Master Thesis

The Connection between the Madden-Julian Oscillation and European Weather Regimes and its Modulation by low frequency Forcings

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Publication Date:
2017-04-10

Permanent Link:
https://doi.org/10.3929/ethz-b-000238793

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THE CONNECTION BETWEEN THE MADDEN-JULIAN OSCILLATION AND EUROPEAN WEATHER REGIMES AND ITS MODULATION BY LOW FREQUENCY FORCINGS

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Zurich – April 2017
Progress in extended range numerical weather prediction for Europe relies on a correct representation of the large-scale midlatitude circulation which can be described by specific weather regimes for the Atlantic-European region. Therefore, it is important to understand their life cycles and identify processes that are responsible for their favoured occurrence, persistence or transition. Recent studies have shown that convectively active phases of the Madden-Julian Oscillation (MJO) in the tropics impact and control part of the distribution and sequences of the daily weather regimes defined over the North Atlantic-European region. Thereby, El Niño-Southern Oscillation (ENSO), the Pacific-North American teleconnection pattern (PNA), and the strength of the stratospheric polar vortex modulate the background states through which the MJO and its global response patterns propagate during Northern Hemisphere winter.

Within this thesis, we here present how the frequency of defined Atlantic-European weather regime occurrences is modulated following an MJO activity. The lagged relationship between active MJO episodes and weather regime occurrences is explored for 37 extended winters from 1979 to present. We examined for unmodulated and modulated background states the potential predictability, focusing separately on the influence of ENSO, PNA and the strength of the stratospheric polar vortex.

The results indicate that the lagged relationship between the MJO phases and the weather regimes strongly differs during different states of ENSO, PNA and the stratospheric circulation. Hence, the European response to MJO activity substantially changes with a varying background state. Our findings demonstrate the importance of considering both the MJO activity in its phase and the concurrent low frequency forcings to determine the statistically expected regime frequency due to a MJO event.
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Introduction

The Madden-Julian Oscillation (MJO) represents the most important mode of atmospheric variability in the tropics on intraseasonal time scales (Zhang, 2005). It involves an eastward propagation of large-scale convective systems along the equator in approximately 30 to 60 days, appearing predominantly in the Indian Ocean and over Indonesia (Madden and Julian, 1972; Zhang, 2005). This eastward displacement is associated with negative anomalies in the outgoing longwave radiation (OLR). It is proven that the MJO has wide-ranging impacts on a global scale, for instance on Monsoon systems or the development of tropical cyclones (e.g. in Liebmann et al., 1994). In addition, there exists an intriguing interaction with the extratropics. The impact of the MJO on the midlatitudes is most obvious for Asia and North America, since the magnitude of convection anomalies induced by the MJO is largest in the Indian and the Pacific Ocean (e.g. in Mo and Higgins, 1998; Riddle et al., 2013). But Cassou (2008) could also investigate statistically significant impacts with the Atlantic-European sector that is located further downstream. Dynamically, the evolution of Rossby wave breaking (RWB) initiated in the Pacific and Western Atlantic sector is modulated by the outflow of the convection anomalies connected to a MJO activity. This modulation leads to different types of RWB that are known to be precursors for weather regime transitions in the American and also in the European midlatitudes (Knutson and Weickmann, 1987; Ferranti et al., 1990; Kiladis and Weickmann, 1992; Hendon and Salby, 1994; Mo and Higgins, 1998; Cassou, 2008; Moore et al., 2010). Hence, the MJO influences the leading modes of low frequency variability in the Northern Hemisphere, including the Pacific North-American teleconnection pattern (PNA) and the North Atlantic Oscillation (NAO), and consequently, the extratropical weather regimes and its transitions in both sectors (Cassou, 2008; Rivière and Drouard, 2015). Through these mechanism, the MJO may provide some degree of enhanced predictability in the Northern Hemisphere extratropics, especially during winter months at extended range time scales (e.g. in Cassou, 2008; Riddle et al., 2013). Therefore, it is important to correctly simulate and forecast the evolution of the initialized MJO dynamics (Cassou, 2008). Beside the MJO, the weather regime patterns in the Northern Hemisphere are also influenced by the El Niño Southern Oscillation (ENSO) and...
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the stratospheric polar vortex. ENSO is the most prominent year-to-year periodic fluctuation of sea surface temperature and the air pressure of the overlying atmosphere across the equatorial Pacific Ocean. Its different phases (El Niño and La Niña) have worldwide impacts and also change the global response to the MJO (Roundy et al., 2010). On the other hand, the stratospheric polar vortex appears as a belt of strong westerly winds including high potential vorticity in the Northern Hemisphere stratosphere during the winter months (Schoeberl and Hartmann, 1991; Baldwin and Dunkerton, 2001; Waugh et al., 2017). At this time, the stratospheric polar vortex has a large impact on the development of specific weather patterns in the midlatitudes due to the variability of its strength (Baldwin and Dunkerton, 2001). With this information, it is important to consider both the MJO activity in the tropics and the different low frequency variabilities to improve the understanding of recurrent weather patterns as well as to identify specific causes, which are responsible for their favoured occurrence, persistence or transitions. Furthermore, this can help making a significant progress in both medium-range and seasonal-to-interannual climate prediction.

This thesis aims at improving the relation of the MJO and weather regimes over the North Atlantic-European region by applying a novel definition of weather regimes. Therefore, we focus on evaluating the frequency of occurrence of different European weather regimes during Northern Hemisphere winter (November-March) after active MJO days. First, we present a similar study as introduced by Cassou (2008), including the four classical weather regimes defined over the North Atlantic-European region in winter (Section 4.1). In contrast to Cassou (2008), we supplement a category «No Regime» to the four mentioned regimes in order to strengthen the attribution procedure and reduce possible uncertainty in the classification based on k-clustering. Second, we apply an European weather regime classification, which is extended from four to seven circulation patterns by taking the seven leading empirical orthogonal function analysis (EOFs) (Cassou, 2008). In a statistical framework in Section 4.2, we provide the lagged relationships between the eight phases of the MJO and the seven North Atlantic weather regimes. This offers a detailed analysis of the statistical links between flow regimes and mean conditions. In a next step, we investigate the statistical lagged MJO weather regime relationship stratified by different ENSO and PNA phases, as well as strong and weak phases of the polar vortex (Section 4.4). It is our goal to examine whether different background states alter the lagged relationship between the MJO and the European weather regimes. Finally, we present a case study of the MJO activity during different Northern Hemisphere winters (November-March) in Section 4.5. The aim of this case study is to analyse different winters and gain a better understanding about how well the statistical MJO weather regime relationship can be applied to single MJO events. Hence, we gain more refined insights into the usefulness of the statistical framework for improving extended range forecasts over the Atlantic and European sector.
Outlook

In Chapter 2, we start with further background on the MJO and its relationship with the extratropical climate anomalies. Additionally, we describe the weather regimes and offer a brief introduction of ENSO, PNA and the stratospheric polar vortex. In Chapter 3, we describe our data and methods. Further, we introduce the novel definition of the seven weather regimes and the statistical approach in detail. The results of our statistical study are presented in Chapter 4. We show how the occurrence probabilities of the seven weather regimes are modulated during and after MJO phases. Additionally, the relationship between the resulting regimes and the ENSO, PNA and the stratospheric polar vortex is examined. We discuss the case-to-case variability of impacts of the MJO activity in different phases on European weather and give explanations for the different responses, including modifications by different ENSO, PNA, and the stratospheric polar vortex conditions. The case study in the last part of Chapter 4 shows an application of the statistical analysis in recent winters and consider the advantages and disadvantages of such a statistical framework. Finally, we summarize our conclusions and suggest some future work by closing our discussion with Chapter 5.
In this chapter, we will first introduce the Madden-Julian Oscillation and explain its characteristics, mechanism and global impacts, and the phase diagram for tracking its propagation. A brief explanation of El Niño-Southern Oscillation, the Pacific-North American teleconnection pattern, and the stratospheric polar vortex is also given.

2.1 Madden-Julian Oscillation

The Madden-Julian Oscillation (MJO) is an intraseasonal variability in the tropics, characterized by a typical 30- to 60-day cycle (Madden and Julian, 1972; Zhang, 2005). It is related to large-scale anomalies in tropical convection and atmospheric circulation that propagates eastward around the globe, predominantly in the warm waters of the Indian and Pacific Ocean (Zhang, 2005). Historically, Madden and Julian first described the phenomenon in 1971. It is clearly distinguishable from other types of oscillations in the tropical region such as El Niño-Southern Oscillation (ENSO) or recurring monsoon circulation patterns (Zhang, 2005; Oliver, 2005).

Characteristics

The main observed feature of the MJO is an eastward moving centre of strong deep convection and precipitation, described as active MJO (Figure 2.1). The eastward propagating MJO can be subdivided in eight phases that correspond to a specific location at the equator (Wheeler and Hendon, 2004; Zhang, 2005). Most often the MJO is first evident over the Indian Ocean (phase 2 and 3) and remains apparent as it propagates to the Western and Central tropical Pacific (phase 4, 5, 6, and 7) (Wheeler and Hendon, 2004; Zhang, 2005). Over the cooler Eastern Pacific, the pattern of tropical rainfall generally becomes nondescript, but often reappears over the tropical Atlantic and Africa (phase 8). It is flanked to both east and west by regions of reduced deep convection and precipitation, called inactive or suppressed phases. Overturning zonal circulations connect the active and inactive phase (Zhang, 2005). In addition, positive anomalies in the sea surface tem-
2 Background

Temperature and negative anomalies of sea level pressure (SLP) have been observed and are linked to the propagating system. Furthermore, it is known that different types of tropical waves such as eastward propagating equatorial Kelvin waves and westward propagating equatorial Rossby waves play an important role in the composition of the MJO (Zhang, 2005).

Figure 2.1: Wintertime composite of OLR (colour) and stream function anomalies at 300 hPa (contours) for the eight MJO phases. Blue colours correspond to enhanced convection activity and wetter conditions, and red colours correspond to reduced convection activity and drier conditions. Shading intervals are 4 Wm$^{-2}$ for OLR. Contour intervals are $1 \cdot 10^6$ m$^2$s$^{-1}$ for 300 hPa, starting at $2 \cdot 10^6$ m$^2$s$^{-1}$. Positive values (solid) in the Northern Hemisphere and negative values (dashed) in the Southern Hemisphere represent anomalous anticyclonic circulation. Source: Cassou (2008).

The MJO activity propagates at an average speed of 5 ms$^{-1}$ (Wheeler and Hendon, 2004; Zhang, 2005). Due to its slowly evolving nature, one can identify the position...
2.1 Madden-Julian Oscillation

of the MJO on global maps of outgoing longwave radiation (OLR) (BOM, 2017a). OLR is often used to monitor deep convective rain clouds, because it is related to the temperature of the emitting surface. Therefore, these maps show the difference from expected cloudiness. Negative OLR anomalies correspond to more convective activity than normal, whereas positive OLR anomalies relate to less convective activity (Figure 2.1).

Figure 2.2: Schematic shows (RMM1, RMM2) phase space points for all available days during December - February from 1974 to 2003 by Wheeler and Hendon (2004). Eight defined regions of the phase space are labeled, as is the region considered to signify weak MJO activity. Also labeled are the approximate locations of the enhanced convective signal of the MJO for that location of the phase space, e.g. the «Indian Ocean» for phases 2 and 3. Source: Wheeler and Hendon (2004).

MJO Phase Diagram

Wheeler and Hendon (2004) introduced a MJO phase diagram to characterize the location as well as the intensity of the MJO activity (e.g. given in Figure 2.2). Today, it is widely used in research and MJO forecasting. The different phases (1-8) generally coincide with locations along the equator (Wheeler and Hendon, 2004). According to Wheeler and Hendon (2004), RMM1 and RMM2 (Real-time Multivariate MJO series 1 and 2) are mathematical methods, describing the evolution of the MJO along the equator independent of the seasons. The methods are based on a pair of empirical orthogonal functions (EOFs) of combined fields of near-equatorially averaged 850-hPa zonal wind, 200-hPa zonal wind, and satellite-observed OLR.
2 Background

data (Wheeler and Hendon, 2004). Thereby, it provides a measure of the strength and the location of the actual MJO. Each day is represented by a dot on the phase diagram and belongs to a particular phase. When the dot is within the centre circle, the MJO is considered very weak or not existing (no MJO observed). Hence, outside of this circle the MJO is stronger, whereas the distance of the dot from the centre measures the amplitude of the MJO on that day. It usually moves in an anti-clockwise direction as the MJO moves from west to east.

Processes establishing the Tropical-Extratropical Teleconnection

After detecting the MJO (Madden and Julian, 1972), numerous studies have shown that the tropical convection anomalies associated with the MJO tend to excite large-scale responses in form of Rossby waves which affect also the extratropics (e.g. in Knutson and Weickmann, 1987; Ferranti et al., 1990; Kiladis and Weickmann, 1992; Hendon and Salby, 1994; Mo and Higgins, 1998). Later Matthews et al. (2004) emphasized that the extratropical response is consistent with the theories of Rossby wave forcing and dispersion on the climatological flow. Due to the complexity, it was proven difficult to determine the precise dynamical mechanism linking the tropical convection and the observed flow anomalies that can occur on a global scale. Moore et al. (2010) provide intriguing evidence that Rossby wave braking (RWB) along the dynamical tropopause may play a seminal role in the evolution of the subtropical and extratropical flow due to MJO events. There exist two RWB types, appearing at the end of two distinct baroclinic wave life cycles (Thornicroft et al., 1993): LC1 ending with an anticyclonic and LC2 with a cyclonic wave breaking. The anticyclonic wave breaking features a wave tilting in the southwest-northeast direction, whereas the cyclonic wave breaking features one tilting in the southeast-northwest direction. Moore et al. (2010) found that dynamical distinction between LC1 and LC2 wave breaking is useful in that the two different characteristic life cycles exhibit significantly different anomalous behaviour during the MJO. Therefore, they described in a schematic representation the general characteristics of the atmosphere in response to an evolving MJO event as briefly summarized in the following section:

The impact of the MJO tropical convection on the midlatitude circulation is explained based on phase 1 and 2, when it is located in the Indian Ocean (Figure 2.3a). The direct Rossby wave, characteristic of the convectively active phases of the MJO, generates an upper-level anticyclone to the northwest of the area of maximum tropical convection located over South Alaska. In this region, the jet stream is strengthened and shifted to the northern part of the Pacific. As a response to the convection, an upper level anticyclone forms to the northwest and southwest of sustained, anomalous tropical convection. Due to the northern position of the jet stream over eastern Asia, there is LC1 RWB in the Western Central Pacific. LC1 RWB is associated with a double jet stream configuration, momentum fluxes that shift the jet stream to the north in the Central Pacific, and induced subtropical and tropical convection on the southeastern periphery of the breaking Rossby wave.
2.1 Madden-Julian Oscillation

Figure 2.3: The MJO life cycle presented by Moore et al. (2010). CPC MJO indices (top) 10–2, (middle) 3–5, and (bottom) 6–8. The solid and dashed black contours represent the dynamical tropopause on a representative potential temperature surface. Dashed contour precedes the solid contour in time. Source: Moore et al. (2010).
According to Moore et al. (2010), the RWB induced convection may project back onto the MJO diabatic heating field. Thereby, it aids the eastward propagation of the MJO (Kiladis and Weickmann, 1992).

