Answer to anonymous Referee #3

We thank the anonymous Referee for her/his comments and suggestions. We answer point by point in the following with the Referee's comments added in *red/italics*. Text added to the revised version of the manuscript is included here in *blue/italics*.

I find the study of high interest and worthy of publication. I do provide some comments below for consideration. In brief, these focus firstly on the solar irradiance dataset aspect of the study. I find the adoption of a common spectrum from which to baseline differences in the solar cycle 'amplitudes' of the various datasets novel. Secondly, the messaging of the study could be improved to provide the background of why the study was undertaken.

SSI comments

a. The general reader may be unclear why it was necessary to use 5 different SSI datasets, or why you chose the ones you did, or even that there isn't agreement across SSI datasets on longer time scales (observed or modeled). I would suggest adding a paragraph or two to improve the messaging behind your study, probably in the Intro or in Section 2.

We have chosen these five SSI data sets, as they are available for long time periods. Therefore they are of special interest for climate modellers in simulations that cover these long time periods. We have added this sentence to the introduction of Section 2.

The SSI/TSI reconstructions of SATIRE, NRLSSI/TSI, and the combination of both in the CMIP6 SSI/TSI data set, are the most common SSI/TSI data sets used in GCMs and CCMs and, therefore, subject to our investigation.

b. I agree that TSI observations are relatively short (since 1978) and that SSI observation record is even shorter, nor full spectral coverage, and has time gaps. However, your study does select a relative short period of time to investigate the impacts of SSI over (1989-1994). Therefore, it begs the questions of why that particular time range and not another when full spectrum observations existed (i.e. during the SORCE era) or even partial spectrum observations (265-500 nm) by the AURA OMI instrument. In essence, I'm asking you to more directly draw the line between your "focused" study and the SSI dataset needs of the model intercomparisons studies like CMIP6 which require full spectrum and very long time coverage. This leads to necessary use of modeled SSI datasets, which have differences between them and with observations. It would be helpful to bring the discussion of the Coddington et al and Yeo et al. results (Page 6, line 7 through end of paragraph) in earlier in the section for this reason.

We have moved the paragraph to the introduction of Section 2.

However, there is an ongoing debate about the reliability of TSI and SSI reconstructions. Coddington et al. (2019) compare solar amplitudes of 11–year solar cycles in the satellite period produced with the NRLSSI2 and SATIRE-S for a number of broad wavelengths bands to SSI amplitudes derived from the SOLID composite. In the FUV spectral region they report the highest SSI amplitude for the SATIRE-S data set and a negative secular interminima trend over the satellite period in the SATIRE-S TSI and SSI from the FUV to NIR spectral regions which is not present in any observational record or other TSI/SSI reconstructions. Yeo et al. (2015) compare the SSI variability of NRLSSI1 and SATIRE-S with SSI observations over the satellite period and report the low UV variability of NRLSSI compared to the SATIRE-S data set, whereas the latter is in better agreement to the satellite SSI observations.

c. I do like that you've chosen a single spectrum to adopt as a common baseline for solar minimum conditions. I feel that's quite novel. I am concerned, though, that the manuscript doesn't adequately address how this approach might impact results. You do say that a reference baseline would lead to a certain climatology state (end of page 13 to page 14) and that differences from that baseline, as would occur from using SOLAR-ISS as the reference, would result in a different climatology. However, is it necessarily true that the solar response variations are truly linear from an adopted baseline? Maybe more clear way to ask is whether gas phase reaction rates or water vapor abundances that you mention on page 14 might "bottom out" or "max out" if the baseline climatology/temperature was too high or too low? I would also suggest bringing this discussion up earlier, in addition to where it is in the conclusions.

It is true that the adaptation of atmospheric processes and gas phase chemical reactions to a different reference spectrum or a different solar cycle amplitude is not necessarily linear. However, the differences in the reference spectrum or the solar cycle amplitude are relatively small and the expected changes in temperature should not be that large to reach "bottom out" or "max out" effects in the chemistry.
We have moved the discussion about alternative reference spectra and different solar cycles to Section 2. The respective part in Section 7 is shortened.

d. In conclusions you also discuss how choosing SC 22 (selected, I understand, because of time range of ATLAS 3 observations) should be reflective of other solar cycles in the 21st century. You examined the irradiances in the Lyman alpha through UV for the various SSI datasets with other solar cycles and found a linear relationship. Was that relationship with TSI magnitude, sunspot number, or something else?

