Baroclinic Development in Observations and NASA/GSFC General Circulation Models

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ABSTRACT

Comparative diagnostic analyses of developing synoptic-scale baroclinic disturbances in NCEP-NCAR reanalyses and the NASA/NCAR (NASCAR) and Aries (NSIPP) general circulation model simulations are performed. In particular, lag composite analyses of wintertime cyclonic and anticyclonic events occurring in the North Pacific and North Atlantic storm tracks are constructed to pursue a synoptic and dynamic characterization of eddy development. The data are also seasonally stratified to study aspects of the North Pacific midwinter suppression phenomenon.

Winter-averaged results indicate that the model simulated events are generally too weak in amplitude, particularly in the upper troposphere. For the North Pacific storm track, model simulated events are also anomalously distended in the meridional direction. The existing model biases in eddy structure and magnitude lead to anomalously weak baroclinic energy conversions for both cyclonic and anticyclonic events over the North Pacific. For the North Atlantic storm track the NASCAR model provides a very good representation of the structure of developing cyclonic events. However, growing North Atlantic cyclones in the NSIPP model are anomalously weak and horizontally too isotropic (meridionally retracted). These latter two characteristics are also observed in both models for developing anticyclonic flow anomalies over the North Atlantic. The relative weakness of NSIPP synoptic events over the North Atlantic region is largely responsible for the 50% deficiency in areal-averaged baroclinic energy conversions. Conversely, the NASCAR model climatology features anomalously strong temperature gradients over the western North Atlantic which provide local enhancements to the baroclinic energy conversion field.
A seasonally stratified diagnostic analysis reveals that the simulated climatological storm tracks over the North Pacific undergo larger spatial migrations during the cool season compared to observations. We further determine that the suppression of synoptic eddy activity observed in the Pacific storm track is associated with a relative midwinter weakness in the magnitude of the growing cyclonic anomalies. Specifically, during midwinter the cyclonic perturbations entering the Pacific storm track are deficient in magnitude compared to their early and late winter counterparts. We also discover that the midwinter suppression pattern over the North Pacific region has a clear organized extension upstream into Siberia, the region from which incipient upper tropospheric short wave features emanate. This behavior is found in both observations and the model simulations. Our results support the idea that the North Pacific midwinter suppression phenomenon is linked to a midwinter weakness in the upstream formation of upper level short waves, leading to anomalously weak “seeding” of baroclinic disturbances in the Pacific storm track.
1. Introduction

Synoptic-scale transient eddies play fundamental roles in both (a) local weather variability and (b) the global atmospheric transport of heat and momentum. Localized regions harboring the largest variances associated with synoptic eddies are typically known as storm tracks (Blackmon et al 1977). The synoptic eddies comprising the midlatitude storm tracks are often also referred to as baroclinic waves, since they are thought to arise from baroclinic instability. Interestingly, observational analyses indicate that the seasonal variation in the magnitude of the climatological storm track does not always directly correlate with the level of baroclinicity. More specifically, Nakamura (1992) illustrated that the mean baroclinic wave activity over the North Pacific positively correlates with upper-tropospheric jet speeds up to 45 m sec$^{-1}$. During the midwinter, however, the correlation reverses when the average jet speed exceeds this threshold. No such phenomenon is observed over the North Atlantic as the climatological jet in this region does not reach such a threshold windspeed.

In principle, one would expect basic features of synoptic eddies to be well represented by general circulation models of the atmosphere. Storm track characteristics, including the Pacific midwinter suppression, provide important benchmark tests in validating the climate of general circulation models (GCMs; e.g., Christoph et al. 1997; Zhang and Held 1999). Comparison studies examining the midwinter suppression have led to insight on the interannual and interdecadal variability of the regional storm tracks. Zhang and Held (1999) noted that the intraseasonal extent of the Pacific midwinter suppression is related to the relative strength of the winter jet core. In a comparison study using the GFDL GCM and reanalyses datasets, Chang (2001) found that these
interannual variations in Pacific storm track intensity stemmed from changes in the structure and residence time of the synoptic eddies. Nakamura and Sampe (2002) explored subseasonal variations in the midwinter suppression by noting anomalously strong Pacific jet cores in the midwinter modify the eddy structure by spatially trapping the synoptic eddies and weakening their interaction with the baroclinic zone. The knowledge gained by comparative diagnostic studies of observed and simulated storm tracks provide a means for enhancing our ability to simulate and predict regional climate variability.

