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Interactions between hydrological sensitivity, radiative cooling, stability and low-level cloud amount feedback.

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Abstract:	Low-level cloud feedbacks vary in magnitude, but are positive in most climate models, due to reductions in low-level cloud fraction. This study explores the impact of surface evaporation on low-level cloud fraction feedback by performing climate change experiments with the aquaplanet configuration of the HadGEM2-A climate model, forcing surface evaporation to increase at different rates in two ways. Forcing the evaporation diagnosed in the surface scheme to increase at 7%/K with warming (more than doubling the hydrological sensitivity) results in an increase in global mean low-level cloud fraction and a negative global cloud feedback, reversing the signs of these responses compared to the standard experiments. The Estimated Inversion Strength (EIS) increases more rapidly in these surface evaporation forced experiments, which is attributed to additional latent heat release and enhanced warming of the free troposphere. Stimulating a 7%/K increase in surface evaporation via enhanced atmospheric radiative cooling however results in a weaker EIS increase compared to the standard experiments and a slightly stronger low-level cloud reduction. The low-level cloud fraction response is predicted better by EIS than surface evaporation across all experiments. This suggests that surface-forced increases in evaporation increase low-level cloud fraction mainly by increasing EIS. Additionally our results show that increases in surface evaporation can have a very substantial impact on the rate of increase in radiative cooling with warming, by modifying the temperature and humidity structure of the atmosphere. This has implications for understanding the factors controlling hydrological sensitivity.

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Response to Editor and Reviewer comments on "Interactions between hydrological sensitivity,
radiative cooling, stability and low-level cloud amount feedback." by Mark Webb, Adrian Lock and Hugo Lambert.

We are grateful to the reviewer and the editor for their helpful comments which have helped us to improve the paper.

Responses to comments from the Editor:

L. 244 Figure 1(f)

Done. Manuscript amended (L244)

L. 464. Indicate radiative cooling rate corresponds to squares. Or put a legend of symbols on Fig. 4(d).

We now indicate that the radiative cooling rate corresponds to squares. Manuscript amended (L464)

L. 471-475. The description doesn't match the text in boxes in Fig. 5. For example, "enhanced free tropospheric warming" is not in the diagram. How about: "... and is summarised in Figure 5 (blue arrows). As shown above, enhanced evaporation at the surface leads to enhanced free tropospheric warming (reduced lapse rate)." You could then delete "via an enhanced free tropospheric lapse rate feedback." And I think "in part due to enhanced emission of outgoing longwave radiation to space" is probably not necessary as well.

Done. Manuscript amended (L471-474)

L. 505. Indicate colors for experiments.

Done. Manuscript amended (L503-507)

L. 526. "_to_ maintain the _same_ near-surface ..."

Done. Manuscript amended (L527)

L. 557. Maybe indicate orange and grey lines in text?

Done. Manuscript amended (L558-559)

L. 558-559. Enhanced warming compared to what?

We now write “This in turn can explain the enhanced warming in the upper troposphere in APEC4KSurfaceEvap0% (orange) compared to APEC (grey) in Figure 2(c)).

Manuscript amended (L560-561)

L. 571. This sounds like the sign reverses as you go from APEC4K to APECSurfEvap7%. But I think the sign reverses compared with the 0% experiment?

We now write “**With** the surface evaporation increases in the APEC4K, APECSurfaceEvap3% and APECSurfaceEvap7% experiments, the sign of the response of the air-sea temperature difference reverses **compared to that in APEC4KSurfaceEvap0%**, with the near-surface air temperature warming more than the surface, and the magnitude of the **(negative)** air-sea temperature difference reducing (Figure 4(g)).“
Manuscript amended (L571-574)

L. 581. "APEC4KRadCool7% _compared to_ APEC4K"

Done. Manuscript amended (L583)

L. 587. Rather than the "responses of sensible heat flux", maybe the "decreases", so it's clear that increases in wind speeds cannot cause the decreases?

We now write “**The decreases** of the sensible heat fluxes **in response** to increases in surface evaporation and radiative cooling...” Manuscript amended (L589)

L. 606. It might be useful to include the bulk formula here

We prefer to point the reader to Eq 1 of Richter and Xie (2008). Manuscript amended (L608)

L. 609. Mean monthly values are averaged to get annual average in Table 2?

We now write “Long term averages of these predicted monthly values…”
Manuscript amended (L612)

L. 616: "muted increase" compared to what? What's expected from an SST-only change?

We now write “These calculations show that the muted evaporation increase in the standard APEC4K experiment **(weaker than the 7 \%/K increase which would occur with surface warming in the absence of changes in near-surface relative humidity, wind speed and air sea temperature difference)** is primarily due to increases...”
Manuscript amended (L617-619)

L. 619. A "comparable" contribution seems a little contradictory to the "primary" effect of enhanced winds.

Modified to say “secondary”. Manuscript amended (L623)

L. 626. What are "these quantities"?

We now write “These results also demonstrate however that the responses in **the factors controlling the surface evaporation (such as near-surface relative humidity, wind speed and air-sea temperature differences)** are affected…”

Manuscript amended (Text now at L710-711 - see below)

L. 667. Implies that in some cases EIS does change substantially in the radiative experiment. Add a comma between "experiment" and "in"?

Done. Also added missing “in” to read “Substantial low cloud reductions are also seen **in** the radiative cooling forced experiment**,** in the absence of substantial changes in EIS.”
Manuscript amended (L670)

L. 707. "artificially enhancing the radiative cooling with warming" sounds a little contradictory. "artificially enhancing the radiative cooling by warming the atmosphere"?

We now write “Meanwhile, artificially enhancing the radiative cooling **increase which accompanies surface warming**…”
Done. Manuscript amended (L700)

L. 714. This paragraph is almost the same as that at the end of the previous section. Unlike the reviewer, I actually prefer this paragraph here, but agree that it is repetitive, and it would be nice to shorten one of the two.

Agreed. We have removed the paragraph at the end section 3 and merged it in to the paragraph at the end of the conclusions. This now reads:

“It is widely appreciated that increases in near-surface relative humidity will act to damp increases in surface evaporation, while increases in the magnitude of air-sea temperature differences and near-surface wind speeds will act to enhance it. Our results also demonstrate however that the responses in **the factors controlling the surface evaporation (such as near-surface relative humidity, wind speed and air-sea temperature differences)** are affected not only by radiative cooling but also by changes in surface evaporation itself. **We argue that the** hydrological sensitivity will **ultimately** be determined by the point at which various interacting responses in **near-surface relative humidity and wind speed, air-sea temperature difference, surface evaporation, sensible heat fluxes and radiative cooling** come into a new balance **following a given surface warming.** This means that a full understanding of the mechanisms controlling hydrological sensitivity differences in models will require a better appreciation of these various inter-dependent responses. These insights may help to improve our understanding of the factors controlling hydrological sensitivity in the future.”

Manuscript amended (L710-715)

Reviewer #3:

Overall, I have very little to say. The authors have adequately addressed my previous comments. I appreciate their efforts, and I think the revised manuscript is more clear and impactful for the changes. The addition of Figure 3 is especially helpful in linking the results to the model physics. The goal of the paper is clear, the methodology is appropriate, the analysis is well done, and the conclusions are supported. This paper fits well in the current literature, and will help to inspire additional studies.

My only remaining criticism is that the paper is still a little long. The discussion of the new panels of Figure 4 and the regression analysis of Table 2 seem like they could be tightened up.

We have made various minor edits to shorten the sections of text mentioned. Please refer to the tracked changes version to see these.
Manuscript amended (L495-625 in the main manuscript, 516-623 in the tracked-change version)

The "Summary and Conclusions" section could also be shortened substantially. I noted that some of the text in that section is nearly identical to previous sections. For example, the last paragraph (l 714-722) is basically the same as the last paragraph from the preceding section (l 623-632). The repetition is not inherently bad, but I think that the summary should be more concise, just giving the essence of the results.

We have dealt with the duplicated text by removing it from the results section and merging in with the conclusions (see above comment from the editor.) We have also made various minor edits to shorten conclusions section. Please refer to the tracked changes version to see these.
Manuscript amended (L646-698 in the main manuscript, L664-716 in the tracked-change version)

As for the conclusions just giving the essence of the results, I know that there are different views on this. There are so many papers to read these days that many people just read the conclusions and skim the rest. Personally I prefer a more comprehensive summary, and this policy has served me well in the past.

Additional changes.

We corrected an error in the units on Figure 2(a,b) (changing K/K to K).

On re-reading we thought it clearer to add “in a uniform +4K SST perturbation experiment” to line 633-634.

We also added “We are also grateful to Karen Shell and two anonymous reviewers for comments which helped us to improve this paper.” to the Acknowledgements (L723-724)

Thanks again for the helpful comments which have helped to improve this paper.

Interactions between hydrological sensitivity, radiative cooling, stability and low-level cloud amount feedback.

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ABSTRACT

Low-level cloud feedbacks vary in magnitude, but are positive in most climate models, due to reductions in low-level cloud fraction. This study explores the impact of surface evaporation on low-level cloud fraction feedback by performing climate change experiments with the aquaplanet configuration of the HadGEM2-A climate model, forcing surface evaporation to increase at different rates in two ways. Forcing the evaporation diagnosed in the surface scheme to increase at 7%/K with warming (more than doubling the hydrological sensitivity) results in an increase in global mean low-level cloud fraction and a negative global cloud feedback, reversing the signs of these responses compared to the standard experiments. The Estimated Inversion Strength (EIS) increases more rapidly in these surface evaporation forced experiments, which is attributed to additional latent heat release and enhanced warming of the free troposphere. Stimulating a 7%/K increase in surface evaporation via enhanced atmospheric radiative cooling however results in a weaker EIS increase compared to the standard experiments and a slightly stronger low-level cloud reduction. The low-level cloud fraction response is predicted better by EIS than surface evaporation across all experiments. This suggests that surface-forced increases in evaporation increase low-level cloud fraction mainly by increasing EIS. Additionally our results show that increases in surface evaporation can have a very substantial impact on the rate of increase in radiative cooling with warming, by modifying the temperature and humidity structure of the atmosphere. This has implications for understanding the factors controlling hydrological sensitivity.

