A Zonal Wavenumber-3 Pattern of Northern Hemisphere Wintertime Planetary Wave Variability at High Latitudes

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A prominent pattern of variability of the Northern Hemisphere wintertime tropospheric planetary waves, which is referred to here as the Wave3 pattern, is identified based on the NCEP/NCAR reanalysis. It is worthy of attention because its structure is similar to the linear trend pattern as well as the leading pattern of multi-decadal variability of the planetary waves during the past half century.

The Wave3 pattern is defined as the second empirical orthogonal function (EOF) of detrended December-February mean 300 hPa meridional wind (V300) and denotes a zonal shift of the ridges and troughs of the climatological flow. Although its interannual variance is roughly comparable to that of EOF1 of V300, which represents the Pacific/North America (PNA) pattern, its multi-decadal variance is nearly twice as large as that of the PNA. Wave3 is not completely structurally or temporally distinct from the Northern Annular Mode (NAM), but for some attributes the linkage of the observed trend, to Wave3 is clearer than to NAM.

The prominence of the Wave3 pattern is further supported by attributes of many climate models that participated in phase 3 of the Coupled Model Intercomparison Project (CMIP3). In particular, in the Community Climate System Model version 3 (CCSM3), the Wave3 pattern is present as EOF3 of V300 in both a fully coupled integration and a stand-alone atmospheric integration forced by climatological sea surface temperatures. Its existence in the latter experiment indicates that the pattern can be produced by atmospheric processes alone.
1. Introduction

In spite of all the effort that has gone into identifying recurrent patterns of seasonal mean atmospheric circulation anomalies (e.g. the teleconnection patterns of Wallace and Gutzler (1981)), there is still the possibility that there are additional patterns that are worth knowing about. This may be true for several reasons including a) as time goes on the collection of observed states becomes larger, enabling recognition of patterns whose significance could not be established with shorter datasets, b) new patterns may become more prominent if climate changes substantially, c) analysis of new variables and domains may emphasize new characteristics of variability, and d) researchers, by relating patterns to other aspects of climate variability, can bring a new perspective as to which patterns are important.

In this paper we present results suggesting the importance of a pattern of interannual variability that has not been widely noted in the literature but whose significance becomes apparent when meridional wind, rather than the more commonly used geopotential height or sea level pressure, is the analyzed variable (reason c, above) and when finding patterns whose structure is similar to observed circulation trends is the goal (reason d). The pattern whose properties we examine is largely confined to the latitudes between 50°N and 70°N during winter and its signature consists of a distinctive zonal wavenumber-3 disturbance. Previously zonal wavenumber-3 as a prominent pattern of variability has been noticed in the Southern Hemisphere (SH) winter (Mo and White 1985, Cai et al. 1999) but its importance in the Northern Hemisphere (NH) has not been established. We refer to the NH pattern of our study simply as the Wave3 pattern.

The reason we have been motivated to learn about the properties of this pattern is that it is similar in structure to the linear tropospheric circulation trend that has occurred in nature
over the last half century. The top row of Fig. 1 shows the NH trends in December-February (DJF) mean surface air temperature (TAS), sea level pressure (SLP), 500 hPa geopotential height (Z500) and 300 hPa meridional wind (V300) during the period of 1958-2011 as given by NCEP/NCAR reanalysis fields (Kalnay et al. 1996). While the hemispheric-wide warming evident in TAS and Z500 is the signature of global warming that has received most attention, we are struck by the three high latitude locations that exhibit a negative Z500 trend, which become even more apparent when the hemispheric mean is removed (bottom row Fig.1). These same three negative anomaly areas are seen in Hoerling et al. (2001)’s depiction of 1950-1999 Z500 trends, though in that study their amplitude is even stronger. These lobes are also very apparent in V300 (though they are longitudinally shifted relative to the Z500 negative features as one would expect from the geostrophic relationship) and to a lesser degree in SLP. It is this prominent zonal wavenumber-3 pattern that we believe may be related to the pattern of variability that is the focus of our study.

Some previous studies have related the observed trends to other patterns of variability, in particular the Northern Annular Mode/North Atlantic Oscillation (NAM/NAO, Thompson and Wallace 1998, Hurrell 1995). As we discuss in detail later in our paper, the Wave3 pattern we present is not completely structurally or temporally distinct from NAM, but we believe that for certain attributes of the observed trend, the linkage to the Wave3 pattern is clearer than for NAM.

