Testing a Physical Hypothesis for the Relationship Between Climate Sensitivity and Double-ITCZ Bias in Climate Models

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Abstract Tian (2015, https://doi.org/10.1002/2015GL064119) found that Coupled Model Intercomparison Project Phases 3 and 5 (CMIP3 and CMIP5) climate models with too much precipitation in a region of the Southeast Pacific (due to a double-Intertropical Convergence Zone [ITCZ] bias) tend to have lower climate sensitivities and suggested that this might form the basis of an “emergent constraint,” which could rule out lower values of climate sensitivity. However, no physical mechanism has been proposed to explain this relationship. Here we advance the hypothesis that deep convection encroaching into regions that should be dominated by shallow clouds disrupts the formation of shallow clouds in the present climate and reduces the magnitude of positive low-level cloud feedbacks, resulting in smaller values of climate sensitivity. We test this hypothesis first by performing sensitivity tests with the HadGEM2-A aquaplanet model subject to a uniform +4 K sea surface temperature (SST) perturbation, in which we vary the degree to which deep convection associated with the single/double ITCZ extends toward subtropical low-cloud regions. Experiments with more precipitation encroaching into the subtropics have weaker subtropical cloud radiative effects in the present-day simulations and less positive subtropical cloud feedbacks, consistent with our hypothesis. We test this hypothesis further by looking for the predicted relationships across multimodel ensembles of SST forced Atmospheric Model Intercomparison Project (AMIP) experiments subject to a uniform +4 K SST increase. Relationships of the expected sign are found in the CMIP5 AMIP+4K experiments, but not all are statistically significant at the 5% level. We find no statistically significant support for our hypothesis in the currently available CMIP6 AMIP+4K experiments.

Plain Language Summary A previous study found that climate models with too much heavy rainfall extending from the tropics into the Southeast Pacific tend to have smaller amounts of global warming in response to increases in carbon dioxide. It has been suggested that this might mean that climate models that are more sensitive are more realistic. However, it is unclear what physical processes in the climate system might cause such a relationship. Here we propose a potential explanation for this relationship that heavy rainfall extending into regions that should be dominated by low-level clouds is associated with conditions that make it harder to form low-level clouds, which are known to amplify climate warming. We test this idea using two approaches. Modifying a single climate model to vary the degree to which deep convection associated with the single/double ITCZ extends into regions that should be dominated by shallow clouds hampers the formation of shallow clouds in the present climate and reduces the magnitude of positive low-level cloud feedbacks, resulting in smaller climate sensitivities. We test this hypothesis first by performing sensitivity tests with the HadGEM2-A aquaplanet model subject to a uniform +4 K sea surface temperature (SST) perturbation, in which we vary the degree to which deep convection associated with the single/double ITCZ extends toward subtropical low-cloud regions. Experiments with more precipitation encroaching into the subtropics have weaker subtropical cloud radiative effects in the present-day simulations and less positive subtropical cloud feedbacks, consistent with our hypothesis. We test this hypothesis further by looking for the predicted relationships across multimodel ensembles of SST forced Atmospheric Model Intercomparison Project (AMIP) experiments subject to a uniform +4 K SST increase. Relationships of the expected sign are found in the CMIP5 AMIP+4K experiments, but not all are statistically significant at the 5% level. We find no statistically significant support for our hypothesis in the currently available CMIP6 AMIP+4K experiments.

