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On the relative strength of radiative feedbacks under climate variability and change

Robert Colman[1] · **Lawson Hanson[1]**

Abstract Using the method of radiative 'kernels', an analysis is made of feedbacks in models participating in the World Climate Research Program Coupled Model Intercomparison Project phase 5. Feedbacks are calculated for RCP8.5 and abrupt4xCO2 experiments as well as for interannual and decadal variability from pre-industrial runs. Regressions across models are used to elicit relationships across experiments/timescales. Feedbacks between RCP8.5 and abrupt4xCO2 experiments show strong relationships, as expected from surface temperature response similarities arising from the two experiments. The analysis also reveals significant relationships between RCP8.5 and decadal and interannual lapse rate feedback, decadal water vapour and interannual total cloud—the latter confirming results elsewhere. To reveal the impact of warming pattern differences, 'synthetic' feedbacks are also generated, based on RCP8.5, whereby local feedbacks determined from that experiment are scaled by relative temperature changes (per degree of global warming) from the others. The synthetic feedbacks indicate that the (sometimes strongly) differing temperature response patterns themselves should not preclude strong correlations between variability and climate change feedbacks—indeed such correlations would be close if local feedbacks were a robust feature of the climate. Although such close correlations are not manifest, the synthetic feedbacks predict the interannual and decadal feedbacks to some extent (are correlated across models), and reveal the consistency, to a first approximation, of the mean model strength of variability feedbacks. Although cloud feedbacks

at interannual timescales are correlated with those from RCP8.5, and show consistency with the strength of synthetic feedbacks, separate long and short wave components reveal very different, compensating, latitudinal patterns, suggesting the close correlation may be fortuitous.

Keywords Climate feedbacks · Climate variability · Feedback · Climate sensitivity

1 Introduction

Uncertainties in the magnitude of future climate changes remain large, and differences in radiative climate feedbacks are responsible for much of this spread (Bony et al. 2006; Flato et al. 2013). An inherent difficulty in diagnosing and evaluating climate feedbacks is their long-term nature. Secular changes in water vapour, surface albedo and clouds, for instance, may be expected to occur in response to long term surface temperature changes but these may not be quantifiable for many decades. Short-term fluctuations either in forcing or response and inhomogeneities or shortness of observational records serve to both confound the detection of trends, and severely limit evaluation of climate model feedbacks.

In the face of these limitations, researchers have sought feedback 'analogues' from short term fluctuations for evaluation of models or direct estimation of feedback strength. Interannual variability has been used to assess and quantify water vapour and cloud feedbacks (Minschwaner and Dessler 2004; Minschwaner et al. 2006; Dessler and Wong 2009; Gettelman and Fu 2008; Dessler 2010, 2013; Gordon et al. 2013), and for evaluation of total climate sensitivity (e.g. Forster and Gregory 2006). Seasonal variations have been used to test total long wave (LW) feedbacks

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(Tsushima et al. 2005; Chung et al. 2010a, b), and have been proposed as overall constraints on climate sensitivity from observations (Covey et al. 2000; Knutti et al. 2006; Wu et al. 2008). At decadal timescales, fewer studies have occurred (presumably due to observational limitations), although evaluation has been attempted on multi decadal fluctuations in trends in water vapour (Allan et al. 2003). A common assumption of all these studies is that processes such as water vapour, cloud or surface albedo changes occurring under short-term fluctuations are directly relevant to the evaluation and quantification of corresponding secular climate feedbacks.

Yet the pattern of surface temperature fluctuations associated with variability differ from secular climate change, so patterns and strengths and feedbacks may be expected to be different (Lindzen et al. 1995; Hall and Manabe 1999; Colman and Power 2010). For example, interannual fluctuations in temperature are focused much more strongly in the tropics, due to driving El Niño/Southern oscillation variability (Trenberth et al. 2002), and resultant water vapour feedback is consequently much stronger at low latitudes (Dessler and Wong 2009; Colman and Hanson 2013). Vertical profiles of feedbacks differ on global and regional scales (Hall and Manabe 1999; Colman and Power 2010; Colman and Hanson 2013), although with some physical consistency such as tropical upper tropospheric maxima for water vapour feedback (Dessler and Wong 2009).

Despite these differences, it is remarkable that strong consistencies have been found, for example in the overall strength of global water vapour and lapse rate feedbacks operating at interannual, decadal and climate change timescales for global climate models (GCMs) considered collectively. Colman and Hanson (2013) found that mean LW global water vapour feedback in GCMs was 1.8, 1.5 and 2.0 W/m^2/K for climate change, decadal and interannual variability respectively, and that these were all consistent with close to unchanged relative humidity. The exception to this is seasonal timescales, where the feedback was significantly weaker, but even here, considering changes in a single hemisphere alone brought the feedback closely into line with the other timescales.

Despite this global (or hemispheric) agreement however, with two exceptions (discussed below), clear relationships across timescales in *individual model* feedback strength are not apparent. In particular, *across* GCMs there appears to be little or no correlation between climate change water vapour, lapse rate, 'Planck' or surface albedo feedback strength and the corresponding seasonal, interannual or decadal timescales feedback (Colman and Hanson 2013).

The two clear exceptions to this are relationships that have been found between the Northern Hemisphere seasonal feedback and the climate change feedback for the snow component of the albedo feedback (Hall and Qu 2006, 2014; Colman 2013), and between net global cloud feedback on interannual and climate change timescales (Zhou et al. 2015). The former can be understood from the relatively simple process of regional snow cover responding to surface temperature changes in consistent ways regardless of timescales. The latter is more complex, and appears to partially result from consistent responses of low cloud to large scale thermodynamic changes (Zhou et al. 2015), but requires further investigation.

These cases notwithstanding, the almost universal lack of clear relationships between feedbacks from variability and change makes it difficult to use short term variability for direct constraint on climate change feedbacks. This is because it is not then straightforward to directly relate common processes that drive individual model feedback strength under climate variability and change.

Nevertheless, this does not mean that no useful information can be derived from climate feedbacks under variability. The very fact that their average strength is similar overall begs explanation, and may potentially bolster confidence in the magnitude of climate change feedbacks if the processes are understood. It is therefore crucial that the cause of these similarities and differences is clarified. Clearly circulation differences (between climate change and climate variability) will provide different regional and local responses to climate variables such as water vapour and cloud, which may be expected to contribute differently to global feedback. Relevant to this, a number of studies have argued for normalisation of local radiative feedbacks by local, rather than the more conventional global temperature changes (Boer and Yu 2003; Winton 2006; Crook and Forster 2011; Crook et al. 2011; Kay et al. 2012). In an important extension of this approach, Armour et al. (2013) demonstrated that evolution of (effective) global feedback strength in models could, in fact, be understood by the time varying surface temperature increase pattern operating on (essentially) unchanging 'local feedbacks'. In that study, the patterns of temperature change were not dramatically different over most of the globe—with the exception of high southern latitudes. In particular most regions had substantial warming throughout. Could patterns of warming operating on quasi-fixed regional feedbacks 'explain' global feedbacks operating under much more substantial pattern differences—such as those which occur at interannual or decadal timescales compared with climate change, or is something more behind the differences? Can the global strengths of these feedbacks be understood from their pattern of surface temperature fluctuation? These questions are the prime motivation of the present study. Understanding the impact of warming pattern differences on feedback strength differences may provide a more direct link between global feedbacks under climate variability and

change, and a way forward for evaluating and constraining climate change feedbacks.

Section 2 of this paper outlines the calculation of climate feedbacks at different timescales. Section 3 provides discussion and comparison with climate change feedbacks, and Sect. 4 contains a summary and concluding remarks.

