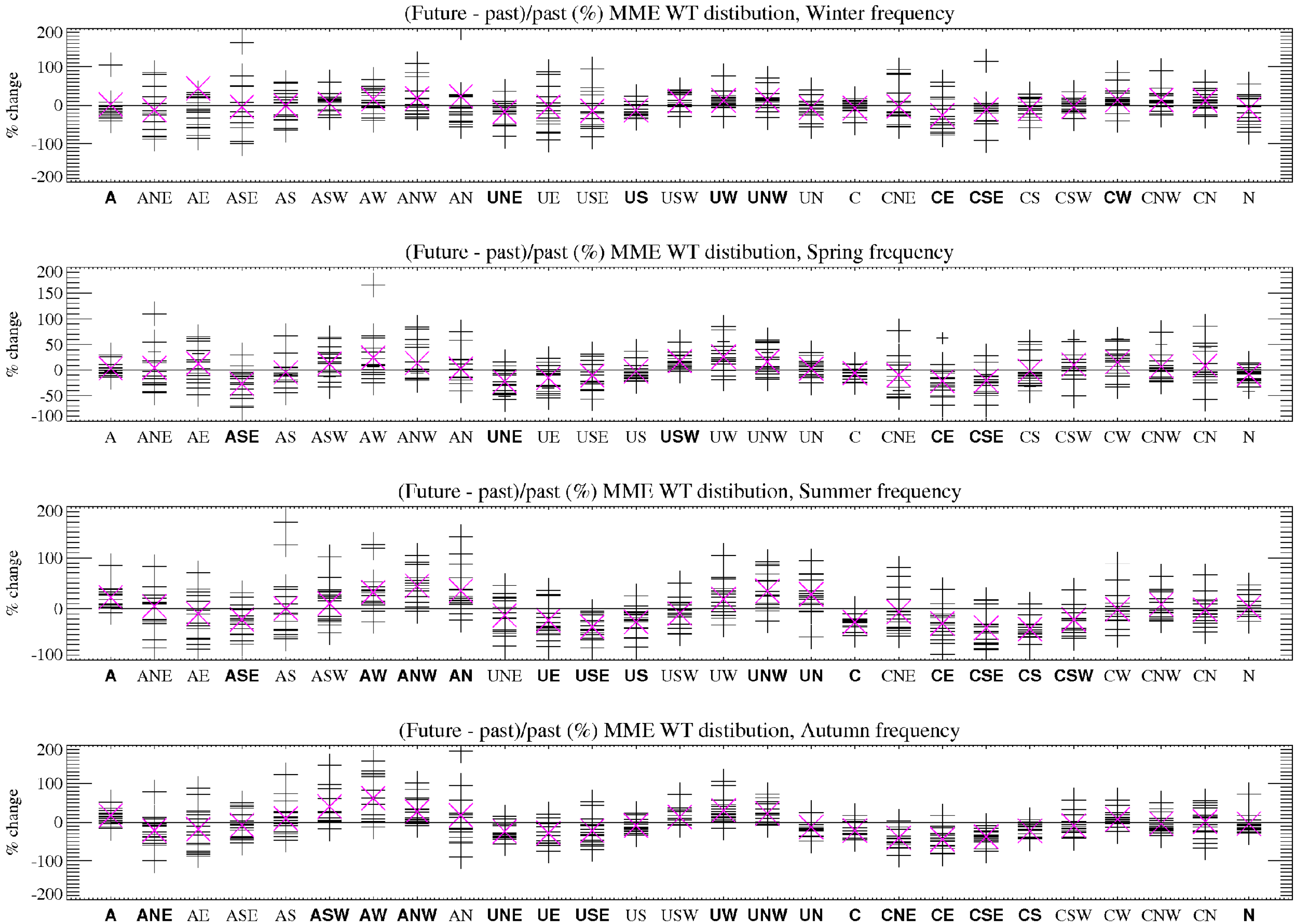

Figure 11: MME future LWT percentage frequency anomalies (Future-Past)/Past for all LWTs, for winter through to autumn (top to bottom). Ensemble mean anomaly shown as pink cross.