The MJO tropical convection continuously influences the midlatitude circulation during the MJO phase 3-5, when it is located over the Maritime Continent (Figure 2.3b). The jet stream maximum extends to the east in conjunction with the eastward propagation of the MJO. LC1 RWB is enhanced and observed to the east of previous LC1 RWB. Simultaneously, the LC2 RWB increases over the Western and Central Pacific and an enhanced probability of a surface cyclone accompanies in time and space. The anticyclone is now located in the Gulf of Alaska. Due to the fact, that the PNA-like signal changes its sign during and shortly after the LC2 RWB, it may be an integral to this process. According to Rivière and Drouard (2015), a poleward-deviated Pacific jet stream favours a southward propagation of the waves across North America and LC1 RWB in the North Atlantic. Hence, the Atlantic jet stream gets pushed poleward and form the positive North Atlantic Oscillation (NAO) phase.

The jet stream attains its furthest eastward extension in Figure 2.3c. Subsequently, the MJO propagates east of the date line (Phase 6-8). Enhanced LC2 RWB has extended to the jet stream exit region in the Eastern North Pacific. The anticyclone is now located over central North America, while increase surface cyclone frequency continues to accompany the LC2 RWB. Conversely to the prior formation of the NAO+, synoptic wave propagation across North America is significantly reduced and more zonal due to the more zonally oriented Pacific jet stream (Rivière and Drouard, 2015). Finally, this leads to LC2 RWB and the formation of the negative NAO phase.

Impacts

Recent works have shown wide-ranging impacts caused by the MJO on the patterns of tropical and extratropical precipitation, atmospheric circulation, and surface air temperature around the global tropics and the extratropics. While propagating, the MJO constantly interacts with the underlying ocean and influences tropical and extratropical weather and climate systems (Zhang, 2005). For instance, MJO can modulate precipitation in the tropics (e.g. in Hendon and Liebmann, 1990) or the tropical cyclogenesis potential in adjacent regions (e.g. in Liebmann et al., 1994). Another important aspect of the MJO is its remoteness in the mid-latitudes. The outflow of the convection anomalies connected to a MJO event can modulate the evolution of midlatitude Rossby waves (e.g. in Ferranti et al., 1990). The impact of the MJO on the extratropics is most obvious for Asia and North America, since the magnitude of MJO-related convection anomalies is largest in the Indian and Pacific Oceans. Many studies described the impact of the MJO on North America and Asia (e.g. in Mo and Higgins, 1998). In addition, Cassou (2008) documented a statistically significant impact of the MJO on Europe. He showed that
the frequency of occurrence of European weather regimes is significantly different from the climatological frequency. Since the physical pathway from the tropical convection to the impact on Europe is comparatively long, there is a high case-to-case variability, regarding the impact of the MJO on European weather.

2.2 Weather Regimes

A weather regime is a circulation pattern of larger scale that remains quasi-stationary for several days to a few weeks. It can be interpreted as quasi-stationary or low frequency atmospheric circulations produced by the interaction between planetary-scale and synoptic-scale atmospheric waves (Vautard, 1990). Weather regimes are spatially well defined and limited in number. The existence of preferred intraseasonal large-scale flow structures in midlatitudes has been recognized since the early 1950s (Hannachi et al., 2017). Later, this field has attracted increasing interest because of the need to understand the predictable part of the atmosphere. In recent years, there was high interest, especially on the impacts of the MJO on these European weather regimes (e.g. in Cassou, 2008; Riddle et al., 2013). This continuing interest leads to a better understanding of recurrent weather patterns and the identification of their specific causes, as they are responsible for the favoured occurrence. An ongoing challenge in this field is to accurately model these weather regime states. Therefore, high horizontal resolutions are often needed to accurately reproduce them (Hannachi et al., 2017).

2.2.1 North Atlantic Oscillation

The North Atlantic Oscillation (NAO) is one of the most prominent and recurrent patterns of atmospheric circulation variability in the Northern Hemisphere during wintertime. The sea-level pressure signature of the NAO (Figure 2.4a) is marked by anomalies of opposing sign over the Arctic polar cap region and the Atlantic Mediterranean sector (Hurrell et al., 2013; Wallace and Hobbs, 2006). The NAO mode swings from one phase to another, producing large changes in the mean wind speed and direction over the Atlantic. Therefore, the heat and moisture transport between the Atlantic and the neighbouring continents is strongly affected (Hurrell et al., 2013).

The NAO is said to be in a positive phase (NAO+), when sea-level pressure is below normal over the polar cap region and above normal over the Mediterranean (Hurrell et al., 2013; Wallace and Hobbs, 2006). At these times the jet streams and storm tracks tend to be displaced poleward compared to their normal positions. This results in an enhanced westerly flow across the North Atlantic during winter. Relatively warm maritime air leads to unseasonably mild temperatures over Eurasia and in the most regions of Northern America (Figure 2.4b). Beside that, North
Europe experiences heavier than normal rainfall while the Mediterranean basks in sunshine (Figure 2.4c). In contrast, episodes of abnormally high pressure over the Arctic during the negative phase of the NAO tend to be marked by relatively frequent occurrence of cold-air outbreaks over Eurasia and the Northern America, raising the probability for intensive storms over the Mediterranean (Hurrell et al., 2013).

The NAO is the only teleconnection pattern evident throughout the year in the Northern Hemisphere (Barnston and Livezey, 1987). The positive and the negative NAO phases can be defined by different approaches using EOF or cluster

Figure 2.4: (a) presents the pattern of sea-level pressure anomalies associated with North Atlantic Oscillation. The colours indicate the sign of the anomalies associated with the positive NAO phase: The negative phase is characterized by anomalies of opposite sign. (b) and (c) show patterns of surface air temperature anomalies and standardized precipitation anomalies observed in months when the NAO mode is in its positive phase characterized by below normal sea-level pressure over the Arctic. Warm colors indicate above normal temperature and below normal precipitation, and shades of blue indicate anomalies of opposing sign. Source: Wallace and Hobbs (2006).
2.2 Weather Regimes

According to recent studies, the two modes control significant parts of the total SLP-variability in the European region (Vautard, 1990; Cassou, 2008; Hurrell et al., 2013). The largest amplitude anomalies in SLP occur during the boreal winter months when the atmosphere is most active dynamically. As a result, the influence of the NAO on surface temperature and precipitation is also greatest at this time of year.

2.2.2 Four Atlantic-European Weather Regimes

Vautard (1990) and Reinhold (1987) initially defined the classical four daily weather regimes for the North Atlantic-European region in boreal winter (November-March). In this season, the majority of the days can be distributed to one of the four winter regimes, whereas in summer the number of days attributed to regimes decreases strongly, because the atmosphere is less active dynamically (Cassou, 2008, Supplementary Information). Therefore, most studies focus on the Northern Hemisphere during boreal winter (Hannachi et al., 2017). Recently, it is traditional to use cluster analysis or classification methods to obtain weather regimes, identifying persistence and recurrent states (e.g. in Cassou, 2008; Michel and Rivière, 2011). Cassou (2008) defined in his study the weather regime using a k-means algorithm presented by Michelangeli et al. (1995). This iteratively finds the partition that minimizes the ratio of the variance within clusters to the variance between clusters centroids for a given number of cluster (k) (Michelangeli et al., 1995; Cassou, 2008). In addition, an empirical orthogonal function (EOF) analysis is performed on the 500-hPa low frequency geopotential field in the Atlantic domain, retaining 14 EOFs which explain about 90% of the variance. As a result, four classical weather regimes can be obtained over the Atlantic sector by applying the k-means method to low frequency 500 hPa geopotential height fields. These findings are similar to results in earlier studies (e.g. in Vautard, 1990). According to Cassou (2008) and Michel and Rivière (2011), the two first regimes can be viewed as the negative and the positive phases of the North Atlantic Oscillation (NAO- and NAO+, respectively). Furthermore, this can be considered as a measure of the variability of the zonal flow over the North Atlantic. The third regime is known as Atlantic Ride (AR) and the fourth is often referred to as Scandinavian Blocking (ScBL). In the next section, the four main winter weather regimes are explained in more detail based on the work of Cassou (2008) as well as Michel and Rivière (2011).

NAO+ or Zonal Regime

The NAO+ features a north/south-oriented dipolar anomaly in 500 hPa geopotential and the jet stream has a southwest-northeast orientation from North America to England (pattern 2 in Figure 2.5). During intense phases, it is responsible for most of the European winter storms. Generally, NAO+ leads to a strong westerly wind in the northern latitudes of Europe and hence, usually to higher temperatures than normal.
2 Background

NAO- or Greenland Anticyclone

NAO- is also characterized by a north/south-oriented dipolar anomaly, but with an anticyclone centered over Greenland (pattern 1 in Figure 2.5). The Atlantic jet stream is zonally oriented, more to the south than usual, and connected with the subtropical African jet in the Eastern Atlantic. NAO- leads to a weakening of usually prevailing westerly flow and clearly favours cold outbreaks over a large northern domain.

Atlantic Ridge (AR)

AR features a strong anticyclone over the Central North Atlantic (pattern 3 in Figure 2.5). In addition, the jet stream is shifted from the south to the north over the eastern coast of North America and then zonally extended to Scandinavia. Thus, Europe is affected by a northwesterly flow.

Scandinavian Blocking (ScBL)

The fourth classical weather regime is often referred to as ScBL. It is characterized by a strong positive anomaly over Scandinavia, while a mild deeper trough extends southeastward from the Labrador Sea to the Iberian Peninsula (pattern 4 in Figure 2.5). It blocks the usually predominantly westerly flow from the Atlantic over Scandinavia. As a result, advection of cold air in Western and Central Europe is generally frequent.

2.2.3 Seven Atlantic-European Weather Regimes

In the second part of this thesis, the statistical framework extends from the four classical winter weather regimes defined by Cassou (2008) to the seven Atlantic-European weather regimes. The new definition accounts for seasonal variability and is explained in more detail in Section 3.1.4 of Chapter 3. The weather regime flow pattern has an annual definition introduced by Grams (oral communication). To analyse the correspondence between these weather regimes and the North Atlantic Oscillation (Section 2.2.1), the daily NAO index of the Climate Prediction Center (CPC) at the National Oceanic and Atmospheric Administration (NOAA)\(^1\) is used. Here, a meteorological perspective on the seven Atlantic-European weather regimes is given based on 500 hPa geopotential height anomalies (Z500').

2.2 Weather Regimes

Figure 2.5: Representation of the wintertime North Atlantic weather regimes obtained from daily anomalous geopotential height at the 500-hPa altitude (Z500', colour). Source: Cassou (2008).
2 Background

No Regime

The «No Regime» conditions are representative of the winter climatological mean. There are no distinct anomalies in Z500’ (shading in Figure 2.6 H). The absolute Z500 field is characterized by a climatological trough over North America and a weak ridge in the Eastern North Atlantic and Western Europe. Strong westerly upper-level flow prevails in the eastern and central North Atlantic and reaches into Europe. The «No Regime» constitutes the positive phase of the NAO (+0.23).

The seven weather regimes are deviations from these climatological mean conditions. Three of these seven weather regimes are considered as cyclonic (Atlantic Trough, Zonal Regime, Scandinavian Trough (Figure 2.6 A-C)). They are more frequent in winter months (November-March), in particular the Zonal Regime. Summer months (May-September) are typically more associated with blocked regimes (Atlantic Ridge, European Blocking, Scandinavian Blocking, Greenland Blocking (Figure 2.6 D-F)), with a dominance of Scandinavian Blocking.

Atlantic Trough (AT)

During the Atlantic Trough regime, a single dominant negative Z500’ exists around Iceland and Southern Greenland (Figure 2.6 A). An upper-level flow is straight westerly between 40-50°N across the entire North Atlantic and into Europe (contours in Figure 2.6 A). The AT regime has a positive winter NAO index (+0.40) due to the position of the negative Z500’ between Iceland and the Azores.

Zonal Regime (ZO)

The Zonal Regime features a negative Z500’ around Iceland and Southern Greenland (Figure 2.6 B). This pattern is flanked by weakly blocked conditions over Western Continental Europe due to an enhanced ridge. The NAO index is positive during ZO (+0.99). In comparison to AT (Figure 2.6 A) the negative anomaly is shifted poleward. Westerly upper-level flow prevails in the Eastern North Atlantic and turns into southwesterly flow over the North Sea region and into Scandinavia.

Scandinavian Trough (ScTr)

The Scandinavian Trough regime is dominated by a negative Z500’. Compared to ZO (Figure 2.6 B), the negative anomaly is shifted eastward and a broad trough extends into Northern and Eastern Europe (Figure 2.6 C). Simultaneously, a positive Z500’ reflects weak ridging in the North Atlantic between 40-50°N. The prevailing upper-level westerly flow is shifted northward in comparison to AT (Figure 2.6 A). During ScTr the NAO index is positive (+0.88).
Figure 2.6: Mean low-pass filtered (10 days) 500hPa geopotential height anomaly (Z500', shading, every 20 geopotential meters), and mean absolute 500hPa geopotential height (Z500, black contours, every 40 geopotential meters) in winter (DJF) for all days attributed to one of the seven weather regimes (A-G) and to «No Regime» (H). Although the regime definition is based on normalized data for the entire year, here non-normalized data for DJF are shown. Regime name, abbreviation, and relative frequency (for winter, in percent) indicated in the subfigure caption.
Atlantic Ridge (AR)

During the Atlantic Ridge a strong positive Z500’ resides south of Iceland. It is accompanied by a blocking ridge west of Ireland and a trough affecting wide parts of Europe (Figure 2.6 D). The usually prevailing westerly flow is blocked and deflected around the ridge. It turns into northwesterlies over Northern and Western Europe. The NAO is weakly negative (-0.22).

European Blocking (EuBL)

During the European Blocking a positive Z500’ resides over the North Sea region and a blocking ridge expands over Western and Central Europe (Figure 2.6 E). Simultaneously, an upstream trough extends over the Labrador Sea and a downstream trough over Southeastern Europe. Therefore, the upper-level flow is strongly deflected into southwesterlies from Newfoundland over Iceland to northern Scandinavia. The NAO is weakly positive (+0.26).

Scandinavian Blocking (ScBL)

The Scandinavian Blocking features a positive Z500’, which is shifted into Northern Scandinavia. Additionally, the pattern shows a weaker negative anomaly in the Eastern North Atlantic and Western Europe (Figure 2.6 F). The upper-level flow is split. One can observe a branch deflected poleward around the blocking anticyclone and westerly flow over Iberia and the Mediterranean. During ScBL the winter NAO index is weakly negative (-0.18).

