Modelling marine stratocumulus and its radiative properties

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Introduction

Research to improve the representation of clouds and their radiative properties in climate models has been carried out over many years, and tropical boundary layer clouds which cover large regions have been identified as the largest contributor to the uncertainty. Many of these clouds arise in the subtropics at the eastern edge of subtropical anticyclones, where marine air is cooled by coastal upwelling of cold water from the deep ocean to form semi-permanent cloud decks which have a large influence on the global climate. The southeast Pacific has the largest and most persistent stratocumulus deck in the world, where the winds drive intense coastal upwelling so that sea surface temperatures are colder along the Chilean and Peruvian coasts than at any comparable latitude, and the cool moist boundary layer has a strong inversion with the warm dry air aloft.

The clouds are maintained through a balance between radiative cooling, boundary layer fluxes and entrainment across the inversion, and their microphysics and radiative properties are influenced by the presence of drizzle, aerosol number concentration, and the entrainment, all of which are coupled. So a better understanding of the microphysical and dynamical processes operating in these clouds and the controls on their formation and maintainance is needed.

Twomey, 1977, found that pollution increases the droplet number concentration and hence the optical thickness of a cloud. For thin and moderately thick cloud this increases the albedo and therefore has a cooling effect on the climate, but for thick cloud this increases the absorption and therefore has a warming effect.

Albrecht, 1989, found that increases in aerosol concentration act to reduce drizzle from marine stratocumulus, leading to increased fractional cloud cover, and hence increased cloud albedo overall and further cooling of the climate.

Lilly, 1968, constructed theoretical models to relate, explain and predict the features of a radiatively active turbulent cloud layer over the sea and under a strong subsidence inversion. Found that radiative heat loss from the cloud tops is an essential element, using observations from Oakland, California, and that radiative cooling from the low cloud layers maintain the strong inversions in the marine boundary layer.

Intense longwave radiative cooling at cloud top drives turbulent eddies in the boundary layer, these pick up moisture from the sea surface (maintaining the cloud layer), but also entrain filaments of warm dry air from above the capping inversion. This entrainment lifts the cloud top, maintaining the cloud against large-scale subsidence, but also dries the boundary layer. However shortwave absorption and heating at cloud top over the diurnal cycle, and intermittent drizzle from cloud base, heat the upper boundary layer, counteracting the cloud top longwave cooling and weakening the turbulence and entrainment.

Pincus and Baker, 1994, used a simple model of the marine cloud-topped boundary layer to investigate the changes in cloud thickness and albedo resulting from the changes in precipitation as CCN number concentration varies. Found that the sensitivity of albedo to CCN (the albedo susceptibility) is increased by 50-200% when the dependence of cloud thickness to CCN is included, so the cloud thickness response needs to be taken into account for accurate predictions of global albedo in climate models. Their work is supported by observations of the increased albedo in boundary layer clouds modified by ship tracks. When clouds are thin and CCN concentrations small the injection of new CCN into the marine boundary layer increases cloud liquid water and albedo by suppressing precipitation.

Previous campaigns

Stevens et al., 2003, describes the DYCONS II field campaign over northeast Pacific in July 2001, where research aircraft flights from San Diego sampled the clouds at night to measure entrainment. Able to constrain the budgets of heat and moisture in the cloud layer by tracking the changes in the cloud base, which couples these budgets. Also evaluating the drizzle processes in stratocumulus, as the precipitation rates are related to aerosols, cloud thickness and the intensity of turbulence. Used aircraft mounted cloud radars to study the drizzle, as these sample large volumes of cloud and rapidly profile entire columns, and can be used to estimate the mean surface precipitation flux over nearly 7 hours.

Bretherton et al., 2004, describes the EPIC 2001 stratocumulus study (East Pacific Investigation of Climate), the field campaign in the Southeast Pacific in October 2001 (the month when stratocumulus are most extensive). This is one of the world's driest oceanic regions, and the stratocumulus helps to keep the underlying ocean cool by blocking solar radiation. Measurements were made from research ship The Ronald H. Brown, including the area of 20 south and 75-85 west as in the later VOCALS campaign.

The VOCALS campaign

The VAMOS Ocean Cloud Atmosphere Land Study (VOCALS) is a comprehensive observational (field campaign in October and November 2008) and modelling program (over a range of scales) to study the southeast Pacific climate system with the aim of reducing uncertainties in current and future climate projections, especially those associated with marine stratocumulus and coupled ocean-atmosphere processes. The program includes improving the understanding and model representation of cloud-radiative feedbacks and aerosol indirect effects.

The field campaign involved both NERC research aircraft, the FAAM BAe-146 and the ARSF Dornier-228 (flying from Arica, Chile) to provide detailed airborne measurements of aerosols, clouds, radiation and their interactions. VOCALS-UK is a joint activity between members of the UK academic research community and the Met Office, using the measurements and a range of fine scale and mesoscale models to study the detailed processes that maintain the stratocumulus cloud and determine its radiative properties.

The Large Eddy Model

A small scale 3D dynamics, microphysics and radiation model developed by the Met Office to study the formation and development of clouds (Derbyshire et al., 1994, Mason, 1994). Used in VOCALS-UK to study the marine stratocumuus.