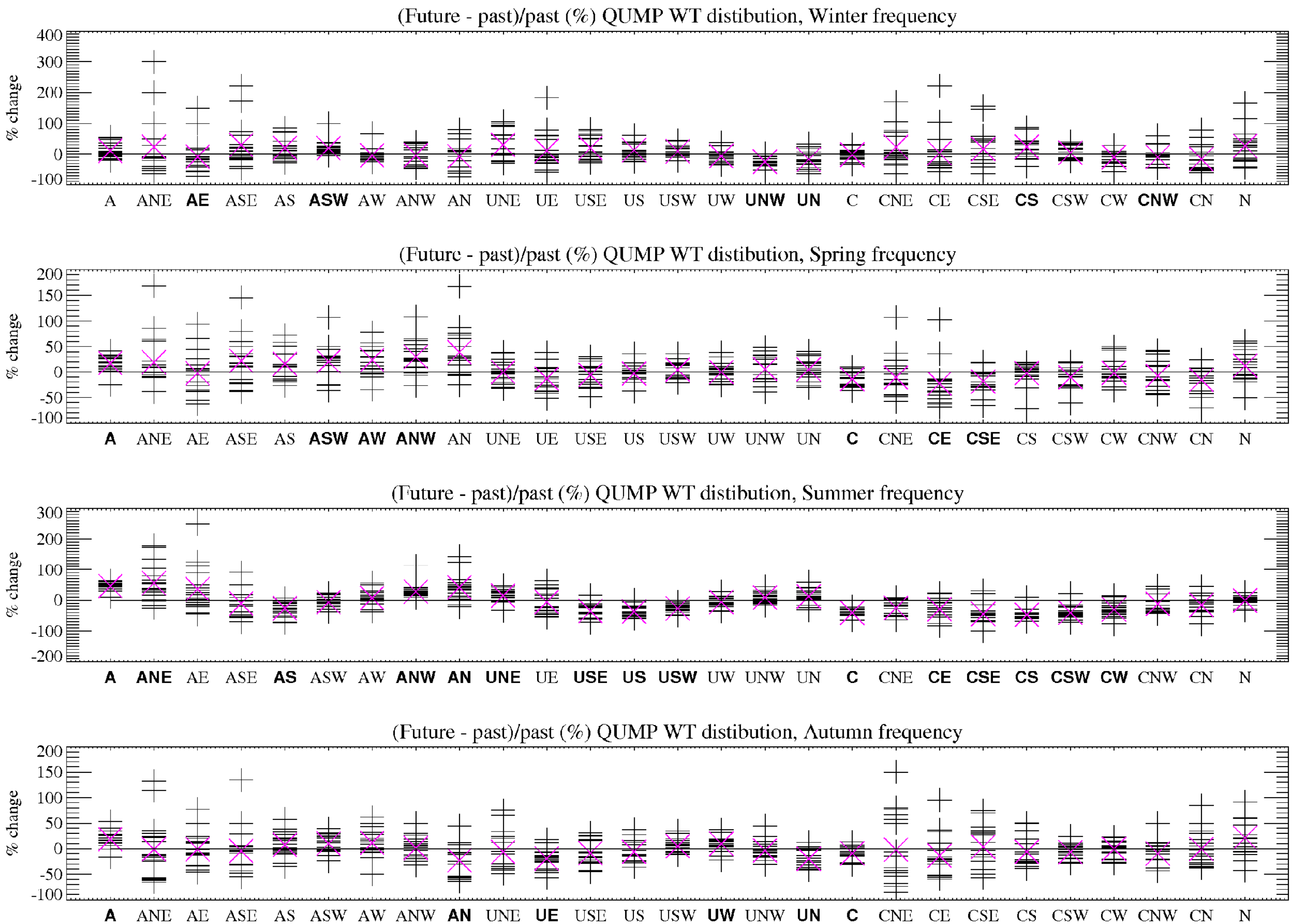

Figure 12: QUMP ensemble future LWT percentage frequency anomalies (Future-Past)/Past for all LWTs, for winter through to autumn (top to bottom). Ensemble mean anomaly shown as pink cross.

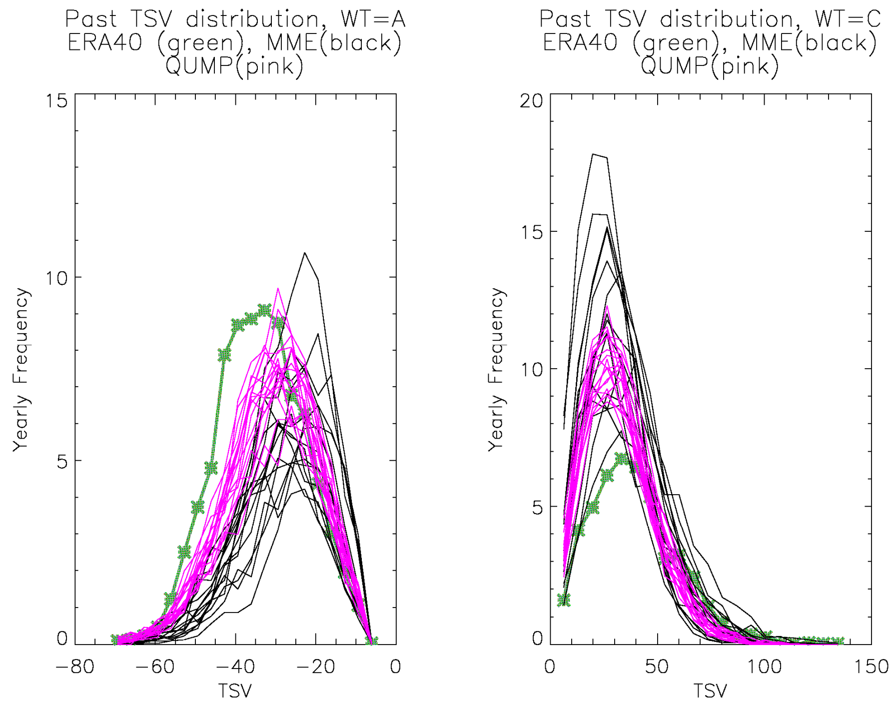

Figure 13: The past yearly frequency of purely anticyclonic (left) LWTs with different total shear vorticity values for individual MME (black) and QUMP (pink) ensemble members and ERA40 (green). The same for purely cyclonic LWT days on the right.

