On the Relationships between Subtropical Clouds and Meteorology in Observations and CMIP3 and CMIP5 Models*

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ABSTRACT

Climate models' simulation of clouds over the eastern subtropical oceans contributes to large uncertainties in projected cloud feedback to global warming. Here, interannual relationships of cloud radiative effect and cloud fraction to meteorological variables are examined in observations and in models participating in phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5, respectively). In observations, cooler sea surface temperature, a stronger estimated temperature inversion, and colder horizontal surface temperature advection are each associated with larger low-level cloud fraction and increased reflected shortwave radiation. A moister free troposphere and weaker subsidence are each associated with larger mid- and high-level cloud fraction and offsetting components of shortwave and longwave cloud radiative effect. It is found that a larger percentage of CMIP5 than CMIP3 models simulate the wrong sign or magnitude of the relationship of shortwave cloud radiative effect to sea surface temperature and estimated inversion strength. Furthermore, most models fail to produce the sign of the relationship between shortwave cloud radiative effect and temperature advection. These deficiencies are mostly, but not exclusively, attributable to errors in the relationship between low-level cloud fraction and meteorology. Poor model performance also arises due to errors in the response of mid- and high-level cloud fraction to variations in meteorology. Models exhibiting relationships closest to observations tend to project less solar reflection by clouds in the late twenty-first century and have higher climate sensitivities than poorer-performing models. Nevertheless, the intermodel spread of climate sensitivity is large even among these realistic models.

1. Introduction

Estimates of the global mean equilibrium temperature response due to a doubling of CO₂ relative to the preindustrial level range from 2.1 to 4.7 K among models in phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012; Flato et al. 2013). This is almost identical to the range produced by CMIP3 models (Meehl et al. 2007; Randall et al. 2007). This spread in climate sensitivity is mostly a result of the wide intermodel

spread of simulated changes in the shortwave cloud radiative effect (SW CRE; defined as clear-sky minus all-sky top-of-atmosphere outgoing solar radiation) (Webb et al. 2006; Andrews et al. 2012). Model disagreement on changes in marine boundary layer (MBL) clouds over eastern subtropical oceans was identified as the dominant driver of the spread of projections of SW CRE among CMIP3 models (Bony and Dufresne 2005). In fact, neither CMIP3 nor CMIP5 models agree on whether subtropical MBL cloud fraction will increase or decrease under anthropogenic climate change (Qu et al. 2014). An understanding of MBL clouds and their simulation in models is therefore important in order to evaluate climate change projections.

MBL clouds, including stratocumulus and shallow cumulus, are prevalent over eastern subtropical oceans. Stratocumulus clouds tend to occur under strongly descending air, a sharp temperature inversion, and within a shallow, well-mixed MBL (Albrecht et al. 1995; Norris 1998; Wood and Hartmann 2006). Shallow cumulus clouds tend to occur under more weakly descending air, a less

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sharp temperature inversion, and within a deeper, more decoupled MBL. Geographical and seasonal-to-decadal statistical relationships between MBL cloud fraction (CF) and the large-scale meteorology have been extensively examined in observations. These studies have found that large CF is favored by strong inversions (Klein and Hartmann 1993; Wood and Bretherton 2006; Sun et al. 2011; Myers and Norris 2013), cool sea surface temperature (Hanson 1991; Norris and Leovy 1994; Clement et al. 2009), enhanced horizontal cold air advection near the surface (Klein et al. 1995; Park and Leovy 2004; Norris and Iacobellis 2005), and weaker subsidence (Myers and Norris 2013). The relationship between free-tropospheric moisture and MBL CF is not as clear from an observational perspective. Klein et al. (1995) found that enhanced free-tropospheric moisture over the eastern subtropical Pacific was associated with small low-level CF, whereas Lacagnina and Selten (2013) found that it was associated with large low-level CF.

These observed relationships can be understood in terms of their connections to the turbulent processes occurring within the MBL. Strong inversions may favor larger MBL CF by reducing entrainment drying and promoting a moister MBL in addition to being associated with cool sea surface temperature (Bretherton and Wyant 1997; Wood 2012). Cool sea surface temperature may favor larger CF by leading to a shallower, more well-mixed MBL containing predominantly stratocumulus by reducing surface latent heating (Bretherton and Wyant 1997). Weaker subsidence leads to larger MBL CF by increasing cloud-top height and stratocumulus cloud thickness (Blossey et al. 2013; Bretherton et al. 2013; Myers and Norris 2013). A moister free troposphere may act to reduce cloud-top radiative cooling (leading to a lowering of cloud top) and reduce entrainment drying (leading to a lowering of stratocumulus cloud base) (Betts and Ridgway 1989). This may result in either an increase or decrease in stratocumulus cloud thickness. The reduction of radiative cooling may also lead to decoupling, favoring cumulus and thinner stratocumulus, by reducing turbulent mixing (Sandu et al. 2010).

The simulation of these observed relationships in climate models serves as a test for how well models represent MBL cloud processes. Clement et al. (2009) found that most CMIP3 models fail to simulate the interannual to decadal positive correlation between lower tropospheric stability and total CF over the eastern subtropical North Pacific. They also found that CMIP3 models exhibit a wide intermodel spread in the magnitude and the sign of the correlations between total CF and both sea surface temperature and pressure vertical velocity at 500 hPa. Similarly, Caldwell et al. (2013) found that most CMIP3 models fail to simulate the climatological positive

correlation between estimated inversion strength and total CF. They also found negligible interannual relationships between total CF and both sea surface temperature and horizontal surface temperature advection in CMIP3 models. Webb et al. (2013) found that most models fail to simulate the observed climatological enhancement of SW CRE (i.e., more SW radiation reflected to space) associated with stronger lower tropospheric stability. These findings suggest considerable deficiencies in models' representation of MBL clouds.

One drawback of the aforementioned model evaluation studies is that total CF was examined rather than the vertical profile of CF. The relationships found in those studies therefore represent mixed effects of low-level and higher-level clouds. Indeed, Broccoli and Klein (2010) note that if low-level CF is examined in the GFDL CM2.1 model, the simulated relationships examined in Clement et al. (2009) are all of the correct sign. This motivates looking beyond the total CF metric in examining the simulation of clouds in climate models. It also suggests that variability of higher-level CF over the eastern subtropics may be nonnegligible in models and oppose variability of low-level CF, yielding confounding total CF changes.

