AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL067989

Key Points:

- The SH jet position/jet shift correlation is highly seasonal in CMIP5 models
- It is strong in JJA but weak in DJF, opposite to the spread in SAM timescales
- Proposed theories for the jet position/jet shift relationship appear inadequate to explain this seasonality

Supporting Information:

- Figure S1 and Table S1

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Citation:
Simpson, I. R., and L. M. Polvani (2016), Revisiting the relationship between jet position, forced response, and annular mode variability in the southern midlatitudes, *Geophys. Res. Lett.*, *43*, 2896–2903, doi:10.1002/2016GL067989.

Received 28 JAN 2016
Accepted 26 FEB 2016
Accepted article online 1 MAR 2016
Published online 19 MAR 2016

Revisiting the relationship between jet position, forced response, and annular mode variability in the southern midlatitudes

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Abstract Climate models exhibit a wide range in latitudinal position of the Southern Hemisphere westerly jet. Previous work has demonstrated, in the annual mean, that models with lower latitude jets, exhibit greater poleward jet shifts under climate forcings. It has been argued that this behavior is due to stronger eddy/mean flow feedbacks in models with lower latitude jets, as inferred from the timescale of the Southern Annular Mode (SAM). Here we revisit this question with a focus on seasonality. Using a larger set of models and forcing scenarios from the Coupled Model Intercomparison Project, phase 5, we find that the jet position/jet shift relationship is strong in winter but insignificant in summer, whereas the model spread in SAM timescales arises primarily in summer, with winter timescales similar across models. The results, therefore, question previous interpretations and motivate an improved understanding of the spread in model behavior.

1. Introduction

Accurate model predictions of future changes in the Southern Hemisphere (SH) westerlies are necessary for accurate prediction of SH regional climate, Antarctic sea ice cover [*Sigmond and Fyfe*, 2010; *Smith et al.*, 2012] and the ocean circulation and its uptake of heat and carbon [e.g., *Marshall and Speer*, 2012; *Gent*, 2016]. A long standing barrier to our confidence in model predictions of the SH westerlies, however, is the current inability to simulate their observed climatology and variability.

Many climate models place the SH zonal mean westerly jet maximum, equatorward of the observations [*Fyfe and Saenko*, 2006; *Swart and Fyfe*, 2012; *Wilcox et al.*, 2012; *Bracegirdle et al.*, 2013], and studies have suggested that the extent of a model's equatorward jet bias correlates with how much the jet shifts in latitude under climate forcings (*Kidston and Gerber* [2010, KG2010, hereafter], *Son et al.* [2010], and *Bracegirdle et al.* [2013]). Ultimately, one would want to alleviate this equatorward bias, but such a correlation might also serve as an emergent constraint on the future evolution the climate system [*Collins et al.*, 2012]. Any such constraint must, however, be grounded on a solid understanding of the physical processes involved.

Our current understanding of the jet latitude/jet shift relationship is that it arises because models with lower latitude jets, exhibit stronger eddy/mean flow feedbacks. This has been inferred from a relationship between jet latitude and the persistence of the Southern Annular Mode (SAM), as measured by its decorrelation timescale. Lower latitude jets exhibit greater SAM persistence, as shown by KG2010 with global coupled models, and several idealized modeling studies [*Son and Lee*, 2005; *Gerber and Vallis*, 2007; *Barnes et al.*, 2010; *Simpson et al.*, 2010]. The greater persistence of this dominant mode of natural variability is taken to indicate stronger feedbacks onto that mode. Since these same feedbacks are expected to be involved in the jet response to forcings, it makes sense that a jet with greater SAM persistence shifts further under forcing. Such reasoning follows the theoretical arguments of the fluctuation-dissipation theorem (FDT) [*Leith*, 1975], and it is assumed that the forced response is well predicted by the character of the dominant mode of natural variability (in this case the SAM).

Here building on the work of KG2010, we analyze a large set of models from the Coupled Model Intercomparison Project, Phase 5 (CMIP5) and revisit the relationships between jet latitude, forced response, and the SAM timescale. Our focus is on seasonality and we find that the correlation between jet latitude