The nearly linear relationship of the SSI solar cycle amplitude applied in the paper with other solar cycle amplitudes refers to the wavelength dependency of the scaling factor which can be used to convert one solar cycle amplitude to another. Within one SSI data set there exist a nearly linear scaling factor for wavelengths from 121 to 280 nm among different solar cycle amplitudes. We agree that this sentence is confusing and therefore have removed it.

To better classify the solar amplitude used in the paper, we compare it with other possible solar amplitudes. The Table 1 (Table S1 in the supplement) includes the ΔSSI and $\frac{\Delta SSI}{\Delta TSI}$ of other solar cycle amplitudes. The average and the standard deviation over these solar cycles is given in Table 2 (Table S2 in the supplement). We have added the following paragraph to Section 2. The Figure 1 is now included in the manuscript as the new Figure 2.

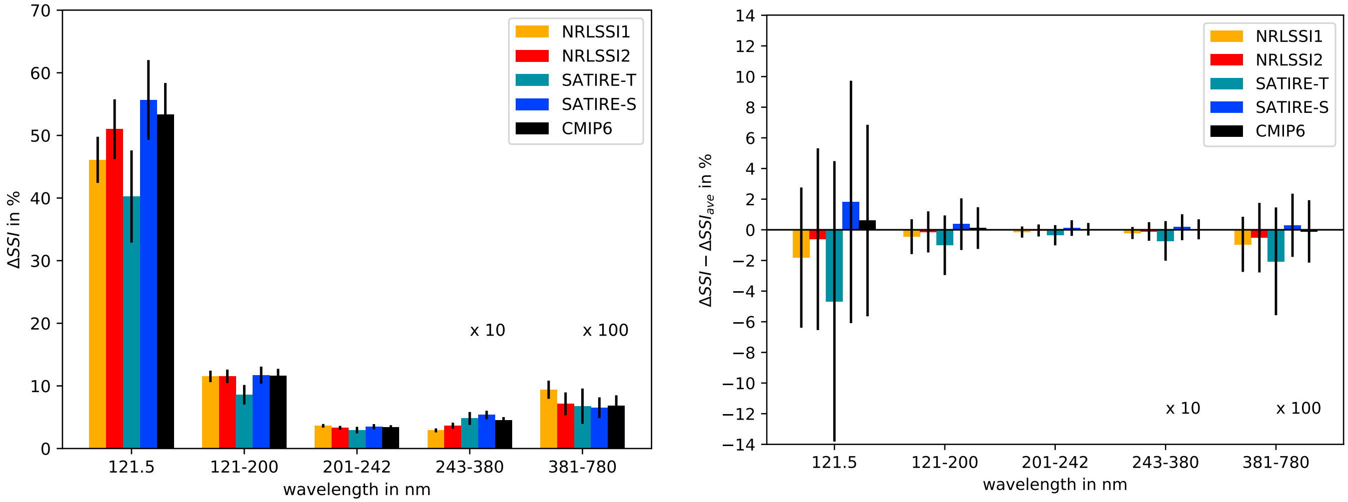
Compared to other solar cycle amplitudes in the satellite era (see Table S1 in the supplement), the one used in this study is neither especially weak nor especially strong. The averaged ΔSSI is shown in Figure 2a, with the error bars indicating the 95% confidence interval of the ΔSSI within each spectral region. The main characteristics of the solar amplitude chosen here are also present in the averaged solar cycle amplitude, such as the small solar amplitude of SATIRE-T in the FUV and most of the ranking of the SSI data sets within the spectral regions. All deviations of the chosen solar cycle amplitude from the averaged solar cycle amplitude are within the range of the 95% confidence intervals (Figure 2b). Therefore, the selected solar cycle amplitude can be regarded as representative for most of the solar cycle amplitudes of the satellite era.

Table 1. Solar cycle spectral solar irradiance variations for Solar Cycles indicated in the first row relative to ATLAS3 (ΔSSI) in % and relative contribution of SSI changes to the TSI change ($\frac{\Delta SSI}{\Delta TSI}$) in % for the Lyman-$\alpha$ (121.5 nm), Far-UV (121–200 nm), Herzberg continuum/Hartley bands (201–242 nm), Hartley-/Huggings-bands (243–380 nm) and visible (381–780 nm) spectral ranges.