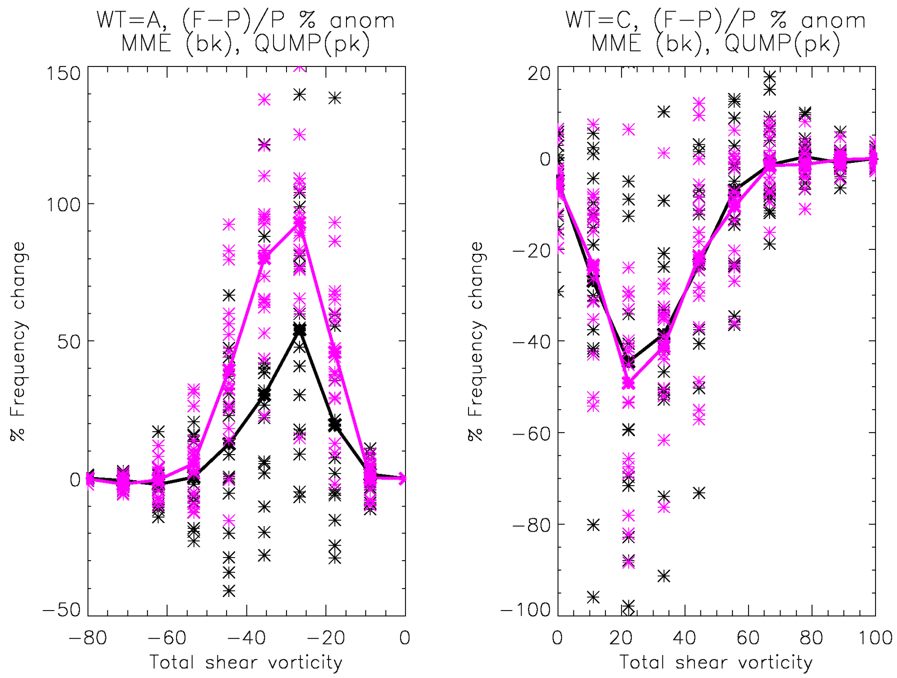

Figure 14: The future frequency anomaly percentage change of purely anticyclonic (left) LWTs with different total shear vorticity values for individual MME (black) and QUMP (pink) ensemble members (starred, ensemble mean = line). The same for purely cyclonic LWT days on the right.