2 Calculation and analysis of climate feedbacks

All feedbacks are evaluated here following the 'radiative kernel' approach (Soden et al. 2008; Shell et al. 2008), whereby the radiative change (ΔR) for a perturbation to parameter x_i is calculated by:

$$
\begin{aligned}
\Delta R_i(\theta, \phi) &\approx \sum_z \frac{\partial R(\theta, \phi, z)}{\partial x_i(\theta, \phi, z)} \Delta x_i(\theta, \phi, z) \\
&\equiv \sum_z K(\theta, \phi, z) \Delta x_i(\theta, \phi, z),
\end{aligned}
\tag{1}
$$

where the kernel, $K(\theta, \phi, z)$, is the radiative response for a 'standard' perturbation of variable i at level z (although with the albedo operating at the surface only), calculated with a single model. The 'standard' perturbations used are similar to those described in Soden et al. (2008), namely: 1 K perturbation at the surface and individual pressure levels; water vapour increase at pressure levels corresponding to a 1 K warming with fixed relative humidity; and a 1% surface albedo increase.

This kernel is then applied to the full range of models under consideration, using the appropriate model monthly perturbations of T_s (surface temperature) and x_i. The kernels used here were derived from the Australian Bureau of Meteorology model, and are the same as the 'BMRC/CAWCR SES' kernels discussed in Soden et al. (2008). Feedback variables, i, specified here are: vertically uniform change of magnitude T_s, (the so called 'Planck' response), water vapour, q, lapse rate, Γ, clouds, C and surface albedo, α. An alternative approach is a division using relative humidity as the state variable (Held and Shell 2012), which diagnoses feedbacks closer in magnitude to each other and avoids strong 'offsetting', for example, between water vapour and lapse rate. That approach is not adopted here however, to permit direct comparison of results with other papers using the 'standard' division of feedbacks, and to anticipate discussion of the processes controlling, for example, water vapour and lapse rate at different timescales.

Different radiative kernels can diagnose different radiative changes, but these have been shown to be relatively small at global scales compared with the feedback spread (Soden et al. 2008). Global and zonal calculations of feedbacks associated with both climate variability and change

with the BMRC/CAWCR kernels using two different radiation schemes also found no significant differences in the results (Colman and Hanson 2013).

The models analysed here are those from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al. 2012). Where multiple model integrations were available, only the first was used. The 35 models used are those described in the CMIP5 archive (Taylor et al. 2012) that have the appropriate fields (ACCESS1-0, ACCESS1-3, BNU-ESM, CESM1-BGC, CESM1-CAM5, CESM1-FASTCHEM, CESM1-WACCM, CMCC-CM, CNRM-CM5, CSIRO-Mk3-6-0, CanESM2, FGOALS-g2, FGOALS-s2, FIO-ESM, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2 M, GISS-E2-H, GISS-E2-R, HadGEM2-CC, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC-ESM, MIROC-ESM-CHEM, MIROC5, MPI-ESM-LR, MPI-ESM-MR, MPI-ESM-P, MRI-CGCM3, NorESM1-M, NorESM1-ME, BCC-CSM1-1 and BCC-CSM1-1-m). Prior to all calculations, model fields were interpolated to a common $2.5° \times 2.5°$ grid with 50 hPa vertical spacing.

Armour et al. (2013), conjectured that 'local feedbacks' (i.e. the *local* change in radiation as a function of *local* temperature change) can be to first order considered invariant of the pattern of temperature change. Such feedbacks can then in a straight-forward way be scaled by the local temperature change pattern, and then summed to give the total global feedback response. To follow this approach, then, first we express the total climate change radiative feedback, λ_c as the global mean of the sum of localised feedbacks operating at each latitude/longitude (θ/ϕ) point:

$$
\lambda_c = \sum_i \overline{\lambda_i(\theta, \phi) \frac{dT_c(\theta, \phi)}{d\overline{T_c(\theta, \phi)}}}
\tag{2}
$$

where dT_c is the perturbation to surface (air) temperature under climate change and the overbar denotes the global mean. The local feedback, following Armour et al. (2013), is calculated by:

$$
\lambda_i(\theta, \phi) = \frac{dR_{ic}(\theta, \phi)}{dT_c(\theta, \phi)}
\tag{3}
$$

where R_{ic} is the *local* radiation change due to each of the feedback variables, i, under climate change (in this study both RCP8.5 and Abrupt4xCO2 experiments). To the extent that local feedback parameters are applicable for different surface temperature pattern changes, we can express the global feedback occurring under *climate variability* as:

$$
\lambda_{vi} \approx \overline{\lambda_i(\theta, \phi) \frac{dT_v(\theta, \phi)}{d\overline{T_v(\theta, \phi)}}}
\tag{4}
$$

where the derivative in Eq. 4 is evaluated by regression of local with global temperature for the climate variability timescale of interest, following Colman and Hanson (2013). For convenience in this paper we will refer to feedbacks generated using Eq. 4 as 'synthetic' feedbacks—i.e. denoting that they are derived from climate change feedbacks.

A principal question in this paper, then, is how well the 'synthetic' feedbacks calculated from Eqs. 3 and 4 compare with the feedback calculated directly from regression of radiation change with global temperature under climate variability (e.g. Dessler and Wong. 2009):

$$\lambda_{vi} = \frac{d\overline{R_{iv}(\theta,\phi)}}{d\overline{T_v(\theta,\phi)}} \tag{5}$$

where R_{iv} is the local radiation change due to feedback parameter, i. A close match between feedbacks calculated by Eqs. 4, 5 would mean that the difference between feedbacks for climate change and climate variability relate primarily to the different temperature patterns associated with a unit increase in global mean surface temperature. A substantial difference would mean that other processes are more important and that the notion of regional feedbacks is less applicable.

Several sets of CMIP5 experiments were considered here. Pre-industrial runs were used for diagnosing feedbacks under climate variability (interannual and decadal). In most cases 200 years of monthly data were available. For interannual variability, differences in fields required in Eq. 5 were calculated from corresponding months between (100) adjacent year pairs. For decadal variability, the preindustrial run was divided into 10 year average blocks, then corresponding months used between the (19) adjacent decadal means. Further details of the calculation techniques are provided by Colman and Hanson (2013). In all variability cases, the radiative perturbations (calculated using Eq. 1) were regressed against the corresponding global surface temperature perturbation to calculate the climate feedback parameter (Eq. 5). Error bars shown in this paper are calculated from 90% confidence levels for standard regression.

Climate change feedbacks were calculated using two sets of experiments: RCP8.5 and abrupt4xCO2. Both of these are examined for two reasons: (1) because they are each used widely in feedback studies, and (2) because they permit examination of the role of radiative forcing in determining feedback response, including the importance of so called 'rapid adjustments' (see discussion below). In the former, differences were taken between the period 2005–2014 and 2090–2099 (i.e. kernels were applied to monthly pair differences in corresponding years in this

period, followed by averaging over each of the 10 years, before the final 10–year mean). For the latter, differences were calculated by comparing years 5–14 of the experiment, with years 90–99. Both regional feedbacks (using Eq. 3) and global feedbacks were calculated in each case, although the RCP8.5 regional feedbacks are the ones principally used in this paper. This is because, although there are potential complications caused by 'rapid adjustments' in the calculation of the cloud feedbacks from RCP8.5 (see further discussion below), RCP8.5 is most relevant to real world climate change feedbacks, so necessarily forms the basis of comparison. Finite differences were used to approximate the differential in Eq. 3, and errors shown below are calculated as the standard error in mean estimation from the 10 separate samples of annual feedbacks.
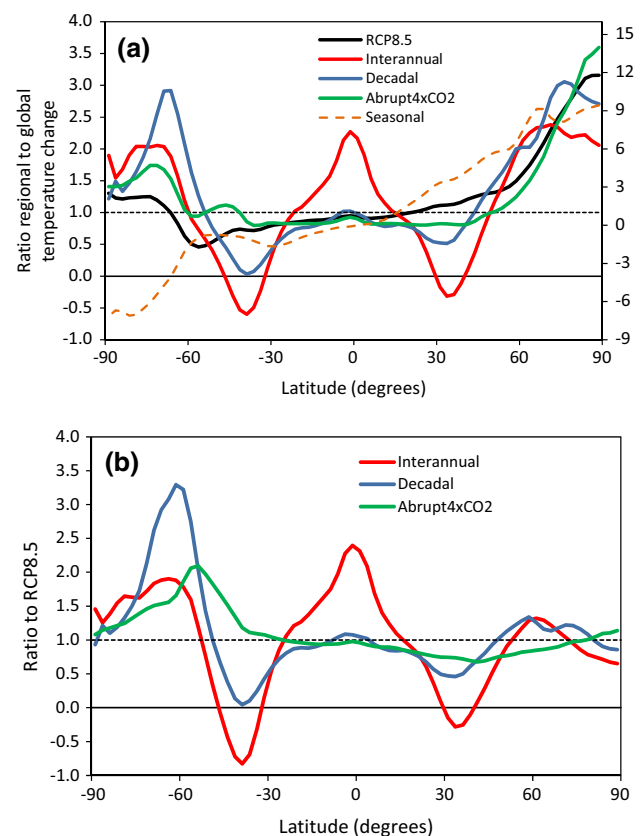
Fig. 1 a Multi-model zonal mean temperature change per degree of global warming for the experiments considered. Values are calculated by normalisation of regional temperatures by global temperature (RCP8.5 and Abrupt4xCO2) or by regression against global temperatures (interannual and decadal). Seasonal changes (e.g. as analysed in Colman and Hanson 2013) are shown for comparison, and refer to the *right hand axis*. **b** Ratio of temperature changes per degree to those from the RCP8.5 experiment (seasonal not shown). The values here are calculated from multi-model mean of the ratio rather than the ratio of the multi-model means (i.e. of the values shown in **a**). *Dashed line* for ratio value of 1 is shown for reference