1. Introduction

Inter-model differences in cloud feedbacks constitute the largest source of spread in estimates of equilibrium climate sensitivity in climate models, and this is primarily due to differences in the responses of low clouds. While low-level cloud feedbacks vary substantially in magnitude, they are positive in most models, where they are associated with reductions in low-level cloud fraction, increasing the amount of solar radiation absorbed at the surface (Boucher et al. (2013)).

Many arguments have been advanced to explain the reduction in low-level cloudiness seen in climate models with the warming climate. Rieck et al. (2012) proposed a mechanism where increasing surface moisture fluxes would deepen the boundary layer, increase entrainment of dry air from above the trade inversion, and reduce relative humidity and low-cloud fraction. Webb and Lock (2013) argued that reductions in surface sensible heat and surface buoyancy fluxes with warming could reduce turbulent moistening of the cloud layer. Brient and Bony (2013) proposed a mechanism whereby increases in the vertical gradient of moist static energy in the warmer climate result in a larger influx of low moist static energy and dry air into the boundary layer through subsidence. Bretherton and Blossey (2014) proposed a mechanism related to that of Rieck et al. (2012), whereby increases in cloud-layer humidity flux in the warmer climate lead to an entrainment liquid-flux adjustment which dries the cloud layer. Sherwood et al. (2014) argued that vertical mixing by large and small-scale processes would be expected to dry the boundary layer as the climate warms. Following this, Brient et al. (2015) argued that low-cloud reductions in some models are caused by stronger convective mixing which dries the boundary layer more efficiently as the surface warms, but that the low-cloud responses of many models are dominated by low-cloud shallowing caused by weakened turbulent moistening.

It is recognised that the magnitude of any low-level cloud reduction will be determined by a number of competing factors (Rieck et al. (2012),Webb and Lock (2013),Zhang et al. (2013),Bretherton et al. (2013),Blossey et al. (2013),Jones et al. (2014),Qu et al. (2015b),Vial et al. (2016)). While factors which break up clouds may be dominant, their impact will be offset by other processes that, if acting in isolation, would act to increase low-level cloud fraction. Such negative cloud feedback mechanisms may include the effects of increasing stability on low cloud fraction (e.g. Blossey et al. (2013),Qu et al. (2015b)) and enhanced moisture supply to the cloud layer from increasing surface evaporation (e.g. Webb and Lock (2013),Zhang et al. (2013)). If we are to understand why low-level cloud feedback is positive, it is therefore necessary to understand both positive and negative low cloud feedback mechanisms and the reasons for their differing strengths.

One way to quantify the contribution of a hypothesized cloud feedback mechanism in a climate model is to prevent it from operating in a climate change experiment, and to measure the impact on the overall cloud feedback. Similarly a given mechanism may be strengthened to explore the extent to which it compensates for other effects. Webb and Lock (2013) tested a number of mechanisms in this way in the HadGEM2-A GCM, performing sensitivity experiments targeting positive subtropical low cloud feedback. These included experiments where surface evaporation was forced to increase at different rates, following similar sensitivity experiments with a very high resolution process model run over a small domain representative of a trade cumulus boundary layer (Rieck et al. (2012)).

The rate of increase in global mean surface evaporation and precipitation per degree warming in a climate change scenario is often referred to as the hydrological sensitivity. As pointed out by Fläschner et al. (2016), it is important to distinguish between estimates of hydrological sensitivity which include temperature-independent effects of radiative forcing agents such as carbon dioxide on the global precipitation increase and those which cleanly isolate the temperature-dependent components. Here we use the term hydrological sensitivity to refer specifically to the temperature-dependent increase in global precipitation with surface warming, excluding the effects of radiative forcing agents, consistent with the approach of Mitchell et al. (1987), Lambert and Webb (2008), Andrews et al. (2010) and Fläschner et al. (2016).

If relative humidity, surface wind speed and air sea temperature differences were to stay fixed with future climate warming then global mean surface evaporation and precipitation would increase at 7 %/K (Mitchell et al. (1987), Richter and Xie (2008), Rieck et al. (2012)). However, the radiative cooling of the atmosphere is widely thought to regulate the hydrological sensitivity, limiting the rate of increase of global mean surface evaporation and precipitation to something closer to 3 %/K (e.g. Mitchell et al. (1987), Lambert and Webb (2008), Pendergrass and Hartmann (2014), Fläschner et al. (2016)). This is achieved through a combination of increases in near-surface relative humidity and reductions in near-surface wind speed/air sea temperature differences (e.g. Richter and Xie (2008)).

Webb and Lock (2013) noted that the surface evaporation in a region of strong subtropical cloud feedback in the north-east Pacific between Hawaii and California increased very little in a climate change experiments with HadGEM2-A, considerably less than the 3 %/K increase seen globally and much less than the 7 %/K increase which would occur with warming in the absence of changes in near-surface relative humidity, wind speed and air sea temperature difference. By forcing the local surface evaporation to increase more strongly in the warmer climate, they were able to weaken this local cloud feedback considerably, demonstrating that much of the positive low cloud feedback at that location could be attributed to the relatively weak increase in surface evaporation. A limitation of that study was the fact that the surface evaporation was perturbed over a small region, and one which focused on the location with the strongest low cloud feedback ; hence it was not clear whether this mechanism explains the low cloud feedback more generally in this model.

More recently, highly idealised 'aqua planet' configurations of climate models forced with zonally symmetric sea-surface temperatures (SSTs) have been shown to be remarkably successful in reproducing the global cloud feedbacks predicted by climate models in realistic atmosphere only and coupled ocean-atmosphere configurations (Ringer et al. (2014), Medeiros et al. (2015)).

In this study we apply the approach of Webb and Lock (2013) globally to investigate the positive low-level cloud feedback in the aquaplanet configuration of HadGEM2-A. We pose the following question: Does the muted (i.e. sub-7 %/K) increase in global surface evaporation contribute substantially to the low cloud amount reduction and positive low cloud feedback? We test this idea by performing climate change experiments with an SST forced 'aquaplanet' configuration of HadGEM2-A which is subject to a uniform +4K SST perturbation, and where surface evaporation is forced to increase at 7 %/K. We stimulate surface evaporation in two ways. In the first set of experiments we add a term to the surface evaporation diagnosis which brings the zonal mean evaporation in each time step into agreement with a target climatological value. In an additional experiment we stimulate the hydrological cycle by adding an artificial radiative cooling term in the atmosphere designed to approximately double the hydrological sensitivity.

Our model and experimental approach are described in more detail in Section 2. We present and discuss our results in Section 3. We start by discussing the low cloud responses from the surface evaporation forced experiments in Section 3a and those in the radiative cooling forced experiment in Section 3b. We then go on to discuss the implications of our results for understanding the hydrological sensitivity in Section 3c, and provide our concluding remarks in Section 4.

2. Model Experiments and Methods

We explore the impact of increasing surface evaporation on low-level cloud feedbacks in the HadGEM2-A climate model (Martin et al. (2011)) by specifying surface evaporation following a similar approach to that in Webb and Lock (2013), but at a global scale. Our experiments are summarised in Table 1. The basis for our experiments is an aquaplanet configuration of HadGEM2-A which is forced with time invariant, zonally and hemispherically symmetric sea surface temperatures (SSTs), taken from the Aqua-Planet Experiment (APE) project 'Control' experiment (Neale and Hoskins (2000)) (here denoted as APEC). This is accompanied by an idealised climate change experiment, in which the APEC SSTs are subject to a uniform increase of 4K (APEC4K), following the approach of Medeiros et al. (2015). The APEC and APEC4K experiments are referred to throughout as the standard experiments. These differ slightly from the aqua planet experiments in CMIP5, which were based on the APE 'Qobs' SSTs (Medeiros et al. (2015)). We chose the APE 'Control' dataset, which has slightly more peaked SSTs in the tropics, as we found that, in spite of their hemispherically symmetric forcings, the experiments based on the Qobs SSTs were prone to having strong hemispherically asymmetric responses when we applied the surface evaporation forcing. We perform a number of sensitivity experiments based on the standard APEC and APEC4K experiments in which we force the model to have various specified values of global mean surface evaporation. We apply two approaches, which we call the surface evaporation forced and radiative cooling forced methods.

For our first surface evaporation forced experiment (APECSurfaceEvap) we repeated APEC, but forcing the zonal mean surface evaporation on each model time step to agree with the APEC climatological zonal mean. This was done by diagnosing the surface evaporation in the usual interactive manner and calculating the zonal mean at every model time step. A constant value was then added at all points in a given line of latitude to force the zonal mean to agree with the target value. This sets the zonal mean evaporation to the target value while retaining variations along a line of latitude, maintaining synoptic structure in the surface evaporation field. Similarly we repeated the APEC4K experiment, fixing the zonal mean surface evaporation to the zonal mean climatology from APEC4K (APEC4KSurfaceEvap3%). These two experiments allow us to assess whether or not the positive low cloud feedback can be reproduced with specified zonal mean surface evaporation (see Section 3a). Two further experiments were then performed. In one we repeated APEC4K, fixing the zonal mean surface evaporation to the climatology from APEC, preventing the surface evaporation from increasing with warming (APEC4KSurfaceEvap0%). In the other we forced the surface evaporation in the APEC4K experiment to increase at 7 %/K relative to that in APEC specifying the zonal mean surface evaporation climatology from the APEC experiment multiplied by a factor of 1.28 (APEC4KSurfaceEvap7%). This is what we would expect to see for a warming without any changes in near-surface relative humidity, wind or air-sea temperature difference.

