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RESEARCH ARTICLE

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The effect of human land use change in the Hadley Centre attribution system

Fraser C. Lott | **Nikolaos Christidis** | **Andrew Ciavarella** | **Peter A. Stott**

Met Office Hadley Centre, Exeter, UK

Correspondence
Fraser C. Lott, A2-094 Met Office, Fitzroy Road, Exeter EX1 3PB, UK.
Email: fraser.lott@metoffice.gov.uk

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Abstract

We have investigated the effects of land use on past climate change by means of a new 15-member ensemble of the HadGEM3-A-N216 model, usually used for event attribution studies. This ensemble runs from 1960 to 2013, and includes natural external climate forcings with the addition of human land use changes. It supports previously-existing ensembles, either with only natural forcings, or with all forcings (both anthropogenic and natural, including land use changes), in determining the contribution to the change in risk of extreme events made by land use change. We found a significant difference in near-surface air temperature trends over land, attributable to the effects of human land use. The main part of the signal derives from a relative cooling in Arctic regions which closely matches that of deforestation. This cooling appears to spread by polar amplification. A similar pattern of change is seen in latent heat flux trend, but significant rainfall change is almost entirely absent.

KEYWORDS

climate, ensembles, land-atmosphere

1 | INTRODUCTION

Event attribution studies (Allen, 2003; Stott *et al.*, 2013) typically examine the change in the probability of an event due to human influences. They do this by comparing an ensemble of simulations with all known external climate forcings (both anthropogenic and natural) to another ensemble with only natural forcings. However, there are cases where one might wish to compare the effect of atmospheric changes for a given land use. For example, for an analysis of an urban flooding event in Oxford such as that discussed by Allen (2003), we may wish to determine the change in event risk with the city of Oxford present in both factual and counter-factual situations. Therefore, we need to consider simulations with only natural atmospheric forcings, while still retaining anthropogenic land use changes.

To keep the simulations tied to real-world weather, observed SSTs have been used in the HadGEM3-A model (Christidis *et al.*, 2013b; Ciavarella *et al.*, 2018) to drive the all-forcings simulations, while an estimate of anthropogenic SST changes is subtracted from the observations when driving the natural-only simulations. We expand on this by running parallel simulations to those already performed, this time including human land-use changes alongside only natural forcings in the atmosphere, thus determining how much of the human component is due to land use change, and how much to emissions. In order

to do this, we must be able to estimate the size of the SST change due to land use change, so that this may be added onto the natural SST conditions.

2 | EXISTING LAND-USE-ONLY SIMULATIONS PRODUCED FOR CMIP5

As with previous studies of the total anthropogenic component (Pall *et al*., 2011; Christidis *et al*., 2013b), we rely on existing simulations with coupled atmosphere and ocean processes in order to estimate the SST changes at the boundary of atmosphere-only simulations. In this case, we require coupled simulations where land use is the only human forcing. As before (Ciavarella *et al*., 2018; Stone and Pall, 2020), the CMIP5 archive (Taylor *et al*., 2011) provides the data necessary (specifically a subset of submissions to the historicalMisc experiment which only include human land-use change), though climate modelling centres contributed far fewer such simulations than for natural forcings. This difference in availability produces an unavoidable inconsistency in model weightings between the human land use forcings and the natural forcings that can be estimated by multi-model means. Acknowledging this, these simulations, plus four members of the HadGEM2-ES model produced at the time of CMIP5 but never submitted to the archive, are used to evaluate the behaviour of SSTs with changing land use. Table 1 details the complete set of simulations used in this study.

The SST pattern was produced for each simulation from the surface air temperature over grid boxes with a land fraction of 20% or less. Surface air temperatures were both more readily available than the reported skin temperature from the ocean simulation, and judged to be more consistently defined across models (Jones, 2020). These patterns were produced for the 1960–2013 period as per the initial natural-only simulations. Interannual variability was smoothed using a 5-year boxcar filter, and the spatial field was regridded to the $1 \times 1^{\circ}$ grid used in NOAA OISST version 2 (weighted by area with a missing-data tolerance of one third), all as defined by Stone and Pall (2020).