Robinson and Black (2005) studied the time averaged statistics and structure of midlatitude storm tracks in AMIP (Atmospheric Model Intercomparison Project)-type simulations of the NASA/NCAR and Aries (NSIPP) GCMs (developed at NASA/GSFC). They found that both models have important shortcomings in representing the regional structure and magnitude of the primary storm tracks. In particular, the simulated synoptic eddy activity tends to be too weak compared to observations (especially NSIPP), while low-frequency events in the GCMs are more strongly driven by baroclinic dynamics (particularly over the Pacific region). Nonetheless, both models reproduce a midwinter suppression in the Pacific climatological storm tracks. Interestingly, the NSIPP model also produces a midwinter suppression within the Atlantic climatological storm track (Fig. 6 of Robinson and Black). Here we investigate the development of synoptic eddies in an effort to understand the physical reasons behind the model shortcomings identified in Robinson and Black (2005). We also aim to provide mechanistic insight regarding the midwinter suppression phenomenon.

In the current paper, we study the structure and dynamical properties of growing baroclinic
waves in the storm track regions for NASA/GSFC GCM simulations and compare the results with parallel observational analyses derived from the NCEP/NCAR reanalyses. Our general approach is to perform lag composite analyses of discrete cyclonic and anticyclonic events, focusing on the period of anomaly growth (negative lags). Our research objectives are two-fold: We first wish to assess the fundamental model representation of the structure and dynamics of anticyclogenesis and cyclogenesis events considering the winter season as a whole. An ancillary goal is to comparatively diagnose cyclogenesis activity for seasonally stratified periods to isolate the period of midwinter suppression. In the former case, we present results focusing on the winter-averaged properties of growing synoptic eddies. For the latter, we present parallel assessments of growing cyclones by partitioning the cool season into 3 distinct parts: late fall/early winter, midwinter, and late winter/early spring. The results for the early and late stages are then contrasted with midwinter results. The next section (2) overviews the datasets and general approach used. Sections 3 and 4 present winter average and seasonally stratified results, respectively. Section 5 summarizes the main results of our study and offers concluding remarks.

2. Data and Methods

The observational data used are the daily-averaged NCEP/NCAR reanalyses archived on 2.5° latitude by 2.5° longitude over 17 pressure levels (Kalnay et al. 1996). For consistency, the results presented in this study focus on the same time-period in each dataset, specifically the 17 calendar years from 1979 to 1995. The model datasets used in our study are AMIP-II type simulations of two general circulation models developed at NASA/GSFC. The first is a subset of the env05 AMIP run of version 1 of the Aries model used in NASA’s Seasonal-to-Interannual
Prediction Project (here referred to as the NSIPP model). With a horizontal resolution of 2.0° latitude by 2.5° longitude and 34 vertical levels, the NSIPP simulation implements a finite-differenced, primitive equations dynamical core (Suarez and Takacs 1995). The second model simulation is the AMIP fvccm3-1.2.0 run of the NASA/NCAR (or NASCAR) model developed jointly between NASA/GSFC and the NCAR. NASCAR employs a finite-volume approach to computational fluid dynamics (e.g., Lin and Rood 1997) with a horizontal resolution of 2.0° latitude by 2.5° longitude and 55 vertical levels. For both model simulations we sample daily averaged data interpolated to the 17 standard pressure levels used in the NCEP/NCAR reanalyses.

