Examining Southern Ocean Cloud Controlling Factors on Daily Time Scales and Their Connections to Midlatitude Weather Systems

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ABSTRACT

Clouds and their associated radiative effects are a large source of uncertainty in global climate models. One region with particularly large model biases in shortwave cloud radiative effects (CRE) is the Southern Ocean. Previous research has shown that many dynamical “cloud controlling factors” influence shortwave CRE on monthly time scales and that two important cloud controlling factors over the Southern Ocean are mid-tropospheric vertical velocity and estimated inversion strength (EIS). Model errors may thus arise from biases in representing cloud controlling factors (atmospheric dynamics) or in representing how clouds respond to those cloud controlling factors (cloud parameterizations), or some combination thereof. This study extends previous work by examining cloud controlling factors over the Southern Ocean on daily time scales in both observations and global climate models. This allows the cloud controlling factors to be examined in the context of transient weather systems. Composites of EIS and midtropospheric vertical velocity are constructed around extratropical cyclones and anticyclones to examine how the different dynamical cloud controlling factors influence shortwave CRE around midlatitude weather systems and to assess how models compare to observations. On average, models tend to produce a realistic cyclone and anticyclone, when compared to observations, in terms of the dynamical cloud controlling factors. The difference between observations and models instead lies in how the models’ shortwave CRE respond to the dynamics. In particular, the models’ shortwave CRE are too sensitive to perturbations in midtropospheric vertical velocity and, thus, they tend to produce clouds that excessively brighten in the frontal region of the cyclone and excessively dim in the center of the anticyclone.

1. Introduction

Recent studies have shown that many current global climate models (GCMs) and reanalyses have large biases in shortwave cloud radiative effects (CRE) at the top of the atmosphere (TOA) over the Southern Ocean (Trenberth and Fasullo 2010; Ceppi et al. 2012), potentially limiting the ability of models to project changes to the climate under future anthropogenic forcing. For example, many GCMs indicate a large negative cloud feedback over the Southern Ocean in a warming climate (Trenberth and Fasullo 2010; Zelinka et al. 2012; Ceppi et al. 2016; Frey and Kay 2018), which some studies have suggested is overestimated due to incorrect ice–liquid

partitioning in mixed-phase Southern Ocean clouds (Gordon and Klein 2014; McCoy et al. 2016; Terai et al. 2016; Tan et al. 2016). Southern Ocean cloud biases within GCMs have also been linked to circulation and precipitation biases in both the extratropics (Ceppi et al. 2012; Ceppi et al. 2014) and the tropics (Hwang and Frierson 2013). It is thus important to understand and accurately simulate Southern Ocean clouds in order to better represent the climate system and make future projections of Earth’s climate.

One method by which to evaluate whether models are accurately representing observed cloud processes is the “cloud controlling factor” framework [see review by Klein et al. (2017)]. In this framework, observed relationships between clouds and their large-scale environment are diagnosed and compared to those in models. While the cloud controlling factor framework has been extensively applied in understanding tropical and subtropical clouds (Myers and Norris 2013, 2015, 2016; Qu et al. 2014, 2015; Seethala et al. 2015; McCoy et al. 2017;

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Klein et al. 2017), fewer studies have focused on the dynamic and thermodynamic factors controlling midlatitude clouds and their TOA radiative effects.

At midlatitudes, key cloud controlling factors identified by previous studies include vertical velocity (Gordon et al. 2005; Norris and Iacobellis 2005; Li et al. 2014; Grise and Medeiros 2016, hereafter GM16; Wall et al. 2017), lower tropospheric stability (Wood and Bretherton 2006; GM16; Naud et al. 2016; Terai et al. 2016; Wall et al. 2017; Zelinka et al. 2018), near-surface temperature advection (Norris and Iacobellis 2005; Wall et al. 2017; Zelinka et al. 2018), surface sensible heat fluxes (Miyamoto et al. 2018), sea surface temperature (Frey and Kay 2018), and atmospheric temperature (Tselioudis et al. 1992; Gordon and Klein 2014; Terai et al. 2016; Ceppi et al. 2016). Upward vertical velocity anomalies in the midlatitudes are associated with the increased presence of clouds with tops in the mid-to-upper troposphere (e.g., Weaver and Ramanathan 1997; Li et al. 2014), as deep rising motion within the warm sector of extratropical cyclones drives nimbostratus and high-topped convective clouds (Lau and Crane 1995, 1997; Gordon et al. 2005). Downward vertical velocity anomalies inhibit the production of clouds with tops in the mid-to-upper troposphere but have been shown to be favorable for the formation of low clouds over midlatitude oceans (Booth et al. 2013; Govekar et al. 2014; Li et al. 2014).

Enhanced subsidence above cool sea surface temperatures is conducive to the development of a strong boundary layer temperature inversion, which favors the development of low-level stratocumulus clouds (e.g., Klein and Hartmann 1993). A strong boundary layer inversion is associated with a decoupling of the boundary layer from the free troposphere, inhibiting dry air entrainment from the free troposphere and promoting the maintenance of low stratocumulus clouds within the boundary layer (e.g., Wood and Bretherton 2006). Cold advection into the midlatitudes can also increase low cloud cover by enhancing turbulent fluxes from the relatively warm ocean surface into the relatively cold and dry air above (Norris and Iacobellis 2005; Zelinka et al. 2018; Miyamoto et al. 2018). In contrast, warmer sea surface temperatures strengthen the moisture gradient between the boundary layer and the free troposphere, enhancing the effectiveness of mixing dry air into the boundary layer and consequently decreasing low cloud amount and optical depth (Rieck et al. 2012; Frey and Kay 2018).

Finally, in the midlatitudes, there is a positive correlation between cloud temperature and cloud optical depth (Gordon and Klein 2014). This occurs for two main reasons. First, for warmer temperatures, for the

same increase in height from a cloud base, more water vapor is condensed, increasing the optical depth of the cloud (Betts and Harshvardhan 1987; Tselioudis et al. 1998; Gordon and Klein 2014). Second, warmer temperatures change the liquid–ice partitioning in the cloud leading to more liquid drops in the warmer environment, and thus resulting in increases in cloud optical depth (Tsushima et al. 2006; McCoy et al. 2014; Ceppi et al. 2016).

