Aerosol indirect effects on temperature-precipitation scaling

By N. Da Silva, S. Mailler and Ph. Drobinski

Dear ACP Editor,

We are grateful to both Reviewers for their careful reading of our manuscript and for pointing out points such as the second indirect effect. We have taken into account all of the Reviewers suggestions and modified the text accordingly. In the text below, the Reviewer's comments are in italics, our answers in straight black fonts, and the text in blue describes (and generally reproduces) the changes that have been brought to the manuscript.

We hope that with these changes our study will be retained for publication in ACP.

The Authors.

Response to the comments of Anonymous Referee #1

My one potentially major comment, depending on the answer, is whether the aerosols included in this setup of WRF (and presented in section 2.1) include any amount of shortwave absorption? If they do, then the added heating rate through the atmospheric will also affect convection and stability (rapid adjustments, or the semi-direct effect), which might affect the results throughout the paper. If not, then this is not an issue - but it should still be noted. For a recent investigation of the rapid adjustments due to strongly absorbing aerosols (BC), see Stjern et al. JGRA 2017; this is potentially a very significant effect in some regions.

We used 2 different aerosol climatologies in this setup, one for the microphysical scheme and one for the radiative scheme. In our sensitivity experiment, only the climatology of the microphysical scheme is modified. Therefore, aerosols do include shortwave absorption, but this absorption is identical in both simulations since the aerosol radiative climatology is the same.

This explanation is in the text on line 16 of page 4:
« Another climatology of aerosols from Tegen et al. (1997) is used in this radiative scheme and therefore is not affected by any changes in the microphysical aerosol climatology, which enables us to perform sensitivity experiments of the indirect effects of aerosols
with fixed aerosol direct effect. »

A reference to the study of Stjern et al. (2017) has been added in the introduction.
«They have shown that the consecutive surface cooling not only reduces the water content but also stabilizes the atmosphere as suggested by Fan et al. (2013); Morrison and Grabowski 2011; Stjern et al. (2017) ...»

**The abstract opens with "Indirect effects of aerosols were found to weaken..." Where? In the present manuscript, or in the previous litterature it builds on? (Both seem to be the case, but please clarify.)*

It refers to the previous literature, and especially the Da Silva et al. (2018) study, for which the present manuscript can be seen as a follow-up. The first sentence of the abstract has been modified in order to be explicit:
«Convective precipitation are known to be negatively affected by aerosol indirect effects through reduced precipitable water and convective instability, as stated in the previous literature.»

** P1L18: "a hook shape". This term is used throughout the paper, but never fully explained. Please expand a bit, so the reader won't have to dig it out of the references.*

This term has been explicited in the new version of the manuscript:
«Although less documented than extremes, a "hook shape" of the temperature-precipitation relationship, that is a positive slope at low temperatures and a negative slope at high temperatures, is also suggested for mean precipitation (Zhao and Khalil, 1993; Madden and Williams, 1978; Crhova and Holtanova, 2017; Rodrigo, 2018) as well as differences between land and sea areas (Adler et al., 2008; Trenberth and Shea, 2005).»

** P2L21: Malavelle 2017, Nature Geoscience, should probably also be cited in this context.*

This citation was added in the manuscript.

** P3L29-30: How are the max and min values in WRF determined? Do they have any physical meaning, or are they simply the endpoints of the validity of some internal parametrization? This matters, because it affects how we should interpret the ranges found later in the study.*

These values maximize the potential effect of aerosols and correspond to the lowest and highest values that the microphysical parameterization tolerates. They are too extreme compared to observations and therefore do not have any physical meaning. The ranges found later in the study should be interpreted as upper bounds. The following sentence has been added in the 'simulation experiment' section: « It is however important to keep in mind that the ranges that will be found in this study should be interpreted as an upper bound of aerosol indirect effects. »

** P6L11: Have you tested that daily averaged temperature is indeed representative? How about days with strong diurnal cycle (which would be predominantly low-cloud conditions) vs weak (prevailing clouds), which could have the same average temperature but quite different convective precip event statistics?*

The choice of the daily averaged temperature has also been done for consistency with previous literature. However we have not tested if this temperature is indeed representative of the air mass. Days with strong diurnal cycle (sunny days) versus days with weak diurnal cycle (cloudy days) are indeed confused in our analysis. We think that the daily averaged value is not perfect, but might be more representative of the airmass than an instantaneous value which is might be affected by rain for example.

** P6L20: most -> more?*
It has been corrected in the new version of the manuscript.

** P6L20: Here and elsewhere, consider replacing "SBCAPE" with another term. It is not an intuitive abbreviation, nor short enough to function as a symbol. This becomes very clear on page 12 and in Figure 11, for instance. Why not just E_C, as the rest of the term is clear from the definition?*

SBCAPE is the usual abbreviation to state for the convective energy that would acquire a parcel that is raised from the surface. It is used by several prediction centers like the Storm Prediction Center and the European Severe Storm Laboratory. It might be subjective, but we think that SBCAPE is more intuitive than E_C which is less used in the literature. However, we admit that this term is a bit long to be used in our study. Since the fact that it is a ‘surface-based’ CAPE is not discussed in our article (with respect to other possible CAPE calculations such as ‘Most Unstable’ CAPE), we propose to remove SB and keep CAPE. It has been modified in the new version of the manuscript.

** Figures 3 and 4: Here I would have liked to see some ranges in addition to the lines. E.g. 25th-75th percentile for the medians, and 90th-99th for the extremes? This helps in interpreting the difference between the cases. Later figures have ranges shown, which makes them very clear.*

The new version of the manuscript include ranges for these figures. The ranges chosen are the 95% confidence intervals, as in figure 6 and 7. Descriptions of these errobars have been added in the caption of the corresponding figures.

** P9Eq3: This would be a partial derivative decomposition, I guess?*

It is indeed a partial derivative decomposition done from the logarithm of Eq. 2:

$$\ln(Pr)=\ln(\varepsilon)+\ln(W)+\ln(Q)+C$$

where C is a constant.

$$d(\ln(Pr))=d(\ln(\varepsilon))+d(\ln(W))+d(\ln(Q))$$

which gives:

$$\frac{d\,Pr}{Pr}=\frac{d\,\varepsilon}{\varepsilon}+\frac{d\,W}{W}+\frac{d\,Q}{Q}$$

Assuming small changes between both simulations, one can write the approximate equation by replacing infinitesimal differences (d) by differences between both simulations (Δ):

$$\frac{\Delta\,Pr}{Pr}\approx\frac{\Delta\,\varepsilon}{\varepsilon}+\frac{\Delta\,W}{W}+\frac{\Delta\,Q}{Q}$$

In the manuscript, the equal sign has been replaced by an approximately equal sign.

** P12L16: "Extreme precipitation are mostly of convective nature" -> add "events" and a reference, perhaps? (Or is it still Da Silva 2018? Not quite clear.)*

This sentence was written in order to explain why the scaling seems to work better for extreme total precipitation than in median total precipitation. The argument is that the proportion of convective precipitation is higher in total extreme precipitation than in total median precipitation. Since the scaling (Pr = epsilon W Q) is more adapted to convective precipitation, one can expect a better fit for extreme total precipitation than for extreme median precipitation, which is actually the case. Loriaux et al. (2013) stated that "On an hourly time-scale, precipitation extremes are predominantly stratiform at low temperatures, while at high temperatures convective extremes become dominant." In our LR simulations, we found that convective precipitation start to dominate precipitation extremes from 10°C (not shown), which corresponds to almost the whole range of temperature in our case. On the contrary, we found that stratiform precipitation dominate median precipitation for the whole range of temperature. It is therefore conform with our explanation.

We added a short explanation and a reference to the work of Loriaux et al. (2013).

** Figure 11: Again, this just illustrates the concept of partial derivatives... Perhaps this figure is overly complex? The point is made nicely by figure 8 already*

It indeed illustrates the concept of partial derivative. This figure was done to introduce variables that are discussed in the text, so that the text is easier to read and the reader can refer to this figure if needed.

** Finally: This entire study is performed within WRF. That's OK, but I find little discussion of any possible limitations of that particular model. How broadly applicable do the authors think their results are? Are crucial elements still missing, even for WRF at such high resolution? (There is some discussion in the conclusions, but I would encourage expanding a bit on it.)*

We expanded a bit the conclusion in order to reveal the main limitations of our model setting. A deeper discussion is made on the previous companion paper (Da Silva et al., 2018).

Response to the comments of Anonymous Referee #2

1. The results show a statistical relationship between precipitation and temperature, which is fine, but the subsequent comparison with a Clausius-Clapeyron expected increase needs some clarification or modification. The authors are conditionally sampling on precipitation, but across two seasons, this will blend together different weather regimes together as the optical depth vs temperature plot indicates. It seems to me that what is happening here is that different dynamical regimes driven by large scale dynamics are being conflated with the surface temperature. If you isolated one case and increased the atmospheric temperature then i would expect to see the ClausiusClapeyron-like behaviour, but the negative gradient suggests to me that changes in atmospheric stability driven by the global circulation is the main controller of the T-P relation. I think that this is not a useful comparison between the median observations and C-C as it stands.

We do not deny any contribution from large scale dynamics changes in our temperature-precipitation relationship which is indeed spread over several seasons as many other studies of the temperature-precipitation relationship (Lenderink, 2008; Hardwick, 2010; Utsumi, 2011; Drobinski, 2016). The Clausius-Clapeyron scaling is a proxy of the expected precipitation change with constant weather regimes, relative humidity and precipitation efficiency. Comparisons with the CC-law, thus inform us on the validity of the latter hypotheses accross the temperature range covered by these 2 seasons. We found that the CC scaling is quite similar to the scaling of median convective precipitation even across two seasons. The explanation of this scaling is not the main topic of the article, that is why it is not investigated. For median total precipitation, we found a negative slope. Indeed, although not specified in our article, it is most likely due to changes in large scale dynamics between spring season (cool temperatures) and summer season (warmer temperatures).

We believe that adding some possible explanation of the scalings that we observe would clarify the text. It has been done modifying the first paragraph of the result section.

I recommend that the data be reanalysed in a way that conditionally samples one type of convection (e.g. 'popcorn convection' only), perhaps by using cloud fraction thresholds. In some ways, the extremes analysis is doing the job of conditionally sampling on strong convection. By focusing on the most intense events the precipitation is probably linked to the strongest convection events in that temperature bin.

If the goal of the suggested reanalysis is to select events with similar large scale dynamics, it does not appear to be necessary in the scope of our article which is more focused on the study of precipitation differences between each simulation. The question of convection type impact on the temperature-precipitation scaling is obviously an interesting question, but it needs to be treated in an entire study.

2. The title mentions indirect effects. In the introduction the first and second indirect effects are discussed, but observational evidence for the second indirect effect is felt to be inconclusive. That may be true, but the model used in this work does explicitly represent the second indirect effect through modification of the autoconversion process that will lead to reduced precipitation for increased aerosol, all things being equal. Given that one result of this analysis is that indirect effects appear less important than temperature changes it would be simple to confirm this in the model by running a sensitivity test with the droplet number-autoconversion link disabled or fixed.

This is indeed a point that seems to be missing in our study, but several issues forced us not to do these additional simulations. The «all things being equal» assertion would not be respected when running such a sensitivity test. In particular, when one would modify the autoconversion rate it would also have an effect on the averaged mass of precipitating clouds and then on cloud albedo. Thus, accelerating the autoconversion rate in the MAX simulation may as well reduce the radiative background effect in such 6-months simulations. A potential solution was to initiate each day of this new MAX simulation by the old MAX simulation, considering that the radiative effect is an effect that forms only trough several days of simulation (which might not be totally true). The problem of such a setup is that the same water may be precipitated several times in the simulation, which would overestimate the second indirect effect.

In our study, the precipitation extreme scaling budget clearly shows that changes in convective/extreme precipitation are similar to changes in vertical velocity and are not very sensitive to changes in thermodynamics, which indirectly discard an important effect of precipitation efficiency. Another argument is the similarity of the curves (fig. 6b vs fig. 7b) with and without convective parameterization.

Other points:
p1 line 2-3. Indirect effects.... are these effects caused by increasing aerosol?

These effects are indeed caused by an increase in aerosol concentrations used in the microphysics scheme.

p1 line 8. Is this surface temperature or aloft?

It is precisely the temperature at the first vertical grid level. The term « surface » has been added in the abstract of the new version of the manuscript.

p1 line 6-7. I don't follow this sentence. I thought that figure 3c, 4a showed that the mean precipitation did not follow C-C?

Indeed, as shown in figure 3c and 4a, mean precipitation does not follow the C-C law. However the abstract mentions convective precipitation, which are displayed in figure 3a (medians) and 3b (extremes), and which do follow the C-C law.

p1 line 14. Can you explain more why the first guess is that the extremes are most likely to follow C-C? Is it because you are assuming that these are the most precipitation efficient events that can *wring out all of the moisture from an ascending parcel? Can you argue against the means not following C-C?*

It is expected that extremes would follow the CC law since extremes are supposed to remove all the vapour content of the atmosphere. On the other hand, mean precipitation are constrained by an energetic budget between atmospheric radiative cooling and surface sensible and latent fluxes (Allen and Ingram 2002; Held and Soden 2006; Muller and O'Gorman 2011; Muller et al 2013). As a result, the increase of mean precipitation is expected to be lower than the one of precipitation extremes with temperature. This discussion has been added in the first paragraph.

p1 line 24. What percentiles characterise the extremes referred to here?