Composite analyses of unfiltered, daily-averaged anomalies are performed. Daily anomalies are computed by systematically removing seasonal and interannual variability from the raw data. The daily seasonal cycle is derived by smoothing the long-term daily-averaged climatological trend with a 91-point Parzen window (Fuenzalida and Rosenbluth 1990). Daily anomalies are then computed by successively subtracting (a) the smoothed daily climatology and (b) the interannual (seasonal mean) anomalies from the raw data. Two measures of synoptic-scale variability are used as references to select events for compositing. First, we identify cyclonic and anticyclonic events from the 300 hPa geopotential height anomaly time series associated with synoptic eddies at a central core point within each of the climatological storm tracks (defined independently for each of the three datasets). Synoptic eddies, having periods of 2.5 - 6 days, are extracted from the unfiltered anomaly field using a 151-point Lanczos filter. Once the synoptic events are identified, the 300 hPa envelope function of Nakamura and Wallace (1990) is areally averaged over each climatological storm track core region, and a minimum threshold value is applied to identify suitable dates for compositing (defined as Day 0). Using this threshold value
assures that the events composited are of coherent wave packets propagating through the core of the climatological storm tracks. Although the choice of the threshold is arbitrary, the results presented are not sensitive to the precise threshold value chosen. Our assessment of synoptic eddy growth upstream of the storm track core focuses on the composite fields at Day –1, since the largest growth typically takes place during this time.

The lag composite anomaly fields are then used to directly infer key information regarding the 3-D structure and dynamical interactions of synoptic eddies for the different observational and model categories discussed earlier. In the current study we assess the areally-averaged baroclinic and barotropic energy conversions occurring between the composite eddy field and the climatological-mean flow during synoptic eddy growth. Our approach follows the methods applied by Robinson and Black (2005) in their study of the mean dynamical characteristics of persistent flow anomalies. Further details can be found in Robinson and Black (2005).

3. Winter Mean Characteristics

The first part of our study focuses on the winter-averaged properties of growing synoptic eddies located just upstream of the core regions of the storm tracks, where winter is defined as the 90-day period from December 1st to February 28th (DJF). Specifically, we study the Day -1 features of cyclonic and anticyclonic synoptic eddies in the North Pacific and North Atlantic storm tracks using both observations and model simulations. Supplementing the material presented in this section, Robinson and Black (2005) provide a detailed comparison of the winter-mean zonally asymmetric circulation among the NASCAR and NSIPP simulations and NCEP/NCAR reanalyses.
As a practical first step in this analysis the vertical structure of the horizontally averaged eddy strength during growth is presented. Figure 1 displays the vertical profile of the DJF and areal-averaged eddy kinetic energy (EKE) associated with each case at Day -1, where the horizontal extent of the averaging is chosen to encompass the entire wave packet. Generally speaking, EKE increases less quickly with respect to height for the GCM events (especially NSIPP) compared to observed events. This relationship holds for both models over the Pacific storm track and for NSIPP over the Atlantic storm track. The NASCAR model generally compares better with the observed profiles, actually exceeding the observed profile throughout the troposphere for Atlantic cyclonic events. The NSIPP model is quite deficient in all cases except for Pacific anticyclonic cases, where it outperforms the NASCAR model. These results are consistent with the relative magnitudes of the simulated winter-mean storm tracks (as will be shown later). The main point to emphasize in Fig. 1 is that the upper tropospheric EKE is under-represented by the models in many of the event categories just as the eddy enters the period of strongest baroclinic development (Day -1).

To illustrate the three-dimensional circulation anomaly structure of the ensemble averages, Figs. 2-5 superpose 300 hPa height anomalies (contours) with 700 hPa height anomalies (shading) for the 4 event categories: Pacific cyclonic (PACCYC), Pacific anticyclonic (PACANT), Atlantic cyclonic (ATLCYC), and Atlantic anticyclonic (ATLANT). For PACCYC events, the primary (cyclonic) anomaly feature (~160-170E) of the simulated events at both levels is weaker in amplitude, exhibits a greater SW-NE tilt, and has a greater meridional extent than observed events. In terms of vertical structure, the PACCYC events in observations and the NSIPP model exhibit a notable southwestward tilt with height, the southward component of which is exaggerated in the
NSIPP model. This southward shift of the upper level feature from its lower level counterpart is reminiscent of the meridional trapping observed by Nakamura and Sampe (2002) in association with the midwinter suppression phenomenon. On the other hand, the NASCAR PACCYC cases exhibit westward tilts with height.

As illustrated in Figure 3, the GCMs do a much better job representing the magnitude and vertical structure of the growing anticyclonic feature of PACANT events. In fact, the local upper level anomaly for the NSIPP cases is larger in magnitude than observations (The discrepancy with Fig. 1b is attributable to the relative weakness of the upstream and downstream anomaly features in the NSIPP wave packet). We note, however, that the model simulated anticyclonic features have larger meridional extensions and there is slight SW-NE horizontal eddy tilt in the NSIPP model. We also note that the ensemble wavetrain in the NSIPP model exhibits a strong arcing towards the SE compared to the observed anomalies while the NASCAR wavetrain has a greater northeastward arc compared to observations.