Previous model evaluation studies generally have not compared the vertical profile of CF in models to satellite observations because satellites cannot, unlike a model, perfectly specify cloud fraction, liquid water content, and other cloud properties at each vertical level in the atmosphere. For example, passive satellites, such as those used for the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1999), can only detect low clouds unobstructed by higher clouds. Active satellites, such as the *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (CALIPSO; Chepfer et al. 2010), provide a more realistic vertical profile of cloud properties than passive satellites, but this type of observational data has only existed since ~2006 compared to ~1983 for passive satellite data. Still, both types of data represent retrieved cloud properties, not actual cloud properties. Contrastingly, within climate models and regardless of their realism, the values of various cloud properties are known exactly. Several CMIP5 models utilize “simulator” packages that provide cloud properties that an imaginary satellite orbiting the modeled world would detect (Bodas-Salcedo et al. 2011). One such property is CF obtained using simulated retrieval methods similar to those of ISCCP and the *CALIPSO–GCM Oriented CALIPSO Cloud Product* (CALIPSO–GOCCP; Chepfer et al. 2010). Differences between observed CF and modeled CF using simulator packages can be mostly attributed to deficiencies in model physics rather than differences in the definition of CF.

TABLE 1. Summary of satellite data used in the investigation. The values in the n_{eff}/n column are the ratio of the number of statistically independent points to the nominal number of points for the different cloud variables, computed as described in the text.

Satellite dataset	Time period used	Variables used	n_{eff}/n
ISCCP	1983–2008	CF	1/72*
CALIPSO-GOCCP	2006–12	CF	1/10
CERES	2000–12	SW CRE	1/36
		LW CRE	1/36
		Net CRE	1/36

* For the five (two) ISCCP layers closest to the surface (top of the atmosphere), $n_{\text{eff}}/n = 1/72$ (1/96).

Motivated by the shortcomings of previous studies, in this work we examine the interannual relationships of top-of-atmosphere SW, longwave (LW), and net CRE over eastern subtropical oceans to sea surface temperature, estimated inversion strength, horizontal surface temperature advection, free-tropospheric humidity, and subsidence in 11 CMIP3 models, 14 CMIP5 models, and observations. We complement this with an analysis of the relationship between the vertical profile of CF and the same meteorological variables. This will allow us to physically interpret the SW, LW, and net-CRE relationships in models and observations. Furthermore, assessment of CMIP5 CF derived from ISCCP and CALIPSO-GOCCP simulators will make possible an apples-to-apples comparison between models and observations.

2. Data and methods

a. Observational data

Tables 1 and 2 summarize the observational cloud and meteorological data used in this investigation, respectively. Each dataset was bilinearly interpolated onto a $2.5^\circ \times 2.5^\circ$ equal-angle grid, which is the grid with the coarsest resolution of all datasets. SW, LW, or net CRE is defined as clear-sky minus all-sky top-of-atmosphere SW, LW, or net outgoing radiation (positive outward). According to this definition, clouds almost always exert a negative SW CRE and a positive LW CRE, acting to

increase outgoing SW radiation (cooling effect) and decrease outgoing LW radiation (warming effect) at the top of the atmosphere, respectively. Therefore, hereafter, more negative (positive) SW CRE will be referred to as enhanced (weaker) SW CRE, and more positive (negative) LW CRE will be referred to as enhanced (weaker) LW CRE. The CRE data are provided by the Clouds and Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) dataset version 2.7 (Loeb et al. 2009).

We use CF from the GCM simulator-oriented ISCCP cloud product (Pincus et al. 2012; Zhang et al. 2012) and CALIPSO-GOCCP datasets. ISCCP provides CF in 7 pressure layers and 6 optical thickness categories. CALIPSO provides CF in 40 vertical layers specified in geometric height. We converted these height coordinates to pressure coordinates by assuming that pressure p decreases exponentially with height z such that $p = p_0 e^{-z/H}$, where surface pressure $p_0 = 1010$ hPa and scale height $H = 8000$ m. Total ISCCP CF for each pressure layer was computed by summing CF over all optical thickness categories. We use two versions of ISCCP cloud data: one that assumes clouds are not overlapped, which is what the ISCCP retrieval method assumes (satellite view), and one that assumes clouds are randomly overlapped. To estimate the true total CF at some level using the random overlap assumption, we divided the retrieved, unobstructed total CF by the clear-sky fraction above that level (Rozena et al. 1995). The use of ISCCP CF data corrected for artifacts as in Norris and Evan (2015) yields no appreciable difference to our results.

We use meteorological variables from four atmospheric reanalyses, including the Climate Forecast System Reanalysis (CFSR; Saha et al. 2010), the Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim; Dee et al. 2011), the Japanese 55-year Reanalysis Project (JRA-55; Ebata et al. 2011), and the Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al. 2011). Because meteorological observations over the oceans are sparse, using four reanalyses ensures that we robustly capture the range of observational uncertainty.

TABLE 2. Summary of reanalysis data used in the investigation. Values in the $\omega_{700} > 0$ column are the percentage of ocean grid boxes within 30°S – 30°N satisfying the criteria specified in the text for the different reanalyses.

Reanalysis	Time period used	Variables used	$\omega_{700} > 0$ (%)
CFSR	Coincident with paired cloud data (ISCCP, CALIPSO-GOCCP, or CERES)	SST, EIS, SSTadv, q_{700} , ω_{700}	36
ERA-Interim	Same as CFSR	Same as CFSR	31
JRA-55	Same as CFSR	Same as CFSR except T_{2m} used instead of SST	30
MERRA	Same as CFSR	Same as CFSR	32

TABLE 3. CMIP models used in the investigation. Values in the $\omega_{700} > 0$ column are the percentage of ocean grid boxes within 30°S–30°N satisfying the criteria specified in the text for the different models. Asterisks denote those models providing ISCCP and *CALIPSO*-GOCCP simulator-derived cloud fraction. (Expansions of model acronyms are available online at <http://www.ametsoc.org/PubsAcronymList>.)

Modeling group	CMIP3 models	ID	$\omega_{700} > 0$ (%)	CMIP5 models	ID	$\omega_{700} > 0$ (%)
National Center for Atmospheric Research	CCSM3	a1	28	CCSM4	A1	23
	PCM	a2	18	CESM1 (CAM5)	A2	23
Canadian Centre for Climate Modelling and Analysis	CGCM3.1 (T47)	b	28	CanESM2*	B	29
Max Planck Institute for Meteorology	ECHAM5	c	28	MPI-ESM-LR*	C	28
LASG/Institute of Atmospheric Physics	FGOALS-g1.0	d	28	FGOALS-g2	D	27
NOAA/Geophysical Fluid Dynamics Laboratory	GFDL-CM2.0	e	32	GFDL CM3	E1	22
				GFDL-ESM2G	E2	27
NASA Goddard Institute for Space Studies	GISS-EH	f	19	GISS-E2-H	F	27
L'Institut Pierre-Simon Laplace	IPSL-CM4	g	35	ISPL-CM5A-LR	G1	32
				IPSL-CM5B-LR	G2	24
				MIROC5*	H1	36
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC3.2 (hires)	h	37	MIROC-ESM-CHEM*	H2	33
Meteorological Research Institute	MRI-CGCM2.3.2	i	32	MRI-CGCM3*	I	23
Met Office Hadley Centre	HadCM3	j	27	HadGEM2-ES*	J	30

The meteorological variables include sea surface temperature (SST), estimated inversion strength (EIS), advection by the surface wind over the SST gradient (SSTadv), specific humidity at 700 hPa (q_{700}), and pressure vertical velocity at 700 hPa (ω_{700}). For JRA-55, air temperature two meters above the surface (T_{2m}) was used since SST was not provided.