Fig. 2 Global feedbacks for **a** Abrupt4xCO2, **b** decadal and **c** inter- ▶
annual timescales plotted against corresponding RCP8.5 feedbacks
for LW water vapour (q(LW)), lapse rate (LR), surface albedo (a),
surface temperature (Planck), scaled by a factor of 0.5 (TSx0.5) and
total cloud feedback (C). All units are W/m²/K. Lines of best fit are
shown. *Dashed line* shows 1:1. Note that *horizontal* and *vertical* axes
differ between the plots

3 Results and discussion

Before calculating the 'synthetic' feedbacks, we determine
the rate of local temperature change with global mean tem-
perature for the four experiments—shown in Fig. 1a. These
are calculated by either regressing zonal mean surface tem-
perature change against global mean change (for interan-
nual and decadal) or by normalising zonal by global change
(for abrupt4xCO2 and RCP8.5). These may be compared
with results from the CMIP3 models (Meehl et al. 2007),
shown in Fig. 1 of Colman and Hanson (2013). The ratios
of these, in turn relative to the RCP8.5 ratios, are shown
in Fig. 1b. Values greater than/less than 1 here represent
latitudes where the rate of local increase in temperature
per degree global 'warming' is greater/less than that in the
RCP8.5 experiment.

For the abrupt4xCO2 experiment, greater local warm-
ing (relative to RCP8.5—Fig. 1b) is apparent at mid-high
southern latitudes, and weaker warming throughout the
northern hemisphere, commensurate with stronger south-
ern ocean warming under the consistently stronger forc-
ing. Global warming can be considered to have 'proceeded
further' in this experiment, than in RCP8.5, with the pat-
tern consistent with later years of warming discussed in
Armour et al. (2013, their Fig. 3). At interannual timescales
very large positive excursions from unity are apparent at
low latitudes and high (up to 2.5 times as much warming
per degree at the equator), with very muted warming in
mid-latitudes, culminating in cooling at around 40° north
and south. For decadal timescales the low to mid latitude
'warming pattern' is consistently closer to that of RCP8.5
(i.e. closer to 1 in Fig. 1b), but high latitude southern
warming is even more strongly enhanced. This latter fea-
ture is consistent with strong surface albedo feedback that
has been noted at southern high latitudes at decadal time-
scales (Colman and Hanson 2013).

By contrast, in the north all experiments have reason-
ably similar local to global warming rate ratios in mid-high
latitudes. From Fig. 1 we might expect synthetic feedbacks
to be closer approximations of the actual feedback for the
abrupt4xCO2 experiment, intermediate for decadal vari-
ability and least accurate for interannual.

How do the global feedback strengths compare? Fig-
ure 2 shows global feedbacks for individual models for
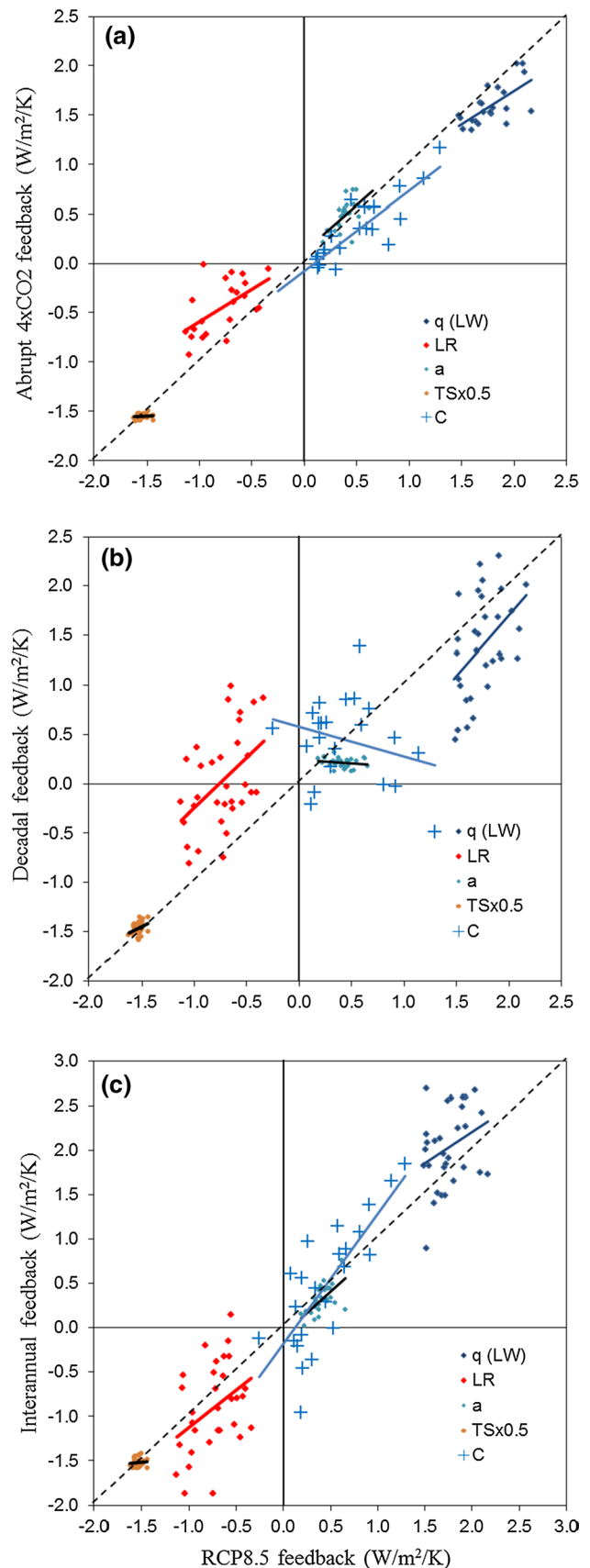
abrupt4xCO2, decadal and interannual plotted against the RCP8.5 feedback. Table 1 shows regression coefficients from linear least squares fits, and indicates where these are statistically significant (at the 90% level). Also shown are correlation coefficients. For clarity, 'error bars' showing uncertainties in the estimates are not shown in Fig. 2, however they can be substantial, particularly for decadal, where temperature deviations are small and sampling is more limited (Colman and Hanson 2013). Uncertainties tend to be much smaller for abrupt4xCO2 and RCP8.5 because of the large temperature change involved. For example, for water vapour feedback, average uncertainties across the models for RCP8.5, abrupt4xCO2 decadal and interannual are 0.03, 0.08, 0.56 and 0.28 W/m^2/K respectively. Statistical significance of results shown in Table 1 is calculated from ordinary least squares fitting. More sophisticated fitting, using a Bayesian approach which samples the uncertainty range in the data points, provides similar results and significance (see discussion in Colman and Hanson 2013), and is not shown.

