Varied midlatitude shortwave cloud radiative responses to Southern Hemisphere circulation shifts

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Abstract
Changes in midlatitude clouds as a result of shifts in general circulation patterns are widely thought to be a potential source of radiative feedbacks onto the climate system. Previous work has suggested that two general circulation shifts anticipated to occur in a warming climate, poleward shifts in the midlatitude jet streams and a poleward expansion of the Hadley circulation, are associated with differing effects on midlatitude clouds. This study examines two dynamical cloud-controlling factors, mid-tropospheric vertical velocity, and the estimated inversion strength (EIS) of the marine boundary layer temperature inversion, to explain why poleward shifts in the Southern Hemisphere midlatitude jet and Hadley cell edge have varying shortwave cloud-radiative responses at midlatitudes. Changes in vertical velocity and EIS occur further equatorward for poleward shifts of the Hadley cell edge than they do for poleward shifts of the midlatitude jet. Because the sensitivity of shortwave cloud radiative effects (SWCRE) to variations in vertical velocity and EIS is a function of latitude, the SWCRE anomalies associated with jet and Hadley cell shifts differ. The dynamical changes associated with a poleward jet shift occur further poleward in a regime where the sensitivities of SWCRE to changes in vertical velocity and EIS balance, leading to a near-net zero change in SWCRE in midlatitudes with a poleward jet shift. Conversely, the dynamical changes associated with Hadley cell expansion occur further equatorward at a latitude where the sensitivity of SWCRE is more strongly associated with changes in mid-tropospheric vertical velocity, leading to a net shortwave cloud radiative warming effect in midlatitudes.

KEYWORDS
Hadley cell expansion, midlatitude jet shifts, shortwave cloud radiative effects

1 | INTRODUCTION

In a changing climate, large-scale circulation features (such as the eddy-driven midlatitude jets and the poleward edges of the Hadley circulation) are expected to shift meridionally. While variability in positions of the jet and Hadley cell extent on subseasonal-to-seasonal time scales is primarily associated with internal variability in...
the climate system (Nguyen et al. 2013; Thompson & Wallace 2000), variability in their positions on longer time scales can be strongly affected by anthropogenic forcing. Climate models forced by stratospheric ozone depletion show a poleward shift of the summertime Southern Hemisphere (SH) midlatitude jet and Hadley cell edge (Thompson & Solomon 2002; Gillett and Thompson 2003; Polvani et al. 2011), and climate models forced by increased atmospheric greenhouse gases show poleward shifts in the midlatitude jets (e.g., Barnes & Polvani 2013) and the extent of the Hadley cell (e.g., Lu et al. 2007) in both hemispheres. As changes in clouds associated with shifts in large-scale circulation patterns are considered a potential source of radiative feedbacks on climate change (Boucher et al. 2013), it is important to understand how these circulation shifts impact clouds and what large-scale dynamical changes are responsible for altering the associated cloud radiative effects (CRE).

As the midlatitude jet shifts poleward, large-scale ascending motion and the high-topped clouds associated with the extratropical storm tracks closely follow (e.g., Grise et al. 2013), suggesting a possible shortwave warming feedback as the clouds move to a higher latitude where they reflect less sunlight to space (e.g., Bender et al. 2012). However, several studies have documented little to no net shortwave warming response in SH midlatitudes associated with a poleward jet shift in observations and varied cloud radiative responses to poleward jet shifts across models (Grise & Polvani 2014; Grise & Medeiros 2016, hereafter GM16). This is because low clouds and their attendant shortwave CRE (SWCRE), which are closely related to boundary layer stability changes, often increase in the region vacated by the storm track clouds, a commonly underestimated effect in models (Ceppi & Hartmann 2015; GM16). Studies of dynamical controls on midlatitude clouds have mainly focused on the role of the midlatitude jet, but Ts Elioudis et al. (2016) found that shifts in the Hadley cell extent more strongly affect midlatitude clouds than shifts in the jet position, particularly at lower midlatitudes (30°–40°).

As the position of the SH eddy-driven jet and Hadley cell edge strongly co-vary (Kang & Polvani 2011), it is surprising that variability in the positions of the SH jet and Hadley cell edge are associated with different cloud responses. The purpose of this work is to reconcile the differing SWCRE responses to these two circulation feature shifts through the use of dynamical “cloud-controlling factors” (see review by Klein et al. 2017). This framework to connect large-scale dynamical variability to variability in cloud radiative effects has been widely used in understanding both tropical (Myers & Norris 2013; Qu et al. 2015) and midlatitude (Gordon et al. 2005; GM16; Kelleher & Grise 2019) environments.