1. Introduction

Equilibrium climate sensitivity (ECS) is a basic measure of the sensitivity of the climate system to increases in carbon dioxide concentrations, defined as the equilibrium change in the annual global mean near-surface temperature following a doubling of atmospheric CO₂ concentration (Collins et al., 2013). Modern climate models with dynamical oceans are rarely run to equilibrium, and so climate sensitivity is often estimated using effective climate sensitivity, hereafter S (e.g., Andrews et al., 2012). Models from the last phase of the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012) took a range of values for S from 2.1–4.7 K (Collins et al., 2013). The AR5 assessment report concluded that ECS was likely (>66% probability) in the range 1.5–4.5 K, very unlikely (<10% probability) >6 K, and extremely unlikely (<5% probability) <1 K. Cloud feedbacks remain the largest source of uncertainty for ECS, and uncertainty in the sign and magnitude
of the cloud feedback is due primarily to continuing uncertainty in the impact of warming on low clouds. Although a highly idealized quantity, $S$ is a strong predictor of the diverse model responses in global and regional temperature in transient and equilibrium climate change scenarios (Grose et al., 2018).

Since AR5, an increasing number of studies have attempted to constrain $S$ using so-called “emergent constraints.” An emergent constraint can be defined as a relationship between something we can observe and something we want to predict which emerges from a model ensemble. Since correlations between unrelated variables may arise by chance, it is considered desirable for emergent constraints to be associated with credible physical mechanisms (Klein & Hall, 2015). Caldwell et al. (2018) assessed a number of emergent constraints against this criterion amongst others. One such emergent constraint study Tian (2015) found a robust statistical relationship between $S$ and an index measuring the extent of double-Intertropical Convergence Zone (ITCZ) biases in CMIP3 and CMIP5 models. This indicated that models that have too much precipitation in a region of the Southeast Pacific (which is indicative of a double-ITCZ error) tend to have lower climate sensitivities, while models with smaller biases tend to have higher sensitivities. A weaker relationship was also found between subtropical free-tropospheric specific humidity and $S$. Taken at face value, these relationships suggest that $S$ is greater than 3 K, which rules out models in the lower half of the AR5 1.5–4.5 likely range. However no physical hypothesis has yet been put forward to explain why such a relationship should exist between such measures of the double-ITCZ and $S$. The aim of this study is to develop and test a physical hypothesis that has the potential to explain this relationship seen in the CMIP3 and CMIP5 models.

Given the substantial contribution of low-level cloud feedbacks to the intermodel spread in cloud feedback and climate sensitivity, an obvious possibility is that low-cloud feedbacks are in some way dependent on the strength of the double-ITCZ bias in models. The extent to which deep convection encroaches into the subtropics will affect the free-tropospheric humidity, with a more double-ITCZ having a moister subtropical free troposphere as shown by Tian (2015). This could in principle affect subtropical low-cloud feedbacks. For example, Christensen et al. (2013) argued that increases in water vapor expected with global warming would cause a reduction in low-cloud-top cooling rates that could cause stratuscumulus to thin and breakup, as suggested by their results and the Large Eddy Simulation (LES) results of Bretherton et al. (2013). However, while Tian (2015) showed that an index of midtropospheric humidity was strongly correlated with their Southeast Pacific precipitation index, the midtropospheric humidity index was less strongly correlated with $S$ than the precipitation index. This suggests that the relationship between Southeast Pacific precipitation and $S$ is not mediated by free tropospheric humidity.

A stronger double-ITCZ may also increase the amount of free-tropospheric cloud overlying subtropical low clouds. A number of studies have suggested that upper-level clouds can affect low-level clouds directly below them. Christensen et al. (2013) showed using satellite observations and LES models that the effects of free tropospheric clouds on downwelling longwave radiation can affect the vertical development and thickness of stratuscumulus clouds by reducing their cloud-top cooling, although competing effects were present due to the shortwave effects of overlying clouds during the daytime. Bony et al. (2016) made a thermodynamic argument to explain reductions in upper-level cloud amount with warming in climate models and suggested that associated reductions in the downward longwave radiation at the top of low-level clouds could increase low-cloud cover. Additionally, they suggested that a reduction in anvil clouds could expose more of the climate system to the effects of positive feedbacks from low clouds. Coppin and Bony (2015) also argued that increased convective aggregation will expand the area covered by large-scale subsidence; this could have a similar effect. Also Coppin and Bony (2017) showed that increasing subsidence with convective aggregation increased low-level cloudiness in a climate model.