If there is a pattern of interannual variability whose structure is similar to the observed trends, presumably the processes that produce it are also important for the generation of the trend. Hence identifying such a linkage should help identify processes that need to be well represented in climate models. Furthermore there are dynamical reasons to expect a similarity
in the structure of the observed circulation trend and prominent interannual patterns. For example there are theories that suggest the response of a dynamical system to a stimulus will tend to have a structure similar to that of prominent intrinsic patterns of the system (Leith 1975, Corti et al. 1999, Branstator and Selten 2009). Hence if the atmospheric trend is externally forced (as in the reaction to greenhouse gas increases) or if it is forced by natural fluctuations of slow components of the climate system (for example oceanic or coupled ocean/atmosphere modes), one would expect such a similarity.

To present our results we have organized the paper as follows. Section 2 describes the data sources and analysis methods we have used. This is followed in Section 3 by the definition of the Wave3 pattern and a description of its characteristics as seen in the interannual variability of reanalysis fields, including its relationship to other patterns of variability. In Section 4 we report on the presence of Wave3 in various GCM simulations, including the 20th-century integrations from the Coupled Model Intercomparison Project phase 3 (CMIP3, Meehl et al. 2007). These results confirm that climate variability at the NH high latitudes tends to favor Wave3-like patterns and that the Wave3 pattern can be produced by processes intrinsic to the atmosphere. In Section 5 we demonstrate, to the degree possible from the observational record, that the Wave3 pattern is more prominent on long time scales and is the leading pattern of multi-decadal variability in the past half century or so. The paper concludes in Section 6 with a summary and discussion of results.

2. Data, models and methods

The primary dataset used in our study is the NCEP/NCAR reanalysis (Kalnay et al. 1996) for the period of 1958-2011. In addition to the more reliable 1958-2011 period, in results
not shown here, we have repeated our analysis using data from 1948-2011 and from ERA40 (Uppala et al. 2005). Our results are not sensitive to either change.

We have used several time-varying indices to represent a number of previously identified patterns of climate variability. The NAM pattern is defined as the first empirical orthogonal function (EOF) of detrended DJF-mean SLP at 20°-90°N in the period of 1958-2011 and the NAM index is the corresponding principal component (PC). The DJF Pacific/North American (PNA) time series is obtained from http://jisao.washington.edu/data/pna/#djf which was constructed following its original definition (Wallace and Gutzler 1981).

In addition to the reanalysis data, we have examined the structure of variability in 20th century simulations during the period of 1950-1999 performed by 19 CMIP3 models (Meehl et al. 2007). We have also employed two long integrations of one particular CMIP3 model, namely Community Climate System Model version 3 (CCSM3) (Collins et al. 2006). One is a 1000-year fully coupled present-day control run, with only the last 700 years analyzed in order to avoid the spin up period. The other is a 12,000-year stand-alone integration of CCSM3’s atmospheric component (CAM3) forced with present-day climatological SSTs that only vary with month of the year. Both runs have a spatial resolution of T42 in the atmospheric model.

All results presented here are based on DJF means. In our study we are especially interested in V300 because it has almost no zonal mean and thus emphasizes regional features, and because it is far enough removed from the surface to have structures that are likely to be largely controlled by planetary wave dynamics. Throughout our study we have either analyzed trends or departures from trends and trends are formed simply from least squares fitting a line through seasonal mean values at each grid point north of 20°N during the period 1958-2011.
3. **Interannual variability**

   *a) Latitudinal and hemispheric structure*

   As the first step in investigating whether there is an interannual counterpart to the distinctive high latitude zonal wavenumber-3 pattern in trend fields we have simply determined whether zonal wavenumber-3 is a prominent structure for year-to-year wintertime fluctuations at any latitude. This has been done by decomposing V300 anomalies into zonal harmonics in 2.5° latitude bands for DJF means in the NH and June-August means in the SH for each year between 1958 and 2011, and then averaging the amplitude squared of each harmonic (middle panels of Fig.2). For reference, we plot corresponding values derived from the climatological mean and linear trend (m/s per 50 years) in the left and right panels of Fig.2 respectively. Although only NH shows a strong wavenumber-3 trend, the V300 variability is dominated by wavenumber-3 anomalies between approximately 50° and 70° latitude in both hemispheres. For the climatological mean, in both hemispheres wavenumber-3 prevails in latitudes about 10° equatorward of this band. Hence, even though factors, including the structure of the subtropical jet, stationary waves and stormtracks, that are thought to contribute to the organization of interannual variability, are markedly different in the two hemispheres, zonal wavenumber 3 is prominent at high latitudes during winter in both domains.

