A line of convection embedded in a stratocumulus-topped boundary layer

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SUMMARY

During the Southern Ocean Cloud Experiment a line of convection embedded in an otherwise homogeneous stratocumulus layer was sampled at four levels by means of an instrumented aircraft. At the lower levels there was an abrupt change in microphysical and thermodynamic properties from the updraught region to the environment. At the upper level the change was more gradual and extended over a larger region, indicating the spreading out of the convective region underneath the strong inversion capping the boundary layer. Precipitation was observed at all levels, even in the convective region except near its centre core. Vertical-velocity fluctuations in the convective region near the inversion were indistinguishable from the surroundings. At these high levels the horizontal wind in the convective region was from the same direction as the air close to the surface, but was at an angle of up to 60° with the horizontal wind from the surroundings. The convective region was characterized by cloud droplet concentrations that were often more than double those recorded in the surrounding cloud. This indicates that the modifications to the cloud droplet spectra associated with the onset of precipitation starts in the convective region and is enhanced in the stratiform region.

KEYWORDS: Aircraft observations Cloud microphysics Precipitation Stratocumulus

1. INTRODUCTION

Marine boundary-layer clouds can be roughly classified as belonging to either the stratocumulus regime or the cumulus regime. The stratocumulus regime is widely observed near the west coast of continents in the subtropical regions over cold coastal waters, while the cumulus regime is observed in the trade-wind regions of the (sub)tropical oceans. Many observations have been made over the years, characterizing either one or the other regime. Stratocumulus layers usually cap a shallow boundary layer (less than 1 km deep), while the (trade wind) cumulus regime is usually found in deeper boundary layers (up to 2 km deep). In the cumulus-capped boundary layers, the cloud layer is separated from the subcloud layer by small but distinct jumps in thermodynamic variables.

The manner in which the stratocumulus-capped boundary layer transforms to a cumulus-capped layer is not well understood, but is believed to be caused by changes in sea surface temperatures, atmospheric stability, subsidence rates and upper atmospheric moisture content (Albrecht et al. 1995). The Atlantic Stratocumulus Transition EXperiment (ASTEX) was specifically designed to study this transition from a mostly observational standpoint in a subtropical region where the transition most often occurs. Several observations from ASTEX have now been published which demonstrate the important role of penetrating updraughts in the transport of moisture-laden air into the cloud regions (Wang and Lenschow 1995; Martin et al. 1995).

The fact that observations demonstrate that the cloudy boundary layer does not confine itself to a single-cell circulation, but on many occasions exhibits two vertical scales (sub-cloud, and cloud layer), leads to a conceptual problem in models that describe the boundary-layer evolution. Single-scale models (Lilly 1968; and models of his type) do not describe the trade-wind cumulus regime, while dual-scale models (Albrecht et al. 1979; and models of his type) do not describe the single-scale stratocumulus regime. The transition between the two regimes can only be resolved by models that include multiple scales (Bougeault 1985). A cloud-topped boundary layer for which the dual-scale structure is evident is often referred to as being decoupled.

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Stratocumulus decoupling has been observed in extratropical regions, which indicates that the transition process is not confined to the subtropical regions of the globe. In fact, the decoupling as observed by Nicholls (1984) was shown to be caused by diurnal variations in solar heating (Turton and Nicholls 1987), all other conditions being equal.

From an observational standpoint it is hard to discern whether a boundary layer adheres mostly to the single-scale, or to the dual-scale or decoupled mode. Much of the evidence for decoupling comes from vertical profiles where the transition between the cloud layer and the subcloud layer is recorded as a discontinuity in both temperature and mixing ratio. However, when measured by aircraft these discontinuities are registered by imperfect probes in a hostile environment, and the fact that many vertical profiles do not register discontinuities does not mean that they did not exist. In fact, for a stratocumulus layer in the process of decoupling, discontinuities may rarely be manifest.

The existence of updraught regions that have a lower cloud base than non-updraught regions can be used to indicate decoupling. Variations in cloud base are, when taken by themselves, no evidence of decoupling, as a lower cloud base near updraught regions can be explained by a single-cell circulation (Betts 1983). However, observations of convective regions such as recently shown by Martin et al. (1995) are evidence of organization of the boundary layer in distinct regions where moisture from the ocean surface is transported into the cloud. This transport can compensate moisture losses due to entrainment of the boundary layer with the upper atmosphere or due to precipitation from the cloud layer into the subcloud regions. It may be part of, or the precursor to, the decoupling of stratocumulus layers.

