Workshop on Atmospheric Blocking
6-8 April 2016, University of Reading

	Day 1 Weds 6th	Day 2 Thurs 7th	Day 3 Fri 8th
09:00			
09:30		Session 1	Session 1
10:00			
10:30	Arrival/Registration	Coffee	Coffee
11:00		Poster session (room 1L04)	
11:30	Session 1		Session 2
12:00			
12:30	Lunch	Lunch	Lunch
13:00			
13:30			
14:00	Session 2	Session 2	Session 3
14:30			
15:00	Coffee	Coffee	Coffee
15:30			
16:00	Session 3	Session 3	Discussion
16:30			
17:00			Close
17:30	Discussion	Discussion	
18:00			

Workshop Dinner

19:30

Day 1 (Weds 6 April):
Blocking diagnostics and its representation in reanalyses

A review of some ideas on blocking (30 MINS)
Brian Hoskins (University of Reading & Imperial College)

A review will be given of some of the theoretical ideas on blocking, its origin, maintenance and decay, and the role of transient eddies, from Rossby's hydraulic jump to the present day.

Blocking detection and analysis with GPS radio occultation observations
Lucas Brunner (Wegener Center, University of Graz)

Atmospheric blocking has received a lot of attention in recent years due to its impacts on midlatitude circulation and subsequently on weather extremes such as cold spells and heat waves. So far blocking studies have been based mainly on re-analysis data or model output. However, it has been shown that blocking frequency exhibits considerable inter-model spread in current climate models and that blocking trends can differ depending on the employed re-analysis. We use, for the first time, satellite-based observations from Global Positioning System (GPS) radio occultation (RO) and explore their ability to resolve blocking in order to potentially open up new avenues complementing models and re-analyses. RO is a satellite-based active limb sounding technique which exploits radio signals transmitted from GPS satellites and received on low Earth orbit satellites. RO delivers vertically high resolved profiles of atmospheric variables such as temperature and geopotential height (GPH) in the troposphere and lower stratosphere. This new observation-based data set is available globally at the same quality so that blocking in the Southern Hemisphere (SH) can be studied with the same reliability as in the Northern Hemisphere (NH).
We demonstrate the feasibility of blocking detection based on the RO data set from 2007 to 2013 for which about 1600 high quality RO profiles per day are available globally. Using an adequate sampling strategy, RO data are found dense enough to well resolve atmospheric variability on a daily basis. Daily fields on a 2.5x2.5 degree longitude-latitude grid are calculated by applying a weighted average to the RO profiles. For blocking detection we use a standard blocking detection algorithm based on 500 hPa GPH gradients. Investigating two well-known NH blocking events over Russia in summer 2010 and over Greenland in late winter 2013, we found that that RO data robustly capture blocking. Atmospheric patterns in GPH and temperature and their temporal evolution during blocking events are fully resolved. Moreover, the global blocking frequency and distribution derived from RO data is in excellent agreement with existing literature. The highest blocking frequencies are found in the Atlantic/European region and the north Pacific in the NH, as well as in the Australian/New Zealand region and the south Pacific in the SH. Our findings demonstrate that RO observations can valuably contribute to blocking research.

Persistent ridges related to near-stationary Rossby waves
John Methven (University of Reading)

In the last decade, Western Europe has seen a number of extreme seasons. For example, anomalously high precipitation totals for the summers of 2007 and 2012 as well as the exceptionally high temperature of summer 2003 and the coldness of winter 2009/10. One common feature in all these examples is the existence of persistent, near stationary Rossby wave patterns on the tropopause. There is not necessarily a block with the classic dipole or omega structure. Here a rigorous framework is used to extract these "slow modes of variability" from data in such a way that each mode has an intrinsic phase speed related only to its spatial structure, in a similar way that a bell rings with a characteristic note. The phase speed is derived from global conservation properties.
Modes of variability in the perturbations are extracted from ERA-Interim data using the empirical normal mode (ENM) technique. This combines amounts to EOF analysis using pseudomomentum (wave activity) as the norm. For a linear system the ENMs would equal the dynamical normal modes since they are also

orthogonal under this norm. Although the system is nonlinear, only a few ENMs dominate the variability and the ratio of pseudoenergy to pseudomomentum yields a unique phase speed for each. Periods of westward, stationary (blocked) or eastward propagation ("zonal regime") of Rossby waves are shown to be related to the speed obtained.

Characterizing blocking episodes with local finite-amplitude wave activity: lifecycle and climatology
Clare Huang (University of Chicago)

We propose the use of Finite-amplitude Local Wave Activity (LWA) as a 2D blocking index as well as a diagnostic for blocking life cycle. LWA itself is a measure of ‘waviness’ of quasi-geostrophic potential vorticity (QGPV) field and it is capable of identifying the locations of blocking episodes on a 2D map. Dynamically, LWA satisfies an approximate local non-acceleration theorem (Huang & Nakamura, JAS, in Press). The growth of LWA therefore implies an instantaneous local deceleration of zonal wind. This is what we observe in a blocking episode.
In this presentation, I will first present the seasonal climatology of LWA (from reanalysis data) and the corresponding blocking statistics. I will then illustrate how LWA characterizes the life cycle of blocking episodes in two aspects: (1) budget of LWA and zonal wind and (2) vertical structure of LWA. Lastly, I will examine whether blocking frequency and spatial extent in different seasons will change in a warming climate. Comparison will be done between North Pacific, North Atlantic and Southern Ocean.

Finite-amplitude local wave activity as a diagnostic of blocking events and persistent extreme weather
Patrick Martineau (Cornell University)

Diagnostics of Local Wave Activity (LWA) are applied on the 500-hPa height field to detect events of large wave activity in the Norther-Hemisphere. It is found that when persistence criteria similar to those used in recent studies of blocking events are applied, the climatology of LWA events in reanalysis data sets recovers qualitatively the main centres of action associated with classical blocking events. By considering the cyclonic and anticyclonic components of LWA separately, persistent weather systems associated to large-amplitude troughs and ridges are contrasted. While anticyclonic LWA events are predominantly found over United Kingdom and Alaska, cyclonic LWA events are usually occurring over the sea of Okhotsk and Baffin Island. The detailed evolution of LWA events and their impact on tropospheric weather are presented and contrasted to the impact of blocking events described in the literature. The differences between short-lived and long-lived LWA events are also addressed.

Importance of latent heat release in ascending air streams for atmospheric blocking
Stephan Pfahl (ETH Zurich)

Atmospheric blocking is a key component of extratropical weather variability and can contribute to various types of extreme weather events. Changes in blocking frequencies due to Arctic amplification and sea ice loss may enhance extreme events, but the mechanisms potentially involved in such changes are under discussion. Current theories for blocking are essentially based on dry dynamics and do not directly take moist processes into account. Here we analyse a 21 year climatology of blocking from reanalysis data with a Lagrangian approach, to quantify the release of latent heat in clouds along the trajectories that enter the blocking systems. We show that 30 to 45% of the air masses involved in Northern Hemisphere blocking are heated by more than 2 K – with a median heating of more than 7 K – in the three days before their arrival in the blocking system. This number increases to 60 to 70% when considering a seven-day period. Our analysis reveals that, in addition to quasi-horizontal advection of air with low potential vorticity, ascent from lower levels associated with latent heating in clouds is of first-order importance for the formation and maintenance of blocking. We suggest that this process should be accounted for when investigating future changes in atmospheric blocking.

The role of individual synoptic-scale weather systems and cloud diabatic processes in the life cycle of European weather regimes
Christian Grams (ETH Zurich)

The variability of the atmospheric circulation in the Atlantic-European sector on sub-seasonal time scales is strongly modulated by quasi-stationary and recurrent large-scale flow patterns, so-called weather regimes (Vautard, 1990). Three out of the four European weather regimes, classically described in literature, involve blocking anticyclones. From a forecast perspective the onset, persistence, and transition of weather regimes present a severe challenge in current numerical weather prediction models (Ferranti et al., 2015). Recently, Pfahl et al. (2015) revealed that, due a net transport of air with low potential vorticity (PV) to the tropopause, latent heat release in ascending air streams is a first order process in blocking onset and maintenance.
In this study this idea is expanded to European weather regimes. It is investigated whether and how diabatic outflow from latent heat release in individual synoptic-scale weather systems impact European weather regime life cycles. The study is based on ERA-Interim reanalysis data for the 36-year period1979-2014. Weather regimes are identified using standard EOF analysis and k-means clustering. The role of latent heat release in the weather regime life cycles is assessed based on the warm conveyor belt (WCB) climatology of Madonna et al. (2014).
First results indicate that the period prior to regime onset is characterized by important changes in location and frequency of WCB occurrence. These changes persist during the early stage of a regime life cycle and weaken thereafter. Most importantly, 5 to 0 days prior to the onset of the "Atlantic Ridge" and "European Blocking" regimes, a statistically significant increase in WCB frequency occurs upstream of the evolving blocking anticyclone. This suggests that WCB outflow helps to establish the upper-level negative PV anomaly associated with a blocking anticyclone. This early result also corroborates that scale interactions between smaller-scale diabatic outflow from latent heat release in synoptic-scale weather systems play an important role in the life cycle of the larger-scale European weather regimes. In a next step the role of WCB outflow will be explored in more detail and the study will be expanded on the role of other synoptic-scale weather systems in European weather regime life cycles.

A unified nonlinear multi-scale interaction model for atmospheric blocking and NAO events
Dehai Luo (Institute of Atmospheric Physics, Chinese Academy of Sciences)

Under the scale separation assumption, a unified nonlinear multi-scale interaction (NMI) model is developed to describe the interaction between the planetary-scale wave and synoptic-scale eddies associated with the blocking and North Atlantic Oscillation (NAO) life cycles. It is found that the spatial structure of the eddy-induced planetary-scale streamfunction tendency (EPST) field prior to the NAO onset determines whether a positive or negative (blocking) NAO event occurs. When the EPST has a positive-over-negative dipole structure, a negative NAO (NAO-) or blocking event is produced and undergoes a life cycle of 10-20 day timescales. In contrast, a positive NAO (NAO+) event is produced if the EPST has an opposite spatial structure.
Moreover, it is shown that the onset of NAO- or blocking events is followed by the eddy straining, cyclonic wave breaking (CWB) and eddy merging, but the phenomena cannot be seen for the NAO+ event. Once the feedback of the amplified NAO- pattern on synoptic-scale eddies is excluded, the CWB, eddy straining and eddy merging also disappear. Further, the feedback of the intensified NAO anomaly on synoptic eddies is found to affect significantly the asymmetry of the NAO between NAO- and NAO+ phases in amplitude and persistence through the presence or absence of the CWB.
For the NAO+, the stretching deformation role of the NAO+ field seems dominant in the eddy variation. Because the eddy energy generation rate (EGR) weakens and tends to be negative in the downstream side of the NAO+ region, the synoptic eddies lose their energy to the NAO+ type zonal flow, thus leading to the weakening of synoptic-scale eddies. However, for the NAO-, the EGR variation shows that synoptic eddies grow over the upstream two sides of the NAO- region by extracting energy from the NAO- shearing deformation field, while lose energy to the mean flow over the middle upstream region through the stretching deformation. This process results in the eddy straining (splitting and strengthening) associated with the CWB.