   *b) Definition of the Wave3 pattern*

   Next, to learn about the pattern or patterns that contribute to the NH high latitude wavenumber 3 maximum in interannual variability, we have used EOF analysis. The leading two EOFs of *detrended* DJF-averaged V300 between 20°N and 90°N are shown in the bottom panels of Fig.3, and for comparison the climatological mean (contours) and 1958-2011 linear trend (shading) of V300 are displayed in the top panel. EOF1 suggests a wave train spanning
from the subtropical North Pacific to the midlatitudes of North America. By contrast, all six
centers of action of EOF2 are largely confined to 50°-70°N and form a pattern that closely
resembles the linear trend (Fig.1, upper right). There is no quadrature pattern of EOF2 among
EOFs 3-5, suggesting the wavenumber-3 anomalies tend to be longitudinally phase locked.
Compared with the climatological mean, EOF2 in its positive phase indicates an eastward shift
of the climatological ridges and troughs, especially in the western hemisphere where the
climatological high latitude waves are strongest. Previously, this pattern has not been singled
out or named in the scientific literature. We hereafter refer to it as the Wave3 pattern¹, and
projections of detrended V300 anomalies onto the pattern we refer to as the Wave3 time series.
The variance explained by the two leading interannual V300 EOFs is so close (16% for
EOF1 and 14% for EOF2) that they cannot be separated by the criterion of North et al. (1982).
(On the other hand EOF2 is well separated from EOF3.) This raises the question of whether
Wave3 and V300 EOF1 should be considered to be distinct patterns or whether mixtures of
Wave3 and V300 EOF1 are just as relevant. But as we show in Section 3d, EOF1 corresponds
to the PNA pattern (Wallace and Gutzler 1981), so it and EOF2 are likely to be physically
distinct. The separation between EOF1 and EOF2 is also supported by lack of clear indication
of dependence between the two time series in scatter plots of concurrent values (not shown),
and by their temporal behavior on multi-decadal time scales, as explained in Section 5.
c) Vertical structure
To investigate the vertical structure of the Wave3 pattern, we have calculated the
latitudinal average of detrended meridional wind and air temperature at 50°-70°N regressed

¹ If we calculate the EOFs using DJFM instead of DJF means, the resulted EOF2 has similar
wavenumber3 structure except that the amplitude of the positive anomaly over the North
Atlantic and negative anomaly over Europe is much reduced.
upon the Wave3 time series (Fig. 4 top). The meridional wind anomalies have strongly
barotropic structure in the entire troposphere with maxima located at 300 hPa. The air
temperature anomalies also have a zonal wavenumber-3 structure from surface to 300 hPa. The
locations of the maxima and minima of the regressed air temperature anomalies correspond to
the zero-value contours of the meridional wind and are consistent with the thermal wind
relationship.

To make the comparison of Wave3’s vertical structure to that of the observed trend
clear, we use the same format to display the structure of the observed 1958-2011 trend of air
temperature and meridional wind at 50°-70°N (Fig. 4 bottom). The air temperature trend
generally has the signature of cooling in stratosphere and warming in troposphere seen in many
studies. Superimposed on that are local features that closely match the structure of the Wave3
pattern as do the placement and patterns of the wind anomalies.

d) Teleconnection

Centers of action in EOF patterns do not necessary co-vary (Deser 2000, Ambaum et al.
2001), but if they do, it is an indication of a pattern that is likely to be a physical mode. In
order to examine the co-variability, or “teleconnectivity”, of the Wave3 pattern, we have
calculated a correlation matrix that relates detrended V300 at the six centers of action of the
Wave3 pattern. We find 12 of the resulting 15 correlation coefficients are significant at the
95% level. Moreover, when we use regression to remove the contribution of EOF1 to the year-
to-year DJF anomalies, all 15 correlation coefficients become significant at the 95% level.