Parallel analyses for the ATLCYC and ATLANT cases are displayed in Figures 4 and 5, respectively. Referring to the ATLCYC cases in Figure 4, the three-dimensional structure of the primary anomaly features in the NASCAR model compares very well with the observed structure, although the simulated cyclone is anomalously deep. In both cases the cyclonic anomaly feature is meridionally elongated with a southwestward tilt with height. In the NSIPP model, growing ATLCYC events are considerably weaker in magnitude and more isotropic (weaker meridional distension). On the other hand both models do a good job representing the longitudinal placement of the upper-level downstream anticyclonic anomaly feature. For the ATLANT cases (Fig. 5) the
anticyclonic feature in each model is anomalously weak and meridionally retracted in comparison to observations. In terms of the horizontal structure of the primary feature, while observed cases are meridionally aligned (N-S), the NASCAR (NSIPP) structures exhibit SW-NE (NW-SE) phase tilts. There are similar asymmetries in the great circle arcs of the two wavetrains. In this case the NSIPP pattern better corresponds to observations. Finally, it is of interest to note that in all three cases the downstream cyclonic circulation anomalies have notably greater amplitudes (unlike for PACANT events). This is consistent with the asymmetries in the relative structure and magnitude of cyclones and anticyclones predicted by nonquasigeostrophic models of baroclinic instability (e.g., Rotunno et al. 2000).

For each of the categories discussed above, the areal-averaged baroclinic and barotropic energy conversions calculated at 700 hPa and 300 hPa, respectively, are listed in Table 1 (Pacific cases) and Table 2 (Atlantic cases). To help assess the dynamical impact of the above-noted structural discrepancies between simulated and observed anomaly fields, we compute additional sets of energy conversions by respectively swapping the anomaly fields and climatological mean background flows among the datasets. These new conversions are also listed in Tables 1 and 2.

Initially focusing on the PACCYC (Table 1a) and PACANT (Table 1b) cases, the 700 hPa baroclinic energy conversions for the GCM cases are markedly lower than for observed events, especially in the NSIPP model where values are about 33% lower. Interestingly, when the eddy fluxes associated with the GCM composite anomalies are paired with the observed background flow, the baroclinic conversions are effectively unchanged. Conversely, when the observed eddy fluxes are paired with the simulated background flow fields, the observed conversion values are
approximately replicated. The latter correspondence is fractionally better for NASCAR, indicating a relative weakness in NSIPP’s representation of the climatological-mean flow. These results indicate that the simulated deficiencies in representing baroclinic energy conversions are primarily due to the misrepresentation of the synoptic eddy structure. For the NSIPP cases there is a second order influence that can be attributed to deficiencies in NSIPP’s representation of the background temperature gradient.

Before discussing the details of the barotropic energy conversions in Table 1, it is useful to note that baroclinic eddies (which are meridionally elongated) generally lose kinetic energy to the mean flow in the storm tracks, which are characterized by horizontal diffluence in the jet exit regions (Black and Dole 2000). However, this energy loss can be locally offset if a disturbance has a SW-NE (NW-SE) horizontal anomaly tilt on the north (south) side of the jet axis. Referring to Fig. 2, we recall that the GCM simulated PACCYC cases exhibit a greater SW-NE tilt. Since this feature occurs on the north side of the climatological jet, this will lead to an enhanced local transfer of kinetic energy from the mean flow into the eddies (Black and Dole 2000). For the PACANT cases, we do not observe a strong model bias in the horizontal anomaly tilt but we do observed a larger meridional elongation (Fig. 3). These differences in eddy structures for the Pacific cases are consistent with the variations in 300 hPa barotropic conversions observed in Table 1. The eddy mean flow swapping exercise confirms that this is indeed true for the NASCAR cases. However, a similar exercise performed for the NSIPP Pacific cases indicates that the background mean flow plays a larger role in determining the local barotropic energy conversion. In particular, barotropic damping of NSIPP Pacific cyclones events (Table 1a) is anomalously weak in large part because of existing deficiencies in the background zonal
windfield. In particular, the NSIPP model is characterized by a westward displacement and relative localization of the climatological barotropic deformation field compared to observations (Robinson and Black 2005).