Stevens et al., 1998, used large-eddy simulation to study statocumulus in marine boundary layers and determine the effects of drizzle on the cloud and dynamics, finding that drizzle reduces both cloud top entrainment and turbulent kinetic energy by buoyancy by net latent heating in the cloud, and that the subsequent evapouration of drizzle below cloud base reduces deep mixing by cooling and moistening the air.

Hill et al., 2008, used the Meteorological Office large eddy model (LEM) to study the effects of increasing cloud condensation nuclei (CCN) number concentration in marine stratocumulus, finding that the reduced droplet effective radius lead to increased radiative cooling at cloud top, driving increased boundary layer dynamics and entrainment which reduces the cloud liquid water path.

Here model simulations are carried out and are validated against measurements from the FAAM BAe-146. We have incorporated the new Morrison microphysics scheme into the LEM and compared simulations with the Morrison scheme to those from the LEM standard bulk microphysics. Though even the standard bulk microphysics now takes place in a double moment cloud droplet scheme, liquid water content and number concentration in each grid element, with individual values for the effective radius (Re), calculated using the Morrison routine, used in the LEM radiation field calculations.

The Morrison microphysics scheme

We created new modules for the LEM containing the Morrison microphysics scheme (Morrison et al., 2005), to use instead of the standard bulk microphysics. This is a more complex scheme looking in detail at the activation of Cloud Condensation Nuclei (CCN), these are not all activated at once so that there are fewer and larger cloud droplets, and in more detail at the formation of rain which is now slower. We now use the rain formation scheme of Seifert and Beheng, 2006, instead of the Kesler scheme. The changes in the microphysics will affect the cloud dynamics, radiative properties and evolution.