Little direct evidence has been obtained on the convective organization of stratocumulus clouds, because the absence of visual references while flying long legs inside a cloud makes it impossible to localize and sample the updraught regions. Furthermore, the process of decoupling and recoupling may be very rapid, so that the sampling of convective regions is a matter of chance. In this paper we present some evidence of organized convection embedded in a region of extensive stratocumulus cover. Data gathered from four flight legs penetrating the convective regions are described. This is followed by an extended discussion on what we believe to be the interpretation of the results.

The observations shed light on the transport of moisture into stratocumulus cloud, and the manner in which the microphysical structure of the cloud layer is modified by the existence of such transport regions.

2. EXPERIMENT AND SAMPLING STRATEGY

The observations to be presented next were gathered during the second phase of the Southern Ocean Cloud EXperiment (SOCEX). The purpose of this experiment has been the collection of microphysical and radiation data of stratocumulus clouds in a marine atmosphere under conditions where anthropogenic influences are minimal. Two experiments were carried out, one in July 1993 to characterize the winter clouds, the other in January/February 1995 to characterize the summer clouds. A summary of SOCEX I results has been published by Boers et al. (1996). A complete summary of SOCEX II will be published at a later date.

The platform from which all observations were made was the F27 aircraft formerly owned by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). For many years this aircraft has been the mainstay of airborne observations in Australia. Instruments consisted of several Particle Measuring Systems (PMS) microphysical probes including a precipitation particle probe (PMS Optical Array Probe 2D-C), a PMS Forward Scattering Spectrometer Probe (FSSP), which registers the non-precipitating cloud
droplets, and instruments to record all state variables and long- and short-wave radiative fluxes (Boers et al. 1996). The FSSP measures droplets with radii that are smaller than approximately 22 μm, the 2D-C probe measures the larger drizzle droplets up to 1000 μm radius. Most of the precipitation is confined to the drizzle range and in fact rarely reached the surface. The uncertainty of the liquid water measurements is difficult to assess, but based on the measurements gathered during SOCEX I is estimated to be about 20–30%. The observations were gathered in four level flight legs on the morning of 1 February 1995. The location was south-west of Cape Grim, Tasmania (Fig. 1) in a south-westerly airstream. The region was covered by an extensive stratocumulus field.

When the cloud layer was viewed from the bottom up, there appeared to be a localized line of convection where the cloud base was approximately 300 to 400 m lower than the rest of the cloud layer. When viewed from the top down, domes that were estimated to be 30 to 50 m high protruded above the otherwise uniform cloud top. These were the only visible manifestations of the organization of convection within the layer.

The sampling strategy was optimized for the systematic collection of microphysical and radiation data which was the main purpose of the experiment. Initially, after a region was determined suitable for sampling, a 45 km cross-wind radiation leg was flown above the cloud layer. Then a slow descent to the surface was done. Subsequently, the boundary-layer structure near the surface, at cloud base and inside the cloud was sampled. Figure 2 shows the four levels at which the convective region was sampled. The surface flight leg preceding the four legs is not shown. Flight levels were respectively at 920, 905, 880, and 855 hPa. Including turns and altitude changes total flying time in these four legs was 37 minutes.

For the purpose of selective sampling of organized updraughts and downdraughts this may not be the optimum solution, as the penetration of convective regions could be a matter of chance. However, on this day the convection appeared to be organized in lines rather than in isolated updraughts. The orientation of the flight legs was at an angle to the
line of convection with the fortuitous result that the convective region was penetrated on all four flight legs. The exact angles at which the flight legs intersected the cloud line could not be determined, but from visual observations were estimated to be about 60 to 80°.

3. DATA

(a) Introduction

Figure 3 shows a close-up of the four flight legs and the approximate position where the convective line was penetrated. Vertical profiles of potential temperature (θ), equivalent potential temperature (θ_e), water vapour mixing ratio (q_v), and liquid water content were

Figure 3. Geographic position where the convective region was sampled. The lower flight leg is indicated by 'Leg 1', the upper flight leg by 'Leg 4'. The location of the convective region is indicated by the thick part of the line.
obtained 10 minutes before the start of the first of the four horizontal flight legs (Fig. 4). There is clear evidence of decoupling of the cloud layer from the surface mixed layer because of the abrupt increase in $\theta$ (Fig. 4(a)) at 920 hPa. Thus, the first flight leg, flown at 920 hPa, was positioned very close to the small inversion near the convective cloud base. The moisture profile in Fig. 4(b) also shows a break, but it is quite small. A large vertical gradient in moisture is present in the surface mixed layer. Several spikes are present in the $\theta_e$ profile. One of these spikes (at 965 hPa) is mirrored in a spike at the same level in the profile of the water vapour mixing ratio. The value of this spike corresponds to the near-surface value of $\theta_e$ and was recorded when the aircraft traversed the convective region as it descended towards the surface. The other double spike (at 845 hPa) is not mirrored in the profiles of $\theta$ or $q_v$. It is caused by the response delay of the humidity sensor (EG&G dewpoint), a common problem with this type of instrument.