EIS was calculated as in Wood and Bretherton (2006), who derived the formulation

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

Here, LTS stands for lower tropospheric stability and is the difference in potential temperature between the 700-hPa level 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 relative to the surface, and LCL is the height of the lifting condensation level relative to the surface. We assume a surface relative humidity of 80% as in Wood and Bretherton (2006) and use the method of Georgakakos and Bras (1984) for the calculation of LCL. We computed SSTadv as the advection by reanalysis near-surface wind over the SST gradient (or T_{2m} gradient for JRA-55) using a centered finite differencing scheme in spherical coordinates.

b. Model output

We use monthly output from 25 coupled climate models from 10 different modeling centers participating in both CMIP3 and CMIP5, summarized in Table 3. This will allow us to assess the overall progress, if any, in modeling of subtropical cloud processes from CMIP3 to

CMIP5. For a particular modeling center, each of the model variants examined incorporates a different atmospheric model. For the CMIP3 models, we use output from the climate of the twentieth-century experiment runs, and the “run1” ensemble member is used for each model. For the CMIP5 models, we use output from the historical runs, and the “r1i1p1” ensemble member is used for each model. These scenarios use anthropogenic and natural forcing constituents, and run from the late 1800s until 1999 for CMIP3 and until 2005 for CMIP5. So that the time periods examined are the same length as the ISCCP record (26 yr), time periods of 1974–99 and 1980–2005 were used for CMIP3 and CMIP5 data, respectively. The results of our study, however, are insensitive to the chosen time period.

The model variables used are the same as the observed variables, with the exception of CF. We use the vertical profile of CF of each model in our analysis, but these profiles cannot be directly compared to those of ISCCP or *CALIPSO*-GOCCP due to the imperfect retrievals of cloud properties by satellites and inconsistent definitions of CF between models and the satellite datasets. Nonetheless, qualitative analysis of these profiles will provide insight into the relationships between CRE and the meteorology. ISCCP and *CALIPSO*-GOCCP simulator-derived CF will be examined from the six CMIP5 models providing such data (indicated in Table 3).

c. Computation of cloud relationships to meteorological variables

Because we are primarily interested in MBL clouds, we chose to define our domain dynamically, rather than

spatially, as in Bony et al. (2004). The domain includes all ocean grid boxes within 30°S–30°N that have long-term mean $\omega_{700} > 0$ hPa day^{−1} for every calendar month and monthly-mean $\omega_{700} > 0$ hPa day^{−1} for at least 80% of the time record; only months for which $\omega_{700} > 0$ hPa day^{−1} were examined. This method allows us to focus on dynamically similar regimes predominantly containing MBL clouds. It also implies that positive (negative) anomalies of ω_{700} represent strong (weak) subsidence relative to the mean. Since the models have different subsidence climatologies, each domain is specific to each reanalysis and model. The percentage of ocean grid boxes within 30°S–30°N satisfying our criteria are shown in Tables 2 and 3 for reanalyses and models, respectively.

Before examining relationships between the cloud and meteorological variables, we computed linearly detrended interannual monthly anomalies for each grid box. By detrending, we avoided the possibility of our results being affected by potential unphysical, low-frequency artifacts in the satellite cloud observations and reanalyses. We calculated relationships of CRE or CF to a meteorological property x by splitting values of x from all grid boxes into two subsets, one with anomalies above the median x and one with anomalies below the median. This is nearly identical to separating values of x according to positive and negative anomalies. We then took the difference in mean CRE or CF between these two subsets and divided by the difference in mean x for each subset. This is essentially a centered finite-differencing scheme for estimating the slope. We refer to the resulting quantity as the relationship of CRE or CF to x , which we write mathematically as $D(\text{CRE})/D(x)$ or $D(\text{CF})/D(x)$. Although not shown in the paper, slopes were also computed using linear regression, and the results are quantitatively similar. It is important to note that the computed relationships are not necessarily independent because the predictor variables may covary. They can therefore be thought of as total derivatives. This is in contrast to Myers and Norris (2013), who examined the independent effects of subsidence and inversion strength on subtropical MBL clouds (i.e., partial derivatives).

Each relationship is normalized by the 1984–2012 standard deviation of observed interannual anomalies of each meteorological variable x . This allows us to more easily compare the magnitudes of each relationship, which can be viewed as the response of CRE or CF to a typical anomaly in x . Because there are four reanalyses, there are four standard deviations for each x . We use the average of these four standard deviations of each x to normalize each observed and modeled quantity. Since observed and modeled values of a given relationship are normalized by a single standard deviation, relative differences among

values and their statistical significance are unchanged compared to nonnormalized values.

A two-tailed t test for the difference between two sample means provided an assessment of the statistical significance of individual relationships and the difference between modeled and observed relationships. The range of observational uncertainty of a CRE relationship is defined as the envelope of 95% confidence intervals of the four observed values (one derived from each reanalysis), and statistical significance of the observations is gauged by this range of uncertainty. A modeled CRE relationship is considered to be outside the range of observational uncertainty if it is more positive or more negative than each of the four observational estimates with 95% confidence. We also assess whether models simulate the correct sign of each CRE relationship. A model is considered to simulate an incorrect sign if 1) it simulates a statistically significant CRE relationship of opposite sign to the observed relationship, 2) it simulates a statistically significant CRE relationship when the observed relationship is statistically insignificant, or 3) it simulates a statistically insignificant CRE relationship when the observed relationship is statistically significant. If none of these conditions occurs, the model is considered to simulate the correct sign of the CRE relationship.