We advance the following hypothesis to explain the link between double-ITCZ and climate sensitivity, which has three components. First, models with double-ITCZs will have more deep convection encroaching into subtropical low-cloud regions. Second, because of this, it will be harder for models to form low-level clouds in subtropical subsidence cloud regions. Third, models with fewer low-level clouds will have weaker/less positive low-cloud feedbacks and higher climate sensitivities. Tian (2015) already provides evidence to support the first component of this argument. The second component is motivated by the observation that low clouds are prevalent in subtropical regions associated primarily with strong subsidence, a dry free troposphere and strong low-level temperature inversions, conditions that are incompatible with the primarily unstable conditions associated with deep convection and heavy precipitation seen in the ITCZ and South
Figure 1. Zonal mean longwave cloud heating rate (a) and precipitation (b) from the aquacontrol simulation of HadGEM2-A APEQ and sensitivity tests where the longwave cloud heating rate is approximately doubled and tripled. Global mean values are shown in the legend.

Pacific Convergence Zone (SPCZ). The third component is supported by existing studies with models such as Williams and Webb (2009), Brient and Bony (2012), and Webb et al. (2015).

We test this hypothesis in two ways. First, we perform sensitivity tests in the aquaplanet configuration of the HadGEM2-A climate model, where we vary the degree to which deep convection encroaches toward subtropical low-cloud regions to see if this has the effect predicted by our hypothesis on subtropical low clouds and cloud feedbacks in perturbed sea surface temperature (SST) experiments. Second, we perform a regional correlation analysis to see if the predicted relationships are present in two multimodel ensembles of SST forced climate change experiments.

This paper is organized as follows. Section 2 describes the HadGEM2-A aquaplanet experiments and the method we employ to perturb the degree of the double-ITCZ and gauge the impact on the cloud feedbacks. Section 2 also describes the multimodel ensembles that we analyze. Section 3 presents and discusses the results from these experiments and our investigation of statistical relationships across CMIP5 and CMIP6 era atmosphere-only experiments subject to a uniform SST increase. Section 4 presents a summary and concluding remarks.

2. Model Experiments and Methods

We test our hypothesis first by perturbing the ITCZ in the Cloud Feedback Model Intercomparison Project (CFMIP)-2/CMIP5 aquaplanet configuration of HadGEM2-A (Martin et al., 2011). The CFMIP +4 K aquaplanet configuration has been shown to reproduce global cloud feedbacks in fully coupled model configurations to a remarkable degree (Medeiros et al., 2015; Ringer et al., 2014). Aquaplanet simulations such as these produce a zonally symmetric idealized representation of the ITCZ and subtropical shallow cloud regions, where the degree to which the ITCZ splits and deep convection encroaches into the sub tropics...
Table 1
Models Used in This Study