To compute the magnitude of change caused entirely by land use, a baseline is required. This was established by using the "pre-industrial" (i.e., as free as possible of external climate forcings) control runs of each model. Slices of the control of equivalent length to the land-use simulations (i.e., 53 years) were extracted by the method above. Five such slices could be extracted from the shortest available control run (that of GISS-E2-H), so an equal number was extracted from each other model to ensure that the noise contribution of each model is equivalent. The mean of the five control slices of a given model was subtracted from each member of its ensemble of land-use-driven simulations. A multi-model mean SST change was then computed for each month in the period by averaging all the land-use simulations, treating each member of the ensemble equally irrespective of the underlying climate model.

This SST change field driven by human land use change may now be added to that of previously-used natural-only SST changes (Christidis *et al*., 2013b; Ciavarella *et al*., 2018) to form the boundary conditions of our anticipated experiments on the effect of land use on extreme events. However, we may also make some useful observations of the SST changes themselves.

TABLE 1 List of available CMIP5 simulations driven by human land use only

Model	Number of members driven by human land use only
CanESM2	5
CCSM4	3
GFDL-ESM2M	1
GISS-E2-H	5
GISS-E2-R	5
HadGEM2-ES	4
	Total: 23

3 | MODEL-DERIVED SPATIAL PATTERNS OF SST CHANGE

Initial examination of the effect of human land use changes on SST was made using the four members of HadGEM2-ES. These are illustrated in Figure 1 (bottom right) as the mean difference between the most recent complete decade (1996–2005) and the climatological period 1961–1990, chosen to match observation datasets such as HadCRUT4 (Morice *et al*., 2012). A Kolmogorov–Smirnov test is used to compare the distribution of monthly SSTs in these two periods, and the regions whose differences are not significant at the 1% level are shaded out. Though the cooling in this plot might be expected, and has been particularly noted in this model (Andrews *et al*., 2017), the strength in parts of the polar regions and the global extent might be surprising. It has been argued (Brovkin *et al*., 2013; Lorenz *et al*., 2016) that land use effects only have teleconnections of limited range. We might therefore only expect to see regional effects, and the strength of cooling at the poles would not seem to fit with this. However, one could argue that the polar amplification seen in other studies of climate change (Holland and Bitz, 2003) would also apply here.