For the radiative cooling forced experiments, we use the APEC experiment as the present day control and force the global mean surface evaporation to increase more rapidly in an additional +4K experiment (APEC4KRadCool7%) by artificially enhancing the atmospheric radiative cooling rate. First we calculated the zonal mean climatology of the response in the clear-sky longwave radiative heating rate between the APEC and APEC4K experiments as a function of height, which takes negative values due to the radiative cooling increase. We then ran the APEC4KRadCool7% experiment, adding this additional radiative cooling climatology (as a function of latitude and height) to the actual radiative heating rate calculated by the model's radiation code in each model timestep. This constitutes an extra 4.4 W/m^2/K of atmospheric radiative cooling. We expected this to approximately double the rate of increase in longwave clear-sky radiative cooling with warming, in turn approximately doubling the increase in global mean surface evaporation (see Section 3a).

All experiments were run for 72 months, and climatological means were formed over the full period. As in many studies, we diagnose cloud feedbacks using the climatological mean change in the cloud radiative effect (CRE) between the aquaplanet control and +4K experiments, divided by the global mean near-surface temperature response. This can be considered a measure of cloud feedback, including the climatological masking effects of clouds on the non-cloud feedbacks (see Webb and Lock (2013) for a discussion of the merits of this approach compared to the alternatives).

3. Results and Discussion

a. Low Cloud Responses in Surface Forced Evaporation Experiments

Figure 1 shows the effects of forcing surface evaporation to increase at various different rates with a uniform +4K warming applied to the HadGEM2-A aquaplanet configuration forced with the APEC SSTs. Figure 1(a) shows the responses in zonal mean surface evaporation in the standard APEC4K experiment relative to APEC, and in the various experiments where surface evaporation is specified using the surface evaporation and radiative cooling forcing methods. The global mean surface evaporation increases by 3.2 W/m^2/K in the standard experiments APEC and APEC4K, an increase of 3.4 %/K relative to the global mean control value in APEC, which is 94.2 W/m^2. As expected by design, the zonal mean evaporation increase in APEC4KSurfaceEvap3% relative to APECSurfaceEvap (red line on Figure 1(a)) agrees well with that in the standard experiments (black line), and APEC4KSurfaceEvap0% (orange line) shows no increase, while APEC4KSurfaceEvap7% (blue line) shows an increase of 7.0 %/K in the global mean, approximately twice that in the standard experiments. The APEC4KRadCool7% (green line) experiment is also quite successful in reproducing an increase close to 7 %/K, with a global mean increase of 7.5 %/K, with only minor differences in the meridional structure of the response. Figure 1(b) shows the concomitant responses in zonal mean precipitation. We note some differences in the precipitation responses in the APEC4K and APEC4KSurfEvap3% responses, with a tendency for the precipitation to decrease at the equator and increase more on the flanks of the ITCZ in APEC4KSurfEvap3% compared to the more concentrated increases seen in APEC4K. We do not expect the responses in these experiments to be exactly the same, because the method used to force the surface evaporation in the APEC4KSurfEvap3% experiment removes any temporal variability in the zonal mean surface evaporation. The precipitation responses between the two experiments are however much more consistent in the subtropical regions between 10-25^o N/S where the positive low-level cloud feedbacks occur (see below).

Many previous studies have pointed out the association between positive subtropical cloud feedback and reductions in low-level cloud. The net cloud feedback (which we define here to include cloud masking - see Section 2) in the standard experiments is positive in the global mean and between 10 and 25^o N/S, with the strongest positive feedback at 17^o N/S (black line, Figure 1(c)). The variations in the net cloud feedback are primarily due to the shortwave component (Figure 1(d)). Meanwhile the low cloud fraction reduces in the global mean and throughout the latitudes where a positive net cloud feedback is present (black line, Figure 1(e)). The difference between the surface-forced evaporation experiments APECSurfaceEvap and APEC4KSurfaceEvap3% successfully reproduces the signs of the positive global mean cloud feedback and the global reduction in low-level cloud fraction in the standard experiments, and also captures well the magnitudes of their global responses. The zonal distributions of these quantities are also well captured (compare black and red lines on Figure 1(c-e)). This demonstrates that the surface-forced evaporation method does not substantially distort the cloud feedbacks, and is therefore a suitable method for exploring the impact of differing levels of surface evaporation increase on cloud feedback.

Figures 1(c,e) also show that forcing the evaporation to increase at a rate closer to 7 %/K with a +4K warming using the surface evaporation forcing method (experiment APEC4KSurfaceEvap7%, (blue line)) reverses the sign of both the global mean cloud feedback and the low cloud fraction response, resulting in a negative global mean net cloud feedback and an increase in global mean low cloud fraction. Although the signs of the global mean low-level cloud fraction and cloud feedback responses reverse, the meridional structures of the responses relative to their global means are not greatly affected. The most positive cloud feedback and the associated low-level cloud fraction reduction located near to 15^oN/S in the standard experiments are not completely eradicated in the APEC4KSurfaceEvap7% experiment, indicating that part of the positive cloud feedback in the APEC4K experiment cannot be explained by the muted increase in surface evaporation.

One possible explanation for this might be that while increases in surface evaporation in the climate change context generally increase low cloud fraction on occasions where there is little mixing across the inversion, in a small fraction of cases where shallow convection is able to penetrate the inversion, enhanced surface evaporation might help to break up cloud. That said, the area between the positive part of the curve and the zero line gives an indication of the contribution of this remaining positive feedback to the global mean, which is small compared to the positive contribution in the APEC/APEC4K experiments, and is dwarfed by that from the negative feedback elsewhere.

The sensitivity of the global cloud feedback and low cloud response to the strength of the surface evaporation increase is further demonstrated by the results from the APEC4KSurfaceEvap0% experiment in which the surface evaporation does not increase at all with the warming climate; in this scenario the global mean low cloud reduction is amplified compared to the standard experiment and the global cloud feedback becomes more strongly positive (compare orange and black lines on Figures 1(c,e)).

Our experiments also show substantial differences in the response of the Estimated Inversion Strength (EIS, Wood and Bretherton (2006)) to climate warming (Figure 1(f)). EIS is a measure of lower tropospheric stability which is based on the potential temperature difference between the surface and 700 hPa level, and which gives an indication of the strength of low level temperature inversions, for example those which are present at the top of subtropical boundary layers. EIS has been shown to be a good predictor of spatio-temporal variations in low-level cloud fraction in the present climate (Wood and Bretherton (2006)). Stronger values of EIS are generally associated with a stronger capping inversions in subtropical boundary layers, which are widely thought to encourage the formation and maintenance of low-level clouds by inhibiting entrainment of dry air into the boundary layer from above and promoting shallow, well mixed boundary layers with stratocumulus clouds which are strongly coupled to surface evaporation (Bretherton and Wyant (1997), Wyant et al. (1997), Wood and Bretherton (2006)). Our results indicate that the magnitude of the EIS response to the warming climate is very sensitive to the rate of the surface evaporation increase in our surface-forced evaporation experiments, with a 7 %/K increase more than doubling the magnitude of the EIS response compared to the standard case, and a modest EIS reduction in the absence of an evaporation increase (Figure 1(f)). This suggests a second route whereby increasing surface evaporation can increase low-level cloud fraction beyond the local argument put forward in Webb and Lock (2013), namely that a stronger global increase in surface evaporation results in stronger increases in EIS and stronger low level inversions in low cloud regimes, reducing drying of the boundary layer due to mixing with the free troposphere. Such an effect would mean that the muted evaporation increase acts to reduce low-level cloud fraction more relative to the 7 %/K scenario than would be expected via the local argument of Webb and Lock (2013) alone.

Why should the rate of increase in surface evaporation affect changes in EIS? Many studies (e.g. Held and Soden (2006)) have suggested that the tropical lapse rate (the rate of decrease of temperature with height) weakens in the warming climate because the free troposphere tends to follow a temperature profile which is close to a moist adiabat, which becomes more statically stable with surface warming. A saturated adiabat has increasing potential temperature with height, which strengthens as the lapse rate weakens with surface warming. Qu et al. (2015a) showed that a number of climate models run in a similar aquaplanet configuration to that used here show increases in potential temperature between 850 and 600 hPa which are too strong to be explained by the moist adiabatic lapse rate argument alone. Figure 2(a) shows the increases in potential temperature in our various experiments with warming in the tropical deep convection region centred on the equator. In the surface-forced experiments, larger increases in surface evaporation are associated with larger levels of upper tropospheric warming and larger increases at 700 hPa relative to the surface. In the APEC4KSurfaceEvap7% experiment in particular (blue line), the 700 hPa potential temperature increases considerably more than would be predicted by the change in the saturated moist adiabat. Figure 2(c) shows that in the APEC control experiment (gray line), the potential temperature increases with altitude throughout the lower troposphere, at a rate which is less than that predicted by a saturated adiabat. This is also the case for the APEC4KSurfaceEvap7% experiment, although its profile is closer to a saturated adiabat than is the case in the APEC control experiment. Thus, while the increase in potential temperature with warming between APEC and APEC4KSurfaceEvap7% at 700 hPa is more than that predicted by a change in the saturated moist adiabat, the vertical potential temperature gradient does not exceed that predicted by the moist adiabat in either of these experiments individually. This explains how the potential temperature response at 700 hPa can be more than that predicted by a change in the saturated adiabat, without violating the generally accepted principle that the absolute vertical potential temperature gradient cannot exceed that predicted by a saturated adiabat. Similar behaviour is seen in the free troposphere from 700 hPa upwards in the subtropics (Figures 2(b,d)).