The observed relationships among midlatitude clouds, their radiative properties, and cloud controlling factors are often misrepresented in GCMs. For Southern Ocean clouds, many models overestimate the dependence of shortwave CRE on vertical velocity (GM16), and underestimate the dependence of low cloud fraction and shortwave CRE on both lower tropospheric stability and near-surface temperature advection (GM16; Zelinka et al. 2018). The temperature dependence of Southern Ocean cloud optical depth and shortwave CRE is also overestimated in many GCMs, which has been linked to an incorrect ice–liquid partitioning in mixed-phase Southern Ocean clouds (Gordon and Klein 2014; McCoy et al. 2016; Terai et al. 2016; Tan et al. 2016).

Apart from Norris and Iacobellis (2005) and Wall et al. (2017), the above studies have focused on monthly or longer time scales, but the processes driving midlatitude cloud variability are primarily forced by synoptic-scale weather systems that operate on much shorter time scales. While there are different ways to understand midlatitude clouds on daily time scales, such as the “weather states” approach (Oreopoulos and Rossow 2011; Tselioudis et al. 2013), in this study we focus on composites about the centers of extratropical cyclones and anticyclones. The cyclone compositing methodology has been used extensively by previous studies to understand the relationships between cloud properties in an extratropical cyclone and the surrounding dynamic and thermodynamic environment (Lau and Crane 1995, 1997; Naud et al. 2006; Field and Wood 2007; Posselt et al. 2008; Naud et al. 2010; Field et al. 2011). Previous studies using the cyclone compositing methodology have suggested that Southern Ocean cloud biases are most notable within the region dominated by extratropical cyclones, particularly in the cold-air sector of the cyclone (Bodas-Salcedo et al. 2012, 2014; Williams et al. 2013; Naud et al. 2014). However, the relationship between these cyclone composite studies (based on subdaily or daily time scales) and the cloud controlling factor studies discussed above (based on monthly time scales) has not been explored in detail.

The purpose of this study is to extend the cloud controlling factor analysis of GM16 from monthly to daily time scales. GM16 examined the relationship among

midlatitude cloud radiative effects, vertical velocity, and lower tropospheric stability on monthly time scales, and found a large fraction of GCMs (so-called type I models) underestimated the observed relationship between shortwave CRE and lower tropospheric stability and overestimated the relationship between shortwave CRE and vertical velocity, while a separate set of models (so-called type II models) better represented the relationship between shortwave CRE and lower tropospheric stability. Here, we re-examine these relationships on daily time scales, and in the context of extratropical cyclones and anticyclones for the Southern Hemisphere (SH) mid-latitudes. Our results show that models on average tend to accurately reproduce the dynamics associated with observed extratropical cyclones and anticyclones over the Southern Ocean, but fail to reproduce the daily shortwave CRE anomalies associated with these synoptic-scale weather systems. In contrast to studies that have focused on the climatology (e.g., [Bodas-Salcedo et al. 2014](#), hereafter [B14](#)), we find that day-to-day fluctuations in shortwave CRE in models are most biased in anticyclones and in the frontal region and warm sector of extratropical cyclones. In these regions, models substantially overestimate the sensitivity of shortwave CRE to vertical velocity anomalies and underestimate the sensitivity of shortwave CRE to perturbations in the strength of the boundary layer temperature inversion.

The paper is organized as follows. [Section 2](#) describes the data and methods used in the study. In [section 3](#), we examine the connections among TOA shortwave CRE, vertical velocity, and lower tropospheric stability over the Southern Ocean on daily time scales, and in [section 4](#), we explore these relationships in the context of extratropical cyclones and anticyclones. [Section 5](#) concludes with a summary and discussion of our results.

2. Data and methods

a. Data

To assess the connections between Southern Ocean CRE and its dynamical cloud controlling factors on daily time scales, we use two observation-based datasets. First, we obtain vertical velocity, temperature, surface pressure, and surface dewpoint temperature from ERA-Interim ([ECMWF 2009](#); [Dee et al. 2011](#)). Second, we obtain daily-mean all-sky and clear-sky TOA longwave and shortwave radiative fluxes from the CERES SYN1deg-day version 4a product ([CERES Science Team 2017](#); [Doelling et al. 2016](#); [Loeb et al. 2018](#)). Both observational datasets used in this work are analyzed over the time period from 2001 to 2016, as 2001 marks the first full year of CERES data availability.

To assess the connections between Southern Ocean CRE and its dynamical cloud controlling factors in GCMs, we use output from 10 models that participated in CMIP5 ([World Climate Research Program 2011](#); [Taylor et al. 2012](#); see list of models in [Table 1](#)). The model data were obtained from PCMDI at Lawrence Livermore National Laboratory. We restrict our analysis to these 10 models (of which half are type I and half type II), as only a subset of the models examined by [GM16](#) on monthly time scales contain the necessary output to calculate CRE and the dynamical cloud controlling factors on daily time scales.

For this study, we focus on the AMIP runs of each model, which are 30-yr-long atmosphere-only model runs in which the observed radiative forcings, sea surface temperatures (SSTs), and sea ice concentrations are prescribed over the time period from 1979 to 2008. The first ensemble member (r1i1p1) for the AMIP scenario will be considered for each model. We focus on the AMIP runs for two reasons. First, Southern Ocean SSTs are standardized across models, ensuring that intermodel variance in cloud fields is not caused by variance in the SST climatology. Second, use of the AMIP runs allows for direct comparison of our results with previous studies that examined connections between SH midlatitude CRE and synoptic-scale weather systems ([Bodas-Salcedo et al. 2012](#); [B14](#)).

b. Methods

Following [GM16](#), we consider two dynamical controlling factors on SH midlatitude CRE, 500-hPa vertical velocity ω_{500} and estimated inversion strength (EIS; [Wood and Bretherton 2006](#)). EIS is defined by the following calculation:

$$\text{EIS} = \text{LTS} - \Gamma_m^{850}(z_{700} - \text{LCL}), \quad (1)$$

where lower tropospheric stability (LTS) is defined as the difference between the potential temperature at 700 hPa and the surface, Γ_m^{850} 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 calculated using the method of [Georgakakos and Bras \(1984\)](#). While both LTS and EIS are metrics of lower tropospheric stability, EIS is more strongly correlated with low cloud amount in midlatitude low cloud regimes ([Wood and Bretherton 2006](#); [Naud et al. 2016](#)). For this reason, we choose to analyze EIS in this study.