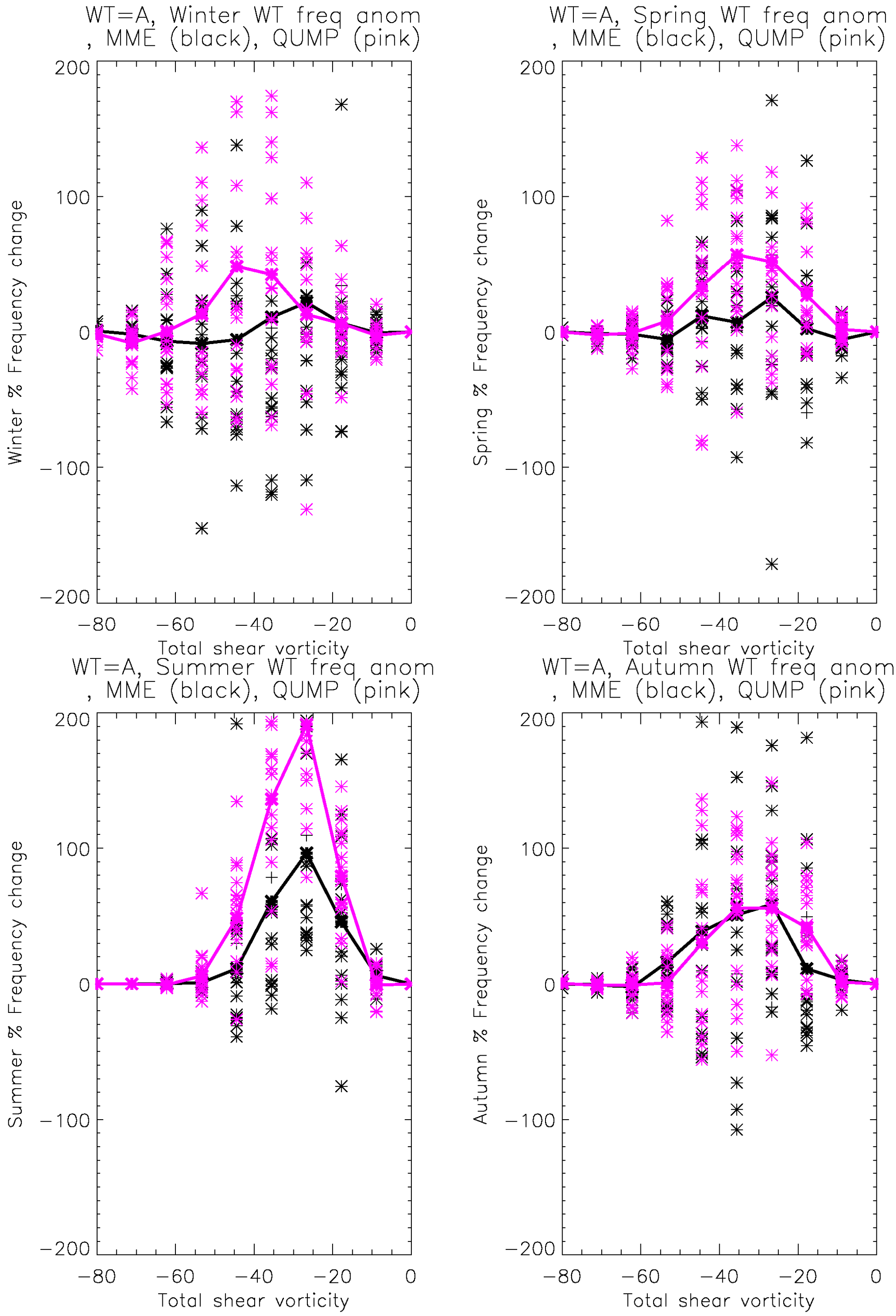

Figure 15: As for Figure 14 (left) but for individual seasons

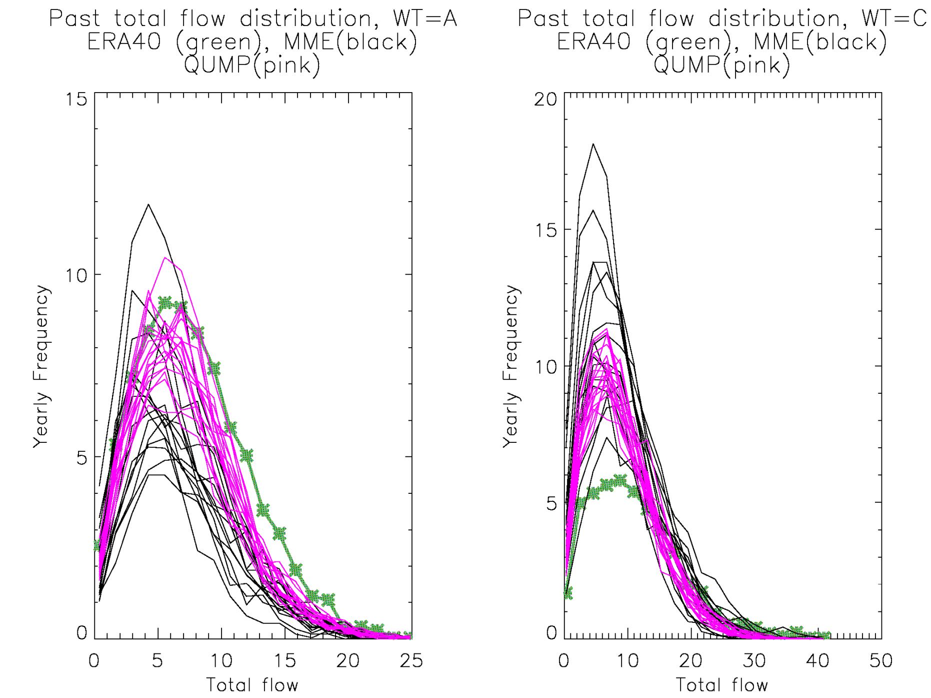

Figure 16: The past yearly frequency of purely anticyclonic (left) LWTs with different total flow values for individual MME (black) and QUMP (pink) ensemble members and ERA40 (green). The same for purely cyclonic LWT days on the right.

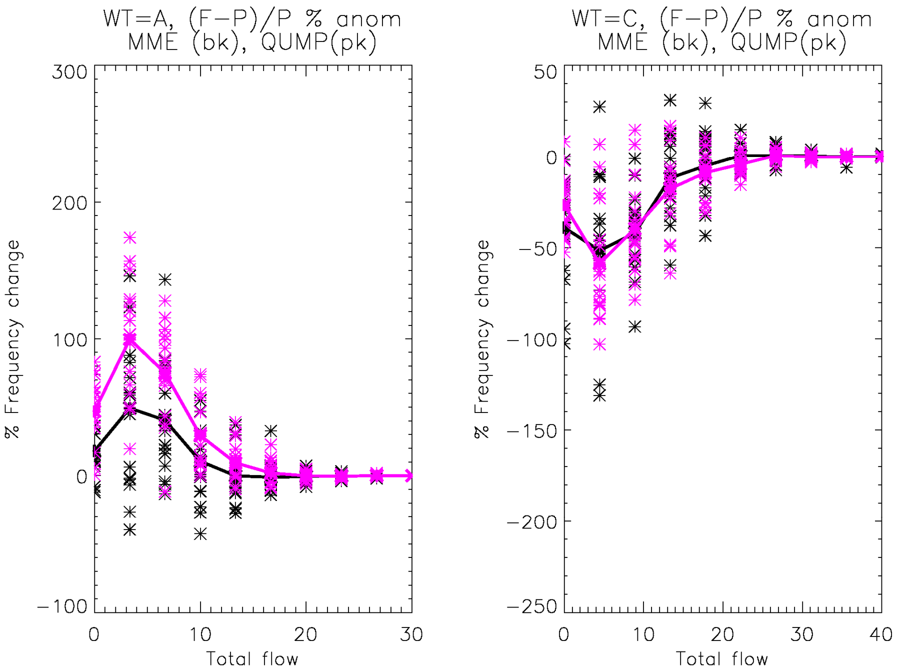

Figure 17: The future frequency anomaly percentage change of Purely Anticyclonic (left) LWTs with different total flow values for individual MME (black) and QUMP (pink) ensemble members (starred, ensemble mean = line). The same for Purely Cyclonic LWT days on the right.