| Model          | Project      | Reference                                      |
|----------------|--------------|------------------------------------------------|
| BCC-CSM1.1     | CFMIP-2/CMIP5| Wu et al. (2014)                               |
| CanAM4         | CFMIP-2/CMIP5| Von Salzen et al. (2013)                       |
| CESM1-CAM5-FV2 | SPOOKIE      | Neale et al. (2010) and Webb et al. (2015)     |
| CNRM-CM5       | CFMIP-2/CMIP5| Martin et al. (2011)                           |
| GFDL-HIRAM     | SPOOKIE      | Zhao et al. (2009) and Webb et al. (2015)      |
| GFDL-AM2       | SPOOKIE      | GFDL GAMDT (2004) and Webb et al. (2015)       |
| HadGEM2-A      | CFMIP-2/CMIP5| Martin et al. (2011)                           |
| IPSL-CM5A-LR   | CFMIP-2/CMIP5| Dufresne et al. (2013)                         |
| IPSL-CM5B-LR   | CFMIP-2/CMIP5| Dufresne et al. (2013)                         |
| MIROC5         | CFMIP-2/CMIP5| Watanabe et al. (2010)                         |
| MRI-CGCM3      | CFMIP-2/CMIP5| Yukimoto et al. (2012)                         |
| MPI-ESM-LR     | CFMIP-2/CMIP5| Stevens et al. (2013)                          |
| BCC-CSM2-MR    | CFMIP-3/CMIP6| Wu et al. (2019)                               |
| CanESM5        | CFMIP-3/CMIP6| Swart et al. (2019)                            |
| CESM2          | CFMIP-3/CMIP6| Gettelman et al. (2019)                        |
| CNRM-CM6-1     | CFMIP-3/CMIP6| Voldoire et al. (2019)                         |
| GFDL-CM4       | CFMIP-3/CMIP6| Held et al. (2019)                             |
| HadGEM3-GC3.1-LL | CFMIP-3/CMIP6| Kuhlbrodt et al. (2018)                        |
| IPSL-CM6A-LR   | CFMIP-3/CMIP6| Boucher et al. (2020)                          |
| MIROC6         | CFMIP-3/CMIP6| Tatebe et al. (2019)                           |
| MRI-ESM2.0     | CFMIP-3/CMIP6| Yukimoto et al. (2019)                         |
| GISS-E2-1-G    | CFMIP-3/CMIP6| Not available                                  |

may vary depending on the model formulation. While we do not consider the characteristics of the ITCZ in an aquaplanet experiment to be a perfect analog or limiting case for the extension of the SPCZ and the double-ITCZ bias in realistic model configurations, we do consider aquaplanets a useful, idealized configuration for exploring the effects of deep convection encroaching into subtropical subsidence zones. As such we consider these experiments to be a useful vehicle for testing the physical credibility of our hypothesis.

Many theories have been put forward to explain the controls on the degree of ITCZ splitting in aquaplanets (e.g., Dixit et al., 2018; Harrop & Hartmann, 2016). Harrop and Hartmann (2016) showed that aquaplanet configurations of models tend to show more of a double-ITCZ when cloud radiative effects (CREs) are suppressed. This has been shown to be due to the atmospheric longwave cloud heating effect from middle- to high-level clouds in the tropics (Dixit et al., 2018) rather than the atmospheric cooling effects of subtropical low clouds (Fermepin & Bony, 2014). We exploit this fact to manipulate the ITCZ in HadGEM2-A. Figure 1b shows the zonal mean precipitation in the HadGEM2-A CFMIP-2 standard aquaplanet configuration (APEQ), based on the “QOBS” configuration of the Aqua-Planet Experiment Project (Blackburn et al., 2013) (black line). This exhibits a moderately bimodal/double ITCZ, as evidenced by the two local maxima in the zonal mean precipitation on either side of the equator. For our first sensitivity experiment (2XLWCLCLOUD) we approximately double the longwave cloud heating by adding an additional heating to the longwave radiative heating in the model, based on the zonal mean climatological longwave cloud heating rate in the control experiment (Figure 1a). In a second experiment (3XLWCLCLOUD) we double the size of this perturbation. We then run climate change experiments with these two perturbed model configurations, by uniformly increasing SSTs by 4 K, for comparison with the standard CFMIP aquacontrol and aqua4K experiments. All experiments are run for 5 years each. We diagnose cloud feedback using the change in the net CRE per K change in global mean SST, noting that this includes the climatological effects of clouds on noncloud feedbacks (Soden et al., 2004; Yoshimori et al., 2019).
Second, we look for relationships predicted by our hypothesis in SST forced experiments subject to uniform +4 K warming from CFMIP-2/CMIP5 (Bony et al., 2008), SPOOKIE (Selected Process On/Off Klima Intercomparison Project, Webb et al., 2015), and CFMIP-3/CMIP6 (Webb et al., 2017) (see Table 1). One reason to use SST forced experiments is that we can diagnose regional cloud feedbacks without needing to resort to linear regression approaches and their associated uncertainties (e.g., Gregory et al., 2004).