99th and 99.9th for hourly precipitation and only 99.9th for daily precipitation.
It has been added between parentheses in the text.

p2 line 3. Can you define what is meant by 'hook' shape? Is it anomalously high precipitation for the warmer temperatures compared to C-C?

'Hook shape' has the same meaning than in the Drobinski et al. (2016) study. It refers to the shape of the temperature-precipitation scaling which displays an increase slope at low temperatures, a precipitation peak at middle temperatures, and a negative or weaker slope at high temperatures. The definition has been added in the text.

p2 line 5. ...with respect to ... -> ...in constrast to... ?

The text has been modified accordingly.

p2 line 19-20. ...reduced droplet radius with increased aerosol concentrations for constant liquid water content.

The text has been modified accordingly.

p2 line 25-26 ...through a decrease in evaporation from the surface due... (could be confusion with droplet evaporation)

The text has been modified accordingly.

p2 line 20. Observations may be inconclusive but the model you are using explicitly links aerosol-> droplet number-> autoconversion.

The second aerosol indirect effect is discussed in the core and in the conclusion of the new manuscript (cf other points).

p4 line 4. The MR configuration should also be introduced in this subsection.

The text has been modified accordingly.

p4 line 30. While recognising that this is a sensitivity test - a concentration of 10,000 cm-3 for ice is 1000-100000 times more than typically observed. This is likely to result in large extensive ice anvils that impact the radiative balance of the simulation. If the nudging timescale were longer than 6 hours this might become a problem. What do the cloud fields simulated look like when compared to observations? What does the precipitation time series look like for HR, LR and observed?

Extreme aerosol concentrations were taken to avoid noise, that we observed at first when realizing a pair of simulation with a factor 2 in aerosol concentrations. As indicated in the table of Da Silva et al. (2018) study, there are some unrealistic values in terms of drop number, liquid water content, cloud optical depth. But these values only affect a little the radiative budget at the surface (while being sufficient to decrease surface temperatures by 0,5 K in the MAX simulation). Thus the extreme change of aerosol concentrations does not result in a drastic change in the radiative balance of the simulations. The reason is that the parameterization of cloud condensation only depends on sursaturation and not on aerosol concentration. It means that an increase in aerosol concentration does not explicitly favors condensation. It leads to very thick anvils but not necessary larger. The precipitation time serie of one grid point for both HR and LR simulations is also shown in the Da Silva et al. (2018) study and seems realistic.

p5 line 6 - are these the MR mentioned in the figure 2 caption? Perhaps description should be included in section 2.1?

This sentence indeed refers to MR simulations. The meaning of MR has been added to the manuscript.

p6 line 22. How sensitive are the results to the use of values computed 1 hour earlier? How about 2 hours or 30 minutes?

Results were found similar when using values computed at the same hour or 2 hours before, with sometimes higher variability. The 1 hour earlier was chosen arbitrary, and considering that the output frequency is hourly.

p9 line 8 - 'at the surface' - is this truly at the surface or a screen level value (e.g. 1.5m)?

It is taken at the first grid vertical level that is around 28 m above the surface for oceans. For readability, we used 'surface' to designate this level. A parenthesis has been added in the method section : « (centered around 28 m above the ground, hereafter referred to as surface) »

p12 line 1-2. I don't really follow this. Why should the C-C predict changes in convective precipitation due to indirect effects? Given that the model explicitly represents a suppression of autoconversion due to increased droplet number concentration (from increased aerosol number concentration) the change in precipitation efficiency, to first order, would seem to be more of a predictor of changes in precipitation due to aerosol effects.

Indirect effects were found to reduce surface temperatures and thus water vapor availibility for precipitation. In the hypothesis of constant relative humidity, convective instability and precipitation efficiency, the change of convective precipitation would be similar to the one expected by the CC law.

Instead, the change in surface temperature is accompanied by a change in convective instability which has much more impact. For precipitation efficiency, note that it can only be impacted indirectly in the LR simulation, since the convection scheme does not explicitely take into account aerosol concentrations. In the HR simulation, precipitation efficiency, while hard to evaluate, is indeed an explicit function of aerosol concentrations. However for extremes, we can see that the relative changes in precipitation are very similar to the one of vertical velocity, suggesting that the contribution of precipitation efficiency is also low.

p12 line 11-19. This discussion ignores the fact that the microphysical scheme has autoconversion, and related processes, that is directly affected by the number concentration of aerosol and hence droplets. The HR can represent these effects explicitly in the convective clouds whereas the parameterised convection in the LR configuration will not represent aerosol effects. The assertions made here could be tested by disabling the link between droplet number and autoconversion in a sensitivity test of the HR configuration

A discussion was added at the end of this paragraph with justification on discarding the second indirect effect of aerosol (as stated above).

p19 conclusions. Figure 14 has no links to changes in microphysical processes directly affected by changes in aerosol. This may be true of the real world, but as far as i can see this was not cleanly demonstrated with the model (see comment about p12 line 11-19).

Figure 14 is a snapshot of the bigger scheme presented in figure 1. The conclusion has been enlarged to discuss the second indirect effect.

Aerosol indirect effects on the temperature-precipitation scaling

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Abstract.

Indirect effects of aerosols were found to weaken convective precipitation Convective precipitation are known to be negatively affected by aerosol indirect effects through reduced precipitable water and convective instability, as stated in the previous literature. The present study aims at quantifying the relative importance of these two processes in the reduction of summer precipitation using the temperature-precipitation scaling. Based on a numerical sensitivity experiment conducted over central Europe aiming to isolate indirect effects, all others effects being equal, the results show that the scaling of hourly convective precipitation with temperature follows the Clausius-Clapeyron (CC) relationship whereas the decrease of convective precipitation does not scale with the CC law since it is mostly attributable to increased stability with increased aerosols concentrations rather than to decreased precipitable water content. This effect is larger at low surface temperatures for which clouds are statistically more frequent and optically thicker. At these temperatures, the increase of stability is mostly linked to the stronger reduction of temperature in the lower troposphere compared to the upper troposphere which results in lower lapse rates.

1 Introduction

The temperature-precipitation relationship has often been studied because it has been hypothesised to give an insight of the change of precipitation in a warming climate. In this context, one may distinguish extreme precipitation studies from mean precipitation studies. The Clausius-Clapeyron (CC) relation is a first guess for the temperature-precipitation extremes scaling because it law relates changes in temperature to changes in water vapor content assuming constant relative humidity:

$$\frac{\partial e_s}{\partial T} = \frac{L_v e_s}{R_v T^2} \tag{1}$$

where e_s is the water vapor saturation pressure, T is the temperature, L_v is the latent heat of vaporization and R_v is the gas constant for air. Precipitation extremes are supposed to wring out all of the moisture from an ascending parcel and are therefore expected to scale with the CC law. However many departures from the CC-scaling have been observed. Literature has described a hook peaklike shape for the temperature-precipitation extremes relationship with CC-scaling for the cold season and negative scaling for the warm season (Drobinski et al., 2016). Sub-CC scaling for warm temperatures can be explained by either the decrease of relative humidity (Hardwick et al., 2010; Panthou et al., 2014), the decrease of precipitation duration (Utsumi et al., 2011; Singleton and Toumi, 2013; Panthou et al., 2014), the decrease of precipitation efficiency or changes in dynamics (Drobinski et al., 2016). Conversely, Lenderink and van Meijgaard (2008) has found an increase of precipitation extremes (their 99.9th and 99th percentiles) beyond the CC-scaling for temperatures between 12°C and 23°C at de Bilt in Netherlands. It has been argued that this "super-CC" scaling is due to the transition between stratiform and convective precipitation (Haerter and Berg, 2009; Berg and Haerter, 2013; Molnar et al., 2015) and enhanced dynamics in convective clouds at higher temperatures (Lenderink et al., 2017). Although less documented than extremes, a hook shape is "hook shape" of the temperature-precipitation relationship, that is a positive slope at low temperatures and a negative slope at high temperatures, is also suggested for mean precipitation Zhao and Kalil, 1993; Madden and Williams, 1978; Lenka and Eva, 2017; Rodrigo, 2018) (Zhao and Khalil, 1993; Madden and Williams, 1978; Crhová and Holtanová, 2017; Rodrigo, 2018) as well as differences between land and sea areas (Adler et al., 2008; Trenberth and Shea, 2005). The CC scaling is less expected for mean precipitation which are more constrained by an energetic budget than extreme precipitation (Allen and Ingram, 2002; Held and Soden, 2006; Muller et al., 2011; Muller, 2013). Hardwick et al. (2010) have systematically found lower slopes for median precipitation with respect to than extreme precipitation in their 4 studied areas in Australia.

The fact that the CC law is not always adequate for describing the temperature-precipitation relationship in a given climate does not mean that if one would perturb the climate, the change in precipitation would not follow a CC-scaling. Indeed, using Regional Climate Models (RCM) in the Mediterranean region and within the frame of the HyMeX program (Drobinski et al., 2014), Drobinski et al. (2018) found a CC-scaling between past and future climate while observing hook shapes for both past and future climate temperature-precipitation relationships. It has often been shown that extreme precipitation would increase at a rate similar to the CC law whereas mean precipitation would increase at a lower rate in a warming climate (Allen and Ingram, 2002; Boer, 1993; Trenberth, 1998; Held and Soden, 2006).

Apart from the greenhouse gases forcing, the forcing of aerosols is another feature that can modify climate and therefore temperature-precipitation relationship. Aerosols affect climate through their direct and semi-direct effects as well as through their effects on cloud microphysics (indirect effects). While their direct effect is rather well understood, many uncertainties remain for the indirect effects. Stevens and Feingold (2009) described aerosol cloud interactions as a buffered system in which many processes seem to partly compensate each other. Among these effects, the Twomey (1977) effect, also called "first indirect effect", is an increase of the Cloud Optical Depth (COD) through reduced cloud droplet radius for constant liquid water content with increased aerosol concentrations. Aerosols indirect effects may also increase cloud lifetime (Albrecht, 1989) but as of today no consensus exists on the reality of this effect (Small et al., 2009; Seifert et al., 2015) (Small et al., 2009; Seifert et al., 2015; Malavelle et al., 2017), and its representation in climate models is highly dependent on the model's microphysical formulation (Zhou and Penner, 2017). An invigoration effect has been diagnosed for convective precipitation (Fan et al., 2013) through an increased release of latent heat due to ice formation associated with a decrease of warm rain formation with increased aerosol loads.

A common feature of both direct and indirect effects of aerosols is a global decrease of precipitation through a decrease of evaporation from the surface due to the reduction of shortwave downwelling fluxes at the surface (Ramanathan et al., 2001; Lelieveld et al., 2002; Bollasina et al., 2011; Salzmann et al., 2014). In their study of aerosol indirect effects over the Euro-Mediterranean area, Da Silva et al. (2018) diagnosed the same path for their simulated decrease of precipitation (see Figure 1).

They have shown that the consecutive surface cooling not only reduces the water content but also stabilizes the atmosphere as suggested by Fan et al. (2013); Morrison and Grabowski (2011)Fan et al. (2013); Morrison and Grabowski (2011); Stjern et al. (2017) , and hence acts in reducing precipitation with increased aerosol concentrations. A third path is possible as a combination of these two paths since the reduction of water vapor mixing ratio at the surface would also contribute to increase the stability of the atmosphere through less latent heat released with increased aerosol concentrations. To our knowledge, an evaluation of the relative contribution of these paths to precipitation reduction due to aerosol indirect effects has not been proposed yet. This study aims at determining these contributions and therefore can be seen as a natural follow-up of Da Silva et al. (2018). For that purpose, we use the temperature-precipitation relationship which appears to be a natural framework since both effects are a consequence of the decrease of surface temperature.

Section 2 details the configuration of the WRF model used, the simulations, and the method that have been performed for this sensitivity analysis. Section 3 analyses the temperature-precipitation scaling and quantifies each contribution to the reduction of central Europe summertime precipitation under the effect of a massive concentration of cloud condensation nuclei. Section 4 concludes the study.

2 Methods

2.1 Model configuration

The version 3.7.1 of the Weather Research and Forecasting Model (WRF, Skamarock et al., 2008) is used in this study. The model was run with a 50 km (LR), a 16.6 km (MR), and a 3.3 km (HR) horizontal resolution on a domain displayed in Fig. 2. It is forced by the Global Forecast System (GFS) model (National Centers for Environmental Prediction National Weather Service, 2000) as initial and boundary conditions. Temperature, humidity, geopotential and velocity components are nudged towards GFS analysis data with a Newtonian-type method using a relaxation coefficient of $5 \times 10^{-5}\,\mathrm{s}^{-1}$ as recommended by, e.g., Salameh et al. (2010); Omrani et al. (2013, 2015).