Our interpretation of these results is as follows, and is summarised by the blue arrows in the schematic in Figure 5. In the APEC4KSurfaceEvap7% experiment, the additional moisture supply into the boundary layer from the enhanced surface evaporation with climate warming will increase near-surface humidity, generate convective instability and increase the amount of precipitating deep convection, resulting in additional net latent heat release in regions of deep convection (allowing for the effects of evaporating clouds and precipitation). This is supported by Figure 1(b) which shows enhanced precipitation near the equator in APEC4KSurfaceEvap7% compared to APEC4K. Figure 3 shows global mean heating and moistening rates from various components of the model physics in our experiments. Our interpretation is also supported by Figure 3(a) which shows enhanced heating by convection and cloud condensation above 700 hPa with increasing surface-forced evaporation (see orange, red and blue lines). Enhanced free tropospheric warming in convective regions of the tropics is then expected to propagate to the subtropics via horizontal heat transport by tropical waves and the mean overturning circulation (Sobel et al. (2001)). This will result in enhanced temperature increases in the free troposphere and reductions in the lapse rate, increasing the amount by which the mid-upper free troposphere warms compared to the standard APEC4K experiment (compare blue and black lines on Figure 2(a,b)), and resulting in larger increases in EIS (Figure 1(f)) and a stronger subtropical inversion. This would in turn result in reduced entrainment of dry air into the boundary layer from above, and increasing (or weakening reductions in) low-level cloud fraction. This interpretation could be tested further in the future with additional sensitivity experiments - for example by artificially enhancing the rate of latent heat release in the free troposphere with warming.

Figure 4 shows scatterplots of the responses in various global mean quantities. The differences in the global mean responses in the standard experiment (black symbols) compared to the APEC4KSurfaceEvap0% experiment (orange symbols) are qualitatively similar to the differences in the APEC4KSurfaceEvap7% experiment (blue symbols) compared to the standard experiments (black symbols). Hence the arguments outlined above may be used to interpret both sets of responses to increasing surface evaporation. For example, in both cases stronger increases in surface evaporation are associated with more positive EIS responses (Figure 4(a)), and weaker decreases or stronger increases in low level cloud fraction (Figure 4(b)). The APEC4KSurfaceEvap0% experiment does not show an increase in EIS, which indicates that we can attribute the increase in EIS in the standard experiments to the increasing surface evaporation - i.e. the fact that the hydrological sensitivity is positive.

It is interesting to note that modifying the surface-forced evaporation increase with warming in both the APEC4KSurfaceEvap7% and APEC4KSurfaceEvap0% experiments affects the EIS and low-cloud fraction responses and the net cloud feedback considerably poleward of 30^o N/S (Figure 1). This suggests that the mechanisms discussed above are also relevant to understanding extra-tropical cloud feedbacks. The standard experiments show a relatively weak net cloud feedback here compared to the subtropics, in spite of substantial reductions in low cloud fraction (Figure 1). We attribute this partly to the fact that the annual mean insolation is less at higher latitudes, and partly to compensating effects of changes in mid-high level clouds, condensed water path and cloud phase changes. The surface-forced evaporation experiments clearly change the degree to which these effects compensate for each other in contributing to the extra-tropical cloud feedback. This may not only be because of the effects of changing stability on low cloud. Enhanced free-tropospheric warming would also be expected to result in a stronger lifting of the freezing level. This might strengthen negative phase change feedbacks associated with increasing mid-level cloud fraction and albedo (e.g. Senior and Mitchell (1993)).

b. Low Cloud Responses in Response to Enhanced Radiative Cooling.

We now discuss the results from the experiment where we artificially increase the rate at which the atmospheric radiative cooling increases with warming, thus stimulating the surface evaporation indirectly. The global mean surface evaporation increases by a comparable amount in APEC4KRadCool7% to that in the equivalent surface-forced evaporation experiment APEC4KSurfaceEvap7% and the regional distribution of the surface evaporation increase is also very similar (compare blue and green lines on Figure 1(a)). However the cloud feedback and the cloud response is quite different; the net cloud feedback becomes more positive in APEC4KRadCool7% rather than negative, and the low cloud fraction reduces slightly more than in the standard experiments, rather than increasing strongly as it does in the APEC4KSurfaceEvap7% experiment (Figure 1(c,e)). This very different cloud response with warming given a similar surface evaporation increase indicates that the surface evaporation is not the sole factor determining the different cloud feedbacks in our experiments. Figure 4(b) shows a scatterplot of the global mean low cloud fraction response against the global surface evaporation increase, and while this supports there being a relationship between surface evaporation and the low cloud fraction response in the surface-forced experiments, this relationship is not maintained when the APEC4KRadCool7% experiment (green square) is included. The EIS response in APEC4KRadCool7% (green) is also very different compared to that in APEC4KSurfaceEvap7% (blue), being much weaker than that in the standard APEC4K experiment (black), while APEC4KSurfaceEvap7% increases more strongly (Figure 4(a)).

Our interpretation of the different responses in APEC4KSurfaceEvap7% and APEC4KRadCool7% is as follows, based loosely on the arguments of tropospheric energy balance outlined by Mitchell et al. (1987). In the APEC4KSurfaceEvap7% experiment, as argued above and as summarised by the blue lines in Figure 5, the additional moisture supply at the surface will stimulate deep convection, resulting in additional latent heat release and free tropospheric warming compared to that seen in the standard experiments, a reduced lapse rate, a larger increase in EIS and an increase in low cloud fraction.

In the APEC4KRadCool7% experiment however (as indicated by the green arrows on Figure 5), the artificially enhanced radiative cooling (Figure 3(b)) will reduce the amount by which the free troposphere warms compared to the standard APEC4K experiment (Figure 2(a,b)), resulting in a more enhanced lapse rate and a reduced increase in EIS (Figure 1(f)). The enhanced lapse rate will also make the atmosphere more convectively unstable and enhance precipitating deep convection (Figure 1(b)). The additional latent heat release in the free troposphere (Figure 3(a)) will act to balance the imposed radiative cooling (Figure 3(b)). Near-surface relative humidity, air-sea temperature differences and winds will adjust accordingly, increasing the surface evaporation to balance the enhanced latent heat release. (This last aspect is explained in more detail in Section 3c below.)

The relatively small change in EIS in the APEC4KRadCool7% experiment compared to that in the APEC4KSurfaceEvap7% experiment is consistent with the smaller low cloud response (Figure 1(a,b)), and Figure 4(c) shows that the global EIS response is in fact a better predictor of the low cloud response across all of our experiments than is surface evaporation (cf Figure 4(b)). Figure 4(c) shows a linear regression line which fits the data very well, with a correlation coefficient of 0.98.

It is interesting to note that the relationship illustrated here shows a substantial reduction in low cloud amount with warming in the absence of an EIS change, a reduction of 0.56 %/K as shown by the intercept. The results from the APEC4KRadCool7% experiment reproduce this very well. The slope of the regression line is 1.34 %/K. Wood and Bretherton (2006) found a regression slope of 6%/K for spatiotemporal variations in stratus cloud amount with EIS in observations. We would not expect these numbers to agree however, for a number of reasons. One is that the global mean low-cloud fractions used in our calculation are much smaller than those in the stratus cloud regions examined by Wood and Bretherton (2006), in part because the global mean includes contributions from areas with few low level clouds. Another is that the global mean low cloud fraction response will include contributions from changes in other low cloud regimes (e.g. trade cumulus) whose responses would not necessarily be expected to be the same as those in the stratus regions.

Although the main emphasis of this work is on understanding the role of changing surface evaporation on low cloud fraction feedback, it is interesting to note that it is in the absence of a surface evaporation response that the strongest low cloud reduction is seen (Figure 4(b)). This suggests that the underlying cause of the positive low cloud feedback in this model is not explained by the surface evaporation and radiative cooling changes explored here (see the orange arrow on the left hand side of the schematic in Figure 5). EIS reduces slightly in the APEC4KSurfaceEvap0% experiment (Figure 4(c)) suggesting that the positive feedback is partly due to a reduction in EIS in the absence of a surface evaporation increase. However substantial low cloud reductions are also seen in the radiative cooling forced experiment in the absence of substantial changes in EIS, indicating that other factors must also contribute to the positive low cloud feedbacks seen in the absence of surface evaporation increases. For example, APEC4KSurfaceEvap0% shows a substantial drop in the in near-surface relative humidity (discussed below) which may be indicative of a drop in relative humidity throughout the boundary layer, and which may in turn contribute to the strong low cloud reduction.

In summary, we argue that increasing SSTs without allowing substantial changes in surface evaporation or radiative cooling results in a reduction in low cloud fraction and a strong positive cloud feedback (see orange arrows in Figure 5). Allowing surface evaporation to increase in response to increasing SSTs stimulates convection and free tropospheric latent heat release, warming the free troposphere, increasing EIS and opposing the reductions in low cloud fraction (blue arrows on Figure 5). The net effect of these competing mechanisms in the standard experiment is a modest reduction in low-level cloud fraction. (The thickness of the arrows in the schematic aim to give an indication of the relative contribution of these two mechanisms in the standard experiment.) Meanwhile, artificially enhancing the radiative cooling with climate warming reduces free tropospheric warming, increases the lapse rate and weakens increases in EIS, slightly strengthening the low cloud feedback compared to the standard experiment (green arrows on Figure 5).