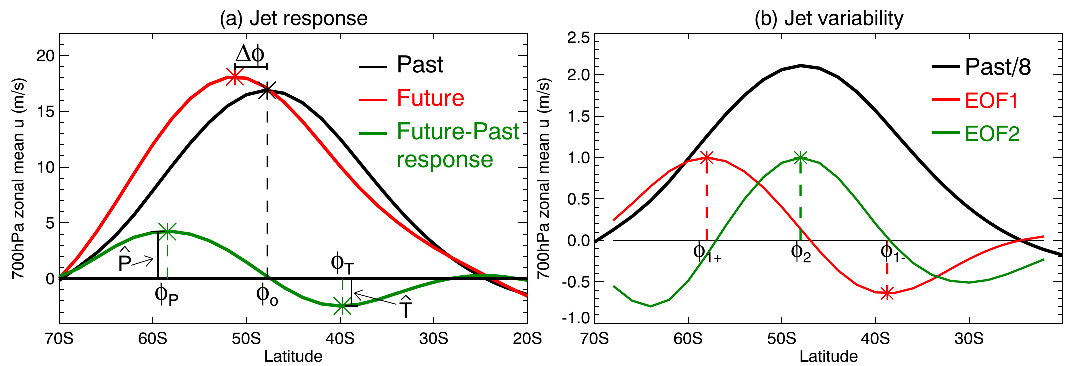

Figure 1. An illustrative example (DJF, CanESM2) of parameters used. (a) Geometric parameters characterizing Past and Future climatologies and (b) parameters characterizing the structure of the Past EOF1 and EOF2. In (a) ϕ_o = Past jet latitude, $\Delta\phi$ = Future-Past jet shift, ϕ_P and ϕ_T = locations of the peak and trough of the Future-Past difference dipole, and $\hat{P}$ and $\hat{T}$ are their magnitudes. In Figure 1b ϕ_{1+} and ϕ_{1-} are the peak and trough latitudes of EOF1 and ϕ_2 the peak latitude of EOF2 and the structure of the past climatological jet is shown for reference.

and forced response is strong in winter (June, July, and August (JJA)) but insignificant during the summer months (December, January, and February (DJF)). In contrast, the model spread in SAM timescales displays the opposite seasonality, being minimal in JJA. The previously reported relationships between annual mean jet response and annual mean SAM timescale in global climate models are, therefore, mixing relationships in different seasons. This questions the appropriateness of interpretations following the FDT, highlights the present lack of understanding of the fundamental processes involved, and motivates future work that should aim to remedy this.

2. Data and Diagnostics

2.1. Data

We use data from 35 models that participated in CMIP5 (supporting information Table S1). Our focus is primarily on the historical and RCP8.5 runs, defining the "Past" as 1979–2005 of historical, and the "Future" as 2070–2099 of RCP8.5. A complementary analysis is also performed using a 200 year sample from the piControl runs, and years 50 to 100 of the abrupt4xCO2 runs, to eliminate uncertainties that may be introduced by varying model representations of forcings other than CO_2. The primary field of interest is the 700 hPa zonal mean zonal wind u, but we also use 500 hPa zonal mean geopotential height Φ, for the calculation of the SAM timescales (for consistency with the majority of previous studies on SAM persistence [e.g., *Baldwin et al.*, 2003; *Gerber et al.*, 2010; *Kidston and Gerber*, 2010]). These fields are first interpolated onto a common 2° latitude grid. ERA-Interim reanalysis data [*Dee et al.*, 2011] from 1979 to 2005 are also used.

2.2. Diagnostics

The jet "response" is characterized by both simple geometric parameters and its relation to the first two empirical orthogonal functions (EOFs) of natural variability. The geometric parameters are depicted in Figure 1a. Jet latitude is defined as the location of the maximum 700 hPa u in the SH, obtained by a quadratic fit using the maximum grid point and two points either side. The Past and Future jet latitudes are denoted ϕ_o and $\phi_o + \Delta\phi$, respectively, so that $\Delta\phi$ is the future jet shift. The Future-Past difference in u typically consists of a dipolar structure, producing a poleward shift (Figure 1a, green line). The peak and trough latitudes of this structure are denoted ϕ_P and ϕ_T, and the peak and trough magnitudes are denoted $\hat{P}$ and $\hat{T}$.

The structure of the natural variability of the jet is characterized by the first two EOFs of Past daily u, for the 23 models with daily data available (supporting information Table S1). These EOFs are calculated for the DJF and JJA seasons separately, using 20°S to 70°S detrended and deseasonalized u, following *Baldwin et al.* [2009]. The EOF1 and EOF2 wind anomalies as a function of latitude, ϕ, for each model, i, are denoted $u_1(\phi, i)$ and $u_2(\phi, i)$ and these are normalized such that the maximum anomaly is 1 m s^{-1}. An illustrative example is shown in Figure 1b: EOF1 (i.e., the SAM) typically represents latitudinal shifts of the jet, whereas EOF2 typically represents variations in jet speed. The peak and trough latitudes of EOF1 are denoted ϕ_{1+} and ϕ_{1-}, and the peak latitude of EOF2 is denoted ϕ_2.