For the Atlantic cases (Table 2), baroclinic conversions in the NSIPP model are seriously deficient (~50% too low) which can be largely attributed to the structure and magnitude of the ATLCYC and ATLANT cases, respectively. This is confirmed by the eddy-mean flow swapping exercise as the NCEP and NSIPP background temperature configurations result in virtually identical energy conversions (for a given eddy heat flux field). Conversely, the NSIPP 300 hPa mean flow over the Atlantic region modestly impacts the relative barotropic conversions. For NASCAR, although the baroclinic conversions compare more favorably with NCEP, they are overestimated for ATLCYC events (Table 2a). Although this is partly due to the anomalously strong eddy magnitudes in the NASCAR events (Fig. 4), it is also attributed to variations in the background temperature gradient. This is consistent with Robinson and Black (2005) who noted the average temperature in proximity to the climatological stationary trough over Hudson Bay is considerably colder in the NASCAR model. Consequently, larger horizontal temperature gradients exist over the east coast of North America in NASCAR. The results of eddy-mean flow swapping indicate the general tendency of the NASCAR temperature gradients to enhance the baroclinic energy conversion magnitudes over the North Atlantic storm track. Finally, we note that it is possible for errors in the simulated mean flow and eddy fields to feedback upon one another as (a) the mean flow helps determine the time evolving eddy structure and (b) the eddy heat and momentum fluxes provide local alterations to the background flow field.
4. Seasonal Stratification

We next apply similar diagnostic methods but focused on growing Pacific cyclones during different parts of the cool season. We first stratify the cool season into three stages: an early stage taken as November and December, a middle stage of January and February, and a late stage taken to be March and April. The early and late (middle) stages approximately correspond to the seasonal maxima (minimum) in synoptic eddy activity that occur over the North Pacific in association with the midwinter suppression phenomena (e.g., see Fig. 6 of Robinson and Black 2005). A core point marking the relative maximum of climatological synoptic eddy activity for each stage is chosen separately in each dataset. In doing so, we isolate the general characteristics of growing cyclones occurring within each stage taking account the seasonal migration of the climatological storm tracks. Our primary goals in this effort are to (a) identify synoptic and dynamic differences among the three stages and (b) test the extent to which the model behavior mimics observations.

Figure 6 displays Day -1 composite analyses of the 300- and 700-hPa height anomalies for the early, middle, and late stages for observed PACCYC events. The most apparent difference between the stages is the magnitude of the growing cyclonic anomaly. During the midwinter, the primary cyclonic height anomaly at 300 hPa is about -90 m, while the magnitudes for the early and late stages exceed -120 m (a similar disparity is observed at 700 hPa). This indicates that midwinter cyclones enter their strong growing stage somewhat deficient in magnitude (On the other hand, the upstream and downstream anticyclonic feature is actually strongest during the midwinter). Comparing the early and late stages, the primary cyclonic feature in the early stage
is deeper and more isotropic at both levels than that of the late stage. In each stage, the vertical tilt of the growing cyclone has a notable southwestward component, which is relatively enhanced in the middle and late stages. In addition to the southwestward tilt with height, the horizontal anomaly structure during midwinter features a bowing structure that rotates with respect to height. At 700 hPa there is a NW-SE anomaly tilt while at 300 hPa the eddy is oriented N-S. We note that the horizontal wavetrain pattern is more zonally oriented during the early and late stages than the middle stage.