It is interesting to contrast our findings with the widely accepted understanding of the mechanism underlying the break up of clouds observed while following air masses undergoing the subtropical stratocumulus to trade cumulus transition (Bretherton and Wyant (1997), Wyant et al. (1997), Qu et al. (2015b)). Both scenarios relate to increasing surface temperatures and increasing surface evaporation, but our argument suggests an increase in boundary layer cloud while the conventional wisdom predicts the observed breakup of clouds. There are however important differences between the two scenarios which can explain the differing responses. The observed Lagrangian transition takes place in the context of a weakening trade inversion as SSTs increase while free tropospheric temperatures change relatively little, producing conditions more favourable to mixing or entrainment of dry air into the boundary layer from the free troposphere. In contrast, the context of the climate change experiment is one where free tropospheric temperatures increase faster than those at the surface, increasing the strength of the inversion and inhibiting cloud top entrainment. As we have shown, this increasing inversion strength can in itself be a consequence of a globally strengthening surface evaporation and hydrological cycle, which sets a very different context to the situation in which we observe the Lagrangian stratocumulus to trade cumulus transition. Hence while the two scenarios may seem superficially similar from the point of view of the surface evaporation increase, they are associated with opposite EIS changes. Therefore there is no inconsistency between the interpretations of these two scenarios.

We have also considered the possibility that HadGEM2-A shows an increase in low-level cloud in response to increasing surface-forced evaporation because it incorrectly captures the sign of the low cloud fraction response under the subtropical stratocumulus to trade cumulus transition. This is however not the case; HadGEM2-A does show a reduction in low-level cloud fraction when forced with conditions representative of a subtropical marine low-level cloud transition from stratocumulus to fair-weather cumulus (Neggers (2015)). HadGEM2-A also performs very well in reproducing observed relationships between variability in low cloud fraction, SST and EIS (Qu et al. (2015b)).

c. Implications for understanding the hydrological sensitivity

Our experiments also provide some new insights into the mechanisms which underlie the enhanced hydrological cycle in the warming climate. Many studies have pointed out that a change in the global mean radiative cooling of the atmosphere will result in an equivalent response in surface evaporation and precipitation, assuming that the sensible heat flux does not change substantially. For example, it has been shown that rapid precipitation adjustments in the absence of surface temperature change which occur in response to various atmospheric radiative forcings can be predicted accurately using offline radiation calculations which diagnose the effect of such radiative forcings in the atmospheric radiative heating (e.g. Andrews et al. (2010)). In the case of radiative forcings (e.g. due to carbon dioxide or black carbon) we do not expect that changes in the hydrological cycle will affect the radiative forcings themselves. Hence we can say that in these cases the perturbation in the radiative heating of the atmosphere is a good predictor of the hydrological cycle response. In the somewhat different case of climate warming however, previous studies are unclear on the degree to which changes in surface latent heat fluxes affect atmospheric radiative cooling. Here we show that increases in surface evaporation can have a very substantial impact on the rate of increase in radiative cooling itself with warming. We use our experiments to quantify the magnitude of this effect, and to explain how this dependence arises.

Figure 4(d) shows the changes in the main components of the global mean atmospheric energy budget, which sum to zero. If increases in surface evaporation with warming did not influence the radiative cooling, then we would expect to see the same radiative cooling response across the surface-forced experiments, and the increase in surface evaporation would have to be balanced by an equal and opposite decrease in the sensible heat flux. However, Figure 4(d) indicates that the radiative cooling rate (indicated by the squares) increases by only a small amount (0.6 $W/m^2/K$) with warming when surface evaporation is held fixed in APEC4KSurfEvap0%, but increases progressively more with larger increases in surface evaporation in the surface-forced experiments by (2.6 $W/m^2/K$ in APEC4KSurfEvap3% and 4.9 $W/m^2/K$ in APEC4KSurfEvap7%). The general agreement between the responses in the APEC4KSurfEvap3% experiment and standard APEC4K experiment suggests that the radiative cooling increases in APEC4K are to a substantial degree a consequence of the surface evaporation increases.

Our interpretation of this is as follows, and is summarised in Figure 5 (blue arrows). As shown above, enhanced evaporation at the surface leads to enhanced free tropospheric warming (reduced lapse rate). This would be expected to contribute to the larger increase in the atmospheric longwave radiative cooling rate. This enhanced radiative cooling to space might be expected to be offset to some extent by increases in specific humidity, assuming that upper-tropospheric relative humidity does not change greatly (Ingram (2010)). However enhanced boundary layer specific humidity may also enhance atmospheric radiative cooling by increasing the longwave radiation emitted from the atmosphere to the surface (Pendergrass and Hartmann (2014)). (Note the increase in near-surface specific humidity with increasing surface-forced evaporation shown in 4(e)). In the absence of substantial changes in surface sensible heat flux, a new tropospheric energy balance will be reached where the radiative cooling increases to a level which balances the enhanced net latent heat release in the atmosphere, and equivalently the enhanced surface latent heat flux.

The regression line for the surface-forced experiments shown in Figure 4(d) indicates an increase in radiative cooling of 0.6 $W/m^2/K$ with surface warming in the absence of an increase in surface evaporation. The slope of the regression line indicates that the radiative cooling response increases by 0.66 $W/m^2/K$ per unit increase in hydrological sensitivity in the surface-forced experiments. Breaking this down into radiative heating components (not shown) indicates that the slope is mainly attributable to the clear-sky longwave component (-0.65 $W/m^2/K$), with -0.1 $W/m^2/K$ coming from changes at the top-of-atmosphere and -0.55 $W/m^2/K$ at the surface. This suggests that the enhanced radiative cooling with increasing surface evaporation is primarily due to the impact of changes in the temperature and humidity structure of the atmosphere on the downwelling surface fluxes. This is consistent with the findings of Fläschner et al. (2016), who demonstrated that the net effect of changes in humidity and lapse rate in the lower troposphere with warming is to increase atmospheric radiative cooling.

Additionally the surface-forced evaporation experiments allow us to diagnose the dependence of near-surface humidity, air-sea temperature difference and near-surface wind speed on changes in surface evaporation, by cutting the feedback loop that normally operates to bring them into balance as the climate warms. Similarly the APEC4KRadCool7% experiment allows us to see how these quantities respond to changes in radiative cooling while maintaining these two-way interactions near the surface. Together these experiments can inform our understanding of how changes in these near-surface properties respond to and at the same time influence changes in surface evaporation and radiative cooling.

The interactions discussed below are summarised in Figure 5. The colours give an indication of the effects of increasing SST while holding surface evaporation fixed (orange, as in APEC4KSurfaceEvap0%), increasing surface evaporation (blue, as in APEC4KSurfaceEvap3% and APEC4KSurfaceEvap7%) and increasing radiative cooling (green, as in APEC4KRadCool7%). Figure 4(f) shows that near-surface relative humidity drops with climate warming when surface evaporation is held fixed, but increases with increasing surface-forced evaporation. The near-surface relative humidity increases in the standard experiment, but less so in the radiative cooling experiment. The differences in these responses cannot be explained by changes in near-surface temperature; Figure 4(g) shows changes in air-minus-sea temperature difference which, in the absence of changes in specific humidity, would be expected to have the opposite effect on near-surface relative humidity. (Note that surface temperatures increase by 4K everywhere in our experiments, so differences in air-sea temperature responses between our experiments are solely due do differences in the near-surface temperature responses.) The reasons for the air-sea temperature responses will be discussed below, but for now we can conclude that the different responses in near-surface relative humidity are in the main due to differences in the responses of the near-surface specific humidity (Figure 4(e)).

In general, near-surface specific humidity would be expected to be enhanced by increased surface evaporation, but depleted by any enhanced vertical mixing by small-scale processes such as convection, turbulence or resolved large-scale overturning (e.g. Sherwood et al. (2014)). In the absence of increases in evaporation and assuming that other sink terms for near-surface specific humidity do not change appreciably, we might expect only small changes in near-surface specific humidity, and hence a drop in near-surface relative humidity with warming in the APEC4KSurfaceEvap0% experiment. The near-surface specific humidity actually does increase in the APEC4KSurfaceEvap0% experiment (Figure 4(e)), but less than half as much as in the standard experiment, and not enough maintain the same near-surface relative humidity with warming.

In the APEC4K, APEC4KSurfaceEvap3% and APEC4KSurfaceEvap7% experiments, progressively larger increases in surface evaporation result in progressively stronger increases in near-surface specific and relative humidity. Increasing surface-forced evaporation results in progressively larger near-surface moistening rates from the boundary layer scheme, which distributes the surface evaporation in the vertical via turbulent mixing (Figure 3(c)). The increasing near-surface relative humidity in response to increasing surface evaporation will provide a negative feedback on the surface evaporation and the hydrological sensitivity in the standard experiment.

Meanwhile, the APEC4KRadCool7% experiment shows slightly weaker increases in near-surface humidity than in APEC4K in spite of a stronger increase in surface evaporation (Figure 4(e-f)) and the associated enhanced near-surface moistening rate from the boundary layer scheme (Figure 3(c)). We attribute this to enhanced upward transport of near-surface humidity by convection in response to the enhanced radiative cooling. This is supported by Figure 3(d) which shows enhanced convective drying of the boundary layer in APEC4KRadCool7% compared to APEC4K. We argue that this enhanced convective drying reduces the near-surface humidity, resulting in an increase in surface evaporation, and a new balance where the surface-evaporation-driven turbulent moistening rate increases to balance the enhanced convective drying rate. The weaker increase in near-surface humidity in the APEC4KRadCool7% experiment compared to the standard APEC4K response is therefore part of the mechanism whereby the surface evaporation increases at a faster rate in the APEC4KRadCool7% experiment.