Greenland Blocking (GL)

During the Greenland Blocking a strong positive Z500’ is centred over Greenland accompanied by a zonally negative anomaly stretching from the Eastern North Atlantic into Northern Europe (Figure 2.6 G). The prevailing westerly flow is deflected southward and extends into the Mediterranean. At the same time Northern Europe is affected by northerly upper-level flow. The GL regime constitutes the negative phase of the NAO (-0.84).

Each of the seven regimes can be related to the four weather regimes introduced in Section 2.2.2. The GL regime corresponds to the NAO- in the new definition, whereas the NAO+ refers to the ZO, but also to the AT and the ScTr regime. The AR regime defined by Cassou (2008) is mainly represented in the new AR regime, but also partly in the ScTr regime, if cyclonic activity dominates. The ScBL of the four regimes is refined in the EuBL regime, which is the dominant winter blocking, and the new ScBL regime, which is known as dominant summer blocking.
2.3 Low Frequency Forcing

In the following subsections, we introduce El Niño Southern Oscillation (Section 2.3.1), the Pacific-North America teleconnection pattern (Section 2.3.2) and the stratospheric polar vortex (Section 2.3.3), as they can influence the leading modes of low frequency Northern Hemisphere variability. Therefore, they are relevant for exploring the link between the MJO in the tropics and the Atlantic-European weather regimes.

2.3.1 El Niño-Southern Oscillation

The El Niño-Southern Oscillation (ENSO) is the most prominent year-to-year periodic fluctuation of sea surface temperature (El Niño)\(^2\) and the air pressure of the overlying atmosphere (Southern Oscillation)\(^3\) across the equatorial Pacific Ocean (Bjerknes, 1969; Julian and Chervin, 1978; Rasmusson and Wallace, 1983; Wallace and Hobbs, 2006).

One can distinguish between El Niño episodes, neutral ENSO conditions and La Niña episodes (Figure 2.7). Here, a brief summary over these three phases is given based on Julian and Chervin (1978) and Wallace and Hobbs (2006).

Neutral ENSO conditions are characterized by (first panel in Figure 2.7):

- trade winds blowing east to west across the surface of the tropical Pacific Ocean
- warm moist air and warmer surface water is transported towards the Western Pacific, keeping the Central Pacific Ocean relatively cool
- the thermocline is deeper in the west compared to the east

El Niño episodes are characterized by (second panel in Figure 2.7):

- a weakening of the easterly trade winds converging across the equatorial Pacific
- a weakening of the equatorial cold tongue in the sea-surface temperature field, which leads to a slow down in the ocean current and a reduction of the upwelling of cold, nutrient-rich water from the deeper ocean, flattening out the thermocline

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\(^2\)El Niño is a recurrent pattern characterized by persistent above normal sea surface temperatures over the Central and Eastern equatorial Pacific (Bjerknes, 1969; Julian and Chervin, 1978; Rasmusson and Wallace, 1983). Its counterpart, La Niña, is characterized by persistent below normal sea surface temperatures in the same region.

\(^3\)The Southern Oscillation describes a bimodal variation in sea level barometric pressure between the Indian Ocean (Darwin, in Northern Australia) and the Eastern Pacific Ocean (Tahiti, in French Polynesia) (Walker, 1924; Rasmusson and Wallace, 1983).
2 Background

- a rise in sea level in the equatorial Eastern Pacific and lowering of sea level in the Western Pacific, which is indicative of a weakening of the climatological-mean east-to-west gradient

On the other hand, La Niña episodes are characterized by (last panel in Figure 2.7):

- a strengthening of the equatorial trade winds
- unusually cold ocean temperatures in the equatorial Pacific
- thermocline slopes down to the west more steeply than usual along the equator
- reduction of the zonal extent of the western Pacific warm pool

The phase and strength of ENSO events can be defined by many different indices. Commonly used indices to classify ENSO events include SST anomalies (e.g., Niño-1+2, Niño-3, Niño-4, Niño-3.4, and Japan Meteorological Agency), exceeding a preselected threshold in a certain region of the equatorial Pacific and the surface atmospheric pressure-based SOI (Hanley et al., 2003). More recently, other indices have been proposed and have shown to be effective in describing ENSO events (e.g. Trans-Niño index (TNI) and multivariate ENSO index (MEI)) (Hanley et al., 2003). In this thesis, we arbitrarily decide to stratify ENSO events based on the Niño-3.4 index.

ENSO can change the background state (moist deep convection, wind, and temperature) through which the MJO and its global response patterns propagate (Roundy et al., 2010). Moreover, it can modulate the propagation characteristics of the MJO itself (Pohl and Matthews, 2007). According to Roundy et al. (2010), high-latitude response to the MJO varies with ENSO over all longitudes, especially across the North Pacific Rim, North America and the North Atlantic. The results showed that when both modes are present simultaneously, both need to be considered to diagnose the associated global weather pattern. Further analysis demonstrated that the three ENSO conditions lead to differences in the MJO influences on indexes of the NAO. In conclusion, ENSO is an important seasonal teleconnection pattern which can change the global response to the MJO. Thus it plays a relevant role in this thesis.

2.3.2 Pacific North-American Teleconnection Pattern

The Pacific-North American teleconnection pattern (PNA) is a prominent mode of low frequency variability in the Northern Hemisphere extratropics (Oliver, 2005; NOAA, 2017). Appearing in all months except of June and July, it reaches its most expansive spatial scale during winter months. The PNA pattern is associated with a Rossby wave train and refers to the relative amplitudes of the ridge over Western
2.3 Low Frequency Forcing

Figure 2.7: The three phases of the El Niño-Southern Oscillation (ENSO) and its characteristics. Source: BOM (2017b).
2 Background

North America and the troughs over the Central North Pacific and the Southeastern United States.

According to Wallace and Gutzler (1981), the PNA is a quadripolar pattern of pressure height anomalies with four centres of action. The anomalies with similar signs are located south of the Aleutian Islands and the Southeastern United States and those with opposite signs compared to the Aleutian centre are in the vicinity of Hawaii and the intermountain region of Canada.

Figure 2.8: (a) presents the sea-level pressure anomalies associated with the Pacific-North American teleconnection pattern (PNA). The colours indicate the sign of the anomalies associated with a positive PNA pattern. The negative patterns is characterized by anomalies of opposite sign. (b) and (c) show patterns of surface air temperature anomalies and standardized precipitation anomalies observed in months when the PNA pattern is in its positive mode, characterized by below normal sea-level pressure over the North Pacific. Warm colors indicate above normal temperature and below normal precipitation and shades of blue indicate anomalies of opposing sign. Typical amplitudes of the temperature and standardized precipitation anomalies are indicated by the color scale. Source: Wallace and Hobbs (2006).
There exists two phases of this teleconnection. A positive phase occurs when deeper than normal troughs occur over the Eastern United States and the region of the Aleutians. A negative phase features troughs and a lowered ridge over the Rocky Mountains. While the positive phase is associated with meridional upper air flow, the negative phase shows a zonal upper air flow (Oliver, 2005).

The PNA pattern has been found to be strongly influenced by the ENSO phenomenon. The positive phase of the PNA pattern tends to be associated with El Niño, whereas the negative phase preferentially occurs during La Niña (Horel and Wallace, 1981; Simmons et al., 1983).

### 2.3.3 Stratospheric Polar Vortex

The stratospheric polar vortex is defined as belt of strong westerly winds in the stratosphere, showing large variations in its strength (Schoeberl and Hartmann, 1991; Baldwin and Dunkerton, 2001; Waugh et al., 2017). The stratospheric polar vortex appears in the beginning of fall and strengthens during winter as a consequence of the large-scale temperature gradients between the midlatitudes and the pole. As the vortex spins up in the beginning of winter, potential vorticity (PV) builds up rapidly in the polar region and leading to an increased PV gradient between the subtropics and the pole. As the sunlight returns to the polar regions in early spring, leading to a decrease in large-scale temperature gradients, the polar vortex breaks down.

Rossby waves that originate mainly in the troposphere can propagate into the stratosphere and perturb the stratospheric polar vortex away from the radiative equilibrium, weakening it and distorting its shape away from circular symmetry about the pole (Waugh et al., 2017; Baldwin and Dunkerton, 2001; Ambaum and Hoskins, 2002). These perturbations cause temporal variability in the Northern Hemisphere stratospheric polar vortex.

According to Baldwin and Dunkerton (2001), observations suggest that the large circulation anomalies in the lower stratosphere are related to substantial shift in the Arctic Oscillation (AO), which is a climate index of the state of the atmospheric circulation over the Arctic and recognized as the North Atlantic Oscillation (NAO) over the Atlantic sector. The AO refers to an opposing pattern of pressure between the Arctic and the northern midlatitudes. If the atmospheric pressure is high in the Arctic and low in the midlatitudes, the AO is in its positive phase. Baldwin and Dunkerton (2001) show that periods with a stronger than normal stratospheric polar vortex are often accompanied by prolonged periods of positive AO (see left schematic in Figure 2.9), whereas periods with a weaker than normal stratospheric polar vortex are often accompanied by negative AO (see right schematic in Figure 2.9).

During AO- accompanied by a weak polar vortex, air pressure systems weaken
and allow cold air to move south with the meandering jet stream (Mohanakumar, 2008). This often leads to stormy winter weather in Europe and North America (black arrows in the right schematic of Figure 2.9). On the other side, AO+ accompanied by a strong polar vortex usually protects the midlatitudes from cold Arctic air masses. Arctic air is kept in the northern part of Europe and North America, resulting in colder winters for Canada, Greenland, Northern Scandinavia, and Russia. On the other hand, extratropical storms reach Alaska, the UK and Scandinavia more frequently (orange arrows in the left schematic of Figure 2.9). The southwest of the US and the Mediterranean usually remain dry.

To summarize, there is a related observed connection between the variability of the winter- and spring-time stratospheric polar vortex and the modulations in AO/-NAO (Baldwin and Dunkerton, 2001; Ambaum and Hoskins, 2002; Tripathi et al., 2015). The variations of the strength of the stratospheric circulation are associated with the probability distributions of the Arctic and North Atlantic Oscillations, the location of the storm tracks, and therefore also for the local likelihood of midlatitude storms (Baldwin and Dunkerton, 2001). It has been increasingly recognized that the stratospheric polar vortex affects extratropical tropospheric weather and can contribute significantly to extratropical tropospheric predictability.
Data and Methods

In this chapter, we introduce the datasets and give a brief summary of the multivariate MJO index and the calculation of the provided weather regimes. In addition, we define the statistical approach to obtain the case-to-case variability of the impact of MJO events on European weather regimes.

3.1 Dataset

We work with ECMWF Inter reanalysis (ERA-Interim) data for the weather regime clusters (Dee et al., 2011) and outgoing longwave radiation (OLR) data to track the MJO. Section 3.1.1-3.1.4 introduce the specification of the two datasets.

3.1.1 OLR Dataset

The baroclinic, convectively-driven circulation in the equatorial plane of the MJO can be captured using outgoing longwave radiation (OLR) and zonal winds in the upper and lower troposphere. In general, the combination of these fields is applied to detect the MJO. Following Wheeler and Hendon (2004), we work with the OLR and zonal wind data as a database. It consists of daily averaged OLR values from the National Oceanic and Atmospheric Administration polar-orbiting series of satellites (Liebmann and Smith, 1996) and zonal wind data from the National Center for Atmospheric Research reanalysis dataset. Both are continuous in time from 1979 to the present and analysed on a 2.5° latitude-longitude grid (Wheeler and Hendon, 2004). This data is the base for an independent index to monitor the MJO investigated by Wheeler and Hendon (2004). A brief summary of this seasonally independent multivariate MJO index is given in Section 3.1.2.

3.1.2 Multivariate MJO Index

The seasonally independent multivariate MJO index is used for monitoring and predicting the MJO. It is based on a pair of empirical orthogonal functions (EOFs) of the combined fields of zonal winds and satellite-observed OLR data (Wheeler
3 Data and Methods

and Hendon, 2004). Therefore, the EOFs describe the basic baroclinic, eastward-propagating structure of the MJO. According to Wheeler and Hendon (2004), the daily observed data is projected onto the multiple-variable EOFs. The annual cycle and components of interannual variability are removed. This projection yields to a principal component time series that varies mostly only on the intraseasonal time scale of the MJO. Hence, this projection serves as an effective filter for the MJO. Wheeler and Hendon (2004) call the principal component time series that form the index Real-time Multivariate MJO series 1 (RMM1) and 2 (RMM2). An useful application of this index is the investigation of the temporal evolution of the MJO as the trajectory in the RMM1/RMM2 phase space (e.g. in Figure 2.2). It provides information about the activity, the strength, and the location of the convectively active center of the MJO.

3.1.3 ERA-Interim Reanalysis Dataset

The database consists of the full ERA-Interim reanalysis dataset from the European Centre for Medium Range Weather Forecasts (ECMWF). ERA-Interim is a global atmospheric reanalysis starting from 1979 and continuing in real time (Berrisford et al., 2011). The aim of such a reanalysis is the generation of a high temporal resolution and homogeneous dataset, which enables extended climatological studies (Dee et al., 2011). This data set has a spatial resolution of approximately 80 km on 60 vertical levels from the surface up to 0.1 hPa and is available at a regular 1°x1° grid four times daily (Berrisford et al., 2011).

3.1.4 Weather Regime Definitions

Traditionally, the Atlantic-European weather regimes are obtained using empirical orthogonal function analysis (EOF) and k-means clustering applied to a time series of two-dimensional geopotential height or pressure fields in the region of interest (Cassou, 2008; Ferranti et al., 2015; Santos et al., 2016). Therefore, EOF-clustering organizes time series of two-dimensional fields. In this thesis, we start our work with four weather regimes and expanded to seven regimes in a second part. Here, we present the two regime definitions and highlight the main differences.

**Definition of the four Atlantic-European Weather Regimes**

For the definition of the four Atlantic-European weather regimes an EOF analysis is performed on the 10-day low-pass filtered geopotential height anomaly at 500 hPa (Z500') in the domain 80°W to 40°E, 30°N to 90°N. The anomaly is computed with respect to a 90-day running average at each calendar time. ERA-Interim data is used for the weather regime definition, as this reanalysis is thought

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1K-means algorithm (Michelangeli et al., 1995) for the k-mean clustering find iteratively the partition that minimizes the ratio of the variance within clusters to the variance between the cluster centroids.
to feature the best depiction of the large-scale circulation. In this definition (see Supplementary Information Cassou, 2008), the global data is used from 01.01.1979 to 21.12.2014 during Northern Hemisphere winter. The analysis defines winter as the time from November to March. Considering this five-month NDJFM-period instead of the traditional DJF definition for winter has the following advantage: Statistically, clustering is known to be sensitive to the sampling size (Wilks, 2011). Hence, adding two more months into the pool of days for the classification reinforces the significance of the weather regime partition (Supplementary Information Cassou, 2008). Prior to the EOF clustering, the seasonal cycle in the amplitude of the anomaly is removed. This is done by computing at each grid point the temporal standard deviation in a 30-day window centred on each calendar time. Then, we normalize Z500’ by the spatial mean of this quantity in the EOF domain. The leading four EOFs are used for the k-means clustering, which is repeated ten times to test convergence to a stable solution. The four EOFs explain 65.48% of the total variance.