Time period	SSI dataset	121.5 nm		121–200 nm		201–242 nm		243–380 nm		381–780 nm	
		ΔSSI	$\frac{\Delta SSI}{\Delta TSI}$	ΔSSI	$\frac{\Delta SSI}{\Delta TSI}$	ΔSSI	$\frac{\Delta SSI}{\Delta TSI}$	ΔSSI	$\frac{\Delta SSI}{\Delta TSI}$	ΔSSI	$\frac{\Delta SSI}{\Delta TSI}$
Cycle 21 descent Max:Dec.1979 Min:Sep.1986	NRLSSI1	45.602	0.214	11.373	0.913	3.599	4.300	0.311	20.748	0.109	55.521
	NRLSSI2	51.609	0.228	11.668	0.882	3.360	3.778	0.402	25.251	0.095	45.247
	SATIRE-T	47.283	0.199	10.081	0.724	3.445	3.684	0.592	35.363	0.106	48.028
	SATIRE-S	47.178	0.281	9.907	1.008	2.987	4.523	0.477	40.368	0.069	44.130
	CMIP6	49.405	0.250	10.788	0.932	3.175	4.080	0.440	31.585	0.082	44.785
Cycle 22 ascent Max:Nov.1989 Min:Sep.1986	NRLSSI1	50.740	0.250	12.673	1.067	3.994	5.006	0.319	22.315	0.104	55.470
	NRLSSI2	56.657	0.273	12.808	1.053	3.668	4.488	0.407	27.845	0.081	42.196
	SATIRE-T	44.322	0.247	9.454	0.899	3.235	4.580	0.529	41.801	0.075	45.107
	SATIRE-S	59.989	0.331	12.634	1.191	3.756	5.269	0.576	45.149	0.070	41.540
	CMIP6	58.338	0.300	12.722	1.117	3.715	4.855	0.492	35.938	0.076	42.139
Cycle 22 descent-2 Max:Nov.1989 Min:Nov.1994	NRLSSI1	44.286	0.266	11.067	1.137	3.482	5.324	0.268	22.913	0.084	54.902
	NRLSSI2	50.377	0.291	11.388	1.125	3.257	4.788	0.354	29.039	0.066	41.415
	SATIRE-T	35.572	0.297	7.576	1.081	2.583	5.486	0.407	48.288	0.047	42.340
	SATIRE-S	57.481	0.329	12.090	1.183	3.601	5.244	0.552	44.874	0.068	42.130
	CMIP6	53.943	0.309	11.741	1.149	3.431	4.997	0.453	36.855	0.068	41.856
Cycle 22 descent Max:Nov.1989 Min:Jun.1996	NRLSSI1	49.420	0.250	12.343	1.066	3.890	4.999	0.311	22.306	0.102	55.503
	NRLSSI2	53.857	0.279	12.175	1.078	3.485	4.594	0.384	28.299	0.075	42.076
	SATIRE-T	46.024	0.233	9.820	0.848	3.363	4.321	0.557	39.972	0.085	46.134
	SATIRE-S	64.121	0.304	13.546	1.096	4.044	4.869	0.629	42.293	0.085	43.436
	CMIP6	59.005	0.291	12.862	1.083	3.767	4.722	0.507	35.494	0.080	42.850
Cycle 23 ascent Max:Mar.2000 Min:Jun.1996	NRLSSI1	40.457	0.286	10.116	1.223	3.177	5.716	0.237	23.772	0.070	53.692
	NRLSSI2	42.445	0.360	9.594	1.388	2.730	5.879	0.274	32.971	0.040	36.438
	SATIRE-T	27.988	0.383	5.989	1.399	2.066	7.180	0.312	60.660	0.025	37.320
	SATIRE-S	49.546	0.473	10.446	1.704	3.041	7.380	0.439	59.580	0.034	35.442
	CMIP6	46.007	0.407	10.021	1.514	2.887	6.492	0.357	44.849	0.037	35.713

Table 2. Solar cycle SSI variations for an average of five Solar Cycle amplitudes relative to ATLAS3 (ΔSSI) in % and relative contribution of SSI changes to the TSI change ($\frac{\Delta SSI}{\Delta TSI}$) in % for the Lyman-$\alpha$ (121.5 nm), Far-UV (121–200 nm), Herzberg continuum/Hartley bands (201–242 nm), Hartley-/Huggings-bands (243–380 nm) and visible (381–780 nm) spectral ranges. $\pm$ 95% CI indicates the confidence interval.