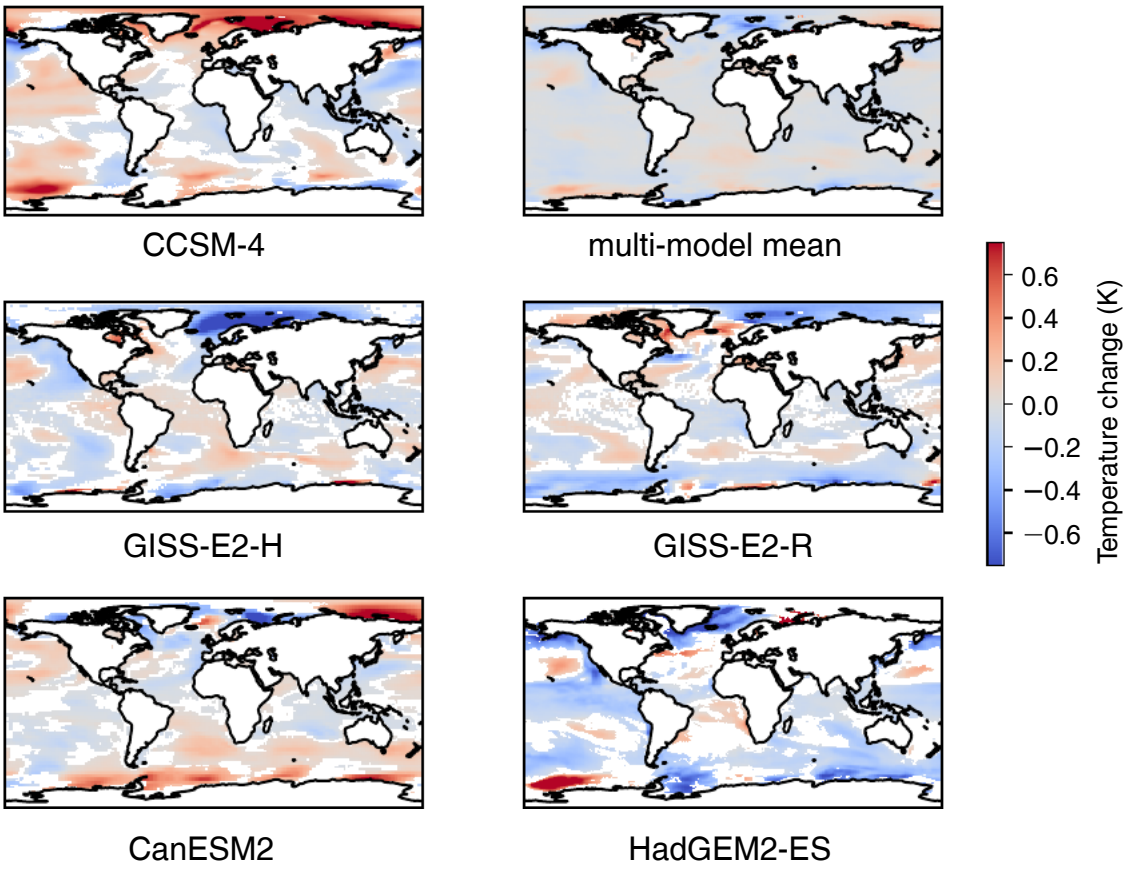

FIGURE 1 Changes in sea surface temperature (SST, in Kelvin) due to human-induced land use change only, showing the difference between the 1996–2005 average and the 1961–1990 average for each of the CMIP5 models in Table 1 consisting of multiple members, plus the multi-model mean. Individual models have regions where change is not significant at the 1% level shaded out in white. The full field is shown for the multi-model mean, to illustrate the SST boundary conditions used for subsequent atmosphere-only simulations

Thus once land use change cools SSTs relatively locally, we could then expect this cooling to be even stronger at the poles. Since the sea ice coverage for the atmosphere-only simulation (detailed in the following section) is computed based on SST, this is of some relevance. By contrast, the pattern of temperature change in the rest of the world is still within the range encompassed by natural internal variability.

If we now examine the other models' SST change patterns (also shown in Figure 1, not including the single member of GFDL-ESM2M), it becomes clear that the strength of cooling particular to HadGEM2-ES is not fully reproduced by other models. CanESM2 has a reduced strength of change globally, with no overall sign. The change still appears to be enhanced at the poles, but this seems to result in a mixture of strong heating and cooling in the Arctic, and only heating in the Antarctic. CCSM4 has a similar lack of overall signal in the low latitudes to CanESM2, but has a strongly warming Arctic and both warming and cooling in the Antarctic.

Both GISS models have a somewhat smaller polar change. This is broadly cooling in the Arctic for GISS-E2-H and mixed in the Antarctic, with the usual weaker change in the lower latitudes. GISS-E2-R however, exhibits low latitude change which is near the level of that in the Arctic, with only the Antarctic being somewhat stronger.

It is clear that there is some disagreement between models in ocean areas, particularly at the poles. However, there are common factors, which can be clarified by examining the multi-model average SST change (Figure 1, top right). This was performed considering each member equally, irrespective of model, so that the internal variability from the single member of GFDL-ESM2M would not be overweighted.

The notable features, such as cooling in the Greenland-Iceland-Norway Sea or warming in the Southern Ocean, are only an average signal across models, and there is no common sign across all realizations. Nonetheless, this represents our best estimate of the effect of human land use changes on sea surface temperatures. The SST changes illustrated by these plots will now be used to compute the boundary conditions for the event attribution simulations that follow.

4 | ATMOSPHERE-ONLY EXPERIMENTAL SETUP

The SST changes derived above were combined with those produced for the C20C+ project (Stone and Pall, 2020) which estimate the difference between SST in an all-forcings world and one with only natural climate forcings. In turn, this was used to provide the SST and calculate the sea ice boundary conditions for an ensemble of HadGEM3-A-N216 atmosphere-only simulations (Ciavarella *et al.*, 2018). New simulations were then created using the atmospheric setup from natural-only runs of HadGEM3-A-N216, but adding in the variation in land use from the all-forcings runs, as well as the SST changes calculated above. These are referred to hereafter as Nat + LU simulations. The land use varies in time according to values pre-computed by the ISAM-HYDE scheme, derived from harmonizing the HYDE3.1 dataset with satellite data. It differs from HadGEM2-ES (the Met Office model contributed to CMIP5), which uses TRIFFID interactive vegetation in addition to HYDE3.1 data. For more details, compare Ciavarella *et al.* (2018) to Jones *et al.* (2011).