We calculate CRE as the difference in outgoing radiation at the top of the atmosphere between clear-sky and all-sky scenes (e.g., [Ramanathan et al. 1989](#)). We focus on shortwave CRE (and not longwave CRE) in this study, as there is a greater discrepancy between

TABLE 1. List of the CMIP5 models used in this study. The model types reflect the categorization of Grise and Polvani (2014).

Model name	Modeling center	Model type
BCC-CSM1.1(m)	Beijing Climate Center, China Meteorological Administration	I
CanAM4	Canadian Centre for Climate Modeling and Analysis	I
CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique	I
GFDL CM3	National Oceanic and Atmospheric Administration (NOAA)/GFDL	II
HadGEM2-A	Met Office Hadley Centre	II
IPSL-CM5A-LR	L'Institut Pierre-Simon Laplace	I
IPSL-CM5B-LR	L'Institut Pierre-Simon Laplace	II
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	II
MPI-ESM-LR	Max Planck Institute for Meteorology	I
MRI-CGCM3	Meteorological Research Institute	II

observed and modeled relationships of shortwave CRE and the two dynamical cloud controlling factors considered in this study (see also GM16). Observations and models both show a strong dependence of longwave CRE on ω_{500} on monthly (GM16) and daily time scales (see Fig. S1 in the online supplemental material). Because we focus on shortwave CRE in this study, we confine our analysis to austral summer (DJF) when incoming solar radiation is maximized in the SH midlatitudes.

We construct composites of fields about the centers of extratropical cyclones and anticyclones over the Southern Ocean as follows. First, the minimum and maximum oceanic sea level pressure (SLP) anomalies over the 45°–60°S latitude band are located for each austral summer (DJF) day over the period 2001–16 for the observations and 1979–2008 for the AMIP model runs. These time periods are chosen to maximize the amount of data present in the analysis, and our results are nearly identical if the common 2001–08 period is used for both the observations and models (not shown). The 45°–60°S latitude band is chosen as it is the latitude band where EIS and shortwave CRE anomalies are inversely correlated, signaling the presence of low-cloud regimes as opposed to the deep convective regime that dominates the tropics (see Fig. 6b of GM16). Next, a

rectangular box (4000 km $\times$ 4000 km) centered on the location of each SLP minimum and maximum is constructed. Finally, the radiative and dynamical fields within this box for each daily SLP minimum and maximum are averaged across cases to yield the composite extratropical cyclone (shown in section 4a) and anticyclone (shown in section 4b) structures, respectively. Prior to the averaging, the seasonal cycle is removed from all radiative and dynamical fields. To do this, means for each calendar day over the analysis period (2001–16 for observations, 1979–2008 for models) are subtracted from the daily values to find anomalies. Last, data points over land are excluded from the analysis.

While simple, the method described above faithfully captures the average structures of SH extratropical weather systems, as composites of SLP anomalies about the centers of the cyclones and anticyclones show bull's-eyes of negative and positive pressure anomalies, respectively (not shown). We have verified that composites constructed about the center of extratropical cyclones identified using the Hodges (1994, 1995, 1999) feature tracking algorithm on the 850-hPa relative vorticity field produce nearly identical results (see Fig. S2). Note, however, that the simpler method described above tends to depict a stronger cyclone on average than the Hodges algorithm, as cyclones and anticyclones with weaker central SLP anomalies are not included in the composites.

Feature tracking algorithms require the movement of transient weather systems to effectively track them, and while the Southern Ocean is characterized by transient ridges (e.g., Williams et al. 2013), extratropical anticyclones may be slow moving and nearly stationary features. Consequently, feature tracking algorithms that require the movement of weather systems may not be well suited to capture all anticyclones. The decision to use the simpler method to identify extratropical cyclones over the feature tracking method is thus made to ensure that the analysis of the cyclones and anticyclones is functionally equivalent.

3. SH midlatitude cloud controlling factors on daily time scales

In this section, we investigate the relationship between SH midlatitude dynamics and shortwave CRE on daily time scales in both observations and GCMs. GM16 identified the important roles of midtropospheric vertical velocity (ω_{500}) and lower tropospheric stability (EIS) in controlling shortwave CRE anomalies at SH midlatitudes on monthly-mean time scales. Here, we repeat several of their key analyses to see whether the same relationships hold on daily time scales, so that a more

FIG. 1. Correlation coefficients between shortwave CRE anomalies and anomalies of (a),(c) ω_{500} and (b),(d) EIS on a daily time scale. (top) The observed correlation coefficients and (bottom) the average of correlation coefficients from 10 CMIP5 models.

process-based (weather system) level of understanding of midlatitude cloud biases in GCMs can be developed.

The left column of Fig. 1 shows the correlation of daily-mean ω_{500} anomalies and shortwave CRE anomalies at each grid point over the SH oceans for both observations and CMIP5 models (as shown in Fig. 6 of GM16 for monthly mean anomalies). Here, the term “anomalies” indicates that the seasonal cycle has been removed from all fields. Removing seasonality ensures that the analysis does not merely capture the climatology and instead captures the sensitivity of clouds and CRE to day-to-day perturbations in the cloud controlling factors. Removing seasonality in this manner retains interannual variability (e.g., El Niño–Southern Oscillation) within the data. However, similar results are found if we instead use a high-pass filter to filter out variability on time scales longer than 10 days (not shown), confirming that our results are primarily associated with the high-frequency variability of synoptic-scale weather systems and not interannual variability. In Fig. 1 and in all subsequent figures, we focus on the relationships between the dynamical cloud controlling factors and shortwave CRE over the SH oceans and exclude land data points where additional controlling factors must be considered.