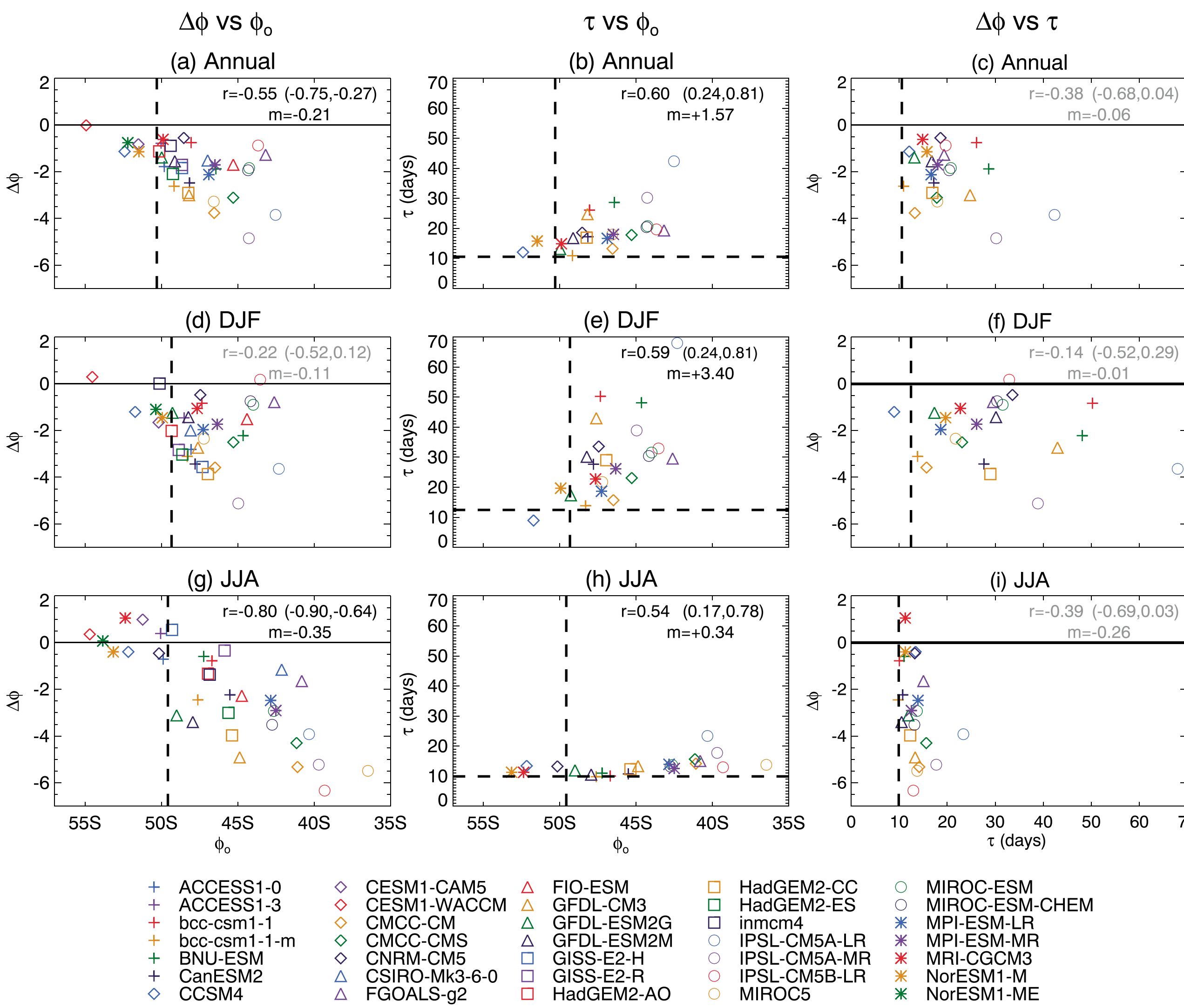

Figure 2. (a, d, and g) $\Delta\phi$ versus ϕ_o, (b, e, and h) τ versus ϕ_o, and (c, f, and i) $\Delta\phi$ versus τ. (a–c) annual means, (d–f) DJF, and (g–i) JJA. Correlation coefficients (r) and their 95% confidence interval calculated using the Fisher transform [*Devore*, 1999] are quoted along with the best fitting regression slope (m) (in grey where the confidence interval on the correlation coefficient encompasses zero). Dashed lines depict ERA-Interim values where appropriate.

The SAM timescale (τ) calculation is performed using 500 hPa Φ following *Gerber et al.* [2010]. In brief, the autocorrelation function (ACF) of the first EOF of daily Φ is calculated after removing the global mean, deseasonalizing and detrending. Unlike for the u EOFs above, the EOF here is defined using all days of the year, for consistency with previous studies. The timescale for each day of the year is the 1/e-folding timescale of this ACF after smoothing over a 181 day window with a Gaussian filter with full width half maximum of 42 days. Seasonal or annual averages of these smoothed daily values of τ are then computed.

