16-day free-traveling Rossby waves and their association with Northern Hemisphere blocking

Ernesto W. Findlay

University at Albany, State University of New York, efindlay@albany.edu

The University at Albany community has made this article openly available. Please share how this access benefits you.

Follow this and additional works at: https://scholarsarchive.library.albany.edu/legacy-etd

Part of the Atmospheric Sciences Commons

Recommended Citation

This Master’s Thesis is brought to you for free and open access by the The Graduate School at Scholars Archive. It has been accepted for inclusion in Legacy Theses & Dissertations (2009-2024) by an authorized administrator of Scholars Archive. Please see Terms of Use. For more information, please contact scholarsarchive@albany.edu.
16-DAY FREE-TRAVELING ROSSBY WAVES AND THEIR ASSOCIATION WITH NORTHERN HEMISPHERE BLOCKING

by

Ernesto W. Findlay

A thesis
Submitted to the University at Albany, State University of New York
in partial fulfillment of
the requirements for the Degree of
Master of Science

College of Arts and Sciences
Department of Atmospheric and Environmental Sciences
2019
ABSTRACT

An analysis of the 16-day free Rossby wave is performed. The behavior of this wave includes a barotropic vertical structure that is independent of local forcing. An Empirical Orthogonal Function (EOF) analysis was performed on 15–30-day filtered geopotential height anomalies to extract the spatial patterns of the wave. Results show that the first two EOFs are in quadrature with each other, representing a westward moving signal with an average period of around 23 days and a phase velocity of $15 \text{ m s}^{-1}$. The Principal Components (PCs) from these EOFs were used to construct a 16-day wave index, which was employed as a tool to monitor and track the 16-day wave across eight phases. A composite analysis of each phase was performed to analyze the spatial structures of the wave, which is represented by a wavenumber-one pattern in the geopotential height anomaly field. The signal has the same sign in the Southern Hemisphere, but with amplitude smaller than that in the Northern Hemisphere. Meridional temperature transport plays a role in the westward movement of the geopotential height anomalies. A vertical composite of the wave was also performed for each of the phases of the index. Results show that the vertical structure is consistent with that theorized and with the previously observed vertical structure of the wave.

An analysis of the possible links of this wave to Northern Hemisphere blocking was conducted. It was found that the North Atlantic Oscillation was more likely to be negative during phases where ridging was expected by the 16-day index in the North Atlantic. In addition, a blocking index was developed to extract events for the Pacific region. The index shows that the largest number of blocking events occurred when the wave index was in phase 5, which is categorized by ridging anomalies over the North Pacific region. Furthermore, when data were split
into their transient and stationary components, a larger number of transient ridging events were encountered during phases 4–6 blocking episodes.
# Table of Contents

Abstract............................................................................................................................................................. iii

List of Figures.................................................................................................................................................... v

List of Tables ................................................................................................................................................... viii

1. Introduction ................................................................................................................................................. 1
   1.1 Motivation............................................................................................................................................... 1
   1.2 Literature review ..................................................................................................................................... 1
      1.2.1 Large-scale free Rossby wave theory and structure ............................................................. 1
      1.2.2 Observations ................................................................................................................................. 2
      1.2.3 Effects on weather and climate ................................................................................................. 3
   1.3 Research goals and thesis structure .................................................................................................... 4

2. Data and methods ......................................................................................................................................... 7
   2.1 Data .......................................................................................................................................................... 7
   2.2 Methods ................................................................................................................................................. 7
      2.2.1 Spectral analysis ............................................................................................................................. 7
      2.2.2 Empirical Orthogonal Function (EOF) analysis ........................................................................ 7
      2.2.3 The 16-day Rossby–Haurwitz wave index (RHWI) ................................................................. 8
      2.2.4 Blocking analysis ......................................................................................................................... 8

3. Results and discussion ............................................................................................................................... 12
   3.1 Spectral analysis .................................................................................................................................... 12
   3.2 EOF analysis ......................................................................................................................................... 12
   3.3 The 16-day Rossby–Haurwitz wave index (RHWI) ............................................................................. 13
      3.3.1 Phase composites ......................................................................................................................... 13
      3.3.2 Vertical composites ...................................................................................................................... 15
   3.4 Blocking ................................................................................................................................................ 15
      3.4.1 North Atlantic Oscillation comparison .................................................................................... 15
      3.4.2 Blocking index analysis .............................................................................................................. 16

4. Conclusions and future work .................................................................................................................... 35
List of Figures

Fig. 1.1 Hough function depictions of the latitudinal structure of $u$ (dashed), $v$ (dotted), and $Z$ (solid) for zonal wavenumber $s$ (rows), and meridional index $l–s$ (columns). Hough functions are after Kasahara (1976). Each variable is normalized to a maximum amplitude of one. Adapted from Madden (2007).