A number of conclusions are apparent from Fig. 2 and Table 1. Firstly, the abrupt4xCO2 feedbacks, as expected, show high correlation with those from RCP8.5. All regression coefficients are statistically significant apart from short wave (SW) water vapour and the Planck response. A possible explanation for these latter is that they have significant high latitude contributions (see below), and high southern latitudes show the greatest differences in warming patterns between the experiments—although it is notable that there is very high correlation between surface albedo feedbacks, which also has a strong southern high latitude contribution. Total cloud feedback, and its SW term, show the highest explained variances of all feedbacks.

By contrast, for decadal and interannual timescales, most correlations are not significant at the 90% level. These findings are overall consistent with those derived from CMIP3 results by Colman and Hanson (2013). What differs from that earlier study is that both lapse rate feedback correlations are significant, as is that for decadal LW water vapour timescales. There may be several reasons for this difference. For a start CMIP5 has a substantially larger number of models (35 vs. 23) with much longer preindustrial control runs (at least 200 vs. only 100 years) enabling greater sampling—which is particularly important at decadal timescales. Furthermore CMIP5 represents a later generation of models, and models with very strong negative climate change lapse rate feedbacks (< -1.2 W/m^2/K) are now absent in CMIP5, whereas there were five such models in CMIP3. Given that they were lapse rate 'outliers', these models played a strong statistical role in the fitting for CMIP3 (see Fig. 8d, e from Colman and Hanson 2013), and their removal from the (CMIP3) regression makes the CMIP3 and CMIP5 results much more consistent.

The water vapour and lapse rate feedbacks are closely coupled, and have been found to be anti-correlated across models at interannual, decadal and climate change timescales (Colman 2003; Soden and Held 2006; Colman and Hanson 2013). This same relationship holds for the CMIP5 models (not shown). Furthermore, both show maximum contributions (of opposite signs) in the tropical upper troposphere (Randall et al. 2007; Colman and Hanson 2013), so they are often considered as a combined feedback. The findings here, however, show that the combined feedback is significantly correlated across models only for the abrupt4xCO2/RCP8.5 pair (see Table 1). This is perhaps not surprising since these feedbacks offset one another, and so the combined feedback has much smaller a range than either water vapour or lapse rate on their own. Furthermore Table 1 shows more statistically significant relationships between Abrupt4xCO2 and RCP8.5 (and in particular for lapse rate and for both LW and SW water vapour), than between decadal or interannual and RCP8.5. This greater number of significant correlations is to be expected given the closer similarity of the SST change patterns from the two climate change experiments, than between interannual and decadal variability and RCP8.5 (Fig. 1).

Perhaps the most striking correlation in Table 1 is that of total cloud feedback at interannual timescales versus RCP8.5. This explains more than 70% of the variance of the feedback. This echoes the results of Zhou et al. (2015), but extends it to RCP8.5—Zhou et al. (2015) considered only the correlation between interannual and abrupt4xCO2 (although they noted significant correlations for CMIP3 transient runs). Importantly, however, neither the short nor long wave cloud feedback separately shows significant correlation. Nor is the decadal

Table 1 Regression coefficients from linear regression fits of feedbacks from abrupt4xCO2, decadal and interannual timescales against RCP8.5 feedbacks

	Abrupt4xCO2	Decadal	Interannual
q (LW)	**0.71** (0.67)	**1.27** (0.47)	0.74 (0.31)
q (SW)	0.09 (0.19)	-8.0 (0.34)	0.46 (0.20)
LR	**0.73** (0.61)	**1.07** (0.50)	**0.86** (0.38)
$q + LR$	**0.85** (0.52)	1.44 (0.27)	0.99 (0.30)
Ts	0.07 (0.12)	0.52 (0.36)	0.08 (0.07)
a	**0.97** (0.73)	-0.07 (0.16)	**1.22** (0.78)
C (SW)	**0.70** (0.92)	-0.37 (0.38)	0.52 (0.49)
C (LW)	**0.53** (0.71)	-0.04 (0.03)	-0.71 (0.29)
C	**0.76** (0.89)	-0.22 (0.21)	**1.49** (0.85)

Significant coefficients (at the 90% level) are shown in bold. Correlation coefficients (r) are shown in brackets. Feedbacks shown are: water vapour (q), lapse rate (LR), surface albedo (a), Planck (Ts) and cloud feedback (C). For water vapour and clouds, LW/SW components are also shown

correlation significant for total cloud feedback or either of its components. The patterns of these feedbacks will be considered further below.

The question arises: would the correlations between feedbacks be stronger if we 'allowed for' the differences in warming patterns seen in Fig. 1? In other words, can the climate variability feedbacks be understood as simply manifestations of the local feedbacks under climate change, 'amplified or reduced' by the corresponding temperature change pattern, manifest in Fig. 1. And there is a supplementary question: even if one-to-one correspondence is not found, do the patterns shown in Fig. 1, applied to climate change feedbacks, explain the overall strength of the feedback under variability? These questions are answered in three steps. Firstly, we examine how strong 'should' the correlation between climate change and variability feedbacks be, if local feedbacks were a strict reality, and the only differences were the warming patterns. Secondly, how well can the variability feedbacks themselves be reconstructed as synthetic feedbacks? Thirdly, how well do the synthetic feedbacks approximate the average strength of the variability feedbacks? If they are close, then this would suggest that local fixed feedbacks subject to climate variability warming patterns provides a first order explanation for the overall strength of the variability feedback.

The first question is addressed in Fig. 3, which shows synthetic abrupt4xCO2, decadal and interannual feedbacks plotted against RCP8.5 feedbacks. In all cases, at all timescales correlations are higher than in Fig. 2. For abrupt4xCO2, the fits are particularly tight, although for both decadal and interannual, correlations are also high. For example, for decadal total cloud feedback, whereas no significant correlation is found in Figs. 2, 3 shows a significant positive correlation (r = 0.7). The scatter around all lines of best fit is reduced. Overall then, this shows that the warming pattern differences under variability, shown in Fig. 1 do not, in themselves, dictate very different global feedbacks to that of RCP8.5. This, itself, is surprising—as decadal, and particularly interannual, temperature variations follow a dramatically different pattern to that of RCP8.5 (or indeed abrupt4xCO2) (Fig. 1). In some sense, this correlation provides an 'upper limit' on how predictable climate change feedback could potentially be from interannual or decadal observations.