Figure 7 displays corresponding seasonally-stratified composite 300- and 700-hPa height anomalies for the NASCAR model. During the early and late stages, the core points in the NASCAR model are displaced north of the observed Pacific storm track. Consequently, the north-south seasonal migration of the climatological Pacific storm track is anomalously large in the NASCAR model (This can be verified by comparing the location of the downstream anticyclonic features in Figures 6 and 7). During all three stages, the growing cyclone in the NASCAR model exhibits a westward tilt with height (with a slight southward component in the early stage). At both levels the major axis of the cyclonic flow anomaly is oriented NE-SW in the early stage, more N-S during midwinter, and NW-SE during the late stage. Similar to observations, the relative magnitude of the growing cyclonic anomaly is smallest during the middle stage at both levels. However, the downstream anticyclonic feature is also weakest during the middle stage in the NASCAR model, while the growing cyclonic feature is largest in magnitude during the late stage. The upper-level horizontal wavetrain pattern is more zonal during the early and late stages than it is during the middle stage (slight arcing towards the SE).
Figure 8 displays corresponding seasonally-stratified composite 300- and 700-hPa height anomalies for the NSIPP model. From the middle to late stage, the core point in the NSIPP model shifts westward by 10°, while a there is only a 5° westward shift in the observed core point (No such zonal shift occurs in the NASCAR model). The vertical tilt of growing cyclones in the NSIPP model has a notable southwestward component, especially during the middle and late stages. In the upper troposphere there is a greater NE-SW tilt in the cyclonic feature during the early stage relative to observations, and this relatively greater tilt prevails during the midwinter as well. The horizontal wavetrain feature in the NSIPP model bends towards the SE during the early stage, becomes more zonal in midwinter, and is slightly oriented from SW-NE during the late stage. For the middle stage, the 300 hPa cyclonic anomaly extends much further south than in the observed cases (likewise for the upstream anticyclonic feature), yet we note that the growing cyclone at 300 hPa during the middle stage is weaker in magnitude than during the early and late stages. However the corresponding cyclonic features at 700-hPa are similar in magnitude during the middle and late stages, and the downstream anticyclonic feature is weakest during the late stage.

One common element of the above analyses is the relative weakness of midwinter growing cyclones as they enter the period of strongest baroclinic growth. One factor proposed by Nakamura (1992) to explain the decreased baroclinic wave activity in the Pacific storm track in association with the midwinter suppression phenomena is a concomitant weakening in the upstream source of short waves (the “seeds” for downstream baroclinic development). Hakim (2003) recently demonstrated that Pacific baroclinic wave packets originate upstream poleward of the Himalayas. Following Nakamura’s (1992) idea, we posit that the midwinter suppression could be partly related to a relative lack of upstream short wave activity emanating from over
Siberia, where high static stability prevails during midwinter.

To test this idea directly we next analyze the regional difference in 300 hPa synoptic eddy activity between the midwinter period and an average of the early and late periods. This difference is shown in Fig. 9 along with contours of the winter mean RMS in the 300 hPa height field for all three datasets considered. Consistent with the profiles of EKE (Fig. 1), the magnitude of the simulated winter-averaged storm tracks over the North Atlantic correspond much more closely to observations than the Pacific storm track. For the NASCAR model, the magnitude of the Pacific climatological storm track is slightly weaker, whereas that of the Atlantic track compares very well with observations. Both storm tracks in the NSIPP model are much weaker than the observed winter-mean storm tracks (Robinson and Black 2005). As one would expect from the analyses of Robinson and Black (2005), there are prominent reductions in synoptic eddy activity observed over and north of the winter-averaged storm track during midwinter. Interestingly, this anomalous weakening pattern is observed to extend upstream into Siberia, precisely the region from which the upstream short waves emanate.

As mentioned earlier, one of the interesting things found by Robinson and Black (2005), was that the NSIPP model not only produces a midwinter suppression of the North Pacific storm track but also a midwinter suppression of the North Atlantic storm track (which is weaker and confined between January 15 through February). As such, one might wonder whether the idea put forth above for the Pacific storm track has any relevance for NSIPP’s North Atlantic storm track. Interestingly, Fig. 9 provides evidence that this may, indeed, be the case as the NSIPP difference pattern includes an organized area of suppressed synoptic eddy activity located over eastern North
America which is a regional source of synoptic wave activity for the North Atlantic storm track.
Similar patterns are not observed for NCEP or NASCAR. The current results provide
circumstantial evidence that the midwinter suppression phenomenon may be linked to midwinter
weaknesses in the upstream formation of upper level short waves, leading to anomalously weak
“seeding” for baroclinic growth in the downstream storm track of interest.