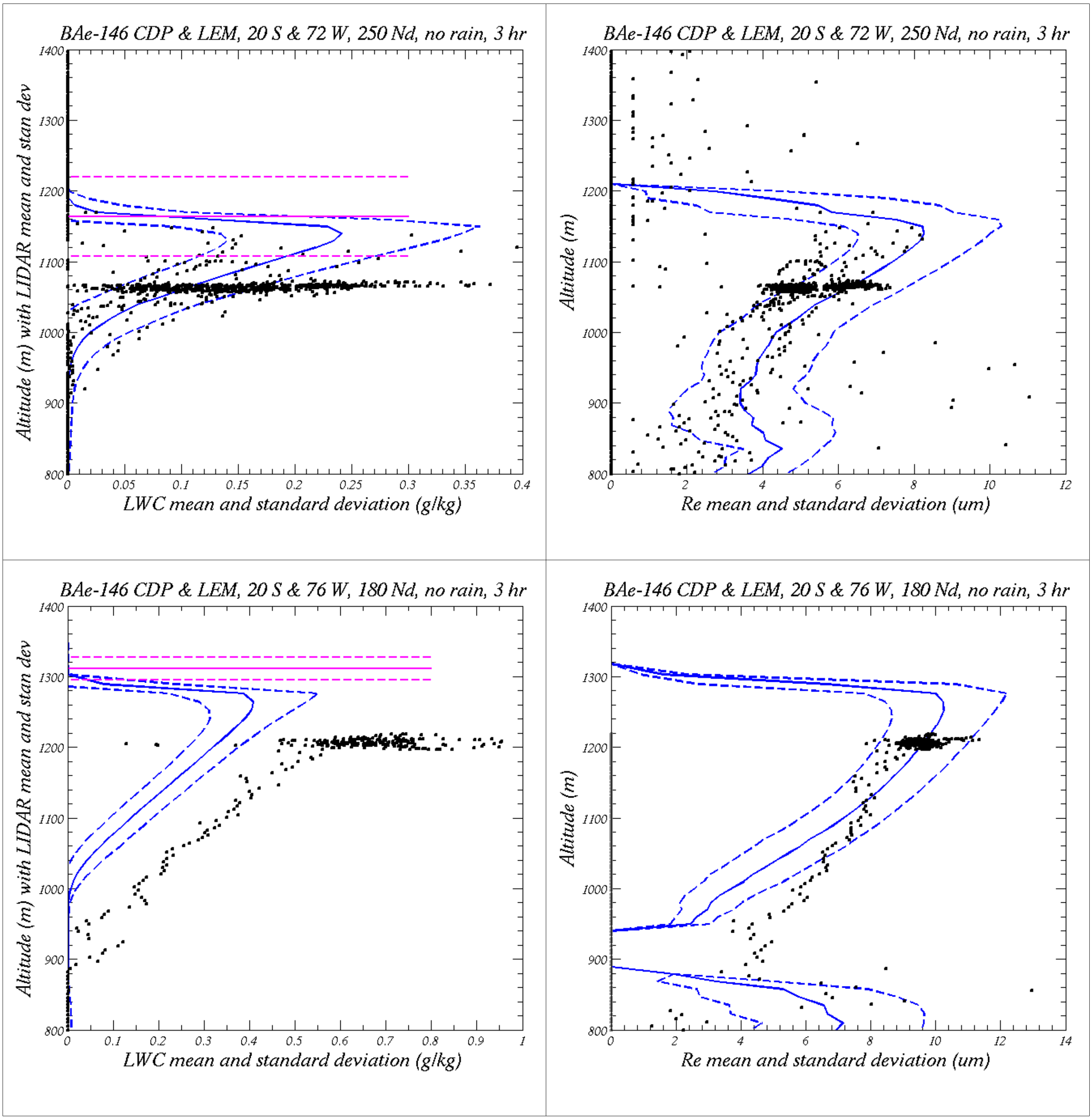
Model runs

The LEM simulations are initialised with profiles of humidity, potential temperature and windspeeds measured by dropsondes at 20 south and 72 and 76 west during a BAe-146 flight on the 13th November 2008. The initial humidity values are increased and the amount of water above saturation put in as cloud, according to the aircraft measurements of cloud top height and Liquid Water Content (LWC), the CCN loading is taken from the measurements of droplet number concentration.

The simulations followed 3 hours of cloud development between 8 and 11 AM local time, the model radiation field was updated every 150 seconds. The 3D grid was 3 km high and almost 4 km long and wide, with 30 m horizontal resolution and 10 m vertical resolution where the cloud layer was. The results were recorded at the end of each run.

Comparison to aircraft measurements

The simulations produce a thin cloud layer with small droplet effective radii (Re) at 72 west, and a thicker cloud layer with larger Re at 76 west. The cloud layers after 3 hours (using the Morrison scheme with the greatest CCN up to 1.5 km and without precipitation) are compared to the BAe-146 Cloud Droplet Probe (CDP) measurements of LWC and Re, and also aircraft LIDAR measurements of cloud top height (figure 1 a-d). The model simulation compares well to the measurements at 72 west, but at 76 west the LWC values are too small although the Re values are close to the measurements.



BAe-146 CDP & LEM, 20 S & 72 W, 250 Nd, no rain, 3 hr

BAe-146 CDP & LEM, 20 S & 72 W, 250 Nd, no rain, 3 hr

BAe-146 CDP & LEM, 20 S & 76 W, 180 Nd, no rain, 3 hr

BAe-146 CDP & LEM, 20 S & 76 W, 180 Nd, no rain, 3 hr

Figure 1: BAe-146 Cloud Droplet Probe measurements of liquid water content (a, c) and droplet effective radii (b, d) (black), with model profiles (mean and standard deviation) (blue), and aircraft LIDAR measurements of cloud top heights (pink). From flight B420 on 13th November 2008, at 20 south and 71-73 west and 75.8-76.2 west.

Sensitivity studies

Using the Morrison microphysics scheme we carried out sensitivity studies to quantify the effects of increased CCN number concentration, of entraining clean air at the cloud tops rather than new CCN, and of precipitation on the simulated clouds and their radiative properties, including the amount of horizontal inhomogenity and skewness over different domain sizes. Model simulations were carried out with CCN number concentrations of 50, 100 and 250 per mg of air (at 72 west), and 50, 100 and 180 per mg of air (at 76 west), the largest values matching the measured droplet number concentrations. The simulations had CCN up to 1.5 km altitude or only up to cloud top, and were either without and with precipitation, making 24 simulations in total.

A further 12 simulations were carried out using the standard bulk microphysics scheme to compare the results to those using the Morrison scheme. These used the same CCN number concentrations, without and with precipitation, but all had CCN up to 1.5 km.

Results from the Morrison scheme

Using the Morrison scheme the simulated cloud layers are deeper with lower cloud tops, and the Liquid Water Path (LWP) is greater than with the standard bulk microphysics, and the differences are greater with the smaller CCN number concentrations (model simulations without precipitation) (figure 2a). As not all the CCN have been activated the droplet effective radius (Re) is larger, so radiative cooling at the cloud tops is less, and because this drives turbulent mixing both the vertical mixing below the cloud layer and the entrainment across the inversion are reduced.

Without the entrainment the cloud tops are not raised against the large scale subsidence, but also the boundary layer is not dried out so much. The profiles plot shows that the with the Morrison scheme the boundary layer is moister and cooler, the air above the inversion is drier and warmer, and vertical mixing is reduced (figure 4a). Albedo may be increased or reduced overall (figure 2b), since the increased LWP will act to increase albedo while the increased Re will reduce albedo. When precipitation is switched on it is greatly reduced with the Seifert and Beheng scheme, initialized more slowly and mostly evapourates in the air below the cloud layer, compared to the Kesler scheme.

Results from sensitivity studies

Increasing the CCN number concentration leads to increased albedo, higher cloud tops, reduced LWP, and greatly reduced precipitation when this is switched on, with both the standard bulk microphysics and the new Morrison scheme (figure 2a-b). Increased CCN means reduced Re, giving increased albedo and also increased radiative cooling at cloud tops, leading to increased turbulent vertical mixing and entrainment across the inversion. Hence the cloud tops are raised against large scale subsidence, and the boundary layer is dried. The profiles plot shows that with increased CCN the boundary layer becomes drier and warmer, the air above the inversion moister and cooler, and vertical mixing is increased (figure 4b).