The choice to produce a Nat + LU ensemble rather than, for example, all forcings minus land use change, is to enable future impact-focussed event attribution studies to directly compare the distribution of events of interest in the Nat + LU ensemble to that with all forcings. Desirable or not, this has the effect of combining all of our uncertainty (the difference between the all-forcings and natural worlds, plus the difference between pre-industrial and modern-day land use) into a single ensemble.

To help understand which land use changes have resulted in changes in the climate, Figure 2 shows the changes from 1880 to 2010 for the nine different land uses identified in the model (the MOSES-II tile types described in Ciavarella *et al.* (2018)). This period was intended to represent the difference between Nat + LU and the natural-only ensemble.

5 | LAND TEMPERATURE TIME SERIES

As an initial comparison, the time series of mean near-surface air temperature was computed over land, then smoothed using a 5-year moving average in order to remove major atmospheric modes of variability. In doing so, we choose to eliminate seasonal variations, and we leave evaluation of extremes for future attribution studies using the relevant index. This series was compared between Natural-only and Nat + LU ensembles. As can be seen in Figure 3a, the two ensembles yield very similar time series, emphasized by the shared phase of internal variability and natural forcings. It is unclear from such a plot whether there is a significant difference between the two ensembles, though, from previous studies such as Andrews *et al.* (2017), we would expect a net cooling effect from human land use. This is remedied by examining the distribution of linear trends across the ensembles, shown in Figure 3b.

We can easily see by eye that the two trend distributions are significantly different. However, the globally-averaged land temperature is only one part of the story.

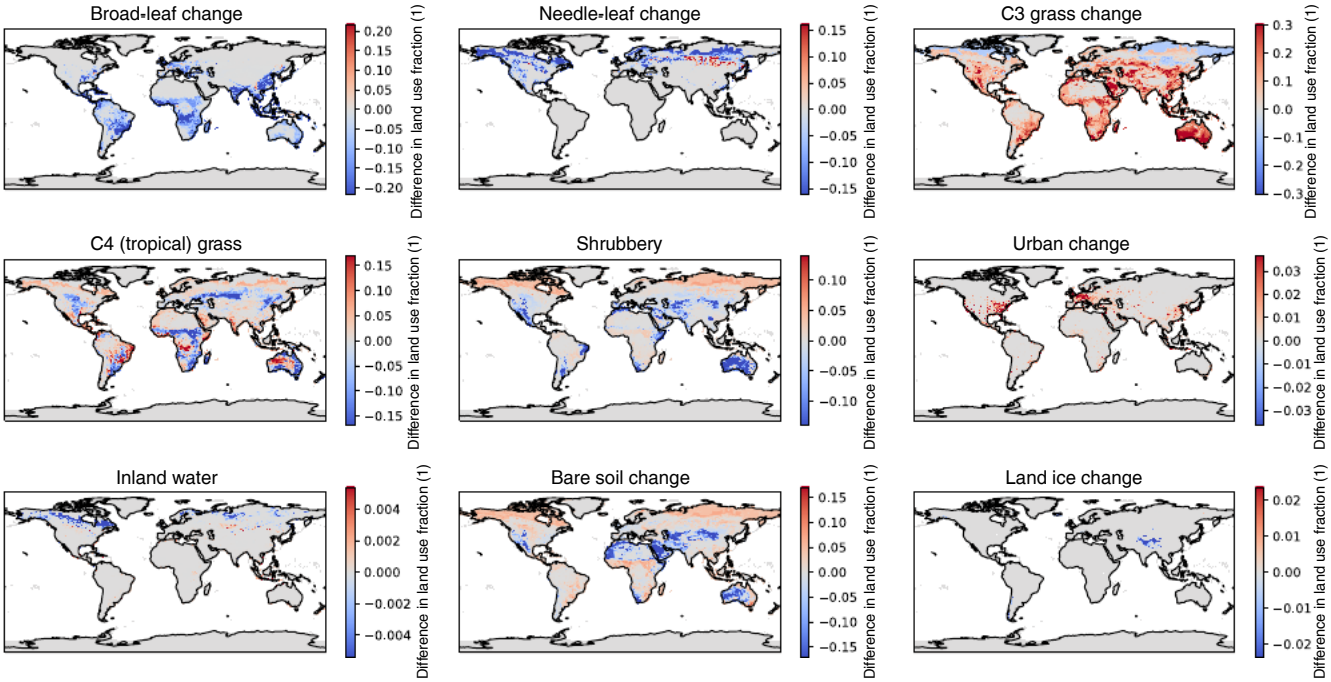

FIGURE 2 Fractional land use changes from 1880 to 2010 for each of the nine modelled uses in HadGEM3-A-N216