5. Summary and Concluding Remarks

We have performed comparative diagnostic analyses of developing baroclinic disturbances
in observations and NASA/GSFC general circulation model simulations. Growing synoptic-scale
cyclones and anticyclones are first identified for both the North Pacific and North Atlantic storm
tracks during boreal winter. Lag composite analyses are then used as a basis for synoptically and
dynamically characterizing observed and simulated eddy structures (eddy development is isolated
by selecting negative phase lags). The dynamical interactions between the growing synoptic
eddies and the background climatological-mean flow are assessed using local baroclinic and
barotropic energy conversions. Following Robinson and Black (2005), we further determine the
relative roles of separate model biases in (a) eddy structure and (b) background mean flow
representation by directly swapping the respective observationally-derived and model simulated
terms in the energy conversion analyses.

Our study first contrasts the observed and simulated structure and dynamics of developing
synoptic events considering the winter season as a whole. These results indicate that the model
simulated events are generally too weak in amplitude, particularly in the upper troposphere. Over
the North Pacific, cyclonic and anticyclonic simulated events are anomalously distended in the
meridional direction with the cyclonic events additionally marked by enhanced SW-NE horizontal phase tilts. The model biases in eddy structure and magnitude are associated with anomalously weak baroclinic (cyclones and anticyclones) and barotropic (cyclones) energy conversions over the North Pacific. Barotropic damping of Pacific cyclones in the NSIPP model is further reduced from observations due to deficiencies in the background zonal wind field (with anomalously weak barotropic deformation).

For the North Atlantic storm track the NASCAR model provides a good representation of the three-dimensional structure of developing cyclonic flow anomalies. The primary difference is that the model events are too large in magnitude. However, growing North Atlantic cyclones in the NSIPP model are anomalously weak in magnitude and horizontally too isotropic (anomalously weak meridional distension). For both NASCAR and NSIPP models, the developing anticyclonic flow anomalies over the North Atlantic are anomalously weak and meridionally retracted. The relative weakness in the amplitude of NSIPP synoptic events over the North Atlantic region is largely responsible for the 50% deficiency in the areal-averaged baroclinic energy conversion. In NASCAR model, there is a general tendency for anomalously strong temperature gradients in the North Atlantic storm track, leading to local enhancements in the baroclinic energy conversions (for a fixed circulation anomaly structures).

We next seasonally stratified our diagnostic analyses for the North Pacific storm track in order to isolate the period of midwinter suppression of synoptic eddy activity (Nakamura 1992). Throughout the cool season, meridional (zonal) migrations in the NASCAR (NSIPP) Pacific climatological storm track are greater than observed migrations. Composite structural analyses
reveal that the most apparent difference between midwinter and early winter and late winter periods is that the magnitude of the growing cyclonic anomalies is weaker during midwinter, consistent with the studies of Chang (2001) and Nakamura and Sampe (2002). Thus, during the midwinter suppression period cyclonic perturbations entering the North Pacific storm track core are deficient in magnitude compared to early and late winter stages. This feature is common to both observations and model simulations.

Collectively considering the above information, we have also studied the idea put forth by Nakamura (1992). In the closing remarks of his paper, Nakamura suggested that one factor that may contribute to the North Pacific midwinter suppression is a midwinter weakening in the upstream source of tropospheric short waves (the “seeds” for downstream baroclinic development). We have performed an preliminary test of this idea by calculating the local differences in the time-averaged synoptic eddy activity between midwinter and the early and late winter periods. In both observations and model simulations we find that the North Pacific midwinter suppression feature has a clear organized extension upstream into Siberia, the region from which the key upper tropospheric short wave features are believed to emanate (Hakim 2003). Further, similar upstream behavior is observed in association with the parallel midwinter suppression of the North Atlantic storm track that is (erroneously) simulated in the NSIPP model (Robinson and Black 2005).

Our results provide initial evidence in support of the idea that the North Pacific midwinter suppression phenomenon may be linked to midwinter weaknesses in the upstream formation of upper level short waves, leading to anomalously weak “seeding” of baroclinic disturbances in the
storm tracks. Future investigations will consider the roles of upstream variations in static stability, wave packet trajectories (e.g., Chang 2005), and other factors in producing systematic weakening of initial upstream disturbances. It will be of particular interest to study the interannual variability of any potential factor, since the extent of the midwinter suppression of synoptic eddy activity corresponds to the relative strength of the Pacific jet core (Zhang and Held 1999).