When switched on precipitation formation is strongly dependent on the cloud droplet number concentration (figure 3a-b). While the horizontal inhomogeneity (standard deviation / mean) of the cloud albedo is reduced and the skewness of the albedo is increased (more negative) by increasing CCN across all domain sizes (figure 5a-b). In general the thinner simulated cloud layers with less albedo at 72 west have greater inhomogeneity and less skewness in their albedo than the thicker simulated cloud layers at 76 west.

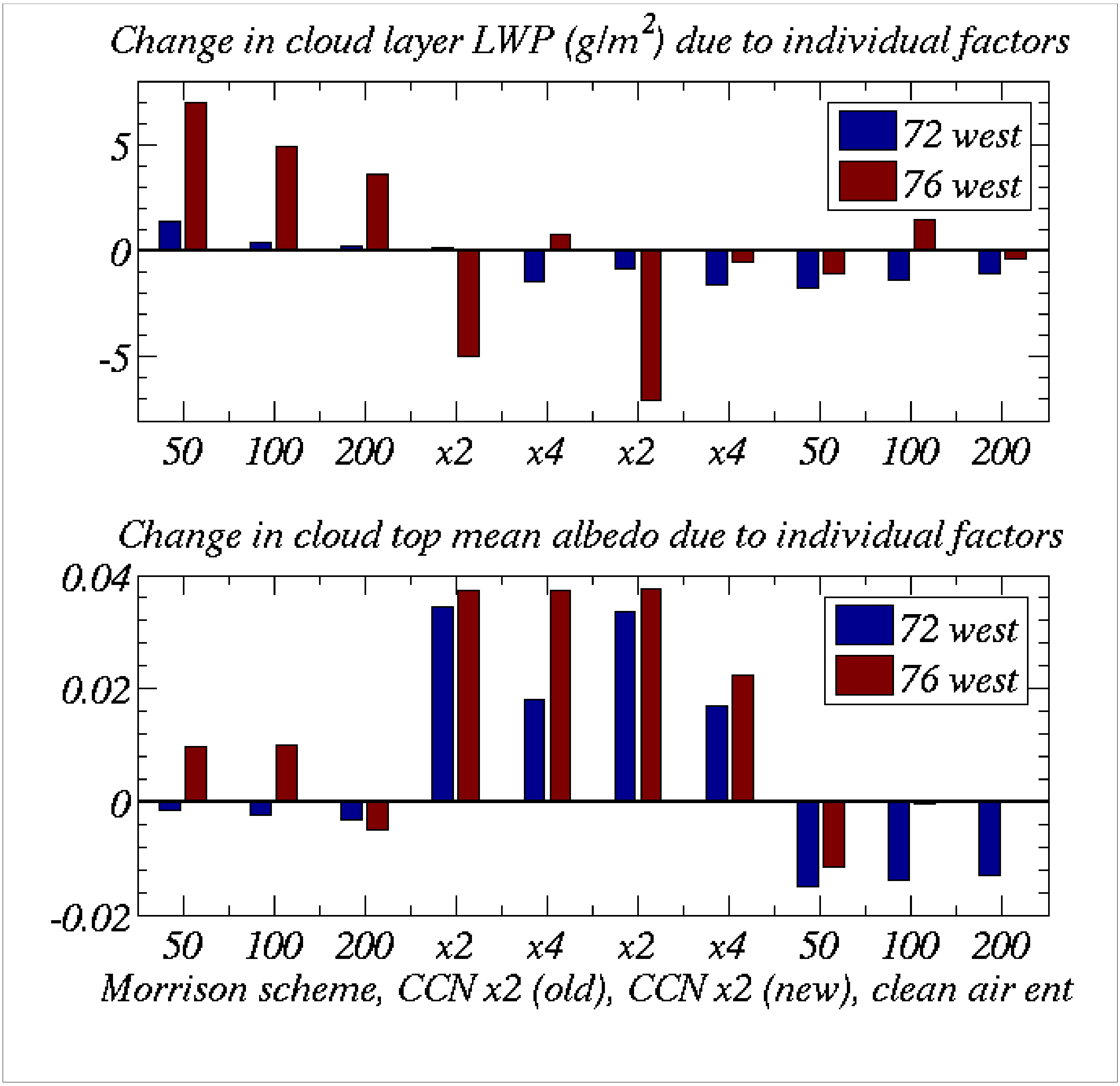


Figure 2: *The change in the model cloud mean liquid water path (a) and mean albedo (b) due to individual factors. Using the new Morrison microphysics scheme instead of the standard bulk microphysics (at CCN number concentrations of 50, 100 and 250 or 180 per mg of air, and no precipitation), increasing the CCN number concentration from 50 to 100 per mg of air and from 100 to 250 or 180 (no precipitation) with the strandard bulk microphysics and the new Morrison scheme, and entraining clean air instead of new CCN at the cloud tops (at the 3 CCN number concentrations and no precipitation) with the new Morrison scheme.*

Then if the CCN in the model only goes up to the cloud tops so that entrainment across the inversion introduces clean air into the cloud layer instead of new CCN, the albedo and LWP are reduced (figure 2a-b), cloud tops are lower, and precipitation (when it is switched on) is increased (figure 3a-b). The entrainment of clean air results in increased Re, so albedo and cloud top radiative cooling are reduced, reducing the vertical mixing and entrainment, and the cloud tops are not supported against subsidence.