Time period	SSI dataset	121.5 nm		121–200 nm		201–242 nm		243–380 nm		381–780 nm	
		ΔSSI	$\frac{\Delta SSI}{\Delta TSI}$	ΔSSI	$\frac{\Delta SSI}{\Delta TSI}$	ΔSSI	$\frac{\Delta SSI}{\Delta TSI}$	ΔSSI	$\frac{\Delta SSI}{\Delta TSI}$	ΔSSI	$\frac{\Delta SSI}{\Delta TSI}$
Average Cycle	NRLSSI1	46.101	0.253	11.514	1.081	3.628	5.069	0.289	22.411	0.094	55.018
	$\pm$ 95% CI	4.576	0.029	1.138	0.127	0.363	0.578	0.039	1.228	0.018	0.871
	NRLSSI2	50.989	0.286	11.527	1.105	3.300	4.705	0.364	28.681	0.071	41.474
	$\pm$ 95% CI	5.931	0.053	1.341	0.203	0.393	0.843	0.061	3.098	0.023	3.533
	SATIRE-T	40.238	0.272	8.584	0.990	2.938	5.050	0.479	45.217	0.067	43.786
	$\pm$ 95% CI	9.150	0.079	1.945	0.291	0.660	1.504	0.129	10.883	0.035	4.617
	SATIRE-S	55.663	0.344	11.725	1.236	3.486	5.457	0.535	46.453	0.065	41.335
	$\pm$ 95% CI	7.910	0.084	1.685	0.302	0.510	1.241	0.085	8.435	0.021	3.832
	CMIP6	53.340	0.311	11.627	1.159	3.395	5.029	0.450	36.944	0.069	41.468
	$\pm$ 95% CI	6.249	0.065	1.362	0.239	0.411	0.988	0.065	5.392	0.020	3.792



(a) Solar Cycle amplitude average

(b) Anomaly of Solar Cycle 22 (descent-2)

Figure 1. (a) Averaged solar cycle SSI variations for solar cycle amplitudes relative to ATLAS3 (ΔSSI) in % for the Lyman-α (121.5 nm), Far-UV (121–200 nm), Herzberg continuum/Hartley bands (201–242 nm), Hartley-/Huggings-bands (243–380 nm) (multiplied by a factor of 10) and visible (381–780 nm) (multiplied by a factor of 100) spectral ranges; with the standard deviation indicated as error bar. (b) Anomaly of SSI variations for solar cycle 22 (descent-2) with respect to the averaged solar cycle shown in (a).

In the Coddington et al., 2019 paper you reference, their Tables 3 and 5 show a larger change in integrated SSI (in the 100-200 nm bin) from solar cycle to solar cycle than occurs in differences across some of the datasets you use in your study. Similar to the above comment, you might want to bring this up earlier in Section 2 as well.

The values in the Tables 3 and 5 of Coddington et al. (2019) are given in W m^{-2} whereas the values of Table 1 in our study are given as percentage changes. When the values of Coddington et al. (2019) for the SSI range from 100 to 200 nm are converted to percentage changes, these value are not in contradiction to our values.

	$\frac{\Delta SSI}{\Delta TSI}$ NRLSSI2	$\frac{\Delta SSI}{\Delta TSI}$ SATIRE-S
Coddington et al. (2019) (100–200 nm)	1.17%	1.20%
Table 1 this study (120–200 nm)	1.13%	1.19%

The values of Coddington et al. (2019) are slightly larger, as they are calculated for the full descending phase of solar cycle 22 which ended in September 1996, whereas in our study we use November 1994 as solar minimum.

e. It's possible this is jargon in the CCM community, but is it typical to use phrases of 'solar cycle response' for simulations where the transition from perpetual solar minimum to perpetual solar maximum is quite abrupt?

In this study, where time slice simulations for solar minimum and maximum conditions are analysed, it is justified to interpret the significant differences between the time slice at solar maximum and solar minimum as the "solar response". The only parameters that changed are the prescribed SSI and TSI values.