3. Results and Discussion
3.1. ITCZ Perturbation Experiments

Here we test the physical credibility of our hypotheses by performing sensitivity experiments with the aquaplanet configuration of HadGEM2-A (see section 2). Figure 1b shows that scaling up the longwave cloud radiative heating in the aquaplanet configuration of HadGEM2-A results in a narrower/less double-ITCZ as expected, with reductions in precipitation on the subtropical flanks of the ITCZ, a transition from a bimodal to unimodal ITCZ, and an increase in the peak precipitation rate. The area encompassed by mean ascent at 700 hPa in the ITCZ also contracts, while the area of mean subsidence expands toward the equator (Figure 2a). The peak ascent rate increases in the ITCZ, as does the maximum subsidence rate in the subtropics.

A more concentrated ITCZ is also associated with a stronger subtropical inversion as measured by the estimated inversion strength (EIS) index (Wood & Bretherton, 2006) (Figure 2b). Again, the largest changes are on the equatorward flank of the subtropics. Since the SSTs are the same in these experiments, the increase in EIS is caused by increases in temperatures at 700 hPa. We argue that this may in part be a response to enhanced subsidence warming in the subtropics and also to some extent to increased longwave radiative heating at 700 hPa in the subtropics (Figure 2a) and also to radiative heating in the ITCZ, which is propagated into the subtropics by gravity waves. The increase in EIS in the subtropics is associated with an increase in the net radiative cooling effect of subtropical clouds (Figure 2c), consistent with the expectation that cloud fraction and/or liquid water path will increase with EIS (Wood & Bretherton, 2006). These more reflective clouds are in turn associated with more positive subtropical cloud feedbacks, which in turn enhance the global mean cloud feedbacks (Figure 2d).

Looking across these experiments, we see that model versions with more precipitation encroaching into the subtropics have weaker subtropical CREs in the present climate, less positive subtropical cloud feedbacks,
Figure 3. (a) Emergent constraint on cloud feedback in AMIP+4K experiments arising from models’ Southeast Tropical Pacific precipitation versus GPCP over the region (150–100°W, 30°S to 0°N). The central gray line shows the best linear fit to the data, and the upper and lower lines are plotted at ±2 standard deviations of the residuals in the y direction. The vertical lines indicate the observed precipitation rate from GPCP (1.4 mm/day) ±20% (Qu et al., 2018), and the horizontal red line indicates the notional implied lower bound for the net CRE feedback.

3.2. CMIP5/CMIP6 AMIP+4K Analysis

Next, we perform a correlation analysis to see if the relationships predicted by our hypothesis are present in two multimodel ensembles of SST forced climate change experiments. Our argument is based on mechanisms operating in the atmosphere and does not depend on or require changes in SST patterns or ocean heat transport with climate change. Ringer et al. (2014) showed that cloud feedbacks from the CMIP5 coupled models are reproduced remarkably well in CFMIP-2/CMIP5 SST forced experiments subject to a uniform SST increase of 4 K, which suggests that intermodel spread in cloud feedback in the CMIP5 models is not strongly dependent on SST warming patterns or changes in ocean circulation. To confirm that intermodel differences in ocean responses are not important for the Tian (2015) constraint, we examine the relationship between the mean Southeast Pacific precipitation in a number of Atmospheric Model Intercomparison Project (AMIP) experiments and global cloud feedbacks diagnosed from a number of +4 K experiments. We separate the available models into two groups (Table 1). The first comprises a set of CFMIP-2/CMIP5 experiments plus some additional experiments run for the SPOOKIE project (Webb et al., 2015), including some older model versions. The second comprises some newer AMIP+4K experiments from CFMIP-3/CMIP6.
Table 2

