Planetary Waves, Cyclogenesis, and the Irregular Breakdown of Zonal Motion over the North Atlantic

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ABSTRACT

Numerous observational and modeling studies have suggested the importance of cyclogenesis to the breakdown of the zonal flow and the maintenance of atmospheric blocks, whereas other studies have shown that low-frequency dynamics are sufficient to produce and maintain these patterns. Experiments with a simple model of the general circulation and empirical evidence obtained from reanalysis and cyclone tracking data are used to develop a conceptual understanding of this irregular response. The model’s results and observational data are consistent with the idea that the North Atlantic flow response to cyclone forcing is preconditioned by the state of the hemispheric circulation. A characteristic hemispheric flow configuration reminiscent of the shedding of a potential vorticity (PV) filament and tightening of the PV gradient is particularly responsive to cyclogenesis, with the likelihood of below 10th percentile North Atlantic zonal flow under these conditions increased by a factor of 2.37 for each cyclone event. A second characteristic pattern, reminiscent of the PV wave-breaking anticyclonic roll up, responds in an opposite way to cyclogenesis, with a decrease in the likelihood of below 10th percentile zonal flow by a factor of 0.67. This perspective is connected to the decades of research on blocking and opens an opportunity for the development of medium-range forecast model post-processors that might provide probabilistic forecasts of North Atlantic flow transitions.

1. Introduction

The role of cyclogenesis in producing substantial reorganization of the large-scale atmospheric flow remains somewhat unclear. Numerous observational and modeling studies have implicated the role of cyclones in producing one characteristic flow reorganization: the atmospheric block (Berggren et al. 1949; Rex 1950; Schilling 1982; Hansen and Chen 1982; Shutts 1983; Colucci 1985; Mullen 1987; Vautard and Legras 1988; Konrad and Colucci 1988; Malguzzi 1993; Anderson 1995; Luo and Chen 2006; Woollings et al. 2008; and many others). Additional research (e.g., Colucci 1987, 2001) suggests that blocking onset may depend on the phasing between features on the planetary and synoptic scales. Colucci and Alberta (1996) further investigate the relationship between cyclogenesis and blocking and find some association between cyclone developments of various intensities and block onset but that the relationship is not sufficient to develop an empirical prediction rule. Woollings et al. (2008) suggests that, when blocking is viewed from the potential vorticity (PV) perspective, wave breaking/blocking occurs through the interaction of low-frequency wave anomalies and high-frequency transients, and enhanced cyclone activity at the start of the Atlantic storm track is a precursor to wave breaking.

Conversely, evidence has recently emerged that emphasizes the independent role of low-frequency dynamics in producing blocks. Nakamura (1994), Nakamura et al. (1997), and Swanson (2001) have shown that dynamics on these scales can produce blocking structures in the absence of synoptic-scale transient eddy forcing. Given that numerous diagnostic and theoretical studies have underscored the nonlinearity of blocking onset and the apparent contradictions concerning the understanding of the role of cyclones, a conceptual possibility is that the irregular response of the atmospheric flow to cyclogenesis may be governed in part by the character of the planetary flow at the time of the cyclone activity. More precisely, in the language of nonlinear dynamics, the sensitivity
may be the result of the “position” of the cyclone event in phase space (Gibbs 1902).1

Whereas cyclogenesis is neither a necessary nor a sufficient condition for blocking onset (or more generally, substantial reorganization of the large-scale flow), under some conditions (i.e., in some portions of the phase space) cyclone-scale feedback will increase the chance that such reorganizations will occur. In other portions of the phase space, similar forcing will have little effect. For example, Buizza and Molteni (1996) and Colucci and Alberta (1996) find that a local weakening of the large-scale westerlies may be a necessary but not a sufficient precondition for block onset prior to the flow reversal that defines the block itself. Given the inherent nonlinearity of atmospheric flow, inopportune phasing of the cyclogenesis and associated forcing might lead to a variable response and therefore be perceived as quasi-random.

The purpose of the paper is to revisit the problem of atmospheric flow reorganization from the perspective of nonlinear dynamics using both a low-order model (section 2) and building upon those theoretical results with consideration of analysis data (section 3). Here, flow reorganization is considered more generally than strictly blocking phenomena and is measured in terms of patterns characterized by faster or weaker zonal flow. A concluding discussion is provided in section 4.