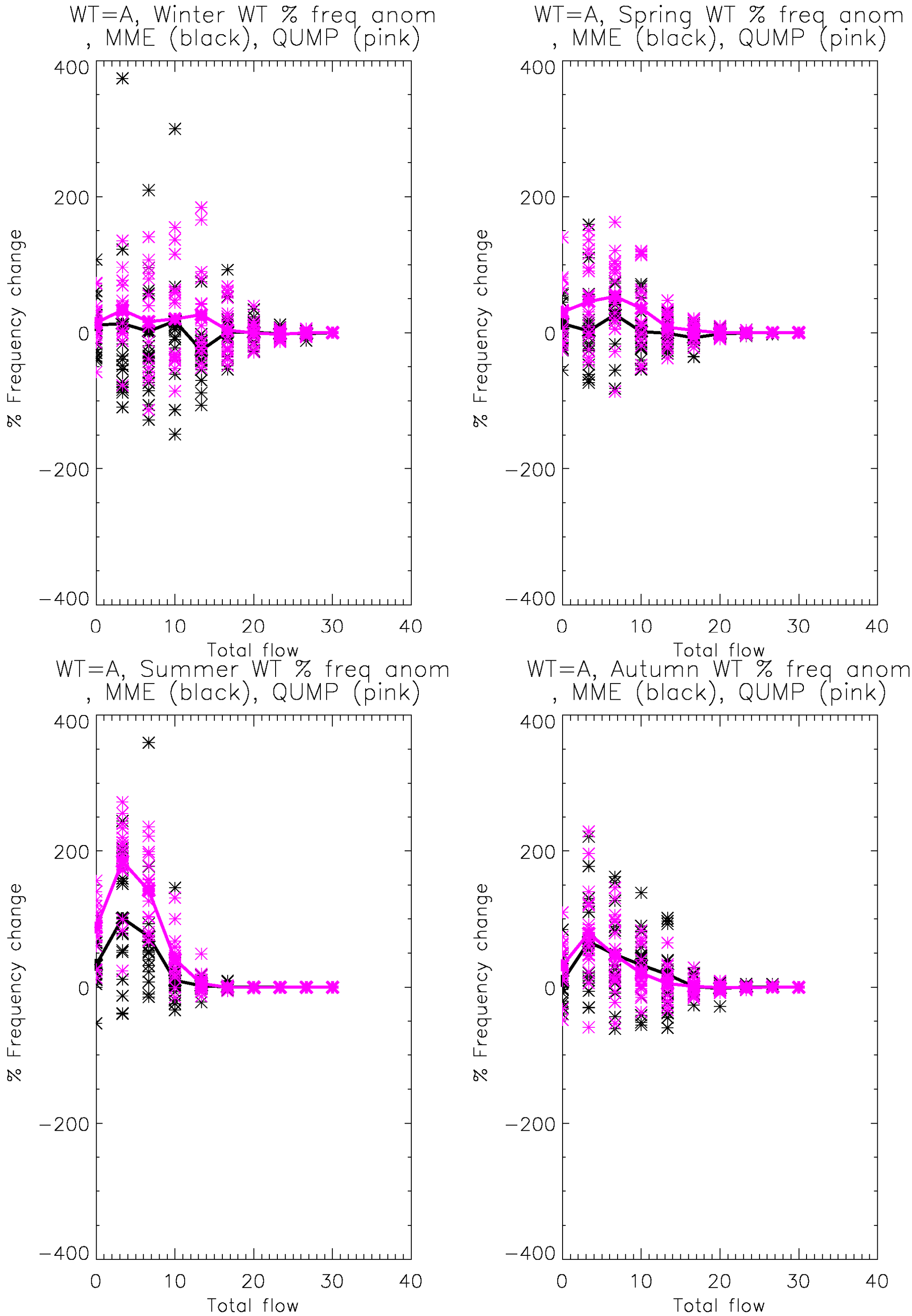

Figure 18: As for Figure 17 (left – Purely Anticyclonic) but for individual seasons

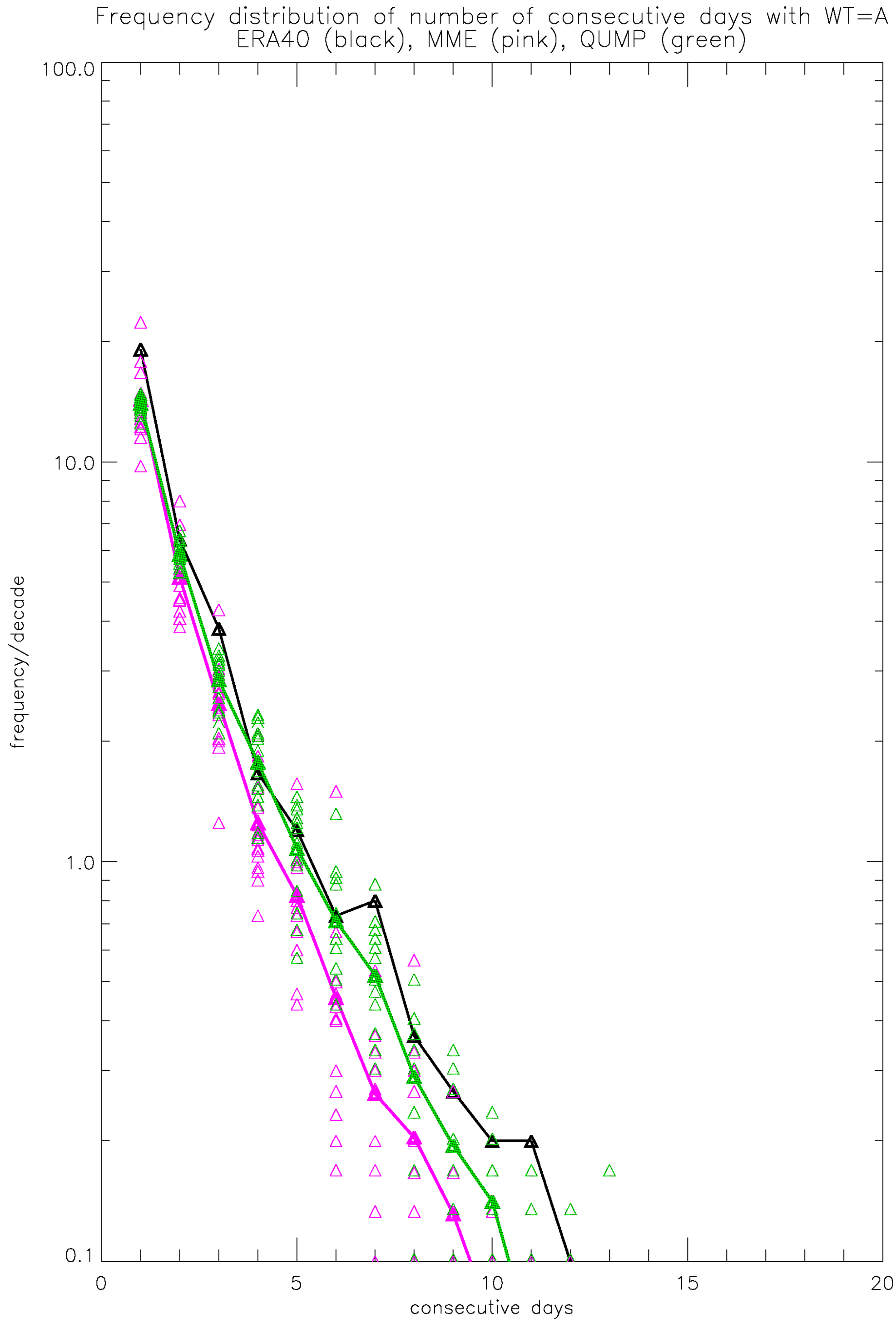

Figure 19: Frequency distribution of number of consecutive days with Purely Anticyclonic LWT, ERA40 (black), MME (pink) and QUMP ensemble (green). Individual models (triangle) and ensemble mean (line)