Dynamical analysis of blocking events: Spatial and temporal fluctuations of covariant Lyapunov vectors
Sebastian Schubert (University of Hamburg)

One of the most relevant weather regimes in the mid latitudes atmosphere is the persistent deviation from the approximately zonally symmetric jet stream to the emergence of so-called blocking patterns. Such configurations are usually connected to exceptional local stability properties of the flow which come along with improved local forecast skills during the phenomenon. It is instead extremely hard to predict onset and decay of blockings.
Covariant Lyapunov Vectors (CLVs) offer a suitable characterization of the linear stability of a chaotic flow, since they represent the full tangent linear dynamics by a covariant basis which explores linear perturbations at all time scales. Therefore, we will test whether CLVs feature a signature of the blockings.
As a first step, we examine the CLVs for a quasi-geostrophic beta-plane two-layer model in a periodic channel baroclinically driven by a meridional temperature gradient ΔT. An orographic forcing enhances the emergence of localized blocked regimes. We detect the blocking events of the channel flow with a Tibaldi-Molteni scheme adapted to the periodic channel.
When blocking occurs, the global growth rates of the fastest growing CLVs are significantly higher. Hence against intuition, globally the circulation is more unstable in blocked phases.
Such an increase in the finite time Lyapunov exponents with respect to the long term average is attributed to stronger barotropic and baroclinic conversion in the case of high temperature gradients, while for low values of ΔT, the effect is only due to stronger barotropic instability. In order to determine the localization of the CLVs we compare the meridionally averaged variance of the CLVs during blocked and unblocked phases. We find that on average the variance of the CLVs is clustered around the center of blocking. These results show that the blocked flow affects all time scales and processes described by the CLVs.

The connection between Northern Hemisphere heat waves and large-amplitude quasi-stationary Rossby wave packets
Georgios Fragkoulidis (Johannes Gutenberg University, Mainz)

The onset, strength, and persistence of blocking can be particularly relevant during summer in the Northern Hemisphere, where several devastating heat waves have occurred in recent years (Europe 2003, Russia 2010, USA 2011). We hypothesize that an important role for such extreme events is played by large-amplitude upper tropospheric Rossby wave packets, which under certain conditions turn quasi-stationary and become quasi-resonant with stationary forcing on the synoptic scale. This hypothesis is distinct from an earlier hypothesis which implied quasi-resonance of circumglobal Rossby waves. We investigate our hypothesis through wavelet analysis (rather than Fourier analysis) applied to a number of cases of strong heat waves in the Northern Hemisphere. The analysis indicates that in some of these cases the heat wave is not associated with a circumglobal Rossby wave, but there is always a large amplitude wave packet overlying the region of the heat wave.

On the dynamics of persistent states and their secular trends in the waveguides of the Southern Hemisphere troposphere
Terence O'Kane (CSIRO)

We identify the dynamical drivers of systematic changes in persistent quasi-stationary states (regimes) of the Southern Hemisphere troposphere and their secular trends. We apply a purely data-driven approach, whereby a multiscale approximation to nonstationary dynamical processes is achieved through optimal sequences of locally stationary fast vector autoregressive factor processes, to examine a high resolution atmospheric reanalysis over the period encompassing 1958–2013. This approach identifies regimes and their secular trends in terms of the predictability of the flow and is Granger causal. A comprehensive set of diagnostics on both isentropic and isobaric surfaces is employed to examine teleconnections over the full hemisphere and for a set of regional domains. Composite states for the hemisphere obtained from nonstationary nonparametric cluster analysis reveal patterns consistent with a circumglobal wave 3 (polar)–wave 5 (subtropical) pattern, while regional composites reveal the Pacific South American pattern and blocking modes.
Comparison is made with blocking indices commonly used in weather forecasting and climate analysis to identify dynamically relevant meta- stable regimes in the 500-hPa circulation. The blocking pattern

dominates in the early 1980s, and then gradually de- creases. There is a corresponding increase in the SAM frequency of occurrence. Further comparison with the split- flow blocking indices reveals a superficial correspondence between the cluster hidden state frequency of occurrences and split-flow indices. Examination of composite states shows that the blocking indices capture splitting of the zonal flow whereas the cluster composites reflect coherent block formation. Differences in blocking climatologies from the respective methods are discussed.
The respective roles of potential vorticity sources, stationary Rossby waves and baroclinic instability on the dynamics of these circulation modes are shown to be reflected by the seasonal variations of the waveguides, where Rossby wave sources and baroclinic disturbances are largely contained within the wave- guides and with little direct evidence of sustained remote tropical influences on persistent synoptic features. Warm surface temperature anomalies are strongly connected with regions of upper level divergence and anticyclonic Rossby wave sources. The persistent states identified reveal significant variability on interannual to decadal time scales with large secular trends identified in all sectors apart from a region close to South America.

Long-term changes in blocking and persistent circulation states and their relation to extreme weather events
Christian Franzke (University of Hamburg)

Society is increasingly impacted by persistent weather and climate related extreme events which can cause significant economic damages and increase mortality. Blocking is one example of such persistent weather event which can cause extreme heat waves and cold spells. Here we will use modern statistical space-time clustering methods to systematically identify persistent circulation states and blocking. These statistical clustering methods are able to objectively identify blockings and deal with non-stationary data sets (e.g. trends in blocking). We will show that these persistent states exhibit strong decadal variability. We will also discuss the dynamics of the persistent states. We will show evidence that the persistence is due to an eddy-mean flow feedback and the type of Rossby wave breaking. The persistent states also exert a strong influence on the propensity of extreme surface wind speeds in the North Atlantic region. We will also discuss the potential role of persistent circulation states in leading to the clustering of extreme wind speed events.

Initiation of an extremely long-lived North Pacific, cold-season dipole-type block
Melissa Breeden (University of Wisconsin-Madison)

Within the last few decades renewed attention has been directed toward understanding of blocking initiation, maintenance and dissolution. Intimately related to the dynamics of blocking structures is the tropopause-level jet stream, which has been shown to impact the formation and maintenance of blocks by modifying the background shear of the environment in which these disturbances evolve. Previous work by Jaffe et al. (2011) objectively identified periods during which the wintertime north Pacific jet stream rapidly retracts to the west on time scales of a week, finding 19 such cases of jet retraction from 1980-2007. Their composite analysis five days after retraction onset reveals the presence of sprawling negative (positive) potential vorticity anomalies in the central midlatitude (subtropical) Pacific which combine to form a dipole-type blocking feature.
In February 2006, a 66-day-long retraction (the longest identified by Jaffe et al. 2011) that coincided with a period of extraordinary rainfall over Hawaii was initiated by high-amplitude anticyclonic wave breaking in the eastern north Pacific. This talk will present results from a diagnosis of this case that provide insight into the processes that led to and set up the persistent blocking feature. Consistent with previous studies regarding the role of deformation in breaking (Nakamura and Wallace, 1993), we employ piecewise tendency diagnosis (Nielsen-Gammon and Lefevre 1996) to show that barotropic deformation is a leading contributor to the formation of the ridge whose ultimate anticyclonic breaking coincides with initiation of the retracted jet. The role of diabatic heating in the formation of this antecedent ridge is also quantified after Evans and Black (2003). In the aftermath of this breaking event, the evolution of the disorganized North Pacific flow into a well-organized block is diagnosed with particular attention paid to the role played by the weakened, retracted jet stream.
The maintenance of the blocking circulation is considered in the context of the newly proposed ‘selective absorption mechanism’ by Yamazaki and Itoh (2013). Similar analyses of other objectively identified

Pacific jet retractions point to a variety of physical processes affecting the duration of blocked flows. The leading such candidates are discussed.

The influence of the Madden-Julian Oscillation on Northern Hemisphere winter blocking
Stephanie Henderson (Colorado State University)

The quasi-stationary and persistent nature of atmospheric blocking is associated with long-lasting extreme weather conditions that disrupt much of the Northern Hemisphere. Previous studies have demonstrated that the primary mode of tropical intraseasonal variability, the Madden-Julian Oscillation (MJO), has an impact on important factors for blocking, including Rossby wave breaking and the North Atlantic Oscillation (NAO). However, the extent to which the MJO influences winter blocking across the Northern Hemisphere is not yet fully understood.
Employing a two-dimensional blocking index, composites of North Pacific, North Atlantic, and European blocking are generated relative to the approximate location of MJO convection, or MJO phase. In the west and central Pacific, all MJO phases demonstrate significant changes in blocking, particularly at high latitudes. In the east Pacific and Atlantic, a significant decrease in blocking follows phase 3 of the MJO, characterized by enhanced convection over the tropical East Indian Ocean and suppressed convection in the west Pacific. The opposite signed MJO convective anomalies occur during phase 7, which is followed by a significant increase in east Pacific and Atlantic blocking. A significant decrease in European blocking follows MJO phase 4, with a significant increase after phase 6. The phase 6 European blocking increase is hypothesized to result from two pre-existing conditions: 1) an anomalous anticyclone over the North Atlantic, and 2) a preceding negative Pacific North American (PNA) pattern initialized and influenced by MJO convection.

North Pacific blocking and high-latitude atmospheric rivers
Elizabeth Barnes

Atmospheric rivers (ARs) are intense synoptic-scale plumes of tropospheric water vapor that can lead to extreme precipitation and flooding when they make landfall. These features cause extreme flooding events not only along the west coast of the contiguous United States (CONUS), but also in Canada and Alaska. Here, we demonstrate a relationship between winter-time ARs hitting Alaska and CONUS and the presence of blocking anticyclones over the east Pacific. We further present evidence that blocking over this region is tied to phases 7/8 of the Madden-Julian Oscillation. Thus, this work suggests there is a potential to forecast the probability of North Pacific blocking and thus AR occurrence along the west-coast of North America through knowledge of tropical variability weeks ahead.

Day 2 (Thurs 7 April):
Recent trends and impacts of blocking

Reevaluating the impact of atmospheric Blocking in precipitation and temperature distributions in Europe
Ricardo Trigo (University of Lisbon)

Here we provide an updated analysis on the impacts of blocking episodes on seasonal and annual European precipitation and the associated physical mechanisms. Distinct domains were considered in detail taking into account different blocking center positions spanning between the Atlantic and western Russia. Significant positive precipitation anomalies are found for southernmost areas while generalized negative anomalies (up to 75 % in some areas) occur in large areas of central and northern Europe. This dipole of anomalies is reversed when compared to that observed during episodes of strong zonal flow conditions.