Consistent with the monthly mean results of GM16, Figs. 1a and 1c show a positive correlation between ω_{500} and shortwave CRE anomalies on daily time scales over the majority of the SH oceans in both observations and models. In other words, increases in midtropospheric vertical velocity (decreases in ω_{500}) are associated with increased cloud reflection. Only in the marine stratocumulus regions on the eastern boundaries of the subtropical oceans are the correlations between ω_{500} and shortwave CRE anomalies near zero or weakly negative. While both observations and models display a general positive correlation throughout the SH oceans,

it is important to note that the values of the correlations are greater in the CMIP5 multimodel mean when compared to observations, particularly in the extratropics. This suggests that the shortwave CRE anomalies in models on average tend to be too sensitive to changes in midtropospheric vertical velocity (see also Norris and Weaver 2001).

Figures 1b and 1d show the correlation of daily mean EIS anomalies and shortwave CRE anomalies at each grid point over the SH oceans for observations and models, respectively. Similar results for monthly mean time scales are shown in GM16 (cf. their Fig. 6b). In deep convective regions of the tropics, increases in EIS are associated with decreased cloud reflection (increases in shortwave CRE), presumably because increasing EIS will inhibit the development of the deep convection that drives much of the cloud formation in these regions. Outside of the tropical deep convective regime, however, increases in EIS are associated with increased cloud reflection (decreases in shortwave CRE). The magnitudes of the negative correlations in Figs. 1b and 1d are largest in the subtropical marine stratocumulus regions (off the western coasts of the continents) and over the Southern Ocean (45°–60°S) where low clouds are known to be prevalent (e.g., Haynes et al. 2011; Bromwich et al. 2012).

The correlations between daily mean EIS and shortwave CRE anomalies are qualitatively similar in both observations and the CMIP5 multimodel mean (cf. Figs. 1b,d). However, the magnitude of the negative correlations in the low cloud regions of the subtropics and midlatitudes is weaker in models than in observations, suggesting that the shortwave CRE anomalies in models are not sensitive enough to changes in EIS within SH low cloud regimes (see also Qu et al. 2015). This may be due in part to the subset of 10 models that we use in this study (Table 1), half of which fall into the type I

TABLE 2. Correlations between shortwave CRE anomalies and anomalies in cloud controlling factors using daily mean data in the top row and monthly mean data in the bottom row. Correlations are averaged over all oceanic grid points from 45° to 60°S during austral summer (DJF).

Time scale	ω_{500} (observations)	ω_{500} (multimodel mean)	EIS (observations)	EIS (multimodel mean)
Daily	0.40	0.52	−0.24	−0.07
Monthly	0.17	0.40	−0.30	−0.08

category of Grise and Polvani (2014). Type I models systematically underestimate the observed dependence of low cloud cover on EIS, whereas type II models more realistically simulate the observed relationship (cf. Fig. 7 of GM16).

While the correlations in Fig. 1 are qualitatively similar to the correlations shown in GM16 for monthly mean data, Table 2 explicitly quantifies whether the magnitude of the correlations varies between daily mean and monthly mean time scales. Table 2 reveals that the magnitudes of the correlations between EIS and shortwave CRE anomalies within the region of study (45°–60°S) are very similar on both monthly and daily time scales, whereas the correlations between ω_{500} and shortwave CRE anomalies are larger on daily time scales (particularly in observations). Vertical velocity anomalies at SH midlatitudes are primarily associated with synoptic-scale weather systems, so the influence of vertical velocity on shortwave CRE is therefore stronger on the shorter time scales at which these weather systems occur.

Next, to better understand the relationships between shortwave CRE and the two cloud controlling factors (ω_{500} and EIS) at SH midlatitudes (45°–60°S), we composite the shortwave CRE anomalies in a phase space defined by daily anomalies in ω_{500} and EIS for both observations and CMIP5 models (as shown in Fig. 4 of

GM16 for monthly-mean anomalies). The results are shown in Fig. 2, where anomalies in EIS construct the y axis, anomalies in ω_{500} construct the x axis, and the shading represents the shortwave CRE anomalies. Negative shortwave CRE anomalies (blue) represent increased cloud reflection, and positive shortwave CRE anomalies (red) represent reduced cloud reflection. Note that the axes of the phase space in Fig. 2 span a much broader range of values than that shown in GM16, as anomalies in the dynamical cloud controlling factors and radiative fields have substantially larger magnitudes on daily time scales (due to synoptic-scale weather systems) that are averaged out in the monthly mean. For reference, the frequency of data values that fall at each point on the phase space is shown in Fig. S3. The data are approximately normally distributed across the phase space with some skewness toward negative anomalies in ω_{500} , consistent with the large upward vertical velocity anomalies in extratropical cyclones. Additionally, the four quadrants of the phase space are well distributed geographically within the region of study and are not biased toward one particular geographic region of the Southern Ocean (not shown).

The ω_{500} –EIS phase space for the CMIP5 multimodel mean is shown in Fig. 2b. Consistent with Fig. 1, the shortwave CRE anomalies in the models are more sensitive to changes in ω_{500} and less sensitive to changes

FIG. 2. Composites of daily shortwave CRE (SWCRE) anomalies (W m^{-2}) over the Southern Ocean (45°–60°S) during DJF, plotted as a function of the coinciding anomalies in EIS (y axis; K) and ω_{500} (x axis; Pa s^{-1}). Shown are (a) the observed composite, (b) the average of the composites from 10 CMIP5 models, and (c) the difference [(b) – (a)]. The dashed lines in each panel are placed at $\text{EIS}' = 0$ and $\omega'_{500} = 0$ to distinguish the four quadrants of the phase space.

TABLE 3. Average model bias in shortwave CRE anomalies within each of the quadrants (dynamical regimes) of the EIS– ω_{500} phase space diagram (Fig. 2c).