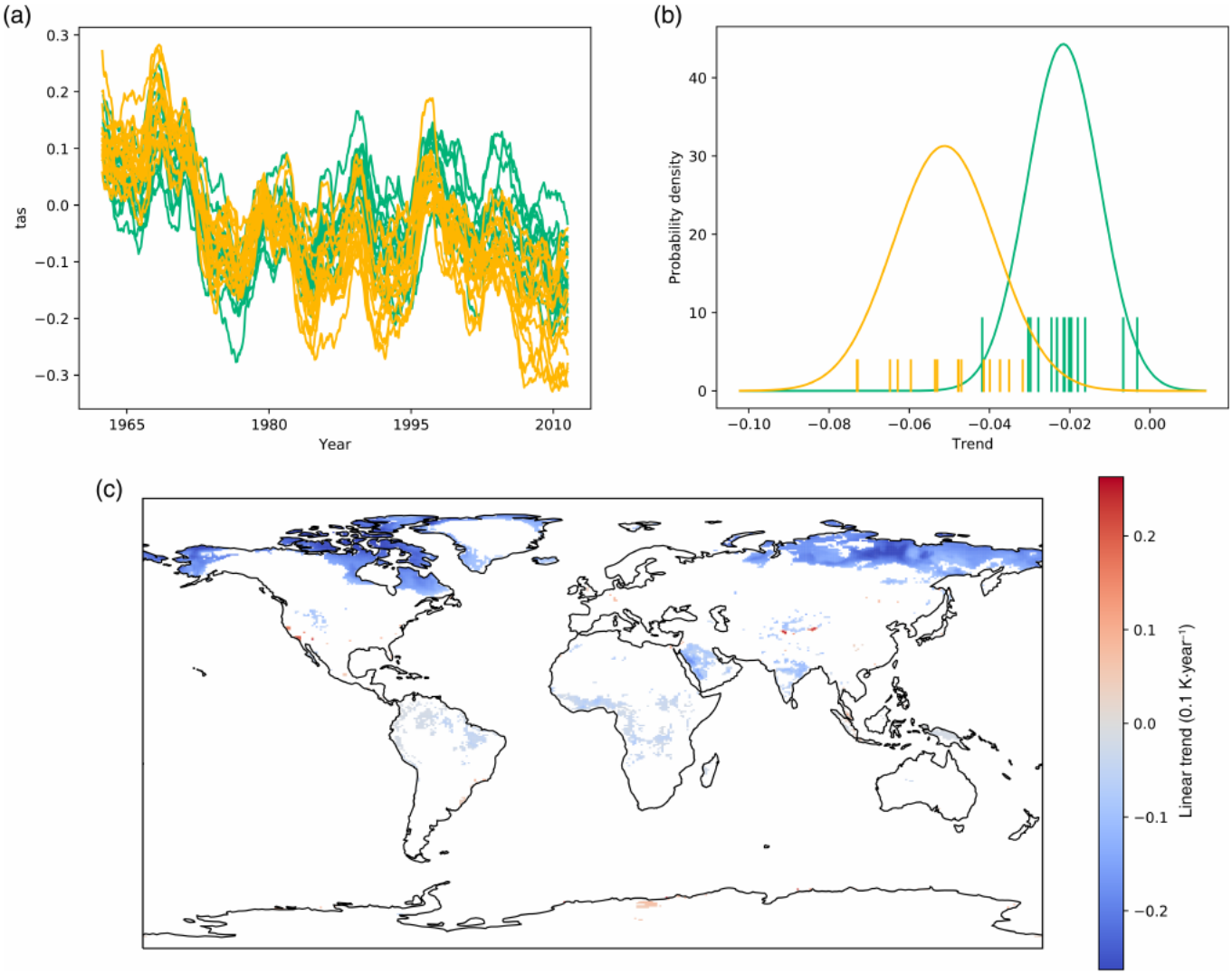

FIGURE 3 (a, above left) Time series of mean near-surface air temperature (tas) anomaly (in Kelvin, relative to the 1961 to 1990 period) over land, smoothed using a 5-year moving average. Fifteen members of the natural-forcings-only ensemble are shown in green, while the gold lines are the 15 natural plus land-use forcings members. (b, above right) Linear trends in the time series (in Kelvin per decade) shown as vertical lines for each natural-only simulation (green) and Nat + LU simulations (gold). Gaussian fits to the distributions are also shown. (c, below) Grid-box trend in mean near-surface air temperature (Kelvin per decade) difference between the Natural-only and Nat + LU simulations. We only include those grid boxes where the difference in trends between Natural and Nat + LU are significant at the 1% level according to a Kolmogorov–Smirnov test

Consequently, the time series of Natural-only was subtracted from that of Nat + LU on a grid-box scale, then linear trends were computed. The map of temperature changes over land in Figure 3c was produced, excluding those grid boxes where the Natural and Nat + LU trends were not found to be significantly different at the 1% level using a Kolmogorov–Smirnov test.

The difference in temperature trend is significant in a number of regions, particularly in the northern polar regions. This explains the SST pattern cooling pattern seen in the Arctic, particularly in HadGEM2-ES (Figure 1) since it is of the same family of models, and supports the theory that polar amplification is spreading land-based cooling over the sea. Previous work (Christidis *et al.*, 2013a) has suggested that deforestation for the expansion of grassland appears to be the principal cause of climatic changes due to land use. Figure 2 would appear to support this to some degree, though this pattern is arguably most closely matched by the rise in bare soil and shrubs, rather than the deforestation itself. Snow-covered bare soil and grasses in polar regions would certainly have the high reflectivity which could result in polar feedback.