To better understand the precipitation anomalies, we explore the blocking influence on cyclonic activity. The results indicate a split of the storm-tracks north and south of blocking systems, leading to an almost complete reduction of cyclonic centers in northern and central Europe and increases in southern areas, where cyclone frequency doubles during blocking episodes. However, the underlying processes conductive to the precipitation anomalies are distinct between northern and southern European regions, with a significant role of atmospheric instability in southern Europe, and moisture availability as the major driver at higher latitudes. This distinctive underlying process is coherent with the characteristic patterns of latent heat release from the ocean associated with blocked and strong zonal flow patterns.

We also analyzed changes in the full range of the precipitation distribution of several sectors during blocked and zonal days. Results show that precipitation reductions in the areas under direct blocking influence are driven by a substantial drop in the frequency of moderate rainfall classes. Contrarily, southwards of blocking systems, frequency increases in moderate to extreme rainfall classes largely determine the precipitation anomaly in the accumulated totals. In this context, we show the close relationship between the more intrinsic torrential nature of Mediterranean precipitation regimes and the role of blocking systems in increasing the probability of extreme events.

A similar analysis was developed for temperature distributions, however, in this case it was necessary to separate blocking pattern from ridges.

Atmospheric blocking in the Southern Hemisphere – from the seasonal cycle to interannual and decadal variability
Caroline Ummenhofer (Woods Hole Oceanographic Institution)

Characteristics of atmospheric blocking in the Southern Hemisphere (SH) are explored on seasonal, interannual to decadal timescales using reanalyses, idealised atmospheric general circulation model (AGCM) experiments, and a coupled 1300-yr pre-industrial climate model simulation. The Australia-New Zealand sector is a preferred location of SH blocking. The seasonal cycle of blocking in this region is shown to be associated with major seasonal temperature changes over continental Antarctica and Australia and minor changes over the surrounding oceans. These changes are superimposed on a favourable background state for blocking in the region resulting from a conjunction of physical influences: the geographical configuration and topography of the Australian and Antarctic continents and the positive west to east sea surface temperature (SST) gradient in the Indo-Australian sector of the Southern Ocean. Blocking, represented by a blocking index (BI) measuring the strength of split-zonal flow developed by the Australian Bureau of Meteorology, has marked seasonality that reflects seasonal changes in the strength of the mid-troposphere westerly winds at select latitudes. Significant correlations between the BI at Australian longitudes and southern Australian rainfall are due to cut-off lows, forming the cyclonic

components of blocking dipoles. In simulations with the Community Atmosphere Model 3, preferred locations of SH blocking and the associated seasonal cycle in the BI are well represented, but the observed magnitude of blocking is underestimated. This relates to overly zonal flow due to an enhanced meridional pressure gradient in the model, resulting in decreased amplitude of the longwave trough/ridge pattern. AGCM sensitivity experiments explore the effect on SH blocking of tropical heating, midlatitude SST, and land-sea temperature gradients created over the Australian continent during austral winter. The combined effects of tropical heating and extratropical temperature gradients are further explored in a blocking-favourable configuration with warm SST anomalies north of Australia, cold to the southwest, warm to the southeast, and cool Australian land temperatures. In this configuration, significant strengthening of the subtropical jet and a reduction in midlatitude flow occurs, resulting from changes in thermal wind.
Using a pre-industrial 1300-year Community Earth System Model simulation, we examine extreme blocking years and sustained periods with high/low blocking activity for a decade or longer: interannual blocking activity is associated with tropical SST affecting the subtropical jet and midlatitude zonal winds. In contrast, sustained extreme blocking periods display distinct signals in circulation and SST anomalies limited to the extratropics. Periods with sustained high/low blocking in observations exhibit consistent changes in the extratropical SST, split in the zonal jet, and associated southern Australian rainfall response.

Southern Ocean blocking: interannual variability and trends
James Renwick (Victoria University of Wellington)

A new climatology of Southern Hemisphere blocking will be presented, based on the ERA-Interim and MERRA reanalyses, and extended back in time using the 20th Century reanalysis. The main approach for identifying blocking events is based on persistent anticyclonic anomalies in the 500 hPa height field, but results will be compared against a gradient reversal approach to defining blocking. The main blocking region in the Southern Hemisphere lies across the southern Pacific Ocean, and blocking in that sector is well known to affect West Antarctic climate and sea ice extent. Blocking occurrence in this region is strongly modulated by the ENSO cycle, with greater frequency of blocking during El Niño conditions. Blocking is also negatively correlated with the Southern Annular Mode (SAM) index, such that blocking occurrence is reduced when zonal winds across the southern Pacific are enhanced. Relationships between ENSO, the SAM and blocking occurrence will be discussed and compared between reanalyses. Decadal-scale trends in blocking occurrence will be outlined, in the context of large-scale circulation variability and trends.

Changes in the global character of blocking anticyclones in the first part of the 21st century
Anthony Lupo (University of Missouri)

A study published which examined the character of blocking from about 1970 – 1999, defined the intensity of blocking and applied this to northern (NH) and southern (SH) hemisphere blocking along with the occurrence and duration of these events. NH events occurred more often, were more persistent, and stronger than SH events. This study showed that blocking was on the decrease in the SH, but the numbers for occurrence and duration were consistent with those of other studies.

Here, we examine the character of blocking over the entire globe since 1999 and compare the character of blocking over the last 16 years to the earlier period using the NOAA-NCEP re-analyses. The occurrence of NH blocking has increased, been more persistent, but weaker across all sectors than events of the previous period. These changes in character are consistent with some studies that projected the future occurrence of blocking in a warmer world. There is also evidence that blocking occurred more often in the early 20th century. In the SH, the occurrence of blocking has increased, but the persistence and intensities have not changed appreciably. These results are statistically significant at the 95% confidence level. Finally, there have been no changes in where blocking events form and occur in either hemisphere.

Greenland Blocking Index 1851-2015: a regional climate change signal
Edward Hanna (University of Sheffield)

We present an extended monthly and seasonal Greenland Blocking Index (GBI) from 1851- August 2015, which more than doubles the length of the existing published GBI series. We achieve this by homogenising the Twentieth Century Reanalysis version 2c-based GBI and splicing it with the NCEP/NCAR Reanalysis-based GBI. For the whole time period there are significant decreases in GBI in spring, March and May and a significant increase in October. However, apart from spring, there are no significant overall trends in seasonal or annual GBI. More recently, since 1981 there are significant GBI increases in all seasons, with the strongest monthly increases in July and August. A recent clustering of high GBI values is evident in summer, when seven out of the top eleven values in the last 165 years – including the two latest years 2014 and 2015 - occurred since 2007. Also, 2010 is the highest GBI year in the annual, winter and December series but 2011 is the record low GBI value in the spring and April series. Moreover, since 1851, there have been significant changes in GBI variability in several months. One of the increasingly variable GBI months December has shown a significant clustering of extreme high and low GBI values since 2001, mirroring a similar, recently identified phenomenon in the December North Atlantic Oscillation index, suggesting a related driving mechanism. We discuss changes in hemispheric circulation that are associated with high compared with low GBI conditions. Our GBI time series should be useful for climatologists and other scientists interested in aspects and impacts of Arctic variability and change.

Present day and future trends in Northern Hemisphere blocking
Etienne Dunn-Sigouin (Columbia University)

Recent studies have linked arctic amplification to an increase in the frequency of persistent mid-latitude weather patterns and atmospheric blocking. In addition, high profile extreme weather events in the last decade have generated discussion about possible increases in extreme weather under climate change. To partially address these points, this talk reviews trends in atmospheric blocking, an important source of atmospheric mid-latitude variability linked to extreme weather, in the present day and future climate using reanalysis and CMIP5 simulations.
A comprehensive study involving multiple blocking indices, reanalyses and time periods over different seasons indicate no robust hemispheric wide trends in blocking frequency consistent with large interannual and decadal variability. There are however significant localized increasing and decreasing trends with some consistency across studies in certain seasons.
In the future, robust multi-model mean trends across different indices and forcing scenarios suggest decreasing blocking frequencies over the oceans and an increase/eastward extension into the eastern Europe/Ural region, albeit with large inter-model spread. There is less agreement on future changes in blocking duration across different studies. Possible explanations for multi-model mean trends and sources of model spread are discussed with an emphasis on changes in the mean state and eddy variance.

North Atlantic Blocking Variability and Role of the Atlantic Multidecadal Oscillation
Young-Oh Kwon (Woods Hole Oceanographic Institution)

Spatial and temporal variability of the winter (December-March) atmospheric blocking in the North Atlantic region are examined for 1900-2010 from the 20th Century Reanalysis. DJFM number of blocking days exhibit a strong interannual-to-multidecadal variability with four centres of action: (1) near Greenland (Greenland Blocking; GB), (2) around the British Isles (European Blocking; EB), (3) near Azores (Southern European Blocking; SEB), and (4) over the North Sea (Northern European Blocking; NEB). GB and SEB are anti-correlated (r=-0.6) and associated with the North Atlantic Oscillation (NAO). In the years with more frequent GB, the negative phase of the NAO is favoured (r=-0.8), while the positive NAO is correlated with enhanced SEB (r=0.6). On the other hand, the EB and NEB are significantly correlated with the seasonal mean circulation associated with the Eastern Atlantic Pattern. Statistically significant influence from sea-surface temperature (SST) variability associated with the Atlantic Multidecadal Oscillation (AMO) is found when the positive AMO leads by 3-10 years the anomalous blocking pattern with reduced SEB and enhanced NEB and GB. This anomalous blocking pattern projects well onto the second EOF pattern of the winter blocking days and associated with the negative NAO. However, this relationship is not significant with the negative AMO. The mechanism of the AMO impact on the blocking will be discussed. Furthermore, the corresponding atmospheric blocking variability is examined in climate models and the impact of mean biases of the ocean and atmosphere will be discussed.