The microphysical scheme used is the Thompson and Eidhammer (2014) scheme which explicitly calculates the number concentrations of aerosols. The latter are represented in a simplified way according to their capacity to nucleate cloud water ("water friendly", WFA) or ice water ("ice friendly", IFA). Aerosol number concentrations are initialized and forced at domain boundaries by a climatology based on Goddard Chemistry Aerosol Radiation and Transport (GOCART) model (Ginoux et al., 2001) simulations. While no surface emissions are applied to IFA, surface emission fluxes are applied to WFA in order to approximately equilibrate the loss of WFA due to scavenging and nucleation. The radiation scheme is RRTMG (Rapid Radiative Transfer Model for General circulation models, Iacono et al., 2008) and uses the cloud water droplets, ice and snow effective radii of the Thompson and Eidhammer (2014) microphysical scheme to resolve the radiative transfer equations. Another climatology of aerosols from Tegen et al. (1997) is used in this radiative scheme and therefore is not affected by any changes in the microphysical aerosol climatology, which enables us to perform sensitivity experiments of the indirect effects of aerosols with fixed aerosol direct effect. The Kain (2004) scheme is used to parameterize convection. The microphysical effects of

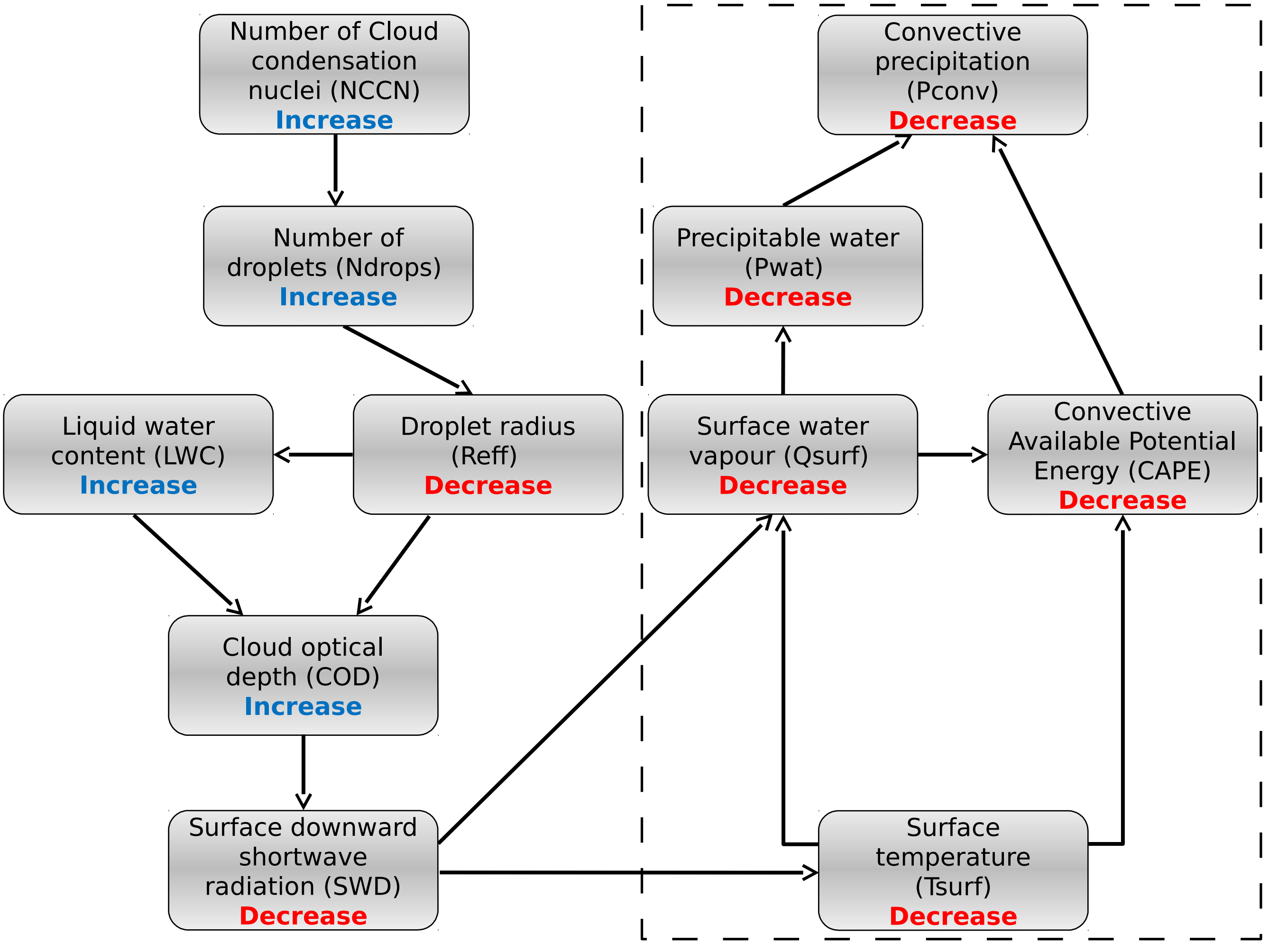

Figure 1. Schematic summary of the aerosol causal sequence for the indirect effects of aerosols on convective precipitation (from Da Silva et al. (2018)). The dotted rectangle indicates the part of the scheme which is detailed in the present study.

aerosols are not taken into account explicitly in this parameterization although they can affect convection indirectly through modifications in the temperature or moisture profiles.

This configuration is the same as in Da Silva et al. (2018) to which the reader is referred for additional detail.

2.2 Simulation experiments

The model was run to make two extreme simulations in terms of WFA and IFA microphysical concentrations. Both simulations start on April 1st, 2013 (after one month of spin-up) and end on September 17, 2013. A very high aerosol emission level (1.75×10^7 kg s^{-1} for the whole domain) is applied in the first simulation, referred as MAX or polluted simulation and a very low aerosol emission level (1.75×10^{-4} kg s^{-1} for the whole domain) is applied for the other simulation, referred as MIN or pristine simulation. Although these emission rates are extreme, maximal and minimal value permitted by the microphysics scheme reduce the range of variation of the number of WFA (NWFA) between $\sim 10\,\mathrm{cm}^{-3}$ and $\sim 10,000\,\mathrm{cm}^{-3}$ and of the number of IFA (NIFA) between $0.005\,\mathrm{cm}^{-3}$ and $10,000\,\mathrm{cm}^{-3}$. Therefore these latter extreme emission rates ensure that both NIFA and NWFA in the MIN (resp. MAX) simulation remain close to their minimal (resp. maximal) permitted values, which corresponds to a 2×10^6 factor for NIFA and a 10^3 factor for NWFA between the MAX and the MIN simulations. Such high differences of aerosol concentrations between the two simulations ensure that aerosol indirect effects are strong enough to emerge from the potential noise between the MAX and the MIN simulations. It is however important to keep in mind that the ranges that will be found in this study should be interpreted as an upper bound of aerosol indirect effects.

Another set of MIN and MAX simulations has been performed at a resolution where convection is resolved (3.3 km) and on a smaller domain (HR domain) as seen in Figure 2. An intermediate set of simulations was used to perform one-way nesting between the LR and the HR simulations, ensuring that the LR simulations force the HR simulations at their boundaries. These intermediate simulations were done at 16.6 km of resolution in an intermediate domain (MR, see Fig.2) and with the same configuration as the LR simulations. In these conditions, each grid cell of the LR domain corresponds to exactly 15×15 grid cells of the HR domain. The HR simulations have been performed without activating any convection scheme, since horizontal resolution (3.3 km) is sufficient to resolve convection processes, which is the only difference in model configuration between the LR simulations and the HR simulations.

2.3 Temperature-precipitation bin method

The simulation domain covers the Euro-Mediterranean region as displayed in Figure 2. This figure also shows the difference of accumulated convective precipitation over the period of study between the MAX and the MIN simulations. It shows that most of the negative signal is concentrated over land regions where precipitation are more intense in this period of the year (Da Silva et al., 2018). The following analysis of convective precipitation reduction in the MAX simulation is conducted over the HR domain. Indeed, location of the HR domain was chosen because of the high negative values of convective precipitation differences between the MAX and the MIN simulations in this area and because it is far away from oceanic areas where flux imbalance with the non-coupled oceanic surface may hinder interpretation as discussed in Da Silva et al. (2018). Because of the short duration of our simulations, temperature at first vertical grid level (centered around 28 m above the ground, hereafter referred to as surface) and convective precipitation hourly time series were collected for all grid points of the WRF model that were inside the HR domain and then concatenated. To avoid snow precipitation we selected only the events with daily mean temperatures warmer than 5°C.

The method used to scale precipitation with temperature is similar to the one used by Hardwick et al. (2010). Temperature has a diurnal variation and may be impacted by precipitation events. Since for each precipitation event we want the corresponding temperature that represents the air mass, the daily averaged temperature is used. We select hours with strictly positive precipitation amount in both the MIN and MAX time series and place the pairs of daily mean temperatures and hourly precipitation

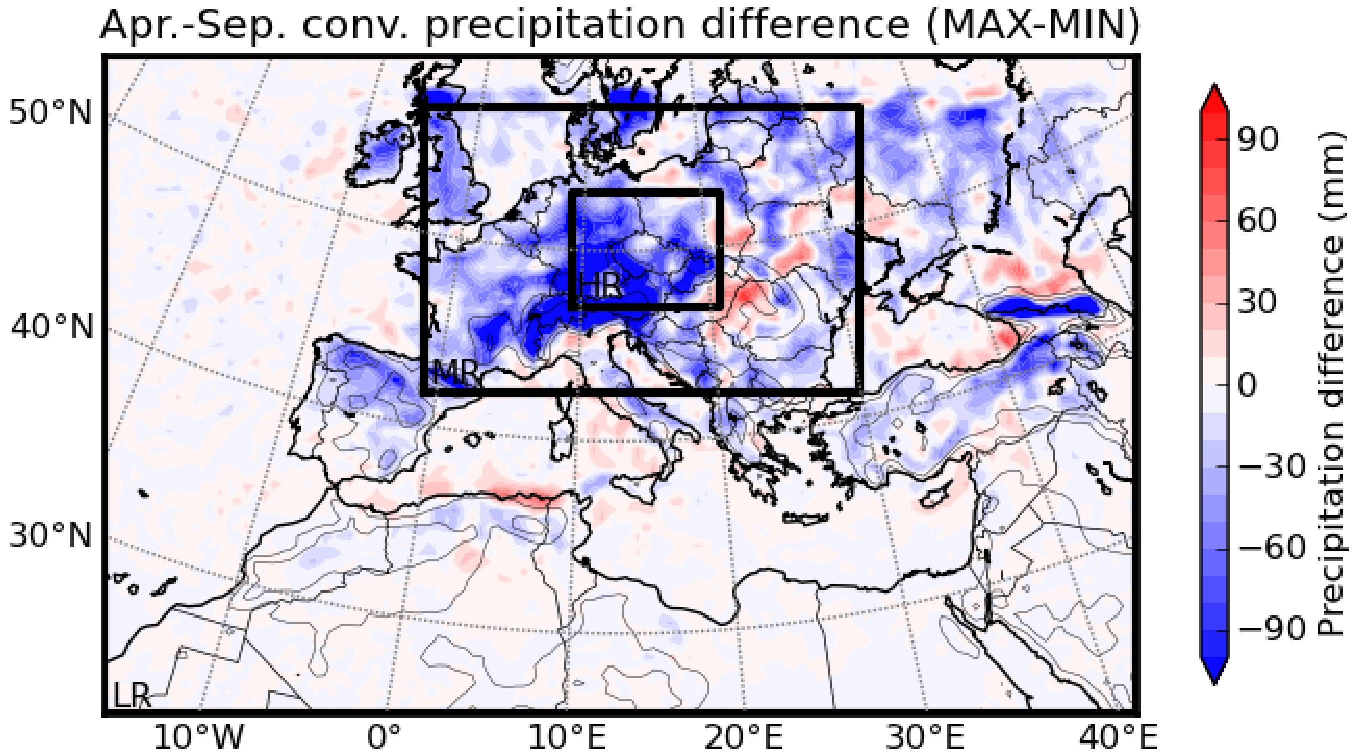

Figure 2. Differences of convective precipitation between the MAX and the MIN simulations. The whole map is the LR simulation domain, the medium black box is the intermediate domain MR, and the small box is the HR domain.

into 8 bins of 5896 samples according to the daily temperatures. In each bin the 50^{th} percentile of daily mean temperature, the 50^{th} percentile of precipitation and the 95^{th} percentile of precipitation are used for our analysis.

We focus on the contributions of precipitation efficiency, surface water vapor mixing ratio, and maximum vertical wind speed to the difference of convective precipitation scaling with temperature between the MAX and the MIN simulations. Precipitation efficiency is calculated using hourly output variables of WRF, and following the parameterization of Kain (2004) implemented in the model in which precipitation efficiency is a decreasing function of cloud base height and vertical wind shear. Because model output frequency is lower than the typical convective characteristic time, we expect large uncertainties. For the LR simulations, the maximum vertical wind speed is calculated using the square root of ~~Surface Based~~ surface based Convective Available Potential Energy (~~SBCAPE~~CAPE) which is ~~most~~ more representative of convective vertical motions than the resolved vertical velocity. These three variables are computed one hour before the convective precipitation occurrence to better represent the air inside the updraft of the convective cell rather than the air inside its downdraft.

The contribution of each variable to the change of precipitation between the MAX and MIN simulations is computed for both median and extreme precipitation events which are defined as following. Median events are all events where precipitation is between the 40^{th} and the 60^{th} percentile in at least one of the simulations (MIN or MAX). Extreme events are all events beyond the 90th percentile in at least one of the simulations (MIN or MAX). Median and extreme events are sorted as a function of the corresponding daily mean temperature and placed in 8 bins with the same number of events per bin. For median or extreme precipitation, the median of daily mean temperature is paired with each of the 4 variables (precipitation, precipitation efficiency, surface water vapor mixing ratio and maximum vertical wind speed along the atmospheric column) in the MIN and the MAX simulations.