These indications of co-variability do suggest that the six lobes of Wave3 are a
collection of points at which the meridional wind co-varies to a detectable degree, but
meridional wind is an unfamiliar quantity for pattern identification. Because teleconnection
patterns are conventionally defined with Z500 (Wallace and Gutzler 1981), we have
determined whether Wave3 also has a noticeable influence on this variable. To this end, we
have first regressed detrended DJF mean Z500 upon each of the leading two principal
components of V300 (Fig.5 top). The EOF1 regressed pattern appears to strongly resemble the
PNA pattern, a conclusion bolstered by the fact that there is a 0.84 correlation coefficient
between V300 PC1 and the PNA index. Like the V300 Wave3 pattern, the pattern regressed
upon V300 PC2 has six centers of action but the maxima and minima are located about 30° of
longitude east of the corresponding centers for V300 EOF2 (Fig.5 top right), as one would
expect based on geostrophy. While the Z500 pattern regressed upon V300 EOF1 resembles
EOF1 of detrended Z500, the pattern regressed upon V300 EOF2 contains features in both
EOF2 and EOF3 of detrended Z500 (figure not shown), so the EOF2s from V300 and Z500
correspond to somewhat different characteristics of variability. Quadrelli and Wallace (2004),
Branstator (2002) and others have made the point that EOFs of different variables tend to
emphasize different aspects of variability.

Next we have calculated one-point correlation maps of Z500 with reference to each of
the six centers of action of the Z500 rendition of the Wave3 pattern (marked as C1, C2… C6 in
Fig.5 top right panel). After using regression to remove the influence of anomalies associated
with EOF1 of V300, the six correlation maps formed from the residuals all exhibit Wave3
characteristics (Fig.5 bottom two rows), though there are only weak connections between C1
and C6, C2 and C5, and C3 and C5, and some small shifts of the centers of action. So
Wave3’s influence does carry over to the more familiar Z500.

e) Comparison with NAM
Another aspect of the Wave3 pattern that needs to be established is how different it is from the more familiar NAM, a pattern of climate variability that is strongly influenced by the zonal mean. We have found that to a certain degree the Wave3 pattern is indeed related to NAM. This is reflected in their full time series during 1958-2011 (Fig.6) calculated by projecting the V300 and SLP departures from climatology, with the trend retained, onto the corresponding signature pattern defined by an EOF of the detrended data. Especially for longer time scale fluctuations, the time series have notable co-variability resulting in correlation coefficients that are significant at the 90% level. However, for interannual time scale fluctuations, at times Wave3 does not vary in concert with NAM.

In order to compare the structure of Wave3 and NAM, we regress detrended DJF-mean SLP, TAS, Z500 and V300 upon the Wave3 and NAM indices (Fig.7). Remarkably, NAM, which is largely characterized by the zonally symmetric component of the SLP field, has a predominantly wavenumber 3 pattern in the high latitude V300 field. In all four examined fields, the two regressed patterns are very similar over the North Atlantic and Europe, which probably results in the significant correlation between the two time series. The major difference is found in the North Pacific and North America. Unlike NAM, the Wave3 pattern in its positive phase has negative SLP anomalies over the North Pacific. This SLP feature is the surface signature of the much stronger zonally asymmetric character of Wave3 throughout the troposphere over East Asia and the North Pacific as seen in the Z500 and V300 regressed fields. Wave3’s in-phase variability between the Aleutian and Icelandic Lows seems to resemble the Cold Ocean Warm Land pattern (COWL, Wallace et al. 1996). However, COWL was not presented as a circulation mode when it was first introduced, and it still remains controversial whether it should be regarded as an intrinsic atmospheric mode (Broccoli et al. ...
The area weighted pattern correlation coefficient between each pattern in Fig. 7 and the trend is marked at the top right corner of each panel in that figure. They suggest Wave3 can capture the trend slightly better than NAM and are probably a reflection of the good match between the trend and Wave3 in the North Pacific and western North America. One needs to make a linear combination of the leading two EOFs of the SLP in order to replicate the trend structure (Quadrelli and Wallace 2004). None of these regressed patterns can capture the hemispheric distribution of TAS trend which is dominated by Arctic warming, suggesting processes other than those responsible for the Wave3 or NAM variability play an important role in producing the TAS trend.