The positive North Atlantic Oscillation with downstream blocking and Middle East snowstorms
Yao Yao (Institute of Atmospheric Physics, Chinese Academy of Sciences)

In this study, the atmospheric conditions for the December 2013 Middle East snowstorm are examined from a case study perspective and by performing a composite analysis of extreme winter events from 1950 to 2013 using reanalysis data. It is revealed that this snowstorm arises from the occurrence of an omega (Ω)-type European blocking (EB) with a strong downstream trough that is associated with a southward-displaced positive-phase North Atlantic Oscillation (NAO+) event. In the anomaly field, the EB exhibits a northeast–southwest (NE–SW)-tilted dipole structure. The composite analysis shows that the NE–SW [northwest–southeast (NW–SE)]-tilted EB dipole occurs with a southward (northward)-displaced NAO+ event. This tilting has the most favourable structure for cold air outbreaks over the Middle East and south-eastern Europe because this tilting leads to an intense downstream trough over this region. In contrast, a NW–SE-tilted EB dipole anomaly leads to low temperatures over north-western Africa and south-western Europe.
In addition, we also examine the North Atlantic conditions that determine the EB tilting direction, defined as being perpendicular to the dipole anomaly orientation. Using daily reanalysis data, the NAO+ events are classified into strong (SJN) and weak (WJN) North Atlantic jet types. A composite analysis shows that the EB is generally stronger and located more westward and southward during SJN events than during WJN events. During SJN events, the NAO+ and EB dipoles exhibit NE-SW tilting. In contrast, northwest-southeast (NW-SE) tilting is seen during WJN events.
Moreover, a modified nonlinear multi-scale interaction model is used to investigate the physical mechanism through which the North Atlantic jet (NAJ) affects EB with the NAO+ event. It is shown that when the NAJ is stronger, an amplified EB event forms due to enhanced NAO+ energy dispersion. For a strong (weak) NAJ, the EB tends to occur in a relatively low (high) latitude region because of the suppressive (favourable) role of intensified (reduced) zonal wind in high latitudes and exhibits NE-SW (NW-SE) tilting. The results suggest that the NAJ can modulate the tilting direction of EB, leading to different weather effects over the Middle East.

Link between atmospheric blocking and South America rainfall in Austral summer
Regina Rodrigues (Federal University of Santa Catarina (Brazil) - University of Oxford)

Atmospheric blocking represents an important feature for regional climate and weather patterns and plays an important role in extreme events, such as heat waves and droughts. In spite of its importance, our knowledge of the physical mechanisms inherited to intensity and frequency of atmospheric blocking is very limited, particularly for the Southern Hemisphere. In this study, we investigate atmospheric blocking over east South America using different indices in austral summer for the period of 1979-2014. Our results show that in general blocking over this area is a consequence of propagating Rossby waves that grow to large amplitudes eventually breaking anticyclonically over central South America. The wave trains seem to be triggered over the southwestern Indian Ocean. They then travel eastward along the atmospheric jet and are refracted over the tip of South America, propagating equatorward, During blocking episodes the establishment of the South Atlantic Convergence Zone is inhibited causing deficient rain over central South America and excess rainfall over the Amazon and southeast South America. Moreover persistent blocking can also lead to heat waves in South America and warming of western South Atlantic (in some cases the sea surface temperature can reach up to 3°C above average).

The link between atmospheric blockings and Central European flood events – A case study
Sina Lenggenhager (University of Bern)

Flood events are among the most devastating weather-related events in Europe and can lead to large economic losses and even fatalities. Several processes, such as heavy precipitation or snow melt, can be involved in the triggering of flood events. Here we focus on precipitation only. Important characteristics of the flood triggering precipitation events are their intensity and their duration, which in return depend on the intensity and the stationarity of the associated weather system.

Atmospheric blockings, due to their longevity and stationarity can be influence flood related precipitation event in several ways:

i) The progression of the upstream weather systems is slowed and thereby the precipitation period over a catchment can be prolonged.

ii) The cumulative effect of recurrent precipitation events occurring upstream- or downstream of a block can result in a flood event. The interaction between blockings and flood triggering weather events potentially works in both directions. Cloud diabatic processes can be central to the establishment and maintenance of blocking anticyclones. The precipitation responsible for the flood could hence potentially extend the lifetime and strength of a blocking anticyclone located downstream of the flooded area.

Here we illustrate the different interactions based on a flood event of a major lake in southern Switzerland in October 2000. During the flood event and in the month before blockings were present downstream, over Scandinavia as well as upstream, over the North-Atlantic. Three extreme precipitation episodes occurred in southern Switzerland in

September and October 2000. The first one took place on 20 September and was associated with an atmospheric blocking over the north Atlantic. This blocking together with a downstream anticyclone led to the formation of a PV streamer over western Europe that was responsible for the heavy precipitation. The two anticyclonic systems then merged and formed a persistent blocking over the northern north Atlantic and Scandinavia. This resulted in a similar flow configuration 10 days later with an even heavier rainfall over Switzerland on 30 September. These two precipitation events were essential for the preconditioning of the catchment. After the second extreme precipitation event the lake level was already high. Ten days later the flood-triggering event took place from October 11 to 15. During this event a block was situated downstream. This block was responsible for the stalling of the precipitation triggering weather system directly over Switzerland and heavy precipitation over five days. We also find evidence for a feedback between the heavy precipitation and the block. Backward trajectories calculated from the blocking region over Scandinavia show that some of the low PV air masses in the block passed through the heavy precipitation region over Switzerland two days early where they ascended and their PV was diabatically depleted.

Tropospheric blocking, the stratospheric Aleutian high and distorted polar vortex, and cold-air outbreaks during the 2013-2014 winter season

Stephen Colucci (Cornell University)

Severe cold-air outbreaks over middle latitudes during the 2013-2014 winter season were each preceded by anomalous elongations of the stratospheric polar vortex. One such elongation during early February 2014 resulted in a near split of the 10-mb polar cyclonic vortex. This in turn was preceded by the anomalous intensification of the “Aleutian High”, a 10-mb anticyclone over the north-central Pacific Ocean during late January 2014. Finally, this feature was preceded by the onset of tropospheric blocking, objectively defined by a persistently large positive anomaly at 500 mb over the north-central Pacific Ocean.

A possible sequential relationship among these phenomena is being explored. Preliminary results from potential vorticity inversions applied to reanalysis data during this winter season reveal that thermally forced geopotential height rises originated in the troposphere near the blocking anticyclone, then propagated upwards into the stratosphere, helping to form and intensify the Aleutian High. This stratospheric anticyclone, coupled with another over the Atlantic Ocean, helped displace and distort the stratospheric polar vortex. Anomalously cold lower tropospheric temperatures then followed over much of North America.

Blocking precursors of Sudden Stratospheric Warmings

David Barriopedro (Universidad Complutense de Madrid / IGEO)

Major Sudden Stratospheric Warmings (SSWs) are large disruptions of the polar vortex and a potential source for more skilful seasonal forecasts of tropospheric winter weather in the northern extratropics. In the 1980's atmospheric blocking was first proposed as a potential precursor of SSWs but the connection between blocking and SSWs has remained controversial. Some studies have not found clear links between blocking and SSWs, while others report precursor signals in blocking activity when SSWs are stratified into displacement and splitting types. The blocking role in SSWs also depends on slowly-varying forcings of the polar vortex, such as the El Niño-Southern Oscillation.
Herein, three different blocking methods and available reanalysis products are used to explore the connection between blocking and SSWs and its robustness with respect to the reanalysis and the blocking definition. The analysis focuses on the geographical location of the blocking precursors of SSWs and its dependence with the type of SSW. The results show differences between the blocking precursors of wavenumber-1 and wavenumber-2 SSWs, which are larger than those reported between displacement and splitting SSWs. There is also an ENSO modulation of the blocking precursors of SSWs. The precursor patterns are quite robust across reanalyses, but there are differences among blocking definitions that may contribute to the discrepancies found in previous studies.

Testing of blocking precursors to stratospheric sudden warmings in an idealized model framework
Daniela Domeisen (GEOMAR Helmholtz Centre for Ocean Research)

Research has shown that in both reanalysis and complex model simulations, winter blocking tends to be present before the occurrence of Stratospheric Sudden Warming (SSW) events. Large-scale and long-lived blocking anomalies have the potential to influence the stratospheric flow, e.g. by modifying the poleward heat flux over a large region and for an extended time. Long-lived poleward heat flux anomalies are also predominantly observed before SSW events suggesting the possibility for a relationship.
We investigate this relationship in an idealized dynamical core model by systematically varying the tropospheric stationary wave forcing in order to evaluate the model setup which is most conducive for tropospheric winter blocking, while testing the sensitivity of the stratosphere to the presence of precursor blocking patterns.

Diagnosing Anthropogenic Contributions to Heavy Colorado Rains in September 2013
Pardeep Pall (Lawrence Berkeley National Laboratory)

The Colorado floods of September 2013 caused severe damage and fatalities across the Front Range region, with record rainfall totals recorded in several locations. It was associated predominantly with a large-scale blocking pattern (akin to the North American Monsoon, which occurs earlier in the year) that drove a strong plume of deep moisture inland from the eastern tropical Pacific and Gulf of Mexico towards the Front Range foothills. This situation challenges contemporary frameworks investigating the potential role of anthropogenic climate change in recent extreme weather events, because they struggle to connect large-scale meteorology with local weather processes. Here we use a novel part observational- part dynamical-model-based approach to investigate how the influence of anthropogenic climate drivers on observed large-scale meteorological conditions might subsequently affect regionally-modelled Colorado rainfall. Subject to little change in the imposed blocking conditions, our simulations indicate anthropogenic drivers increased the magnitude of heavy northeast Colorado rainfall for the wet week in September 2013 by 30%, with the occurrence probability of a week at least that wet increasing by at least factor 1.3. We argue this increase was due primarily to the additional moisture-carrying capacity of a warmer atmosphere – allowing more intense local convective precipitation that induced a secondary dynamical positive feedback in moisture flow. Tailoring analysis tools to better tackle particular aspects of extreme weather events, as demonstrated here, should prove a useful addition to furthering understanding of the effects of anthropogenic climate change on complex hydrometeorological events.

The dynamics behind extreme event attribution: links to impacts
Dann Mitchell (ECI, Oxford University)

Atmospheric modes of variability relevant for extreme temperature and precipitation events are evaluated in models currently being used for extreme event attribution. Jet variability, storm tracks, blocking frequency and duration are all assessed and implications for event attribution given. Taking the 2003 heat wave as an example, we quantify explicitly the role of human influence on climate, relating the large scale blocking to heat-related mortality in an event attribution framework, analysing both the Europe-wide temperature response in 2003, and localised responses over London and Paris. Using publicly-donated computing, we perform many thousands of climate simulations of a high-resolution regional climate model to generate a comprehensive statistical description of the 2003 event and the role of human influence within it using the results to drive a health impact assessment model of human mortality. We find large-scale dynamical modes of atmospheric variability remain largely unchanged under anthropogenic climate change for this event, and the direct thermo-dynamical response is responsible for the increased mortality.

Day 3 (Fri 8 April):
Representation in models and response to forcing

Diagnostics of the prediction and maintenance of Euro-Atlantic blocking
Mark Rodwell (ECMWF)

The talk will discuss probabilistic forecasts of blocking, including predictability estimates and forecast reliability. The roles of physical and dynamical processes, for example in the maintenance of blocking, will also be discussed.

Evaluation of European blocking across timescales
Keith Williams (UK Met Office)

The Met Office Unified Model (UM) is used across timescales, from NWP prediction for days ahead, through seasonal forecasting, to centennial climate projections. Across all these timescales, the ability of the model to simulate European blocking is of crucial importance to the users of the model, and the customers who they are delivering forecasts and projections to. Using a variety of diagnostic techniques such as wave breaking indices, clustering and feature tracking, an assessment of European blocking in the current configuration of the UM across the timescales will be presented. It will be demonstrated on what timescale biases in blocking start to develop in the UM. By using case studies to explore the initial development of these systematic errors, combined with nudging experiments to identify their source, the potential mechanisms leading to these biases will be discussed.