3 Results

3.1 Sensitivity of temperature-precipitation scaling to change in aerosol loads

Figure 3 displays the 50th (a, c) and 95th (b, d) percentiles of hourly convective (a, b) and total (c, d) precipitation as a function of daily mean temperature at the surface for both the LR MIN (magenta) and the LR MAX (blue) simulations. Median ~~convective precipitation follow a nearly CC-scaling in our LR simulations. However, there is a negative slope when considering total precipitation. It is therefore not surprising to find sub-CC scaling for total precipitation in the~~ total precipitation displays a negative scaling with surface temperature for both LR and HR simulations (figure 4a). ~~Lower slopes~~ Since the temperature range is spread over 2 seasons, it is likely that changes in large scale forcings between spring and summer events may explain the decrease of median precipitation with surface temperature. Sub-CC scaling for median total precipitation are consistent with the study of Hardwick et al. (2010) in Australia. On the other hand, median convective precipitation follow a nearly CC-scaling in our LR simulations indicating that, unlike median total precipitation events, convective precipitation events seem to be mostly affected by changes in surface temperatures rather than changes in large scale dynamics.

Regarding convective precipitation extremes, a nearly CC-scaling appears in the LR simulation. Using in-situ measurements in Switzerland, Molnar et al. (2015) found a scaling of 8.9%.°C^{-1} of hourly convective precipitation as a function of daily mean temperature. Lower but similar slopes are obtained in our study with a value of 6.1%.°C^{-1} for the LR MIN simulation and a value of 8.6%.°C^{-1} in the LR MAX simulation. Berg and Haerter (2013) and Loriaux et al. (2013) showed that the scaling between total extreme precipitation and daily mean temperature could be super-CC because of the distribution of convective and stratiform precipitation with respect to daily mean temperature. Convective precipitation are generally more intense and occur at higher temperatures. Supposing that both convective and stratiform precipitation follow a CC-scaling, they argued that total precipitation will display a super-CC scaling for temperatures corresponding to the transition between stratiform and convective precipitation. Such an effect does not appear in our study since we can observe a slight sub-CC scaling for total extreme precipitation. The scaling of total extreme precipitation is therefore different from the hook shape found in the Drobinski et al. (2018) study in the Mediterranean area. As expected (Li et al., 2011), precipitation extremes are increased in the HR simulations with respect to the LR simulations. However the slopes of the HR simulations are rather similar to the slopes of total precipitation in the LR simulations.

Differences between the MAX and the MIN simulations are similar for both extremes and medians in HR and LR simulations. We find that convective precipitation are reduced in the MAX simulation but only at low temperatures. This temperature dependency slightly changes the scaling between the MAX and the MIN simulations, with higher slopes in the MAX simu-

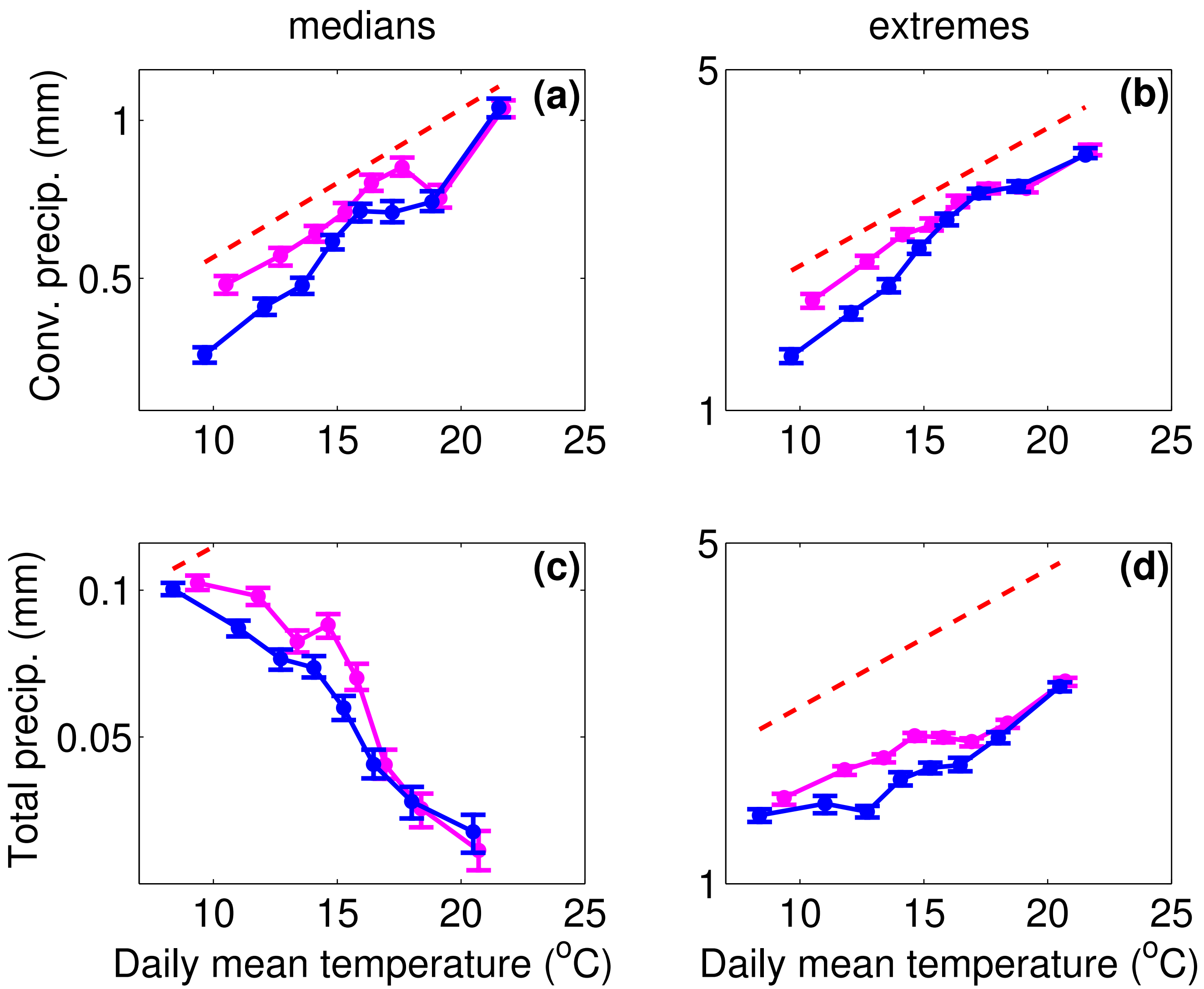

Figure 3. Hourly convective (a, b) and total (c, d) precipitation as a function of daily mean temperature at the surface for median (a, c) and extreme (95^{th} percentile, b, d) precipitation and for both the LR MIN (magenta) and LR MAX (blue) simulations. The dashed red line indicates the CC-slope calculated using the August-Magnus-Roche approximation for saturated vapor pressure (Alduchov and Eskridge, 1996). Errorbars represent the 95 % confidence interval of the precipitation percentiles.

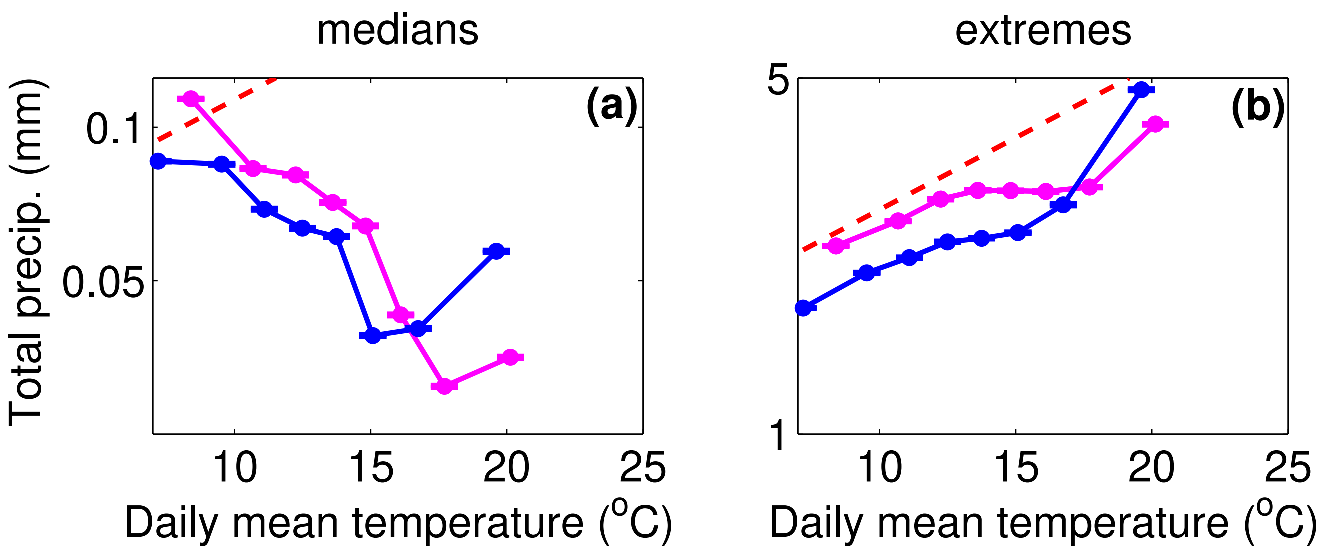

Figure 4. Hourly total precipitation as a function of daily mean temperature at the surface for median (a) and extreme (95th percentile, b) precipitation and for both the HR MIN (magenta) and HR MAX (blue) simulations. The dashed red line indicates the CC-slope calculated using the August-Magnus-Roche approximation for saturated vapor pressure. Errorbars represent the 95 % confidence interval of the precipitation percentiles.

lation (around 8.5%.$^{o}C^{-1}$ in LR) compared to the MIN simulation (around 6.2%.$^{o}C^{-1}$ in LR). The fact that indirect effects of aerosols are weaker at high temperatures is probably due to the lower occurrence of clouds in these conditions. Figure 5 shows COD calculated as in Da Silva et al. (2018), as a function of daily mean temperature for both the MIN and MAX simulations for low and high resolutions. It confirms the weaker occurrence of clouds at high temperatures in our simulations, which results in weak differences in COD between the MAX and the MIN simulations for low and high resolution. On the contrary, clouds are numerous at low temperatures and create important differences of COD between the MAX and the MIN simulations which maximize indirect effects of aerosols. In their study of the impact of the microphysical scheme on the scaling of precipitation extremes with temperature, Singh and O'Gorman (2014) have also shown that the main effect occurs at low temperatures. They attributed the change of slope at low temperatures to a change of hydrometeor fall speed, parameterized differently depending on the microphysical scheme. In our case, convective precipitation are diagnosed with the same convective scheme in the MAX and MIN simulations, which neither takes into account aerosol concentrations nor rain fall speed. Such microphysical effect is therefore impossible in our configuration. We believe that the inhibition of convective precipitation is mainly due to the processes described in Da Silva et al. (2018), i.e. a stabilisation of the atmosphere and a reduction of precipitable water in the polluted simulations.

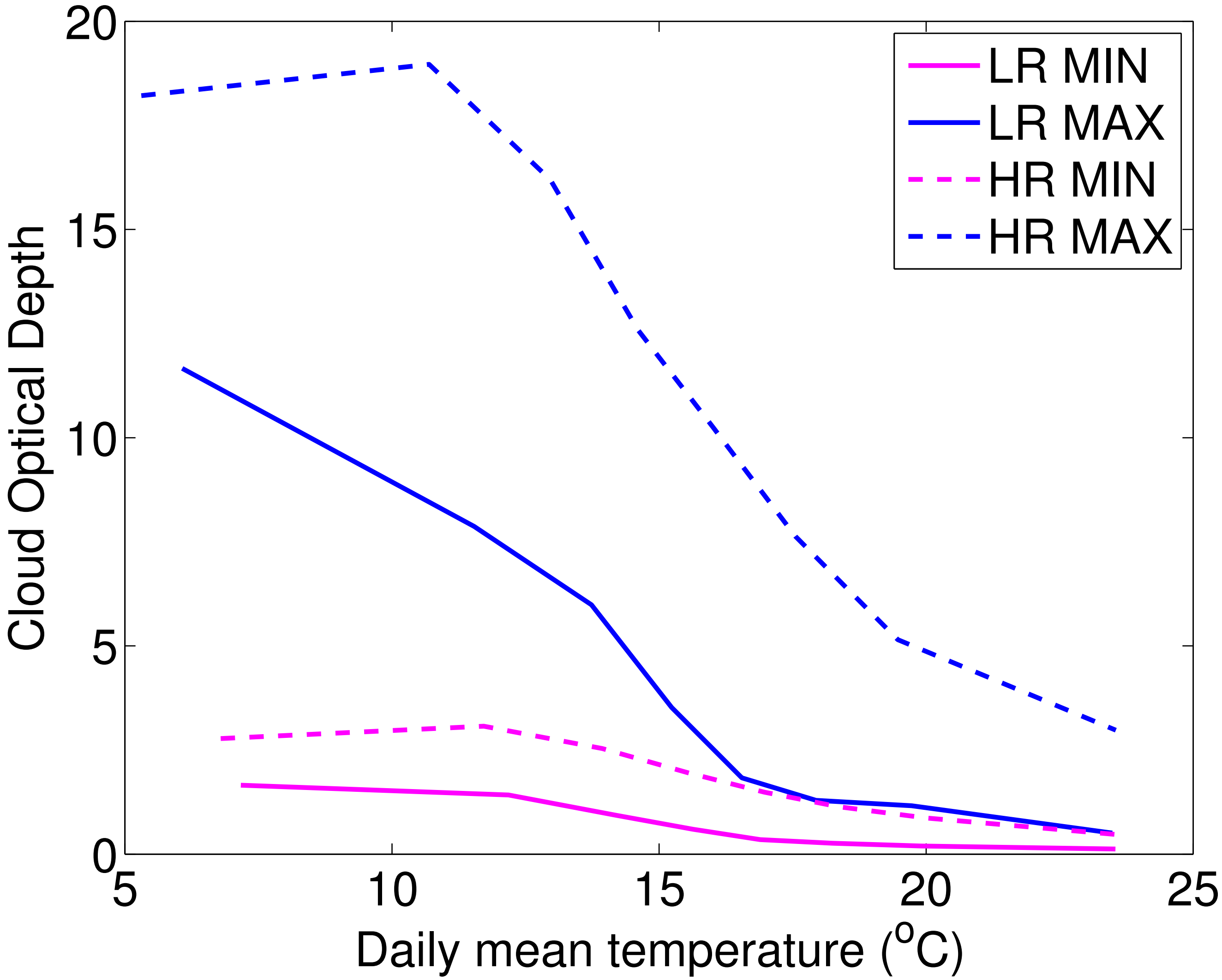

Figure 5. Hourly COD as a function of daily mean temperature for the LR MIN (full magenta line), LR MAX (dashed blue line), HR MIN (dashed magenta line) and HR MAX (dashed blue line) simulations.