Quadrant	Average model SWCRE' bias (W m^{-2})
Q1 ($\omega'_{500} > 0$, EIS' > 0)	21.75
Q2 ($\omega'_{500} < 0$, EIS' > 0)	−1.88
Q3 ($\omega'_{500} < 0$, EIS' < 0)	−23.48
Q4 ($\omega'_{500} > 0$, EIS' < 0)	−4.53

in EIS when compared to observations. As noted above, half of the models used in this study are type I models (see Table 1), which systematically underestimate the dependence of SH midlatitude shortwave CRE anomalies on EIS (cf. Fig. 4b of GM16). When comparing the model average phase space to observations (Fig. 2a), two quadrants are qualitatively similar in terms of the sign of the shortwave CRE anomalies: quadrant II ($\omega'_{500} < 0$, EIS' > 0) and quadrant IV ($\omega'_{500} > 0$, EIS' < 0), and two quadrants are qualitatively different: quadrant I ($\omega'_{500} > 0$, EIS' > 0) and quadrant III ($\omega'_{500} > 0$, EIS' < 0). While there are model biases in all four quadrants of the phase space (Fig. 2c), the model biases in quadrants I and III are, on average, quantitatively larger than those in quadrants II and IV (Table 3). As the models tend to be too sensitive to changes in ω_{500} , it stands to reason that at least one of the quadrants (or “dynamical regimes”) with large average model biases should be present in transient weather systems, such as extratropical cyclones, that contain large anomalies in ω_{500} on daily time scales. Consistent with this, quadrants I and III correspond to specific sectors of SH midlatitude synoptic-scale weather systems where models have biases in their representation of clouds (see section 4).

In summary, the results in this section have confirmed that many of the findings of GM16 for monthly mean time scales also apply to daily time scales. In particular, shortwave CRE anomalies in GCMs are too sensitive to perturbations in large-scale vertical motion at SH midlatitudes and not sensitive enough to perturbations in the strength of the boundary layer temperature inversion. However, examining daily time scales reveals some nonlinearities in these relationships that are not apparent in the monthly mean (cf. Fig. 2 herein and Fig. 4 of GM16). For example, Fig. 2a suggests that, as anomalies in ω_{500} become more positive, the sensitivity of shortwave CRE anomalies to anomalies in EIS decreases in observations, a result not detected in monthly mean data. In the next section, we discuss how these relationships between SH midlatitude shortwave CRE anomalies and their dynamical controlling factors are manifested in the context of midlatitude weather systems.

4. Composites of SH extratropical cyclones and anticyclones

Synoptic-scale weather systems drive the dominant dynamical variability at SH midlatitudes on daily time scales. Directly examining extratropical cyclones and anticyclones allows us to identify how and where the dynamical regimes identified in Fig. 2 manifest themselves in individual weather systems. Consequently, the daily relationships between the two cloud controlling factors and shortwave CRE anomalies shown in Figs. 1 and 2 can be linked to specific sectors of midlatitude weather systems. To do this, we form composites of anomalies in the cloud controlling factors and shortwave CRE for both extratropical cyclones and anticyclones in the SH midlatitudes (45° – 60° S) during austral summer (DJF). The cyclone and anticyclone composites are constructed following the methods outlined in section 2b.

a. Extratropical cyclones

Figures 3a and 3b show the composite of ω_{500} anomalies around a SH extratropical cyclone for both observations and the CMIP5 multimodel mean, respectively. Note that the orientation of these composites (and all subsequent cyclone and anticyclone composites) is such that positive y values represent points north of the cyclone center (equatorward in the SH). The pattern of ω_{500} anomalies associated with the cyclone is qualitatively very similar in observations and models, depicting a classic “comma-head” shape of negative ω_{500} anomalies along the fronts and within the warm sector where rising motion would be expected to occur as in a typical “Norwegian” cyclone (e.g., Bjerknes 1919). These negative ω_{500} anomalies are accompanied by a region of subsidence (positive ω_{500} anomalies) in the post-cold-frontal region in both observations and models.

Figures 3c and 3d show the composite of EIS anomalies around a SH extratropical cyclone for both observations and the CMIP5 multimodel mean. Again, the anomalies in observations and models are qualitatively similar. Both exhibit a negative anomaly across much of the cyclone (in both the frontal¹ and post-cold-frontal regions), with the minimum anomaly shifted equatorward of the cyclone center. For reference, composites of potential temperature anomalies at 700 hPa and the

¹ For brevity, we refer to the regions where both ω_{500} and EIS anomalies are negative as the “frontal region” of the cyclone. In practice, this region not only encompasses the cold and warm fronts, but also much of the warm sector of the cyclone.

FIG. 3. Composites of daily anomalies of cloud controlling factors around the centers of extratropical cyclones over the Southern Ocean (45° – 60° S) during DJF: (left) observed cyclone composites and (right) CMIP5 multimodel-mean cyclone composites of (a),(b) ω_{500} anomalies (Pa s^{-1}) and (c),(d) EIS anomalies (K). (e),(f) The locations of different dynamical regimes (quadrants of Fig. 2) in the context of a composite SH extratropical cyclone.

surface around a SH extratropical cyclone are shown in the supplemental material (Fig. S4). The negative EIS anomaly in the post-cold-frontal region is produced primarily by greater cold anomalies in potential temperature at 700 hPa than at the surface, whereas the negative EIS anomaly extending into the warm sector of the cyclone is produced by warm anomalies in potential temperature at the surface with weak anomalies in potential temperature at 700 hPa (negative LTS anomalies in both cases). Note that the negative EIS anomaly in the models has a slightly

smaller magnitude because of the smaller absolute value of the 700-hPa potential temperature anomalies within the cold sector of the cyclone in models (cf. Figs. S4a,b).