In this work, following GM16, we consider two cloud-controlling factors to explain the midlatitude SWCRE anomalies associated with poleward circulation shifts: 500-hPa vertical velocity (ω500) and estimated inversion strength (EIS), a metric for the strength of the marine boundary layer temperature inversion (Wood & Bretherton 2006). Upward vertical velocity anomalies at midlatitudes are associated with increased mid-to-upper tropospheric cloud coverage (Li et al. 2014; Weaver & Ramanathan 1997), such as the high-topped clouds that occur in regions of deep rising motion within extratropical cyclones (Gordon et al. 2005; Lau & Crane 1995, 1997), whereas the development of a strong boundary layer temperature inversion acts to reduce dry-air entrainment from the free troposphere into the boundary layer, favoring the development of low-level stratocumulus clouds (e.g., Klein & Hartmann 1993). As a result, while “storm-track” clouds are likely to follow the jet poleward as it shifts (Grise et al. 2013), large-scale dynamical changes equatorward of the shifting jet act to compensate for this shift and increase low-level maritime clouds in those regions (GM16).

Through the use of this cloud-controlling factor framework, we will assess the relative impacts of large-scale dynamical changes on midlatitude SWCRE associated with meridional shifts in the SH midlatitude jet and Hadley cell edge. We find that, as in GM16, large-scale dynamical changes associated with a SH midlatitude jet shift occur at latitudes where the effects of changing EIS and mid-tropospheric vertical velocity on SWCRE are nearly balanced, leading to a near-zero net change in SWCRE associated with meridional shifts of the SH midlatitude jet. In contrast, we find that large-scale dynamical changes associated with a poleward extension of the SH Hadley cell occur at latitudes where the effects of vertical velocity anomalies on SWCRE dominate over those associated with changes in EIS. This difference leads to a small net shortwave warming effect at midlatitudes associated with a poleward shift of the SH Hadley cell extent.

2 | DATA AND METHODS

2.1 | Data

To assess the relationships among circulation shifts, dynamical cloud-controlling factors, and SWCRE, we use two observation-based datasets. First, we use ERA-5 reanalysis (Hersbach et al. 2020) to obtain monthly mean dynamical variables to compute ω500, EIS, and the midlatitude jet and Hadley cell edge locations. Second, monthly mean top-of-atmosphere (TOA) shortwave radiative fluxes from CERES EBAF-TOA version 4.1a (Loeb et al. 2018) are used to compute SWCRE.
To assess whether the current generation of global climate models (GCMs) is able to reproduce the relationships derived from observations, we use output from 39 models that participated in CMIP6 (Eyring et al. 2016; listed in Supporting Information, Table S1). For this study, we use the pre-industrial control (piControl) run of each model, which is a coupled atmosphere/ocean control run that imposes nonevolving pre-industrial conditions.

2.2 | Methods

Following previous work (GM16), we consider two dynamical cloud-controlling factors: $\omega_{500}$ and EIS. EIS is defined as follows (Wood & Bretherton 2006):

$$
EIS = LTS - \Gamma^{850}_m (z_{700} - LCL)
$$

where lower tropospheric stability (LTS) is the difference between potential temperature at 700-hPa and the surface, $\Gamma^{850}_m$ is the moist adiabatic lapse rate at 850-hPa, $z_{700}$ is the height of the 700-hPa level, and LCL is the height of the lifted condensation level (as in Georgakakos & Bras 1984). While both LTS and EIS are measures of boundary layer stability, we focus on EIS which is more strongly correlated with low cloud amount in midlatitude low cloud regimes (Wood & Bretherton 2006). Additionally, while other cloud-controlling factors impact midlatitude SWCRE (such as low-level temperature advection and sea surface temperature), they play a minor role in the observed SWCRE anomalies associated with a poleward shift in the SH midlatitude jet (Grise & Kelleher 2021), so we do not consider them here.

As in Grise and Polvani (2014), we calculate the position of the SH midlatitude jet by computing the latitude of the 850-hPa zonal-mean zonal wind maximum using a quadratic fit to the three grid points nearest the maximum gridded zonal-mean zonal wind. We calculate the latitude of the SH Hadley cell extent by computing the zero-crossing latitude of the meridional mass stream function at 500 hPa using the Tropical-width Diagnostics (TropD) software package (Adam et al. 2018).

We calculate SWCRE as the difference in outgoing shortwave radiation at TOA between clear-sky and all-sky scenes (e.g., Ramanathan et al. 1989). We focus on SWCRE here, which is affected by both high and low clouds. In contrast, longwave CRE anomalies associated with poleward circulation shifts more closely follow the high clouds of the midlatitude storm track and are thus dominated by changes in $\omega_{500}$ (GM16).