The second question is how useful variability feedbacks are in practice for shedding light on climate change feedbacks. To determine this we need to explore how well the synthetic feedbacks, calculated from RCP8.5 feedback,
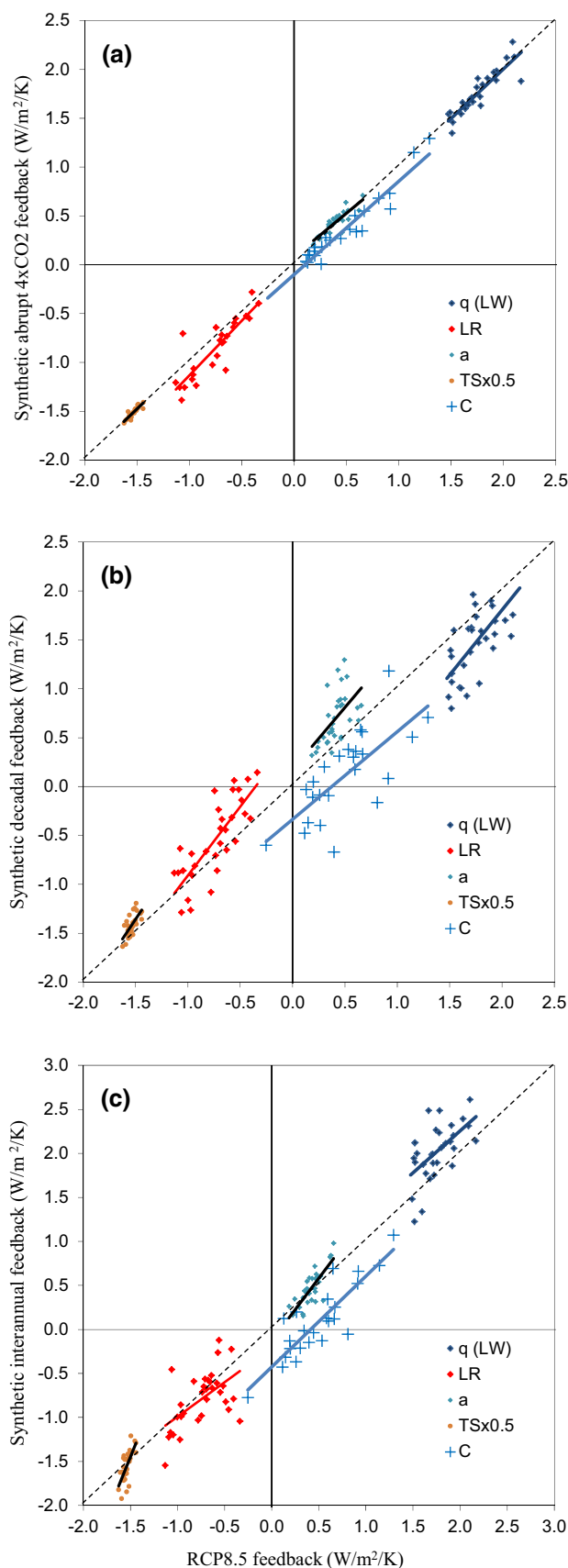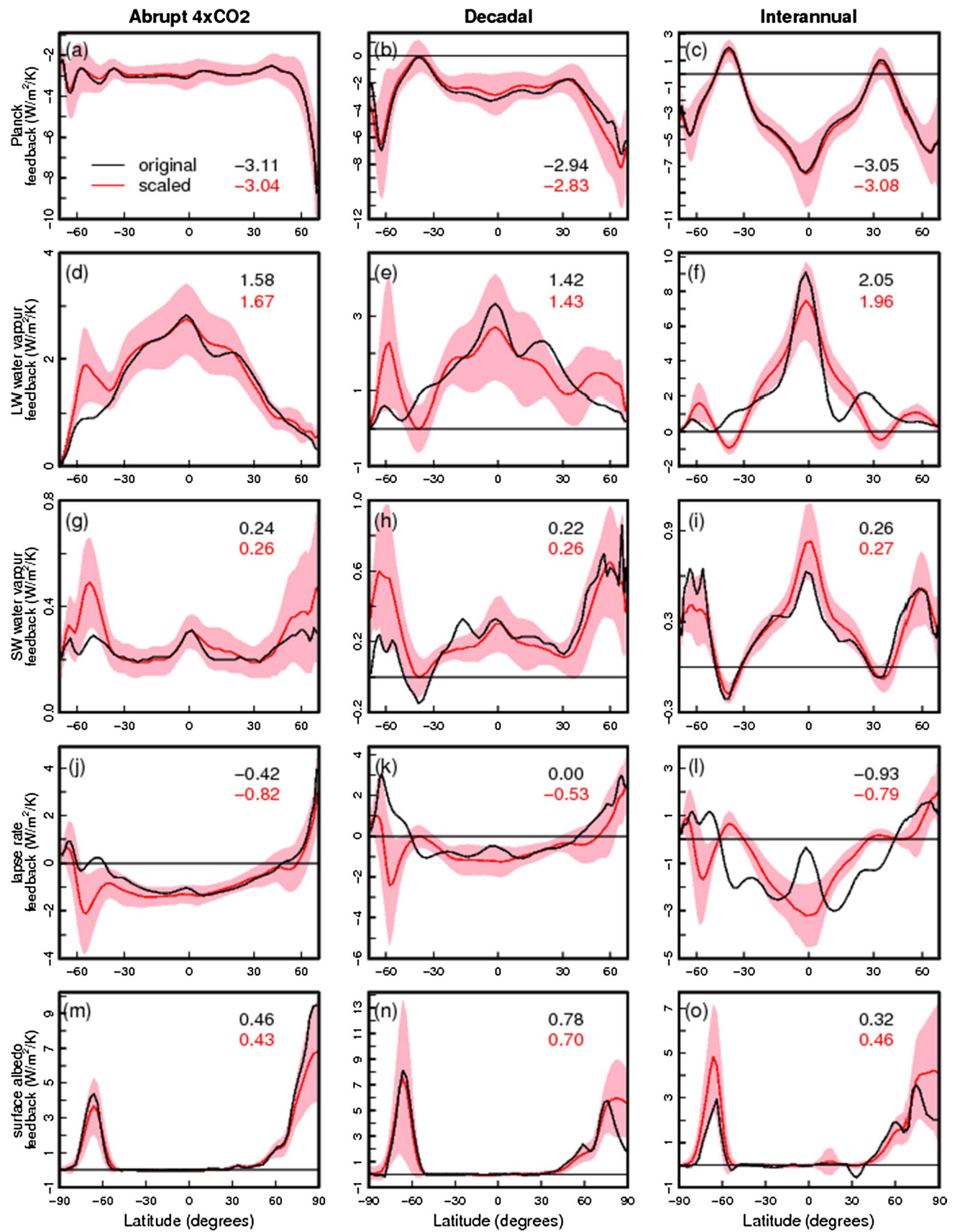
Fig. 4 Zonal mean climate feedbacks from the CMIP5 models for the Abrupt4xCO2 (*left*) experiment and for decadal (*centre*) and interannual (*right*) variability in the pre-industrial experiment, as derived from RCP8.5 models regional feedbacks scaled by the appropriate regional to global temperature ratios (i.e. using Eq. 4). Black lines show the MMM of the 'synthetic' feedbacks, and the pink shading 1 standard deviation of model spread. The *red line* shows the MMM of the feedbacks calculated directly (i.e. by regression for decadal and interannual variability, and by normalisation for abrupt4xCO2). Shown are the Planck response ('feedback') and the water vapour (LW and SW), lapse rate and surface albedo feedbacks. All but the surface albedo feedbacks are shown as weighted by cosine (latitude) to display contribution to the global mean. Numbers in *red* and *black* show the MMM global feedbacks by the directly derived and 'synthetic' methods respectively. All units are W/m^2/K

match those actually found under variability. If these, too, showed close correlation, then this would provide very strong evidence that 'local feedbacks' are robust under very different patterns of temperature change, and global feedbacks under variability would then be very strong predictors of RCP8.5 feedbacks.

Before looking at the global figures, to understand the differing meridional structures, zonal mean synthetic feedbacks are shown in Fig. 4 (non-cloud feedbacks) and 5 (cloud feedbacks). These figures show the multi model mean feedback (for abrupt4xCO2, decadal and interannual) the multi-model synthetic feedback, and the spread (one standard deviation) of synthetic feedbacks around the mean. Latitude is cosine weighted (except for albedo), so the area represents contribution to global mean feedback. For comparison, the (non-cosine weighted) RCP8.5 feedbacks are shown in Fig. 6. Global mean feedbacks, and their spread, at all timescales are summarised in Table 2, and for the synthetic feedbacks in Figs. 4, 5.

The Planck meridional feedback pattern (top row Fig. 4) is the simplest to understand. At all timescales it mimics the temperature change pattern (Fig. 1), and is well reproduced meridionally simply by scaling the RCP8.5 local feedback. Even at interannual timescales, the meridional distribution is extremely well matched by the synthetic feedback, as is the multi model mean global value.

LW water vapour (2nd row Fig. 4) is not so well matched. For abrupt4xCO2, and decadal, in the tropics and subtropics there is reasonable match in the meridional pattern between the feedback, but more mismatch in the extra tropics, particularly at high southern latitudes. For interannual timescales synthetic feedbacks match the actual feedbacks less well, showing a much broader than expected tropical/subtropical peak, and 'predicting' regions of negative feedbacks in mid-latitudes. Nevertheless, despite this mismatch the magnitude of the tropical peak is reasonably reproduced, and the global multi-model mean feedback strength is well matched for all 3 experiments by the synthetic values. From the global perspective then, the simple

scaling of RCP8.5 feedback 'explains' the overall strength of water vapour feedback at these timescales.