ACKNOWLEDGMENTS

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Table 1a: The winter-mean, areal-average 700-hPa baroclinic and 300-hPa barotropic energy conversions for Pacific cyclonic cases at Day -1 for the NCEP/NCAR reanalyses, NASCAR and NSIPP models, and the swapped energy conversions. The averaging region for the Pacific cases is 110°E-130°W and 20°N-60°N.
(b) PACANT

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<th>300-hPa Barotropic Conv. ( \times 10^{-5} \text{ m}^2 \text{sec}^{-3} ): DJF / Day -1</th>
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Table 1b: As in Table 1a except for Pacific anticyclonic cases.
Table 2a: The winter-mean, areal-average 700-hPa baroclinic and 300-hPa barotropic energy conversions for Atlantic cyclonic cases at Day -1 for the NCEP/NCAR reanalyses, NASCAR and NSIPP models, and the swapped energy conversions. The averaging region for the Atlantic cases is 240°E-360°E and 30°N-70°N.
(B) ATLANT

<table>
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<th>NSIPP</th>
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Table 2b: As in Table 2a except for Atlantic anticyclonic cases.
**FIGURE LEGENDS**

Figure 1. Vertical profiles of the areal averaged eddy kinetic energy for each dataset derived from the winter-averaged unfiltered anomalies for (a) Pacific Cyclonic, (b) Pacific Anticyclonic, (c) Atlantic Cyclonic, and (d) Atlantic Anticyclonic cases. The averaging region for the Pacific cases is 110°E-130°W and 20°N-60°N and for the Atlantic cases is 120°W-0° and 30°N-70°N.

Figure 2. Winter-averaged composite height anomalies at 300-hPa (contour intervals: 20 m) and 700-hPa [dark (light) gray shaded regions are greater (less) than 20 (-20) m at 20 m intervals] for Pacific Cyclonic cases at Day -1 for the (a) NCEP/NCAR reanalyses and (b) NASCAR and (c) NSIPP models. Day 0 is defined as when the synoptic eddies are at maximum amplitude in the core of the regional storm track.

Figure 3. As in Figure 2 except for Pacific Anticyclonic cases.

Figure 4. As in Figure 2 except for Atlantic Cyclonic cases.

Figure 5. As in Figure 2 except for Atlantic Anticyclonic cases.

Table 1a: The winter-mean, areal-average 700-hPa baroclinic and 300-hPa barotropic energy conversions for Pacific cyclonic cases at Day -1 for the NCEP/NCAR reanalyses, NASCAR and NSIPP models, and the swapped energy conversions. The averaging region for the Pacific cases is 110°E-130°W and 20°N-60°N.

Table 1b: As in Table 1a except for Pacific anticyclonic cases.
Table 2a: The winter-mean, areal-average 700-hPa baroclinic and 300-hPa barotropic energy conversions for Atlantic cyclonic cases at Day -1 for the NCEP/NCAR reanalyses, NASCAR and NSIPP models, and the swapped energy conversions. The averaging region for the Atlantic cases is 240°E-360°E and 30°N-70°N.

Table 2b: As in Table 2a except for Atlantic anticyclonic cases.

Figure 6. Composite height anomalies at 300-hPa (contour intervals: 20 m) and 700-hPa [dark (light) gray shaded regions are greater (less) than 20 (-20) m at 20 m intervals] for Pacific Cyclonic cases at Day -1 for the NCEP/NCAR reanalyses during the (a) early (b) middle and (c) late stage of the Northern Pacific cool season. The early stage of the cool season is taken as November and December, a midwinter of January and February, and late stage taken to be March and April.

Figure 7. As in Figure 6 except for the NASCAR model.

Figure 8. As in Figure 6 except for the NSIPP model.

Figure 9. The rms highpass-filtered geopotential height anomalies for the winter average (contour intervals: 10 m) and the difference between the midwinter period and an average of the early and late periods (shaded regions: units m) at 300-hPa during the (a)-(c) Pacific cool season for the NCEP/NCAR reanalyses, NASCAR, and NSIPP datasets, respectively and (d) during the Atlantic cool season for the NSIPP model. The early stage of the Atlantic cool season is taken as December through January 15, a midwinter between January 15 through February, and late stage taken to be March through April 15.
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