We use a simple multiple linear regression model to predict SWCRE anomalies associated with shifts in the SH midlatitude jet and Hadley cell extent:

$$
\Delta SWCRE = \frac{\partial (SWCRE)}{\partial \omega_{500}} \Delta \omega_{500} + \frac{\partial (SWCRE)}{\partial EIS} \Delta EIS
$$

where $\Delta SWCRE$ is the predicted SWCRE anomaly, $\Delta \omega_{500}$ and $\Delta EIS$ are the changes in each cloud-controlling factor associated with a 1 SD shift in the SH midlatitude jet or SH Hadley cell extent, and $\frac{\partial (SWCRE)}{\partial \omega_{500}}$ and $\frac{\partial (SWCRE)}{\partial EIS}$ are the sensitivities of SWCRE to anomalies from the mean-state of each cloud-controlling factor.

3 | RESULTS

In order to assess whether there are differences in the SWCRE anomalies associated with shifts in the SH midlatitude jet and Hadley cell extent, we first separately regress monthly zonal-mean anomalies in SWCRE against monthly anomalies in the position of the SH jet and Hadley cell extent (Figure 1). The results here (and in subsequent figures) are only for SH summer months (DJF) when incoming solar insolation is maximized, and the curves shown are for a 1 SD shift in the circulation features poleward. Note that, while a 1 SD poleward shift in the midlatitude jet (2.15°) is larger than a 1 SD shift in the Hadley cell extent (1.26°), we plot results in terms of SD as it represents a similar deviation from the norm for both circulation features.

While shifting each circulation feature poleward has similar impacts on SWCRE in the tropics, there are noteworthy differences at midlatitudes. For example, there is little SWCRE change for a poleward shift of the jet at midlatitudes (~45°S–55°S; solid blue line), but there is a positive SWCRE anomaly at similar latitudes for a shift in the Hadley cell extent (solid red line). Although the two circulation features strongly co-vary with one another during the SH summer season (Kang & Polvani 2011), there remains a substantial fraction of the variance of each circulation feature that is independent of the other, leading to different SWCRE anomalies for each circulation shift. A simple multiple linear regression model (Equation 2) with only two dynamical predictors (EIS and $\omega_{500}$) can approximately capture the differing SWCRE response between poleward shifts of the jet and Hadley cell extent (blue and red dashed lines; $R^2 = 0.23$ and 0.52, respectively; see summary statistics in Table S2). While this simple model is not able to fully capture the observed SWCRE responses (particularly to poleward jet shifts), it is able to capture distinct SWCRE responses at midlatitudes between jet shifts and Hadley cell extent changes, suggesting that EIS and $\omega_{500}$ may be helpful in explaining the differing SWCRE responses.

By regressing zonal-mean anomalies in the two dynamical cloud-controlling factors against anomalies in
the position of the circulation features, we can investigate what dynamical differences exist between meridional shifts of the SH midlatitude jet (Figure 2, blue lines) and Hadley cell extent (Figure 2, red lines). The EIS anomalies associated with a poleward jet shift peak more strongly at SH midlatitudes near 50°S, while the EIS anomalies associated with a poleward shift in the circulation features peak more strongly at higher latitudes.

**FIGURE 1** Zonal mean SWCRE response to a one standard deviation poleward shift of the SH midlatitude jet (blue lines) and extent of the SH Hadley cell (red lines). Solid lines represent the observed SWCRE response, and dashed lines represent the predicted SWCRE response from Equation 2. Shaded areas represent the 95% confidence interval related to a 1 SD poleward shift in the circulation features.

**FIGURE 2** Response of zonal mean EIS (a, square markers) and $\omega_{500}$ (b, triangle markers) to a one standard deviation poleward shift in the SH midlatitude jet (blue lines) and extent of the SH Hadley cell (red lines). Panel c shows the dynamical changes for each circulation shift normalized by the standard deviation of the dynamical cloud-controlling factors. Shaded areas (a, b) represent the 95% confidence interval related to 1 SD poleward shift in the circulation features.
anomalies associated with a poleward shift in the Hadley cell extent are spread out more broadly in latitude (Figure 2(a)). The $\omega_{500}$ anomalies associated with a poleward jet shift similarly peak near 50°S, but are offset from the $\omega_{500}$ anomalies associated with a poleward shift in the Hadley cell extent, which peak around 45°S (Figure 2(b)). While these differences are notable, in order to directly compare the dynamical changes associated with the shifting circulation features, we normalize the anomalies in the two cloud-controlling factors by their SDs (Figure 2(c)). The results confirm that the positive dynamical anomalies associated with a poleward shift in the SH Hadley cell extent (red lines, square markers for EIS and triangle markers for $\omega_{500}$) are broader in latitudinal extent and peak equatorward of the dynamical anomalies associated with a poleward shift in the SH midlatitude jet (blue lines, square markers for EIS, and triangle markers for $\omega_{500}$). Furthermore, Figure 2(c) shows that the maximum normalized anomalies of $\omega_{500}$ and EIS have similar magnitudes and positions both for the jet shift (~0.75 SDs near 50°S) and the shift in Hadley cell extent (~0.5 SDs near 45°S). Overall, Figure 2 reveals that the latitude where a poleward shift in the SH jet most affects the dynamics is about 5° poleward of the latitude where a poleward shift in the SH Hadley cell extent most impacts the dynamics.