The resolution sensitivity of northern hemisphere blocking in four 25-km atmospheric global circulation models
Reinhard Schiemann (NCAS Climate / University of Reading)

Climate models tend to underestimate blocking frequency and it has been suggested that their relatively coarse resolution limits their ability to represent mid-latitude blocking.
Assessing the role of model resolution for blocking is computationally expensive, as multi-decadal simulations at the desired resolution are necessary for a robust estimation of blocking statistics. Here, we use an ensemble of four atmosphere-only global models for which simulations that fulfil this requirement are available at resolutions of roughly 25 km horizontal grid spacing in the midlatitudes. This corresponds to about a fourfold increase in atmospheric resolution over the highest-resolution CMIP5 (Coupled Model Intercomparison Project, Phase 5) models. The four models are (i) the ECMWF model (IFS) as used in the project Athena, (ii) the MRI-AGCM 3.2, (iii) CAM5, and (iv) our own HadGEM3-GA3 simulations obtained in the UPSCALE project (UK on PrACE - weather-resolving Simulations of Climate for globAL Environmental risk). We also use coarser (100-200 km grid spacing) versions of these four models with an as similar as possible model formulation to assess the sensitivity to resolution in a controlled modelling setup.
We use a two-dimensional blocking index to assess the representation of blocking in these simulations and in three reanalyses (ERA-Interim, ERA-40, MERRA). We quantify biases in the representation of blocking throughout the year and assess the sensitivity of these biases to the model resolution. Furthermore, we determine to what extent any blocking bias and resolution sensitivity are associated with the mean-state bias of the models.
We find that the three reanalyses agree very well on the blocking climatology. It is shown that Euro/Atlantic blocking is simulated overall more credibly at higher resolution, i.e. in better agreement with a 50-year reference blocking climatology created from the ERA-40 and ERA-Interim reanalyses. The improvement seen with resolution depends on the season and to some extent on the model considered. Euro/Atlantic blocking is simulated more realistically in winter, spring and autumn, and robustly so across

the model ensemble. The improvement in spring is larger than that in winter and autumn. Summer blocking is found to be better simulated by one model only, with little changes seen in the other three models. The representation of Pacific blocking is not found to systematically depend on resolution. Despite the improvements seen with resolution, the 25-km models still exhibit large biases in Euro/Atlantic blocking. For example, three of the four 25-km models underestimate winter northern European blocking frequency by about one third. The resolution sensitivity and biases in the simulated blocking are shown to be in part associated with the mean-state biases in the models' mid-latitude circulation.

Model resolution, physics and atmosphere-ocean interaction – How do they influence atmospheric blocking?
Karstin Hartung (Stockholm University)

Atmospheric blocking is known to locally explain a large part of climate variability. Several cases of extreme impacts on weather related to blocking events have been observed and studied in the past. Despite the relevance and impact of blocking, current climate models still struggle to represent the observed statistics.
In this study a wide range of EC-Earth simulations is compared to detect the origins of the underlying deficiencies with respect to the numerical model setup. Therefore, the simulations are grouped into three categories and their ability to represent the atmospheric climate state is analysed. These groups are (i) the model version/model physics, (ii) the horizontal resolution and (iii) the coupling between atmosphere and ocean. In addition, ERA-Interim is used as a substitute for the real climate state and briefly compared to ERA-20C and JRA-55 reanalyses. Blocking is detected by a Tibaldi-Molteni type index adapted to a varying central blocking latitude and blocking frequencies are calculated for 26 seasons. Here, we focus on the winter (DJF) and spring (MAM) seasons over the Atlantic/European sector. The results are discussed based on conditional blocking frequencies depending on duration of and migration during each event. Statistical significance is tested with a bootstrapping approach.
Differences among the reanalyses are not significant, models tend to underestimate blocking in winter and overestimate in spring months. However, in spring no simulation differs significantly from ERA-Interim and only a few simulations do in winter, mainly those using older model physics. Large inter-annual variability explains why differences of up to four percentage points are not significant. In addition, between zero and six winters in models and reanalyses are without any blocking.
In spring, model peak frequencies exhibit less spread among simulations than in winter. Although peak frequencies tend to decrease and improve with increasing resolution this is not a significant signal. In addition, no signal is found either for differences among model physics or the impact of atmosphere-ocean coupling. The mean winter frequencies of coupled simulations are closer to the reanalyses than atmosphere-only runs but coupled simulations exhibit a large spread. Furthermore, newer physical parameterisations significantly reduce the Atlantic bias both for coupled and atmosphere-only simulations and have larger impact than changes of the horizontal grid spacing.

Evaluating and improving blocking in models
Tim Woollings (University of Oxford)

Since 2011 an informal UK-wide group has met regularly to discuss the evaluation and improvement of blocking and storms in weather and climate models. This group acts as a Process Evaluation Group (PEG) in the UK Met Office evaluation and development strategy. The group shares experience from the weather, climate and modelling communities and attempts to synthesise results focusing on different timescales, regions and models. This presentation will give an overview of the work of the PEG, including some highlights where progress has been made in recent years and also some ongoing challenges.

European blocking simulations in Global Climate Models: 20 years of improvements?
Paolo Davini (LMD-ENS)

The representation of mid-latitude atmospheric blocking has always been a big concern for global climate models, both from a numerical weather prediction and from a climate perspective. In this talk, we will explore the advancement in blocking simulations in Global Climate Models (GCMs) in the last 20 years.
Making use of a series of equivalent metrics, three generations of GCMs (AMIP, CMIP-3 and CMIP-5) are compared. It is found that even though large improvements are seen over the Pacific Ocean, only minor advancement has been achieved over the Euro-Atlantic sector. Many recent GCMs still exhibit the same negative bias as 20 years ago in this region, associated with large geopotential height systematic errors. Some individual models, nevertheless, have improved and show good performances in both sectors.
The origins of the European negative bias are briefly investigated. Negligible differences emerge among ocean-coupled or atmospheric-only simulations, suggesting weak relevance of sea surface temperatures biases. It is also found that the bulk of the error is associated with the mean state rather than with the blocking pattern or frequency. Finally, recent results from the high resolution Climate SPHINX project will be also presented: they confirm that increased horizontal resolution seems cardinal to resolve European Blocking.

Atmospheric blocking and sources of forecast error in short-term prediction of drought in the UK
Tess Parker (University of Oxford)

Atmospheric blocking has been identified as one of the key drivers of drought in the UK, and is associated with Rossby wave breaking. However, blocking is generally poorly captured in climate models. In order to investigate some of the challenges in the prediction of drought in the UK on monthly to seasonal time scales, several models from the TIGGE dataset are used to examine the ability of the models to forecast modes of variability such as the North Atlantic Oscillation, which is a measure of the variability of the zonal flow over the Atlantic and is linked to variations in high-latitude blocking. We also assess the impact of, for example, mid-tropospheric geopotential height anomalies and stratospheric warming events on blocking in the European region through the use of sensitivity analyses.

Forecast variability of the blocking system over Russia in summer 2010 and its impact on surface conditions
Lisa-Ann Quandt (IMK-TRO, KIT)

As atmospheric blocking may cause high impact weather like heat waves and flooding (e.g. Matsueda, 2009), there is a special interest in its prediction and the involved physical processes which limit forecast quality. Often, blocking is associated with low predictability regarding its onset and decay phase as well as its flanks during its whole lifecycle (e.g. Tibaldi and Molteni, 1990; Frederiksen et al. 2004; Matsueda, 2009).
The predictability of the Euro-Russian blocking in summer 2010 is examined. This blocking event was linked to high impact weather by causing a heat wave in Russia and flooding in Pakistan. We focus on its onset, its decay and a period about one month after its onset which is characterized by low predictability of its western flank. There are several studies, which deal with the blocking and the high impact weather events in summer 2010. In this study, we wanted to combine two aspects: the forecast variability of the blocking system and the resulting impact on surface conditions.
This was done by employing an empirical orthogonal function analysis and fuzzy clustering methodology to a multimodel ensemble that comprises the ECMWF, UK Met Office and NCEP EPS derived from the THORPEX Interactive Grand Global Ensemble (TIGGE). In this way, different forecast scenarios were identified for further investigation and the contribution of the different EPS to the total variability was investigated. To identify the blocked latitude for certain members, the blocking index by Tibaldi and Molteni (1990) as well as the index by Pelly et al. (2003) were calculated. Furthermore, two heat indices and a fire index were computed to highlight the reflection of forecast variability in surface variables.
Although the onset of the blocking system was associated with high predictability, strong differences in the representation of surface conditions were visible. The increase in surface temperature as well as the extension of the area, which was affected by heat, differed from scenario to scenario. In the end of July, the variability of the block's western flank had a considerable influence on the precipitation distribution. Since the blocking was still existing after the analysed decay in two of three scenarios, the predictability of the decay was low. The heat wave's end was independent on blocking's decay, as the surface temperature as well as the heat indices and the fire weather index decreased in all scenario. From the

three EPS contributing to our multi-model ensemble, only the ECMWF EPS covered the full range of forecast variability, while the other EPS missed one or more of the identified scenarios.

The representation of wintertime jet variability in the North Atlantic by three seasonal forecasting systems: climatological biases, predictive skill and links to teleconnections and blocking
Panos Athanasiadis (CMCC, Bologna)

The low-frequency variability of the atmospheric circulation in the North Atlantic has been associated by early studies to the variability of the zonal wind. Recent studies have brought this aspect back on focus, suggesting that the dynamics of the mid-latitude jet have a central role not only in guiding weather systems but also in shaping the teleconnection patterns that dominate climate variability in this area. At the same time, state-of-the-art seasonal forecasting systems have reached unprecedented levels in providing skilful predictions of the extratropical winter-mean atmospheric circulation anomalies, including forecasts of the North Atlantic Oscillation (NAO) and the associated blocking frequency.
The objective of this study is twofold. It aims to connect the above-mentioned recent developments by examining the representation of the mid-latitude jet variability by three seasonal forecasting systems (CFSv2, UKMO, CMCC), all of which exhibit good predictive skill for the NAO. In addition, it will assess the associated predictive skill and selected jet statistics, such as the distribution of jet latitude and its relationship with blocking frequency.
Key to this analysis is the idea that an accurate space-time representation of the intraseasonal jet variability by the models is fundamental for a skilful determination of the seasonal mean climatic anomalies. Knowledge of the jet latitude distribution for each individual season arguably contains more information, in terms of predictive capability, than any single teleconnection index.