3. Results

3.1. The Relationship Between $\Delta\phi$, ϕ_o, and τ

We start by extending the findings of KG2010 to CMIP5 and show in Figures 2a–2c, the annual mean relationships of $\Delta\phi$ and τ with ϕ_o (denoted Cor(ϕ_o, $\Delta\phi$) and Cor(ϕ_o, τ)), as well as the correlation between $\Delta\phi$ and τ. As already noted by *Wilcox et al.* [2012] with a smaller subset, the CMIP5 models exhibit similar behavior to those examined by KG2010: lower latitude jets shift further poleward in the future (Figure 2a) and exhibit greater SAM timescales (Figure 2b). Note that these correlations are significant. The correlation between $\Delta\phi$ and τ is not statistically significant (Figure 2c), although it is of the same sign reported by KG2010, i.e., models with greater SAM timescales exhibit larger jet shifts.

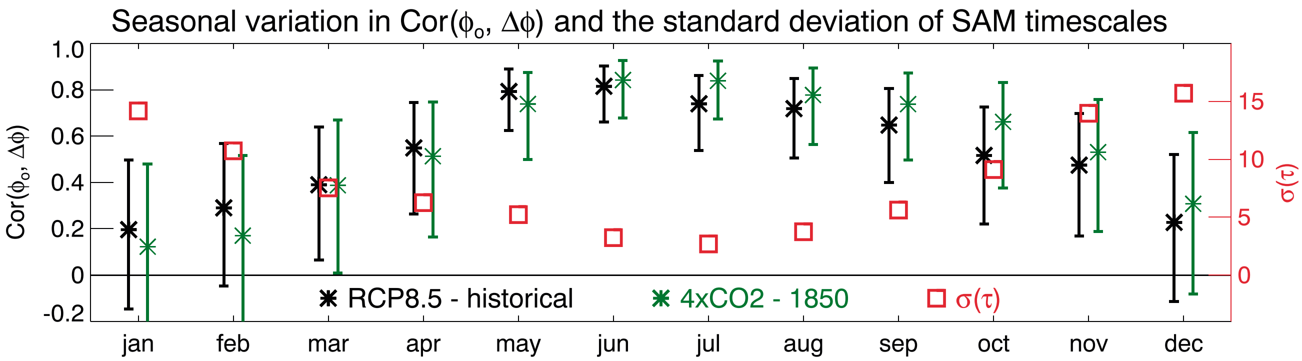

Figure 3. Seasonal cycle of monthly Cor(ϕ_o, $\Delta\phi$) (black and green) and the standard deviation, across models, of monthly averaged τ (red). Black points: Future = RCP8.5, Past = historical. Green points: Future = abrupt4xCO2, Past = piControl. Error bars display 95% confidence intervals on Cor(ϕ_o, $\Delta\phi$) calculated using the Fisher transform [*Devore*, 1999].

These relationships are then shown separately for DJF and JJA in Figures 2d–2i. Cor(ϕ_o, $\Delta\phi$) is much stronger in JJA (panel g) than in DJF (panel d). In fact, it smoothly evolves between a minimum in summer (DJF) and a maximum in winter (JJA) (Figure 3). This seasonality was also noted by KG2010, who speculated that the reduced correlation in DJF may be due to disparity in the representation of stratospheric ozone forcing among models [*Son et al.*, 2008]. However, it persists in CMIP5, despite the more standardized treatment of ozone depletion [*Eyring et al.*, 2013]. To further confirm that this seasonality occurs regardless of the representation of stratospheric ozone, the green points in Figure 3 show that for the abrupt4xCO2-piControl runs, Cor(ϕ_o, $\Delta\phi$) displays the same seasonality.

If the aforementioned FDT arguments explain Cor(ϕ_o, $\Delta\phi$), then a similar seasonal dependence of the relationship between τ and ϕ_o would be expected. However, quite the opposite is seen. While Cor(ϕ_o, τ) is significant in both DJF and JJA, it is clear that the majority of the variance in τ, present in the annual mean, comes from DJF (Figure 3 and compare Figures 2e and 2h). During JJA, τ is fairly constant across models, and much closer to the reanalysis, with the slope of the best fitting regression line between τ and ϕ_o being an order of magnitude less than in DJF. Versions of Figures 2h and 2i with more appropriate axes for viewing the model spread in JJA are shown in supporting information Figure S1, making clear that models at opposite ends of the ϕ_o, and hence $\Delta\phi$, range, exhibit virtually identical values of τ. Hence, the annual relationships in Figures 2a–2c are mixing strong relationships between $\Delta\phi$ and ϕ_o in JJA and τ and ϕ_o in DJF.