In APEC4KSurfaceEvap0% the global mean near-surface temperature increases less than the surface with warming, giving a small negative response in air-minus-sea temperature difference, and an increase in the magnitude of the negative air-sea temperature difference (Figure 4(g)). Our interpretation of this is as follows. Increasing the SST will initially increase the magnitude of the air-sea temperature difference, resulting in a large increase in the sensible heat flux. The near-surface air temperature will warm in response, providing a strong negative feedback on the sensible heat flux increase until a balance is reached with a smaller increase than initially. This is supported by Figure 4(d) which shows that the sensible heat flux does indeed increase slightly. This will increase the surface buoyancy flux and enhance the vertical sensible heat transport by the convection scheme. This is supported by the enhanced near-surface cooling seen in the convective heating rates in Figure 3(a) in APEC4KSurfaceEvap0% (orange) compared to the APEC control (grey) , and the increase in convective heating in the free troposphere. This in turn can explain the enhanced warming in the upper troposphere in APEC4KSurfaceEvap0% (orange) compared to APEC (grey) in Figure 2(c). The radiative cooling also increases slightly in the absence of an increase in surface evaporation (Figure 4(d)), as would be expected given the increases in upper tropospheric temperatures. Increases in near-surface specific humidity are also present (Figure 4(e)), but examination of the radiative cooling profile in Figure 3(b) indicates that the radiative cooling is enhanced in the free troposphere rather than the boundary layer, suggesting that the enhanced upper tropospheric temperatures are the main cause in this case. In the case of the APEC4KSurfaceEvap0% experiment, tropospheric energy balance dictates that the changes in radiative cooling and sensible heat flux must balance each other. The interpretation above explains how the sensible heat flux and radiative cooling adjust to maintain tropospheric energy balance with warming in the case where surface evaporation cannot change.

With the surface evaporation increases in the APEC4K, APECSurfaceEvap3% and APECSurfaceEvap7% experiments, the sign of the response of the air-sea temperature difference reverses compared to that in APEC4KSurfaceEvap0%, with the near-surface air temperature warming more than the surface, and the magnitude of the (negative) air-sea temperature difference reducing (Figure 4(g)). Thus we can attribute the reduction in the magnitude of the air-sea temperature difference in the standard experiment to the effects of increasing surface evaporation. This is we argue a result of enhanced latent heat release in the boundary layer, which is supported by Figure

3(a) which shows reduced cooling from the convection scheme from the surface up to 1km with increasing surface evaporation.

The air-sea temperature difference changes little with warming in the APEC4KRadCool7% experiment in contrast to the weakening in the magnitude of the air-sea temperature difference in the standard experiments. We attribute this to an enhanced near-surface cooling rate from the convection scheme in APEC4KRadCool7% compared to APEC4K (Figure 3(a)), due to enhanced convection in response to the prescribed radiative cooling. The small change in the air-sea temperature difference in APEC4KRadCool7% compared to the reduction in magnitude in APEC4K will also contribute to the enhanced surface evaporation in APEC4KRadCool7%.

Additionally we note that responses in the sensible heat fluxes with warming (triangles on Figure 4(d)) are broadly consistent with what would be expected from the changes in the air-sea temperature differences. The decreases of the sensible heat fluxes in response to increases in surface evaporation and radiative cooling cannot be explained by the changes in the near-surface wind speeds (Figure 4(h)), which increase in both cases. Hence these responses can largely be explained in the same way as the air-sea temperature differences as outlined above. The increases in near-surface winds will offset these effects to some degree, but not by enough to change the signs of the responses. This means that the reduction in the global mean sensible heat flux with warming in the standard experiment is a direct consequence of the increasing surface evaporation.

Near-surface wind speeds increase slightly on average with warming in the standard experiments, more so in the APEC4KSurfaceEvap7% experiment, and even more so in the APEC4KRadCool7% experiment, while they reduce in the APEC4KSurfaceEvap0% experiment (Figure 4(h)). The change in the global mean surface wind speed is well correlated with the change in the total radiative cooling (Figure 4(i)). Our interpretation of this is that the atmospheric overturning circulation is enhanced by the progressively stronger radiatively-driven subsidence in the subtropics. This effect will also contribute to the increased surface evaporation in APEC4KRadCool7%.

To quantify the impact of these changes in near-surface properties on the interactively diagnosed surface evaporation, we decompose the hydrological sensitivities in APEC4K and APEC4KRadCool7% into contributions from changes in SST, near-surface relative humidity, air-minus-sea temperature difference and near-surface wind speed using the bulk formula for surface evaporation (see Eq. 1 of Richter and Xie (2008)). We use linear regression to estimate a bulk turbulent transfer coefficient suitable for use with local monthly mean values from the APEC experiment, and then use the bulk formula to predict the surface evaporation responses in the APEC4K and APEC4KRadCool7% experiments using local monthly mean values of SST and near-surface properties. Long term averages of these predicted monthly values agree with the actual changes to within 10-20%, while the difference in responses between APEC4KRadCool7% and APEC4K is predicted to within 3% (Table 2). The changes in surface evaporation can be decomposed into contributions from changes in SST and near-surface properties by repeating the calculations, adding changes in each property to the calculation in turn. These calculations (Table 2) show that the muted evaporation increase in the standard APEC4K experiment (weaker than the 7 %/K increase which would occur with surface warming in the absence of changes in near-surface relative humidity, wind speed and air sea temperature difference) is primarily due to increases in near-surface relative humidity, but with a non-negligible contribution from increases in near-surface air temperature which reduces the magnitude of the air-minus-sea temperature difference. The additional surface evaporation in the APEC4KRadCool7% compared to APEC4K is primarily due to the enhanced near-surface winds, with a secondary contribution from the smaller increase in near-surface relative humidity, and a more modest contribution from the smaller reduction in magnitude of the air-sea temperature difference.

4. Summary and Conclusions

We explore the impact of surface evaporation and hydrological sensitivity on cloud feedback by performing climate change experiments with the HadGEM2-A aquaplanet configuration where surface evaporation is forced to increase at different rates, ranging from 0-7%/K. We modify the surface evaporation response and global hydrological sensitivity firstly by specifying the evaporation rate at the surface, and secondly by adding an artificial radiative cooling term in the atmosphere.

Forcing the evaporation to increase at 7 %/K in the surface scheme in a uniform +4K SST perturbed experiment results in a negative global cloud feedback and an increase in global low cloud fraction, reversing the signs of these responses compared to those in the standard model configuration. Conversely the equivalent experiment with surface evaporation held fixed strongly increases the magnitudes of the global mean low level cloud reduction and positive cloud feedback. In these experiments, the estimated inversion strength (EIS, a measure of the lower tropospheric stability) increases proportionally with the surface evaporation, due to enhanced free tropospheric warming in response to additional latent heat release. We argue that this enhanced stabilisation of the tropics results in a progressively more negative low cloud feedback with increasing surface-forced evaporation, via the well established effect of lower tropospheric stability on low cloud fraction. Hence our results demonstrate that modifying surface evaporation and global hydrological sensitivity can have a substantial impact on the global low cloud feedback in a climate model, on a larger scale than the local dependence on surface evaporation demonstrated by Webb and Lock (2013).

Additionally we force the surface evaporation to increase at 7 %/K by enhancing the rate at which atmospheric radiative cooling increases with warming. In contrast to the surface-forced evaporation increase, this reduces the free tropospheric warming, which weakens the increase in

EIS and slightly strengthens the low-level cloud reduction and the positive cloud feedback relative to the standard experiments. Hence very different cloud feedbacks can arise in experiments with similar hydrological sensitivities and changes in surface evaporation. This indicates that surface evaporation is not the sole control on cloud feedback. Across all of the experiments performed, EIS is a better predictor of low cloud feedback than surface evaporation. This suggests that surface-forced increases in evaporation act to increase low cloud fraction mainly by increasing EIS. As such our results also emphasise the important role that the free tropospheric temperature response and the lower tropospheric stability play in low cloud feedback.

Although the main emphasis of this work is on understanding the role of changing surface evaporation on low cloud fraction feedback, it is interesting to note that it is in the absence of a surface evaporation increase that the strongest low cloud reductions are seen. Substantial low cloud reductions are also seen in the radiative cooling forced experiment , in the absence of substantial changes in EIS. We do not explore the reasons for this further here, but note that experiments where surface evaporation increases are prevented or where radiative cooling is perturbed may be a useful vehicle for future investigation of the mechanisms responsible for breaking up low cloud as the climate warms. Such experiments may help to separate positive cloud feedback mechanisms from negative cloud feedback mechanisms associated with increases in surface evaporation and EIS across cloud regimes, complementing existing approaches which have been used to separate competing terms statistically in specific cloud regimes (e.g. Qu et al. (2015b)). It should be noted however that such experiments may not perfectly separate positive and negative feedbacks.

Inter-model differences in the strength of negative low cloud feedback mechanisms may also contribute substantially to the overall spread in cloud feedback, in addition to the contribution from positive mechanisms. As such, inter-model differences in hydrological sensitivity may also contribute to inter-model spread in cloud feedback. Quantifying the extent to which positive low cloud feedback mechanisms are offset by negative cloud feedback mechanisms such as those demonstrated here may be a necessary step towards to understanding why low cloud feedbacks are positive in models generally, and the extent to which this is true in nature.