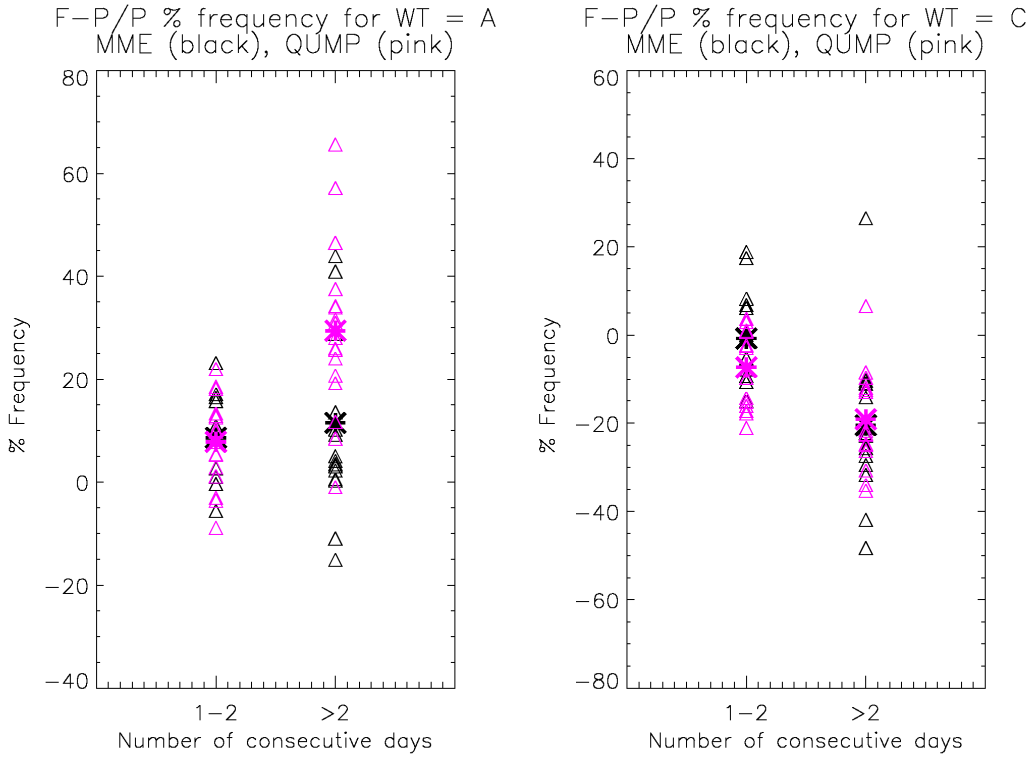

Figure 20: The future frequency anomaly percentage change of 1-2 or 3 or more consecutive days of PA (left) or PC (right) for each ensemble member (MME (black triangles), QUMP ensemble (pink triangles)) and for the ensemble mean (larger star).

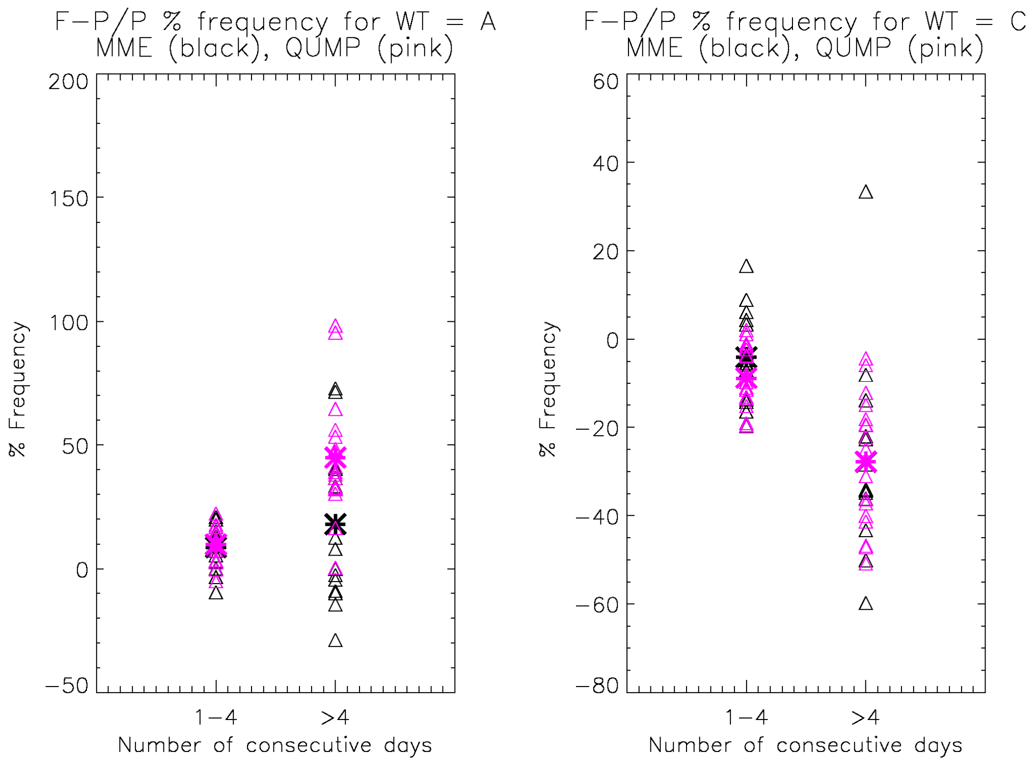

Figure 21: The future frequency anomaly percentage change of 1-4 or 5 or more consecutive days of PA (left) or PC (right) for each ensemble member (MME (black triangles), QUMP ensemble (pink triangles)) and for the ensemble mean (larger star).