The influence of the Gulf Stream on wintertime European blocking
Christopher O'Reilly (University of Oxford)

Wintertime blocking is responsible for extended periods of anomalously cold and dry weather over Europe. In this study, the influence of the Gulf Stream sea surface temperature (SST) front on wintertime European blocking is investigated using a reanalysis dataset and a pair of atmospheric general circulation model (AGCM) simulations. The AGCM is forced with realistic and smoothed Gulf Stream SST, and blocking frequency over Europe is found to depend crucially on the Gulf Stream SST front. In the absence of the sharp SST gradient European blocking is significantly reduced and occurs further downstream. The nature of the Gulf Stream influence on European blocking development is investigated using composite analysis. The presence of the Gulf Stream SST front is important in capturing the observed quasi-stationary development of European blocking. The development is characterised by increased lower-tropospheric meridional eddy heat transport in the Gulf Stream region and increased eddy kinetic energy at upper-levels, which acts to reinforce the quasi-stationary jet. When the Gulf Stream SST is smoothed the storm track activity is weaker, the development is less consistent and European blocking occurs less frequently.

Characteristics of atmospheric blockings in the Northern Hemisphere: Estimates of changes from CMIP5 ensemble simulations with different RCP scenarios for the 21st century
Aleksandr Timazhev (A.M. Obukhov IAP RAS)

The analysis of changes in the characteristics of atmospheric blockings (number, duration, frequency, intensity) within various sectors of the Northern Hemisphere during the 21st century using multi-model CMIP5 simulations with different RCP scenarios was carried out. We used different published methods for detecting blocking events. This allows us to estimate the degree of uncertainty for the obtained results. We selected also from the full ensemble of 10 global climate models, and used the models with the best correspondence to estimates from reanalysis data for different seasons and sectors for the 20th century. Tendencies of change for blocking activity in the 21st century were estimated both for the full ensemble of climate models used and for ensembles from selected models with best correspondence to reanalysis data.

Response of blocking frequency to the Arctic amplification in a primitive equation model

Seok-Woo Son (Seoul National University)

There is a significant debate on the response of atmospheric blocking to the Arctic amplification. While several studies have documented a hint of increasing blocking frequency due to the Arctic amplification, other studies have shown essentially no such evidence. The present study re-]visits this issue by performing a series of idealized model experiments. A primitive equation model is integrated with the Held-Suarez forcing (Held and Suarez, 1994) with varying equator--to-pole temperature difference (ΔT) in the equilibrium temperature. Specifically, by mimicking the Arctic amplification, ΔT is systematically reduced from 100 K to 40 K with a 20 K interval. With decreasing ΔT, westerly jet becomes weaker and moves equatorward. Likewise, both high- and low-frequency eddies get weaker and shift equatorward along the jet. Blocking frequency is evaluated by applying the blocking index to 500-hPa geopotential height fields. The two blocking indices are used to separately examine weak-to-moderate blockings and strong blockings. The former are evaluated with a simple anomaly index whereas the latter are identified with the hybrid index that incorporates the anomaly index and the gradient reversal of geopotential height. For both definitions, blockings primarily form on the poleward flank of the jet and move with the jet. As ΔT decreases, the intensity of blocking anomaly gets weaker and the blocked area becomes smaller. However, the frequency of blocking tends to increase. Such an increase in blocking frequency is partly caused by the slowdown of the phase speed by a weaker jet that provides a favourable condition for quasi-stationary anomalies. Implication of this finding to the real atmosphere and a comparison to the previous studies are further discussed.

Blocking variability: relationship with Arctic Oscillation, Arctic Amplification, and synoptic eddies
Pedram Hassanzadeh (Harvard University)

How blocking events and the resulting weather extremes change with climate change and in particular with Arctic Amplification (AA) has been a subject of extensive research; however, the results have been inconclusive, mainly due to the incomplete understanding of blocking dynamics, shortcomings of weather/climate models, and short observational records. To predict future changes in blocking in response to AA, some studies have proposed the negative phase of Arctic Oscillation (-AO) as an analogue for AA because of similarities between their mean-states: reduced midlatitude-to-pole temperature gradients and weakened, equatorward-shifted jet-streams. Using well-controlled experiments with an idealized GCM, we show that blocking variations associated with mean-state anomalies are opposite depending on whether these anomalies are driven by the internal dynamics as in AO or forced externally as in AA (Hassanzadeh & Kuang 2015 GRL). While blocking increases and its latitudinal-distribution shifts poleward in -AO, we find opposite responses when a mean-state identical to the -AO mean-state is externally forced. These findings suggest that the observed blocking-AO relationship is a correlation which does not imply that the -AO mean-state causes increased blocking, and should not be employed as a prototype for AA. These results are consistent with the observed variability of blocking with the seasonal cycle, and with the results of our previous paper (Hassanzadeh et al. 2014 GRL) in which we showed that when the high latitudes of an idealized GCM are forced to warm, blocking activity decreases despite the weakening of the westerlies. Our results show that blocking variability cannot be understood by only considering the changes in the jet’s mean-state (e.g., speed/latitude); rather, changes in synoptic eddies and their interaction with the blocking patterns should be taken into account as well. Furthermore, our GCM simulations show that strong persistent blocks occur even with zonally-symmetric forcings and boundary conditions, which also suggest the essential role of synoptic eddies in blocking dynamics. Interaction of synoptic eddies with the blocking patterns and the forcing they exert on the blocking pattern to counter-balance the mean-flow advection has been investigated in various observational and theoretical studies in the past. Here we discuss results of ongoing GCM experiments in which we quantify the synoptic-eddy-feedback on the blocking patterns and the dependence of this feedback on the amplitude and spatial distribution of the blocking pattern, speed/latitude of the midlatitude jet, baroclinicity, and model resolution among others. The goal of this work is to develop a deeper quantitative understanding of the interaction of blocking patterns and synoptic eddies, which is expected to contribute to the ongoing efforts to better project, simulate, and predict blocking events.

Response of blocking to idealized climate-like thermal forcing: local finite amplitude wave activity as an objective diagnostic

D. Alex Burrows (Cornell University)

The relationship between atmospheric blocking and midlatitude extreme weather, such as heat waves, droughts, and cold spells, underlies its importance from the meteorological and climate community to the general public and policy makers. Synoptic-scale, blocking anticyclones may persist for days to weeks, underpinning its predictability implications, leading to shifts in the mean westerlies and associated weather patterns. Classically, blocking described persistent, large amplitude, Rossby wave breaking in the middle to high latitudes leading to midlatitude easterlies and stalled weather systems. The resulting persistent advection patterns of cold air, warm air, or moisture demonstrate its potential for cold spells, heat waves, or atmospheric rivers. Two classes of definitions are used to quantify blocking. One characterizes blocking by a large-scale reversal in a dynamical quantity, a Rossby wave breaking event, that persists for typically greater than four days. The other characterizes blocking as a large-scale, large-amplitude anomaly associated with anticyclones. The subjectivity of defining which large-scale, large-amplitude, or duration to consider underlies the difficulties presented when considering the dynamical evolution of blocking or assessing past and future trends in blocking.
Recent studies have determined that blocking indices do not readily agree on statistics and trends in blocking. The conflicting results of changes in wave amplitudes and blocking to climate change and the lack of a universal and objective definition of blocking motivate this issue. Through the use of a dry general circulation model with Held-Suarez forcing, this study analyses the effects of idealized climate change-like thermal forcing on blocking events. Thermal forcings representing general greenhouse gas warming and El Niño/Southern Oscillation variability which increase the equator-to-pole temperature gradient and Arctic Amplification which reduces the equator-to-pole temperature gradient are used, in an idealized setup, to determine the relationship between blocking and climate change. A wave breaking and anomaly definition, based on the 500hPa geopotential height, are compared in terms of duration and size of events under climate change. To complement these statistics, the recently developed local finite amplitude wave activity (LWA) based on potential vorticity will be used. Anomaly definitions based on LWA and geopotential height readily agree on blocking related statistics. The relationship between LWA and the eddy fluxes of PV, momentum, and heat leads to a dynamically significant definition of blocking and its relationship to extreme weather events.

Effects of Arctic sea ice loss on northern hemisphere blocking highs
Blanca Ayarzaguena (University of Exeter)

Stronger warming over the Arctic than over lower latitudes is a robust feature of climate change projections. This phenomenon is called Arctic or polar amplification and is tightly connected with sea ice loss. As a result of the change in the meridional temperature gradient, several studies have suggested a change in mid-latitude weather patterns, and the frequency of extreme weather events. In particular, some authors have shown an increase in the occurrence of blocking highs (BHs) over certain areas such as Europe or United States. However, those results are still controversial since other studies have not found any significant change. Model biases or artefacts of the applied methodology might explain at least part of these discrepancies. In this study, we will analyse in detail possible changes in BHs associated with the Arctic sea ice loss by means of sensitivity runs of HadGAM2 and CAM4 models where future projected sea ice loss is prescribed. BHs will be identified by applying different algorithms and comparison between these allows us to test the robustness of projected changes, and to examine the sensitivity of our results to the choice of blocking metric. We will also extend the analysis to changes in BH-related weather extremes such as cold air outbreaks (CAOs) associated with sea ice loss in order to determine whether these phenomena are also affected in the same way as BHs are.

Poster session (Thurs 7 April, 11am)
Room 1L04

Representation of blocking anticyclones in the new global model ICON and the role of horizontal resolution
Roman Attinger (ETH Zurich)

Blocking anticyclones are an important component of the large-scale midlatitude flow, as they perturb the upper-level midlatitude jet stream and influence the regional flow pattern on sub-seasonal time scales. In this study we assess the representation of atmospheric blocking in the new global numerical weather prediction model ICON (Zängl et al., 2015), which is operational at the Deutscher Wetterdienst (DWD) since January 2015. To this end we investigate the ability of ICON to develop blocking anticyclones and to reproduce the climatological distribution of blocking frequencies at different horizontal resolutions in an AMIP-type setup.
For this study, ICON is initialised from ERA-Interim reanalysis and integrated for a five year period (2000-2005). Sea ice and sea surface temperature from ERAInterim are updated monthly. The representation of blocking in ICON simulations at three horizontal resolutions (80/40/20km) is tested with respect to an ERAInterim blocking climatology. Blocking is defined following the method of Schwierz et al. (2004), based on the vertically averaged PV anomaly, spatial overlap, and temporal persistence.
Preliminary results indicate that ICON accurately represents blocking frequencies in amplitude and location. Strongest discrepancies exist in the lower midlatitude North Pacific. Increasing the horizontal resolution from 80 to 40km yields lower differences compared to ERA-Interim. Details of the dependence of blocking frequencies on horizontal resolution are currently under investigation. In a future step the representation of blocking life cycles in ICON will be explored.