3.2 Process analysis

To analyse the reduction of convective precipitation at low temperatures we consider that precipitation can be approximately described by the following equation:

$$Pr \propto \epsilon \times Q \times W \qquad (2)$$

with ε corresponding to the precipitation efficiency, Q the water vapor mixing ratio at the surface and W the maximum vertical wind speed. This description is mostly valid for convective precipitation which result from a parcel that raises from the surface.

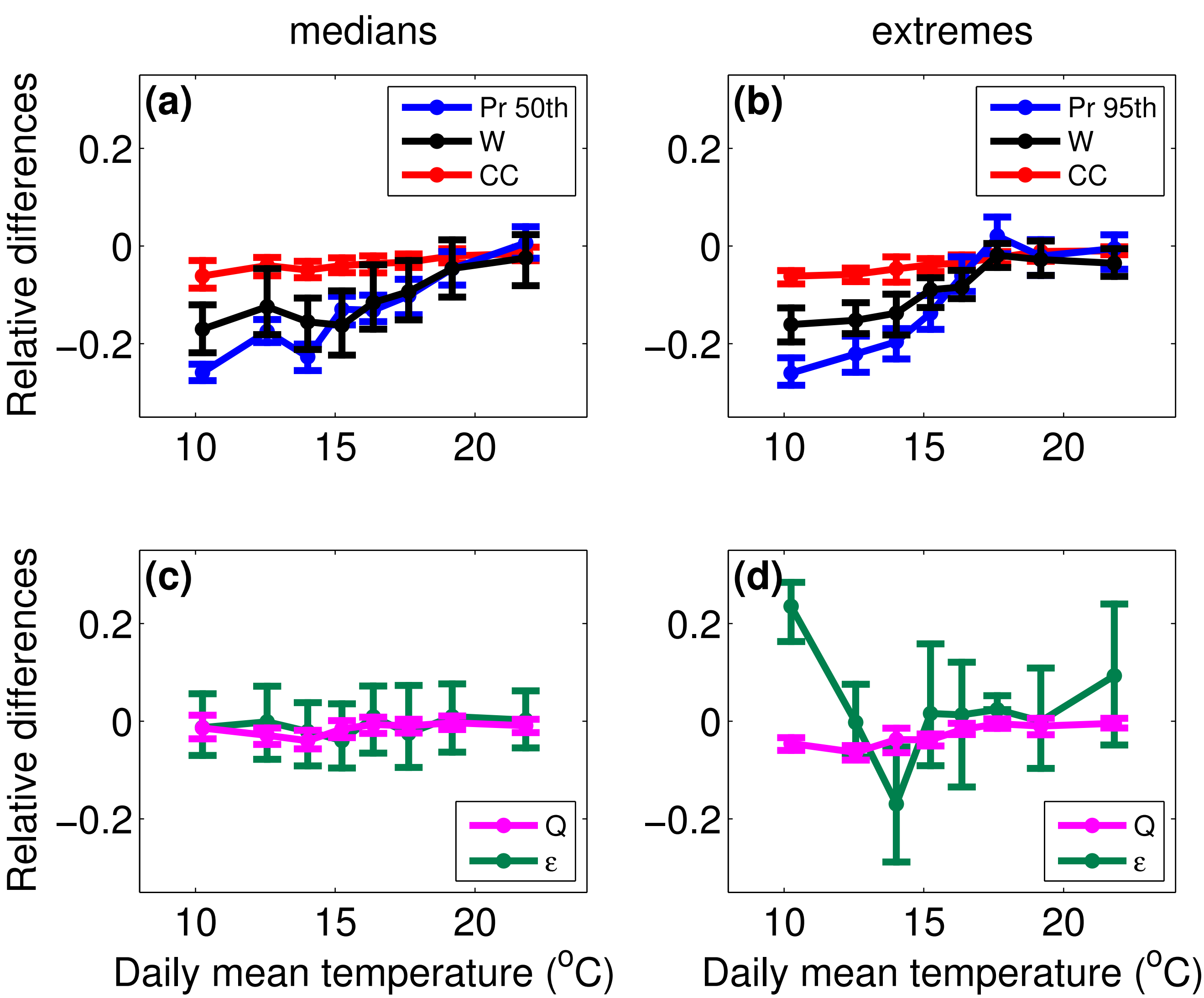

Figure 6. Relative differences between LR MAX and LR MIN simulations of convective precipitation (blue, a and b), vertical velocity (black, a and b), surface water vapor mixing ratio (magenta, c and d), precipitation efficiency (green, c and d) for median (a and c) and extreme (b and d) convective precipitation events as a function of the mean between the MIN and MAX daily mean temperature. The change expected according to the Clausius-Clapeyron law is displayed in red (a and b). Errorbars represent the 95 % confidence interval of the precipitation percentiles.

Assuming the small changes of precipitation that we observe between the MAX and the MIN simulations, one can write :

$$\frac{Pr_{MAX}-Pr_{MIN}}{Pr_{MIN}} = \approx \frac{\epsilon_{MAX}-\epsilon_{MIN}}{\epsilon_{MIN}} + \frac{Q_{MAX}-Q_{MIN}}{Q_{MIN}} + \frac{W_{MAX}-W_{MIN}}{W_{MIN}} \quad (3)$$

Figure 6 displays relative changes in convective precipitation vertical wind speed, precipitation efficiency, and surface water vapor mixing ratio between the LR MAX and LR MIN simulations for median and extreme precipitation. As expected from figure 5, the decrease of convective precipitation in the MAX simulation with respect to the MIN simulation tends to be weaker with increasing temperatures, from -25% at 10^{o}C until almost 0% at 22^{o}C. Among the three factors that may impact the precipitation intensity, the vertical velocity seems to explain much of the reduction of convective precipitation. Indeed, among the 25% of precipitation reduction at low temperatures, around 15% are attributable to the weakening of vertical velocity in the MAX simulation. It is also striking in Fig. 6 that the variations of the difference of vertical velocity and of convective precipitation with temperature are perfectly similar, with stronger reductions for low temperature than for higher ones, while both precipitation efficiency and surface water vapor mixing ratio display insignificant or erratic variations with temperature. Indeed, the high variations of precipitation efficiency differences with temperature for precipitation extremes may not reflect a physical process but only the difficulty in retrieving precipitation efficiency from hourly outputs.

The fact that vertical velocity drives the changes in convective precipitation explains why the CC-scaling is completely inaccurate for predicting changes in convective precipitation by indirect effects. In fact, even the differences of surface water vapor mixing ratio between the MAX and MIN simulations do not exactly follow a CC-scaling due to increased relative humidity in the MAX simulation: while the CC law prediction is around -4%, the reduction of surface water vapor mixing ratio in the MAX simulation is often less important. One would expect that the sub-CC scaling of surface water vapor mixing ratio differences would result in a sub-CC scaling of convective precipitation differences but it is actually the reverse (super-CC scaling) because of stronger changes in vertical velocity.

Results are similar for both extreme and median precipitation except for precipitation efficiency differences which displays small variations for median precipitation and erratic variations for extreme precipitation which may not have a physical meaning.

Figure 7 is the same as figure 6 but for the HR total precipitation. We did not evaluate precipitation efficiency, since it is not parameterized for explicitly resolved precipitation. Although the differences of vertical velocity and surface water vapor mixing ratio for median precipitation events have approximately the same behavior with temperature in the HR simulation with respect to the LR simulation, MAX-MIN differences of total HR precipitation are stronger than the differences of LR convective precipitation. Such positive bias compared to LR convective precipitation differences may be expected since Da Silva et al. (2018) showed that stratiform precipitation are increased in the MAX simulation. ~~Extreme precipitation are mostly of convective nature, therefore~~ On the contrary it was found that hourly extreme precipitation are dominated by convective events at high temperatures (Loriaux et al., 2013). The decomposition of precipitation as a product of a thermodynamics, dynamics and a microphysics term made in the present study is better adapted to convective precipitation than to stratiform precipitation and thus is not efficient in explaining differences of total median precipitation. In our LR simulations, we found that convective precipitation dominates extreme total precipitation from 10ºC (not shown), thus for most of our temperature bins. Therefore differences of extreme total precipitation in the HR simulation are similar to the convective ones in the LR simulation and scale well with the differences of maximum vertical velocities. In this set of simulations with explicit convection, changes in aerosol concentrations may have an impact on precipitation efficiency through a change in autoconversion rate (second indirect effect).

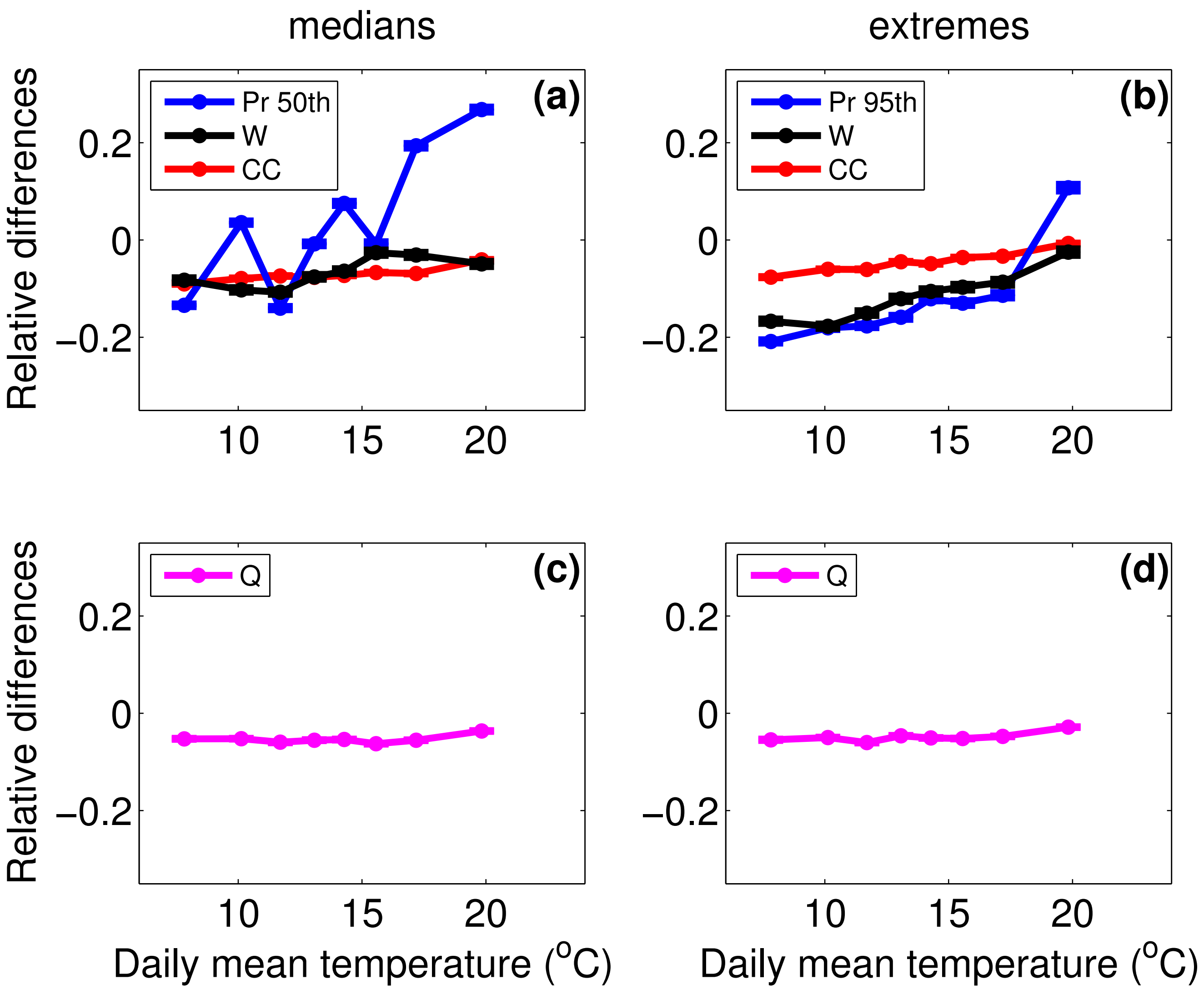

Figure 7. Relative differences between HR MAX and HR MIN simulations of total precipitation (blue) and vertical velocity (black, a and b) and surface water vapor mixing ratio (Q, magenta, c and d) for median (a and c) and extreme (b and d) precipitation events as a function of the mean between the MIN and MAX daily mean temperature. The change expected according to the Clausius-Clapeyron law is displayed in red (a and b). Errorbars represent the 95 % confidence interval of the precipitation percentiles.