Definition of the seven Atlantic-European Weather Regimes

The normalization effectively removes the seasonal cycle in the amplitude of Z500’ and therefore allows to apply the EOF-clustering year-round. Grams (oral communication) uses this approach to define weather regimes independent of the season, using all six-hourly timesteps from 11.1.1979-31.12.2015. He found an optimal number of annual clusters of seven, based on the criteria of the anomaly correlation coefficient (ACC) between the clusters being below 0.4. The seven leading EOFs explain 76.7% of the total variance.

3.1.5 ENSO, PNA and stratospheric Polar Vortex Dataset

For determining the ENSO, PNA and stratospheric polar vortex conditions during the MJO activities, we use the data available on the NOAA Climate Prediction Centre (CPC)².

3.2 Statistical Treatment

In general, we follow the methodology described by Cassou (2008) to obtain a case-to-case variability of the impact of MJO events on European weather. For the eight MJO phases and for lags up to +14 days (MJO activity at day one), we count the number of occurrences of each weather regime. We test the results with a two-sided test at the 95% level. Therefore, we employ a Monte-Carlo approach in order to generate robust representations of the weather regime distribution. The detailed process is explained in the next sections and represented in Figure 3.1 and 3.2.

²Website: http://www.cpc.ncep.noaa.gov/products/analysismonitoring/
3 Data and Methods

3.2.1 Data Filtering and Processing

Multivariate MJO Index

We filter the multivariate MJO index for winter days over the years, ranging from 11 January 1979 until the end of March 2016 (referred to as Step 1 in Figure 3.2). Afterwards, we identify active MJO episodes by taking only days with an amplitude > 1, before distributing the days to the corresponding phases. To build up a lagged relationship, we add for each filtered day +14 lagged days.

Weather Regimes

For filtered MJO days and its lagged days, we search the corresponding weather regimes in the weather regime data. We determine the daily weather regime out of six-hourly weather regime attribution data. Therefore, we calculate for each day the occurrence of the weather regimes and the «No Regime». The dominant regime (occurrence per day: > 1) during 24 hours is identified as daily regime. If two regimes occur twice within one day, the 00 UTC weather regime is determined as the daily regime. Then, we examine how the frequency of the regime occurrence is modulated in the days following a MJO event with respect to the weather regime climatological occurrence frequency over all 5'677 NDJFM days from 1979-2016. Therefore, we analyse the number of occurrences for all weather regimes at each lag day and divide them by the total number of active MJO days in the study. At a later stage, we also examine how the frequency of the regime occurrence is modulated during different ENSO and PNA phases as well as during variable strengths of the stratospheric polar vortex. In these statistics, the total number of NDJFM days from 1979-2016 is 5'597. The dataset size is reduced by ~1% compared to the unstratified statistical analysis, because we use the 1 November 1979 as start date for our analysis (and not the 11 January 1979). The described approach for determining the frequencies remains the same.

ENSO, PNA and stratospheric Polar Vortex

To examine the effect of ENSO, PNA and the stratospheric polar vortex on MJO-related teleconnections, we need to define the specific conditions.

For ENSO, we distinguish between El Niño, La Niña and ENSO neutral episodes. In line with the standard definition, we define an El Niño episode by a three month running mean of the Niño-3.4 SST anomaly, which has to remain above 0.5°C Celsius for at least five consecutive overlapping seasons. La Niña episodes are taking place, if the three month running mean of Niño-3.4 SST anomaly remains below -0.5°C Celsius for the same time.
For PNA, we take daily index values for NDJFM in the year from 1979 to 2016. Then, we calculate three percentiles. The upper percentile corresponds to the 33.33% strongest positive phase of the PNA measured during our study period. On the other hand, the lower percentile includes the 33.33% strongest negative phase of the PNA. The percentile in between contains neutral PNA modes.

Including the stratospheric polar vortex in our analysis, we look at the stratospheric vortex strength during NDJFM in the years from 1979 to 2016. We use daily polar cap index values on 50 hPa geopotential height available at the CPC website. Similar to the method for the PNA, we calculate an upper, middle, and lower tercile of the dataset. Therefore, two categories include either days when the polar vortex was weak (upper tercile) or very strong (lower tercile) in comparison to other winter days during 1979 to 2016. The third category corresponds to days during which the polar vortex was neither specially strong nor very weak (referred to as «normal»).

3.2.2 Climatological Occurrence Frequency

We calculate the climatological occurrence frequency, since it is used to examine whether the weather regime occurrence under particular conditions is elevated or suppressed with respect to the weather regime climatological occurrence frequency over all days in NDJFM. First, we calculate the monthly frequency for each lag to get the monthly distribution of lag days (corresponding to Step 2 in Figure 3.1). By calculating the climatological occurrence frequency of each regime for all months (NDJFM), we weight the frequency by the monthly distribution of each lagged day (as shown in Step 3 of Figure 3.1).

3.2.3 Statistical Significance

To test the significance of the results, we perform two different Monte-Carlo simulations (version 1 and 2) which are used to calculate the null distribution of the percent change weather regime frequency. The simulation generates 2'000 synthetic partitions of the total NDJFM days into eight different phase lengths with no underlying relationship with either the MJO or one of the different conditions of ENSO, PNA and polar vortex. In version 1, exactly this is done (referred to as Step 4.1 in Figure 3.1).

The Monte-Carlo simulation in version 2 is different, because we include the chunk\(^3\)-lengths appearing in the MJO data. Thus, we sample random dates as often as the number of chunks in each phase (1-8). As in version 1, the simulation generates 2’000 such partitions without considering the monthly distribution of MJO activity. For each random generated date, we add a number of days as long as the chunk-

\(^3\)Chunks refer to a number of following days, which belong to the same MJO phase.
3 Data and Methods

Step 1: Data-set filtering
- Time period: November 1979 – March 2016
- Season: NDJFM
- Active MJO: MJO amplitude > 1
- 8 phases

For each phase (1-8): Create an array for every day during an active MJO by adding the upcoming 14 days (lag).

Search for all dates (active MJO days and lag days) the corresponding weather regime in the weather regime data.

Count the weather regimes at each lag day. Afterwards, calculate the weather regime fraction at all lag days. Repeat this for all eight phases.

Step 2: Monthly distribution of lags
Calculate the monthly frequency of lags for each lag day.

Step 3: Climatological frequency
Calculate the monthly climatological frequency for each weather regime at each lag day. It is weighted by the distribution of the months in which the MJO events occurred.

Step 4.1: Monte-Carlo Simulation (Version 1)
Construct a random sampling of dates of the data period without considering the monthly distribution and the activity of the MJO. For each phase, sample dates as often as the according phase length. Repeat this random sampling 2’000 times.

Figure 3.1: The diagram presents the first steps of the detailed process building up the statistical framework to obtain lagged frequencies of weather regimes after MJO activities. The diagram continues in Figure 3.2.
3.2 Statistical Treatment

Step 4.2: Monte-Carlo Simulation (Version 2)
Compared to version 1 (sampling of single days), the technique is to randomly select time periods (chunks). The distribution of these time periods corresponds to the distribution of the consecutive number of days, in which the MJO was in one phase. Thereby, the serial correlation that is contained in the original dataset can be mimicked with the random sampling. As in version 1, repeat this step 2'000 times. Then, each random generated date gets a tail of following dates with a similar length as the chunk. Finally, each chunk-composition in the original data set is randomly generated 2'000 times for all eight phases.

Search for all dates the corresponding weather regime in the weather regime data. Then, count the weather regimes in each phase (1-8) and calculate the fraction of each regime.

Step 5: Frequency of weather regimes
Calculate for the phases (1-8) and the according lags the frequency of weather regimes during NDJFM minus the frequency expected by the climatological mean.

Step 6: Test of significance
Conduct a two-sided significance test. Therefore, compute the percentiles from the 2'000 random selections. When the anomalies are above 97.5% or below the 2.5% percentile, they are considered significant.

Figure 3.2: The continued diagram of Figure 3.2 presents the further steps required building up the statistical framework to obtain lagged frequencies of weather regimes after MJO activities.

length. To conclude version 2, the chunk-composition of each phase (1-8) in the dataset of the study is randomly generated 2'000 times (corresponding to Step 4.2 in Figure 3.2).

The significance of the observations is assessed with respect to these null distributions (version 1 and 2). The Monte-Carlo simulation version 1 does not consider the correlation between lag days. Therefore, it is overly permissive for significance testing. The alternative approach of version 2 has the advantage that it considers
the chunks-character of the dataset. This leads to insensitivity to correlations and provides modestly conservative results in our case.

We determine the observed frequency of weather regimes during MJO activity minus the frequency expected by the climatological mean (referred to as Step 5 in Figure 3.2). The significance level is chosen to be 95%. Conducting a two-sided significance test, we calculate percentiles for 2.5% and 97.5% from the 2'000 selections (null distribution). As a last step, we test the significance for each regime at each lag during all eight phases (corresponding to Step 6 in Figure 3.2). When the anomalies are above 97.5% or below the 2.5% percentile, they are considered significant.

For the final statistics, we convert the values into percentages. If the calculated values are equal to 100%, the weather regime occurs twice as frequently under the specific conditions as it does in the full record. If it is equal to -100%, the weather regime never occurs under the analysed conditions.

3.2.4 Monthly cumulative Frequencies

In order to gain a deeper insight into the basic monthly distribution of the seven weather regimes, we generate cumulative frequency diagrams for all months (November-March). Independent of its corresponding phase, we determine for the seven weather regimes and the «No Regime» the number of days in each month (November-March), which were distributed to the specific regime class. The frequency is calculated as follows: For each weather regime (including the «No Regime»), the number of its appearances at lag day 10 is divided by the days of each month with detected MJO activity from 1979 until 2016 (e.g. all November days with measured MJO activity during the study period). In addition, we determine the winter climatology by calculating the mean of each weather regime frequency during all five months. Cumulating all frequencies, the sum is equal to 100%.

3.2.5 Case Studies

We provide two case studies to apply the calculated statistics. Therefore, we use the phase diagram of the RMM index for visualisation. As an additional information, the weather regimes, appearing at lag 10 are represented in coloured sections in the MJO phase diagram. We analysed the following winter periods:

- 1 November 2015 until 21 March 2016
- 1 November 2016 until 21 February 2017
This chapter explores the statistical linkage of the MJO and the European weather, exploring how European weather regimes vary with different MJO states under variable hemispheric background conditions. In addition, we examine how they contribute to the practical application for improving extended range weather forecasts over the European region.

We start by describing how these phases of active MJO episodes modulate the occurrence probabilities of the four classical winter weather regimes (Section 4.1). Therefore, we follow the methodology of Cassou (2008), but employ the refined weather regime life cycle instead of a simple cluster attribution, and compare our results with his study. We then expand this perspective on seven weather regimes and discuss their advantages (Section 4.2). In addition, we link the new statistic to the one including only four regimes and highlight the generated advantage. In Section 4.3, the mean frequencies at lag day 10 of the seven weather regimes during NDJFM are represented during MJO activity and compared to the overall climatology, investigating the modulation of weather regime frequencies by the MJO from a different perspective. In a second part, we analysed the modulation of weather regime frequencies by three low frequency forcings (ENSO, PNA and the state of the stratospheric polar vortex). Finally, we investigate the lagged relationship between the MJO phases and the seven weather regimes under different states of the three considered modes of low frequency forcings in Section 4.4.

4.1 Lagged Relationships: MJO Phases and the four Weather Regimes

We present the anomalous chance in occurrence of the four weather regimes after an active MJO episode occurred in the tropics in Figure 4.1. The occurrence
probability for a weather regime is enhanced when the value is positive, whereas a reduction of a regime occurrence during MJO activity is shown with negative values in the statistical analysis. Statistical significant results are calculated, using the Monte-Carlo sampling version 1 (see Section 3.2.3).

We roughly follow the methodology of the weather regime definition applied in the study of Cassou (2008). The difference is that we add a «No Regime» class to the four Atlantic-European weather regimes. Therefore, we replicate the patterns investigated by Cassou (2008). The relationship between phase 1 to 8 of the MJO and the occurrence of the four weather regimes contains more significant results compared to the one of Cassou (2008). We see this especially for the AR and ScBL regimes. In phase 2 and 3, the probability of a ScBL occurrence is increased by $\sim 30$ to $\sim 80\%$, whereas 100\% means a double occurrence frequency compared to the climatology. On the other hand, the occurrence probability of an AR regime seems to be affected by MJO activity in phase 6. The work of Cassou (2008) presents an increased occurrence probability for a ScBL regime after phase 6. In our study, this signal vanishes. Focusing on the NAO- and NAO+ regimes, the results are similar to the study of Cassou (2008) and reveal an asymmetrical sign in the occurrence probabilities, particularly during phase 3 to 6 (increased NAO+ probability and decreased NAO- probability). The clearest signal is shown during the MJO phases 7 and 8. There, the NAO- regime occurs with a probability of up to $\sim 90\%$ for lags greater than day 4 in phase 7, whereas all other regimes appear less frequent. The probabilities are also clearly increased for a NAO- occurrence in phase 1. The NAO+ signal is enhanced for lags greater than day 9 during phase 3. Its occurrence probability builds up to $\sim 80\%$ during phase 4. Afterwards, it persists until lag day 8 in phase 5. In summary, we yield a much clearer picture compared to Cassou (2008). This is most likely due to the sharper weather regime definition with the additional clustering-class, as unclear days are classified as «No Regime».

The simple Monte-Carlo sampling (version 1) as employed by Cassou (2008) does not account for the duration of a MJO phase of several days and thus of correlation between lag days. This might result in artificially high statistically significance. Therefore, we investigated an alternative, more strict approach (see version 2 in Section 3.2.3). The new significant results at 95\% level, which are somewhat conservative due to the strongly reduced degrees of freedom in the new Monte-Carlo sampling (version 2), are presented in Figure 4.2.

The number of significant results is clearly reduced by using the new Monte-Carlo simulation (version 2), if we compare Figure 4.2 with Figure 4.1. Thereby, the occurrence frequencies of NAO- appear still significant after active MJO events in phase 7 and 8. NAO+ regimes occur significantly more often 13 days after a MJO activity in phase 3. The signal remains significant until lag day 11 in phase 4. At the same time, the frequency of NAO- and AR regime is significantly reduced. We recognize a difference in the occurrence probabilities of the AR regime in phase 6. There, only two bars persist significant, while during phase 1 to 5 the results for
4.1 Lagged Relationships: MJO Phases and the four Weather Regimes

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**Figure 4.1:** Lagged occurrence frequencies (day 2–15) of the four classical European weather regimes (columns) after an active MJO at day 1 in each phase (rows). Statistically significant results at the 95% level based on the Monte-Carlo test version 1 are shown with shading, positive significant values in dark and negative significant values in light colours. Active MJO days: 65% (Total NDJFM days: 5,677).
Figure 4.2: Lagged occurrence frequencies (day 2-15) of the four classical European weather regimes (columns) after an active MJO at day 1 in each phase (rows). Statistically significant results at the 95% level based on the Monte-Carlo test version 2 are shown with shading. Positive (dark) and negative (light) significant values are indicated in dark and light colors, respectively.
4.1 Lagged Relationships: MJO Phases and the four Weather Regimes

a frequency reduction often remain significant. Focusing on the ScBL regime, the occurrence frequency is still significantly increased in phase 2 and the first seven lag days during phase 3. However, the negative significant signals during phase 6 to 8 disappeared. The remaining significant results can be interpreted as robust MJO influences on the European weather regimes.