Fig. 1.2 Schematic view of geopotential height and velocity fields for the generalized Laplace tidal equations modes for zonal wave number $s=1$ and meridional wavenumber $l=1$. L and H denote the location of low and high pressure center, respectively. Adapted from Alhquist (1982).

Fig. 2.1 Frequency of blocked flow during the winter season for 55°N–75°N (star line), 50°N–70°N (circle line), 45°N–65°N (triangle line), and 40°N–60°N (square line) latitude bands.

Fig. 3.1 Space–time coherence-squared spectrum (contours) for anomalies in the latitude range 15°N–15°S symmetric about the equator in geopotential height for the DJF season. Solid dispersion curves are those for Kelvin, equatorial Rossby (ER), symmetric inertio–gravity (IG), Antisymmetric Westward Mixed Rossby Gravity (MRG), and eastward inertio–gravity (EIG).

Fig. 3.2 As in Fig. 3.1, but antisymmetric about the equator.

Fig. 3.3 As in Fig. 3.1, but for the JJA season.
Fig. 3.4. As in Fig. 3.2, but for the JJA season.

Fig. 3.5 Spatial structures of EOFs 1 and 2 of the normalized 500-hPa geopotential height. The variance explained by the respective EOFs is 39.8% and 41.2%.

Fig. 3.6 Day-lag correlation of EOF 2 with respect to EOF 1.

Fig. 3.7 PC1 and PC2 phase space points. Labeled are the approximate locations of the 16-day Rossby–Haurwitz wave.

Fig. 3.8 Composite of the standardized anomaly of geopotential height for all phases (σ, shaded). Hatch areas are statistically significant at the 95% level.

Fig. 3.9 Composite of the standardized anomaly of air temperatures for all phases (σ, shaded). Hatch areas are statistically significant at the 95% level.

Fig. 3.10 As in Fig. 3.8, but for DJF.

Fig. 3.11 As in Fig. 3.8, but for JJA.

Fig. 3.12 Vertical composite of geopotential height anomalies for phases 1(a), 3(b), 5(c), and 7(d) along 80°N.
Fig. 3.13 Estimated amplitudes (solid circles) a of the 16-day wave at 30°N during the winter determined from a compositing procedure discussed by Madden (1978). The dashed line is the theoretical expectation of an external wave. Adapted from Madden (1978).

Fig. 3.14 Composite of 500-hPa standardized geopotential height for the Atlantic (55°N–75°N to 45°W–75°W) basin blocking index.

Fig. 3.15 Same as Fig. 3.14, but for the Pacific Basin (55°N–75°N to 165°E–165°W).

Fig. 4.1. Schematic view of the 16-day Rossby–Haurwaitz wave.
List of Tables

Table 3.1. Listing of NAO index values for each phase of the RHWI during the DJF season.

Table 3.2. Listing of values of the stationary and transient components of the 500-hPa geopotential height for each phase of the RHWI for the Pacific Region during blocking episodes.
1. Introduction

1.1 Motivation

Atmospheric blocking plays a significant role in day to day weather prediction, as these events tend to lock in a weather pattern for several days to several weeks. Increased knowledge about blocking has found that planetary waves play a significant role in the initiation, maintenance, and end of blocking episodes (Austin 1980); however, little work has been done to identify the specific type(s) of waves. This study focuses on one type of planetary Rossby wave, named the 16-day wave, and how this wave plays a role in blocking episodes.

1.2 Literature review

1.2.1 Large-scale free Rossby wave theory and structure

The large-scale Rossby–Haurwitz wave (RH) exists as a free oscillation of the atmosphere, with the wave controlled by the rotation of the Earth, rather than gravity or interaction with thermal forcing. Thus, the structure of the wave in the vertical is barotropic with its phase remaining constant with increasing height (Haurwitz 1937). Rossby (1939) derived a wave dispersion relationship for barotropic non-divergent flow:

\[ C_k = U - \beta / k^2 \]

where \( C_k \) is the zonal phase speed, \( U \) is a constant background zonal wind, \( k \) is the zonal wave number, and \( \beta \) is the meridional gradient of planetary vorticity. This simple equation, which employs the geometry of a plane, is what forecasters used to predict the speeds of the waves. Hauwritz (1940) used a more realistic spherical geometry and showed that the horizontal structures of these waves are described by Legendre polynomials. These polynomials are characterized by
zonal wave number $s$ and meridional index $l$. The difference $l-s$ is the number of zeroes in the stream function between the North and South Poles.