The similarity of the precipitation differences differences with and without parameterized convection suggest that the second aerosol indirect effect may not have an important impact in changing the precipitation efficiency of convective precipitation in our configuration.

3.3 Contributions of humidity and temperature to stability changes

As mentioned in section 2.3, vertical velocity is calculated as the square root of ~~SBCAPE~~CAPE. As seen in Fig.1, ~~SBCAPE~~ CAPE may be affected by both surface temperature and surface humidity. ~~SBCAPE~~ CAPE is calculated using the entire profile of temperature and relative humidity (RH). In this line, we want to quantify the contribution of both the temperature and RH profile changes in the decrease of ~~SBCAPE~~ CAPE in the MAX simulation. For that purpose we have substituted the vertical profile of temperature in the MIN simulation, by the vertical profile of temperature from the MAX simulation, and we have calculated two additional ~~SBCAPEs~~CAPEs, i.e. ~~$SBCAPE_T$~~ $CAPE_T$ (resp. ~~$SBCAPE_{RH}$~~$CAPE_{RH}$) calculated with the temperature profile from the MAX (resp. MIN) simulation and the relative humidity from the MIN (resp. MAX) simulation, as represented in Figure 8. Using the 4 ~~SBCAPEs ($SBCAPE_{MIN}$, $SBCAPE_{MAX}$, $SBCAPE_{RH}$ and $SBCAPE_T$~~CAPEs ($CAPE_{MIN}$, $CAPE_{MAX}$, $CAPE_{RH}$ and $CAPE_T$) we can compute relative differences (~~$\Delta SBCAPE_{RH,1}$, $\Delta SBCAPE_{RH,2}$, $\Delta SBCAPE_{T,1}$, $\Delta SBCAPE_{T,2}$, and $\Delta SBCAPE$~~$\Delta CAPE_{RH,1}$, $\Delta CAPE_{RH,2}$, $\Delta CAPE_{T,1}$, $\Delta CAPE_{T,2}$, and $\Delta CAPE$, see Fig. 8) and thus infer the contribution of temperature and RH vertical profiles in the change of ~~SBCAPE~~ CAPE between the MAX and the MIN simulations.

Figure 9 shows the total change of ~~SBCAPE~~ CAPE between the MAX and MIN simulations (~~ΔSBCAPE~~ΔCAPE), the RH contribution (~~$\Delta\mathrm{SBCAPE_{RH}} = \frac{\Delta\mathrm{SBCAPE_{RH,1}}+\Delta\mathrm{SBCAPE_{RH,2}}}{2}$~~$\Delta\mathrm{CAPE_{RH}} = \frac{\Delta\mathrm{CAPE_{RH,1}}+\Delta\mathrm{CAPE_{RH,2}}}{2}$), and the temperature contribution (~~$\Delta\mathrm{SBCAPE_{T}} = \frac{\Delta\mathrm{SBCAPE_{T,1}}+\Delta\mathrm{SBCAPE_{T,2}}}{2}$~~$\Delta\mathrm{CAPE_{T}} = \frac{\Delta\mathrm{CAPE_{T,1}}+\Delta\mathrm{CAPE_{T,2}}}{2}$) as a function of daily mean temperature for median and extreme precipitation events. The quantity ~~SBCAPE~~ CAPE is lower in the MAX simulation with respect to the MIN simulation, and ~~ΔSBCAPE~~ ΔCAPE is more negative at low temperatures (-30%) than at high temperatures (almost 0%). However one can see that ~~$\Delta\mathrm{SBCAPE_T}$ and $\Delta\mathrm{SBCAPE_{RH}}$~~ $\Delta\mathrm{CAPE_T}$ and $\Delta\mathrm{CAPE_{RH}}$ have opposite signs. Indeed, the RH contribution is positive and decreases from about +40% at 10ºC to about 0% at 22ºC for median precipitation events. The fact that this contribution is positive is not a surprise since we have seen in Fig. 6 that the surface RH is higher in the MAX simulation. We can see that this apparently weak increase of RH in the MAX simulation has a strong effect on the ~~SBCAPE~~ CAPE at low temperatures. However the main contribution is negative and comes from the differences of vertical temperature profiles: values are ranging between -70% at low temperatures and -15% at high temperatures. Moreover, one can see similar variations of ~~ΔSBCAPE and $\Delta\mathrm{SBCAPE_T}$~~ ΔCAPE and $\Delta\mathrm{CAPE_T}$ with temperature.

Figure 10 is the same as figure 9 but for the HR simulations and total precipitation. The quantity ~~ΔSBCAPE~~ ΔCAPE is larger in the HR simulation with values that exceed -50% for a wide range of low temperatures in both median and extreme precipitation. These large values of ~~ΔSBCAPE~~ ΔCAPE result in small negative differences of maximum vertical wind speed that do not exceed -10% and are not correlated with total precipitation differences for median total precipitation events (see figure 7) because of the coexistence of convective and stratiform events. Otherwise contributions are similar to those of the

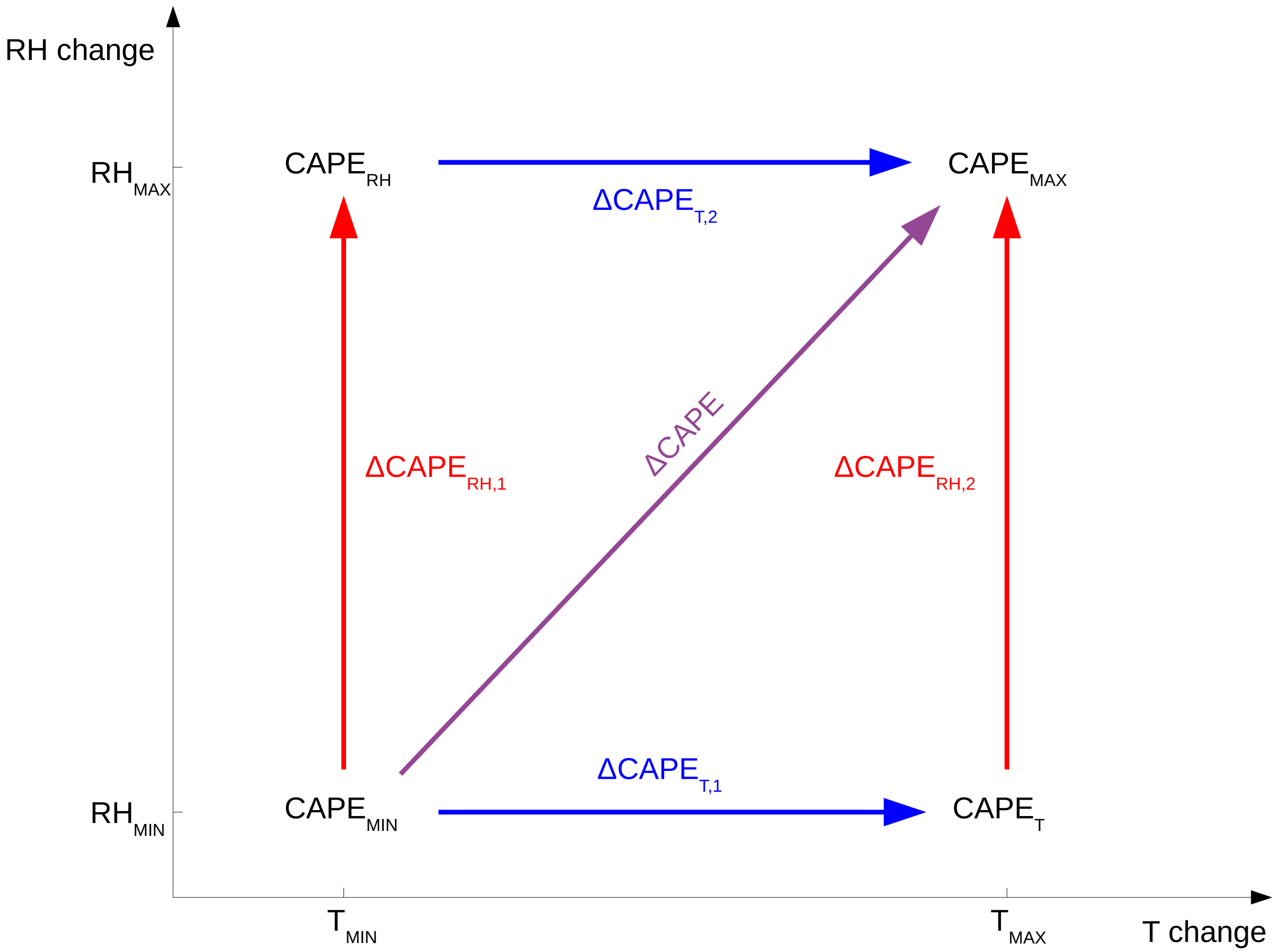

Figure 8. Schematic of the 2 possible ~~SBCAPE~~ CAPE differences that permit to evaluate the contribution of the vertical profile of temperature (~~$\Delta SBCAPE_{T,1}$~~ $\Delta CAPE_{T,1}$ and ~~$\Delta SBCAPE_{T,2}$~~$\Delta CAPE_{T,2}$) and the contribution of the vertical humidity profile (~~$\Delta SBCAPE_{RH,1}$~~ $\Delta CAPE_{RH,1}$ and ~~$\Delta SBCAPE_{RH,2}$~~$\Delta CAPE_{RH,2}$) to the change of total ~~SBCAPE~~ CAPE between the MAX and the MIN simulations (~~$\Delta SBCAPE$~~$\Delta CAPE$).

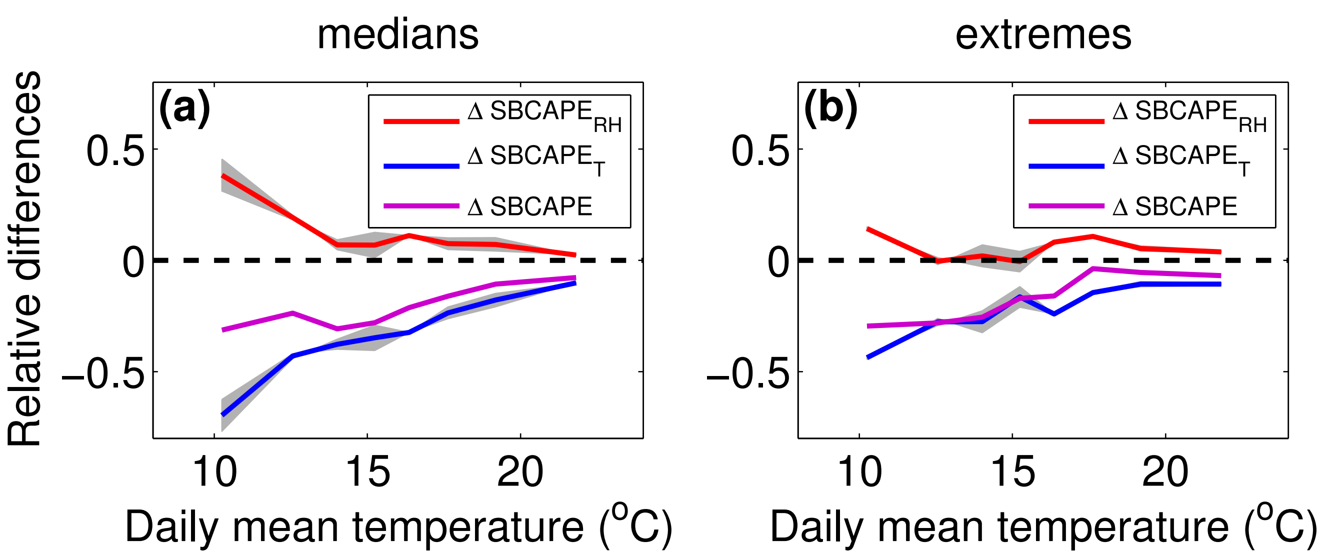

Figure 9. Relative differences of CAPEs for median (a) and extreme (b) convective precipitation events of the relative difference between the LR MAX and the LR MIN simulations (magenta, $\Delta\mathrm{CAPE}$). The temperature contribution ($\Delta\mathrm{CAPE_T}$) is displayed in blue and the relative humidity contribution ($\Delta\mathrm{CAPE_{RH}}$) in red.

LR simulations with mainly a positive contribution of RH and a strongly negative contribution from the temperature vertical profile.