4. Model simulations

As a test of the robustness of the Wave3 pattern, we have examined CMIP3 model integrations reasoning that if it is present in these models, in spite of their varying formulations and climates, it will indicate that the existence of the Wave3 pattern is not sensitive to subtle aspects of the climate system nor is its prevalence in the observational record a random statistical event.

a) CMIP3 models

To provide a characterization of Wave3 in nature that is easily compared to model behavior we have carried out a further analysis of the observational record. This analysis has focused on year-to-year variations of detrended DJF-mean V300 that has been latitudinally averaged between 50°N and 70°N where the Wave3 pattern prevails in nature. To quantify the prevalence of zonal wavenumber-3 variability we have calculated the percentage variance

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explained by each zonal wavenumber, and to investigate whether wavenumber-3 perturbations
have a preferred longitudinal phase we have generated a histogram of the phase values which
wavenumber-3 anomalies attain. In Fig. 8 these two quantities are plotted for observations
during 1958-2011 using thick red lines. Consistent with our earlier results, the dominance of
wavenumber 3 is very apparent (left panel), as is its preferred phases of -90° and approximately
90°. Because of the convention we have used, +90° and -90° correspond to the same
longitudinal placement of features in the canonical Wave3 pattern (Fig. 3, bottom right) in its
positive and negative phases, respectively. (Note that since the phase is associated with
wavenumber-3 anomalies, a 30° difference in phase corresponds to a 10° longitudinal shift in
the location of the ridges/troughs of the analyzed waves.) A similar histogram of phase in the
SH is flatter than in the NH (figure not shown), suggesting the wavenumber-3 anomalies tend
to be more longitudinally phase-locked in the NH.

Following the same procedure, we have analyzed detrended V300 for 20th century
simulations during 1950-1999 from nineteen CMIP3 models. In the left panel of Fig.8 the
variance percentages of each zonal wavenumber are plotted for each model. For seven of the
models wavenumber 3 is not the dominant wavenumber, so the multi-model average of
variance percentage as a function of zonal wavenumber (thick blue line) in the left panel has
smaller contrast between wavenumber 3 and the neighboring wavenumbers than exists in
nature, but the prevalence of wavenumber 3 is still clear. As for histograms of the phase of the
wavenumber-3 anomalies, the results are very noisy, but when for each bin we plot the multi-
model average of histogram values (blue dots) and plus/minus one standard deviation of those
values (the vertical blue lines) (Fig.8 right), the existence of two preferred phases in the vicinity
of -120° and 90° roughly agrees with the observations.
b) CCSM3

The model-to-model differences seen in Fig. 8 may result from differences in model formulation or from sampling fluctuations. To minimize the effect of analyzing short samples, we have looked in more detail at one of the CMIP3 models (CCSM3) and its atmospheric component (CAM3), for which we have long control integrations (cf. Section 2). When we have repeated the V300 variance percentage and phase histogram calculations for CCSM3’s control, we have found the behavior suggested by the short datasets from observations and from the CMIP3 integrations is clearly present (Fig. 9). Zonal wavenumber 3 is the preferred wavenumber with more than 30% of the variance (left panel). For observations wavenumber 3 contains somewhat more variance, namely 37%. For the distribution of phases (right panel), the smoothing effect of having a much larger database compared to nature is apparent but the preference for values near -90° and 90° is obvious.

As a second test of the presence of Wave3 in the long CCSM3 control run, we have calculated EOFs of DJF averages of V300 between 20°N and 90°N (Fig. 10, top row). There is a pattern of variability that strongly resembles Wave3, but it is EOF3 rather than EOF2 as in nature. Moreover, it explains 10% rather than 14% of the variance. Owing to the length of the CCSM3 control integration, that all three leading EOFs are well separated from each other and neighboring EOFs can be readily established (North et al. 1982), giving support to the notion that Wave3 is a distinct pattern.

Figures 9 and 10 also contain results for CAM3. In most respects removing the interactive ocean has little impact on high latitude DJF variability. Zonal wavenumber 3 is still the preferred scale and it has a preferred phase. The longitudinal position of the troughs and ridges are, however, somewhat different for that preferred phase. As implied by the maxima at
phases of -120° and 60° in Fig. 9 (right), zonal wavenumber 3 variability tends to occur about 10° west of where it does in CCSM3. This same shift is visible in the bottom row of Fig.10’s depiction of the leading V300 EOFs of CAM3.

An implication of the CAM3 results is that Wave3 can be produced by atmospheric processes alone as the CAM3 experiment is forced by climatological SSTs that are only a function of month of the year. That Wave3 is an intrinsic atmospheric pattern is further suggested when we plot its vertical structure between 50°N and 70°N in CCSM3 and CAM3 using the same regression methodology employed for nature (Fig.4, top) but key on V300 PC3 rather than PC2. The plots generated in this way (not shown) are very similar for these two experiments and both resemble the observed vertical structure of Wave3 but with weaker anomalies over the Atlantic sector.