In this scenario, waves are non-divergent, which does not provide an accurate estimate of the waves’ phase speeds. Later, Laplace tidal equations were used to allow for divergence; these equations were used to derive Hough functions (Longuet–Hough 1968). Fig.1.1 shows the Hough functions for the latitudinal structures of geopotential height ($Z$), zonal wind ($u$), and meridional wind ($v$) for zonal wavenumbers 1–4 and $l-s =0–4$. For this study, the focus will be on $s$, $l-s (1,1)$, which is the five-day wave and $s$, $l-s (1,3)$ which is the 16-day wave.

The vertical structure of these waves is that of a Lamb wave (Lamb 1932; Lindzen 1967). These waves are barotropic in the vertical with energy decaying with height, and $Z$, $u$, and $v$ perturbations increasing with height. Many studies have been done comparing the structures of these waves to that of Lamb waves (Madden 1978; Speth and Madden 1983; Hirota and Hirooka 1984; Hirooka 2000).

1.2.2 Observations

The five-day and 16-day waves were first presented by Eliasen and Machenhauer (1965). Following this study, many observational analyses were performed finding evidence of the waves, detailing their structure, and discovering other RH waves exist throughout the troposphere, stratosphere, and higher atmosphere (Madden 1975, Madden 1978, 1979; Ahlquist 1982; Hirooka and Hirota 1989; Hirooka 2000). Madden (1978) discovered that the five-day wave coherence is higher during the summer and the 16-day wave coherence is more active during the winter. Madden (1979) found that the amplitude of these increases with height. The amplitude of the five-
day was found to increase from 5 m at 850 hPa to 7 m at 200 hPa, while the 16-day wave was seen to increase from 50 m at 850 hPa to 120 m at 30 hPa.

Ahlquist (1982) used reanalysis data to extract the horizontal structure of the waves. Fig. 1.2 shows a schematic view of the horizontal structure of the geopotential height and velocity for \( s, l-s \) = 1, 1 and 1, 3, which are the five-day and 16-day waves, respectively. In the five-day wave, geopotential perturbations are highest in the midlatitudes and decay towards the poles and equator. In the 16-day wave, geopotential perturbations are highest in the high latitudes with weaker perturbations of the opposite sign at lower latitudes near the equator. Interestingly, the amplitudes of the geopotential perturbations are highest in the Northern Hemisphere; the reasons as to why this is the case are still being argued today (Madden 1979; Lindzen 1984; Weber and Madden 1993).

More recent studies have found evidence of the existence of these waves using radar and satellite observations (Wu et al. 1993; Forbes 1995; Day and Mitchell 2010; Das et al. 2010).

1.2.3 Effects on weather and climate

Despite the barotropic vertical structure and nondivergent horizontal structure of the RH waves, suggesting a minimal relation to vertical and horizontal transport in the atmosphere, there are significant links between these waves and their effects on the general atmospheric circulation. Madden (1975, 1978) suggested that constructive and destructive interference between these waves and forced waves can create time-mean perturbations in the horizontal heat transport and atmospheric energetics. Later, many studies showed that a resonance effect between forced and traveling waves could create time variation in transports (Palmer 1981; Lindzen 1982; Salby 1984) and heat and momentum transports in models (Hirota 1971; Garcia and Geisler 1981; Lindzen
Burpee (1976) found that a global scale, 4–5-day pressure wave modulates precipitation in the tropical regions by as much as 10%. King et al. (2015) discovered that the five-day waves produce a high variance in the precipitation and outgoing long-wave radiation (OLR) in the tropical mountain ranges due to orographic forcing.

RH waves have also been linked to blocking episodes (Lindzen 1986; Quiroz 1987; Lejenäs and Döös 1987; Lejenäs and Madden 1992). Austin (1980) found that the amplitude of wavenumbers 1–3 was large during blocking episodes over the Pacific and the Atlantic Oceans. She also found that a westward-propagating wavenumber-one wave played a significant role in initiating some blocking episodes.

Most of these studies suggested that westward moving free waves may play a role in blocking, but further investigation is needed. This study brings more insight to this topic.

1.3 Research goals and thesis structure

The main goal of this research is to provide forecasters with a tool that will allow them to track and trace free Rossby waves, especially the 16-day wave. In addition, the goal is to bring more insight into how much of a role this wave plays during blocking episodes and to provide another tool to help better forecast blocking episodes.