The cloud data are autocorrelated because processes affecting clouds on monthly time scales have a large spatial scale. To take this into account in statistical significance tests, for each observational cloud variable we computed the ratio of the number of statistically independent points [effective number (n_{eff})] to the nominal number of points n by determining the lag at which the zonal, meridional, or temporal autocorrelation coefficients cross zero. The inverse of this lag is assumed to be equal to this ratio. Zonal and meridional anomalies of each latitude and longitude band, respectively, were used to compute zonal and meridional autocorrelation. The temporal ratio multiplied by the zonal and meridional ratios is assumed to be equal to the overall ratio of effective to nominal number of points. Table 1 shows the ratios for observed cloud variables. We assume that the modeled ratios are equal to the observed ratios multiplied by $(i \times j)/(2.5^\circ \times 2.5^\circ)$, where i (j) is the average latitude (longitude) increment of each model's grid. This ensures that the total number of effective points in models with resolutions higher (lower) than $2.5^\circ \times 2.5^\circ$ is not overestimated (underestimated).

3. Results

a. Observed climatology

Figure 1 shows observed mean annual fields of SW and LW CRE, SST and surface wind velocity, EIS,

FIG. 1. Mean annual: (a),(b) 2000–12 CERES shortwave and longwave cloud radiative effect, respectively, (c) 1984–2012 ERA-Interim sea surface temperature and surface wind velocity, (d) estimated inversion strength, (e) horizontal surface temperature advection, (f) specific humidity at 700 hPa, and (g) pressure vertical velocity at 700 hPa with the $\times$ symbol indicating grid boxes used in the ERA-Interim observational analysis.

FIG. 2. (a) Shortwave cloud radiative effect relationship to meteorological variables in CMIP3 models (orange box plots), CMIP5 models (green box plots), and observations (black squares and error bars); (b) as in (a), but for longwave cloud radiative effect; (c) as in (a), but for net cloud radiative effect. For each modeled relationship, the square denotes the multimodel mean, the horizontal line denotes the median of all modeled values, the box spans the interquartile range of all modeled values, the whiskers extend to the 10th and 90th percentiles of all modeled values, and the two circles are the modeled values outside the 10th and 90th percentiles. For each observed relationship, the error bars span the four 95% confidence intervals derived from CERES and the four reanalyses, and the square is the mean of the four reanalysis values.

SSTadv, q_{700} , and ω_{700} . Over the eastern subtropical oceans, SW CRE (Fig. 1a) is strongly negative due to high amounts of reflection of shortwave radiation by abundant, optically thick low-level clouds. LW CRE (Fig. 1b) is weakly positive due to approximately equal amounts of absorption of longwave radiation by these low-level clouds and by less abundant, optically thin high-level clouds. Inspection of the meteorology reveals that regions of enhanced SW CRE and weaker LW CRE are characterized by cool SST (Fig. 1c), strong EIS (Fig. 1d), cold SSTadv (Fig. 1e), low q_{700} (Fig. 1f), and strong ω_{700} (Fig. 1g). This is qualitatively consistent with previous observational studies that have found large CF of low-level, optically thick clouds and small CF of overlying high-level, optically thin clouds associated with these meteorological conditions (e.g., Hanson 1991; Klein and Hartmann 1993; Klein et al. 1995; Wood 2012; Christensen et al. 2013).

b. Observed and multimodel mean CRE and CF interannual relationships

One might expect these geographical relationships to also occur on interannual time scales, and this is generally confirmed in Fig. 2, which shows interannual relationships of SW, LW, and net CRE to the meteorological variables for both observations and multimodel means. Since subtropical optically thick, low-level (~ 700 hPa and lower in elevation) clouds dominate SW CRE and subtropical optically thin, high-level (~ 400 hPa and higher in elevation) clouds contribute substantially to LW CRE, Fig. 3 complements the results of Fig. 2 by showing vertical profiles of the observed and multimodel mean CF relationships. Because strongly negative SW CRE is a primary climatological feature over the eastern subtropical oceans, in our discussion we speak in terms of which observed meteorological conditions are associated with anomalously enhanced SW CRE.

CMIP3/CMIP5 multi-model mean and observed CF relationships to meteorology

FIG. 3. Cloud fraction relationship to (a) sea surface temperature, (b) estimated inversion strength, (c) horizontal surface temperature advection, (d) specific humidity at 700 hPa, and (e) pressure vertical velocity at 700 hPa as a function of pressure in CMIP3 models (orange lines and shading), CMIP5 models (green lines and shading), ISCCP (gray lines), and *CALIPSO* (black lines and gray shading). For each modeled relationship, the multimodel mean is plotted as a line, and the shading spans the interquartile range among all modeled values. For ISCCP, the horizontal error bars span the eight 95% confidence intervals derived from the four reanalyses and either the "random overlap" or "satellite view" version of ISCCP. Each vertical line spans one of the seven ISCCP cloud-top pressure categories and represents the mean among all reanalyses and both versions of ISCCP. For *CALIPSO*, the shading spans the four 95% confidence intervals derived from the four reanalyses, and the black line is the mean of the four reanalyses values.

1) CRE AND CF RELATIONSHIPS TO SST, EIS, AND SSTADV

Observations show that anomalously cool SST, strong EIS, and cool SSTadv are each associated with enhanced SW CRE (Fig. 2a), a small decrease or no change in LW CRE (Fig. 2b), and more negative net CRE (i.e., more outgoing net radiation at the top of the atmosphere, Fig. 2c). This is physically consistent with the observed increase in low-level CF and small decrease or almost no change in high-level CF for the same meteorological conditions (Figs. 3a–c) and is consistent with previous observational studies (e.g., Hanson 1991; Klein and Hartmann 1993; Klein et al. 1995). The above interpretation is corroborated by composite plots of the ISCCP CF relationships binned according to cloud-top pressure and optical thickness, multiplied by identically binned cloud radiative kernels (Figs. A1–A3; see the appendix for discussion of kernels). It is important to recognize that SST and EIS are anticorrelated ($r \sim -0.6$ over all grid boxes for the detrended interannual monthly anomalies), so that the observed and modeled CRE and CF relationships to these variables are qualitatively similar but with opposite signs. We also note that the maximum magnitude of each of the observed low-level CF relationships occurs at a higher elevation for ISCCP than for CALIPSO, likely because of the well-known problem of ISCCP mistaking low-level clouds for midlevel clouds when there are strong inversions (Garay et al. 2008) or overlying cirrus (Mace et al. 2006). We consider the elevation where CALIPSO places the maximum magnitude of the relationships to be more representative of reality.