2. A low-order model of large-scale flow reorganization

A two-layer quasigeostrophic model is sufficient to represent the interplay between the zonal flow and baroclinic waves. As shown by van Veen (2003), by applying Galerkin truncation in the horizontal coordinates in a manner similar to the derivation of the Lorenz (1963) model of convection, it is possible to reduce a geostrophic baroclinic model in spectral form to a chaotic, dynamical system represented by six ordinary differential equations. A further reduction of this model to a three-dimensional system, which qualitatively exhibits the same dynamics, is obtained through the introduction of a linearization about the model Hadley state (van Veen 2003). These equations preserve the fundamental dynamics, which is the interaction between the jet stream and the baroclinic waves, and are the low-order model of the atmospheric general circulation first introduced by Lorenz (1984).

As noted by that author, models of this kind allow for a more rigorous examination of hypotheses regarding complex dynamics than would be possible using qualitative reasoning alone.

This low-order model is defined by

\[ \dot{X} = -Y^2 - Z^2 - aX + aF, \]  
\[ \dot{Y} = XY - bXZ - Y + G, \]  
\[ \dot{Z} = bXY + XZ - Z, \]

where the dot operator is the time derivative, \( X \) represents the strength of the westerly jet (or equivalently, the meridional thermal gradient), and \( Y \) and \( Z \) are the amplitudes of the cosine and sine components of a large traveling wave (i.e., these are the Fourier modes where \( Y^2 + Z^2 \) represents the squared amplitude of those waves). Therefore, small or negative \( X \) represents a weak or reversed meridional temperature gradient or, from thermal wind considerations, a weak or reversed midlatitude jet. Similarly, large \( Y^2 + Z^2 \) indicate high-amplitude traveling waves and equivalently strong meridional flow.

The coefficients \( a \) and \( b \) govern the rates of dissipation and displacement, respectively. For \( a < 1 \), the damping of the westerly current occurs less rapidly than that of the eddies, while for \( b > 1 \), the eddies are displaced more rapidly than they amplify at the expense of the westerlies. Here \( F \) and \( G \) represent symmetric and asymmetric thermal forcing, the former owing to meridional radiative disequilibrium, and the latter resulting from zonal inhomogeneities in diabatic forcing.

The product terms in these equations, such as \( XY \) in Eq. (2) and \( XZ \) in Eq. (3), represent baroclinic eddy growth. This can be seen more clearly by writing this model in terms of the zonal and eddy energy change components:

\[ \dot{X}^2 = -2X(Y^2 + Z^2) - 2aX^2 + 2aXF, \]  
\[ (Y^2 + Z^2) = 2X(Y^2 + Z^2) - 2(Y^2 + Z^2) + 2YG, \]

and the total energy change as

\[ (X^2 + Y^2 + Z^2) = -2(aX^2 + Y^2 + Z^2) + 2aXF + 2YG, \]

where the amplification of the large-scale eddies at the expense of the westerly current is shown by the cancellation of the term \( 2X(Y^2 + Z^2) \) in Eqs. (4) and (5), whereas the second and third terms on the right-hand

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1 In this context, phase space refers to a multidimensional dynamical space determined by the parameters of the system and for which each possible state is represented as a unique point. The succession of points then represents the time evolution of the system’s state and the resulting geometry demonstrates dynamical behaviors of the system.
side of each equation are the respective dissipation and
generation terms. The dissipation of total energy is gov-
erned by the first term on the right-hand side of Eq. (6),
whereas the second and third terms represent energy
generation through the radiative and diabatic effects,
respectively. Studies of this system (Lorenz 1984, 1990;
Roebber 1995; Masoller et al. 1995; Shilnikov et al. 1995;
Roebber et al. 1997; van Veen 2003) have revealed rich
dynamics and demonstrate the applicability of the model
to a range of dynamical questions.

In the context of the present work, the term \( 2YG \) on the
right-hand side of Eq. (5) shows that the large-scale
eddies can intensify in response to diabatic forcing when
the waves have reached a favorable longitude (the spatial
dimension arising from the fact that these equations are
derived from a projection onto the Fourier modes). This
intensification then leads to an increase in heat transport
and concomitant adjustment in the westerly current. A
cyclone, or cluster of cyclones, occurring in association
with a favorably positioned long wave, then, in principle
could result in a rearrangement of the large-scale flow.