The lagged relationships between the eight phases of the MJO and the four North Atlantic weather regimes provide evidence that phase 2 of the MJO can be interpreted as precursor for a ScBL (Figure 4.2). Moreover, phase 3 and 6 can be regarded as a harbinger for NAO+ and NAO- regimes, respectively. In addition, phase 6 is also a weak precursor of the AR regime. During phase 1 to 5, the MJO seems to constrain the occurrence of an AR regime. Our results for NAO+ and NAO- are consistent with the study presented by Cassou (2008), whereas our findings of the two other regimes differ notably in terms of statistical significance and amplitude. Focusing on the NAO+ and NAO-, we see this clear asymmetry in the tropical forcing during phase 3 and 4. It disappears in phase 7 and 8 where we find slightly increased probabilities for a NAO+ beside the clear signal in NAO-.

During phase 3, the MJO is propagating from the Indian Ocean to the Maritime Continent. The days from a lag of +7 onwards in phase 3 are characterized by an LC1 RWB (Moore et al., 2010) (Figure 2.3). It happens across North America due to a poleward-deviated Pacific jet stream, leading to a formation of NAO+ over the Atlantic and European region (Benedict et al., 2004; Cassou, 2008; Moore et al., 2010; Rivière and Drouard, 2015). During phase 7, the MJO is propagating into the Western Pacific and towards the Western Hemisphere. The days following lag day 7 in phase 7 are characterized by a reduced synoptic wave propagation across North America, whereas the Pacific jet is more zonally oriented. This is associated with LC2 RWB (Figure 2.3) and known as a precursor for NAO- (Cassou, 2008; Moore et al., 2010). The enhanced occurrence of ScBL regimes in phase 2 and 3 and the directly following significant signal of the NAO+ leads to the following interpretation: ScBL regimes may subsequently trigger the onset of NAO+ events during active MJO episodes. Furthermore, the NAO+ excitation during phase 2 and 3 probably leads to the occurrence of an AR regime during MJO activity in phase 6. This seems to change preferably into a NAO- at longer lags. The proposed weather regime transition based on our findings follows the route ScBL to NAO+ to AR to NAO- during MJO activity in the tropics. This transition cycle is anticyclonically in the EOF1/EOF2 space and thus atypical or the second most probable in the studies of Grams (oral communication). According to Grams, the transition usually has a cyclonic pathway from NAO+ to ScBL to NAO-. The here presented results might hint that the pathway is reversed during active MJO. Furthermore, this hypothesis is in line with the weather regime transition time of 6 to 96 hours (oral communication with Grams).

In summary, we show that the recently applied definition of weather regimes, including the additional clustering-class «No Regime», leads to clearer lagged statistical relationship between the MJO and the AR and ScBL regimes. Furthermore,
a new Monte-Carlo approach (version 2) is incorporated to focus on most statistically significant results. This test takes into account that the degrees of freedom have to be decreased since many of the active MJO days are consecutive days. Therefore, this test provides modestly conservative results. Our statistical analysis in Figure 4.2 confirms the findings of Cassou (2008), Moore et al. (2010) and Rivière and Drouard (2015), where the MJO is found to determine the NAO phases in the Northern Hemisphere by initiating Rossby waves. These waves modify the atmospheric background flow, leading to different RWB modes in the midlatitudes, which furthermore determine the NAO phase (+/-) and thus the European weather.

4.2 Lagged Relationships: MJO Phases and the seven Weather Regimes

We present the anomalous change in occurrence of the seven weather regimes and the «No Regime» at lags of 2 to 15 days after a MJO activity occurs in the tropics at lag day 1 (Figure 4.3). The statistical framework of Figure 4.3 is similar to the one explained for Figure 4.2, but extended from four classical winter weather regimes defined by Cassou (2008) to seven Atlantic-European weather regimes (Section 2.2.3 and Section 3.1.4).

In the statistical analysis of seven weather regimes, we identify stronger relationships for the most regimes, in particular for the AR and the EuBL regimes (Figure 4.3). Starting with phase 1, we find a significant reduction in the occurrence of the AR regime after lag day 4. This significant signal persists during phase 2 and 3. In phase 2, we additionally identify an increase in the frequency of a ScBL and a ZO regime (~90% and ~40%, respectively). Similar to the result in Section 4.1, phase 6 is discriminative for the AR regime. The statistical analysis shows an increase in the AR occurrence probability building up to ~90% for lags of more than seven days. A stronger significant result only appears for the GL regime in phase 7. After lag day 10, the regime occurs twice as often as normal. In phase 8, the signal is slightly weaker as in phase 7, but the GL regime is still affected by the progress of the MJO. Clearly reduced is the anomalous chance in occurrence of the GL regime in phase 3 for lags greater than day 10. Significant results can be found for the ZO regime during phase 4 and 6. There, the occurrence probability of the ZO regimes is increased after an active MJO episode in phase 4, whereas it is reduced in phase 6. Although not statistically significant, the ZO regime occurrence frequency is notably increased almost during all eight phases. We identify a variable phase-to-phase signal for the ScTr regime. The resulting probabilities for lags greater than day five in phase 7 appear significant. Another single significant result appears for the EuBL regime. In phase 2, the occurrence probability reaches ~80% for longer lags than day 11. Even if the signal seems to persist during phase 3, it is not significant based on our statistical test. During phases 4 to 8, the MJO
does not clearly affect the EuBL regime. There are no significant signals found for the ScBL and AT regimes. Nevertheless, the occurrence frequency of both regimes vary during the different phases, between ~30% and ~70% above or below normal.

We find the signals of the four classical regimes and the «No Regime» from Figure 4.2 splitted up in the seven weather regimes and the «No Regime» (Figure 4.3). In the new weather regime definition, the GL regime corresponds to the NAO-, whereas the NAO+ is particularly present in the ZO, but also in the AT and the ScTr regime. The AR regime defined by Cassou (2008) is mainly represented in the new AR regime, but also partly in the ScTr regime. And the ScBL of the four regimes can be found in the EuBL and to some smaller extend in the new ScBL (oral communication with Grams).

The lagged relationships between the eight phases of the MJO and the seven North Atlantic weather regimes represented in Figure 4.3 lead to many additional signals and a more detailed analysis of the lagged relationship between the MJO and the European weather. Figure 4.3 still provides evidence that phase 3 and 6 of the MJO can be explained as precursors of a positive and a negative NAO phase, which is now present in the ZO, AT, and ScTr regime and in the GL regime, respectively. In addition, we find a more differentiated result in the occurring regimes during the first five phases. As we already noticed, the increased occurrence probability for NAO+ can lead to either a ZO or a ScTr regime during phase 4 and 5. Besides, it seems that in some cases also phase 1 and 2 can be interpreted as a precursor for NAO+, leading to an AT or an earlier ZO regime developing as supposed before. The favourable occurrence of the GL regime is similar to the result found in Figure 4.2. Phase 6 clearly favours an AR regime over Northern Europe. It seems to progressively decrease in phase 7, whereas we observe the simultaneous increase in the occurrence probability of a GL regime. This observation leads to the assumption that the AR regime may subsequently trigger the onset of a GL regime. By introducing the EuBL and ScBL regimes, the extended statistic indicates a more differentiated result for these regimes compared to the ScBL regime in phase 1, 2, and 3 in Figure 4.2. Phase 2 can be interpreted as a harbinger for an EuBL regime. Additionally, ScBL seems to occur preferably during phase 1. It transfers into an EuBL regime, contributing to the significant result for lags beyond 11 in phase 2. Finally, it is important to highlight that not every MJO episode leads to such weather regime progressions. The slightly increased occurrence probability of the ZO regime during phase 7 and 8 is one example. Therefore, it seems that in some cases phase 6 can also lead to a ZO regime or the AR regime transforms under some atmospheric conditions to a ZO regime.

Summing up, we present the numerous advantages for extending the lagged statistics between the MJO and the seven weather regimes. This approach leads to a more differentiated and informative result of the impacts of the MJO on European weather. The key findings using seven European weather regimes are in line with
Lagged occurrence frequencies (day 2-15) of the seven European weather regimes (columns) after an active MJO at day 1 in each phase (rows). Statistically significant results at the 95% level based on the Monte-Carlo test version 2 are shown with shading, positive significant values in dark and negative significant values in light colours. Active MJO days: 65% (Total NDJFM days: 5'677).

**Figure 4.3**
the analysis including four regimes (Section 4.1 and Section 4.2), but the seven regimes offer more detailed insights. Figure 4.3 shows that connectively active phases of the MJO strongly modulate the frequency of different European weather regimes. Some signals appear simultaneously to others, so it has proved difficult to determine its distinct origins.

4.3 Frequencies of the Weather Regimes

To gain a deeper insight into the monthly distribution of the seven weather regimes, we generated cumulative frequency diagrams for all months. The cumulative frequency of the weather regimes for the winter months and its seasonal mean marked as «NDJFM» is shown in Figure 4.4. Focusing on the seasonal mean in both diagrams, we recognize three differences: The ZO regime occurs \( \sim 5\% \) more often at lag day 10 compared to the climatological mean. This increase is mostly compensated by a reduced occurrence frequency of the AR and the GL regime. The occurrence frequency of the other weather regimes do not change remarkably. Comparing all months, we detect a month-to-month variability for each regime frequency which is different to the climatological one. A difficult task is to evaluate this variability, as the data size for the cumulative frequency during active MJO episodes is reduced by half. In addition, the differences in monthly MJO activity are unclear and perhaps not representative for the rather short sampling period. For example, it is unclear if each month shares the same fraction of active and non-active MJO dates. Therefore, the variability might exist just by chance.

Our results in Section 4.2 demand to regard different background modulations appearing instantaneous to MJO activities. In the upcoming sections, we focus on the lagged relationships including stratified ENSO, PNA and stratospheric polar vortex conditions. Therefore, we present the mean frequencies at lag day 10 for different ENSO, PNA, and stratospheric polar vortex conditions and compare them with the seasonal mean frequencies (Figure 4.4b). We start with the stratospheric polar vortex stratification in the next section, followed by the ENSO stratification in Section 4.3.2 and close with the seasonal frequencies for different PNA phases presented in Section 4.3.3.

4.3.1 Stratospheric Polar Vortex

As introduced in Section 3.2.1, we distinguish between a strong, a neutral and a weak stratospheric polar vortex occurring simultaneously with enhanced MJO activity. The resulting seasonal mean weather regime frequency at lag day 10 for the different stratifications is illustrated in Figure 4.5a. Besides, the distribution of the cumulative frequency of the weather regimes for all active MJO episodes already shown in Figure 4.4b, is added for comparison. It can readily be seen that we
have a large discrepancy in the occurrence frequencies for different stratospheric polar vortex conditions. Mainly the ZO, the ScTr and the GL regime contribute to this variability. During a weak stratospheric polar vortex, the GL, the ScBL, the EuBL, and the AT regime appear more frequent, whereas the occurrence frequency of the AR, the ZO and the ScTr regime is together reduced by \(~20\%\). A neutral stratospheric polar vortex, which means that it is neither very strong nor weak, in combination with an active MJO, shows a roughly similar cumulative frequency distribution for all regimes. The strong stratospheric polar vortex particularly fosters the AR, the ZO and the ScTr regimes. The frequency for other blocked regimes is reduced. Interestingly, the «No Regime» appears less frequently than during a weak and a neutral polar vortex. Compared to the climatological frequency distribution of weather regimes, the total frequency of the seven weather regimes is enhanced by \(~10\%\) during a strong stratospheric polar vortex.

### 4.3.2 ENSO

For the ENSO stratification, we distinguish between El Niño, La Niña and ENSO neutral episodes (Section 3.2.1). The frequencies for all stratifications appear almost identical for most weather regimes. Just small differences can be observed. MJO activities during an El Niño episode lead to a reduced AR regime frequency, which seems mainly to be compensated by a small increase in the ZO regime frequency. If the MJO is propagating during neutral ENSO conditions, we recognize

![Figure 4.4](image)

**Figure 4.4:** Monthly cumulative frequencies (November-March) and the seasonal mean marked as «NDJFM». (a) presents the cumulative weather regime frequencies of the climatology and (b) the monthly cumulative frequencies 10 days after active MJO days. The colours for the stacked bar represent the weather regimes: GL (blue), ScBL (darkgreen), EuBL (green), AR (yellow), ScTr (orange), ZO (red), AT (violet), and the «No Regime» (grey). Values are in percentages for all weather regimes and cumulate to 100% for each month.
4.3 Frequencies of the Weather Regimes

a reduction in the ScBL regime occurrence compared to the normal seasonal mean fraction. It is mainly compensated by an increase in the AR and the AT regime frequency. During La Niña episodes, the ScBL regime frequency increases in comparison to the normal frequencies, whereas the AT regime frequency is reduced.

4.3.3 PNA

As explained in Section 3.2.1, we categorise the PNA pattern into PNA+, neutral PNA, and PNA-. The dominant change in the three cumulative regime frequencies appears due to the large variability of the ZO and AT regime. We recognize an increase of the ZO and AT regimes for neutral and PNA- conditions. The fractions of the blocking regimes stay unmodified, except the EuBL fraction during neutral conditions, which is slightly reduced. The AR and ScTr regimes only vary slightly. Analysing the occurrence frequency of the «No Regime», we detect a small increase in the total development of the seven weather regimes during PNA- and an equal decrease during PNA+ compared to the normal distribution of the cumulative frequency.

Figure 4.5: The diagrams presents the seasonal mean occurrence frequency at lag day 10 of each weather regime for three different stratospheric polar vortex, ENSO, and PNA conditions. The fourth bar represents the seasonal mean without any stratification. Therefore, (a) presents the results for the stratospheric polar vortex, (b) for the ENSO, and (c) for the PNA stratification. The different colours for the stacked bar represent the weather regimes as in Figure 4.4.
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4.3.4 Modulated cumulative Frequencies

Comparing the three diagrams in Figure 4.5, the one of the stratospheric polar vortex appears the most conspicuous. The main difference is the various ZO, ScTr, and «No Regime» frequency for the categories weak, neutral and strong polar vortices. Besides, the resulting ENSO and PNA stratification diagram also shows differences in the frequencies compared to the seasonal mean without stratification with the exception of the neutral bars. These mainly represent a similar distribution as the seasonal mean without stratification. The procedure to compare the stratifications to the normal seasonal mean is not completely satisfying. A better approach would be to compare each result of the stratification by its own climatology (stratospheric polar vortex, ENSO and PNA climatology). Unfortunately, there was no time left for this supplementary work. Nevertheless, the stratification leads to the result that variations in the strength of the stratospheric polar vortex and different ENSO and PNA conditions lead to an evident modulation of the lagged relationship between the MJO and the European weather regimes compared to the unstratified frequencies (Figure 4.4b). These findings lead to the next step, which is to investigate the lagged MJO weather regime relationship for each stratospheric polar vortex, ENSO and PNA stratification. This procedure combines the lagged relationships between the eight phases of the MJO and the seven weather regimes as well as the background state modulations by instantaneous stratospheric polar vortex, ENSO, and PNA characteristics.