Not only is EOF3 similar in the two model experiments but so are EOF1 and EOF2, in terms of both structure and variance explained. As in nature, EOF1 in both runs represents the PNA pattern, but its Asian features are stronger than they are in the observational counterpart (Fig. 3 lower left) and the variance it explains is much higher in the model. EOF2 has a structure that is similar to EOF1, except that longitudinal locations of the centers of action are shifted by about 18° of longitude. Hence these two patterns are in spatial quadrature.

Moreover, both EOF1 and EOF2 have a zonal wavenumber-5 structure in the subtropical-to-midlatitude region, which is reminiscent of the observed waveguide mode found in nature (Branstator 2002). For our purposes what is noteworthy is that even though wavenumber-5 variability is much more prominent in CCSM3 than in nature, there is a high degree of similarity in its Wave3 pattern and the one in nature, a further testament to the robustness of Wave3 as a pattern of variability.
The lengths of the CAM3 and CCSM3 control experiments also have made it possible for us to consider the temporal spectral properties of Wave3 for these models. When we have applied standard power spectrum estimation techniques to DJF averages, we have found CAM3 V300 PC3 has a white spectrum. With the air-sea coupling in CCSM3, PC3 reddens, exhibiting several peaks in the interannual to decadal range (however, its multi-decadal variance is weaker than the rough estimate we have made from observations). The total variance associated with the Wave3 pattern increases by 17% relative to Wave3 variance in the CAM3 run, but our significance tests indicate there is a 15% chance that such an increase could be caused by sampling fluctuations. Variance associated with the other two leading EOFs is also enhanced in the fully coupled run; as a result, the Wave3 pattern remains as the third EOF despite the increased variance. However, if we smooth the V300 anomalies with a 20-year running window and recalculate the EOFs, the Wave3 pattern becomes EOF2 in the fully coupled run. Meanwhile, the temporal smoothing does not change the order of the leading three EOFs in the CAM3 run. This suggests that air-sea coupling can advance the prominence of the Wave3 pattern on the multi-decadal time scale.

5. Predominance of Wave3 on multi-decadal time scales

Because observations show a pronounced multi-decadal fluctuation in the Wave3 time series (Fig.6) and because in CCSM3 the Wave3 pattern becomes relatively more prominent when 20-year running means are considered, we have been encouraged to further analyze the role that Wave3 plays in long time scale planetary wave variability. Of course as in all observational studies of decadal and longer time scale variability, results from such an analysis cannot be definitive because the instrumental record is so short.
To determine the structure of multi-decadal variability in nature, we have calculated the leading EOF patterns of detrended TAS, PSL, Z500 and V300 between 20°N and 90°N from our observational dataset filtered with the same 20-year running mean filter we applied to CCSM3 output. EOF1 from each field is depicted in the top row of Fig. 11. The pattern for V300 is nearly identical to that for Wave3 (Fig. 3c), as confirmed by the fact that the pattern correlation for these two is 0.80. Also, as shown in the bottom panel of Fig. 11, when we have projected detrended DJF-mean anomalies onto these four patterns those projections are highly correlated. Indeed TAS, SLP and Z500 are correlated with the V300 time series by values of 0.80, 0.85, and 0.85, respectively. Hence for each of these fields the leading pattern of multi-decadal variability is strongly related to Wave3.

Interestingly, while the V300 EOF2 pattern of interannual variability (i.e., Wave3) becomes the leading pattern for 20 year running mean data, the EOF1 interannual pattern (the PNA) becomes the second leading pattern and explains only about half as much variance as Wave3. This fact demonstrates that Wave3 and the PNA have different temporal characteristics thus serving to further confirm they are individual physical phenomena. A further piece of evidence of the long time scale preference of Wave3 is in the ratio of 10-year low-pass filtered variance to interannual variance for the NAM, PNA, and Wave3 full time series. These ratios are 30%, 29% and 18% for Wave3, NAM and PNA respectively. Wave3 becomes even more distinct when we replace the 10-year low-pass filter with 20-year running means. One, however, should not conclude from these facts that Wave3 is primarily a pattern with longer than interannual variations. For when we have removed 20 year running means from interannual V300 and again calculate EOFs, we have found little difference in the leading two patterns or the variance they explain compared to the results in Fig. 3 when all interannual
variability is accounted for. And when we have projected daily data onto the Wave3 pattern, the daily Wave3 time series exhibits significant intraseasonal frequency peaks.