Precipitation is increased because of the reduced CCN. The profiles plot shows reduced vertical mixing, the air above the inversion is drier and warmer due to reduced entrainment, but also the cloud layer is drier while the air below the cloud is moister and cooler because less moist air is being carried up into the cloud layer (figure 4c). The inhomogeneity in cloud top albedo is increased, the skewness in the albedo from the thinner cloud with small Re at 72 west is reduced but the skewness from the thicker cloud with larger Re is hardly changed (figure 5c-d).

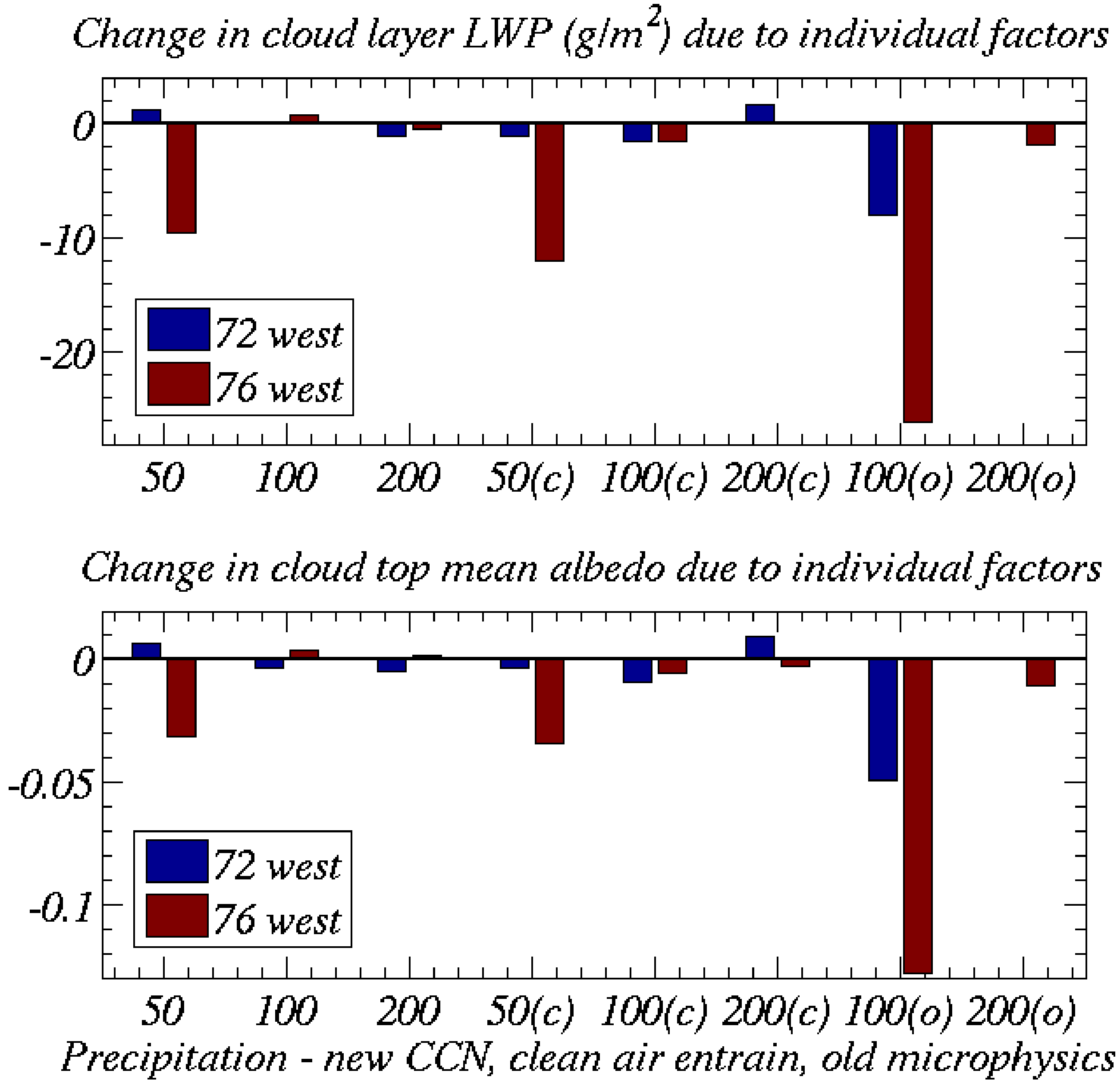


Figure 3: *The change in the model cloud mean liquid water path (a) and mean albedo (b) due to precipitation. With the new Morrison microphysics scheme and new CCN entrained at the cloud tops (at CCN number concentrations of 50, 100 and 250 or 180 per mg of air), with the Morrison scheme and clean air entrained at the cloud tops (at the 3 number concentrations), and with the standard bulk microphysics and new CCN entrained at cloud tops (at 2 number concentrations).*