Note that we might expect skin temperature to have a closer relationship with land use than does 1.5 m air temperature (Monteith, 1981). However, on examination of the simulations, the plots produced for the two variables

were indistinguishable, and hence only air temperature is shown.

6 | PRECIPITATION CHANGES

Figure 4 compares the simulated precipitation with and without human land use change. Neither the time series nor the trend distributions appear to be significantly different by eye, and this is borne out by quantitative significance testing on the grid-box scale. The most extensive regions of significance are on the equatorial Atlantic coasts, both of which show a wetting trend. This is particularly large in Brazil. Beyond this, the very low fraction of significant grid points would suggest that most are locally significant by chance, which fits with the inherent noise in rainfall fields.

7 | LATENT HEAT FLUX

Since latent heat flux has a close link to evapotranspiration (Monteith, 1981), we might expect this to be more closely linked to land use changes than precipitation. The time series in Figure 5 show little difference by eye between the two ensembles, but the trend distributions are far more obviously distinguishable. Note there is spin-up still visible in the first year of data in the time series. However, the presence of this feature makes no appreciable difference to the trend distributions.

Plotted by grid box, latent heat flux shows a similar decreasing trend pattern in the Arctic that was seen in temperature, but other regions are now evident too. There is also a strong reduction in Southern China and Southern Brazil, and a strong increase upstream of the Rio de la Plata. Since there is no single change in land use in Figure 2 where all these areas have the same sign to correspond with the change in latent heat flux, it is likely there is a combination of changes behind this, though the rise in bare soil and shrubbery would, once again, seem major components.

It is notable that none of the variables examined here show any spatial correlation with the urbanization in Figure 2. This means that areas such as China, which have seen significant land use changes in recent years,