As the latitude where dynamical changes occur as a result of the two circulation shifts differs (Figure 2(c)), the SWCRE responses to the two circulation shifts (as shown in Figure 1) may be distinct from one another because of differing SWCRE sensitivities to dynamics at the differing latitudes. To assess this, we regress SWCRE on zonal-mean EIS and $\omega_{500}$ perturbations: that is, $\left(\frac{\partial}{\partial(EIS)} \text{SWCRE} \right)$ and $\left(\frac{\partial}{\partial(\omega_{500})} \text{SWCRE} \right)$ as defined in Equation 2. Figure 3 plots these regression coefficients as a function of latitude, with the regression coefficients normalized by the SDs in the dynamical cloud-controlling factors. The normalization allows us to directly compare the SWCRE sensitivities to EIS and $\omega_{500}$ on the same scale. As expected, in SH midlatitudes, increases in EIS are associated with decreased SWCRE (increased cloud reflection) (Figure 3, square markers), consistent with the connection between boundary layer stability and low clouds. In contrast, increases in $\omega_{500}$ (anomalous descent) are associated with increased SWCRE (decreased cloud reflection) (Figure 3, triangle markers), consistent with the connection between ascending motion and mid-to-high clouds and the connection between subsidence and reduced boundary layer cloudiness (e.g., Myers & Norris 2013).

As the magnitude of the changes in the two cloud-controlling factors are similar (in terms of SDs) for each circulation shift (Figure 2(c)), a direct comparison of the two sensitivities may provide information about whether the changes in $\omega_{500}$ or EIS dominate the total SWCRE response. To this second point, we plot a linear combination of the two normalized sensitivities (Figure 3, black dashed line). We find that in the tropics, subtropics, and lower midlatitudes, the sensitivity of SWCRE to changes in $\omega_{500}$ is larger in magnitude than the sensitivity to changes in EIS. In the upper midlatitudes, however, this relationship reverses with SWCRE sensitivity to EIS becoming larger in magnitude, with the transition occurring near 50°S.

As shown in Figure 2, the peak anomalies in $\omega_{500}$ and EIS associated with a poleward shift in the SH midlatitude jet occur at 49°S (Figure 3, blue dashed line), whereas the peak anomalies in $\omega_{500}$ and EIS associated with a poleward shift in the SH Hadley cell extent occur at 44°S (Figure 3, red dashed line). For a poleward shift in the SH Hadley cell extent, the latitude of maximum dynamical changes occurs solidly within the $\omega_{500}$-dominated regime (i.e., where the black dashed line in

**Figure 3** SWCRE sensitivity to 1 SD change in EIS (square markers) and $\omega_{500}$ (triangle markers). The dashed line represents the linear combination of the two sensitivities, and the vertical dashed lines represent the latitudes of maximum dynamical change for poleward shifts of the midlatitude jet (blue) and extent of the Hadley cell (red) (as shown in Figure 2(c)). Shaded areas represent the 95% confidence interval of the SWCRE sensitivities.
4 | SUMMARY AND DISCUSSION

Changes in clouds as a result of circulation shifts are thought to be a potential source of feedbacks onto the climate system (Bony et al. 2015; Boucher et al. 2013). Recent work has shown that, while the high-topped clouds associated with extratropical cyclones shift with the midlatitude jet stream, there is little to no net shortwave cloud radiative warming effect observed in conjunction with a poleward shift in the SH midlatitude jet, due to competing effects of poleward shifting high-topped extratropical storm-track clouds and increasing low clouds on the equatorward flank of the jet (GM16). Other recent work has suggested that the extent of the Hadley cell correlates more robustly with midlatitude cloud variations than the position of the midlatitude jet, particularly in the lower midlatitudes (Tselioudis et al. 2016). As the SH summertime midlatitude eddy-driven jet and the Hadley cell extent strongly co-vary interannually (Kang & Polvani 2011), this work sought to reconcile the differences in SWCRE responses between the two circulation shifts and to comment on the potential dynamical reasons for any differences.