Correlations Between Southeast Tropical Pacific Precipitation in the Region (150°–100°W, 30°S to 0°N) and Present-Day CRE, EIS, and 700 hPa Subsidence Rate and CRE Cloud Feedback in the Peruvian Stratus Region (10–20°S, 80–90°W) in the CMIP5/CFMIP-2/SPOOKIE AMIP+4K Experiments

| CMIP5+SPOOKIE                                                                 |
|--------------------------------------------------------------------------------|
| SETP precipitation versus Peruvian Sc region net CRE                          | 0.56 |
| Peruvian Sc region net CRE versus Peruvian net CRE feedback                   | −0.44 |
| Peruvian Sc region net CRE feedback versus global net CRE feedback            | 0.58 |
| SETP precipitation versus Peruvian Sc region SW CRE                          | 0.59 |
| Peruvian Sc region SW CRE versus Peruvian SW CRE feedback                    | −0.48 |
| Peruvian Sc region SW CRE feedback versus global net CRE feedback             | 0.51 |
| SETP precipitation versus Peruvian Sc region EIS                             | −0.42 |
| Peruvian Sc region EIS versus Peruvian Sc region SW CRE                      | −0.12 |
| Peruvian Sc region EIS versus Peruvian Sc region Net CRE                     | −0.09 |
| SETP precipitation versus global net CRE feedback                             | −0.69 |
| SETP precipitation versus Peruvian Sc region net CRE feedback                | −0.30 |

Note. Correlations with magnitude of 0.5 or more (in bold) are significant at the 5% level.

Figure 3a shows a negative correlation between precipitation in the Southeast Pacific region used by Tian (2015) and the global net CRE feedback amongst the CFMIP-2/SPOOKIE models with $r = −0.69$, which is significantly different from 0 at the 5% level based on a one-tailed $t$ test. This supports our hypothesis that models with too much Southeast Pacific precipitation tend to have less positive global cloud feedbacks and hence, as found by Tian (2015), lower climate sensitivities. This relationship suggests a notional lower bound for the net CRE feedback of about 0.2 W m$^{-2}$ K$^{-1}$, favoring models with higher sensitivities. However, while Figure 3b also shows an anticorrelation between these quantities across the CFMIP-3/CMIP6 experiments available thus far, this is weak ($r = −0.22$) and not significantly different from 0 at the 5% level. This indicates that our hypothesis does not explain the behavior of the global cloud feedback in the currently available CMIP6 AMIP+4K experiments, although it is possible that the relationship will emerge more strongly if more CMIP6 AMIP+4K experiments become available. Since the main focus of this study is to understand the relationship in the CMIP3/CMIP5 models established by Tian (2015), we do not investigate the CMIP6 models further here.

Since the Tian (2015) relationship is reproduced in the CFMIP-2/SPOOKIE experiments, we can test our hypothesis further by seeing if the other relationships predicted by our hypothesis are present across these models. First, we test the idea that models with more precipitation in the Southeast Tropical Pacific have weaker (less negative) CREs in subtropical low-cloud regions. To do this, we select a priori a region in the Southeast Tropical Pacific where we expect low cloud to be prevalent. Klein and Hartmann (1993) identified a number of regions where marine stratus clouds are prevalent in observations. One of these is their “Peruvian Subtropical Marine Stratus” region 10–20°S, 80–90°W. Our hypothesis predicts a positive correlation between the amount of precipitation in the Southeast Tropical Pacific region used in Tian (2015) and the net and SW CRE in subtropical low-cloud regions such as the Peruvian stratus region. Table 2 shows that positive correlations of more than 0.5 are present, which are significant at the 5% level based on a one-tailed $t$ test, providing strong statistical support for this element of our hypothesis. In addition, Figure 4 shows that Southeast Tropical Pacific precipitation is significantly positively correlated with SW CRE in a number of other locations where low-level stratus clouds are prevalent, not only in the subtropics but also at middle to high latitudes. The additional correlations at middle to high latitudes are not predicted by our hypothesis, but we show them for completeness.