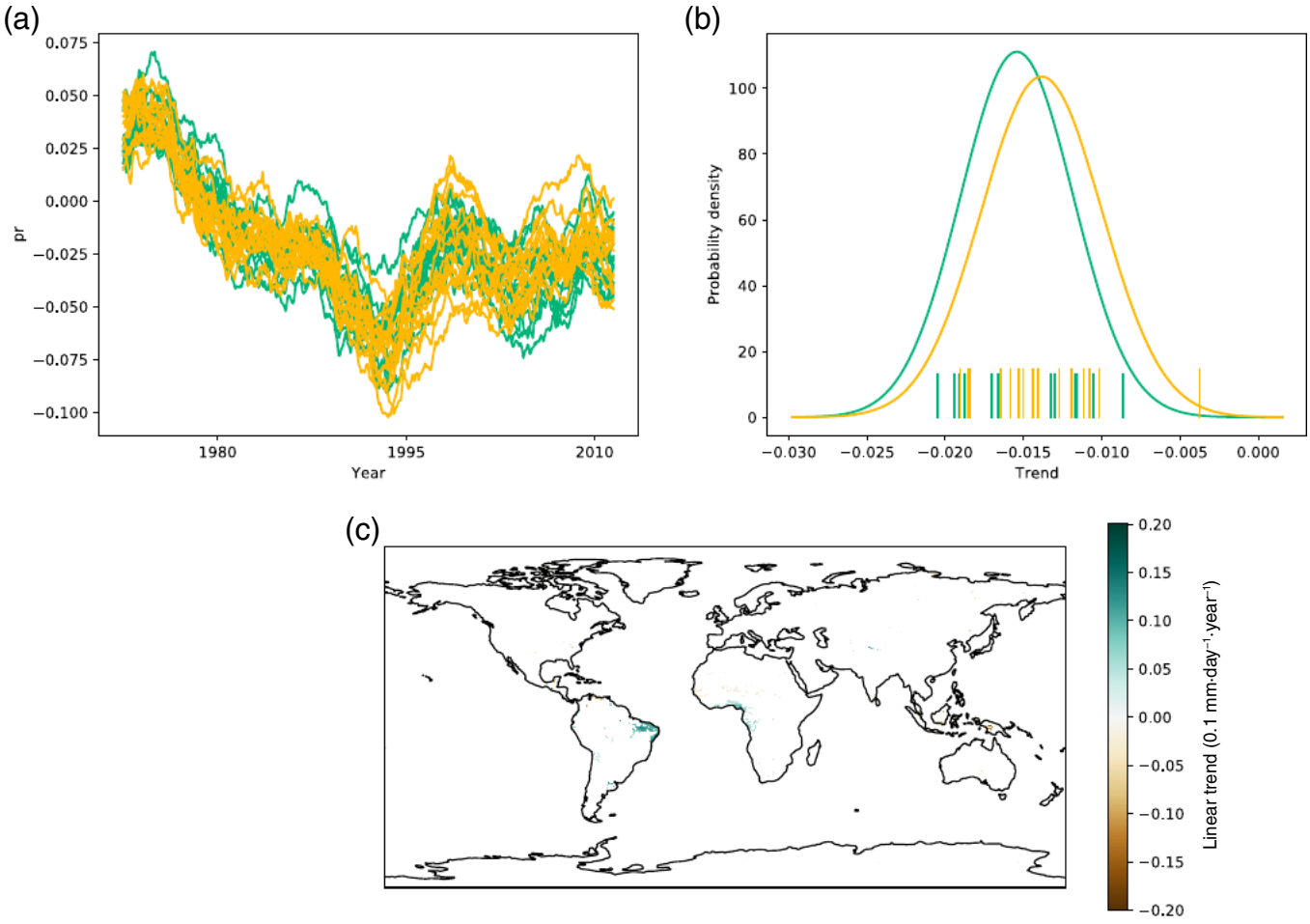

FIGURE 4 As Figure 3, but for precipitation anomaly, in mm per day, or mm per day per decade for trends