General comments

Page 2, lines 24 – 29: The end of the one paragraph is focusing on the CCM model "spread" caused by differences in spectral resolutions of the shortwave radiation parameterizations or photolysis in the models. The next paragraph begins with different spectral distribution of the SSI data set also impacting CCM models. In the 2nd case, you are referring to the magnitude of the SSI within a spectral bin and not differences in spectral resolution of the SSI observations, but this could easily be confused during the transition of one paragraph to the next.

As requested by Reviewer 2, we have extended the paragraph about the model specific influences on the solar response. To better separate the SSI data set influences on the climatological state from the model influence on the solar response, we have added an introductory sentence.

The SSI data prescribed in the models are the second source of uncertainty when modelling the solar response. Shapiro et al. (2011) investigated the influence of the 27-day variations of four different SSI observation on the chemistry of the upper mesosphere in a 1D radiative convective chemistry model. The deviant solar cycle behaviour of the SORCE measurements has motivated a number of CCM studies (e.g. Haigh et al., 2010; Merkel et al., 2011; Ball et al., 2011, 2016; Swartz et al., 2012) comparing simulations prescribing SORCE (Solar Radiation and Climate Experiment) SSI data and reconstructed SSI of the Naval Research Laboratory SSI (NRLSSI) or the Spectral And Total Irradiance REconstructions (SATIRE) model.

Page 3, line 3-4: You end with "the effects of the 11-year solar cycle differences in spectral distribution and amplitude . . . ". However, by adopting the common reference baseline spectrum, you have removed the effects of spectral distribution from the study. It's clear from your earlier text what you mean and that it's just an error here.

The spectral distribution of the SSI amplitudes differs between the five SSI data sets. These charcteristics are preserved even when a common reference SSI is used for the solar minimum.

Page 4, line 12: What type of scaling did you apply to make ATLAS 3 integrate to SORCE TIM TSI? Wavelength independent? "The extended ATLAS-3 spectrum was then scaled to obtain . . . "

The applied scaling is wavelength independent. The integrated original ATLAS-3 SSI data (0.1 to 2395 nm) amounts to 1330.2 W m^{-1}. Adding the missing longer wavelengths requires (i) to scale the NRLSSI1 data set to the same SSI value at 2,395 nm as ATLAS-3, and (ii) to scale the SATIRE-S data set to the same SSI value at 99,975 nm as the combined ATLAS-3/NRLSSI1 sata set before the three SSI data sets are combined. The combined ATLAS-3/NRLSSI1/SATIRE-S SSI data set results in a TSI of 1382.9 W m^{-1} and therefor the extended ATLAS3-3 SSI data are scaled with a constant factor of 0.9842, to achieve a TSI of 1361.05 W m^{-1}. We have changed the text to:

To assure smooth transitions at 2,395 and 99,975 nm, the NRLSSI1 and SATIRE-S data sets are scaled accordingly. The extended ATLAS-3 spectrum was then scaled with a constant factor to obtain the integrated TSI of 1361.05 W m^{-2} . . .

Page 4, line 20: Needs some clarification. The (facular brightening and sunspot darkening) indices themselves do not describe the relationship between sunspots and faculae on the Sun's disk and irradiance. The indices are derived from observations of proxies of faculae and sunspots. It's rather the scaling factors computed from the multiple linear regression of these indices with SSI observations that are used to scale the change in faculae and sunspots into a net, wavelength-dependent, irradiance change.

We have reformulated this description.

. . . based on the empirical, wavelength-dependent relationship between sunspot darkening and facular brightening on the solar disk with SSI changes. Indices which are derived from observations and proxies for sunspot darkening and faculae are used in regression models to determine the coefficients required to estimate the time-varying SSI changes.

Page 4, line 23: "The TSI changes are added . . . " should be "The SSI changes are added.."

We are not sure about that. Maybe it is confusing that NRLSSI1 and NRLSSI2 are given in brackets? The intention is to emphasize the different TSI references in NRLSSI/TSI1 and NRLSSI/TSI2.

Page 4, line 27: While Viereck et al., 2001 is a perfectly appropriate reference for a general discussion of the Mg II index, the correct citation for the University of Bremen Mg II index reference is Snow, M., Weber, M., Machol, J., Viereck, R., & Richard, E. (2014). Comparison of magnesium II core–to–wing ratio observations during solar minimum 23/24. Journal of Space Weather and Space Climate, 4, A04. https://doi.org/10.1051/swsc/2014001

The reference "Viereck et al. (2001)" is now replaced by "Snow et al. (2014)".