Figures 5–8 show time series of relevant variables that highlight the development of the convective region into the upper cloud deck. Shown are droplet number concentration measured by the FSSP and 2D-C probe (Figs. X(a) and (b) where $X = 5–8$), the liquid-water content observed by the FSSP and 2D-C probe (Figs. X(c) and (d)). The cloud droplet effective radius, defined as the fraction of the third and the second moment of the droplet size distribution, is shown in Fig. X(e), with the thick line representing the droplet radius based on the FSSP probe only, and the thin broken line based on data from the FSSP and the 2D-C probe. Figures X(f), (g), (h), (i) and (j) show, respectively, the precipitation flux $F_D$, the vertical wind speed $w$, the horizontal wind speed components $u$ and $v$, the horizontal wind direction and the total water mixing ratio ($q_T = q_v + q_l$, where $q_T$ is the total water mixing ratio, and $q_v$ and $q_l$ its vapour and liquid components). The precipitation flux was calculated by multiplying the droplet density function by a fall velocity and integrating over the full droplet spectrum (see Boers et al. 1996). The turbulent water flux is not taken into account in these calculations. On each of the figures the vertical lines roughly indicate the leading and trailing edge (respectively the left and right side on the plots) of the convective region, although it may not be always obvious where to locate the exact boundary between the convective region and the surroundings. Some of the transitions are smooth, while others are almost discontinuous.

Flight legs 2 and 4 (Figs. 6 and 8) were flown in the opposite direction to Flight legs 1 and 3. Consequently, the time axis is seen to decrease, rather than increase, so that all figures show the penetration from the same side.

(b) 920 hPa flight leg

Figure 5 shows data from the flight track just above cloud base in the convective region. The surrounding area was largely cloud free because of an absence of droplets recorded by the FSSP. The central region of strongest updraught was traversed at 12:18 Eastern Daylight Time (EDT, $\text{EDT} = \text{GMT} + 11$ hours). No drizzle was recorded at this time but on both sides, especially on the right in the figure, drizzle was registered. Well away from the convective region towards the end of the flight line, a region of intense drizzle was penetrated (12:20–12:22 EDT). Video recordings indicated that this drizzle patch was located near the leading edge of a second convective line (with similar orientation to the first line) which was not traversed. The region near the convective core was characterized by strong turbulent fluctuations in the vertical and horizontal wind, but there appeared to be no major shift in horizontal wind direction. Over the complete flight leg, the wind direction was more or less constant at 290°, but horizontal wind speed magnitude (not shown here) decreased from 8 to 4 m s$^{-1}$. Total water mixing ratio increased almost 0.5 g kg$^{-1}$ near the left edge of the convective region, with the maximum of water measured in the strongest updraught (12:18 EDT).
Figure 4. Profiles of (a) potential temperature, $\theta$, and equivalent potential temperature, $\theta_e$, (b) water vapour mixing ratio, $q_{\text{vap}}$, and (c) liquid-water-content profile in the vicinity where the convective region was sampled. The dashed line in (c) indicates the adiabatic liquid-water content.
Figure 5. Traces of variables as functions of time as the aircraft traversed the convective region and surrounding area on flight leg 1. (a) FSSP droplet count, (b) the 2D-C droplet count, (c) the FSSP liquid-water content, (d) the 2D-C liquid-water content, (e) the effective radius (see text for further explanation), (f) the precipitation flux obtained from the FSSP plus 2D-C data, (g) the vertical velocity, (h) the two components \( (u, v) \) of the horizontal velocity, (i) the wind direction, and (j) the total water mixing ratio.
(c) 905 hPa flight leg

Figure 6 shows data from the flight leg penetrating the lower part of the convective cloud. While the same region of extensive drizzle was sampled to the right of the convective region, the flight leg ahead of the penetration was clearly below the base of the extensive stratocumulus shield, because the FSSP recorded no liquid water (Figs. 6(a) and (c)). However, once the convective region had been penetrated, cloud droplets were sampled at the trailing edge. This could indicate that at the trailing edge the cloud base of the stratocumulus shield was lower than at the front. However, the droplet number concentration was quite high in comparison with the concentrations to be shown later for the highest flight leg. This would suggest that these clouds may be less active cumuli with roots in the surface layer. This is supported by the lack of drizzle at 12:26:20 EDT, which was well away from the convective region (at 12:28:30 EDT) but did not have the strong updraught associated with the convective region.