In agreement with observations, the CMIP3 and CMIP5 multimodel means simulate enhanced SW CRE and larger low-level CF for anomalously cool SST and strong EIS, but the magnitude of each relationship is slightly weaker than observed. This is consistent with Bony and Dufresne (2005), who found that CMIP3 models tend to underestimate the enhancement of SW CRE associated with cooler SST in the tropical ocean subsidence regime. In contrast to observations, the multimodel means simulate no change in SW CRE when SSTadv is anomalously cold, physically consistent with producing too little increase in low-level CF for this condition. This indicates that the SW-CRE–SSTadv relationship is on average poorly simulated by the models. There is a substantial increase in intermodel spread of $D(\text{SW})/D(\text{SST})$ and $D(\text{SW})/D(\text{EIS})$ among CMIP5 models compared to CMIP3, physically consistent with the increase in intermodel spread of $D(\text{CF})/D(\text{SST})$ and $D(\text{CF})/D(\text{EIS})$ for low-level clouds evident in Figs. 3a and 3b. In fact, a two-tailed F test for two

sample variances indicates that the CMIP5 intermodel standard deviations of $D(\text{SW})/D(\text{SST})$ and $D(\text{SW})/D(\text{EIS})$ are significantly greater than those of CMIP3 with 95% confidence. Since the multimodel means of these two relationships are well simulated for both generations of models, this suggests on average worse performance by the CMIP5 models.

Both the CMIP3 and CMIP5 multimodel means also simulate weaker LW CRE and decreased high-level CF when EIS is anomalously strong, in agreement with observations. However, the CMIP5 ensemble mean relationships are closer to observations, and the CMIP5 intermodel standard deviation of $D(\text{LW})/D(\text{EIS})$ is significantly less than that of CMIP3 with 90% confidence. This is probably because the intermodel spread of $D(\text{CF})/D(\text{EIS})$ for high-level clouds is smaller among CMIP5 models than among CMIP3 models. The CMIP3 and CMIP5 ensemble means exhibit statistically significant weaker LW CRE for anomalously cool SST and cold SSTadv, while the observed values do not. Composite plots of binned LW-CRE relationships to SST and SSTadv (as in Fig. A2) of models employing the ISCCP simulator suggest that this can be explained by models' simulating too little increase in optically thick, low-level CF for cooler SST and colder SSTadv (results not shown). This allows the overall weaker LW CRE associated with these meteorological conditions to be dominated by reduced absorption of LW radiation due to a decrease in optically thin, high-level CF. In observations, this reduced absorption is equally offset by greater absorption of LW radiation due to a relatively large increase in low-level CF (Fig. A2).

An important feature of Fig. 2 is that, for both CMIP3 and CMIP5, the intermodel spread of each of the SW-CRE relationships to SST, EIS, and SSTadv is much larger than that of the LW-CRE relationships. This is physically consistent with the greater intermodel spread of $D(\text{CF})/D(\text{SST})$ and $D(\text{CF})/D(\text{EIS})$ for low-level clouds than for high-level clouds in the case of CMIP5.

Finally, the multimodel means produce net-CRE relationships to SST, EIS, and SSTadv that are generally similar to the respective SW-CRE relationships. However, for $D(\text{net})/D(\text{SST})$ and $D(\text{net})/D(\text{SSTadv})$, there is some degree of compensating errors by the SW and LW components. This yields changes in net CRE that are artificially closer to the observations relative to the changes in SW CRE for anomalies in SST and SSTadv.

2) CRE AND CF RELATIONSHIPS TO q_{700} AND ω_{700}

In observations, anomalously high q_{700} and weak ω_{700} are each associated with enhanced SW CRE (Fig. 2a) and an approximately equal enhancement of LW CRE (i.e., less LW radiation emitted to space; Fig. 2b),

yielding no change in net CRE (Fig. 2c). The increase in mid- and high-level CF associated with these meteorological conditions is physically consistent with the enhancement of both SW and LW CRE and is sufficient to offset the radiative effects of the decrease in low-level CF also seen in the profiles (Figs. 3d,e; see also Figs. A1–A3). The decrease in low-level CF for weaker ω_{700} evident in the *CALIPSO* profile may seem to contradict the finding of Myers and Norris (2013) that weaker ω_{700} , independent of variations in EIS, increases low-level CF. But the present study does not attempt to remove possible confounding factors affecting the low-level CF– ω_{700} relationship. The results of the two studies may therefore not be comparable. It is important to recognize that ω_{700} and q_{700} are anticorrelated ($r \sim -0.3$), so that the observed and modeled CRE and CF relationships to these variables are qualitatively similar but with opposite signs. Examination of the vertical profile of q_{700} (not shown) indicates that when q_{700} increases, so does q throughout the troposphere. Higher q_{700} and weaker ω_{700} may favor more mid- and high-level clouds by increasing relative humidity. Anomalous high q_{700} is also associated with a decrease in CF in the ~ 850 – 700 -hPa layer, and an increase in CF just below and above that layer (Fig. 3d). This peculiar vertical structure may explain why previous observational studies have found differing effects of free-tropospheric moisture on low-level clouds over the subtropical oceans (Klein et al. 1995; Lacagnina and Selten 2013).

In agreement with observations, the CMIP3 and CMIP5 multimodel means simulate enhanced SW CRE and enhanced LW CRE for relatively high q_{700} and weak ω_{700} . This is physically consistent with the simulated vertical profiles of $D(\text{CF})/D(q_{700})$ and $D(\text{CF})/D(\omega_{700})$, which qualitatively resemble the observed profiles. The offsetting changes in low-level CF when q_{700} is anomalously high, however, are considerably smaller than observed. As in observations, the ensemble mean $D(\text{net})/D(q_{700})$ is nearly indistinguishable from zero for both CMIP3 and CMIP5. Unlike in observations, though, each ensemble mean simulates more negative net CRE for anomalously weak ω_{700} , and the relationship is statistically significant. This is because models on average overestimate the magnitude of the SW-CRE relationship more strongly than they overestimate the magnitude of the LW-CRE relationship. One reason for this may be that the ensemble means do not simulate a decrease in low-level CF at ~ 900 hPa for relatively weak ω_{700} , a feature evident in the *CALIPSO* profile that partially offsets the enhancement of SW CRE associated with higher-level CF. Like the relationships discussed in the previous section, the intermodel spread of each of the SW-CRE

relationships to q_{700} and ω_{700} is much larger than that of the LW-CRE relationships.

c. Individual model CRE relationships

In addition to the multimodel means, we also examine CRE relationships to the meteorological variables in individual models. Figure 4 shows the CRE relationships to SST, EIS, and SSTadv for observations, individual CMIP3 and CMIP5 models, and multimodel means for completeness. Figure 5 shows the CRE relationships to q_{700} and ω_{700} . A sizeable number of models (more than half in several cases) simulate SW and net-CRE relationships outside the range of observational uncertainty. For several relationships, this is true for a majority of models even when the multimodel mean is not outside the range of observational uncertainty. In addition, some models do not even predict the correct signs of the SW and net-CRE relationships. A relatively small number of models simulate the LW-CRE relationships outside the range of observational uncertainty. Generally, when the intermodel spread of a relationship is large relative to the observational uncertainty (Fig. 2), a high percentage of models simulate the relationship outside this range of uncertainty of observations, and vice versa.