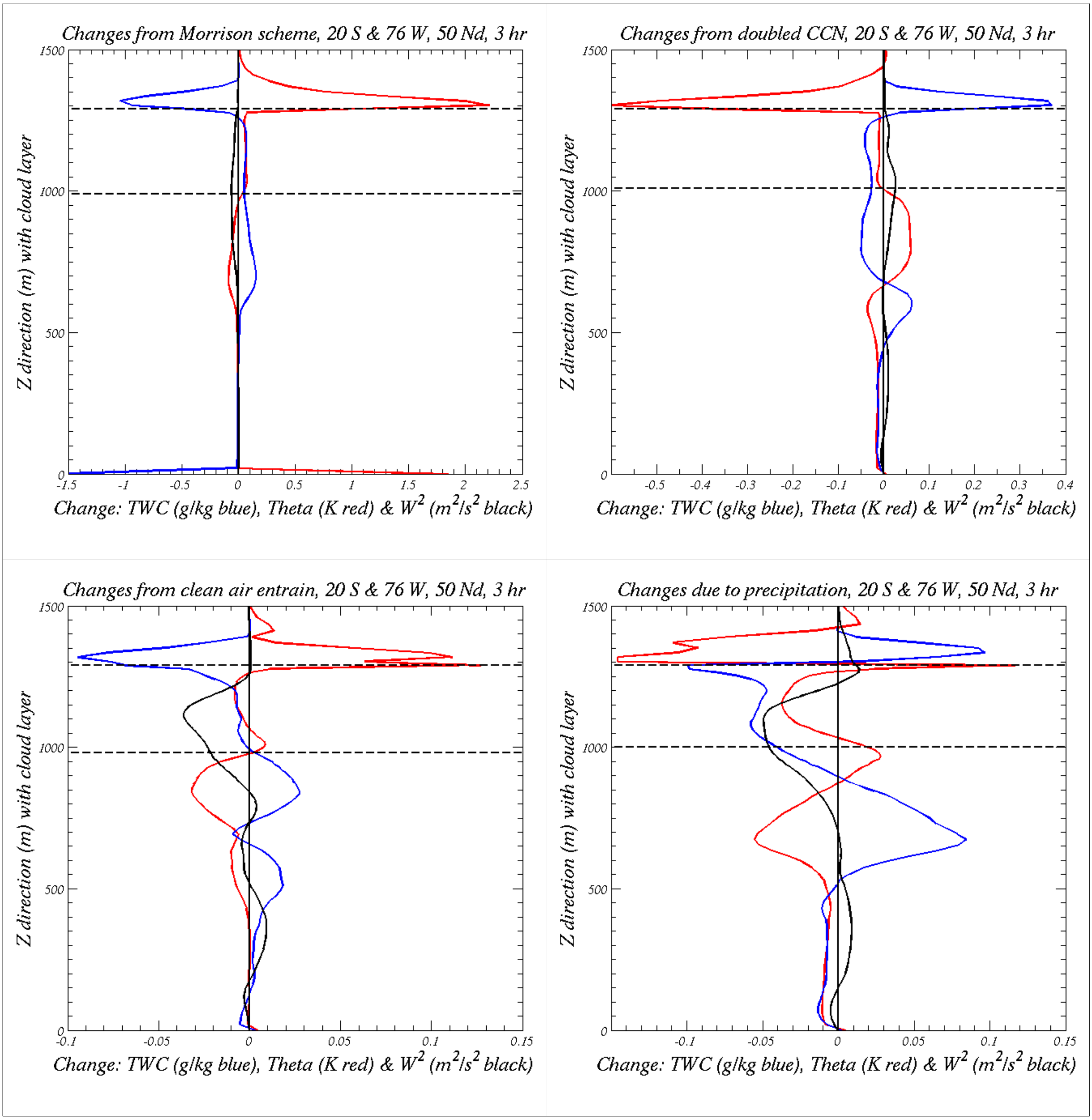
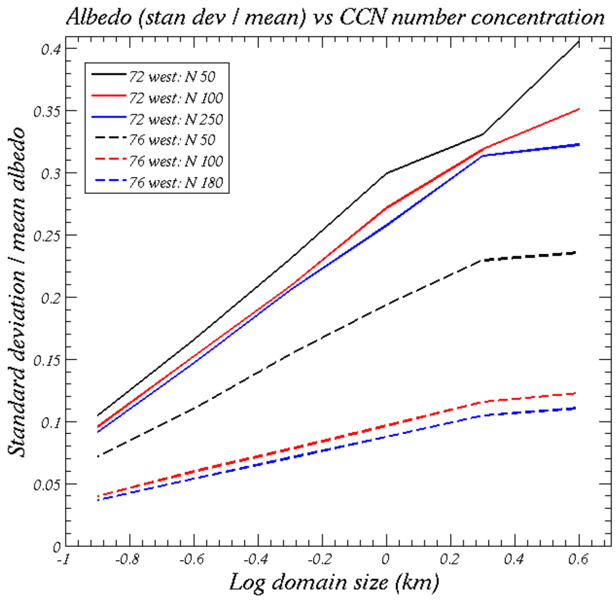
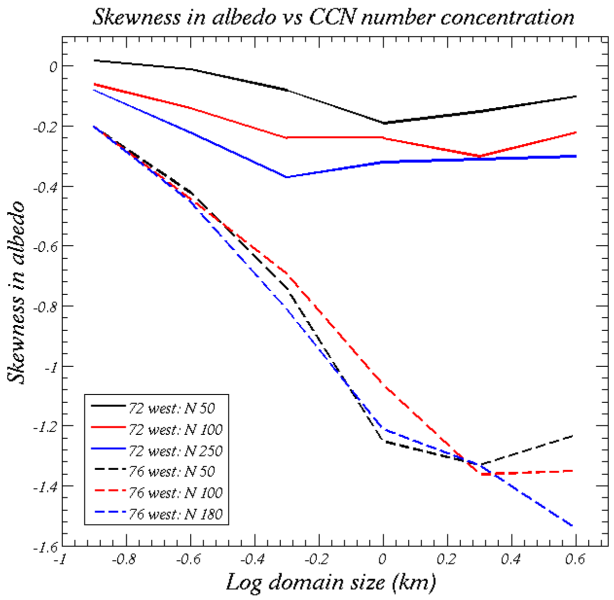