This study begins by gathering reanalysis data. These data are then used to obtain a spectrum of variability of these fields. Further analysis is done to extract the 16-day wave, from which a phase diagram is created to trace the wave as it moves around the globe. A composite structure of this wave is built for each phase to analyze the vertical and horizontal structure as well as its propagation around the globe. Next, the tracking method is used to provide insight into whether there is a correlation between phase and blocking episodes as well as links to the strength of blocking episodes by phase.
Fig. 1.1 Hough function depictions of the latitudinal structure of $u$ (dashed), $v$ (dotted), and $Z$ (solid) for zonal wavenumber $s$ (rows), and meridional index $l-s$ (columns). Hough functions are after Kasahara (1976). Each variable is normalized to a maximum amplitude of one. Adapted from Madden (2007).
Fig. 1.2 Schematic view of geopotential height and velocity fields for the generalized Laplace tidal equations modes for zonal wave number $s=1$ and meridional wavenumber $l=1$. L and H denote the location of low and high pressure center, respectively. Adapted from Alhquist (1982)
2. Data and methods

2.1 Data

The National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset from 1985–2010 was used (Kalnay et al. 1996). From this dataset, the six-hourly average geopotential height and temperature at all levels were obtained.

2.2 Methods

2.2.1 Spectral analysis

To diagnose the source of variability in the relative height field, a space–time spectral method similar to that used by Hendon and Wheeler (2008), was performed. Height data at 500 hPa was partitioned into symmetric and antisymmetric components about the equator and then broken into 96-day long segments that overlap with adjacent segments by 95 days. These data segments are detrended, and the ends are tapered to zero by a half-cosine function covering the first and last five days. This process is performed from 15°N–15°S. A two-dimensional (2D) Fourier Transform (FT) of the detrended data is performed at each symmetric and antisymmetric latitude up to 15° from the equator by first undergoing a complex FT in longitude for each latitude and time, and then a complex FT in time on these Fourier coefficients of each latitude. Annual spectral power and cross powers from these 2D FTs are obtained then averaged into two seasonal bands. The seasonal bands investigated are June–August (JJA) and December–February (DJF).

2.2.2 Empirical Orthogonal Function (EOF) analysis

An EOF analysis is conducted to track and monitor the 16-day wave. For the EOF analysis, the height data is space–time bandpass filtered following Wheeler and Kiladis (1999). The data
are first detrended and then filtered using a 2D Fast Fourier Transform (FFT). From these data, the covariance matrix method was used to calculate the eigenvectors. Principal components (PCs) are obtained from these eigenvectors and later used to create the index used to monitor and track the 16-day wave.

2.2.3 The 16-day Rossby–Haurwitz wave index (RHWI)

An eight-phase index was created using a similar method as the Hendon and Wheeler (2004) RMM index. The six-hourly data was averaged to obtain a daily mean and was then averaged vertically to diagnose barotropic structure. Standardized anomalies were constructed by subtracting the mean and seasonal cycle along with the first three harmonics, and then divided by the seasonal standard deviation at each grid point. Composites for each phase were obtained from the standardized geopotential height and temperature data. In addition, composites of standardized geopotential height anomalies were constructed for each phase to study the vertical structure of the wave. Composites were divided into two seasonal periods, JJA and DJF. All analyses were done for different latitude bands and different seasons, but yielded no significantly different results.

2.2.4 Blocking analysis

The relationship between blocking and the 16-day was analyzed via two methods. In the first method, the North Atlantic Oscillation (NAO) index was obtained for each day from 1 January 1985 to 31 December 2010. Next, cases were divided by phases and between negative and positive NAO index values to analyze the frequency of these events during each phase of the RHWI.
The above method only diagnoses the link of the 16-day wave to blocking in the NAO region. To further analyze the links of the 16-day wave to blocking on other regions, a blocking index was developed. The 500-hPa geopotential height data was Fourier analyzed along each 5° of latitude from 5° N to 85° N retaining the first 18 wavenumbers. The aim is to diagnose the links of planetary-scale waves, such as the 16-day wave, on blocking; therefore, only the first three wavenumbers, i.e., the low frequency of part of the spectrum, are included to compute the blocking index. Blocked flow was identified in the same manner as Lajenäs and Okland (1983) using the following expression to compute the index:

$$BL(\lambda, t) = h_{\varphi 1}(\lambda, t) - h_{\varphi 2}(\lambda, t)$$ (1)

where $h_{\varphi 1}$ is the southern geopotential height and $h_{\varphi 2}$ is the northern geopotential height; therefore, when (1) is negative on a particular day, it is counted as a blocked-flow day.