However, because Eqs. (1)–(3) comprise a nonlinear
system, whether such rearrangement actually occurs,
even in this simple model, will depend on the state of
the system at the time of the cyclone-imposed diabatic
perturbation. The only way to move beyond this quali-
tative reasoning is to check it against full integrations of
the model. This is accomplished by integrating Eqs. (1)–(3),
with respect to time, with \( a = 0.25, b = 4, F = 8, \) and \( G = 1 \),
parameters that allow for chaotic dynamics in what rep-
resent perpetual winter conditions (Lorenz 1984, 1990;
Roebber 1995). The scaling is arranged as with previous
studies of this system, where a nondimensional time unit
is 5 days and the equations are integrated with a 3-h time
step (0.025 time units) for the dimensional equivalent of
10 years.

Two simulations are run: 1) control run with the basic
equations, and 2) perturbed run with random synoptic-
scale cyclone events occurring on approximately 50% of
the days and for which \( G \) is considered to double (qual-
titatively, as might occur through cyclone-induced latent
heat release). In the model context, a synoptic-scale
cyclogenesis event is modeled through this “sudden” di-
abatic heating, rather than any proportionality to the long
waves whose amplitude is represented by \( Y \) and \( Z \). The
two runs are initialized using \( X = 0, Y = 1, \) and \( Z = 1 \).
Although, because the dynamics are chaotic, these initial
conditions are quickly “forgotten” during the integration.
The three-dimensional phase space of the control run
(Fig. 1) shows a region of small \( X \) and large \( Y \); this area of
the attractor represents the weak or reversed westerly
flow and high-amplitude eddies characteristic of a nearly
blocked or blocked state. The perturbed run (Fig. 2)
displays a similar, albeit more amplified, structure, in-
cluding the key blocking region.

A 250-day (50 time unit) excerpt from the perturbed
run (Fig. 3) is illustrative. The normal fluctuations of
the large-scale westerly flow are in evidence from times
450–465. Then, the flow enters the blocking regime,
coincident with an increased frequency of cyclogenesis
(label A in Fig. 3; cyclogenesis frequency here is simply
the seven-day smoothed cyclone count). Note, however,
that similar cyclogenesis, around time 455, did not lead
to this response. Frequent cyclogenesis from 465 to 490
provides the necessary diabatic forcing needed to
maintain the block in opposition to dissipation. At the
same time, there is limited exchange of energy between

FIG. 1. Three-dimensional attractor for the control system (1)–(3)
with \( a = 0.25, b = 4, F = 8, \) and \( G = 1 \). The “blocking” region of the
attractor (black points) and daily values (plotted points) are shown.

FIG. 2. As in Fig. 1, but for the perturbed system and with \( G = 2 \) for
“cyclone events” (see text for details).
the eddies and the westerly flow. Reduced cyclogenesis near 490 (label B in Fig. 3) results in a rapid decrease in the diabatic forcing, and the flow quickly becomes unblocked ($X$ increases). This is qualitatively consistent with the view of block maintenance by the passage of synoptic-scale systems (Hoskins and Sardeshmukh 1987; Woollings et al. 2008). Cyclogenesis thereafter, however, does not restore the block because the flow is no longer in a state that is sensitive to the diabatic perturbations. Specifically, the flow is in the portion of the phase space characterized by fast westerly flow and low-amplitude eddies (the lower right portion of Fig. 2).

Blocks are loosely defined as a three-day average of $X \geq 0.3$ and $Y \geq 0.8$ (indicative of a weak or reversed zonal flow and a higher-amplitude wave component). Whereas the blocking frequency, here defined as the 30-day moving average, is quite variable from year to year, the overall frequency is increased by the cyclone influence from 8% in the control to 48% in the perturbed run (Fig. 4). Notably, the variability of blocking frequency also increases, with a coefficient of variation (the ratio of standard deviation to mean, recognizable as the inverse of the signal-to-noise ratio) of 0.27 in the control versus 0.32 in the perturbed run. Clearly, the cyclone events have an effect on the large-scale flow in this simple model.

The effect of cyclone activity and associated diabatic forcing can be viewed in another way in this model by collapsing the three-dimensional phase space of Figs. 1, 2 into two dimensions (Fig. 5, where the second dimension is the squared wave amplitude $Y^2 + Z^2$). The frequency of weak or reversed flow events (defined over a 3-day interval) within the next 7 days following the current time reveals the portions of the phase space that are responsive to cyclone occurrence (shading and contours in Fig. 5). In the simulations used to construct the figure, cyclone occurrence is random and frequent, so that any point along the trajectory has been “activated” by cyclones, and the differences in the two plots represent the differing response of the two runs. The largest increase of weakened flow is for trajectories that are already in the vicinity of that area of the phase space (cf. the frequencies near $X = 2.5$ denotes the low-to-moderate wave amplitude very fast zonal flow state transitioning to a blocked or nearly blocked state. As most of the phase space is sampled, evidently there are sizeable regions where such a response is infrequent (unshaded areas of Fig. 5), despite the cyclone activity. Although this section has emphasized a particular region of the low-order model attractor consistent with the notion of blocking, it is used in this context more generally to identify transitions between different atmospheric states.