The multi model mean SW water vapour feedback (3rd row Fig. 4) is very well reproduced meridionally by the synthetic feedbacks: the very 'flat' meridional feedback in the RCP8.5 experiment (Fig. 6a) means that surface temperature response strongly dictates the distribution of the feedback.

The lapse rate feedback (4th row of Fig. 4) shows that northward of around 30° south, both the abrupt4xCO2 and decadal feedbacks are reasonably explained by the simple scaling of the RCP8.5 feedbacks. However, major disagreements arise polewards of southern mid-latitudes, because of the differences in the surface warming that arise, and because in particular for RCP8.5, the crossover between positive and negative contributions to this feedback lies far to the south (around 60°), as seen in Fig. 6a. Around these latitudes the temperature change per degree global warming differs most for abrupt4xCO2 and decadal, so differences are amplified here. Differences are also amplified at these latitudes for LW water vapour (Fig. 4d–f), but since that is a tropically dominated feedback, global impacts are smaller. Since the global lapse rate feedback is a balance between positive (high latitude) and negative (elsewhere) contributions, it is sensitive to these high latitude differences, and the global numbers do not agree well. Combined water vapour and lapse rate feedback for abrupt4xCO2 and decadal reveal good agreement between the synthetic and original feedbacks, and reasonable agreement globally, because these high latitude differences cancel out (not shown).

For interannual timescales, meridional contributions to the lapse rate feedback from synthetic and regional feedbacks disagree strongly at almost all latitudes. In particular, the equatorial (negative) minimum is not captured, instead revealing a maximum. Contributions at mid-high latitudes are also poorly matched. Clearly significantly different processes are controlling lapse rate changes, and these are likely sensitive to vertical motion changes, and shifts in circulation that are associated with interannual variability (Trenberth et al. 2002). Mean global strengths of the interannual and synthetic interannual feedbacks are in reasonable agreement, but Fig. 4 shows this to be from compensating differences.

The surface albedo feedback (fifth row Fig. 4) shows good agreement for abrupt4xCO2 and decadal in the Antarctic region, showing that the strong decadal albedo feedback, in particular, can be understood from the strong high latitude southern hemisphere temperature sensitivity to global temperature (Fig. 1). The Antarctic agreement is not quite so good at interannual timescales. In the high Arctic, there is also systematic disagreement between synthetic and actual feedbacks for all timescales.

Table 2 Multi-model mean global feedback strengths for the experiments considered here

	RCP8.5	Abrupt4xCO2	Decadal	Interannual
q (LW)	1.75 (0.19)	1.58 (0.20)	1.42 (0.49)	2.05 (0.43)
q (SW)	0.26 (0.04)	0.24 (0.02)	0.22 (0.05)	0.26 (0.04)
LR	−0.74 (0.23)	−0.42 (0.28)	0.0 (0.48)	−0.93 (0.49)
Ts	−3.07 (0.09)	−3.11 (0.05)	−2.94 (0.13)	−3.05 (0.10)
a	0.42 (0.11)	0.46 (0.15)	0.78 (0.38)	0.32 (0.16)
C (SW)	0.19 (0.43)	0.12 (0.40)	0.20 (0.52)	−0.10 (0.61)
C (LW)	0.34 (0.20)	0.20 (0.20)	0.23 (0.30)	0.51 (0.49)
C	0.53 (0.36)	0.32 (0.33)	0.43 (0.50)	0.41 (0.65)

Numbers in brackets show 1 standard deviation of inter-model spread. Units are W/m²/K. Symbols represent feedbacks as listed in Table 1
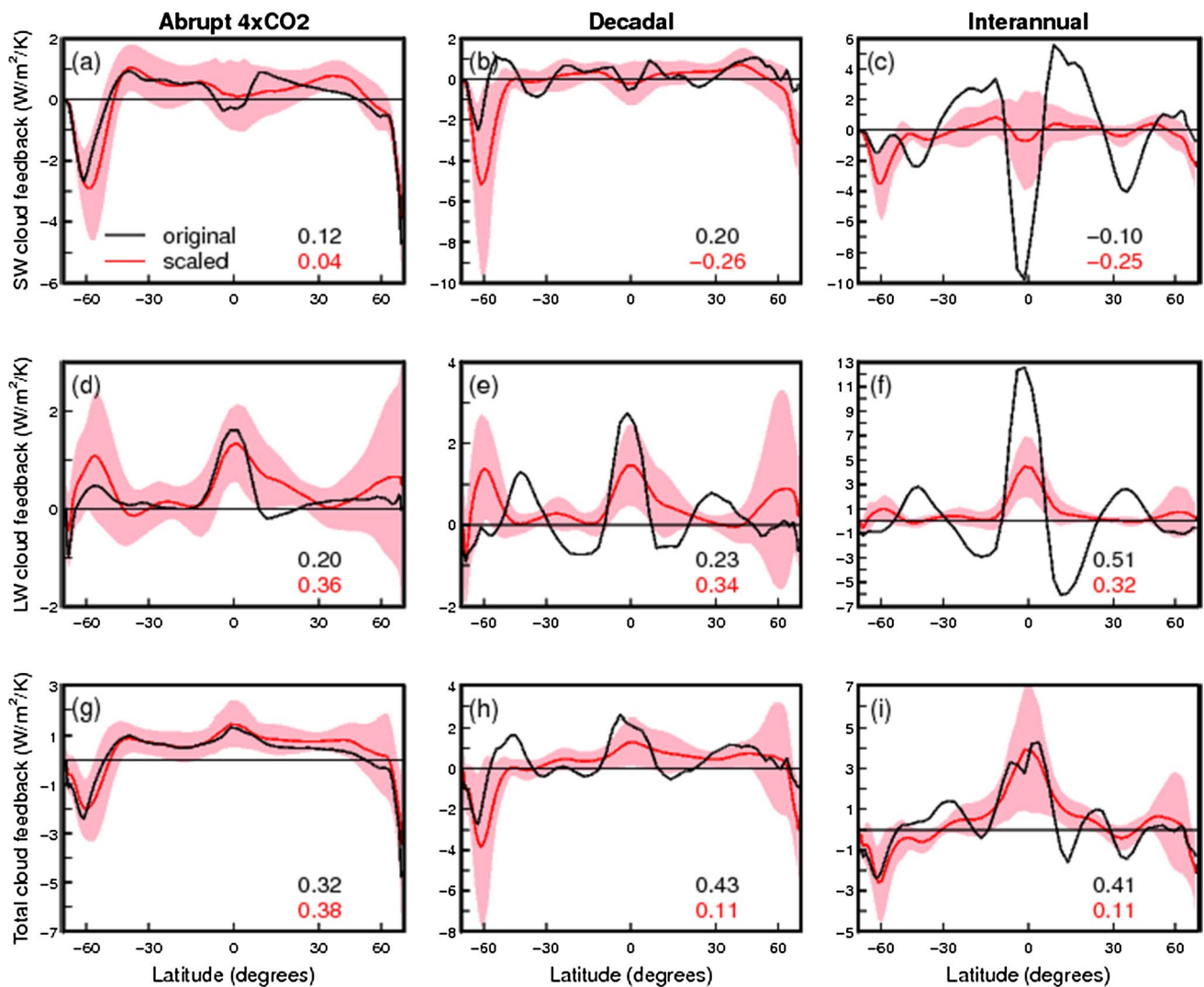
Fig. 5 As for Fig. 4, except for SW, LW and total cloud feedback