Next we test the hypothesis that models with more negative SW and/or net CRE in subtropical low-cloud regions tend to have more positive net and/or SW CRE feedbacks in those regions, which would predict an anticorrelation. Again Table 2 shows that the predicted anticorrelations are present, but in this case they are not strong enough to be statistically distinguishable from 0 at the 5% level. Hence, we cannot exclude the possibility that there is no underlying relationship between present-day cloud and cloud feedback averaged over the Peruvian marine stratus region and that this anticorrelation arises by chance. It is, however, possible...
that the relationship is not significant because the Peruvian stratus region is not representative of regimes that do contribute to an underlying relationship between present-day low clouds and low-cloud feedbacks overall. Figure 5 shows that statistically significant anticorrelations are seen between present-day SW CRE and SW CRE feedbacks in other regions associated with low clouds and even within part of the Peruvian stratus region. These are more prevalent than statistically significant positive correlations that make us think that they are unlikely to arise purely through chance. Note also that Webb et al. (2015) found a statistically significant anticorrelation between present-day SW CRE and net CRE feedback in tropical marine composite regimes with strong lower tropospheric stability in a very similar set of experiments to those analyzed here.

Another element of our hypothesis is that subtropical low-cloud feedbacks contribute substantially to inter-model spread in global cloud feedback. Hence our hypothesis predicts significant positive correlations between SW CRE feedbacks in subtropical low-cloud regions and the global mean net CRE feedback. This is supported at a statistically significant level in the Peruvian region (Table 2) and more broadly by Figure 6.

Figure 4. Correlation between Southeast Tropical Pacific Precipitation and SW CRE in CMIP5/SPOOKIE models. Positive correlations with $r > 0.5$ are significant at the 5% level. The larger box shows the region used for the Tian (2015) index, while the others show the Pacific and Atlantic subtropical marine stratus regions of Klein and Hartmann (1993).

Figure 5. As figure above but correlation between local SW CRE and local SW CRE feedback in CMIP5/SPOOKIE models.
Figure 6. As figure above but correlation between local SW CRE feedback and global net CRE feedback in CMIP5/SPOOKIE models.

Our experiments with HadGEM2-A also suggest that the relationship between Southeast Pacific precipitation and CRE in the marine stratocumulus regions might be mediated by free-tropospheric warming and EIS, for example, if deep convection reduces subsidence warming and EIS. However, our examination of relationships in the CMIP5/SPOOKIE multimodel ensemble does not provide strong support for this. The correlation between precipitation in the Tian (2015) Southeast Pacific region and the EIS in the Peruvian marine stratus region is of the expected sign but is slightly too weak to be significant at the 5% level ($r = -0.42$) (see Table 2). However, the correlations of the EIS with the SW and net CRE in the Peruvian marine stratus region are much smaller ($<15\%$), so EIS does not mediate the relationship between Southeast Pacific region precipitation and Peruvian marine stratus region CRE in the multimodel ensemble. These results indicate that some other explanation is required for this aspect of the problem.

As mentioned above, it is possible that the Peruvian marine stratus region is simply not representative of the areas in which our proposed mechanism is operating in the models. To explore this possibility, we also correlate the precipitation in the Tian (2015) region with the local net CRE feedback in all regions. Figure 7 shows that the cloud feedbacks in the subtropical stratus regions are not in general significantly anticorrelated with the Southeast Pacific precipitation in the Tian (2015) region, which suggests that the relationship

Figure 7. Correlation between Southeast Tropical Pacific Precipitation and local net CRE feedback in CMIP5/SPOOKIE models. Negative correlations with $r < -0.5$ are significant at the 5% level.
between double-ITCZ and climate sensitivity is not mediated by subtropical low clouds as we have hypothesized. Significant anticorrelations are seen in other regions. Such relationships could in principle be used to develop alternative hypotheses in the future, although the risks associated with data mining should always be kept in mind (Caldwell et al., 2014).