Our experiments also provide new insights into the mechanisms underlying the hydrological sensitivity. Many studies have pointed out that a change in the global mean radiative cooling of the atmosphere will result in an equivalent response in surface evaporation and precipitation, assuming that the sensible heat flux does not change substantially, for example in the case of rapid precipitation adjustments which occur following increases in carbon dioxide before substantial surface warming occurs. In the somewhat different case of climate warming however, our results show that increases in surface evaporation can have a very substantial impact on the rate of increase in radiative cooling. Increasing surface evaporation with surface warming modifies the atmospheric temperature and humidity structure, substantially increasing the radiative cooling. Conversely, holding surface evaporation fixed with warming yields only a small increase in atmospheric radiative cooling. Hence, while models' different hydrological sensitivities can usefully be interpreted using offline radiative decomposition methods (e.g. Pendergrass and Hartmann (2014)), DeAngelis et al. (2015), Fläschner et al. (2016)), it should be kept in mind that the inputs to such radiative calculations (e.g. the profiles of the atmospheric temperature and humidity changes) are themselves substantially affected by the rate of surface evaporation increase, and hence the hydrological sensitivity.

We also show that near-surface relative humidity decreases with warming in the absence of increasing surface evaporation, and hence that the increasing near-surface relative humidity in our standard experiments is a direct consequence of increasing surface evaporation. This provides a negative feedback on the surface evaporation and the hydrological sensitivity. Reductions in the magnitude of the air-sea temperature difference and the surface sensible heat flux with warming are also a consequence of the increasing surface evaporation; our results suggest that this is due to enhanced near-surface warming associated with additional latent heat release in the boundary layer. This effect also provides a negative feedback on the hydrological sensitivity. Meanwhile, artificially enhancing the radiative cooling increase which accompanies surface warming reduces the magnitude of near-surface increases in relative humidity by enhancing the rate at which convection removes humidity from the boundary layer. Similarly enhanced removal of heat from the boundary layer by convection increases the air-sea temperature difference. The additional radiative cooling also increases near-surface wind speeds, presumably by enhancing radiatively-forced subsidence. These effects explain how the surface evaporation increases to balance an externally imposed radiative cooling of the atmosphere.

It is widely appreciated that increases in near-surface relative humidity will act to damp increases in surface evaporation, while increases in the magnitude of air-sea temperature differences and near-surface wind speeds will act to enhance it. Our results also demonstrate however that the responses in the factors controlling the surface evaporation (such as near-surface relative humidity, wind speed and air-sea temperature differences) are affected not only by radiative cooling but also by changes in surface evaporation itself. We argue that the hydrological sensitivity will ultimately be determined by the point at which various interacting responses in near-surface relative humidity and wind speed, air-sea temperature difference, surface evaporation, sensible heat fluxes and radiative cooling come into a new balance following a given surface warming. This means that a full understanding of the mechanisms controlling hydrological sensitivity differences in models will require a better appreciation of these various inter-dependent responses. These insights may help to improve our understanding of the factors controlling hydrological sensitivity in the future.

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TABLE 1. Experiment names and descriptions.

Experiment	**Description**
APEC	Aquaplanet experiment based on APE Control SSTs
APEC4K	As APEC with a uniform +4K SST perturbation
APECSurfaceEvap	APEC SST/surface evaporation forced to APEC zonal climatology
APEC4KSurfaceEvap0%	APEC4K SST/surface-forced evaporation to APEC zonal climatology
APEC4KSurfaceEvap3%	APEC4K SST/surface-forced evaporation to APEC4K zonal climatology
APEC4KSurfaceEvap7%	APEC4K SST/surface-forced evaporation 7%/K increase from APEC
APEC4KRadCool7%	APEC4K SST with enhanced atmospheric radiative cooling

TABLE 2. Decomposition of surface evaporation responses in APEC4K and APEC4KRadCool7% experiments.

$W/m^2/K$	**APEC4K**	**APEC4KRadCool7%**	**APEC4KRadCool7% - APEC4K**
Surface Evaporation Response	3.2	7.1	3.9
Predicted Surface Evaporation Response	3.8	7.8	4.0
SST Component	6.8	6.8	0.0
Near-Surface Relative Humidity Component	-2.0	-0.6	1.4
Air-Sea Temperature Difference Component	-0.8	-0.1	0.7
Near-Surface Wind Speed Component	-0.1	1.8	1.9

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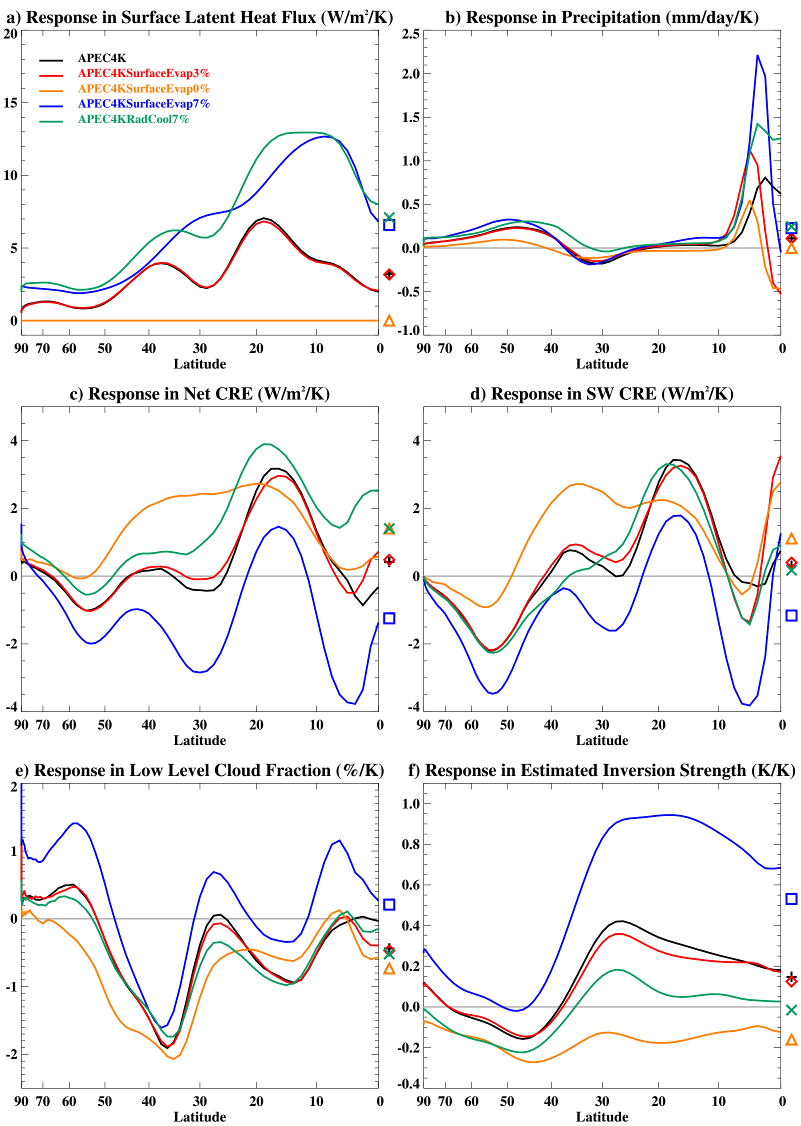

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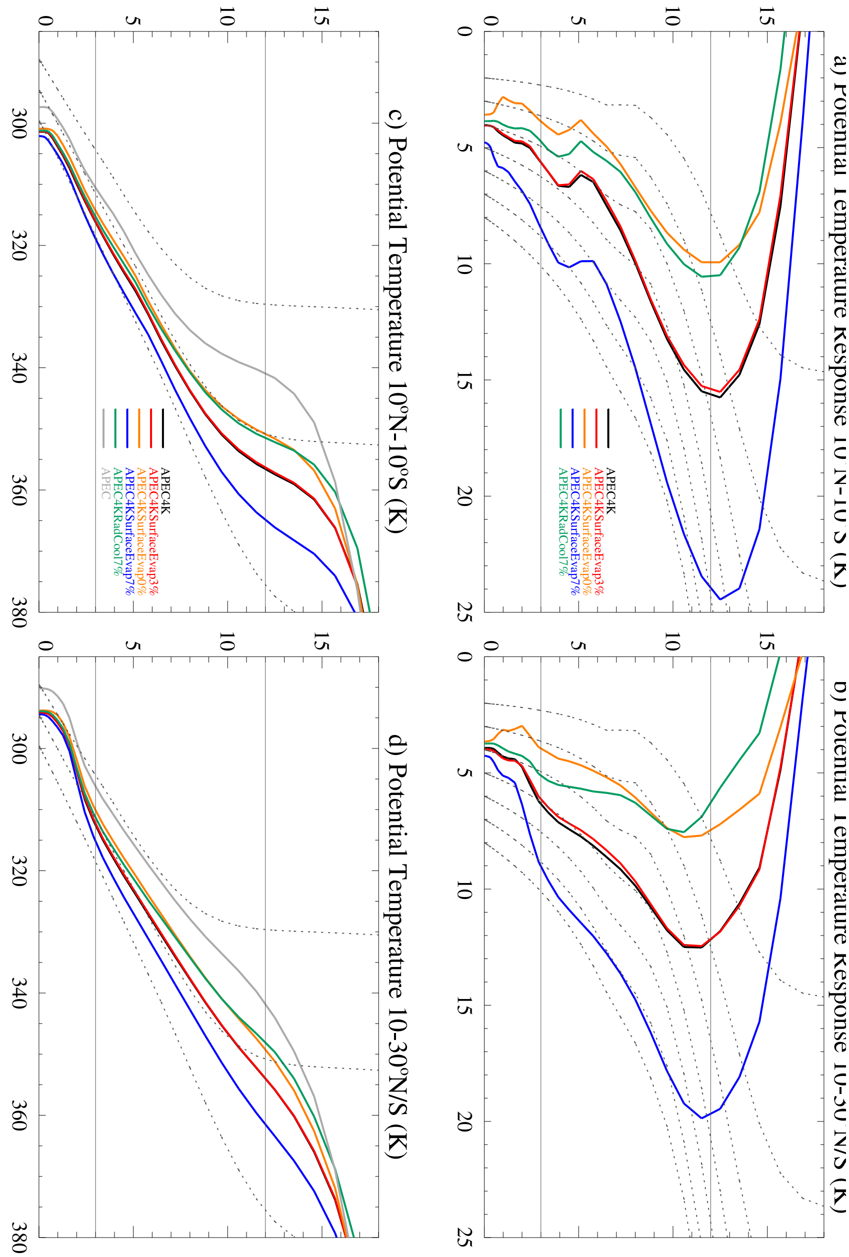