We note (Fig. 6(a)) that the core updraught region had the highest concentration of cloud droplets (190 cm⁻³). Figure 6(e), showing the effective radius of the droplets, illustrates that the effective radius from the combined FSSP and 2D-C measurements far exceeded the effective-radius measurements from the FSSP only.

Once again, the leading edge of the convective region was characterized by a distinct discontinuity in total water mixing ratio (Fig. 6(j)), while the trailing edge did not show this discontinuity. Near the leading edge, the wind direction changed from 300° to 280°. After the penetration of the convective region it fluctuated from 300° near the trailing edge to 260° near the end of the flight leg. Top updraught speed was 3 m s⁻¹. The transition in qₜ at the leading edge was at a later time than the wind direction (Figs. 6(i) and (j)).

(d) 880 hPa flight leg

The 880 hPa flight leg was flown very close to the base of the upper stratocumulus region, with precipitation recorded throughout the flight (Figs. 7(b), (d), and (e)) and with occasional cloudy patches. The precipitation intensities recorded are approximately a factor of four larger than those measured by Austin et al. (1995) during the First ISCCP* Regional Experiment (FIRE). Except for the convective region, the contribution to the total liquid water by the 2D-C probe was substantially larger than by the FSSP. The most intense precipitation was at both edges of the convective core region (Fig. 7(f)). The cloud droplet concentration measured at times when the flight was in cloud but outside the convective region (three periods between 12:35 and 12:38 EDT) was about 50 cm⁻³ compared with 150 cm⁻³ in the convective region (at 12:39 EDT, Fig. 7(a)), indicating that indeed the upper stratocumulus deck was sampled, rather than clouds originating from below (which would have a larger droplet concentration (e.g. compare Fig. 5(a))). Once again the maximum updraught speed in the convective core region was near 3 m s⁻¹ (Fig. 7(g)). The total mixing ratio inside the convective region was almost 1 g kg⁻¹ greater than that of the surroundings (Fig. 7(j)). In fact, the recorded values of 7.5 g kg⁻¹ were very close to the values registered in the surface layer (e.g. Fig. 5(j)). At the same time the horizontal wind at the leading edge of the convective region shifted rapidly from 310° outside to 280–290° inside the convective region.

(e) 855 hPa flight leg

The 855 hPa flight leg was flown in the solid upper stratocumulus layer as evidenced from the continuity in liquid water registered by the FSSP (Figs. 8(a) and (c)). Outside the

Figure 6. The same as Fig. 5, but for flight leg 2. The time axis is reversed, because this flight leg was flown with a heading opposite to the heading of flight leg 1.
convective region the liquid-water content was more or less uniform. Figure 8(b) shows that the droplet concentration registered by the 2D-C probe gradually increased as a function of the distance away from the convective region. However, drizzle droplets were smaller than those observed further down as evidenced from the small drizzle rates (Fig. 8(f)).

Near the strong inversion (5 degC, see Fig. 4(a)), the updraught was negligible (Fig. 8(g)), but there are significant changes in the horizontal wind direction (Figs. 8(h) and (i)). There was a difference of $40^\circ$ in wind direction between the convective region and the surrounding area. In the centre of the convective region (12:48:20 EDT) the droplet number concentration was still close to 150 cm$^{-3}$ but the change in concentration between the convective region and the surroundings was less discontinuous than further down. Outside the convective region the concentration was less than 50 cm$^{-3}$. The range of values registered during the entire flight was smaller than most of the measurements summarized by Seidl (1994), and supports the conclusion by Boers et al. (1996) that the droplet number concentrations that can be measured at this geographical region in an unpolluted environment are among the lowest anywhere. The total water mixing ratio near the core of the convective region was 7.2 g kg$^{-1}$, which represents a slight but significant drop over the values registered further down. This indicates some mixing with the environment, and possibly entrainment, although we have no evidence of this.