6. Concluding remarks

In this paper, we have introduced a pattern of NH wintertime planetary wave variability characterized by longitudinally phase-locked zonal wavenumber-3 anomalies between 50°N and 70°N. It is most prominent in the upper tropospheric meridional wind though it is also seen in other fields throughout the depth of the troposphere. EOF2 of detrended DJF-mean V300 during 1958-2011 isolates this pattern well, so we have used this EOF to define the pattern, which we refer to simply as Wave3. Our analysis supports the notion that it is a distinct pattern of variability, and not one of a family of patterns that can be combined arbitrarily.

Other studies, including Mo and White (1985) and Cai et al. (1999) have recognized a similar pattern of interannual variability in the SH, but the presence of the NH wavenumber-3 pattern has not been recognized before. We believe Wave3 may be important, not only in its own right as a pattern of variability, but because it may shape the structure of trends and/or multi-decadal variability of the wintertime circulation at high latitudes. We have come to this conclusion because our results indicate the Wave3 pattern and associated fields are similar in structure to the circulation trend that has occurred in nature during the last 50 years as well as to the leading pattern of V300 multi-decadal variability during that period. Thus understanding its properties may be a step toward understanding such long time scale features of climate variability and change.

Our analysis of climate model simulations has provided additional reasons to believe the Wave3 pattern should be recognized as a prominent pattern of variability. When combined into an aggregate dataset, the CMIP3 models we considered indicate that V300 variability at
high latitudes favors a zonal wavenumber-3 structure, and that the resulting waves occur at preferred longitudinal positions. We did find considerable model-to-model differences in our results and Wave3 was not prominent in all of them, but this may be a result of sampling fluctuations. For we found that in the model for which we had very long time series, namely CCSM3, the Wave3 pattern clearly stands out. Not only was zonal wavenumber-3 the most important component of high latitude V300 variability, but it had a clear preferred longitudinal phase. As a result the structure of V300 EOF3 in CCSM3 turned out to closely match the observed Wave3 pattern. Also, it is noteworthy that Wave3 is very similar to EOF3 for V300 in a long integration of CAM3, the atmospheric component of CCSM3. Hence the Wave3 pattern is not only a prominent pattern of variability but it can be produced by intrinsic atmospheric processes.

Interestingly, Wave3’s prominence in CCSM3 was even more pronounced on multi-decadal than interannual time scales. This result adds support to our similar finding for nature, where the short climate record makes the statistical significance of our findings difficult to establish. In the introduction we pointed out that a similarity in structure of trends and an intrinsic atmospheric pattern can occur whether the trends are externally forced or are a manifestation of slow intrinsic climate variability. Because Wave3 may be the atmospheric component of an intrinsic multi-decadal mode, we cannot know whether its trend over the last five decades is forced or intrinsic. After all, during the instrumental record it has undergone a single multi-decadal fluctuation (Fig. 6) and a single cycle of even a pure harmonic oscillation produces a substantial signature in a standard trend analysis. Future work, including examination of the CMIP phase 5 experiments, may help determine which possibility is most likely.
Future work is also needed to determine the processes that make Wave3 a leading intrinsic mode of atmospheric variability. Simple wave propagation ideas indicate there should be a preference for small zonal wavenumber disturbances near the poles (Hoskins and Karoly 1981), and Chang and Fu’s (2002) results indicate that interactions with the synoptic eddies may contribute to an in-phase relationship between variations in the Icelandic and Aleutian Lows, so these two mechanisms are likely to be involved. Perhaps once the key mechanisms are understood other issues regarding the Wave3 pattern will be settled, including why wavenumber 3 is prominent during winter in the very different environments of the two hemispheres and why many CMIP3 models react to greenhouse gas increases with a distinct subtropical wavenumber 5 pattern (Brandefelt and Kornich 2008, Meehl and Teng 2007) rather than with the high latitude wavenumber 3 trend pattern observed in recent decades.

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References


Figure captions:

Fig. 1. (top) Linear trend of DJF-mean surface air temperature (TAS, K/50 years), sea level pressure (SLP, hPa/50 years), 500 hPa geopotential height (Z500, 10 m/50 years) and 300 hPa meridional wind (V300, m s⁻¹/50 yrs) during the period of 1958-2011 from the NCEP/NCAR reanalysis. (Bottom) Same as the top but with the Northern Hemisphere area weighted averaged trend (0.65 K, 0.27 hPa, 18.6 m and -0.06 m s⁻¹ per 50 years for TAS, SLP, Z500 and V300 respectively) removed. Stippling indicates the 90% t-test significance level.