The similarity of the anomalies of the cloud controlling factors in observations and models is further illustrated in Figs. 3e and 3f, which divide the composite cyclone into four dynamical regimes associated with the four quadrants of the ω_{500} –EIS phase space shown in Fig. 2. Dynamical anomalies associated with quadrant I ($\omega'_{500} > 0$, $\text{EIS}' > 0$) are shown in blue, quadrant II

FIG. 4. Composites of daily SWCRE anomalies (W m^{-2}) around the centers of extratropical cyclones over the Southern Ocean (45° – 60°S) during DJF: (a) the SWCRE anomalies for the observed cyclone composite, (b) the SWCRE anomalies for the CMIP5 multimodel-mean cyclone composite, and (c) the difference between the two.

($\omega'_{500} < 0$, $\text{EIS}' > 0$) in green, quadrant III ($\omega'_{500} < 0$, $\text{EIS}' < 0$) in red, and quadrant IV ($\omega'_{500} > 0$, $\text{EIS}' < 0$) in yellow. Quadrant IV anomalies typically occur in the cold air sector of the cyclone. Quadrant III anomalies typically occur near the center of the cyclone, along the cold front, and extend into the warm sector of the cyclone. Quadrant II anomalies typically occur in the warm sector farther to the east of the quadrant III anomalies, and quadrant I anomalies are only present far away from the cyclone center and tend to be smaller in magnitude.

The locations of the dynamical regimes in Figs. 3e and 3f are based on the average values across all the extratropical cyclones within the analysis. However, the spatial structure (e.g., orientation of fronts) of individual cyclones can vary greatly, and thus there is variance in the exact location of the four dynamical regimes within individual cyclones. We have verified that the composite structure shown in Fig. 3 does indeed capture the approximate orientation of the dynamical regimes in most individual cyclones. For a large percentage of the cyclones examined, the dynamical regimes occur in the same regions as shown for the composite cyclone (see Fig. S5).

In section 3, we identified quadrants I and III as regimes where CMIP5 models are most biased in representing how SH midlatitude clouds respond to dynamical controlling factors (see Fig. 2). Quadrant III anomalies are readily apparent in the frontal region of the composite cyclone (Fig. 3, bottom, red). Thus, the results in Fig. 2 suggest that a composite of shortwave CRE anomalies around the center of a SH extratropical cyclone should demonstrate a bias in this region when comparing models and observations. This is verified in Fig. 4.

Figure 4 shows the composite of shortwave CRE anomalies around a SH extratropical cyclone for both

observations and the CMIP5 multimodel mean. Both observations and models show enhanced cloud reflection (negative shortwave CRE anomalies) in the region of the cyclone with upward vertical velocity anomalies (Figs. 3a,b) and reduced cloud reflection (positive shortwave CRE anomalies) in the cold air sector of the cyclone, a result consistent with previous studies (e.g., Field et al. 2011). However, there are key differences between the observed and model composites (Fig. 4c). First, the reduced cloud reflection to the west of the cyclone center is generally more pronounced in the models and covers more area when compared to observations. Second, the model clouds are anomalously brighter in the frontal region of the cyclone. This second bias is larger in magnitude than the bias to the west of the cyclone and agrees with our expectation of a model bias in shortwave CRE sensitivity within the region of the cyclone with quadrant III anomalies (Figs. 3e and 3f, red; quadrant III from Fig. 2). Note that, while quadrant I anomalies are also present on average on the outskirts of the cyclone composite (Figs. 3e and 3f, blue; quadrant I from Fig. 2), we do not see large biases in model shortwave CRE anomalies in these regions in Fig. 4c, as the anomalies in the cloud controlling factors in those regions are much smaller (Fig. 3).

Figure 4c shows that the majority of the model bias in shortwave CRE anomalies is located within the frontal region of the extratropical cyclone and not within the post-cold-frontal region of the cyclone. At first glance, this result appears to contradict the findings of some previous studies, which identified the post-cold-frontal region as the most important region of model bias (e.g., Bodas-Salcedo et al. 2012; Williams et al. 2013; B14). However, here we are examining the models' sensitivity to perturbations about their background climatology, whereas many previous studies on Southern Ocean model cloud biases retained the climatology within their cyclone

composite analyses. To demonstrate this difference, in Fig. 5 we composite the shortwave CRE around an extratropical cyclone for a single climate model (HadGEM2-A). In this figure, the top panel (Fig. 5a) shows the difference between the observed and modeled shortwave CRE with the climatology included (cf. Fig. 3f2 of B14), and the bottom panel (Fig. 5b) shows the same result but with the climatology removed prior to performing the analysis. With the climatology included, there is little model bias in the frontal region of the cyclone and much greater model biases in the post-cold-frontal region of the cyclone (Fig. 5a), as documented in previous studies. However, after removing the climatology, it is clear that the HadGEM2-A model's sensitivity to day-to-day fluctuations in dynamics is more biased in the frontal region of the cyclone than in the post-cold-frontal region (Fig. 5b). The difference between our conclusions and those of B14 will be discussed further in section 5.

b. Extratropical anticyclones

While many previous studies have focused on extratropical cyclone composites to understand model cloud biases in the SH extratropics, extratropical anticyclones also play an important role in daily weather patterns and day-to-day cloud variability at SH midlatitudes. To our knowledge, while studies have discussed the role of transient ridges over the Southern Ocean (e.g., Williams et al. 2013), composites of CRE anomalies and the associated cloud controlling factors for extratropical anticyclones have not been shown previously in the literature. Figure 6 shows the composites of ω_{500} and EIS anomalies around a SH extratropical anticyclone for both observations and the CMIP5 multimodel mean. As for the extratropical cyclone (Fig. 3), the composites of ω_{500} and EIS anomalies around the anticyclone are qualitatively very similar between observations and models. Both observations and models show anomalous subsidence located to the east of the anticyclone center (Figs. 6a,b), anomalous rising motion located to the west of the center, and positive EIS anomalies located around the center of the anticyclone (Figs. 6c,d). The east–west dipole of subsidence and rising motion is consistent with the eastward-moving transient ridges that characterize the Southern Ocean (Williams et al. 2013).