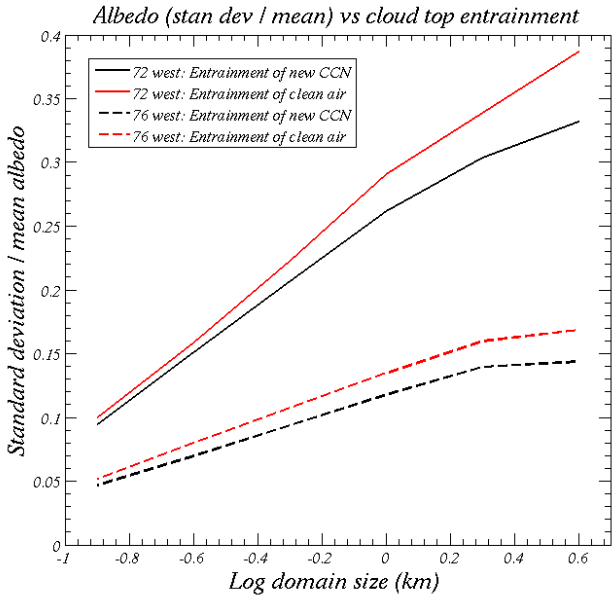
Figure 4: *Changes in the model profiles of total water content (blue), potential temperature (red) and vertical mixing (black) due to (a) using the Morrison microphysics scheme instead of the standard bulk microphysics, (b) increasing the CCN number concentration, (c) entraining clean air at the cloud tops instead of new CCN, and (d) precipitation. All starting from a base case with 50 CCN per mg of air, entrainment of new CCN and no precipitation.*



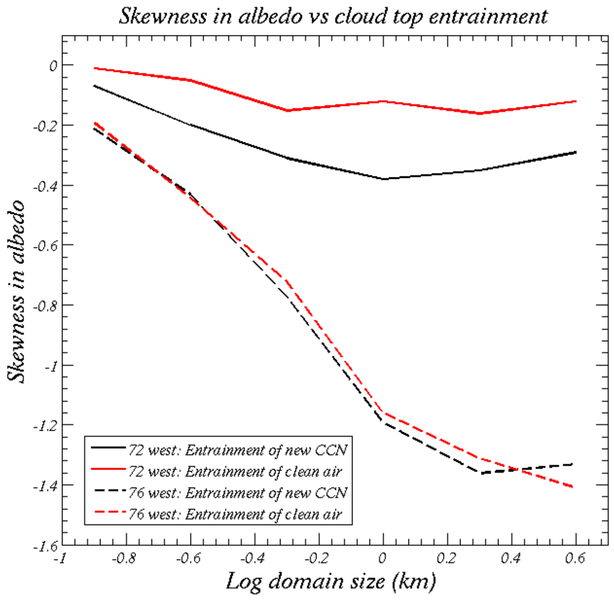
Albedo (stan dev / mean) vs CCN number concentration



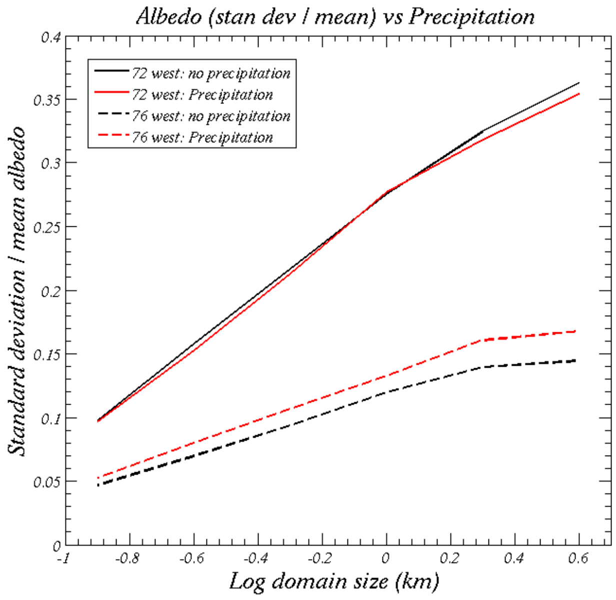
Skewness in albedo vs CCN number concentration