Statistical analysis of the links between blocking and cyclones over the western North Atlantic
James Booth (City University of New York, City College)

Northeasters are extratropical cyclones that develop as they progress northward along the eastern coast of North America. The path of these cyclones makes it possible for these storms to generate multiple hazards in North America: storm surge along the coastline and/or heavy precipitation, or snow, inland. The analysis presented here examines the role of blocking in affecting the path and propagation speed of Northeasters. Lagrangian tracking algorithms are applied to reanalysis products to identify the life cycles of extratropical cyclone paths and blocking events. Using the cyclone paths, Northeasters Are identified and blocking statistics are calculated for the days prior to, during, and following the occurrence of the storms. Similar Statistics are then calculated for all other cyclones that pass through the western North Atlantic basin. The path, strength and intensification rates of the cyclones are compared with the strength and location of the blocks. The Analysis shows that in the event of a Northeaster, The likelihood of the presence of a block at the southeast tip of Greenland Is anomalously high. However no significant link between the strength of the storms and the strength of the block is identified. This suggests that the presence of a block primarily impacts the path of the Northeasters, as expected. The results from the analysis of the relationship between the propagation speed of cyclone centers and block events are more complicated. On the one hand, when all cyclones are considered, regardless of the occurrence of a block, the fastest propagation speeds correspond to an absence of blocking. However, when the cyclones that occur during blocking are considered alone, the amount of blocking is greater during the faster cyclones. In This case, the key factor is the location of the block. The Implications of these results for hazardous events are analyzed and put into the context of existing theories, especially as they relate to the North Atlantic Oscillation.

Coupling of planetary-scale Rossby wave trains to local extremes in heat waves over Europe
Pila Bossmann (KITIMK-TRO, KIT Karlsruhe)

The heat wave of 2003 led to the death of several 10.000 people in Europe. Improving the predictability of such heat wave events is a crucial subject of ongoing research, as heat waves can be expected to become more severe in the future. Within the Transregional Collaborative Research Center “Waves to Weather” the basic understanding of heat waves shall be improved.
Stationary Rossby waves play an important role in the appearance of local heat waves over Europe. In this project, the downscale coupling between the planetary-scale flow in the upper troposphere and the mesoscale processes will be investigated. Blocking indices are calculated for the past heatwaves and single cases are studied in detail. The studies cover not only stationary Rossby waves and blocking situations, but also the advection of warm air masses, short-wave solar radiation, accumulative heat in the boundary layer and soil moisture.

North Atlantic Oscillation, Jet and Blocking in CESM1 Large Ensemble Simulations
Alicia Camacho (Stony Brook University)

Atmospheric blocking is a weather phenomenon that occurs when an upper-level anticyclone blocks the mid-latitude westerly flow causing it to divert to the north or south of the anticyclone. The associated anomalous circulation can often lead to severe weather events such as heat waves, cold spells and droughts. It has been shown that the winter North Atlantic Oscillation (NAO) is anti-correlated with the number of blocking days near Greenland and a southerly displacement of the jet. In this study, the daily jet latitude index is constructed to quantify the origin of blocking bias in the 30 member ensemble simulations of the Community Earth System Model version 1 (CESM1). A previous study showed that the predecessor model of CESM1 exhibited a Gaussian distribution of the jet latitude at 850 hPa, while the observations showed a trimodal distribution. On the other hand, the 20th century historical simulations of the CESM1 exhibit trimodal distributions of the jet latitude at 850 hPa, consistent with the observation. However, the range of the jet latitude simulated in the CESM1 is still narrower and too northerly compared to the reanalysis, which leads to the bias in the blocking frequency near the Greenland. The relationship between the jet latitude and blocking days, as well as the jet latitude change in the 21st century are also examined.

Southern hemisphere atmospheric blocking climatology: A comparison between PV/Theta and geopotential based indices in 2 dimensions
José Leandro Campos (University of Sao Paulo)

Among recent works there is a tendency to see atmospheric blockings as Rossby Wave Breaking events and detect it through tropical potential temperature (θ) intrusions in middle and polar latitudes at the dynamical tropopause. Earlier works see atmospheric blockings as positive geopotential height anomalies at 500 hPa over middle and high latitudes or negative anomalies of zonal wind indicating a eastward wind flux region.
Depending of the approach, identification criteria and persistence, a comparison between different atmospheric blocking climatology can lead to different results in terms of position, intensity as well as blocking frequency. Motivated by this, here is proposed a methodology for atmospheric blocking identification over two dimensions using both the PV/θ (Pelly and Hoskins index) and the geopotential index (Tibaldi and Molteni index – classical index).
Climatology is computed using the PV/θ and the geopotential indices for 31 years (1979-2010) of ERA-Interim data for the Southern Hemisphere. For both the indices an annual blocking cycle is present with maximum blocking frequency in the austral winter decaying in the spring and in the summer rising in the autumn. Maxima of blocking frequency are found over the central and east (210°E – 290°E) South Pacific Ocean sectors for both approaches, secondary maxima are found over the West Pacific Ocean (180°E) and over the South Atlantic Ocean, more enhanced in the PV/θ than in the geopotential height approach.
The PV/θ index represents the atmospheric blocking more equatorward than the geopotential index in some sectors where the blocking is less intense. This result could be due to the PV/θ index identifies a mixing between the tropical and subtropical air position whereas the geopotential index identifies the region where the high is placed, generally poleward to the easterly flux (mixing region). For intense and lasting blockings the location obtained by the two index match in latitude as well as in longitude.

For short period atmospheric blockings (between 3 and 5 days of persistence), the PV/θ index depicts more blockings and more sectors of maximum frequency than the geopotential height based index but for long period blockings (>10 days) both the PV/θ and geopotential approaches agree in frequency and in sectors of maximum frequencies.

Representation of midlatitude atmospheric synoptic variability in global datasets: a spectral perspective
Alessandro Dell-Aquila (ENEA, SSPT_MET-CLIM)

We here present a process oriented metric to evaluate global datasets in terms of their capability in reproducing the midlatitude atmospheric variability. In particular this methodology allows a separation of propagating and standing components of the atmospheric waves following the spatio-temporal spectral decomposition introduced by Hayashi (1979).
This technique has been recently applied to ERA-CLIM simulations (Dell'Aquila et al 2015) in order to evaluate signals of multi-decadal variability for planetary and baroclinic waves in the centennial reanalysis product as well as in the corresponding AMIP runs . The results have been compared with a series of different reanalysis products, which assimilate atmospheric observations with increased diversity: from surface-only to surface, upper air and satellite observations.
All reanalyses are in good agreement regarding the representation of variability during the last decades of the twentieth century. This suggests that the assimilation of surface observations can generate high-quality extratropical upper-air fields. In the first decades of the twentieth century a suppression of synoptic variability is apparent in the centennial reanalysis products. This behaviour does not have a counterpart in the model integrations. The capability of model simulations to reproduce the spatial patterns associated with synoptic disturbances and the corresponding underlying processes (e.g different NAO phases) is also assessed.

The switching between zonal and blocked mid-latitude atmospheric circulation from a dynamical systems perspective
Davide Faranda (CNRS - LSCE - CEA Saclay)

Atmospheric mid-latitude circulation is dominated by a zonal, westerly flow. Such a flow is generally symmetric, but it can be occasionally broken up by blocking anticyclones. The subsequent asymmetric flow can persist for several days. In this paper, we apply new mathematical tools based on the computation of an extremal index in order to re-examine the dynamical mechanisms responsible for the transitions between zonal and blocked flows. We discard the claim that mid-latitude circulation features two distinct stable equilibria or chaotic regimes, in favor of a simpler mechanism that is well understood in dynamical systems theory: we identify the blocked flow as an unstable fixed point (or saddle point) of a single basin chaotic attractor, dominated by the westerlies regime. We also analyze the North Atlantic Oscillation and the Arctic Oscillation atmospheric indices, whose behavior is often associated with the transition between the two circulation regimes, and investigate analogies and differences with the bidimensional blocking indices. We find that the Arctic Oscillation index, which can be thought as a proxy for a hemispheric average of the Tibaldi-Molteni blocking index, keeps track of the presence of unstable fixed points. On the other hand, the North Atlantic Oscillation, representative only of local properties of the North Atlantic blocking dynamics, does not show any trace of the presence of unstable fixed points of the dynamics.

The role of blocking highs in stratosphere–troposphere coupling
Tobias Haufschild (Max- Planck Institute for Meteorology)

Atmospheric blocking plays a role in troposphere- stratosphere coupling through modulating tropospheric planetary wave and so affecting stratospheric variability on the one hand. On the other hand blocking itself is influenced by stratospheric variability. Here, we study the link between stratospheric variability and blocking in general as well as the link between extreme weak and extreme strong stratospheric polar

vortex events and blocking events. This is done by the use of ERA-Interim data and ECHAM-6 AMIP simulations at different resolution (T63L95 and T255L95). As previously reported, significant correlations between stratospheric variability and blocking emerge. However, in our model, the bias in European blocking frequency is not associated with a bias in stratospheric wave number 2 variability, given that the ECHAM-6 model is capable of reproducing wave number 2 variability at all resolutions, although all model resolutions still underestimate European blocking by up to 50%.
Northern annual mode composites with respect to the onset date of extreme weak and strong vortex events are calculated alongside with blocking composites. Different blocking persistence filter are applied, to test the sensitivity of stratosphere – blocking links to the blocking duration. We find that only long lasting European-blocking events occur a few days before the onset of weak stratospheric vortex events. Long lasting European blocking events moreover occur in a period between 40 to 60 days after the onset of strong vortex events. High latitude blocking (Greenland and Pacific) instead is increased after the onset of weak vortex events.

Role of soil moisture vs. recent climate change for the 2010 heat wave in western Russia
Mathias Hauser (ETH Zurich)

The severe 2010 heat wave in western Russia was found to be influenced by anthropogenic climate change. Additionally, soil moisture-temperature feedbacks were deemed important for the build-up of the exceptionally high temperatures. We quantify the relative role of both by applying the probabilistic event attribution framework and analyse ensemble simulations to distinguish the effect of climate change and the 2010 soil moisture conditions for annual maximum temperatures. The climate model captures the general statistics of annual maximum temperatures and soil moistures well but in they are not quite as extreme as observed in 2010. We find that climate change from 1960 to 2000 alone has approximately tripled the risk
of a severe heat wave in western Russia. The combined effect of climate change and the dry 2010 soil moisture yields a 13 times higher heat wave risk. We conclude that internal climate variability causing the dry 2010 soil moisture conditions formed a necessary basis for the extreme heatwave.
While our study concentrates mostly on the effect of climate change and soil moisture on the heat wave, from a dynamical perspective the most important feature was a blocking anticyclone. On the other hand, the employed global climate model has deficiencies capturing these blockings. In the study region it exhibits approximately half the Tibaldi and Molteni blocking frequency compared to ERA-Interim. This offers an explanation for the not quite so extreme soil moisture and temperature conditions found in the climate model ensemble. Thus, a better understanding of blockings and their representation in climate models is crucial for further research on Eurasian heat waves and droughts.