4.4 Modulation by low Frequency Forcings

The stratified dataset of the stratospheric polar vortex, ENSO, and PNA is now used to generate additional statistics, investigating the lagged relationship between the MJO phases and the seven weather regimes under the different states of the three considered modes of low frequency forcings. The framework is similar to the one presented in Section 4.2. The results for strong, neutral and weak stratospheric polar vortex conditions are displayed in Section 4.4.1. Section 4.4.2 presents the three tables corresponding to the ENSO stratification, and the results of the PNA stratification are illustrated and described in Section 4.4.3.

4.4.1 Stratospheric Polar Vortex Stratification

In the statistical analysis focusing on MJO activity during a strong stratospheric polar vortex, we find significant results concentrated in mainly two weather regimes: the ZO and the GL regime (Figure 4.6). Consistent with Figure 4.5a, a stronger than normal stratospheric polar vortex strongly increases the probability for ZO regimes during all MJO phases, except during phase 6. Only occurrences higher than twice as normal appear significant, as the degrees of freedom are a third of the statistics with the full dataset. In comparison to the often increased ZO fre-
Lagged occurrence frequencies (day 2-15) of the seven European weather regimes (columns) after an active MJO at day 1 in each phase (rows) during a strong stratospheric polar vortex. Statistically significant results at the 95% level based on the Monte-Carlo test version 2 are shown with shading, positive significant values in dark and negative significant values in light colours. Active MJO days: 63% (Total NDJFM days: 1'862).

**Figure 4.6**
frequency, the EuBL, the ScBL, and especially the GL regime occurrence probabilities are often reduced (see also Figure 4.5a). We identify a very strong increased occurrence frequency of the AR regime in comparison to Figure 4.3, which remains not only for lags in phase 6, but also in phase 7 and 8. At a few lag days, these signals appear significant. On the other hand, phase 1 to 5 illustrate negative probabilities, but mostly not significant. The ScTr regime shows some variability in occurrence probabilities among the MJO phases. They are notably different during phases 1 to 3 compared to the results in the unmodified statistic, where we found an increase in the probabilities for many lags (Figure 4.3). Focusing on the AT regime, we identify a significantly reduced probability for lag days 2 to 6 in phase 2. During all other phases, no notable change in the variability of probabilities is observed compared to the results in the unstratified statistical analysis (Figure 4.3).

In the statistics of strong stratospheric polar vortex conditions, we generally observe oppositional probabilities for the ZO and the GL regime (Figure 4.6), an increased probability for the ScTr regime and a reduced probability for the EuBL and the ScBL regimes. These results were expected, because according to the study of Baldwin and Dunkerton (2001) a highly positive NAO index is very likely during strong stratospheric polar vortex. In our work, the ZO and ScTr regime constitute the positive phase of the NAO. In these two regimes, mild westerly flow from the Atlantic into Europe is observed and cold Arctic air masses can not penetrate into the mid-latitudes. With these informations, we identify a clear signal in the statistic induced by the stratospheric polar vortex itself. Important to highlight is the fact that even though these signals seem to be dominant, we still observe results that are determined by MJO activity. A strong stratospheric polar vortex increases the probabilities for a ZO regime with the exception of phase 6. The negative probability in phase 6 of Figure 4.3 is still recognized during a strong polar vortex. The resulting probability of the GL regime is influenced by the MJO activity mainly in phase 7 and 8, where it becomes less negative compared to the MJO phases 3 to 6. In phase 7 and 8, MJO activities clearly dominate the direct influence of the strong stratospheric polar vortex. In addition, phase 6 can still be interpreted as a harbinger for AR regimes during strong polar vortex conditions, as we have already seen in the unstratified statistical analysis (Figure 4.3). Additionally, the AR regime appears much more frequently during phase 8 in comparison to the unmodified statistic, even if its NAO index is weakly negative. Therefore, an MJO activity in phase 8 during strong polar vortex conditions seems to force the AR regime (NAO index: -0.22), probably instead of the GL regime (NAO index: -0.84).

Almost contradictory results are identified for the ZO, ScTr and GL regime during weak polar vortex conditions (Figure 4.7). This is in line with the findings in Figure 4.5a. Furthermore, the occurrence of the AT regime is highly increased for lags longer than day 10 in phase 2. The signal remains until lag day 7 in phase 5 and is statistically significant in phase 3 and 4. A weak polar vortex increases the probability for an AT regime, except for great lags in phase 5 and after phase 6. The observed reduction in these frequencies is comparable not only to the un-
Figure 4.7: As in Figure 4.6, but during a weak stratospheric polar vortex. Active MJO days: 66% (Total NDJFM days: 1'862).
stratified statistic (Figure 4.3) but also to the statistical analysis including a strong stratospheric polar vortex (Figure 4.6). The ScBL regime shows a similar variability compared to results found in the unstratified statistic (Figure 4.3), but its amplitude is remarkably increased. During phase 1, we identify a statistically significant increase in the ScBL probability for lag days 9 to 12.

A weak polar vortex modifies the statistic by favouring blocking regimes and constraining mainly ZO and ScTr regimes (Figure 4.3). But even if the polar vortex controls parts of the statistic, the MJO activity in the tropics still impacts the occurrence of the seven weather regimes. At this point, we highlight the less reduced occurrence probability for a ZO regime in phase 4 and 5. For the GL regime we find a similar influence during phase 3: In the unstratified statistic (Figure 4.3) we recognized a significant reduction of the probability for lags of more than 10 days. These lags appear also reduced during a weak stratospheric polar vortex (Figure 4.7), representing the MJO influence during phase 3 for the GL regime. Other interesting results are the alternately positive signals for the EuBL and the ScBL regimes in phase 1 to 6 and that phases 7 and 8 strongly favour the GL regime. Therefore, we suggest preferred regime transitions from ScBL to GL and to EuBL regimes during weak stratospheric polar vortex and active MJO conditions. In addition, phase 2 could be interpreted as a precursor for an AT regime, appearing to be strongly significant in phase 3 and 4. As we go into detail by focusing on the significant results in phase 3 for the GL and the AT regime, we recognize that the signal of the AT just appears subsequent to the GL regime. Thus, we can consider another preferred transition including as well the AT regime. It seems to follow the route ScBL to GL to EuBL or AT. Although there seems to be an increased probability for such transitions, we have to remind that in reality we still observe the occurrence of other weather regimes and transitions.

Overall, we find comparable significant results for a normal stratospheric polar vortex as in the unmodulated statistic (Figure 4.3). This result is in line with the findings in Figure 4.5a. Notable are the increased probabilities during phase 2 and especially phase 3 for the EuBL regime, which deviate from the ones observed without stratification. We recognize for the ScTr and AT regime other remarkable deviations. They are significantly reduced for lags greater than day 6 during phase 5 and for lag days 10 to 13 in phase 4, respectively. A clear signal that we have already seen in the unstratified statistical analysis (Figure 4.3) is the one for the GL regime during phase 7 and 8.

Due to the stratification for normal stratospheric polar vortex conditions, we filter the dataset from the direct strong and weak stratospheric polar vortex influence. With that, we gain some more details and clearer signals in different MJO phases. Phase 1 to 3 can be interpreted as favourable for ScBL, EuBL, and AT regimes. Phase 3 and 6 appear as early precursors for ZO and ScTr regimes and for the GL regime, respectively, as already explained for the unstratified statistical analysis. The probability for an AR regime is already increased during phase 5 and the sig-
Figure 4.8: As in Figure 4.6, but during a normal stratospheric polar vortex. Active MJO days: 66% (Total NDJFM days: 1'863).
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Significant lag days are shifted by nine days.

In summary, the stratospheric polar vortex has an important impact on the lagged relationship between the MJO and the seven European weather regimes as shown and discussed in the different statistics. Whereas a weak and a strong polar vortex dominate parts of the results, the MJO signal is still distinguished. Therefore, the MJO activity also affects the direct influence of the stratospheric polar vortex on the European weather.

4.4.2 ENSO Stratification

Next, we present and discuss MJO activity during different background states of ENSO. It seems that El Niño strongly influences the probabilities of each regime, because many signals in Figure 4.9 differ from the unstratified MJO statistics (Figure 4.3), especially for the AT, ScTr, EuBL and ScBL regimes. After active MJO conditions in phase 1, we observe an enhanced probability for an AT and ScBL regime, which can be observed until phase 4. Thereby, only the signal for the AT regime appears significant, even though the signal for both regimes is remarkably increased. During many lags in phase 4 and 5, the ZO regime dominates. Simultaneously, the frequency of a GL regime is significantly reduced, reaching values of $\sim$80% and less. Compared to phase 6 in the unstratified statistical analysis (Figure 4.3) and all statistics of the stratospheric polar vortex stratifications (Figure 4.6, Figure 4.7, Figure 4.8), we miss the significant result of the AR regime during El Niño episodes. Instead, we observe an increase in the ScBL probability, but not significantly. In phase 7, the probability for a GL regime is significantly increased. Compared to the unmodulated statistic (Figure 4.3), the signal does not persist as strong in phase 8, whereas we find an enhanced probability for EuBL and AR. At the same time, the occurrence of the AT regime is significantly reduced after lag 11.

In summary, the Atlantic-European response to the MJO is modulated by a positive ENSO phase. During El Niño episodes, the probabilities for an AT regime in phase 1 to 4 are strongly enhanced followed by a clear significant signal for a ZO regime in phase 4 and 5. A MJO event in phase 1 is therefore a precursor for the development of an AT regime in the Atlantic-European region, whereas phase 3 still appears as a precursor for a ZO regime. EuBL regimes seem to be less frequent, except during phase 8, whereas the ScBL regimes are likely to occur after phase 2, 3, and 6. Nevertheless, blocking regimes seem to be slightly reduced during El Niño episodes, since there is also a less strong GL regime signal during phase 8. In addition, El Niño episodes might suppress the occurrence of AR regimes after phase 6. On the other hand, we observe an increased frequency of AR at long lags in phase 8. Eventually, the AR signal appears with delay at this time, when a ScBL regime occurs during phase 6. Overall, the results are consistent with the ones presented by Roundy et al. (2010). They showed regions in which anomalies are characterized by significantly different patterns from those obtained by a sum of
### Figure 4.9

Lagged occurrence frequencies (day 2–15) of the seven European weather regimes (columns) after an active MJO at day 1 in each phase (rows) during El Niño episodes. Statistically significant results at the 95% level based on the Monte-Carlo test version 2 are shown with shading, positive significant values in dark and negative significant values in light colours. Active MJO days: 64% (Total NDJFM days: 1,760).
the corresponding individual MJO and ENSO composites. The patterns of geopotential height based on simultaneous occurrence of warm ENSO conditions and the eight MJO phases shown in the study of Roundy et al. (2010) are mostly in line with the weather regime patterns that are statistically significant in our study. Most consistent are the strong increase in the ZO regime frequency, the GL regime forcing for long lags in phase 7 and the slight increase in the EuBL frequency during phase 8. In addition, their results also show that in many cases, the anomaly pattern associated with the MJO during El Niño is roughly the reverse of the signal during La Niña.

The analysis of MJO activities during La Niña episodes (Figure 4.10) results in a clearly different statistic compared to El Niño episodes (Figure 4.9). In addition, the number of significant results is slightly reduced and distributed differently to the eight phases. Interestingly, the results for some regimes show the opposite sign during La Niña compared to El Niño episodes (Figure 4.9), but this varies from phase to phase. In phase 1, we distinguish an enhanced probability for the ZO and the ScBL regime, whereas only the second appears partly significant (Figure 4.10). At the same time, the AT regime probability is significantly reduced. These two signals disappear in phase 2 with each lag day. Instead, the probability for an EuBL regime increases and reaches significant values at lags 12 and 13. During phase 3, we observe no significant result, but a favoured occurrence of EuBL and at some lags for ScBL. Interestingly, the occurrence of the ScTr regime clearly dominates phase 4, probably instead of the ZO regime. Besides, there is still a signal for a ScBL regime. Compared to the unmodulated statistic (Figure 4.3), the results of phase 4 strongly differ during La Niña episodes. In phase 5, we recognize a high probability for the AR regime and a continuous increased probability for the ScBL regime instead of the ZO and the ScTr regimes in the unstratified statistic. Phase 7 and 8 represent a positive but not significant probability for the GL regime. Instead, we can observe a significant increase in the probability of the ZO regime and a significant reduction in the probability of the AR regime for long lags. Overall, the resulting frequencies in phase 8 resemble the ones in phase 7, but without significant results.

MJO activity associated with La Niña episodes leads for some regimes to opposite results compared to active phases during El Niño episodes. Here, we highlight the frequently observed ZO regime in phase 3, 4, and 5, the AR regime occurrence probability during phase 5 and 6, the EuBL and ScBL regime occurrence probability, and the AT regime signal in phase 1 to 4 (Figure 4.10). Compared to the unstratified statistic (Figure 4.3), the majority of the results look overall similar. A big difference exists in the significantly more frequent occurrence of the ZO regime in phase 7 and the reduced probability in phase 3 to 5. During La Niña conditions, phase 3 is therefore not a precursor of the ZO regime. Instead, the ScTr regime, that has also a highly positive NAO index (+0.88), dominates phase 4. Hence, these findings are still in line with the result that phase 3 is a precursor for NAO+ (discussed in Section 4.1). During La Niña episodes, it seems as the AR
**Figure 4.10:** As in Figure 4.9, but during La Niña episodes. Active MJO days: 66% (Total NDJFM days: 1'663).
regime preferably transforms to a ZO regime in phases 5 and 6 compared to other low frequency background conditions. Overall, phases 7 and 8 are precursors of GL and ZO regimes during La Niña conditions, since also both frequencies are increased after these MJO phases. The findings in our study of La Niña episodes are in line with the ones presented by Roundy et al. (2010). The general pattern during a MJO in phase 3 in Roundy et al. (2010) shows that Southern Europe experiences significant ridge anomalies. Furthermore, a ridge anomaly appears over Greenland. This is consistent with the slight increase in the blocking regime frequency and a less strong reduction in the AR regime frequency of our statistic. In phase 4, substantial significant trough anomalies occur in the individual composite for the MJO over Western Europe, and this pattern is significantly more pronounced during La Niña. The strong significant signal of the ScTr regime (Figure 4.10) is in line with the findings by Roundy et al. (2010). The enhanced ridge anomalies over Europe during phase 6 consist with the increased EuBL and ScBL regime frequencies.