The quantity ~~SBCAPE~~ CAPE is a non-linear function of the temperature and humidity profiles. Therefore, the change ~~$\Delta\mathrm{SBCAPE_{T,1}}$~~ $\Delta\mathrm{CAPE_{T,1}}$ is different from the change ~~$\Delta\mathrm{SBCAPE_{T,2}}$~~$\Delta\mathrm{CAPE_{T,2}}$. Similarly, the change ~~$\Delta\mathrm{SBCAPE_{RH,1}}$~~ $\Delta\mathrm{CAPE_{RH,1}}$ is different from the change ~~$\Delta\mathrm{SBCAPE_{RH,2}}$~~$\Delta\mathrm{CAPE_{RH,2}}$. The quantities ~~$\Delta SBCAPE_{T,1}$ and $\Delta SBCAPE_{T,2}$~~ $\Delta CAPE_{T,1}$ and $\Delta CAPE_{T,2}$ (resp. ~~$\Delta SBCAPE_{RH,1}$ and $\Delta SBCAPE_{RH,2}$~~$\Delta CAPE_{RH,1}$ and $\Delta CAPE_{RH,2}$) delimit a grey area in Fig. 9 that represents the uncertainty (relative to the non-linearity of ~~SBCAPE~~CAPE) of the temperature (resp. RH) contribution. One can see that the effects of ~~SBCAPE~~ CAPE non-linearity are generally lower than the difference between each contribution. Where the grey areas do not intersect, i.e. in almost the entire temperature range for median precipitation, and for the cooler part of the distribution for extreme precipitation, comparison of ~~$\Delta\mathrm{SBCAPE_T}$, $\Delta\mathrm{SBCAPE_{RH}}$ and $\Delta\mathrm{SBCAPE}$~~ $\Delta\mathrm{CAPE_T}$, $\Delta\mathrm{CAPE_{RH}}$ and $\Delta\mathrm{CAPE}$ strengthen the interpretation presented above: the negative value of ~~$\Delta\mathrm{SBCAPE}$~~ $\Delta\mathrm{CAPE}$ can be attributed to temperature changes, pently buffered by RH changes.

However the vertical temperature profile can be changed in several ways, e.g. one can only change the vertical gradient of temperature or uniformly reduce the temperature on the vertical. In the first configuration the decrease of ~~SBCAPE~~ CAPE would be purely due to the increase of stability of the environment whereas in the second configuration the decrease of ~~SBCAPE~~ CAPE would be due to the surface air parcel temperature, more precisely to its reduced release of latent heat due to reduction of its initial water vapor content.

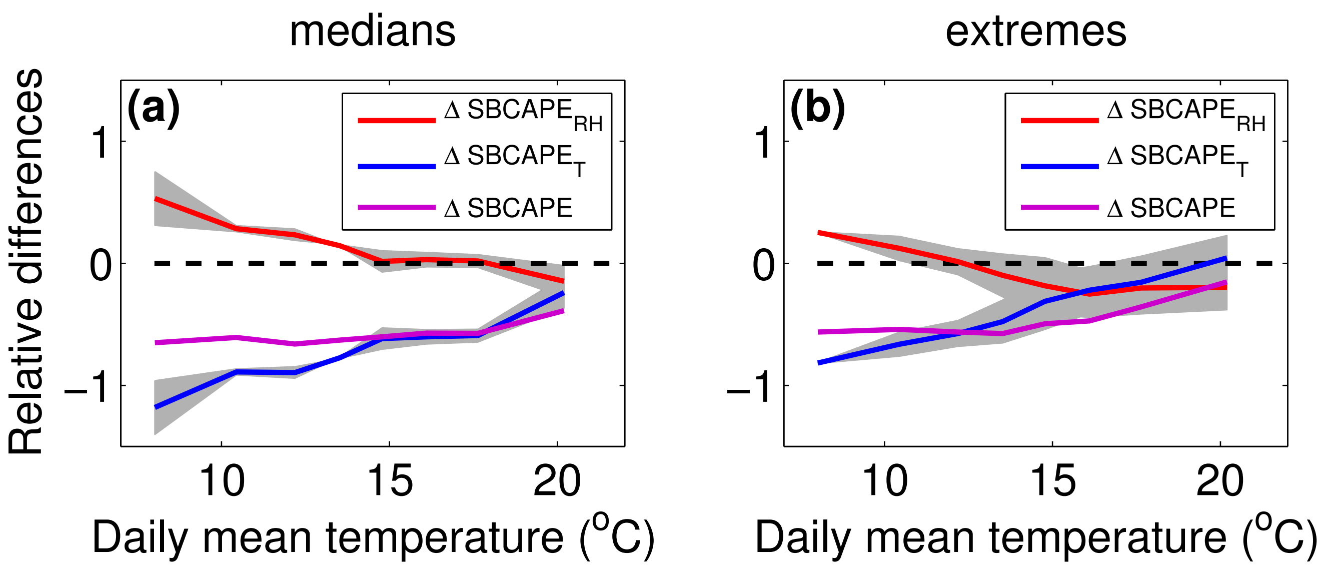

Figure 10. Relative differences of CAPEs for median (on the left) and extreme (on the right) precipitation events of the relative difference between the HR MAX and the HR MIN simulations (magenta, $\Delta\mathrm{CAPE}$). The temperature vertical profile contribution ($\Delta\mathrm{CAPE_T}$) is displayed in blue and the relative humidity vertical profile contribution ($\Delta\mathrm{CAPE_{RH}}$) in red.

In this part, the temperature contribution is decomposed into two contributions, one from the vertical gradient of temperature and one from the surface temperature. The quantity SBCAPE CAPE can now be viewed as a function of three variables: the RH profile, the vertical temperature gradient and the surface temperature. As displayed in Fig. 11, for a given RH profile (from the MIN or the MAX simulation), we have substituted the vertical temperature gradient (resp. surface temperature) from the MIN simulation, by the vertical temperature gradient (resp. surface temperature) from the MAX simulation, and we have calculated 4 additional SBCAPEs CAPEs using the 4 new mixed profiles. By calculating relative differences of SBCAPECAPE, one can evaluate the contribution of the surface temperature ($\Delta\mathrm{SBCAPE_{Ts}} = \frac{1}{4}\sum_{i=1}^{i=4}\Delta\mathrm{SBCAPE_{Ts,i}}$$\Delta\mathrm{CAPE_{Ts}} = \frac{1}{4}\sum_{i=1}^{i=4}\Delta\mathrm{CAPE_{Ts,i}}$) and of the vertical gradient of temperature ($\Delta\mathrm{SBCAPE}_{\nabla_z\mathrm{T}} = \frac{1}{4}\sum_{i=1}^{i=4}\Delta\mathrm{SBCAPE}_{\nabla_z\mathrm{T,i}}$$\Delta\mathrm{CAPE}_{\nabla_z\mathrm{T}} = \frac{1}{4}\sum_{i=1}^{i=4}\Delta\mathrm{CAPE}_{\nabla_z\mathrm{T,i}}$).

Figure 12 shows $\Delta\mathrm{SBCAPE}_{\nabla_z\mathrm{T}}$, $\Delta\mathrm{SBCAPE_{Ts}}$ and $\Delta\mathrm{SBCAPE_T}$ $\Delta\mathrm{CAPE}_{\nabla_z\mathrm{T}}$, $\Delta\mathrm{CAPE_{Ts}}$ and $\Delta\mathrm{CAPE_T}$ (as in Fig. 8) as a function of daily mean temperature for the LR simulations. The contribution of the vertical gradient of temperature and the contribution of the surface temperature are both negative, indicating not only that the surface temperature is lower in the MAX simulation but also that this cooling is less important in the higher layers of the troposphere. Both processes tend to reduce the SBCAPE CAPE in the MAX simulation with respect to the MIN simulation. For median precipitation, the reduction of SBCAPE CAPE due to the vertical gradient of temperature (-10% at high temperatures to -50% at low temperatures) is more important than the reduction of SBCAPE CAPE due to the surface temperature (-10% at high temperatures to -20% at low temperatures). For extreme precipitation, contributions are similar and range between -20% at low temperatures to -5% at high temperatures.

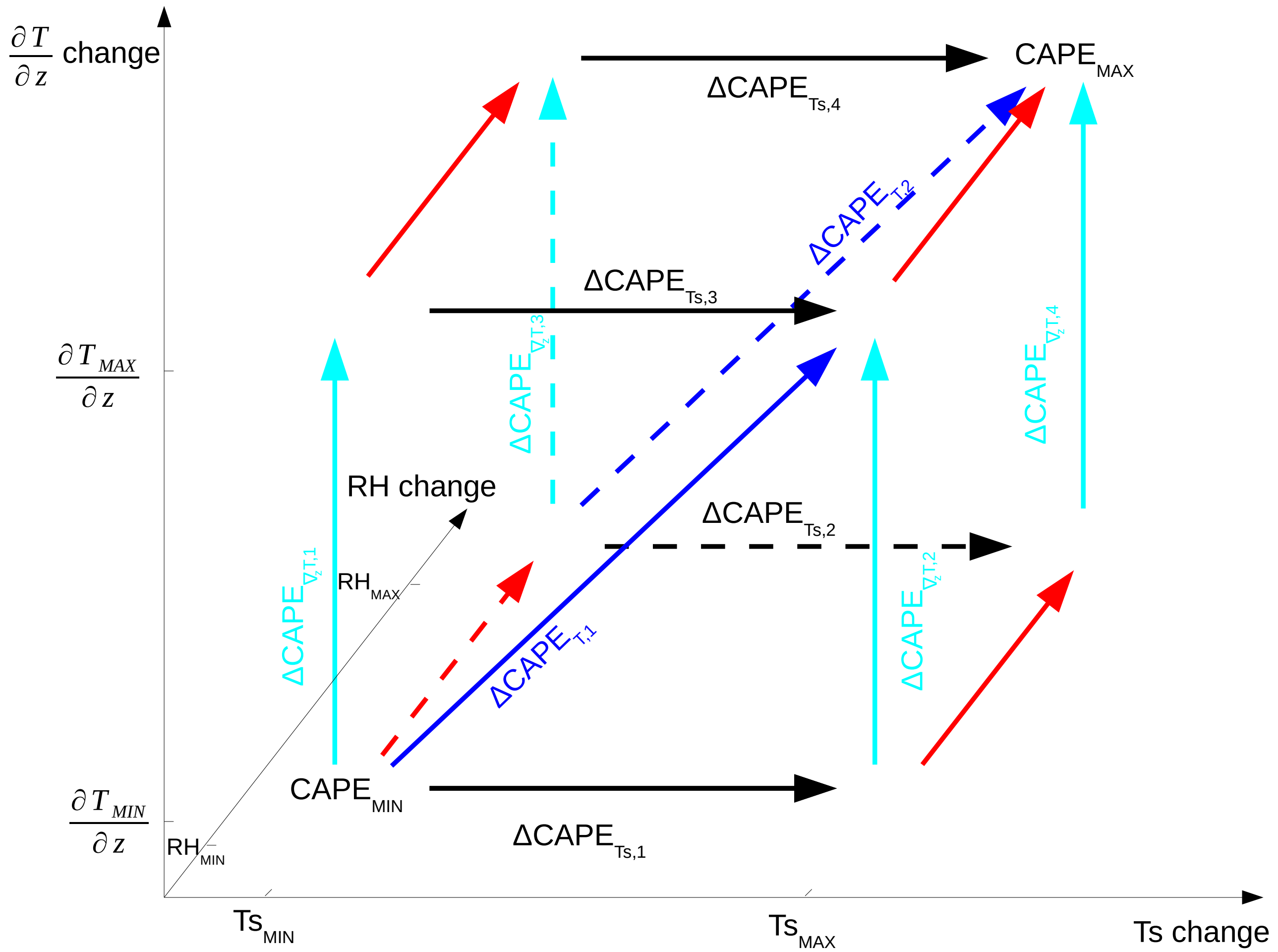

Figure 11. Schematic of the 4 possible ~~SBCAPE~~ CAPE differences that permit to evaluate the contribution of the vertical gradient of temperature (~~$\Delta SBCAPE_{\nabla_z T,1}$~~$\Delta CAPE_{\nabla_z T,1}$, ~~$\Delta SBCAPE_{\nabla_z T,2}$~~$\Delta CAPE_{\nabla_z T,2}$, ~~$\Delta SBCAPE_{\nabla_z T,3}$~~$\Delta CAPE_{\nabla_z T,3}$, and ~~$\Delta SBCAPE_{\nabla_z T,4}$~~$\Delta CAPE_{\nabla_z T,4}$) and the contribution of the surface temperature (~~$\Delta SBCAPE_{Ts,1}$~~$\Delta CAPE_{Ts,1}$, ~~$\Delta SBCAPE_{Ts,2}$~~$\Delta CAPE_{Ts,2}$, ~~$\Delta SBCAPE_{Ts,3}$~~$\Delta CAPE_{Ts,3}$, and ~~$\Delta SBCAPE_{Ts,4}$~~$\Delta CAPE_{Ts,4}$) to ~~ΔSBCAPE~~ΔCAPE.