Controls on blocking under climate change
Daniel Kennedy (University of Oxford)

It is well known that the response of storm tracks to climate change is shaped by several competing processes, the dominant of which are the opposing changes in upper and lower level temperature gradients. Here we extend this line of enquiry to investigate how projected changes in blocking are sensitive to the upper and lower level changes. To achieve this we study targeted model simulations which perturb the relative warming of the Arctic versus a globally uniform warming. Hence we identify sources of uncertainty in the response of blocking to climate change and relate this to uncertainty in the large-scale circulation. We also assess how the impact of blocking on temperatures may change, for example through changes in thermal advection.

How well do medium-range ensemble forecasts simulate atmospheric blocking events?
Mio Matsueda (University of Oxford/University of Tsukuba)

This study assesses forecast performances of medium-range ensemble forecasts, regarding atmospheric blocking events in winter (2006/07-2014/15) and summer (2007-2015) over the Norther and Southern

Hemispheres (NH and SH). The medium-range ensemble forecasts available at the TIGGE data portal, have been provided by CMA (China), CMC (Canada), CPTEC (Brazil), ECMWF (Europe), JMA (Japan), KMA (South Korea), NCEP (US), and UKMO (UK).
Generally, models simulate the frequency of blocking in both NH and SH well, even at a lead time of 15 days, except some extreme blocking events. Verifications based on Brier Skill Scores (BSS) for probabilistic blocking forecasts show that the probabilistic blocking forecasts over NH are better than those over SH, although there are some year-to-year variabilities of the forecast skills. In both hemispheres, probabilistic skills in winter tend to be higher than those in summer. ECMWF shows much higher skill compared to the other models for both seasons in both hemispheres. There are larger skill differences among the models over SH than NH. In both seasons over NH, probabilistic forecasts over the Euro-Atlantic region have comparable skills with those over the Pacific region. The probabilistic forecasts (except CPTEC) become comparable to the climatological forecast after lead times of 15 days in winter and 10 days in summer. In SH where Australia-New Zealand and Andes blockings occur, probabilistic forecasts of Andes blocking in winter show highest skills and are comparable with the climatological forecast after a lead time of 14 days, whereas the other probabilistic forecasts are comparable to the climatological forecast at lead times of 6-12 days.

Links between central Greenland stable isotopes, blocking and extreme climate variability at decadal to multidecadal time scale
Norel Rimbu (Wegener Institute Helmholtz Centre for Polar and Marine Research)

The link between central Greenland stable oxygen isotopes, atmospheric blocking frequency and extreme low temperature variability at decadal to centennial time scales is investigated using observed and proxy data. A composite analysis reveals that positive stable isotope anomalies in central Greenland are associated with enhanced blocking activity in the Atlantic European region. An index of blocking activity in the Atlantic European region is higher correlated with central Greenland stable isotope time series than with the North Atlantic Oscillation index. Furthermore, the blocking frequency anomaly pattern associated with central Greenland stable isotope variability is similar to the blocking anomaly pattern associated with the Atlantic Multidecadal Oscillation. A composite analysis reveals that stable isotope variations in central Greenland are related to a large-scale pattern in the frequency of extreme low temperature with significant positive (negative) anomalies over Europe (central Asia). We argue that long-term variations of the North Atlantic blocking frequency and the associated climate extreme temperatures over Europe and Asia, as derived from observational data, can be put into a long-term perspective using central Greenland stable isotopes ice core records.

Variability of 1000 hpa air temperature and its relation to blocking frequency
Iman Rousta (University of Yazd)

Blocking phenomenon has an important role in climate fluctuations, and any change in the frequency of this phenomenon will be accompanied by changing climate patterns. In this study The Relationship between variability in the air temperature and blocking frequency is studied using the 66-years (1950-2013) daily 500 geopotential height and 1000 hpa air temperature data from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR). The study area is 0° to 90° N and 40° W to 70° E. First, Blocking events were detected using Barripedro et.al method and then their frequency was derived. After this, the 1000 hpa air temperature variability was studied by Rodionov method and finally relationship between air temperature variability with blocking frequency in study area was analyzed. The results show that during the statistical period, 4299 days was of blocking conditions. The results of Rodionov method show two main thermal regimes in 1000 hPa air temperature include: colder periods 1948-1994 and warmer periods 1995-2013. Between latitudes 55 to 75° N, greatest increasing in temperature was occurred respectively at latitude of 75, 72.5 and 70 ° N, and the latitude of 65, 62.5 and 67.5° N respectively have the least of increasing air temperature. in the warmer period (1995-2013) the annual mean of number of days with blocking in the latitude of 55-57.5° N and 65-70° N have a decreasing trend and the latitude of 60-62.5° N and 72.5-75° N have an increasing trend. Overall it seems that the days with blocking condition in response to rising temperature, tend to shift to northern latitudes.

Influence of La Nina on blocking over Europe: a summer and a winter perspective
Andrea Schneidereit (Leibniz-Institute of Atmospheric Physics)

Under La Nina conditions anticyclones occur more frequently over Europe (Fraedrich, 1994). This study revisits this relationship for a summer and a winter case.

During summer 2010, a long-persistent anticyclone occurs over Russia and causes a strong heatwave. It is shown that due to La Nina the quasi-stationary waves in mid-latitudes changes and supports the anticyclone over Russia. Furthermore, transients and intermediate waves are responsible for the maintenance of the anticyclone.

During January 2009 a major sudden stratospheric warming occurs. The January is characterized by moderate La Nina conditions and active MJO phases. Our analysis shows that La Nina creates in a climatologically sense an enhanced anticyclonic flow in two regions: one over Alaska and one over Northern Europe. The active MJO phase 7
and 8 reveal an additional source for the strengthening of the anticyclone over Alaska, which is the starting point for a wave train towards Europe. The embedded transients support the anticyclone over Europe which is in line with the analysis by Fraedrich (1994). This is an extraordinary case showing the importance of the combined tropospheric forcing of La Nina and of MJO phases 7 and 8 on different spatial and temporal scales in the enhancement of two anticyclones.

Blocking of zonal flow and related droughts in Ukraine
Inna Semenova (Odessa State Environmental University)

It is known that in many cases of intensive droughts happen as a result of blocking zonal flow in the atmosphere. As a dynamic indicator for state of the zonal flow related to blocking processes, we have introduced the regional European Continental Blocking Index (ECBI, as an analogue of European Blocking Index), which is determined by a ratio of the current and climatic pentad values of zonal wind component (u) at the level 300 mb. Zonal wind averaged over the region restricted by coordinates 10-60E and 40-60N. As the basic period was taken the time interval of 1980-2010. Positive values of the ECBI indicate the blocking of zonal flow, the negative ones correspond to enhancing of zonal wind. Values of the ECBI close to ±1 specify the extreme cases.

Index ECBI has been calculated using NCEP-NCAR reanalysis data and analyzed for period of 1990-2013. Hidden periodicity of ECBI fluctuations have been evaluated using the method based on Fourier transform, and spectral analysis. It was obtained that the pentad index during the year has periodical fluctuations with significant peaks 1.5-1.8 months, 2.2-3.2 months and 10-10.6 months. Interannual fluctuations shows main peak about 2-2.1 years.

Frequency distribution of monthly ECBI values close to normal. Highest repeatability belongs to interval of the small positive values (+0.2), which corresponding to weak blocking processes. In spring-summer (April-June) and summer-autumn (August-October) seasons are prevail positive values of the ECBI, which demonstrate the high frequency of meridional processes. In summer the regional circulation close to climatic conditions with zonal-oriented synoptic processes. At the present time the index ECBI is calculated and regularly updated on web-site of Educational weather bureau of Odessa
State Environmental University (http://ukr-novosti-pogoda.com).

The drought in Ukraine dominates in spring and summer time. Analysis of distribution blocking areas using the Lejenas-Okland index during the historical (years 1948-1986) strong spring-summer droughts in Ukraine showed that the center of blocking usually located over north border of country and the main blocking longitudes are 30-35E.

In recent two decades the severe spring-summer droughts occurred in 1996, 2003, 2007 and 2012. Anomalous long and intensive autumn drought was observed in 2011. For this cases was performed the synoptic analysis using the ECBI. It was found, that the blocking of zonal flow had an impact on the formation of the persistent and extensive source of drought, provided that its duration reached four or more pentads during a month. However, the blocking not registered in all cases. Dry weather conditions can be created by stationary anticyclones, but also transit anticyclones, that pass through the territory of Ukraine. In steady zonal flow are formed western anticyclones, which continuously moved into Ukraine during long time causing dynamic droughts, such as in September-October 2011.

Understanding anomalous eddy vorticity forcing in North Atlantic Oscillation
Jie Song (Institute of Atmospheric Physics, Chinese Academy of Sciences)

This study proposes an anomalous eddy vorticity forcing (EVF) decomposing procedure to investigate physical mechanisms responsible for the formation of the anomalous EVF associated with North Atlantic Oscillation (NAO)events. Utilizing the Geophysical Fluid Dynamics Laboratory (GFDL) dynamical core atmospheric model, a series of NAO initial-value short-term experiments are conducted. Applying the EVF decomposing procedure to the results of these experiments, the anomalous nonlinear EVF associated with the NAO events in the model can be decomposed into several fundamental linear eddy-eddy interaction terms and a negligible nonlinear eddy-eddy interaction term. Compared with the NAO-free situation, synoptic-scale eddies have faster (slower) eastward phase speeds during the positive (negative) NAO events. Through asymptotic-scale eddy-eddy interaction mechanism, the behaviours of anomalous EVF components in the positive (negative) NAO events are well explained by synoptic-scale eddies with faster (slower) eastward phase speeds. Therefore, synoptic-scale eddies with faster (slower) eastward phase speeds are responsible for the development of the anomalous EVF associated with positive (negative) NAO events. Note that at the initial-stage of the NAO initial-value short-term experiments, the faster (slower) phase speeds of the synoptic-scale eddies are specified by modifying the initial value fields, and then are amplified/maintained by the strengthening (weakening) zonal wind at the middle and high latitudes associated with the approaching positive (negative) phase NAO. Therefore, this study indicates that the properties of the synoptic-scale eddies at the initial-stage determine the upcoming NAO anomalies.

A mechanism and predictability study of Euro-Russian blocking in summer of 2010
Akira Yamazaki (JAMSTEC)

A persistent block occurred over western Russia from July through mid August in 2010. To explain the persistence of Euro-Russian blocking, the maintenance mechanism and the main contributor for the persistence are investigated. As to the maintenance mechanism, the authors proposed the selective absorption mechanism (SAM, Yamazaki and Itoh 2013 JAS), based on the eddy-feedback mechanism between blocking and synoptic eddies, or storm tracks. We adopt the SAM to explain and quantify the maintenance of Euro-Russian blocking. The result indicates that the eddy feedback contributes to the block maintenance.