Examining Fig. 4 in more detail, CMIP3 models generally simulate the correct sign and magnitude of the SW and net-CRE relationships to SST and EIS, whereas CMIP5 models do not. Strikingly, half of CMIP5 models simulate the wrong sign of the SW-CRE relationship to EIS, whereas only two CMIP3 models do so. Moreover, in contrast to observations, most CMIP3 and CMIP5 models simulate a negligible relationship or weaker SW CRE for anomalously cold SSTadv, consistent with the bias of the multimodel means (Fig. 2a). Third, most CMIP3 and CMIP5 models exhibit weaker LW CRE for anomalously cool SST or cold SSTadv, whereas observations show no change in LW CRE for either of these meteorological conditions. This is consistent with the bias of the multimodel means (Fig. 2b). Last, Fig. 5 reveals that most models simulate a statistically significant change in net CRE for variations in both q_{700} and ω_{700} despite observations showing no change in net CRE for the same variations. In the case of $D(\text{net})/D(\omega_{700})$, this is consistent with the bias of the multimodel means (Fig. 2c).

d. Connection between CF and SW-CRE relationships in CMIP5 models

We next assess the physical connection between the sign of individual SW-CRE relationships and the vertical profile of the CF relationships in CMIP5 models. CMIP3 models are not examined because they do not

FIG. 5. As in Fig. 4, but for (from top to bottom) specific humidity and pressure vertical velocity at 700 hPa.

provide vertical profiles of CF derived from the ISCCP and CALIPSO simulators.

In Figs. 6a–c we show the CMIP5 simulated vertical profiles of $D(CF)/D(SST)$, $D(CF)/D(EIS)$, and $D(CF)/D(SSTadv)$ of models that simulate the correct sign of the respective SW-CRE relationships. Observed profiles are also shown. The CF relationships to q_{700} and ω_{700} are not shown since, as previously noted, the SW-CRE relationships to these variables represent varying effects of changes in low-, mid-, and high-level CF (Figs. 2 and 3) and are thus more complicated to interpret. All of these CMIP5 models simulate an increase in low-level CF for anomalously cool SST, strong EIS, and cold SSTadv. Thus they simulate enhanced SW CRE for the appropriate physical reason.

Shown in Figs. 6d–f are the CMIP5 simulated vertical profiles of $D(CF)/D(SST)$, $D(CF)/D(EIS)$, and $D(CF)/D(SSTadv)$ of models that simulate the wrong sign of the respective SW-CRE relationships. Some of these models simulate no change or an unrealistic decrease in low-level CF when SST is cooler, EIS is stronger, and SSTadv is colder. This explains why these models simulate no change or unrealistically weaker SW CRE for these meteorological conditions. Some models, however, appear to simulate the correct sign of the low-level CF relationships despite simulating the wrong sign of the SW-CRE relationships. One such model is FGOALS-g2. When SST is cooler, EIS is stronger, and SSTadv is colder, this model simulates an unrealistically large decrease in CF above ~ 800 hPa in

Observations and CMIP5 CF relationships of models
simulating the correct sign of the SW CRE relationships

Observations and CMIP5 CF relationships of models
simulating the wrong sign of the SW CRE relationships

FIG. 6. Cloud fraction relationship to sea surface temperature, estimated inversion strength, and horizontal surface temperature advection as a function of pressure in CMIP5 models, ISCCP, and *CALIPSO*. For each relationship, only those models that simulate the (a)–(c) correct or (d)–(f) incorrect sign of the shortwave cloud radiative effect relationship to the same meteorological variable are shown.

elevation that offsets the enhancement of SW CRE associated with an increase in CF at a lower elevation. Another model that exhibits similar behavior is GFDL CM3. This model produces the correct sign of

the low-level CF relationship to SSTadv despite simulating the wrong sign of the SW-CRE relationship to SSTadv. When SSTadv is anomalously cold, GFDL CM3 simulates an unrealistically large decrease in CF

in the middle-to-upper troposphere that offsets the enhancement of SW CRE associated with an increase in CF near the surface. These examples show that for models to realistically simulate the relationship between SW CRE and the meteorology in regions of climatological subsidence, they must not only accurately simulate the low-level CF relationships; they must accurately simulate the mid- and high-level CF relationships as well.

In yet another case, CCSM4 simulates the correct sign of the low-level CF relationships to EIS and SSTadv despite simulating the wrong sign of the corresponding SW-CRE relationships. While most models simulate a maximum in mean annual cloud water content (CWC) between 700 and 900 hPa, CCSM4 simulates a local minimum in CWC at ~ 900 hPa and a local maximum in CWC at ~ 500 hPa (Fig. A4). Therefore, the simulated decrease in CF above ~ 700 hPa associated with anomalously strong EIS and cold SSTadv, though small, leads to substantially weaker SW CRE because the clouds are optically thick. In turn this more than offsets the enhancement of SW CRE associated with an increase in CF below ~ 700 hPa where the clouds are optically thin. This shows that for models to realistically simulate the relationships between SW CRE and the meteorology, they must not only accurately simulate the low-level CF relationships; they must reasonably simulate the mean state of cloud optical thickness as well.

Before continuing, we note that changes in cloud optical depth are also found to influence the response of SW CRE to variations in the meteorology (see the supplemental material) in models and observations. However, changes in total cloud amount are sufficient to explain the sign of each of the SW-CRE–meteorology relationships and explain more of the intermodel spread of the SW-CRE–meteorology relationships compared to changes in optical depth. This justifies our focus on CF in the present study.

For those models for which ISCCP simulator-derived CF was available, vertical profiles of the CF relationships are additionally examined as a more direct comparison with the observations. Among these models, Fig. 7 shows the simulated vertical profiles of $D(\text{CF})/D(\text{SST})$, $D(\text{CF})/D(\text{EIS})$, and $D(\text{CF})/D(\text{SSTadv})$ of models that simulate the correct and incorrect signs of the respective SW-CRE relationships. Observed ISCCP profiles are also shown for reference. In all of these models, the low-level CF relationships are sufficient to explain the signs of the respective SW-CRE relationships. This is corroborated by the observed and modeled vertical profiles of the same ISCCP CF

relationships multiplied by the SW cloud radiative kernel profile (Fig. A5). We also note that for these six models, the intermodel spread of each of the low-level CF relationships is larger than that of the corresponding high-level CF relationships, explaining why the intermodel spread of the SW-CRE relationships is larger than that of the LW-CRE relationships. Although not shown, Fig. 7 was replicated using CALIPSO simulator-derived CF, and the results are qualitatively similar.