For decadal and interannual, this suggests Arctic sea ice responses to variability are muted compared to RCP8.5 (e.g. Hall 2004). Perhaps the most surprising result here is the implied strong response of/contribution to southern hemisphere sea ice to decadal timescale warming, and the strong southern hemisphere high latitude warming on

this timescale. Whether this is an artefact of models or analysis, or reveals an important decadal timescale process is beyond the scope of this paper. In any case, global strengths of surface albedo feedback at all three timescales in Fig. 4 are reasonably explained by the scaling of RCP8.5 feedbacks.
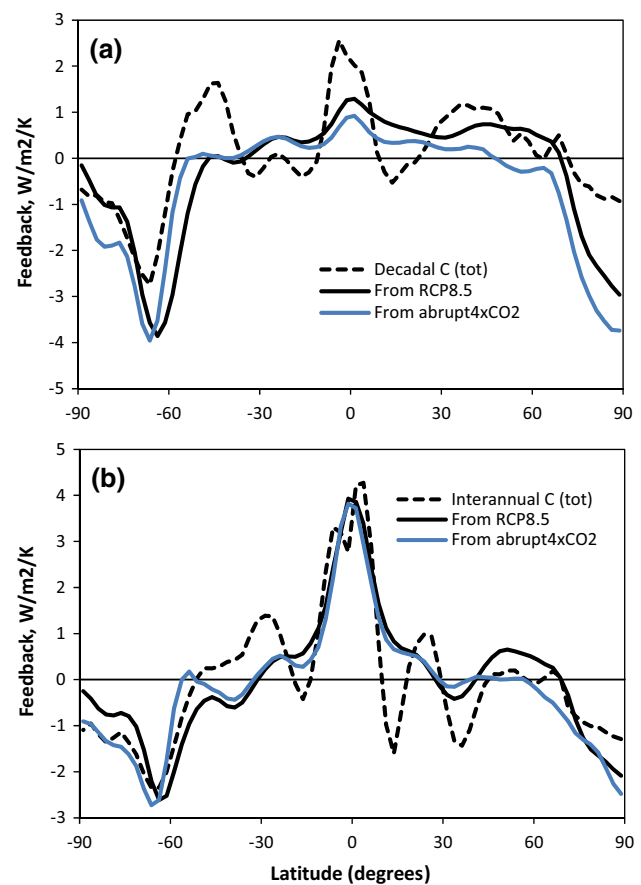
Figure 5 shows that zonal mean total cloud feedback is reasonably reproduced by the synthetic feedback (based on RCP8.5), most particularly for interannual. Decadal cloud feedbacks are relatively weak in the SW at all but high latitudes, in both the synthetic and actual feedbacks. Decadal LW feedback has a low latitude maximum that is too weak in the synthetic case. That the interannual agreement is reasonable, should perhaps come as no surprise, given the strong correlation is found by Zhou et al. (2015), and evident in Fig. 2. Individual long and short wave synthetic feedbacks however, show dramatically different, albeit offsetting, meridional profiles—Fig. 5c, f. Equatorial feedbacks peak at around 13 (−10) W/m²/K for LW (SW). There are smaller, but still large, compensating responses

in the subtropics, and at mid-latitudes. The reasonable meridional agreement evident in Fig. 5i, is then the result of very large, compensating differences. Whether this characteristic is sufficient to render the correlation across models for interannual and RCP8.5 feedbacks less useful for elucidating physical processes remains to be seen.

For clouds, the issue arises that under RCP8.5 the radiative response (particularly in the SW) results from the so-called 'rapid adjustments' to forcing, as well as surface temperature mediated feedback (Gregory and Webb 2008; Colman and McAvaney 2011; Andrews and Forster 2008; Andrews et al. 2012, 2015; Forster et al. 2013; Sherwood et al. 2015). Basing the synthetic feedbacks on RCP8.5 means the rapid adjustments will be included in the local response, which is in turn scaled by the variability related temperature changes. To test the impact of this, synthetic feedbacks were also calculated for decadal and interannual variability based on the abrupt4xCO2 experiment, and are compared with those derived from RCP8.5 in Fig. 7.
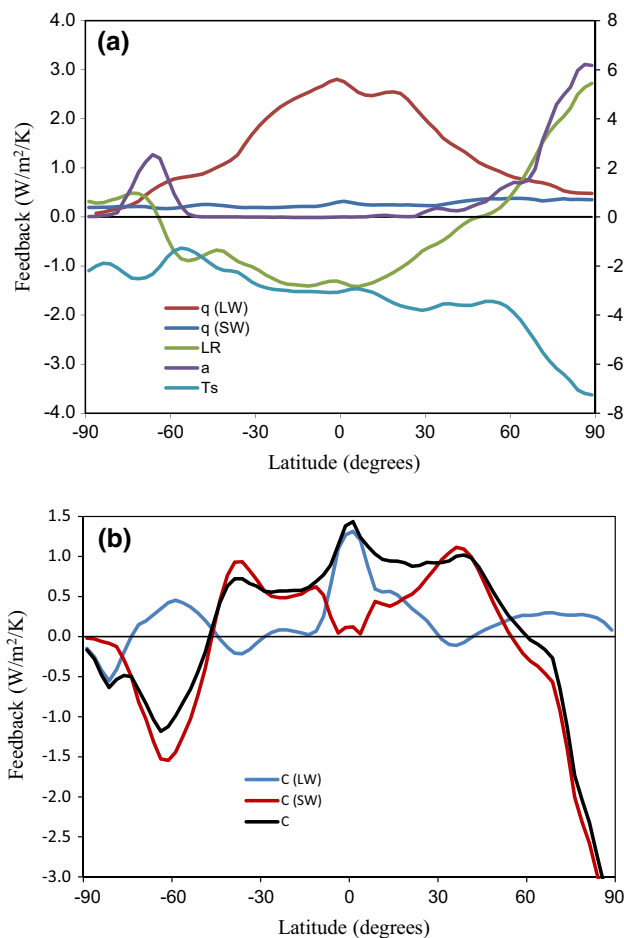
Fig. 6 Zonal mean climate feedbacks from the CMIP5 models for the RCP8.5 experiment. All units are W/m²/K

Fig. 7 Multi-model mean a decadal and b interannual total cloud feedback (*dashed line*) and multi-model mean synthetic feedback derived from RCP8.5 (*black solid line*) and abrupt4xCO2 (*blue*). Units are W/m²/K

Basing the synthetic cloud feedbacks on abrupt4xCO2 does not change the essential message from these findings. Note here that the number of models analysed differ as they are restricted to those that performed the abrupt4xCO2 experiment. Meridional distributions of synthetic versus actual feedbacks for interannual and decadal show similar patterns (comparing Figs. 5, 7). This is the case even at high southern latitudes, where 'base' surface temperature changes are most different between RCP8.5 and abrupt4xCO2. As with the lapse rate feedback, however, since global feedbacks are the sum of competing positive and negative contributions, global numbers can disagree significantly from small differences (total cloud interannual synthetic feedbacks based on abrupt4xCO2 and RCP8.5 differ by nearly 0.3 $W/m^2/K$, despite the similar meridional profiles seen in Fig. 7b).

So given the similarities and differences in the multi model mean meridional distributions discussed above, how do feedback differences between models correlate with those derived from the synthetic feedbacks? Scatter plots are shown for abrupt4xCO2, decadal and interannual against the corresponding RCP8.5 based synthetic feedbacks in Fig. 8. There is, as expected, closest correspondence with abrupt4xCO2 (Fig. 8a). The most 'different' feedback (although still showing strong correlation) is lapse rate, for reasons discussed above.