It is worth cautioning that the SAM timescale is not solely indicative of the strength of feedback processes, as it can be influenced by external intraseasonal drivers of jet variability [*Keeley et al.*, 2009; *Simpson et al.*, 2011]. Ideally, one would want to use a directly calculated measure of feedback strength, such as proposed in [*Simpson et al.*, 2013], rather than τ, but the short timescales in JJA make the feedback strength calculation very uncertain in those months, so we make do with τ as a proxy. External drivers of variability certainly inflate the timescales in DJF compared to JJA [*Keeley et al.*, 2009; *Simpson et al.*, 2011], which could account for some of the increased variance in τ then, but that is unlikely to be the whole story. DJF is the primary season where the eddy feedback strength exhibits considerable spread across the models and is biased relative to the reanalysis [*Simpson et al.*, 2013, their Figure 10].

The seasonal decomposition, therefore, indicates that our understanding of the SH jet response to forcing, and its connection to jet variability and climatological jet position, is fundamentally incomplete. An improved understanding of the relevant processes is needed, if we are to explain this seasonality. In the season when lower latitude jets respond more to forcings (JJA), all models exhibit similar SAM timescales (and thus inferred eddy feedbacks), making it difficult to argue that lower latitude jets shift more because of stronger eddy feedbacks. It is not clear why Cor(ϕ_o, $\Delta\phi$) should be so strong in JJA and we do not provide a complete answer below, but we do shed light on other seasonal dependencies that are likely part of the story.

3.2. The Latitudinal Structure and Magnitude of the Jet Response to Forcing

Considering the properties of the zonal wind response to forcing depicted schematically in Figure 1a, two components could contribute to the jet latitude/jet shift relationship during JJA: a "structural" component and a "magnitude" component. The structural component refers to the fact that the latitude of the wind responses (ϕ_T and ϕ_P) relative to the climatological jet may depend on jet latitude in such a way as to represent more