Page 5, line 23-24: I am aware that CMIP6 SSI and TSI data are the average of output from NRLSSI2 and SATIRE-S. However, it's unclear to me the relation of this is to your choice of using data from November 1989 and November 1994 in the study?

The main reason for choosing November 1994 as the base state for solar minimum condition is the timing of the ATLAS3 reference SSI data. With this choice of the solar minimum the natural choice was to take November 1989 for the solar maximum condition, as the November 1994 is located in the descent to the ending solar minimum of cycle 22 in August 1996. So the choice of this cycle is not related to CMIP6.

Page 6, EMAC section: I'm not an expert on CCMs but I find the description of EMAC difficult to read. It doesn't flow as easily as the following section on WACCM, and the acronyms aren't defined. I would suggest some word–smithing to bring it up to the same high quality as the rest of the paper.

The EMAC section is now slightly revised.

Page 7, between WACCM and section and the start of Section 3.1: Again because I'm not an expert on CCM's, it would be nice to have a summarizing sentence or two here as a take home message for the non-expert. Are these suitable models to compare, and are there obvious reasons why their unique setup and execution would lead you to expect differences in their outputs?

We have included the following paragraph to the introduction of Section 3.

Both CCMs have a good spectral resolution of their SW radiation and photolysis parametrization and therefore are well suited for this study. The main difference between EMAC and WACCM, as applied here, is WACCM's model top in the lower thermosphere which allows for a better representation of the chemical processes in the upper mesosphere in WACCM.

Page 7, lines 27-28: One too many of each of the words, "both" and "simulations".

One of these "both" is now deleted.

Page 9, Section 7: A general comment in this section is to make it is more clear that majority of the uncertainty, or spread, in the CCM output comes from internal variability in the CCM's. Only a fraction of the model spread can be attributed to differences in SSI datasets or differences in the CCM's themselves. (If I understood correctly).

This is correct. It is stated in Section 5:
Note that the contributions of the variances explained by the SSI data set, the CCM, and the interaction of both in Figure 4 do not add up to 100%, as often the random contribution to the total variance is largest.

In Section 7 we have added:
However, in the upper stratosphere/lower mesosphere the largest fraction of solar cycle response variance is random and not related to differences in SSI data sets or the applied CCM.

Page 13, line 20: "... 10-40% of the variability of the solar signal [insert of what component, heating rate, temperature, etc.] in the stratosphere and ... "

We have added the additional information.

The differences in the SSI amplitude are responsible for 10% of the temperature, 30% of the ozone, and up to 40% of the SW heating rate variability of the solar response in the stratosphere and lower mesosphere.

Page 20, line 8-10: Is there a transition in thought from the sentence ending on line 8 about the distinct differences that appear for SATIRE-T to the next sentence discussing how reduced solar cycle amplitude explain the weaker solar signals in temperature? Does that 2nd sentence also refer to SATIRE-T? If so, Table 1 shows that SATIRE-T has a stronger solar cycle amplitude in the 201-242 nm range, not weaker.

The 2nd sentence also refers to SATIRE-T. The ΔSSI and the $\frac{\Delta SSI}{\Delta TSI}$ in Table 1 show opposing characteristics. Whereas for SATIRE-T $\frac{\Delta SSI}{\Delta TSI}$ is largest it is lowest for ΔSSI, and it is ΔSSI which effects the solar responses in SW heating rate and temperature.

Page 21, line 3-4: You provide support that downward transport of thermospheric photolysis reactants is needed to realistically simulate solar cycle effects. Is this a new finding for the CCM community? It seems to me that you might emphasize the importance of this in guiding CCM model development and directing CCM advances.

We have added a remark on a possible 'upper boundary condition' for thermospheric photolysis reactants for CCMs with a model top in the upper mesosphere.

Some of these effects could be included in CCMs with a model top in the upper mesosphere by a thoroughly formulated upper boundary condition, as already included for $\mathrm{NO_y}$ produced in the thermosphere by auroral and medium-energy electrons

Figures: I was finding that the significance hatching in the figures was very difficult to see, particularly in the middle and right hand columns of Figure 1. However, when I look today, it's much clearer on-screen. Perhaps it is just a problem with my printer.

We have changed the single hatching to double hatching.

References

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