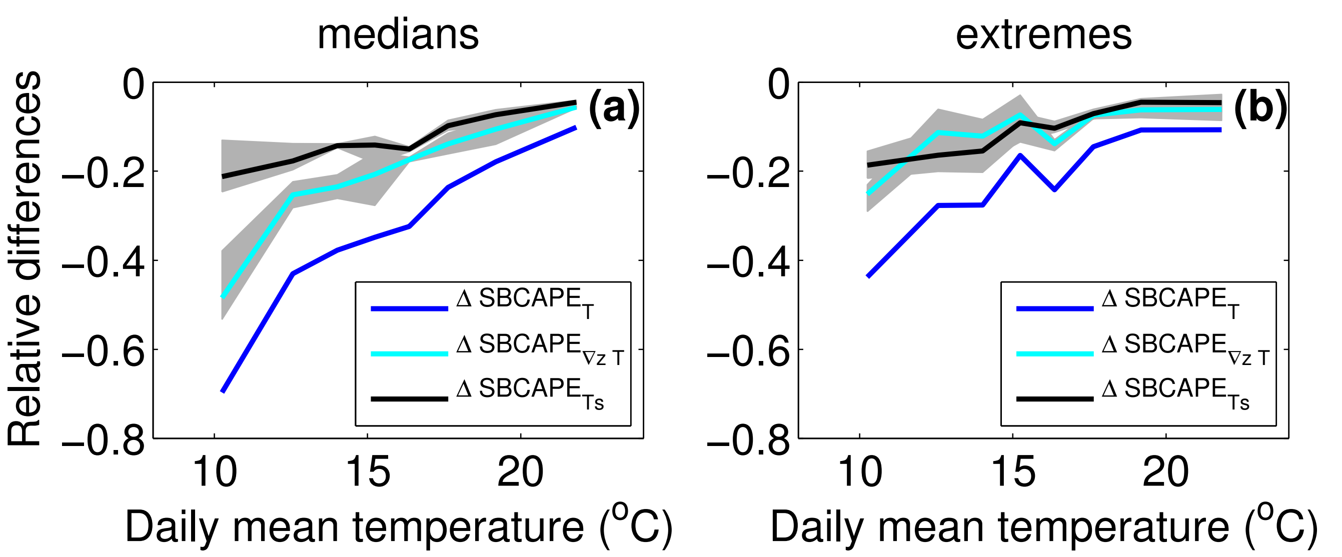

Figure 12. Relative differences of ~~SBCAPEs~~ CAPEs for median (a) and extreme (b) convective precipitation events of the temperature contribution to the relative difference between the LR MAX and the LR MIN simulations (blue, ~~$\Delta SBCAPE_T$~~ $\Delta CAPE_T$). The surface temperature contribution (~~$\Delta SBCAPE_{Ts}$~~ $\Delta CAPE_{Ts}$) is displayed in black and the temperature vertical gradient contribution (~~$\Delta SBCAPE_{\nabla_z T}$~~ $\Delta CAPE_{\nabla_z T}$) in cyan.

A similar analysis in the HR simulations is displayed in figure 13. The results are very similar to those from the LR simulations with the exception that for extreme precipitation with low temperatures, the temperature gradient contribution is significantly larger than the surface temperature contribution.

The maximum and the minimum values of ~~$\Delta SBCAPE_{Ts,i}$~~ $\Delta CAPE_{Ts,i}$ (resp. ~~$\Delta SBCAPE_{\nabla_z T,i}$~~ $\Delta CAPE_{\nabla_z T,i}$) delimit a grey area in Figures 12 and 13 that represent the uncertainty related to the ~~SBCAPE~~ CAPE non-linearity. It shows that for both HR and LR simulations, contributions are clearly different at low temperatures for median precipitation events whereas the uncertainty ranges tend to overlap at high temperatures. For extreme events, the non-linearity of SBCAPE does not permit to distinguish the two contributions for the entire range of temperatures of the LR simulations. In the HR simulations, the non-linearity uncertainty is also too large at high temperatures to differentiate the two contributions. However the contribution of the vertical gradient of temperature is significantly weaker than the contribution of the surface temperature at the lowest temperatures of the HR simulations.

4 Conclusions

An evaluation of the processes involved in the reduction of convective precipitation by aerosol indirect effects is performed in the present study in the frame of the temperature-precipitation relationship. Figure 14 summarizes the various involved processes and their qualitative contribution (size of the arrows). The temperature-precipitation approach permits to show that

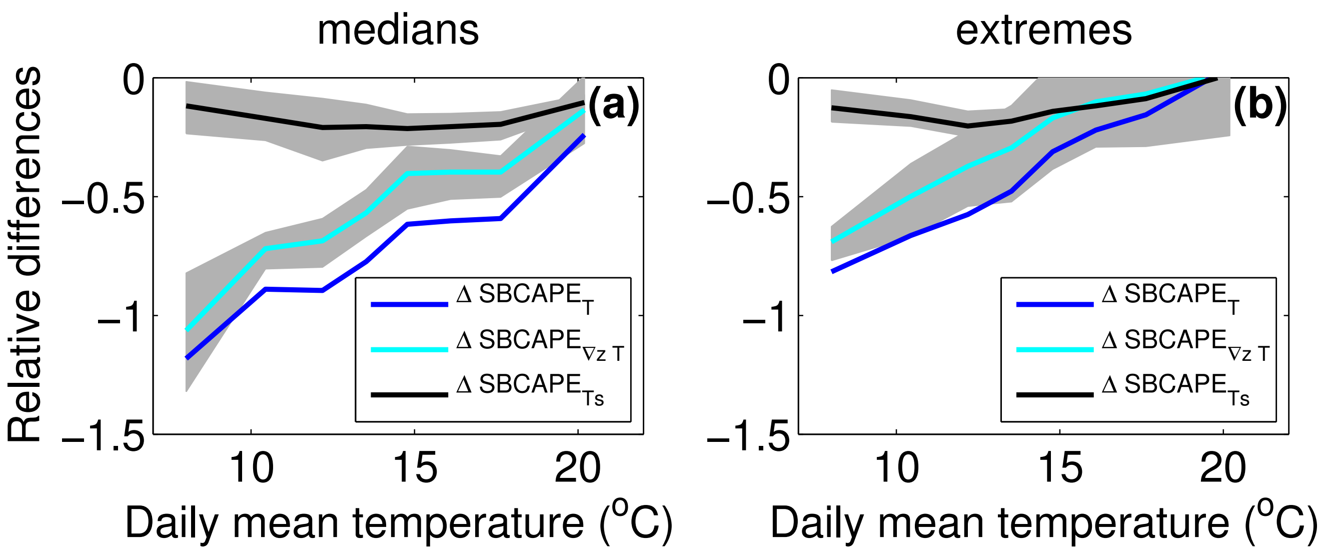

Figure 13. Relative differences of SBCAPEs CAPEs for median (a) and extreme (b) precipitation events of the temperature contribution to the relative differences between the HR MAX and the HR MIN simulations (blue, $\Delta SBCAPE_T$ $\Delta CAPE_T$). The surface temperature contribution ($\Delta SBCAPE_{Ts}$ $\Delta CAPE_{Ts}$) is displayed in red and the temperature vertical gradient contribution ($\Delta SBCAPE_{\nabla_z T}$ $\Delta CAPE_{\nabla_z T}$) in blue.

aerosol indirect effects on convective precipitation are larger at low temperatures than at high temperatures because clouds are statically more frequent and optically thicker at cool temperatures in our area of interest. Da Silva et al. (2018) found that convective precipitation are weakened in polluted environment through reduced atmospheric instability and water availability. With a simple decomposition of the decrease of convective precipitation in the polluted simulation, we show that this decrease is dominated by differences in atmospheric stability rather than differences in the moisture content of air parcels (Fig. 14). Therefore, the reduction of convective precipitation in the polluted simulation does not follow the Clausius-Clapeyron law: the simulated reduction in convective precipitation in a polluted environment compared to a pristine environment as determined in our simulations is actually stronger than the Clausius-Clapeyron scaling.

Using the SBCAPE CAPE parameter as a measure of the atmospheric stability, we perform an in-depth analysis that estimates the contribution of each variable to the weakening of convective updrafts in the polluted simulation. Quantifying uncertainties related to the non-linearity of the SBCAPE CAPE is essential to correctly attribute the contribution of each variable to the stability modifications. Our method gives a first estimation of these uncertainties and shows that they are small enough to assess the following conclusions. The weakening of vertical velocity in convective updrafts is essentially explained by the stabilisation of the vertical profile of temperature, which is partly compensated by an increase of relative humidity in the polluted simulation (Fig. 14). The modification of the vertical temperature gradient, due to a stronger cooling in the boundary layer than in the free troposphere in the polluted simulation, is the most important contribution for median precipitation events whereas for extreme precipitation it is of similar magnitude as the contribution of the surface temperature decrease. Our simulations performed at high resolution are consistent with these results even though their interpretation is made more difficult by the fact that convective and stratiform precipitation are melted together while having opposite responses to aerosol indirect effects (as seen in Da Silva et al., 2018).

These results should be interpreted as an upper bound of the aerosol climatological indirect effect on convective precipitation, since extremely and high aerosol concentrations were used in this study. A more realistic estimation of the aerosol indirect effect on convective precipitation could be carried out with the use of online-coupled models in which aerosol concentrations are evaluated with precise emission and transport schemes. Although taken into account in our simulations with explicit convection, our study suggests that the second aerosol indirect effect may not affect convective precipitation efficiency in a significant way compared to the stabilisation effect. It is however likely that the second indirect effect plays a role in stabilising the atmosphere and hence in reducing convective precipitation, a result that remains to be established.

Data availability. The WRF simulations used in this study can be obtained in the MISTRAL database website (registration required) at http://mistrals.sedoo.fr/?editDatsId=1503 or upon request to the authors.

Author contributions. The authors designed the numerical experiments. Nicolas Da Silva and Sylvain Mailler performed the simulations. Nicolas Da Silva prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflit of interest.

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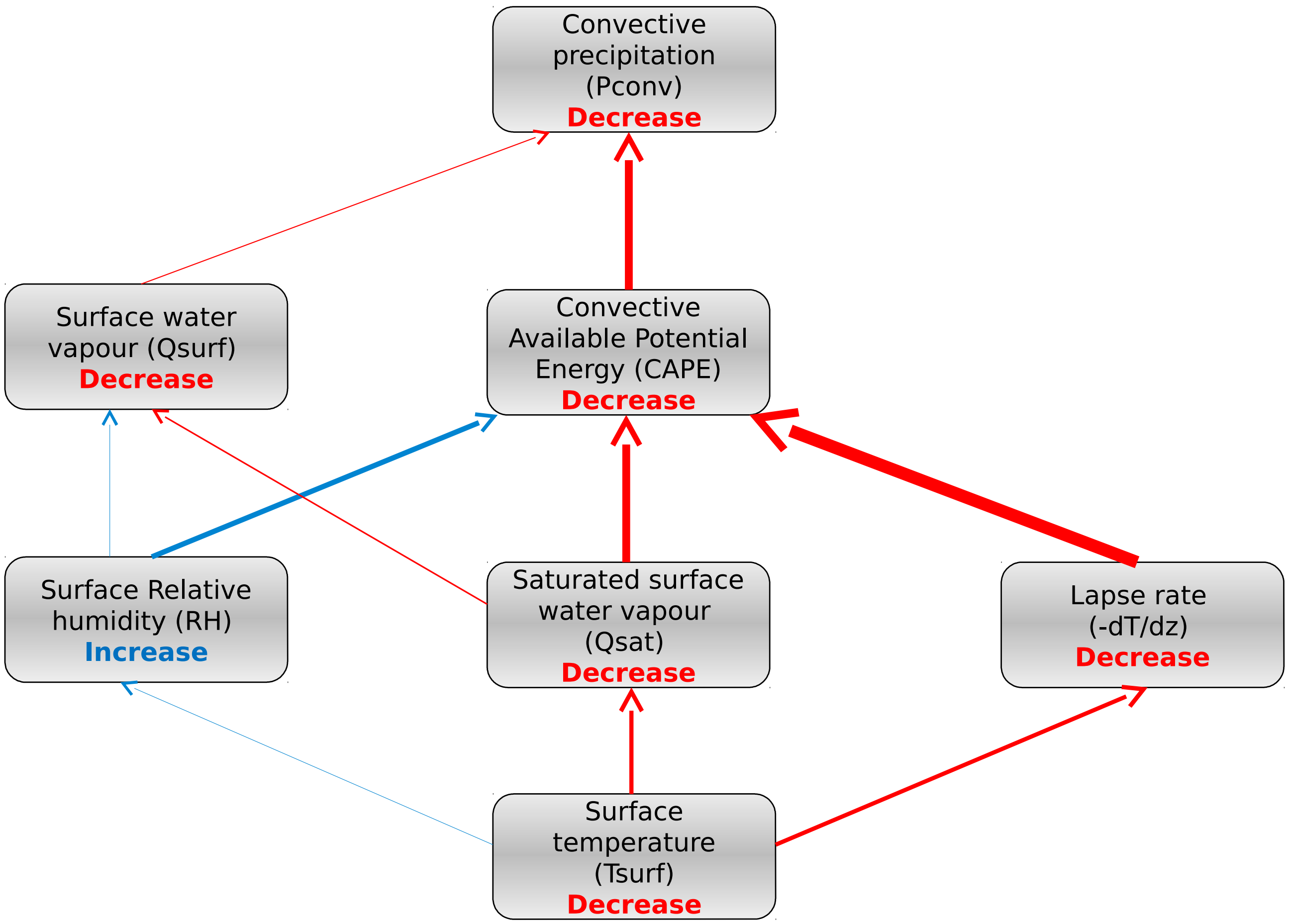

Figure 14. Detailed schematic summary of the causal sequence that links the decrease of surface temperature to the decrease of convective precipitation in a polluted environment. The size of arrows gives a qualitative estimation of the contributions of each processes.

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