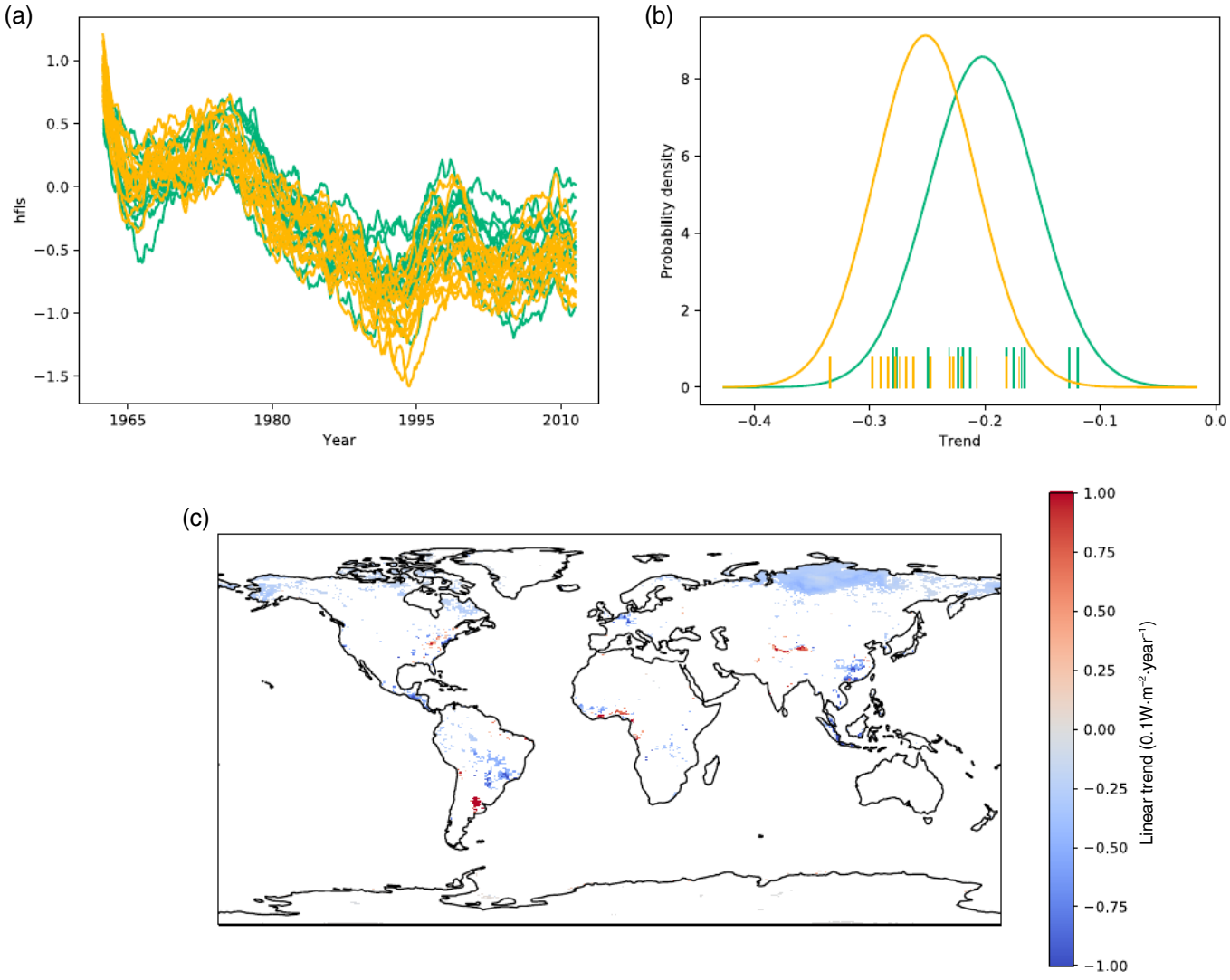

FIGURE 5 As Figure 4, but for latent heat flux trend, in $W \cdot m^{-2}$ (per decade for trends)

have seen relatively little change in their climate by urbanization. This in turn will be dependent on the urban dataset (CCI LC) used to drive HadGEM3-A-N216. The spatial consistence of this dataset is discussed by Hua *et al.* (2018). A more interesting phenomenon for studies in Southern China is the drop in latent heat flux matching an increase in areas of bare soil. The depletion of broad-leaf forest and the rise of C3 grasses in that region also appears to drive little or no climate change.

8 | CONCLUSIONS

We find many areas where there are changes in climate in the immediate area of land use change, though further research is required to clarify the mechanisms and specific correlation between land use and climate. Larger changes are found in temperature and latent heat flux trends, while precipitation shows little change. Northern polar regions see the largest change, particularly in temperature. This coincides with an increase in bare soil, which would suggest cooling from an increased albedo. A corresponding cooling found in Arctic SST changes would then produce a polar feedback effect, which could spread that cooling over a much larger region than seen in other parts of the world. In the case of this study, this causality is complicated by the SSTs deriving from coupled models, and thus it is possible for there to be an effect on the HadGEM3-A-N216 atmosphere due to land use changes in a different model feeding through the SSTs. However, we believe that the technique we have used is consistent, since the land use is changed in both models, and thus this is valid for proceeding to use these simulations for future attributions studies incorporating the effect of land use.

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ORCID

Fraser C. Lott https://orcid.org/0000-0001-5184-4156

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