Figures 6e and 6f divide the composite anticyclone into the four dynamical regimes associated with the four quadrants of the ω_{500} –EIS phase space (as in Figs. 3e and 3f for the cyclone; see quadrants in Fig. 2). Two dynamical regimes dominate the anticyclone composites: quadrant II anomalies ($\omega'_{500} < 0$, $\text{EIS}' > 0$) typically occur to the west of the anticyclone center, and quadrant I anomalies ($\omega'_{500} > 0$, $\text{EIS}' > 0$) typically occur at and to the east of the anticyclone center. As with the cyclone

FIG. 5. Difference between the observed composite of daily SWCRE (W m^{-2}) around a Southern Ocean (45° – 60° S) extratropical cyclone during DJF and the corresponding cyclone composite for the HadGEM2-A model (HadGEM2-A–observations). Results are shown with the SWCRE climatology (a) retained within both the observed and model cyclone composites and (b) removed from both the observed and model cyclone composites (as in Fig. 4c).

composites, for a large percentage of the anticyclones examined, the dynamical regimes occur in the same regions as shown for the composite anticyclone (not shown). Based on the analysis in Fig. 2, we would expect the model shortwave CRE anomalies to be biased in the region of the anticyclone with quadrant I anomalies.

To assess this, Fig. 7 shows the composite of shortwave CRE anomalies around a SH extratropical anticyclone for both observations and the CMIP5 multimodel mean. The observed shortwave CRE anomalies are generally weak in magnitude (Fig. 7a). A small region of reduced

FIG. 6. As in Fig. 3, but for the cloud controlling factor composites around the centers of anticyclones over the Southern Ocean.

cloud reflection (positive shortwave CRE anomalies) is centered just to the east of the anticyclone center, which is surrounded by a broad region of weakly enhanced cloud reflection (negative shortwave CRE anomalies). The CMIP5 models show anomalies with a similar spatial pattern but much greater magnitude (Fig. 7b). In particular, the positive shortwave CRE anomalies near the center of the anticyclone have substantially greater magnitude in models than in observations (Fig. 7c). This result is consistent with our expectation of substantial model bias in the region of the anticyclone with quadrant I anomalies (Figs. 6e and 6f, blue; Fig. 2) and is consistent with Williams et al. (2013), who find too little shortwave radiation reflected along the leading edges of

transient ridges in the Southern Ocean. Consequently, in addition to the frontal regions of extratropical cyclones, the quiescent regions associated with extratropical anticyclones are important in understanding model biases in the day-to-day variability of cloud radiative effects at SH midlatitudes. Note that, just as there are weak quadrant I anomalies on the edges of the cyclone composite, there are regions of quadrant III anomalies on the outskirts of the anticyclone composite (Figs. 6e and 6f, red). However, as with the regions at the edge of the cyclone composite, these regions are not associated with large biases in model shortwave CRE anomalies because of the small underlying average perturbations in the dynamical fields there.

FIG. 7. As in Fig. 4, but for the SWCRE composites around the centers of anticyclones over the Southern Ocean.

5. Summary and discussion

In recent years, a number of studies have sought to understand the climatology and variability of clouds and their radiative effects using a “cloud controlling factor” framework in both the tropics (Norris and Iacobellis 2005; Myers and Norris 2013; Qu et al. 2014, 2015; Klein et al. 2017) and extratropics (e.g., GM16; Zelinka et al. 2018). The cloud controlling factor framework identifies large-scale dynamical properties that are associated with variability and change in observed cloud fields, which can subsequently be used to evaluate how models represent observed cloud processes. GM16 examined two such cloud controlling factors, large-scale vertical velocity (ω at 500 hPa) and boundary layer inversion strength (estimated inversion strength, or EIS; Wood and Bretherton 2006), that were helpful in explaining variability in midlatitude cloud fields on monthly-mean time scales. In this study, we extended their analysis to daily time scales when synoptic-scale weather systems are responsible for the dominant variability in midlatitude cloud fields, focusing exclusively on the SH midlatitudes during the summer season (DJF).

Overall, the key conclusions of GM16 were found to extend from monthly mean to daily mean time scales. First, in both observations and GCMs, large-scale vertical motion is associated with increased cloud reflection (decreases in shortwave CRE) (Figs. 1a,c), confirming the well-known relationship between ascending motion and increased mid- and high-level cloud incidence (e.g., Li et al. 2014; Wall et al. 2017). Second, particularly in observations, a stronger boundary layer temperature inversion (EIS) is associated with increased cloud reflection (decreases in shortwave CRE) at SH midlatitudes (Figs. 1b,d). This finding is consistent with the observed relationship between increased EIS and increased low cloud cover found in both tropical and extratropical low cloud regions (Wood and Bretherton 2006; Qu et al. 2015; GM16; Klein et al. 2017; Zelinka et al. 2018).

On average, GCMs overestimate the sensitivity of midlatitude shortwave cloud radiative effects to anomalies in vertical velocity and underestimate their sensitivity to anomalies in EIS (Figs. 1 and 2). The model biases in sensitivity are particularly pronounced in two dynamical regimes: 1) anomalously rising motion and suppressed inversion strength ($\omega'_{500} < 0$, $EIS' < 0$) and 2) anomalously sinking motion and enhanced inversion strength ($\omega'_{500} > 0$, $EIS' > 0$). On daily time scales, these regimes correspond to specific sectors of extratropical weather systems. The first regime corresponds to the frontal region and warm sector of extratropical cyclones, where model clouds excessively brighten in response to ascending motion (Figs. 3 and 4; see also B14). The second regime corresponds to extratropical anticyclones, where model clouds excessively dim in response to descending motion (Figs. 6 and 7). GCMs well simulate how vertical velocity and EIS vary within extratropical weather systems, suggesting that the model biases result primarily from errors in the sensitivity of model clouds to perturbations in the dynamics (rather than from errors in the dynamics themselves).