Fig 2.1 shows the frequency of blocked-flow days as a function of longitude during DJF for several latitude ranges. This result shows that there is a maximum in the frequency of blocked-flow days in the 55°–75°N latitude band around 180° of 42%, with smaller peaks around 60°W and 60°E of around 6%. Going forward, the 55°–75° N latitude band will be used to calculate the blocking index for two regions, the Pacific region (180°) and the Atlantic region (60°E). To study the role of planetary waves, such as the 16-day wave, on blocking more in detail, all blocked-flow days were extracted using expression (1). To eliminate cases with little horizontal extent, the methods used in Lajenas and Okland (1983) were followed. In addition, the blocking index was averaged over a 30° of longitude centered at 180° (Pacific region) and 60°E (Atlantic region).

To further investigate the specific role of the 16-day wave, the data was partitioned into transient and stationary components. Following Eliaisen and Machenauer (1965), the 500-hPa geopotential height was partitioned for a latitude line into a quasi-stationary part ($Z_{st}$), computed
as a running time average, and a transient part \((z_{TR})\), being the difference between the observed geopotential height value and the stationary part. The length of time used to calculate the running average was 15 days, following Elíasen and Machenhauer (1965).

Finally, cases were divided by phases, and by positive and negative anomalies of the stationary and transient components, to analyze the frequency of each component during each phase of the 16-day wave index during blocked-flow days.
Fig. 2.1 Frequency of blocked flow during the winter season for 55°N–75°N (star line), 50°N–70°N (circle line), 45°N–65°N (triangle line), and 40°N–60°N (square line) latitude bands.
3. Results and discussion

3.1 Spectral analysis

Fig. 3.1 shows the symmetric wavenumber–frequency power spectra of geopotential height in the range 15°N–15°S for the DJF season. A region of high power in the 3–6-day period belongs to the symmetric RH waves, which exist for westward-propagating wavenumbers 1–5. A second peak in the 10–30-day period and westward propagating wavenumbers 1–2 is likely that of the 16-day wave. There is another peak centered on the eastward-propagating wavenumbers 5–7, which follows the theoretical Kelvin waves at short timescales (probably a barotropic Kelvin wave); this peak will not be discussed here. The antisymmetric power (Fig. 3.2) shows a peak along the 10–30-day period, which is thought to be the 16-day wave. Even though the wave, in theory, is symmetric during the DJF season, there is a significant amount of power asymmetric in the region of this wave, with a noisy look in the Southern Hemisphere that is not well understood. This point is supported by Figs. 3.3 3.4 by the increase in power in the symmetric part of the spectrum and a decrease in power in the antisymmetric part of the spectrum during JJA in the 10–30-day period and wavenumbers 1–3.

3.2 EOF analysis

The spatial structures of the leading two EOFs are presented in Fig. 3.5. Together, EOF1 and EOF2 explain about 81% (39.8% and 41.2%, respectively) of the variance of the original field. In addition, the first two EOFs are well separated from the remaining EOFs, based on the criteria of North et al. (1982) (EOF3 explains only 10% of the variance). EOF1 peaks at the longitudes of Africa: positive geopotential height anomalies extend throughout the Indian Ocean region and the western Atlantic Ocean, and negative anomalies extend from the Maritime Continent to the eastern
Atlantic Ocean. EOF2 has positive geopotential height anomalies over the eastern Atlantic Ocean that are in quadrature to those of EOF1. Fig 3.6 shows the day-lag correlation between EOF1 and EOF2, with EOF2 leading EOF1 by five days, suggesting that this is a westward-moving pattern. In addition, the figure also shows an approximately 23-day oscillation in this mode.

3.3 16-day Rossby–Haurwitz wave index (RHWI)

From EOF1 and EOF2, PCs were derived and then plotted in an eight-phase space diagram. Figure 3.7 illustrates the phase space plotting format for the RHWI. The location of the RH wave is objectively defined by drawing a line in the inflection point between a ridge (west) and trough (east) north of the 60°N. This method was employed due to the persistent wavenumber-one pattern throughout all composites north of 60°N.