The statistics for neutral ENSO conditions are shown in Figure 4.11. We find a number of strongly anomalous frequencies for the regimes, but just a few of them are statistically significant. We observe a probability higher than \(\sim 80\%\) for the AT regime in phase 1 and the ZO regime in phase 2, 3, 4, as well as during the first seven lags of phase 5. During the three remaining phases 6 to 8, we identify an increase in frequency of more than \(\sim 90\%\) of the GL and the AR regime. In the results of the other regimes, we frequently observe lag-to-lag variability in the probabilities of the different phases. Some are comparable with the results presented in the unstratified statistical analysis (Figure 4.3), but with a different amplitude of the signal strength. Examples for such observations are: The ScBL regime during phase 1, the EuBL regime during phase 2, 3, 5, 6, and 8, and the AR regime in phase 1 to 3, and 5 to 7. Overall, we see a modified distribution of the occurrence frequencies during all eight MJO phases.

During neutral ENSO conditions, the described increase of signal amplitudes in different phases occurs for many regimes. The strong increased probabilities for the ZO, AR and GL regimes is one of the characteristics of the neutral ENSO statistic. Therefore, we interpret neutral ENSO conditions as a forcing of mainly ZO regime occurrence during phase 2 to 5 and AR as well as GL regime occurrence during the last three phases. In addition, phase 1 and 7 strongly force the AT regime, whereas phase 1 can also force a EuBL regime. It seems often difficult to examine the most favoured regime, as many strong signals occur simultaneously (e.g. for phase 1: High frequencies are observed for the AT, ZO, EuBL, ScBL regime, and the «No Regime»). A recommended improvement of this statistical analysis would be to separate advancing and declining ENSO phases, as these two seem to modulate the background state of the MJO in a different way (seen in the study of Roundy et al. (2010)). With this approach, the results in two different statistics might generate a better basis for further interpretations, but only if the data size does not become too small for a statistical analysis and a reliable significance test. Due to the limited time during the thesis, we could not tackle this
Figure 4.11: As in Figure 4.9, but during neutral ENSO conditions. Active MJO days: 65% (Total NDJFM days: 2'174).
detected difficulty.

In summary, the different ENSO phases can substantially influence the weather over Europe by amplifying and modulating the sign of the extratropical response to the MJO. Especially for El Niño and La Niña episodes, the statistics show many opposite results. Improvements are recommended for the neutral ENSO classification as described above. This would probably lead to a more detailed analysis of the modulated relationship between the MJO and the seven weather regimes, but only if the data size remains sufficiently large.

### 4.4.3 PNA Stratification

The analysis of MJO activities during a PNA+ shows that the only significant result we observe during phase 1 is an increase in the occurrence probability of the «No Regime». It reaches up to 50%, which is a rare result for this regime in our analysis (Figure 4.12). In phase 2, there are no statistically significant frequency anomalies, but the results for the ZO and the EuBL regime indicate probabilities higher than ~70% for some lags. The GL and the AR regimes occur less frequently than normal, but the signal is also not statistically significant. The ScTr, the ScBL and the GL regime show the most notable frequency anomalies in phase 3 and 4. The probability for a ScTr or a ScBL regime is mostly enhanced, whereas the GL regimes present a significantly reduction in frequency anomalies. This signal persists in phase 5. At this point, we also recognize an increased probability of the AT, the ZO, the EuBL and the ScBL regime. The probability of the ScBL regime remains high also in phase 6. It is statistically significant for the lags 3 to 6. We also find an increased signal for the AR regime in phase 5, which is not statistically significant as a contrast to the unmodified statistic in Figure 4.3. Similar to the unmodified statistic are the results of the ScTr and the GL regimes in phase 7 (Figure 4.12). Additionally, we observe significant frequency anomalies for the first two lags of the EuBL regime and during lag day 1 to 4 for the ZO regime. Phase 8 presents an increase of about ~100% in the GL regime frequency and also in the frequency of the AR regime, which is significant for lags 1 to 3.

During a positive phase of the PNA, the MJO seems to influence the European weather the most in phase 5 to 8, where we identify many significant signals. Nevertheless, we find other interesting signals in the phases 1 to 5. In phase 1, the regime development is slightly reduced in comparison to the climatology, which is shown by the statistically significant increase in the «No Regime» frequency (Figure 4.12). Phase 2 to 5 force the occurrence of ZO, ScTr, and AT regimes. At the same time, the GL regime is suppressed. On the other hand, the probability of EuBL and ScBL regimes is repeatedly increased. Therefore, we can not identify a generally blocking regime reduction over the Atlantic-European region. In phase 6, 7, and 8, we clearly distinguish a favourable occurring of ScBL, EuBL and GL regimes. Beside these observations, the probability for an AR regime is increased.
Figure 4.12: Lagged occurrence frequencies (day 2–15) of the seven European weather regimes (columns) after an active MJO at day 1 in each phase (rows) during PNA+. Statistically significant results at the 95% level based on the Monte-Carlo test version 2 are shown with shading, positive significant values in dark and negative significant values in light colours. Active MJO days: 65% (Total NDJFM days: 1’867).
as well. According to the study presented by Pinto et al. (2011), there is a reduced baroclinicity in a southwest-northeast orientated band upstream of Newfoundland during PNA+. Decreased baroclinicity modulates the growth conditions for baroclinic waves on the North Atlantic storm track core. In addition, they showed that the NAO index values are typically lower during PNA+ than during PNA-. This can explain the signals in phase 6 to 8, where we find increased EuBL, GL, and AR regime frequencies (regimes with a low NAO index or reduced baroclinicity in the European weather regime pattern). The results presented by Pinto et al. (2011) are also in line with the increased frequency of ScBL regimes during phase 3 to 7. The ScBL regime, that has a slightly negative NAO index and a reduced baroclinicity pattern, is forced due to the combined appearance of MJO activity and a positive PNA phase. Climatologically, the ScBL regime occurs less than half as frequent compared to the ZO regime. Therefore, it is important to remember that less occurrences are needed for an increase up to 100% compared to the ZO regime. At last the reduced signal in phase 1 appears unexpected in contrast to the unmodified statistic (Figure 4.3). This leads to the interpretation that in some cases in phase 1, the positive PNA phase dominates the MJO influence from the tropics. Overall, we state that a positive PNA phase modifies the MJO influence on the European weather in all phases and for all regimes. In addition, it seems also possible that the PNA+ sometimes dominates the MJO influence.

During a negative PNA phase, the occurrence frequency in phase 1 is mostly increased by more than ~90% compared to the climatological expectation for the three regimes: The AT regime during lags greater than day 9, the ZO regime for lag day 4 to 11, and the ScBL regime during the first 11 lag days (Figure 4.13). The results are only significant during lag day 3 to 5 of the ScBL regime. More significant results appear for the weather regime AR: Lag 1 to 9 are significantly reduced by ~100%, so AR never occurred up to 7 days after phase 1 in PNA- conditions. The frequency of the EuBL regime is also reduced and during lag 3 to 6, the frequency is statistically significantly different from the climatological expectation. Phase 2 presents a mostly significant increase in the probability of the ZO regime. The occurrence of the AR regime is less frequent than normal, but not significant. This signal appears also in phase 3 and it is significant for lags 4 to 8. The result for the ScTr regime in phase 3 looks comparable, whereas the probability for an AT regime is significantly enhanced for many lags. A notable, but not significant increase in the probability, we observe in the frequency for the EuBL and the ScBL regimes. In phase 4, the signal for the EuBL regime persists, but the one for the ScBL regime disappears. The first three lags are significant for the ZO regime and lag 5 for the AT regime. In phase 5, we do not find a noteworthy result. Phase 6 shows a significant decrease in the frequency of the ScBL regime, which is the opposite of the results for PNA+. The frequency of AR is increased at long lags but the signal is not significant. Another clear difference to the results for PNA+ can be found for the ZO regime in phase 7 and 8. The frequency anomaly reaches for nearly half of the lag days ~100%. For PNA-, we do not see such a strong increase in GL as for most other low frequency forcings.
Figure 4.13: As in Figure 4.12, but during PNA-. Active MJO days: 61% (Total NDJFM days: 1'863).
MJO activity during PNA- leads for some regimes and phases to reversed signals in the occurrence frequency. One example represents phase 7 and 8 for the ZO, AR, and GL regime. The increased frequency of the ZO regime persists also in phase 1 and 2. Compared to the unstratified statistical analysis (Figure 4.3), the negative PNA phase strengthens this signal. This effect can not only be recognized for the ZO, but also for the AT, AR, EuBL and ScBL regime, especially in phase 1 and 3. According to Pinto et al. (2011), PNA- leads to a shift in the NAO index to more positive values. A more positive NAO index is an appropriate initial condition for ZO, AT, and EuBL regime formations. Therefore, this can explain the stronger signal of these specific regimes. A last important result is the reduction of the GL regime occurrence probability in phase 7 and 8 indicated by PNA-. The presented results for PNA- show a modulation of the MJO influence on the European weather. As the climatological geopotential height anomalies of the PNA- are roughly reversed compared to the one during PNA+, it is likely to detect also some reversed occurrence probabilities for the regimes in the Atlantic-European region.

During neutral PNA conditions, the probability occurrence of the ScBL regime is highly increased during phase 1 (Figure 4.14). The other regimes show reduced probabilities, except of the ZO and the «No Regime» regimes. Significant results are found for the AT and the ScTr regime. In phase 2 there is an increase in the probability of the blocking regimes. The only significant result can be found for the first few lags of the «No Regime». The results of phase 3 and 4 present a reduced probability for the blocking regimes. Some lags also appear significant. On the other hand, we find an increase in the ZO regime, especially during phase 4. This signal disappears for the advancing lags in phase 5 and finally changes the sign in phase 6. The frequency for the GL regime is significantly reduced in phase 5. The following phase is dominated by a highly increased probability of the AR regime and significant for lag day 7 to 12. In phase 7, we find as for most of the other low frequency forcings significantly increased frequencies for the GL regime. It is not present in phase 8, but in contrast the probability of the ZO regime is increased, especially for lag 10.

The statistical results for neutral PNA conditions resemble the ones without stratification (Figure 4.3). Therefore, phase 3 and 6 appear as early precursors for the ZO and the GL regimes. In the following phases (4 and 7, respectively), these two regimes appear twice as often for many lags. A notable difference is the mentioned reduction of the GL regime frequency afterwards. It seems that phase 8 suppresses the formation of a GL regime during a negative PNA phase. Instead, a ZO regime occurs more frequent than normal. Most of the significant results have an increased amplitude in comparison to the results in the unmodified statistical analysis (Figure 4.3). Beside the ones we already discussed, the EuBL and ScBL occurrence probabilities show much clearer positive or negative signals, especially during phase 4 to 8. From this additional details we can strongly benefit.
Figure 4.14: As in Figure 4.12, but during neutral PNA conditions. Active MJO days: 68% (Total NDJFM days: 1'867).
In summary, we introduce the influence of the MJO on the development of European weather regimes modulated by different PNA phases during Northern Hemisphere winter. Based on our results, the PNA teleconnection patterns substantially influence the European winter weather in combination with MJO activity in the tropics. Therefore, the PNA amplifies or modulates weather regime frequencies. During MJO activity, the PNA+ and the PNA- conditions often lead to reversed frequency anomalies in the European weather regimes, which is likely as the geopotential height anomalies in the Pacific-North America sector for these two phases show also a reversed pattern. Due to this influence, it is crucial to include the PNA state, if we want to identify the occurrence probability for a specific European weather regime during the Northern Hemisphere winter. The PNA modulation of the MJO signal is strongly dependent on the MJO phase.

4.5 Case Studies

Finally, we investigate in case studies if and how the statistical relationships found before hold for specific winters. Therefore, we have chosen the two recent winters 2015/16 and 2016/17 as examples for a winter with El Niño and one with neutral to weak La Niña background states. The studies are provided for the following time periods:

- Winter 15/16: 1 November 2015 until 21 March 2016
- Winter 16/17: 1 November 2016 until 21 February 2017

4.5.1 Winter 2015/16

Winter 15/16 occurred during a very strong El Niño episode. A slightly decreasing Niño-3.4 index and consequently a weakening in the El Niño state was observed in the second half of winter, but ENSO remained still in the El Niño phase. Simultaneously, the standardized PNA index increased from slightly negative values during November to positive values in January and February. The stratospheric polar vortex was mostly strong. Two main MJO activity cycles can be observed in Figure 4.15. The first started in the beginning of December, lasting approximately one month. A shorter cycle we find during February until the beginning of March. The weather regimes in colours represent lag 10, which means that the coloured regime occurred nine days after the MJO was observed in the tropics. During winter 15/16 all regimes occurred at least once.

The weather regime occurrence during winter 15/16 is mostly in line with our unstratified statistical analysis for MJO activity, with the exception of the AT regime after phase 6 and the EuBL regime after phase 8. For a more detailed analysis, we apply the statistics for El Niño episodes, positive PNA phases and strong
stratospheric polar vortex conditions. The ZO regime (red), which is generally favoured during strong stratospheric polar vortex periods, appeared frequently during phase 3, 4, and 5. In addition, a ScTr regime (orange) occurred in phase 4 and 5. A significant signal for the ScTr regime in this phase can be found in statistic including the strong polar vortex (Figure 4.6). Therefore, this rather rare appearance is consistent with our statistical analysis. The ScBL regime, which occurred during phase 5 and 6, corresponds to our findings for the lagged MJO weather regime relationship during positive PNA phases (Figure 4.12). Furthermore, the subsequent GL regime (blue) and the «No Regime» (grey) occurrence coincide with results of the PNA+ statistic either, but also with the statistical analysis during El Niño episodes. Since the analysis focusing on a strong stratospheric polar vortex shows overall decreased frequencies, the positive PNA phase and the strong El Niño event control the influence on the MJO. We find a slightly increased frequency for the AT (purple) regime occurrence after phase 6 in the statistical analysis of El Niño episodes and the strong stratospheric polar vortex conditions. Since the AT frequency is slightly decreased in the statistical analysis for PNA+, it seems that in the end of December El Niño and the strong stratospheric polar vortex were the dominant low frequency forcings, modulating the MJO weather regime relationship in phase 6. We identified an increased EuBL regime (green) frequency for lag 10 in phase 8 in the statistical analysis of the MJO activity during El Niño episodes. As mentioned in the beginning, the observed EuBL regime during win-

![Figure 4.15: Wheeler Hendon phase diagram for the NDJFM period during winter 15/16. Each dot represents one day during the case study period. The coloured line sections represent the occurred weather regime at lag day 10 using the following colour code: GL (blue), ScBL (darkgreen), EuBL (green), AR (yellow), ScTr (orange), ZO (red), AT (violet), and the «No Regime» (grey)](image)
4 Variable Impacts of the MJO on European Weather

ter 15/16 could not be explained by applying the unstratified statistic. However, this result is in line with the statistical analysis focusing on El Niño episodes. All these observations demonstrate that the stratified statistics provide more accurate and therefore very helpful insights into the MJO weather regime relationship in comparison to the unstratified statistical analysis.

