Response to reviewer #1

We thank the reviewer for their time in evaluating our paper and we thank the reviewer for their frank comments. We respectfully disagree with their conclusions. However, the reviewer highlights some weaknesses which we have addressed in the manuscript. The reviewers' criticisms are:

1. That the study only offers small advances over current literature;
2. That the model used is not state of the art;
3. That the experiment configuration is unrealistic.

In the following, we answer those points in turn to stress that:

1. Our study provides novel insights into semi-direct effect processes that suggest they are much more subtle and more elusive than previously thought;
2. The model used in our study contains the appropriate amount of complexity to answer our scientific objective, and that adding complexity would unnecessarily complicate the picture;
3. The experiments that we performed are relevant to understanding real semi-direct perturbations of marine stratocumulus clouds.

These points are reflected in the changes we have made to the revised manuscript to address these arguments.

1. The first major criticism is that this study offers only small advances over previous studies. To date there are only two high-profile reviews of black carbon (BC) semi-direct effect on clouds: Koch and Del Genio (2010) and Bond et al. (2013), which addresses BC impacts on climate more generally. Both reviews rely on just a single high resolution modelling study (Johnson et al., 2004) and a single case to support the conclusion that the semi-direct effect is negative on a global average. More recent studies have focused on stratocumulus-to-cumulus transition (Yamaguchi et al., 2015; Zhou et al., 2017), which makes isolating semi-direct effects difficult. Given this paucity in model and observations, the role of BC over marine stratocumulus is still a major uncertainty. Observations have shown that BC can occur at various heights above marine stratocumulus and this study investigates how this variability translates into the vertical profile of heating produced and the response of the underlying cloud.

   Our results strongly suggest that semi-direct effects are much more subtle than previous literature assessed. We find that the semi-direct effect strongly weakens with increasing gap between cloud and BC layer – as soon as the gap in larger than about 100 m, semi-direct effects become unimportant. We also find a strong diurnal cycle that means that, although semi-direct effects may be large instantaneously, changes of signs with time provide a weak daily average. To our knowledge these conclusions are entirely new and build upon the very small collection of high-resolution modelling studies that have studied the semi-direct effect of elevated BC layers above stratocumulus. If the reviewer is aware of studies that we have missed we would greatly welcome these references.

   Considering the reviewer's criticism, it is apparent that the importance of the main results was not made clear enough. We have therefore amended the abstract and conclusions in the revised manuscript to make this clearer and to highlight the new results.

2. We agree that the model used in this work is microphysically simpler than other recent studies (e.g., Yamaguchi et al., 2015; Zhou et al., 2017). The microphysics in this work is single moment, while the other studies use double moment scheme with impacts on the cloud droplet distribution. While such a simplification would be problematic if we were investigating the interaction of BC aerosols with the cloud, in this work, we instead focus on BC above the cloud. We agree that the issue is simplified by not advecting / subsiding BC aerosols but this type of set-up matches the scientific objective of assessing the impact of aerosol layers above the cloud. The Large Eddy Model (LEM) has a long track record of being used to study cloud-precipitation-aerosol interactions for several cloud regimes and was included in several LES inter-comparisons. To cite only the studies

published in the past 10 years: Hill et al., 2009, Hill et al., 2014, Efstathiou et al., 2015; Efstathiou et al., 2016; Ackerman et al., 2009; Dussen et al., 2013; Ovchinnikov et al., 2014; De Roode et al., 2016). We have added a sentence into the model description section to demonstrate the track record of the LEM.

As recognised by Reviewer #2 we designed our experiments to study the semi-direct effect from the bottom–up with a systematic approach that allowed us to investigate, for the first time, the sensitivity of the thermodynamic response of the boundary layer to properties of the BC layer, as well as the meteorological conditions and key model parameters. In that context, complexity needs to be added where it is useful. The reviewer mentions two specific limitations of our model: the lack of representation of aerosol indirect effects, and the Eulerian framework used by the model.

Our model does not consider indirect effects because they would quickly muddy the water. We however agree that potential mitigating impacts of indirect effects need discussing and have expanded our current discussion on possible impacts from indirect effects in Section 4 of the revised manuscript. As discussed by Petters et al. (2012) some modelling studies focusing on stratocumulus find that LWP decreases with cloud droplet number concentration (Nd), whereas others find that LWP increases. Some studies find increases in entrainment rate, whereas others show decreases. The diversity in response was attributed to differences in modelling frameworks and the profiles of state variables used to initialise the model. In addition, in-situ observations routinely find that the BC over the Southeast Atlantic is transported in moist layers. As the BC layer is entrained into the cloud layer the increased flux of water from the free-troposphere could act to mitigate the changes in LWP and entrainment that occurs alongside an increased Nd.

Our model uses a Eulerian framework where the BC layer remains at a constant height above the cloud whereas the heat perturbation is allowed to subside into the cloud. Although we agree that in reality both should subside, the sensitivity experiments that form the core of our study include changes to the gap between cloud and BC layer. Therefore we learn from our model that if the BC layer could subside with the heat, an enhancement of the inversion strengthening would be seen. We agree that this point should be added to the discussion, and have included this in Section 4, but stress that it does not affect our conclusions and the novelty of the study.

The reviewer believes there may be something wrong with our model due to the large impact that precipitation has on our results. The cloud-base precipitation rate obtained in our model configuration ranges from 0.2 mm day^{-1} at night to 0.01 mm day^{-1} during the day. For a cloud with a LWP of 60 g m^{-2} this is within the range of observations presented by Abel et al. (2010). As discussed in Ackerman et al. (2009) and Wood et al. (2012), drizzle plays an important role in the dynamical processes throughout the boundary layer, therefore we do not believe this aspect of our results is wrong. A brief evaluation of the precipitation rate has been included in Section 3.1 of the revised manuscript.

3. We agree with the reviewer that the steady state stage of our simulations is not realistic. Indeed, that is acknowledged in the text. But the core of the paper, which provides the novel results, focuses on the initial response, which is realistic. The steady state response is not analysed at all for the sensitivity experiments. We have added text to Section 3.2 to clarify the reason for the simulations.

In summary, we stand by our model, its setup, and the range of experiments that we performed. Our bottom–up approach allows us to robustly study the semi–direct effect and test considerably more parameter space than previous studies. Our results build upon a very small collection of modelling studies and provide the community with much needed insight into the subtleties of semi-direct responses of stratocumulus clouds. But we thank the reviewer for highlighting shortcomings in the description of our work, which we have addressed in the revised version.

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