We cannot hope to learn anything quantitative concerning synoptic-scale activity and adjustments in the planetary-scale flow from this idealization. Qualitatively, however, the results mimic the behaviors cited in section 1 and provide a means for organizing a deeper investigation. Specifically, an effort to construct a simple phase space representing the zonal and eddy components of the large-scale flow and correlating that structure with cyclone activity from real data may be revealing. Such a structure, derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset, and linking
that to existing cyclone tracking studies, is described in the next section.

3. A phase space analysis of observed data

Under the assumption of linear superposition of wave components for periodic and stationary processes, Fourier-based spectral analysis methods are a common and useful means for studying atmospheric waves. Here, we focus on the long waves and are not directly interested in wave interactions, but only the inherent spatial context. Accordingly, a Fourier decomposition of the hemispheric 300-hPa meridional winds averaged in the latitude band 45°–60°N is conducted for the cold season (November–March) for a 50-yr period (1958–2007) using the data from the NCEP–NCAR reanalysis. The coefficients of the cosine and sine phases for wavenumber 5, representative of the larger scale of interest, are retained for further analysis.

The composite flow for 20 low cosine–high sine events, selected at random from the larger selection of days [Figs. 6a,b; average coefficient values of −458 and +897, respectively; (“Low”)], reveals the hemispheric wave train structure of this pattern. A second pattern with relatively high cosine–low sine coefficients [not shown; (“High”)] as would be expected, is similar to Low, but with opposite anomaly signs. Compare these to the composite for 20 moderate cosine–low sine events [Figs. 6c,d; average coefficient values of +265 and −746, respectively; (“Moderate”)], where the anomaly pattern is phase shifted and less extensive over the hemisphere, thus demonstrating the ability of this approach to distinguish between various flows. From a local, PV wave-breaking perspective focusing on the North Atlantic, the Low pattern corresponds to an anticyclonic roll up, whereas the Moderate pattern suggests the shedding of a PV filament and tightening of the PV gradient, patterns consistent with the Woollings et al. (2008) paradigm of two Atlantic flow states (blocked, and the basic, unblocked state).

A more comprehensive depiction of the range of hemispheric flows (Fig. 7) and their projection in the North Atlantic includes Low (top left panel), High (bottom right panel), and Moderate (bottom middle panel), as well as others that naturally follow from the decomposition of the long waves into cosine and sine components. In this figure, the middle of the abscissa, or ordinate, yields flows for which the Fourier coefficients are small, whereas either end of the axes provides larger amplitudes. For example, consider the high-amplitude meridional wind oscillations in the Low and High patterns compared to the middle panel of Fig. 7. Similarly, running along the cosine axis for small absolute sine (three middle panels of Fig. 7), or along the sine axis for small absolute cosine (bottom middle, middle, and top middle panels of Fig. 7), shows the amplitude variation and phasing changes that result from the alteration of these coefficients.

Considering the high-dimensional dynamics of the atmospheric flow, there is no guarantee that any such

FIG. 5. Average blocking frequency within 7 days of the current position in phase space for the (left) control and (right) perturbed systems. Amplitude is $Y^2 + Z^2$. Contour interval is 0.1, beginning at 0.1.
hemispheric decomposition will connect to the zonal wind structure specific to the North Atlantic. To investigate this possibility, it is of interest to determine whether the frequency of zonal wind deviations, which are in some way substantial, occurs preferentially for any part of this simplified projection. To determine this, first define a weak flow day as that for which the 300-hPa North Atlantic (45°–60°N; 70°W–0°) zonal wind is below the 10th percentile of all winter days (here, approximately 10 m s⁻¹). Then, count the percentage of the next 7 days for which the Atlantic flow meets this criterion (e.g., 1.00 would be every day for the next 7 days). High frequencies of weak flow occur with the Low pattern and low frequencies of weak flow are most common in the vicinity of the High pattern but also extend across the large cosine phase regardless of the sine phase (Fig. 8). This locally distinct behavior is broadly consistent with Burkhardt and Lupo (2005) and Barriopedro et al.