3.3.1 Phase composites

Figure 3.8 shows an annual phase composite of normalized height anomalies for all eight phases of the RHWI, while Fig. 3.9 shows an annual phase composite of standardized air temperature anomalies for all eight phases of the RHWI. Throughout all eight phases, both the height and temperature fields are symmetric across the equator, where the anomaly structure dominates in the Northern Hemisphere. Nevertheless, there is also symmetry across the equator where there are anomalies of the same sign across the mid- to high-latitudes of both hemispheres. In the equatorial region, there are anomalies of the opposite sign from those found at higher latitudes; these anomalies are also symmetric across the equator. Furthermore, all anomalies are moving westward. This pattern resembles the theoretical structure of a Rossby–Haurwitz wave.
Throughout the rest of this section, the focus is on the Northern Hemisphere exclusively, as anomalies have similar structure in the Southern Hemisphere, but are weaker in most cases. All anomalies are less than 0.25 sigma. The average amplitude is small because there are close to 1200 cases acting over a wide range of amplitudes in each phase, including a large number of relatively weak events. Nevertheless, these anomalies are statistically significant due to the retention of their structure over so many cases.

It is observed in phase 1 (Fig. 3.8a) that there is a wavenumber-one pattern in the height field, with positive height anomalies (ridging) confined to northern Europe, across most of the continental United States, and the tropical western Pacific Ocean. Negative height anomalies (troughing) are confined to western northern Asia and the northern Pacific. Under the ridge anomalies, there are warm temperature anomalies (Fig. 3.9) and under the trough, cold anomalies. In phase 3 (Fig. 3.8), anomalies have moved westward, with ridge anomalies located over northern North America and trough anomalies located over most of Eastern Europe, most of northern Asia, and Central America and northern South America. By phase 7 (Fig. 3.9g), ridge anomalies have moved to northern Asia, while trough anomalies have moved over northern North America, the Indian Ocean, and the Maritime Continent.

Figures 3.10 and 3.11 show the seasonality in the structure of the geopotential height anomalies. In DJF, there is a more defined Northern Hemisphere wavenumber-one pattern versus the pattern in JJA, which is similar but with weaker anomalies. The Southern Hemisphere signal is more difficult to spot and it is slightly more coherent during JJA. The weakening of the geopotential height anomalies during DJF in the Northern Hemisphere and the slightly more organized signal in the Southern Hemisphere work together to increase the symmetric structure in the wave during JJA, which is consistent with spectral analysis.
3.3.2 Vertical composites.

Fig. 3.12 shows the vertical structure of the 500-hPa geopotential field for a few of the phases of the 16-day wave index. In phases 1, 3, and 7, the wave has a deep vertical extent from 850 hPa to 10 hPa, slowly growing with height from about 30 m to over 100 m at 10 hPa. This result is consistent with the theoretical and observed vertical structure of the wave found by Madden (1979) (Fig. 3.13). Phase 5 (Fig. 3.13e) shows a substantial weakening of the overall structure of the wave. Even though this wave in theory is a free wave, there may be some not well-understood process that destructively interferes with the overall structure of the wave in this phase.

3.4 Blocking

3.4.1 North Atlantic Oscillation (NAO) comparison

Table 1 shows the values of the NAO index for each phase of the RHWI. During the first three phases of the RHWI, there are more cases of negative NAO. Negative NAO values tend to have Greenland ridging, which often lead to North Atlantic blocking episodes. Noting Fig. 3.10a–c, these phases are categorized by North Atlantic ridging by the 16-day wave. Phase 4 is also categorized by ridging in the mid-Atlantic; nevertheless, there are more cases of positive NAO during this phase. This index only looks at 15–30-day time scales and wavenumbers 1–3, so there are many other timescales and wavenumbers that can be contributing to the outcomes in phase 4. Phases 5–8 (Fig. 3.10e–h) are categorized by trough anomalies in the North Atlantic region, which correlates with the increasing number of positive NAO index values during these phases.
3.4.2 Blocking index analysis.

The above method only diagnoses one sector in which blocking is dominant; in addition, the NAO is also a smaller-scale feature compared to the 16-day wave, which is a planetary-type wave. Thus, we developed a blocking index that diagnoses the contribution to blocking by only the first three wavenumbers. Figure 3.14 shows the composite structure of the blocking index during DJF for the Atlantic region (55°N–75°N to 45°W–75°W), while Fig. 3.15 shows the same composite structure but for the Pacific region (55°N–75°N to 165°E–165°W). The main difference between these two basins is that Atlantic region blocking episodes resemble more of a wavenumber-two pattern in the geopotential height field, while the Pacific region is a wavenumber-one pattern.

It is known that standing background waves significantly contribute to the outcomes of blocking waves (Lajenäs and Doobs 1987). In this study, we are interested in how the 16-day wave, which is a traveling wave, contributes to blocking. Therefore, the geopotential height field was split into its stationary and transient components. Table 2 shows values of the stationary and transient components of the 500-hPa geopotential height for each phase of the RHWI for the Pacific Region during blocking episodes. The Atlantic region was not included for lack of events, which prevented significant results. As mentioned before, only 6% of days have blocked flow during DJF, because smaller-scales waves may have a more significant contribution to blocking in this region.