At decadal and interannual timescales, correlations are not as close (Fig. 8b, c). Nevertheless, statistically significant (at the 90% level) positive correlations are found for all feedbacks in Fig. 8, apart from decadal total cloud. Despite the gradients for most feedbacks being less than 1, the mean values of feedbacks seen in Fig. 8 are reasonably reproduced by the synthetic feedbacks except for decadal lapse rate and total cloud. Since there is significant scatter around lines of best fit in Fig. 8b and c, clearly factors other than a scaling of unchanged 'local feedbacks' are playing an important role in determining global feedback strength in individual models. Nevertheless, the significant positive correlations between synthetic and actual feedbacks across models and the comparable mean values (apart from those mentioned above), mean that local feedbacks can provide a first-order explanation of the comparable strengths of most feedbacks across the different timescales considered here.
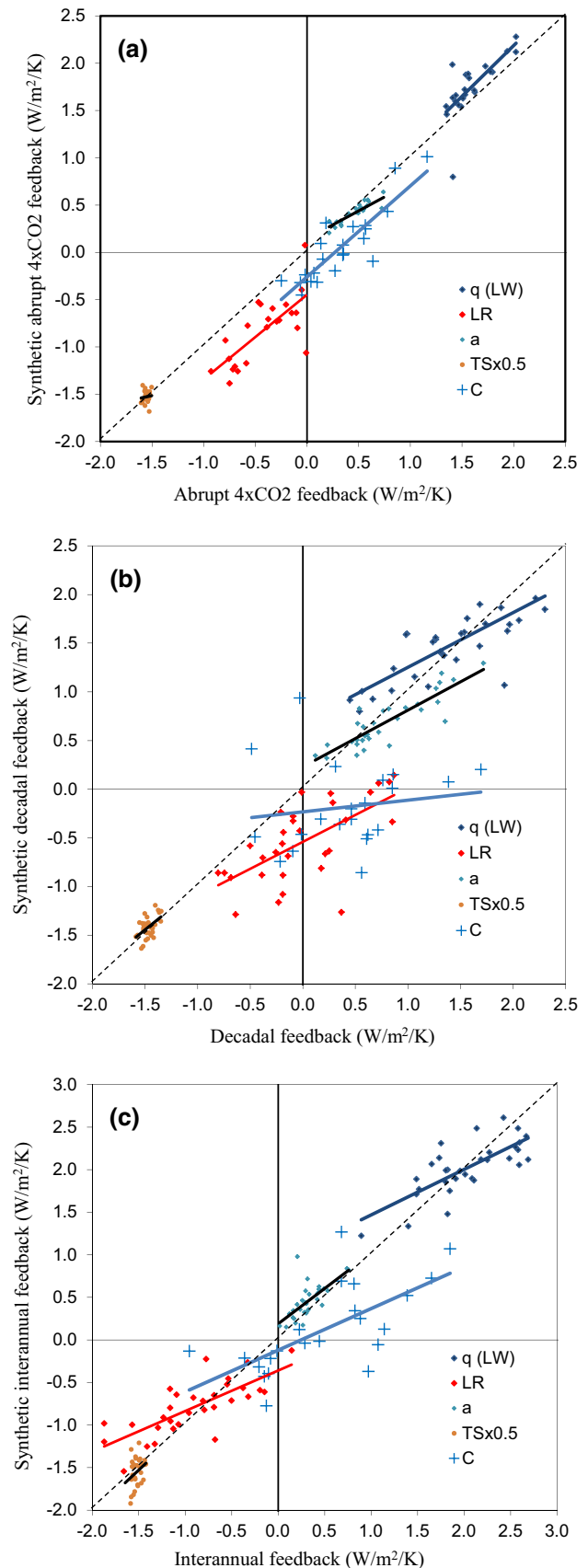
4 Summary and concluding remarks

This study has analysed feedbacks occurring in CMIP5 RCP8.5 and abrupt4xCO2 experiments, as well as for inter-annual and decadal variability from preindustrial runs. We used the 'radiative kernels' approach to evaluate Planck, water vapour, lapse rate, surface albedo and cloud feed-backs—the latter using adjusted cloud forcing (Soden et al. 2008). We compared the feedbacks themselves, as well as 'synthetic feedbacks' generated based on RCP8.5. These latter were calculated by scaling local RCP8.5 feedbacks by the relative surface temperature change in abrupt4xCO2, decadal or interannual experiments per degree of global warming. This means in effect that, for example for inter-annual timescales, the equatorial RCP8.5 feedbacks are greatly magnified in their contribution to global feedback, relative to the subtropics.

For the feedbacks themselves, for abrupt4xCO2, there is a significant positive correlation across models with RCP8.5 feedbacks, except for the Planck response. Further-more, synthetic feedbacks are able to reproduce the meridi-onal distribution of feedbacks, with the exception of high southern latitudes. These results reinforce the validity of the 'local feedback' approach of Armour et al. (2013), at least for experiments where SST changes show this degree of similarity.

For decadal and interannual feedbacks, most feedbacks do not show statistically significant correlations across models (Table 1). The exceptions to these are lapse rate feedbacks (at both timescales), LW water vapour at dec-adal, and surface albedo and total cloud at interannual. The last of these confirms the results in Zhou et al. (2015), extending them to correlations between RCP8.5 and inter-annual. The significant lapse rate and water vapour corre-lations differ from earlier results for CMIP3 models (e.g. Colman and Hanson 2013). The difference here appears to be not just that there are more models, and longer experi-ments, but importantly several 'outlying' models with particularly strong negative lapse rate feedback are absent from the CMIP5 sample. The reasons for those particularly strong feedbacks in CMIP3 models, and the absence of such models in CMIP5 warrants further investigation, but is beyond the scope of this paper. Also despite the significant correlations between lapse rate and water vapour (for dec-adal at least), combined water vapour plus lapse rate do not show significant cross model correlations.

Considering the synthetic decadal and interannual feed-backs, shows that, in principle, if local feedbacks remained invariant, high inter-model correlations with RCP8.5 would be found for all feedbacks, despite the substantial differ-ences in surface temperature response at the two time-scales compared with RCP8.5 (Fig. 3). Furthermore, the assumption of unchanging local feedbacks in many cases reproduces the multi-model mean meridional structure of feedbacks reasonably well (Figs. 4, 5) and across models show significant positive correlations across timescales for all but the Planck response (Fig. 8). Therefore, fixed local feedbacks applied to differing surface temperature response patterns provides first-order explanation of the comparable strengths of most feedbacks across both climate change (both RCP8.5 and Abrupt4xCO2), and decadal and inter-annual variability—they can be expected to be overall as strong as they are, because a simple scaling of climate change feedbacks would give those approximate values.

Another way of considering this is that very high cor-relation in Fig. 3 would indicate that the variability SST warming patterns are 'similar enough' that if local feed-backs really were invariant, then there would indeed be a very high degree of similarity in global feedback strength in individual models for variability and RCP8.5. Very high correlation in Fig. 8 would indicate not that different warm-ing patterns necessarily dictate different global feedbacks, but rather that local feedbacks are indeed close to invari-ant. In the event there is a reasonable degree of correlation in Figs. 3, 8, but it is imperfect correlation. This indicates that 'invariant local feedbacks' is a good, but not perfect assumption, and at the same time that the SST pattern differences are not so different as to imply very different global feedbacks.

The feedback from clouds, of course, has further com-plications due to the 'rapid adjustments' to forcing, so synthetic variability feedbacks based on RCP8.5 may be expected to systematically differ from the feedbacks them-selves. Nevertheless it is found here that basing synthetic feedbacks on abrupt4xCO2 (for which no rapid adjustment is seen) makes only modest difference in the meridional similarities and differences seen, although it does change the derived global feedbacks. This reinforces the findings of Chung and Soden (2015) that show neglecting the rapid adjustment introduces relatively little uncertainty for over-all understanding and comparison of feedbacks.

Significant exceptions to these conclusions occur, e.g. where meridional agreement of synthetic and actual feed-backs is poor for interannual lapse rate and LW water vapour feedback, and interannual SW and LW cloud feed-back. It is striking, then, that RCP8.5 and interannual feed-backs are significantly correlated for both lapse rate and total cloud feedback. It may be that for these feedbacks the correspondence is fortuitous, and the comparable overall strengths of the feedbacks needs further explanation. The present findings suggest these correlations should be fur-ther investigated in this light.

Further analysis would also be useful from determining variability feedbacks from a full 'local feedback' perspec-tive, whereby local radiation change is regressed against local temperature change, then globally summed. This

would provide further insight into local feedbacks by determining the extent to this reproduced the 'standard' variability feedback derived from regression of global temperature changes.

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