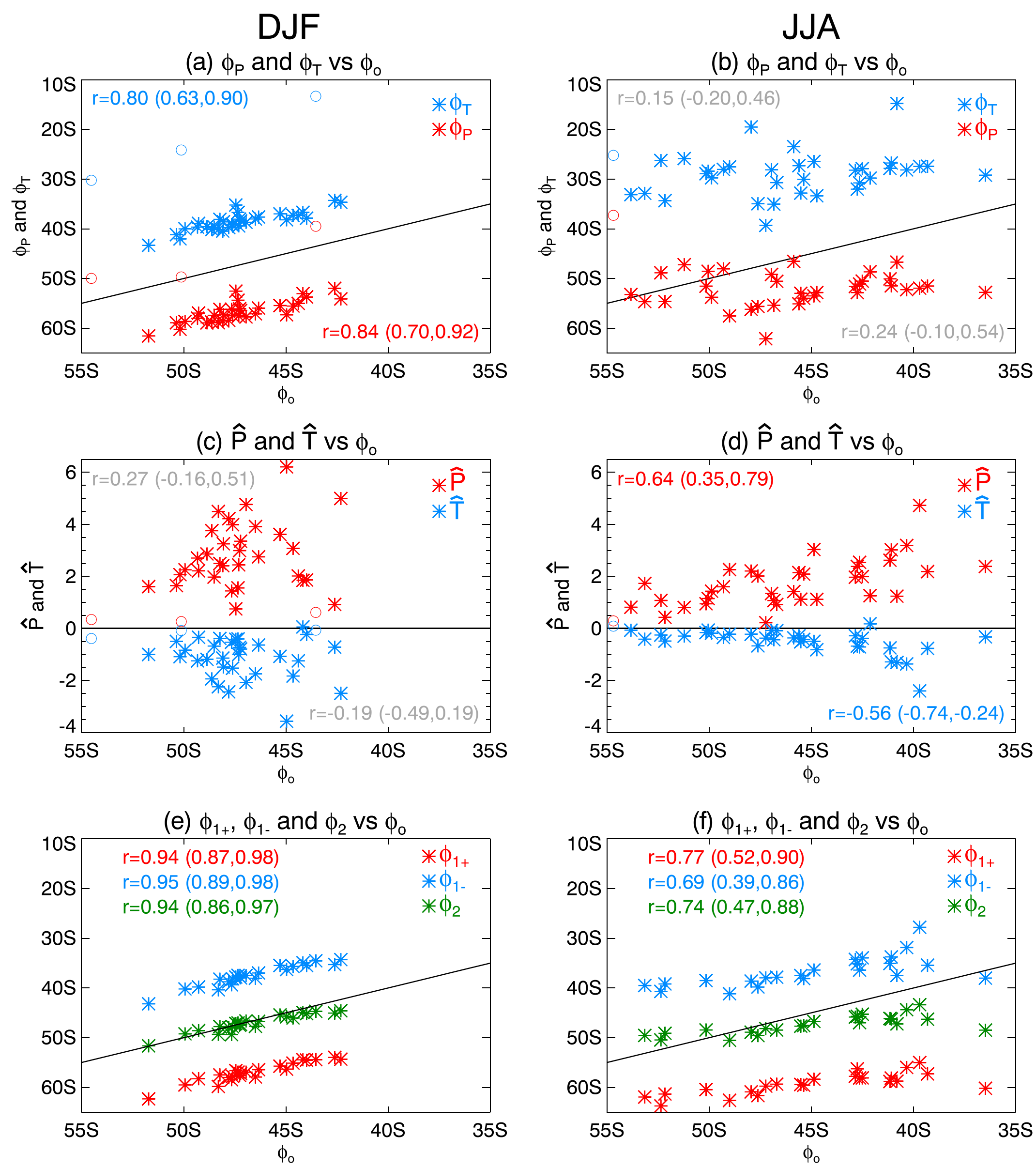

Figure 4. (a, c, and e) DJF and (b, d, and f) JJA. (a–d) relationships between geometric parameters of the RCP8.5-historical difference and ϕ_o. (a and b) ϕ_P and ϕ_T vs ϕ_o and (c and d) $\hat{P}$ and $\hat{T}$ vs ϕ_o. Circled points are considered outliers due to weak responses, leading to difficulty in characterizing the response by the representative dipole structure. These are omitted in the calculation of correlation coefficients. (e and f) ϕ_{1-}, ϕ_{1+} and ϕ_2 versus ϕ_o. Correlation coefficients and their 95% confidence interval are quoted (in grey where statistically insignificant). Solid lines in Figures 4a, 4b, 4e, and 4f depict the 1:1 line.

of a poleward shift for lower latitude jets. The magnitude component refers to the fact that the magnitude of the wind response ($\hat{P}$ and $\hat{T}$) may be greater for the lower latitude jets. The potential for contributions from these two components to the jet latitude/jet shift relationship is explored through Figures 4a–4d.

Consider first the structural component, i.e., how ϕ_T and ϕ_P vary with ϕ_o. Contrasting Figures 4a and 4b, there is a clear difference between DJF and JJA. In DJF, ϕ_P and ϕ_T are centered roughly around ϕ_o, i.e., the wind response represents a poleward shift, regardless of climatological jet position. This is not so in JJA. Rather than being equidistant from ϕ_o, ϕ_T is roughly 30°S and ϕ_P is roughly 50°S regardless of where the climatological jet is located. As a result, the response transitions from a shift to a strengthening as one considers higher latitude jets in JJA. This was previously reported by *Barnes and Polvani* [2013] for the annual mean but appears to be a strongly seasonal effect, occurring primarily in the winter.

Next, consider the magnitude component of the response, depicted in Figures 4c and d, which show $\hat{P}$ and $\hat{T}$ versus ϕ_o. In DJF, neither is correlated with ϕ_o, whereas in JJA, the correlations are significant: lower latitude jets exhibit larger wind responses. So, both the structural and the magnitude component may be contributing to the strong relationship between $\Delta\phi$ and ϕ_o in JJA, whereas neither is present in DJF.

3.3. The Relation of the Response to the Dominant Modes of Variability

The response to a forcing often bears a strong resemblance to the dominant modes of natural variability. Indeed, this is one of the key assumptions underlying the FDT arguments previously proposed as an explanation of the jet shift/jet latitude correlation. It is, therefore, instructive to examine how the forced response, in each season, relates to the dominant modes of variability. Furthermore, as will be shown below, such an analysis allows for quantification of the relative importance of the "magnitude" and "structural" components, discussed above.

In Figures 4e and 4f we illustrate how the structure of the first two EOFs of natural variability depend on the jet latitude, through the parameters ϕ_{1+}, ϕ_{1-}, and ϕ_2 (see Figure 1b). In DJF, much like the forced response in the panels above, EOF1 always represents a latitudinal shift, as the red/blue pairs follow ϕ_o. Similarly, EOF2 (in green) is always a strengthening, since ϕ_2 falls very much on the 1:1 line. In contrast, and similar again to the forced response in the panels above, in JJA the EOF parameters change with ϕ_0 such that EOF1 and EOF2 cannot be said to always represent a clear shift and strengthening, respectively (the colored points have a shallower slope than the black 1:1 line). This too was previously reported by *Barnes and Polvani* [2013] for the annual mean but, again, is primarily a JJA effect.