Fig. 2. Amplitude squared of zonal harmonic 0-6 of wintertime (DJF for the NH and JJA for the SH) seasonal mean V300 (left) climatology, (middle) interannual anomalies, and (right) fifty-year linear trend during the period of 1958-2011.

Fig. 3. (top) Climatology (m s⁻¹) in contour and trend (m s⁻¹ per 50 years) in shading of DJF-mean V300 during 1958-2011. Stippling indicates the 90% significance level of the trend. (bottom) EOF1 and EOF2 of detrended DJF-mean V300 for 20°-90° N during the same period.

Fig. 4. (top) DJF-mean meridional wind (contoured with interval 0.5 m s⁻¹; negative contours are dashed) and air temperature anomalies (shading with units K) regressed upon the Wave3 index and (bottom) their linear trend (wind contoured with interval 0.5 m s⁻¹ per 50 years and temperature shaded with units K per 50 years) during the period of 1958-2011. Stippling indicates the 90% t-test significance level.
Fig. 5 (top) DJF-mean Z500 regressed upon the leading two principal components of detrended V300 during 1958-2011. The six centers of action in the EOF2 regressed map are marked as C1, C2, …, and C6. (bottom two rows) One-point correlation maps showing the correlation coefficient between Z500 anomalies at C1, C2, …, C6 (denoted by the cross) and every other grid points. The V300 EOF1 regressed anomalies have been subtracted from the Z500 anomalies in construction of bottom two rows. Stippling indicates the 90% significance level.

Fig. 6. Standardized full time series of NAM and the Wave3 pattern during the period of 1958-2011. The NAM and Wave3 full time series are calculated by projecting DJF-mean SLP and V300 anomalies containing the linear trend onto the NAM and Wave3 signature patterns, which correspond to EOF1 of detrended SLP and EOF2 of detrended V300 at 20°-90°N, respectively.

Fig. 7. Detrended DJF-mean TAS, SLP, Z500 and V300 regressed upon (a) Wave3 and (b) NAM index. The NAM index is defined as PC1 of detrended DJF-mean SLP at 20°-90°N. Stippling indicates the 90% t-test significance level. Unit for TAS, SLP, Z500 and V300 anomalies is K, hPa, 10m, and ms⁻¹, respectively. The number at the top right corner of each panel indicates the pattern correlation between the regressed pattern and the trend of the corresponding field during the period of 1958-2011 (Fig. 1).

Fig. 8. (left) Percentage variance of interannual variability of detrended DJF-mean V300 averaged for 50°-70°N explained by each zonal wavenumber. The thick red line represents the NCEP/NCAR reanalysis during 1958-2011, the thick blue line is the average of variance percentages from nineteen CMIP3 models from their 20th century simulations during 1950-
1999, and the remaining lines correspond to values for each of these models individually. The nineteen models are listed in the legend with the number in the parenthesis indicating the number of realizations included for each model. (right) histogram of phase of zonal wavenumber-3 harmonics of the V300 interannual anomalies for twelve 30° wide bins (the two bins at the two ends of the x-axis are the same). The red line represents the reanalysis and the blue dot denotes the ensemble averaged histogram from 12 models whose V300 variability is dominated by wavenumber 3 according to the left panel. The thin blue vertical line indicates plus/minus one standard deviation of the histogram values among the twelve models.

Fig.9. Same as Fig.8 but for (left) percentage variance of V300 from a 700-year CCSM3 fully coupled integration (black) and a 12000-year atmosphere stand-alone (CAM3) run (blue). (right) Histogram of phase of the wavenumber-3 harmonics of the two runs (black asterisk for CCSM3 and blue dot for CAM3). Results for the reanalysis are repeated from Fig. 8 with red lines.

Fig.10. Leading three EOFs of DJF-mean V300 from (top) the 700-year fully coupled CCSM3 control integration and (bottom) the 12000-year CCSM3 atmosphere stand-alone integration (CAM3) forced with present-day climatological SSTs. The domain for the EOF analysis is 20°-90°N.

Fig.11. (top) EOF1 of detrended 20-year running averages of DJF-mean TAS, SLP, Z500 and V300 for 20°-90°N in the NCEP/NCAR reanalysis during 1958-2011. (bottom) projection of
the unsmoothed seasonal mean anomalies containing the trend onto the four corresponding EOF1 patterns (top panel). All four time series have been standardized.
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