e. Model performance and anthropogenic climate change

Is there a relationship between models' simulation of subtropical MBL cloud–meteorology relationships and their projections of anthropogenic climate change? To address this question, we compare SW-CRE changes and equilibrium climate sensitivity (ECS) estimates to models' root-mean-square error (RMSE) of all five $D(\text{SW})/D(x)$ values relative to the observed values. Mathematically, the RMSE is expressed as

$$\text{RMSE} = \sqrt{\frac{1}{5} \sum_{i=1}^5 \left(\frac{D(\text{SW})^{\text{model}}}{D(x_i)} - \frac{D(\text{SW})^{\text{obs}}}{D(x_i)} \right)^2},$$

where $D(\text{SW})/D(x_i)^{\text{model}}$ is one of the five simulated relationships for a given model, and $D(\text{SW})/D(x_i)^{\text{obs}}$ is the mean value of the observed relationship over all reanalyses. Twenty-first-century changes in SW CRE (2080–99 minus 2000–19 mean annual SW CRE averaged over the five main low-level cloud regions over the eastern subtropical oceans) are taken from Qu et al. (2014). The simulations examined include the A1B (Nakicenovic et al. 2000) forcing scenario for the CMIP3 models and the representative concentration pathway (RCP) 8.5 (Taylor et al. 2012) for the CMIP5 models. ECS is defined as the equilibrium global mean surface temperature change due to a doubling of CO_2 , and CMIP3 and CMIP5 values are taken from Randall et al. (2007) and Flato et al. (2013), respectively. We note that SW-CRE changes are positively correlated with ECS ($r = 0.92$ for CMIP3 and $r = 0.6$ for CMIP5; Fig. 8a).

Figures 8b and 8c show the RMSE of the SW-CRE relationships plotted against twenty-first-century SW-CRE trends and ECS values for all available models. The plots show that models that simulate large RMSE (unrealistic models) tend to exhibit more negative SW-CRE changes and low ECS compared to models with smaller RMSE (more realistic models). In fact, of the CMIP5 models shown in Fig. 8b, the two with the largest RMSE are

FIG. 7. Cloud fraction relationship for sea surface temperature, estimated inversion strength, and horizontal surface temperature advection as a function of pressure in CMIP5 models employing the ISCCP simulator and ISCCP observations. For each relationship, only those models that simulate the (top) correct and (bottom) wrong sign of shortwave cloud radiative effect relationship to the same meteorological variable are shown. For both models and observations, only the “random overlap” version of ISCCP is shown. The error bars span the four 95% confidence intervals computed from the four reanalyses.

FIG. 8. (a) Twenty-first-century change in SW CRE plotted against equilibrium climate sensitivity in models, (b) root-mean-square error (RMSE) of the simulated SW-CRE-meteorology relationships relative to observations plotted against simulated twenty-first-century SW-CRE change, and (c) RMSE of the simulated SW-CRE-meteorology relationships relative to observations plotted against equilibrium climate sensitivity. CMIP3 (CMIP5) models are denoted as orange (green) letters, which are defined in Table 3. The asterisks denote either the multi-model mean SW-CRE change or equilibrium climate sensitivity and the RMSE of the multimodel mean relationships. Vertical dashed lines show the median RMSE separately for CMIP3 and CMIP5 models. The median RMSEs of (b) and (c) are not identical because data for all models were not available.

the only models simulating enhanced SW CRE. To quantify these inferences, we divide models into two subsets according to whether their RMSE values are less than or greater than the median RMSE (vertically dashed lines in Figs. 8b and 8c). We show the mean SW-CRE change and ECS of each subset in Table 4. For both CMIP3 and CMIP5, models with RMSE less than the median RMSE have a higher mean ECS and more positive mean SW-CRE change compared to models with RMSE

greater than the median, although the difference between the means is statistically significant ($p < 0.1$) in only two cases. Figures 8b and 8c also show that the intermodel spread of twenty-first-century SW-CRE changes and ECS is generally higher among the more realistic models compared to the less realistic models. Collectively, these results suggest that a positive SW cloud feedback associated with subtropical MBL clouds and a high ECS is more likely than a negative cloud feedback

TABLE 4. Mean SW CRE change and ECS of CMIP3 and CMIP5 models with RMSE less than the median RMSE (small RMSE models) and greater than the median RMSE (large RMSE models). Statistical significance of the difference between the SW-CRE change or ECS between small and large RMSE models is assessed using a two-tailed t test for the difference between two means, the p values of which are shown in the right column. All models' values are assumed to be independent.

		Small RMSE models	Large RMSE models	p value
CMIP3	SW CRE change	1.2 W m^{-2}	0.68 W m^{-2}	0.78
	ECS	3.7 K	2.9 K	0.05
CMIP5	SW CRE change	5.3 W m^{-2}	0.97 W m^{-2}	0.07
	ECS	3.6 K	2.9 K	0.14

and a low ECS. It is clear, however, that accurate simulation of SW-CRE–meteorology relationships is not sufficient to constrain either the SW-CRE feedback or ECS in a statistically robust manner. One reason for this may be that the climate change scenarios examined here include changes in aerosols, which can cause changes in cloudiness independent of the meteorology.

4. Conclusions

We have evaluated the performance of CMIP3 and CMIP5 models in simulating the interannual relationships of shortwave, longwave, and net cloud radiative effect to sea surface temperature, estimated inversion strength, horizontal surface temperature advection, free-tropospheric moisture, and subsidence. To ensure dynamically consistent domains among models and observations, we examined grid boxes occurring within the tropical (30°S – 30°N) oceanic subsidence regime for each particular model and reanalysis. Examining the relationships of the vertical profile of cloud fraction to the same meteorological variables allowed us to physically assess the connection between changes in cloud radiative effect and changes in cloud fraction.

We find that, in observations, anomalously cool SST, strong EIS, and cold SSTadv are each associated with larger low-level CF and enhanced SW CRE (i.e., more shortwave radiation reflected to space). Higher q_{700} and weaker ω_{700} are each associated with larger mid- and high-level CF and enhanced SW CRE, enhanced LW CRE (i.e., less LW emitted radiation to space), and no change in net CRE. Changes in LW CRE associated with variability of q_{700} and ω_{700} can thus be as large as changes in SW CRE over the eastern subtropical oceans, even though climatologically the magnitude of SW CRE is much stronger than that of LW CRE. Both the CMIP3 and CMIP5 multimodel means generally simulate the above relationships realistically. Moreover, the intermodel spread of the SW-CRE relationships is larger than that of the LW-CRE relationships. Since previous findings that trends in SW CRE, not LW CRE,

are responsible for the wide spread of cloud feedbacks simulated in CMIP3 and CMIP5 models (Webb et al. 2006; Andrews et al. 2012), this suggests that interannual estimates of CRE–meteorology relationships may project onto the longer time scale of anthropogenic climate change.