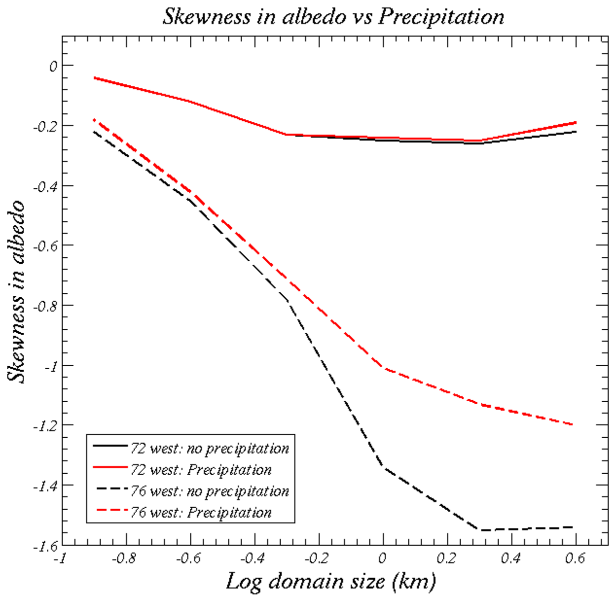
Albedo (stan dev / mean) vs cloud top entrainment



Skewness in albedo vs cloud top entrainment



Albedo (stan dev / mean) vs Precipitation



Skewness in albedo vs Precipitation

Figure 5: *Mean values of the model cloud albedo horizontal inhomogeneity (standard deviation / mean) and horizontal skewness over different domain sizes (120 m to 3840 m) for 72 west (solid lines) and 76 west (dashed lines). Differences due to (a-b) CCN number concentration (black – 50 per mg of air, red – 100, blue 250 or 180), (c-d) entrainment of new CCN at the cloud tops (black) or clean air (red), and (e-f) without precipitation (black) or with precipitation (red).*

When precipitation is switched on it generally reduces the LWP and albedo, and lowers the cloud tops (figure 3a-b). It removes liquid water from the cloud layer, increasing turbulent mixing there, but most of the precipitation then evapourates in the air below the cloud, moistening and cooling this layer and hence reducing the vertical mixing below the cloud. The profiles plot shows the reduced vertical mixing, the drier cloud layer and the moister and cooler air below, but also increased entrainment across the inversion so that the air above also becomes moister and cooler (figure 4d).

The amount of precipitation is strongly dependent on the CCN number concentration, being reduced by increasing CCN and increased by the entrainment of clean air at cloud tops, and precipitation also removes CCN from the cloud layer. With the old standard bulk microphysics scheme precipitation is much greater and is quicker to form (figure 3a-b). Precipitation also increases the inhomogeneity in the albedo and reduces the skewness where precipitation is large in the thicker cloud at 76 west, mostly in the larger domain sizes, but these show little change where there is little precipitation from the thinner cloud at 72 west (figure 5e-f).

Conclusions

The changes made to the Large Eddy Model (LEM) to use the Morrison microphysics scheme work well, and the resulting simulations produce deeper cloud layers with increased Liquid Water Path (LWP) which are a better match to the BAe-146 measurements from VOCALS. The precipitation from the model cloud is reduced and forms more slowly due to using the Seifert and Beheng rain formation scheme instead of the Kesler scheme.

The sensitivity studies demonstrate that Cloud Condensation Nuclei (CCN) number concentration, entrainment and precipitation all have a strong influence of the model cloud structure, LWP and albedo, and the results support those from previous studies. Increasing CCN reduces the droplet effective radii (Re), and this increases cloud top albedo (Twomey 1977) and reduces precipitation (Albrecht 1989, Pincus and Baker 1994). Reduced Re also increases radiative cooling which drives vertical mixing in the boundary layer, and entrainment across the inversion which raises the cloud tops against the large scale subsidence and dries the boundary layer (Lilly 1968). The thermodynamic profiles show that the boundary layer becomes drier and warmer while the air above the inversion becomes moister and cooler.

Using the Morrison microphysics scheme, where not all the CCN are activated, or entraining clean air instead of new CCN both have the effect of increasing Re, and this results in reduced albedo, radiative cooling, vertical mixing and entrainment. The entrainment of clean air also results in reduced LWP and increased precipitation. Precipitation then removes liquid water and CCN from the cloud layer, reducing the LWP and albedo, but the raindrops then evapourate moistening and cooling the air below which reduces the vertical mixing (Lilly 1968). Although the precipitation also increases entrainment.

Increasing CCN also acts to reduce the inhomogeneity in the model cloud albedo across all domain sizes, the skewness in the albedo is increased though mostly in thin cloud with small Re. While precipitation acts to increase the inhomogeneity and reduce the skewness of the albedo, though mostly where precipitaion is large from thicker cloud with larger Re, and in the larger domain sizes. These results imply that measurements of the inhomogeneity and skewness in the albedo of cloud layers over different domain sizes could be used to determine the properties of the cloud.

Acknowledgements

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