FIG. 6. (a),(b) The 300-hPa composite mean and anomalous geopotential height for Low and (c),(d) moderate planetary-scale flow pattern (see text for details).

There are two important consequences of the results shown previously: 1) whereas noted, there is a projection of the hemispheric pattern onto the flow in the North Atlantic, there is at least some likelihood of the reduced flow occurring regardless of the hemispheric pattern (Fig. 8), indicating that no identified pattern can be thought of as a necessary condition for flow reorganization; and 2) whereas the maximum likelihood of reduced North Atlantic flow is small at ~10% for the Low pattern, this is 2–3 times greater than that during the High pattern. This leads to the pivotal question discussed in this paper; given these structures, and related flow tendencies, can cyclogenesis act as a catalyst to reorganizing the North Atlantic flow in some preferred states?

To consider this question, the set of Atlantic cyclones identified by the global cyclone climatology from the NCEP reanalysis (Key and Chan 1999; available online at http://stratus.ssec.wisc.edu/products/cyclones/cyclones.html) for the period 1958–97 is examined. The 300-hPa North Atlantic zonal flow for any winter day during...
this period is categorized as below or above the 10th percentile. Then, a logistic regression (Hosmer and Lemeshow 2000)\(^2\) is performed for each 250-unit bin of the cosine and sine phases of the hemispheric flow as a function of the daily average count of Atlantic cyclones in the 3-day period preceding the day in question.

The coefficients of this regression reveal a mainly positive response of the North Atlantic zonal flow to cyclogenesis, meaning that Atlantic cyclogenesis increases the likelihood of weak zonal flow for most hemispheric patterns (Fig. 9). Most critically from the standpoint of our earlier arguments, however, is that this response is highly variable depending upon the hemispheric state. In particular, for the High and Moderate phases (the flow revealed in the composite of Figs. 6c,d), the data shows that an average of one additional cyclone event during the three preceding days increases the likelihood of below 10th percentile flow by a factor of up to 2.37. Whereas, for the Low phase, the analysis is suggestive that cyclogenesis actually decreases that likelihood by 0.67. The indication is that the inherent sensitivities detailed in Fig. 8 are substantially modulated by cyclone activity. It is interesting that this Moderate

\(^2\) The key characteristic of logistic regression is the ability to estimate the probability of a given outcome arising from a particular factor, under the explicit assumption that the log of the odds of that outcome is a linear response to that factor. In the context of the present study, the outcome is 300-hPa Atlantic zonal flow below the 10th percentile, and the independent factor is the daily average Atlantic cyclone count for the three days preceding the day in question. The slope of the regression coefficient measures the change in the log odds ratio associated with a unit change in cyclone count, allowing one to estimate the relative risk from that factor. The regression coefficient describes the size of the contribution of the factor (measured as \(e^{\text{coefficient}}\)), such that a positive coefficient indicates that cyclone activity increases the probability of the Atlantic flow being below the 10th percentile.

FIG. 7. Mean zonal (solid) and meridional (dotted) winds in the 45\(^\circ\)–60\(^\circ\)N lat band for 1958–2007, plotted along the cosine (sine) axis (up) across the page. (top right) Cosine and sine values in the range of +750 to +1250. (bottom left) Cosine and sine values \(< –500\).
The phase response is consistent with the low-order model results of section 2 for points situated in the fast flow regime near $X = 2.5$ (Fig. 5).

Further analysis of the sensitivity of this response to the latitude band chosen, and to the percentile threshold employed (not shown), yields some quantitative change (e.g., the latitude band from 50° to 65°N is more responsive to the cyclone effect than those situated farther south, whereas the response is relatively insensitive to the percentile threshold for the key patterns such as Moderate) but qualitatively has similar results to those of Fig. 9. This raises the question as to why cyclogenesis events are generally increasing the chances of weaker flows, given that baroclinic life cycle studies describe the acceleration of the zonal flow by the eddies. The answer lies in the distribution of zonal wind changes with cyclone involvement, which exhibits a tail skewed toward reductions in the flow, whereas the median change is an increase.