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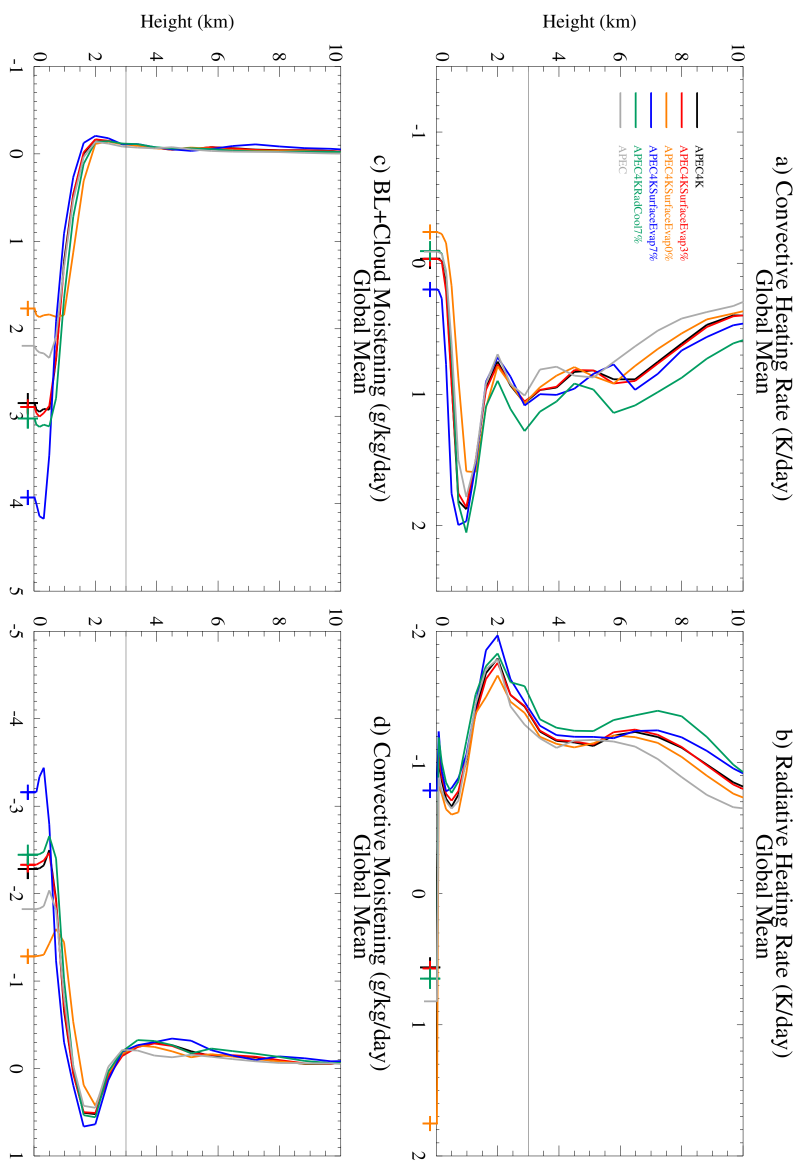

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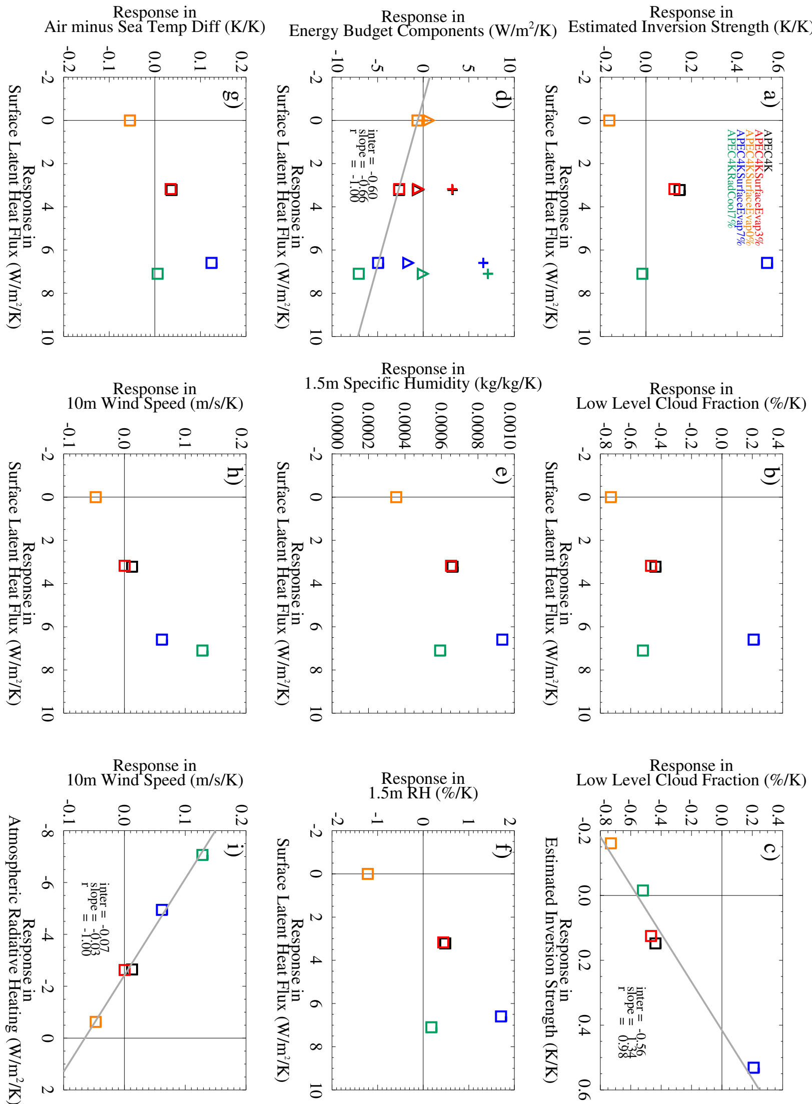

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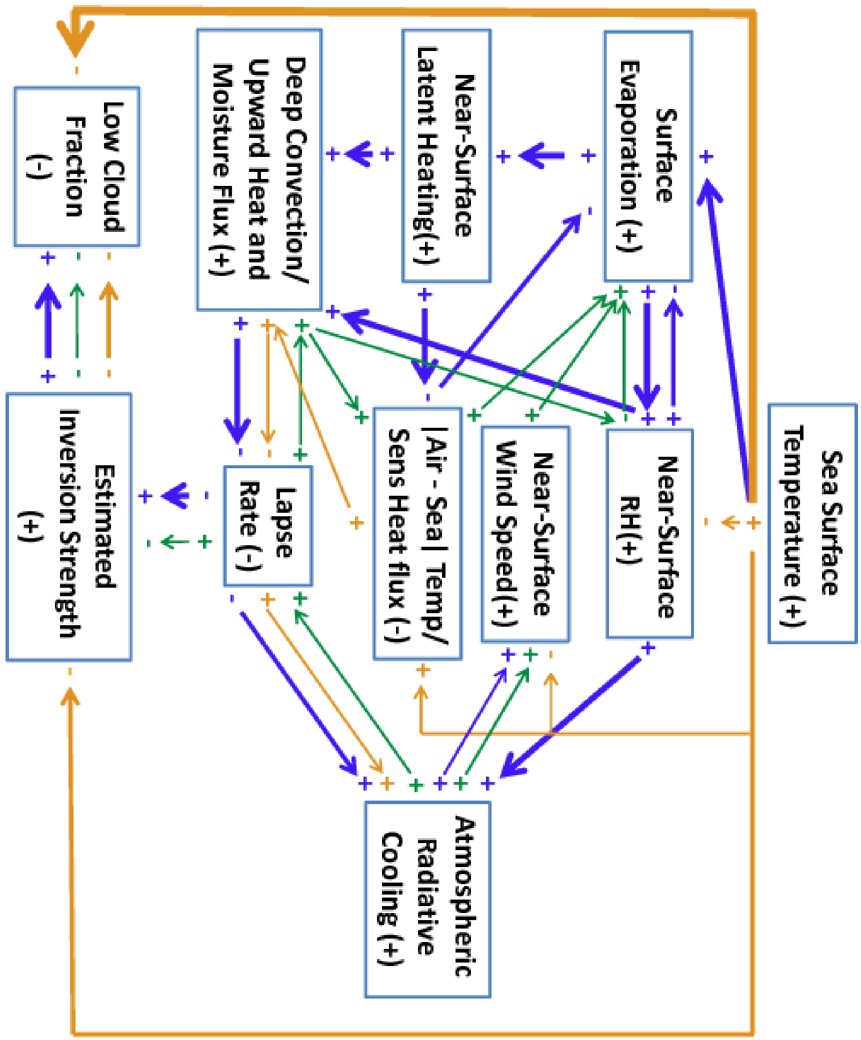

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