Next we relate the forced response of the jet to these modes of variability. First, we synthetically construct the Future winds $u_F(\phi, i)$ using the Past winds (u_P) and the projection of the wind response onto these two EOFs via the expression:

$$\tilde{u}_F(\phi, i) = u_P(\phi, i) + K_1(i)u_1(\phi, i) + K_2(i)u_2(\phi, i), \quad (1)$$

where, for each model i, $\tilde{u}_F$ is the constructed Future wind and $K_1(i)$ and $K_2(i)$ are the projections of the response onto the normalized first and second EOFs (u_1 and u_2). Figures 5a and 5e demonstrate that this reconstruction works exceedingly well for capturing $\Delta\phi$ (except for two models in JJA, shown by open circles, that are omitted from the following analysis).

Next, $\tilde{u}_F$ is decomposed into contributions from the multimodel mean projection onto the EOFs ($\overline{K}_1$ and $\overline{K}_2$) and the deviations therefrom (K'_1 and K'_2), i.e.,

$$\tilde{u}_F(\phi, i) = u_P(\phi, i) + \overline{K}_1 u_1(\phi, i) + \overline{K}_2 u_2(\phi, i) + K'_1(i)u_1(\phi, i) + K'_2(i)u_2(\phi, i). \quad (2)$$

In this framework, the FDT arguments would hold if models which longer SAM timescales also possessed larger values of K'_1. In DJF, the wind response almost entirely projects onto EOF 1 (Figure 5b) but, while lower latitude jets exhibit longer SAM timescales (Figure 2e), K'_1 is completely uncorrelated with ϕ_o (Figure 5c). The behavior in JJA is rather different: the wind response projects onto both EOFs 1 and 2 (Figure 5f). Furthermore, the magnitude of the projection onto EOF 1 is significantly correlated with ϕ_o (Figure 5g), which is another way of capturing the magnitude component of the response already illustrated in Figure 4d.

One advantage of using the synthetically constructed response is that it allows for quantification of the importance of the magnitude and structural components. The former arises from the fourth and fifth terms in equation (2), so omitting those terms in the construction brings out the relationship between ϕ_o and $\Delta\phi$ that arises from the purely structural component alone, i.e., the component due to the differing position of the wind anomalies relative to ϕ_o, here brought about by the differing structures of u_1 and u_2. This gives an idea of the influence of the structural effect, but the complete jet shift is not a simple sum of this and that due to the fourth and fifth terms, due to nonlinearities. Figures 5d and 5h show that in DJF the structural component does not contribute to the dependency of $\Delta\phi$ on ϕ_o, whereas in JJA it explains a good fraction of the dependency. For all models, in JJA, the regression of $\Delta\phi$ on ϕ_o yields a slope of −0.35°/° (Figure 2g) and the smaller model subset in Figure 5 yields a similar slope (−0.34°/°). When the structural component alone is considered the slope is −0.18°/° (Figure 5h) allowing us to conclude that the magnitude and structural components are of roughly comparable importance in contributing to the jet latitude/jet shift relationship in this season. This highlights the fact that the situation is rather complex, as the wind response in JJA does not project uniquely onto EOF1, nor does it vary across models according to the magnitude component alone, as one might have hoped if the FDT arguments were to apply in a simple way.