From Table 2, phases 1–3 have a more significant number of negative stationary and transient components during blocking episodes. This result is consistent with Fig. 3.10 a–c, which shows trough anomalies in the Pacific region during these phases and, therefore, smaller scales are possibly contributing significantly to blocking in these phases. During phases 4–8, there is a higher
number of positive, transient ridging anomalies during blocking episodes, which is also consistent with the riding anomalies during phases 5–8 in the RHWI index (Fig. 3.10 e–h).
Fig 3.1 Space–time coherence-squared spectrum (contours) for anomalies in the latitude range 15°N–15°S symmetric about the equator in geopotential height for the DJF season. Solid dispersion curves are those for Kelvin, equatorial Rossby (ER), symmetric inertio–gravity (IG), Antisymmetric Westward Mixed Rossby Gravity (MRG), and eastward inertio–gravity (EIG).
Fig. 3.2 As in Fig. 3.1, but antisymmetric about the equator.
Fig 3.3 As in Fig. 3.1, but for JJA.
Fig 3.4. As in Fig. 3.2, but for JJA.
Fig. 3.5 Spatial structures of EOFs 1 and 2 of the normalized 500-hPa geopotential height. The variance explained by the respective EOFs is 39.8% and 41.2%
Fig. 3.6 Day-lag correlation of PC 2 with respect to PC 1.
Fig. 3.7 PC1 and PC2 phase space points. Labeled are the approximate locations of the 16-day Rossby–Haurwitz wave.
Fig. 3.8 Composite of standardized anomaly of geopotential height for all phases ($\sigma$, shaded).

Hatch areas are statistically significant at the 95% level.
Fig. 3.9 Composite of standardized anomaly of air temperatures for all phases ($\sigma$, shaded). Hatch areas are statistically significant at the 95% level.
Fig 3.10 As in Fig. 3.8, but for DJF.
Fig. 3.11 As in Fig. 3.8, but for JJA.
Fig 3.12 Vertical composite of geopotential height anomalies for phases 1(a), 3(b), 5(c), and 7(d) along 80°N.
Fig. 3.13 Estimated amplitudes (solid circles) of the 16-day wave at 30°N during the winter determined from a compositing procedure discussed by Madden (1978). The dashed line is the theoretical expectation of an external wave. Adapted from Madden (1978).
Table 3.1. Listing of NAO index values for each phase of the RHWI during DJF.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Case Count</th>
<th>Positive NAO</th>
<th>Negative NAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>267</td>
<td>119</td>
<td>148</td>
</tr>
<tr>
<td>2</td>
<td>276</td>
<td>90</td>
<td>186</td>
</tr>
<tr>
<td>3</td>
<td>289</td>
<td>106</td>
<td>183</td>
</tr>
<tr>
<td>4</td>
<td>284</td>
<td>159</td>
<td>125</td>
</tr>
<tr>
<td>5</td>
<td>286</td>
<td>224</td>
<td>62</td>
</tr>
<tr>
<td>6</td>
<td>260</td>
<td>227</td>
<td>33</td>
</tr>
<tr>
<td>7</td>
<td>287</td>
<td>225</td>
<td>62</td>
</tr>
<tr>
<td>8</td>
<td>302</td>
<td>220</td>
<td>82</td>
</tr>
</tbody>
</table>
Fig. 3.14 Composite of 500-hPa standardized geopotential height for the Atlantic (55°N–75°N to 45° W–75° W) basin blocking index.
Fig. 3.15 As in Fig. 3.14, but for the Pacific basin (55°N–75°N to 165°E–165° W).
Table 3.2. Listing of values of the stationary and transient components of the 500-hPa geopotential height for each phase of the RHWI for the Pacific Region during blocking episodes.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Case Count</th>
<th>Stationary Positive</th>
<th>Stationary Negative</th>
<th>Transient Positive</th>
<th>Transient Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90</td>
<td>40</td>
<td>50</td>
<td>42</td>
<td>48</td>
</tr>
<tr>
<td>2</td>
<td>101</td>
<td>45</td>
<td>56</td>
<td>41</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>129</td>
<td>49</td>
<td>80</td>
<td>59</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>113</td>
<td>47</td>
<td>66</td>
<td>70</td>
<td>43</td>
</tr>
<tr>
<td>5</td>
<td>125</td>
<td>68</td>
<td>47</td>
<td>84</td>
<td>41</td>
</tr>
<tr>
<td>6</td>
<td>105</td>
<td>52</td>
<td>53</td>
<td>65</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>116</td>
<td>58</td>
<td>58</td>
<td>64</td>
<td>52</td>
</tr>
<tr>
<td>8</td>
<td>98</td>
<td>56</td>
<td>42</td>
<td>60</td>
<td>38</td>
</tr>
</tbody>
</table>
4. Conclusions and future work