4. Summary and Conclusions

Tian (2015) proposed an emergent constraint on climate sensitivity where models with a more pronounced double-ITCZ bias and too much precipitation in the Southeast Pacific have lower values of the effective ECS (S) and suggested that this may rule out lower values of S. However, no clear mechanism has been provided to explain why the double-ITCZ should be related to S. We advance a physical hypothesis as a potential explanation for this relationship that deep convection encroaching into regions that should be dominated by shallow clouds hampers the formation of shallow clouds in the present climate and reduces the magnitude of positive low-level cloud feedbacks, resulting in smaller values of climate sensitivity. We tested this first by perturbing the ITCZ in a single idealized climate model and second by looking for the relationships it predicts across models.

We show in targeted experiments with the HadGEM2-A aquaplanet model that increasing the longwave radiative effects of clouds in the atmosphere makes the ITCZ more concentrated, as found by Dixit et al. (2018). This enhances midtropospheric temperatures in the subtropics, increasing low-level stability, enhancing the net radiative cooling effect of clouds in the present climate through enhanced cloud cover and/or condensed water path. This stronger radiative effect of clouds is associated with a more positive subtropical cloud feedback with climate change, resulting in a higher climate sensitivity. Looking across these experiments, we see that model versions with more precipitation encroaching into the subtropics have weaker subtropical CREs in the present climate, less positive subtropical cloud feedbacks, and less positive global cloud feedbacks. These results are consistent with our hypotheses and suggest that it is a plausible physical explanation for the Tian (2015) result.

We test this hypothesis further by looking for the predicted relationships in SST forced experiments subject to a uniform SST increase with 12 models from the CFMIP-2/CMIP5 and SPOOKIE projects. We find no statistically significant relationship between precipitation in the Southeast Tropical Pacific region of Tian (2015) and cloud feedback in the Peruvian marine stratus region of Klein and Hartmann (1993), in spite of the fact that the cloud feedback in the Peruvian region is significantly positively correlated with the global cloud feedback. Significant correlations are seen with feedbacks in other regions but not ones typically associated with subtropical low clouds. We do see a significant anticorrelation between precipitation in the Tian (2015) region and present-day CREs in the Peruvian region and other regions associated with low clouds, which supports part of our argument. The CREs in the Peruvian region are, however, not significantly correlated with local cloud feedbacks, which does not support our hypothesis. Hence, our proposed mechanism cannot explain the relationship in CMIP3/CMIP5 models identified by Tian (2015). Furthermore, we do not see a statistically significant relationship between Southeast Tropical Pacific precipitation and global cloud feedback in ten SST forced CMIP6 models subject to a uniform SST increase.

Although we have not been successful in providing a compelling explanation for Tian (2015) result, we hope that we have at least demonstrated an approach that may usefully be used to develop and test physical explanations for this and other proposed emergent constraints in the future. We conclude by noting that all emergent constraints of this type are based on climate models, and so it is difficult to rule out the possibility that they may be biased, even if they are supported by credible physical explanations. Climate models, with or without emergent constraints, are just one line of evidence on climate sensitivity. Robust assessments of climate sensitivity such as those undertaken by the Intergovernmental Panel on Climate Change (IPCC) take into account multiple lines of evidence relevant to cloud feedbacks and climate sensitivity, including climate models, process models, and observations from the current, historical, and paleoclimate eras. Physically credible emergent constraints on climate sensitivity may affect synthesis estimates of S but to a lesser degree than one might be led to believe if such emergent constraints are considered in isolation.
Acknowledgments
We are grateful to Stephan de Roode, Bjorn Stevens, Angie Pendergrass, Mike Byrne, Peter Caldwell, Steve Klein, and Sandrine Bony for useful discussions about this work and to Bajian Tian and two anonymous reviewers whose comments helped to improve the manuscript. Mark Webb was supported by the Joint U.K. BEIS/Defra Met Office Hadley Centre Climate Programme (GA01001). We acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP5 and CMIP6. We thank the climate modeling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF.

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