Our results confirm that there are differing SWCRE anomalies observed in association with poleward shifts in the SH jet and Hadley cell extent during the summer (DJF) season (Figure 1). Using a cloud-controlling factor framework, we show that dynamical changes related to the shifting circulation features occur at different latitudes, with the largest dynamical changes associated with a poleward jet shift located about 5° poleward of those associated with a poleward shift in the Hadley cell extent (Figure 2(c)). The latitude of maximum dynamical changes observed in association with a poleward shift in the SH Hadley cell extent is within a dynamical regime where SWCRE anomalies are dominated by changes in \( \omega_{500} \) (Figure 3), such that anomalous subsidence near 45°S leads to an increase in SWCRE at nearby latitudes (Figure 1, red). Conversely, the latitude of maximum dynamical changes observed in association with a poleward shift in the SH midlatitude jet is within a dynamical regime where SWCRE anomalies are equally sensitive to changes in \( \omega_{500} \) and EIS (Figure 3), such that the competing effects of anomalous subsidence and positive EIS anomalies near 50°S lead to little net SWCRE change at nearby latitudes (Figure 1, blue).

How well do GCMs capture these observed relationships? The solid lines in Figure 4(a) and (b) show the CMIP6 multi-model-mean zonal-mean SWCRE anomalies associated with a poleward shift in the SH midlatitude jet and Hadley cell extent. The models reproduce the positive SWCRE anomaly at SH midlatitudes associated with a poleward shift in the SH midlatitude jet (Figure 4(a), compare solid and dashed lines), although they overestimate its magnitude compared to observations (see also Lipat et al. 2017, 2018). In contrast, the models also produce a positive SWCRE anomaly at SH midlatitudes associated with a poleward shift in the SH Hadley cell extent (Figure 4(b), compare solid and dashed lines), which does not occur in observations (Grise & Polvani 2014; GM16).

One may suppose that the model bias results from errors in the SWCRE sensitivity to the cloud-controlling factors, which is highly dependent on model cloud parameterizations. Presumably, if we constrain the models to have the same SWCRE sensitivity as observations, they should better replicate the observed response. To test this, we apply the same multiple linear regression model as we did for observations in Figure 1 (Equation 2), but instead we multiply the observed sensitivities of SWCRE to each cloud-controlling factor by the corresponding changes in the cloud-controlling factors from the CMIP6 multi-model mean. The results are shown in the dotted-dashed lines in Figure 4(a) and (b). We find that, by constraining the SWCRE sensitivities to observations, the model dynamics are able to recreate the observed SWCRE anomalies associated with a poleward shift in the SH Hadley cell extent at midlatitudes (Figure 4(b), compare dashed and dotted-dashed lines). However, even after constraining the SWCRE sensitivities to observations, the model dynamics are not able to recreate the observed SWCRE anomalies associated with a poleward SH jet shift (Figure 4(a), compare dashed and dotted-dashed lines; a scatter plot of individual models is shown in Fig. S1). This occurs because the CMIP6 multi-model mean jet location is too far equatorward (Simpson et al. 2020), such that the peak changes in the cloud-controlling factors associated with a jet shift occur too far equatorward on average in models (Figure 4(c); compare blue dashed and dotted-dashed lines). While the peak changes in the cloud-controlling factors associated
with a SH Hadley cell edge shift also occur too far equatorward in CMIP6 models compared to observations (Figure 4(c); compare red dashed and dotted-dashed lines), the equatorward model bias in jet latitude is more consequential, as it shifts the model dynamical anomalies into a different regime from observations, where the SWCRE sensitivity is dominated by changes in $\omega_{500}$. Consistent with this argument, most (but not all) models that have climatological jet positions similar to observations better simulate both the SWCRE and dynamical response to poleward shifts in the jet (not shown). Having both the correct jet position (as shown here) and the correct SWCRE sensitivity to cloud-controlling factors (as shown in GM16) is necessary for models to properly simulate SWCRE changes related to poleward jet shifts.

Furthermore, the results in Figure 4 provide a cautionary example of the limitations of combining sensitivities of cloud properties to dynamical cloud-controlling factors from observations with changes in those cloud-controlling factors from GCMs using a multiple linear regression model. Such a technique is commonly used to provide an observational constraint on cloud feedbacks (e.g., Klein et al. 2017). However, here we have shown that biases in the GCMs’ mean state dynamics may inherently lead to incorrect results from such a procedure.

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