The 16-day wave was analyzed throughout this study. A wavenumber–frequency spectra analysis was done to diagnose the source of variability in the geopotential height fields. Several peaks were found including those of the five-day and 16-day waves. The 16-day wave was found to also have a signal in the antisymmetric part of the spectrum. Even though this wave is theorized to be symmetric across the equator, there are asymmetric signals associated with it, mainly because the structure of this wave is less coherent in the Southern Hemisphere, especially during the Southern Hemisphere summer. The reasoning why this is the case needs to be further explored.

From this spectral peak, an EOF analysis was performed to extract the dominant spatial patterns. Results showed that the first two EOFs contain 80% of the variance. The first two EOFs are in quadrature with each other in space, and their associated Principal Components (PCs) are in quadrature in time, so that they together represent a westward-moving signal with an average period of around 23 days and a phase velocity of $15 \text{ m s}^{-1}$, which was consistent with the theorized and previously observed spatial structures and phase velocity of the 16-day wave.

The PCs were used to build the so-called RHWI, similar to the eight-phase RMM index of the Madden–Julian Oscillation, which was used as a tool to monitor and track this 16-day RH wave. A composite analysis of each phase was performed to analyze the spatial structure of this wave. Fig. 4.1 shows a schematic view of the spatial structure of the 16-day RH wave.

This wave is represented by a wavenumber-one pattern in the geopotential height anomaly field that is of the same sign across the equator in the Southern Hemisphere, but with reduced amplitude. Ahead of the ridge anomalies, northward transport of heat acts to build a ridge in the Northern Hemisphere. Trailing the ridge anomalies, northward energy transport weakens the ridge anomalies in the high latitudes and allows for cold anomalies to build at low latitudes. As the
trough approaches, energy transport turns poleward, allowing for warm anomalies in the low latitudes to be carried northward, and allow for the anomalies to build at the middle and high latitudes. Behind the trough, southward transport of energy allows for cold anomalies to build at low latitudes, completing the cycle. In addition, a vertical composite of this wave was constructed. These vertical composites were also consistent with the previously observed vertical structure of the 16-day wave.

Finally, blocking episodes were linked by two methods. First, using the NAO index as an indicator of blocking, it was found that an increasing number of negative NAO events occur during phases 1–3 of the RHWI, which are characterized by ridging anomalies over the North Atlantic region, while in phases 5–8, a higher number of positive NAO episodes were found, which is consistent with trough anomalies over the North Atlantic region. Even though a link was found between the NAO and the 16-day wave, the NAO often projects onto signals at different spatial scales. In addition, the NAO also located over the North Atlantic, which is only one region in which blocking occurs.

Lastly, a blocking index was developed that diagnoses the contribution to blocking by using only the first three wavenumbers. From the index, the composite structure over the Atlantic resembles more of a wavenumber-two pattern in the geopotential height field, while the Pacific region is a wavenumber-one pattern. When splitting the geopotential height field into the stationary and transient components, phases 1–3 have a higher number of negative stationary and transient components during blocking episodes, while during phases 4–8 there is a higher number of positive transient ridging anomalies during blocking episodes. Both are consistent in terms of the expected structure of the 16-day wave, which is a transient wave during those phases.
Even though this study provided some insight into the behavior and tracking of the 16-day and links to blocking, several questions still need to be answered:

- Is the RHWI a reliable way to track the 16-day wave?
- What are the dynamical contributions by the 16-day to blocking?

To address the first question, further studies need to be performed to further test the developed index. One caveat about this index is that even though a filter was used to acquire the 16-day, there is a possibility that other things can act at the same scales of time and space. One possible way to analyze contributions of other signals will be to perform several case studies to extract the wave from both reforecast and reanalysis data.

To address the second question, a budget analysis on the geopotential field can be performed. This additional analysis will help quantify the contributions from the 16-day wave to blocking, in addition to bringing insights into how dynamically this wave contributes to the initiation, maintenance, and decay of blocking episodes.
Fig. 4.1. Schematic view of the 16-day Rossby–Haurwitz wave.
Bibliography