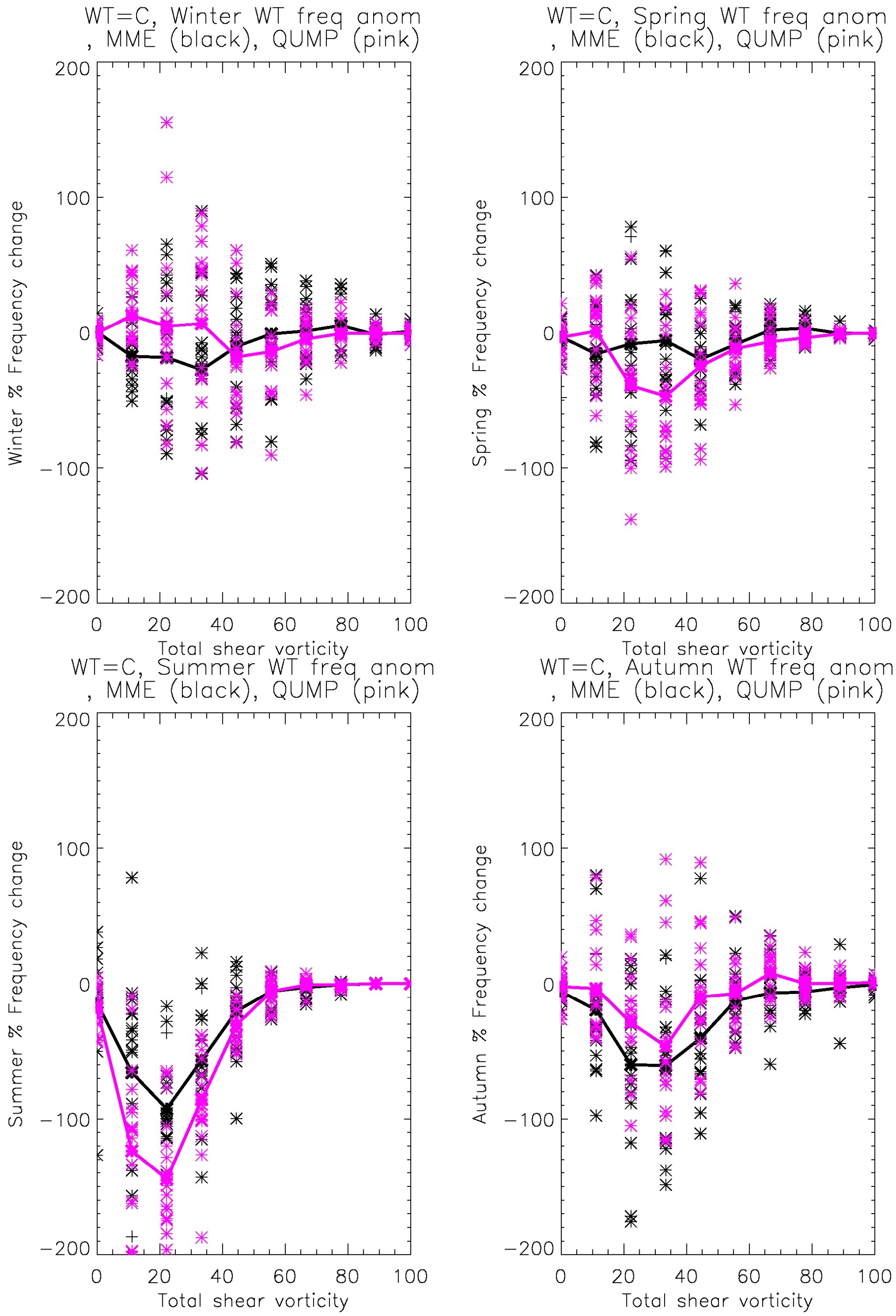

Figure 22: As for Figure 14 (right – Purely Cyclonic) but for individual seasons

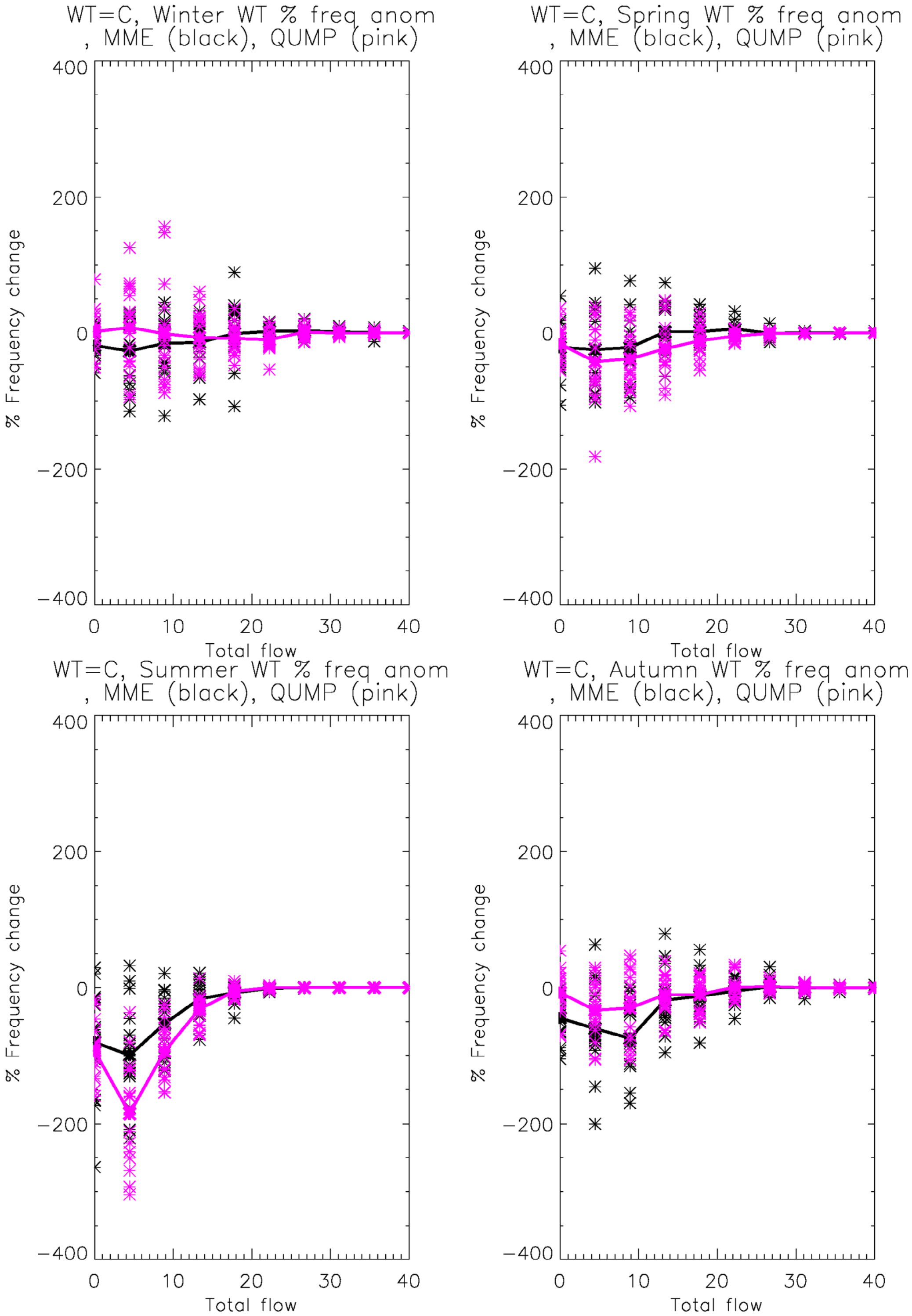

Figure 23: As for Figure 17 (right – Purely Cyclonic) but for individual seasons

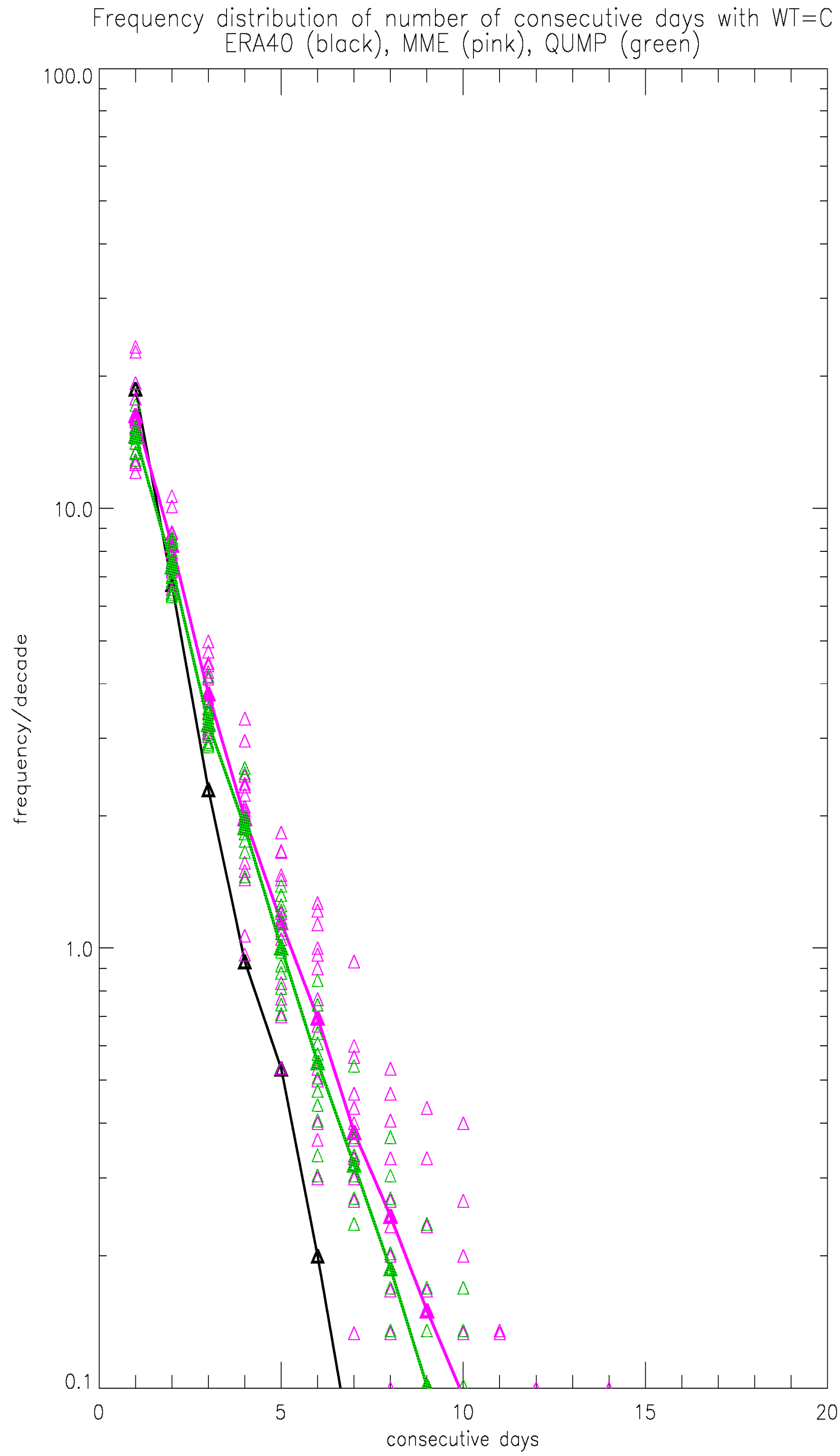

Figure 24: Frequency distribution of number of consecutive days with Purely Cyclonic LWT, ERA40 (black), MME (pink) and QUMP ensemble (green). Individual models (triangle) and ensemble mean (line)

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