What assurance exists that these responses are associated with the hemispheric state rather than representing, for example, a more localized response to the flow over the North Atlantic basin? Instead of performing the Fourier analysis for the entire hemisphere as conducted earlier, consider a sectored version of this exercise. For the 128 hemispheric data points representing the 300-hPa meridional flow in the latitude band 45°–60°N for each day in the period 1958–97, consider 64 points (approximately 180° longitude) centered on a specific longitude. Apply a Hamming filter (Blackman and Tukey 1958) to this data, so that the values taper to zero by 32 points beyond the central longitude. Because of the rapid decay of the filter, this procedure insures that the extracted Fourier components will be isolated primarily to the quarter hemisphere of interest (the 32 points centered on the identified longitude) and that spurious frequencies will not contaminate the analysis. Next, compute the Fourier components and repeat the entire analysis every 16 points around the hemisphere to reveal the loading of the sectors on the hemispheric pattern (Fig. 10). The total variance of the hemispheric wavenumber 5 amplitude accounted for by these sectors is relatively low, ranging from 10% to 25%. Although the maximum accounted variance tends to peak near the Atlantic sector, these data strongly suggest that no specific sector alone accounts for the overall behavior summarized in Fig. 9. Indeed, like analyses to Fig. 9 performed for the sectors centered in the mid-Atlantic and mid-Pacific (not shown), they reveal that neither fully reproduce the overall structure of the hemispheric cyclone response.

The data strongly support the contention that the irregular response of the North Atlantic basin flow to cyclone activity in that basin should be considered in the context of the hemispheric as well as the local pattern; that is, some settings are relatively unsupportive of flow adjustments. One might wonder why the hemispheric pattern should have anything to do with the susceptibility of the Atlantic flow to, for example, blocking. Local expression of systemic properties, however, is readily found in natural systems. When liquid water is subjected to heat, as the water substance nears the point of transition to the

**Fig. 8.** Frequency of weak Atlantic flow within 7 days of the planetary-scale flow pattern characterized by the cosine and sine phases of wavenumber 5 (see text for details).

**Fig. 9.** Cyclone response coefficient obtained from logistic regression as a function of the cosine and sine phases of wavenumber 5 (see text for details).
There is a mixed phase regime, with water in both liquid and vapor form. The entire system is exposed to uniform conditions defined by temperature and pressure, yet the particulars of the state of the water are widely variable within that system.

Another example in nature is the viral disease commonly known as shingles. Infection by the varicella zoster virus, usually in childhood, causes chickenpox. Once the illness has been resolved, the virus becomes latent in the nerve cells. Much later, if the immune system is compromised, for example, through systemic exposure to chemotherapy agents, the virus can reactivate and travel down the nerve to cause a viral infection in patches of skin. The entire system, in this case the human body, is exposed to immunosuppressive conditions, yet the virus is expressed locally rather than globally.

Finally, consider the expected changes in precipitation coincident with global climate change driven by radiative forcing. Held and Soden (2006) and Bernstein et al. (2008) expect an increase in heavy precipitation and floods in the extratropics with continued warming. The climate system is driven globally, but precipitation patterns are local.

This hemispheric view of local flow adjustments, in principle, represents a new piece of predictive information. If one knows that the pattern is in a particular state, which is supportive of a cyclone-induced response, then the expected occurrence of cyclone activity would be more noteworthy than otherwise. It might be possible to incorporate this knowledge into probabilistic forecasts, for example at the medium range, although additional study would be needed to develop and test such a procedure. Whether any predictive information ultimately would be obtainable is unknown; the differences demonstrated here, while substantial as well as statistically significant, nonetheless represent the minority of events. This is not surprising as the dynamics are considerably more complex than is possible to represent in the low-dimensional phase space explored in this study, and such complexity may represent a substantial obstacle in developing reliable predictions.

4. Concluding summary

In this paper, the problem of the irregular response of the planetary-scale flow to cyclone-scale activity is investigated from the standpoint of nonlinear dynamics, using a low-order model and through consideration of analysis data. The results support the notion that the documented sensitivity of the response is a function of the current state of the hemispheric flow. In particular, some flow configurations are resistant to the influence of cyclone-scale forcing, whereas similar forcing under different states of the large-scale flow increases the likelihood of a more robust response. This finding suggests the possibility that postprocessing diagnostics could be developed for medium-range forecast models, which might improve probabilistic forecasts of regime transitions. Medium-range forecast models have produced limited success in anticipating such transitions, but the results of this paper suggest a possible means by which the sensitivity to such transitions could be anticipated regardless of whether the forecast explicitly accounts for a transition. These ideas will be explored in future work.

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