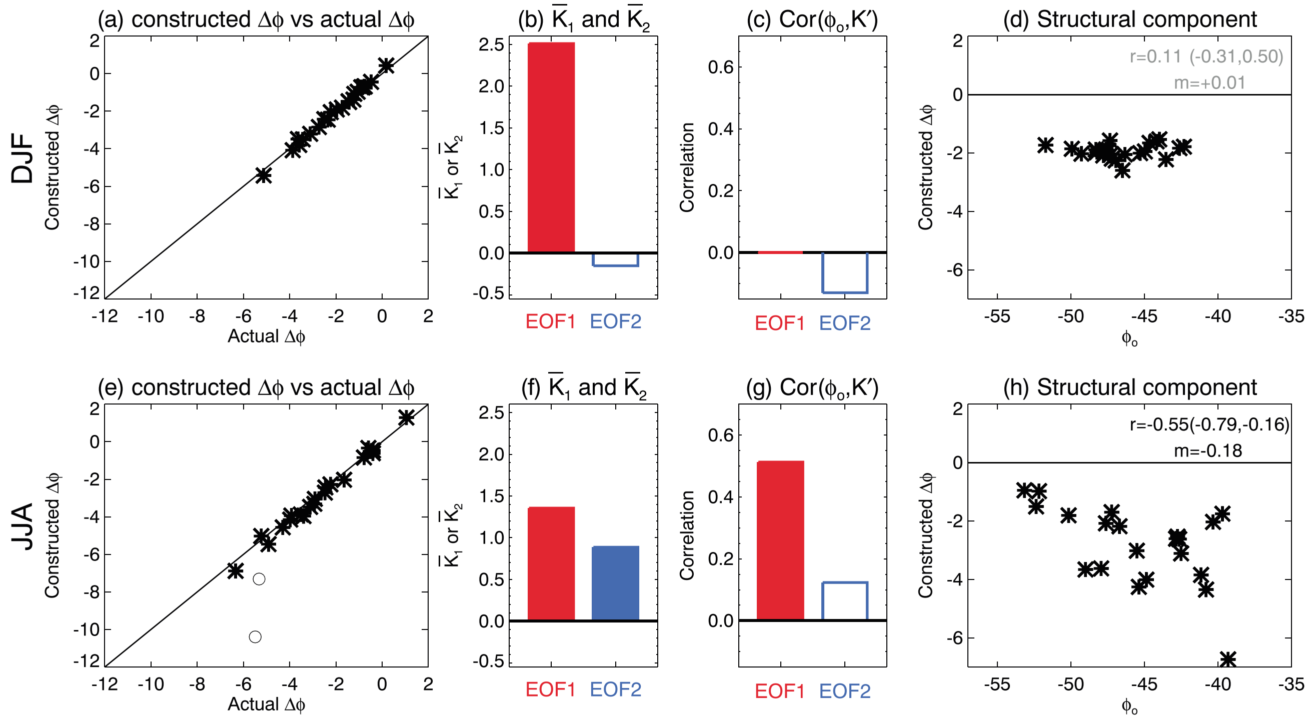

Figure 5. Relating the jet shift to the first two EOFs of natural variability in (top row) DJF and (bottom row) JJA. (a and e) constructed jet shift based on (1) versus actual jet shift. This does not work well for the two circled models in Figure 5e, so these are omitted from the remaining panels. (b and f) multimodel mean projection of the Future-Past difference onto EOFs 1 and 2 and (c and d) the correlation between the projection onto EOFs 1 and 2 and ϕ_o. Shaded bars are statistically significant at the 95% level by a students *t* test in Figures 5b and 5f and by the Fisher transform in Figures 5c and 5g. (d and h) The relationship between $\Delta\phi$ and ϕ_o obtained from the structural effect alone, i.e., omitting the last two terms in (2).

4. Discussion and Conclusions

By revisiting the relationship between each model's climatological jet latitude, forced response, and SAM timescale in the CMIP5 data set, we have demonstrated that a strong seasonality underlies previously reported relationships. In the annual mean, lower latitude jets (a) shift further poleward when forced and (b) exhibit greater SAM timescales in their current climatology. Arguments such as those of the FDT would apply if these two relationships occurred in the same seasons, but they do not. The CMIP5 models reveal that

1. The correlation between jet latitude and jet shift is strong, only during the extended winter season (see Figure 3). The usefulness of this relationship as an emergent constraint [*Collins et al.*, 2012] on future projections is, therefore, restricted to this season.
2. While the correlation between jet latitude and jet shift is very strong during JJA, models exhibit very similar SAM timescales in that season, making it difficult to argue that the jet latitude/jet shift relationship is brought about through a latitudinal dependence of eddy/mean flow feedback strength, inferred from SAM timescales.

Two components, of comparable importance, have been shown to give rise to the strong relationship between ϕ_o and $\Delta\phi$ in JJA: (1) the positioning of the wind response relative to the climatological jet varies with jet location such that it represents less of a poleward shift for higher latitude jets (Figure 4b) and (2) the magnitude of the wind response is larger for lower latitude jets (Figure 4d). However, the reason behind these two components is not known at present. Mechanisms have been proposed, through simplified modeling, to explain a relationship between jet latitude and jet shift [*Barnes et al.*, 2010; *Simpson et al.*, 2012] and whether these are relevant to the JJA relationship in comprehensive models is unclear, since accompanying a greater jet shift is a more persistent annular mode in these idealized studies, an aspect that is not seen in the more complex models analyzed here.

In summary, much remains to be understood about the relationships between a model's climatological jet position, response to forcing, and annular mode variability. While this study perhaps raises more questions than provides answers, it points toward future research directions that should be taken. An improved understanding of the seasonalities identified here should lead to both interesting insights into the dynamics of the SH jet stream as well as an improved understanding of model limitations and their impact on predictions of the SH circulation.

Acknowledgments
The National Center for Atmospheric Research is sponsored by the National Science Foundation (NSF). This work was also partially supported by NSF award AGS-1317469 and the work of LMP is funded, in part, by an NSF grant to Columbia University. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table 1 of this paper) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. We also thank two anonymous reviewers for their helpful comments.

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