4.5.2 Winter 2016/17

In contrast to the winter 15/16 (Section 4.5.2), La Niña conditions were favoured in the beginning of winter 16/17. A transition to neutral ENSO conditions was observed in January 2017. Even as the tropical Pacific Ocean returned to neutral conditions, the atmospheric impacts from La Niña could persist during the beginning of spring. Concurrently, the stratospheric polar vortex occurred weaker than in the previous year. The monthly standardized PNA index changed from positive values during November into negative values during December. The index remained negative during January and increased slightly during February. In winter 16/17, we detect two active MJO cycles: One is observed from November to December 2016 and another one from mid-January 2017 until the end of the study in February (Figure 4.16). We find mostly yellow, orange and red colours according to the AR (yellow), the ScTr (orange) and the ZO regime (red). A temporary AT (purple), a ScBL (darkgreen) and a EuBL regime (green) occurrence can be found in the second active cycle. The GL regime (blue) was absent during this winter.

![Figure 4.16: As in Figure 4.15, but for the NDJFM period during winter 16/17.](image-url)
The phase diagram for the winter 16/17 proves to be a difficult case, because at first glance weather regimes in the Atlantic-European region are not consistent with our represented results at all (unstratified and stratified statistics). Interestingly, our results and the case study agree in its order of the regime occurrence. The weather regime progression in the second cycle from AT to ScBL to EuBL to ScTr accord with the order of the significant results for the PNA- and neutral stratospheric vortex statistic. Nevertheless, they are inconsistent with the MJO phases. It seems as if the majority of the regimes occurred with a delay of approximately five days to one week during winter 16/17. An explanation for a possible delay in the occurrence of the regimes could be the fast propagation during the first cycle (November) in the phase diagram. There, the MJO often propagates through one phase within two to five days. A short phase transition time might lead to a weaker convective signal, which needs more time to affect the Atlantic-European region. On the other hand, a complex constellation of teleconnection patterns and the strength of the stratospheric polar vortex could be a reason for the late development. It is remarkable that the statistics used to analyse the winter 16/17 are highly contradictory in the probabilities for some phases, especially for the ZO and ScTr. To gain insight in this special case, we would have to provide more wintertime case studies with similar constellations to identify, whether this is a single case or not.

The presented case studies demonstrate that our statistical analysis can contribute to the window of opportunity for enhanced predictive skill of the Northern Hemisphere wintertime. Secondly, it shows that the stratified statistics for the ENSO, PNA and the stratospheric polar vortex conditions provide more accurate and therefore important insights into the relationship between the MJO and the seven Atlantic-European weather regimes. But even though the unstratified statistical analysis is a very helpful tool for analysing the influence on the European weather regime development, the real variabilities are way more complex than illustrated with the stratification for ENSO, PNA and the stratospheric polar vortex conditions. During winter, the low frequency variabilities can occur in different constellations as shown in our two case studies. Detecting the dominant modulation and understanding the interaction between the teleconnection pattern and the strength of the stratospheric polar vortex is a demanding task. If we would like to statistically analyse different constellations of frequency variabilities, the dataset is likely to become too small. Therefore, we recommend for further research projects to provide a case study for several Northern Hemisphere winters to analyse the differences between cases where the weather regime evolution was as expected by the statistical evidence («working») and cases, where it was not as expected («not working»). Further investigation of the underlying dynamics between the MJO and low frequency variabilities probably leads to a better understanding of the complex interactions.
The present thesis investigates the impacts of the MJO on European weather during the Northern Hemisphere winter in the Atlantic-European region from 1979 to 2016. A refined definition of Atlantic-European weather regimes is used to characterise the large-scale circulation in that region. It is confirmed that convectively active phases of the MJO in the tropics strongly modulate the occurrence probabilities of the different weather regimes. The change under different concomitant ENSO, PNA, or stratospheric polar vortex states alter the hemispheric background conditions. The thesis examines how the frequency of defined Atlantic-European weather regime occurrences is modulated in the time after following an MJO episode. In particular, we determined how the conditional frequency of a weather regime, occurring under a particular background state, is altered with respect to the weather regimes’ climatological occurrence frequency in extended winter (November to March). Statistical significance is tested by incorporating a Monte-Carlo simulation. The significance level for the anomalous chances in occurrence presented herein is chosen to be 95%.

Based on the statistics introduced and discussed in Chapter 4, we examine how our results might potentially contribute to the practical application for improving extended range forecasts over the Atlantic and European region. The following sections summarise our key results for the unmodulated and modulated lagged relationships between the MJO phases and the weather regimes. Finally, we open further questions and recommend further research.

5.1 The MJO Weather Regime Relationship

For the four classical weather regimes (Section 4.1), the following key results of the statistical analysis aims to replicate the results of Cassou (2008):

- Tropical convection associated with the MJO strongly modulates the occurrence probabilities of the four leading winter weather regimes in the Atlantic-European region (NAO+, NAO-, AR, ScBL), which is consistent with previ-
ous results in Cassou (2008) and others.

• Investigating an additionally «No Regime» class leads to more statistically significant results, especially for the AR and the ScBL regimes.

• To test the significance of the results, we deploy an alternative Monte-Carlo sampling approach that deals with the effects of autocorrelations in the samples. Thus, we are able to indicate the anomalous weather regime frequencies which are significant based on a conservative test.

• Our study confirms the results presented by Cassou (2008), Moore et al. (2010), and Rivière and Drouard (2015), where the MJO is found to determine the NAO phases in the Northern Hemisphere by initiating Rossby waves. Therefore, phase 3 and 6 are interpreted as precursors for NAO+ and NAO−, respectively.

• Additionally, the presented results show evidence that phase 2 acts as a precursor for a ScBL regime.

We extended the statistical analysis from four to seven European weather regimes, which is a refined and more accurate depiction of the large-scale flow. Therefore, the MJO influences on the Atlantic-European region became more obvious. The weather regimes have the following characteristics: The GL regime corresponds to the NAO−, whereas the NAO+ is particularly present in the ZO. The AR regime from the four classical weather regimes is mainly represented in the new AR regime. The AT is a variant of NAO+, whereas the ScTr is a hybrid of NAO+ and the AR. The EuBL and the ScBL regime refined the ScBL from the four classical weather regimes with a more northern and southern blocking center location, respectively.

• Investigating the seven European weather regimes leads to a more differentiated and informative outcome of the anomalous occurrence frequencies of the regimes. Thus, our study provides additional insights to the work done by Cassou (2008).

• As we found phase 3 to be a NAO+ precursor in prior statistics, the occurrence probability for a ZO regime is also significantly enhanced in the upcoming phase. On the other hand, phase 6 can act as a precursor for a negative NAO phase and for a GL regime represented in a significantly enhanced probability in phase 7 and 8. The detailed statistic provides additional information about the relationship between the MJO and positive NAO phase. The results also show evidence for an earlier NAO+ forcing through the MJO, as we identify additional positive occurrence probabilities of ~30 to 50% for the AT and the ZO regimes in phase 1 to 3.

• Further key results are the forcing of an AR regime over Northern Europe during phase 5 and 6 as well as the enhanced probability for an EuBL following an active MJO phase 2. In addition, we determine an increased likelihood for a ScBL regime over Europe during an active MJO in phase 1.
5.2 The MJO Weather Regime Relationship stratified by low Frequency Forcings

Because many signals in the statistical analysis appear simultaneously, it has been proven difficult to determine its distinct origins. It required an advanced study for analysing different background modulations that appear instantaneous to active MJO episodes. Therefore, we stratified the dataset in order to analyse the modification of the lagged MJO weather regime relationship by the strength of the stratospheric polar vortex, ENSO, and PNA. The key results of our statistical analysis for each stratification are summarized separately.

**Stratospheric Polar Vortex**

- A strong polar vortex leads to strongly enhanced probabilities in the ZO regime and reduced probabilities for the GL regime compared to the unmodified statistic. In addition, the ScBL and the EuBL regimes are suppressed by the strong polar vortex. On the other hand, the occurrence of the ScTr regimes is often favoured, especially during phase 2 to 4. Even though we recognize a dominant impact on the development of the mentioned regimes by the polar vortex, we still distinguish an influence by the MJO in the tropics. Based on our results, the MJO is responsible for a weakening or strengthening of the direct polar vortex signal.

- A weak polar vortex modifies the statistical significant results by favouring blocking regimes and constraining mainly ZO and ScTr regimes. Therefore, these signals can be associated with a direct influence of the stratospheric polar vortex. Nevertheless, we still determine impacts of the MJO in the occurrence probabilities, because it can strengthen or weaken the direct influence of the vortex in different phases, especially in the phases where we observed significant results in the previous, unmodified statistic.

- The statistical analysis including normal stratospheric polar vortex conditions shows the following results: A favourable occurrence of ScBL, EuBL, and AT regime during phase 1 to 3. Phase 3 and 6 appear as early precursors for ZO and ScTr regimes and the GL regime, respectively. The occurrence of an AR regime is already more frequent in phase 5 and the regime shows a much longer persistence during normal stratospheric polar vortex conditions.

**ENSO**

- El Niño episodes modulate the the Atlantic-European response to MJO activity in the following way: Phase 1 often seems to act as a precursor for a development of an AT regime, whereas phase 3 favours the occurrence of a ZO regime. A slightly reduction of blocking regimes is observed, but with a
5 Summary

Large phase-to-phase variability, especially for the ScBL. The development of the AR regime in phase 6 is suppressed, and instead forced in phase 8.

- During La Niña episodes, phase 3 is identified as a precursor for a positive NAO phase. This does not lead to a probability increase of the ZO regime as frequently observed in the other statistics, but rather to an enhanced occurrence frequency of the ScTr regime. The occurrence of a ZO regime is forced during phase 7 and 8.

- In conclusion, we observe for neutral ENSO conditions a forcing in the ZO regime development during phase 2 to 5 and a AR and a GL regime forcing during phase 6 to 8. A recommended adjustment is to separate advancing and declining ENSO phases, as these two seem to modulate the background state of the MJO differently. This separation might lead to a more meaningful interpretation, but only if the sample size remains sufficiently large.

PNA

- The PNA+ strongly modulates the influence of the MJO on the European weather development, especially for MJO phases 5 to 8. In these phases, the blocked regimes (EuBL, ScBL and GL) and the AR regime are clearly forced, also in comparison with the unstratified statistic. These results are in line with Pinto et al. (2011), showing that the baroclinicity in a southwest-northeast orientated band upstream of Newfoundland is decreased during PNA+. On the other hand, the AT, ZO and ScTr regimes appear frequently in the phases 1 to 4. Additionally, an active MJO in phase 1 during PNA+ conditions leads more frequently to no clear regime development in the Atlantic-European region compared to the climatology.

- To some extent, the signals are reversed for MJO episodes during negative PNA phases compared to MJO activity during PNA+. According to Pinto et al. (2011), PNA- leads to a shift in the NAO index to more positive values. A more positive NAO index is an appropriate condition for ZO, AT, and EuBL regime formations and leads probably to the observed signal strengthening for the mentioned regimes in the statistical analysis. The ScTr regime frequency is often reduced, probably due to the strong forcing of AT and ZO regimes. On the other hand, the GL regime occurs less frequently in phase 7 and 8 in comparison to the unmodulated statistic. Instead, the ZO regime is significantly enhanced after these two MJO phases. It appears for many lags twice as often compared to the climatology.

- The results for neutral PNA are very similar to the results of the overall lagged MJO weather regime relationship. Consequently, we also identify phase 3 and 6 as early precursors for the ZO and the GL regimes, respectively. In phase 8, the probability for a GL regime occurrence is clearly re-
duced compared to the unmodulated statistic, whereas the ZO regime appears more frequently than normal.

Overall, the European response to the MJO substantially changes with a varying background state due to the modulated lagged relationship between the MJO and the weather regimes by ENSO, PNA and the state of the stratospheric circulation. Therefore, we conclude that it is important to take these low frequency forcings into account in order to determine the favoured weather regimes occurring over the Atlantic-European region due to the concurrent MJO activity. Moreover, our results emphasize the importance of a correct simulation and forecast of the MJO evolution and persistence in the tropics in order to exploit the full potential predictability that the MJO may provide for sub-seasonal range weather forecasts.

5.3 Case Studies

In the final case studies, we analysed the lagged occurrence of weather regimes after active MJO periods exemplary during two Northern Hemisphere winters (2015/16 and 2016/17). In some aspects, the results are in line with the statistical analysis (in particular for winter 15/16) presented above. But there are also instances, where the weather regimes occurring after active MJO periods were surprising given the statistical expectations (in particular for winter 16/17). It would be interesting to further investigate the differences between cases where the weather regime evolution was as expected by the statistical evidence («working») as well as cases, where it was not as expected («not working»). Because it is evident that the atmospheric variabilities are more complex than illustrated in this thesis, it seems crucial to determine the resulting atmospheric signal of combined modulations for a successful forecast of the MJO and lower frequency forcings. In order to gain more insight why sometimes the weather regime evolution was as expected by the statistical evidence and sometimes not, we recommend for further research projects to provide a case study similar to ours, but for several Northern Hemisphere winters to analyse «working» and «not working» cases in comparison with the presented statistical results. Based on this specific separation and the analysis of the underlying dynamics of the cases, one could gain a better understanding of the complex interaction between the MJO and low frequency forcings.

5.4 Outlook

We propose additional future research in order to further deepen our understanding of tropical-extratropical interactions. We recommend to investigate in more detail winter weather regime transitions appearing with and without MJO activity in the tropics, including the state of low-frequency forcings. In the results of our statistics, we occasionally observed potential weather regime transition orders
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and how they changed when including also the low frequency forcings in the statistical analysis. Thus, we suspect that there are a few preferred weather regime transition cycles that could be disturbed or reorganized during active MJO phases in the tropics. The transition could be triggered from a specific MJO phase, which would act as a precursor in forecasts. On the other hand, the trigger could also be independent from a specific MJO phase and rather depend on the persistence or amplitude of a MJO episode. The findings could also lead to an explanation for our case study of the winter 16/17, which could not be sufficiently explained in the present thesis.
Acknowledgements

I wish to thank my research supervisors Remo Beerli and Dr. Christian Grams for the great support and help in achieving the numerous results presented in this thesis. I am very grateful for the many interesting discussions, for comments on the manuscript and their help with statistics. Additionally, I would like to thank them for their shared enthusiasm during the whole thesis. I appreciated all their encouragement very much.

I would also like to thank Prof. Dr. Heini Wernli and his research group for offering this fascinating thesis project and the valuable inputs and discussions during the group meetings.

I wish to thank Roman Attinger for providing the template of this thesis. The uncluttered format and stylish design is very inviting.

Finally, I must express my very profound gratitude to relatives and friends for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.


References


Michel C. and Rivière G. 2011. The link between Rossby wave breakings and weather regime transitions. *Journal of the Atmospheric Sciences*, 68 (8): 1730–1748,
References