The oversensitivity of model cloud radiative effects to vertical velocity anomalies generally exaggerates the anomalous cloud reflection in regions of ascending motion and underestimates anomalous cloud reflection in regions of descending motion (see also Norris and Weaver 2001). These results suggest that models tend to have larger day-to-day variance in their shortwave CRE across the Southern Ocean when compared to observations (see also greater contrast in colors in Fig. 2b compared to Fig. 2a). We have directly confirmed this by calculating the variance in daily shortwave CRE anomalies across 45°–60°S in both observations and models (not shown). Exaggerated cloud-radiative heating gradients between synoptic-scale weather systems may bias horizontal temperature gradients in models and ultimately feed back on the models' ability to

capture key dynamical features. Furthermore, this result could have implications for model cloud feedbacks in a changing climate. We plan to investigate these issues in a subsequent study.

Several previous studies have suggested that the predominant SH midlatitude cloud biases arise from the post-cold-frontal region of extratropical cyclones (e.g., Bodas-Salcedo et al. 2012; Williams et al. 2013; B14). As discussed in section 4a, this is indeed the case when the climatology is retained within composites of SH extratropical cyclones for some models (Fig. 5a). However, removing the climatology allows us to more easily assess the sensitivity of model clouds to perturbations in their underlying dynamical cloud controlling factors. When this is done, models better simulate the cloud perturbations associated with the dynamical anomalies in the post-cold-frontal region of the cyclone ($\omega'_{500} > 0$, $EIS' < 0$; see quadrant IV of Fig. 2) than in the frontal region of the cyclone ($\omega'_{500} < 0$, $EIS' < 0$; see quadrant III of Fig. 2).

B14 concluded that the model bias in the post-cold-frontal region of SH extratropical cyclones is largely responsible for the well-known climatological bias of reflected shortwave radiation at SH midlatitudes, with modeled Southern Ocean clouds on average being too dim when compared to observations (Trenberth and Fasullo 2010). In Fig. 8a, we find a very similar result (cf. Fig. 4 of B14), showing the scatterplot of each model's climatological shortwave CRE at SH midlatitudes (45° – 60° S) during the austral summer (DJF) with its corresponding shortwave CRE in the post-cold-frontal region of a composite extratropical cyclone during the same season. Here, to be consistent with the dynamical regimes identified in section 4, we define the post-cold-frontal region as the area of the cyclone composite for each model where there are negative anomalies of EIS and positive anomalies of ω_{500} (Figs. 3e and 3f, yellow). This differs slightly from the definition used in B14, who considered the post-cold-frontal region to be the western two quadrants of the cyclone composite. As in B14, we find a highly significant correlation between the SH midlatitude shortwave CRE climatology and the climatology in the post-cold-frontal region of a composite extratropical cyclone ($r = 0.96$). Defining the post-cold-frontal region using the definition of B14 produces a comparable correlation coefficient ($r = 0.97$).

In Fig. 8b, we repeat the analysis in Fig. 8a, but now show the scatterplot of each model's climatological mean shortwave CRE with its corresponding average shortwave CRE *anomaly* (i.e., with the climatology removed) within the post-cold-frontal region of the composite cyclone. Now, the correlation is no longer statistically significant, and the relationship is much weaker ($r = 0.11$), suggesting that the overall

FIG. 8. Scatterplots relating the austral summer (DJF) SWCRE climatology (45° – 60° S; y axis) from 10 CMIP5 models to the (on the x axis) (a) model austral summer post-cold-frontal region SWCRE climatology (cf. with Fig. 4 from B14) and (b) model austral summer post-cold-frontal region SWCRE anomalies. The post-cold-frontal region is defined using the quadrant IV dynamical regime shown in Figs. 3e and 3f. The correlation coefficients for each scatterplot are shown in the bottom right of each panel. Two asterisks denote significance at the 95% level or above.

climatological bias in model shortwave CRE is not linked to the day-to-day sensitivity of shortwave CRE within the post-cold-frontal region of the cyclone. In other words, the factors that are responsible for inter-model variance in the climatological value of shortwave CRE over the Southern Ocean are unrelated to the sensitivity of the models' CRE to day-to-day perturbations in the dynamical cloud controlling factors in this region.

One would anticipate that limitations in model cloud parameterizations that drive climatological bias in a

given region would also bias the sensitivity of the clouds in that region to short-term dynamical perturbations. However, our results suggest that, even though the post-cold-frontal region of an extratropical cyclone possesses a large climatological-mean bias, the day-to-day processes governing how the clouds respond to dynamical perturbations are more flawed in the anticyclones and the frontal region of cyclones. Because the post-cold-frontal region of cyclones cover a sizeable fraction of the areas of the Southern Ocean at any given time, the climatological bias in these regions must, by definition, be strongly correlated with the overall climatological bias over the Southern Ocean (i.e., both axes on the scatterplot in Fig. 8a contain the background climatological value from each model). As such, the large correlation shown in Fig. 8a is not unique to the post-cold-frontal region; we find similar correlations for the other dynamical regimes in both extratropical cyclones and anticyclones (not shown). While documenting the locations of large climatological-mean biases is important, the sensitivity analysis presented in this study more directly identifies processes that are inherently misrepresented in models.

Finally, this study only examined two cloud controlling factors on SH midlatitude cloud radiative effects, following from the work of GM16. Additional insight into model biases may be gained by examining some of the other cloud controlling factors discussed in the introduction, such as near-surface temperature advection (Norris and Iacobellis 2005; Zelinka et al. 2018), surface sensible heat fluxes (Miyamoto et al. 2018), and tropospheric temperature perturbations (e.g., Ceppi et al. 2016). While we have showed that the two cloud controlling factors analyzed in this study are approximately time scale-invariant (at least in terms of the signs of the correlations on monthly and daily time scales; Table 2), the same cannot be said for all cloud controlling factors. On monthly time scales, Zelinka et al. (2018) recently identified near-surface temperature advection as being more important for midlatitude low cloud variability than EIS and also found that CMIP5 models poorly simulate the dependence of low cloud cover on thermal advection. However, our preliminary analyses indicate that near-surface temperature advection has a different effect on midlatitude cloud variability on daily time scales than it does on monthly time scales (not shown), and we plan to address this topic in a subsequent study. Future work should carefully consider the time scale dependence of dynamical controlling factors on clouds and their radiative effects in order to develop a better understanding of the processes responsible for observed cloud variability and model cloud biases.

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