A larger percentage of CMIP5 than CMIP3 models are found to simulate the wrong sign or magnitude of the relationship of SW CRE to SST and EIS. In fact, half of CMIP5 models simulate the wrong sign of the SW-CRE relationship to EIS. To the extent that EIS strengthens over the eastern subtropical oceans in simulations of anthropogenic climate change (e.g., Webb et al. 2013), this suggests that for this change a substantial percentage of CMIP5 models simulate the wrong sign of the SW cloud feedback to warming. Furthermore, most CMIP3 and CMIP5 models exhibit the wrong sign of the SW-CRE relationship to SSTadv. Insofar as cold SSTadv will amplify over the eastern subtropical oceans due to anthropogenic climate change (e.g., Caldwell et al. 2013), this suggests that for this change most models fail to simulate the implied negative SW cloud feedback to warming.

We find that for CMIP5 models to realistically produce SW-CRE relationships to SST, EIS, and SSTadv, it is necessary but not sufficient for models to realistically simulate corresponding low-level CF relationships. To produce these observed SW-CRE–meteorology relationships, models must also reasonably simulate the mid and high-level CF relationships and the mean cloud water content. While changes in low-level CF explain much of the CMIP5 intermodel spread in the simulated SW-CRE relationships, some of the spread is explained by changes in mid and high-level CF and differences in the mean cloud water content. Studies that examine the intermodel spread of changes in SW CRE in regions of climatological subsidence (e.g., Bony and Dufresne 2005) should therefore use caution in attributing those changes exclusively to low-level clouds.

Comparing overall model performance of the SW-CRE–meteorology relationships to twenty-first-century

FIG. A1. Observed ISCCP cloud fraction relationships to meteorological variables multiplied by the shortwave cloud radiative kernel, binned by CTP and τ . The area of the box within each bin is proportional to the $D(\text{CF})/D(x)$ value therein, and a solid gray line around a box indicates that a value is significant at the 95% confidence level. The sum of values over all CTP layers and τ categories is shown at the top of each subplot.

trends in SW CRE and equilibrium climate sensitivity suggests that the more realistic models simulate more positive SW-CRE changes and higher climate sensitivities compared to the less realistic models. This is consistent with recent studies that have found that climate models most closely resembling observations simulate strong positive cloud feedbacks and enhanced global warming (Fasullo and Trenberth 2012; Klein et al. 2013; Sherwood et al. 2014; Su et al. 2014). Despite this, there is not a one-to-one relationship between the root-mean-square error of the modeled $D(\text{SW})/D(x)$ values and either SW-CRE trends or climate sensitivity. A thorough assessment of projections of the meteorological and cloud changes in a future study is necessary in order to understand why this is the case.

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APPENDIX

Quantifying the Relationship between Changes in CF and CRE

We also performed a more rigorous assessment of how observed and modeled changes in CF associated

FIG. A2. As in Fig. A1, but for the longwave cloud radiative kernel.

with meteorological variability are related to changes in CRE. To do this, we took advantage of the ISCCP CF data, binned according to cloud-top pressure (CTP) and cloud optical thickness (τ), as well as observational

(Zhou et al. 2013) and model-derived (Zelinka et al. 2012) cloud radiative kernel datasets binned in an identical manner. A cloud radiative kernel is the change in top-of-atmosphere SW, LW, or net radiation per unit

FIG. A3. As in Fig. A1, but for the net cloud radiative kernel.

FIG. A4. The 1980–2005 mean annual cloud water content as a function of pressure in CMIP5 models.

change in CF. For a given month, it depends primarily on τ , CTP, clear-sky albedo, and latitude. The radiative kernels we use are annually averaged between 30°S and 30°N for a clear-sky albedo of 0.07, which is the albedo of the ocean surface used in the ERA-Interim. The observational kernels are very similar to those derived from models.

We computed $D(\text{CF})/D(x)$ as described in the data and methods section for the binned ISCCP data and multiplied the values by the cloud radiative kernels. For each bin, this essentially yields the change in top-of-atmosphere CRE associated with a change in a typical anomaly of the meteorological property x . Mathematically, this can be written as $[D(\text{CF})/D(x)] \times [D(\text{CRE})/D(\text{CF})]$. For the observations, the binned relationships of SW, LW, and net CRE to the meteorological variables are shown in Figs. A1–A3. The overall (i.e., integrated over all CTP layers and τ categories) enhancement of SW CRE associated with anomalously cool SST, strong EIS, and cold SSTadv is dominated by an increase in CF of clouds in the lower troposphere with medium τ . Because the binned LW-CRE changes associated with such meteorological conditions are small, the binned net-CRE changes resemble those of SW CRE. The binned relationships between CRE and both q_{700} and ω_{700} are more complicated. The overall enhancement and offsetting components of SW and LW CRE associated with anomalously high q_{700} and weak ω_{700} each have large contributions from an increase in CF of clouds in the middle and upper troposphere with

varying values of τ . The sum of each of the binned relationships between CRE and the meteorology over all CTP layers and τ categories is quantitatively similar to the CRE relationships computed from CERES (Figs. 2, 4, and 5). This establishes confidence in both sets of results.

Not all CMIP5 models provide the ISCCP simulator output that allows us to compute binned SW-CRE relationships. Therefore, to infer qualitatively how changes in CF in each model impact SW CRE in models not employing the ISCCP simulator, we show in Fig. A4 the 1980–2005 mean annual vertical profile of cloud water content (CWC) of the CMIP5 models (data for CMIP3 models were unavailable). CWC at each model level is defined as $(\rho_a m_t)/\text{CF}$, where ρ_a is the density of dry air, and m_t is the total (liquid plus ice) water mixing ratio in a grid box. Dividing by CF allowed us to examine the total water content within a cloud. The relevant features of Fig. A4 are described in the results section.

For the six models providing ISCCP simulator output, we computed binned SW-CRE relationships to SST, EIS, and SSTadv in the manner described above. For these models and observations, we summed the relationships over all τ categories for each CTP layer to yield profiles of changes in SW CRE for the same meteorological variations, shown in Fig. A5. The results confirm that for these models and observations, changes in low-level CF drive the overall changes in SW CRE associated with variability of SST, EIS, and SSTadv.

FIG. A5. Observed and modeled ISCCP cloud fraction relationships to (left)–(right) SST, EIS, and SSTadv multiplied by the shortwave cloud radiative kernel, summed over all optical thickness categories. The error bars span the four 95% confidence intervals computed from the four reanalyses.

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