4. Discussion

Figure 9 shows a schematic diagram of what we believe to be the interpretation of the flight data shown in Figs. 5–8. This interpretation is supported by viewing the video tapes taken during the flight. Just before the four flight legs a surface leg was flown. The video tape taken of this flight leg indicated that the line of convection existed roughly perpendicular to the orientation of the flight path. On the lowest flight leg, shown in the

![Figure 9. Schematic diagram of convective cloud penetration as interpreted from the in situ data and aircraft video tapes.](image-url)
previous section, the base of this convection line was penetrated less than 100 m above cloud base. This means that the cloud base had its roots in the layer below the potential-temperature discontinuity (see Fig. 4(a)). In fact, the cloud base could be seen on the video just before the penetration. At no time during the flight leg was it possible to see the top of the convective line, as it extended well into the upper-level stratocumulus deck. The bottom of the elevated stratocumulus deck appeared to be uniform with occasional cloud patches below it. The video tapes revealed that several of these convective lines were visible. Each was estimated to be a few tens of kilometres long.

The second flight leg was flown well below the upper stratocumulus deck, and occasional cumulus clouds were sampled which had their roots in the surface layer. Several pieces of evidence support this conclusion. The video tapes clearly indicate that most of the uniform deck existed above the flight level, while many smaller cumuli existed below this level. Some of these cumuli were penetrated (near 12:26 EDT). The total water mixing ratio measured in these penetrations was near 7.5 g kg\(^{-1}\) (see Fig. 6(i)) which corresponds to the amount of water vapour of an unmixed parcel lifted up from the surface layer. Also, the wind direction at the trailing edge of the convective line (see Fig. 6(i)) shifted back from 280° near the core centre (12:28:30 EDT) to about 300° outside the core (12:27 EDT), where the droplet concentration drops to zero (see Fig. 6(a)), and then shifts to 270 to 280° when the next clouds are penetrated (near 12:25 to 12:26 EDT). Drizzle was most intense at this level.

The third flight leg was flown very close to the cloud base of the upper stratocumulus deck and occasionally penetrated it. Drizzle was quite intense (Fig. 7(f)) in this layer which was close to saturation due to the proximity of the cloud base of the upper stratocumulus deck. No clouds emerging from the surface layer were penetrated. The occasional cloudy patches were associated with the upper-level cloud deck, as no significant wind shifts were recorded during cloud penetrations (except for the convective region).

Only the fourth flight leg was flown in the upper cloud deck. However, the convective region was manifest in all traces, except the vertical velocity. The strong inversion acts as a powerful damping mechanism on any vertical movement of air mass, with the result that most of the air mass that had been transported upwards was forced to spread out sideways and mix with its environment. The result is that on this highest flight leg, the intersection length-scale of the convective region (around 10 km) was about twice that observed for the upper middle flights legs (5 to 6 km) where upward transport was still largely unrestricted.

The strongest distinction between the convective region and its surroundings is visible in the microphysical structure. Both at the highest flight level and lower down the droplet number concentration registered by the FSSP was one of the clearest markers distinguishing the updraught region from the surroundings.

On closer examination, it seems that at the higher level, an extensive mixing and/or transformation region existed where the non-precipitation particles from lower in the updraught region were processed by collision and coalescence to precipitation particles. Taken as a whole, the number of droplets as registered by the 2D-C probe at the upper leg gradually increased away from the convective region. This gradual change was absent in the traces of the lower flight leg. At the same time a decrease was evident in the FSSP droplet concentration trace in the surrounding region of the upper leg away from the convective region, i.e. most non-precipitation droplets were present in the vicinity of the convective region, with a decrease at distances further away from it. Thus, it seems that this transformation was a gradual process which extended over tens of kilometres away from the edge of a convective region. Evidently, the transformation to drizzle of cloud droplets that have been transported upwards into the stratocumulus deck by the convective regions together with the mixing of the convective region with its surroundings and with
the overlying atmosphere was capable of reducing the droplet number concentration to less than one-third of its size in the convective region. Since the optical depth of a cloud is proportional to the one-third power of the droplet number concentration this is evidence of the powerful effect of drizzle on the radiative properties of clouds that was referred to by Boers et al. (1996). In fact, all other factors being equal, the observed reduction in cloud droplet number concentration from the centre of the convective region to the surrounding cloud would reduce the optical depth by 30%.

The picture emerging from these observations is not too different from that sketched by Martin et al. (1995) from their ASTEX case study (their Fig. 20): an extensive layer of stratocumulus clouds was penetrated by active convective regions in which moisture was transported upwards. However, what is different is that the convection observed in our case was organized in lines. We appeared to have sampled a cross-section of one of these convective lines. These convective regions had a large diameter (in our case exceeding 6 km) in which precipitation (in the central updraught) was reduced from that registered in the regions surrounding the updraughts. The outflow region in the upper part of the cloud was the region where the coalescence process modified the droplet spectrum to produce precipitation (see Fig. 8). Precipitation in part compensates for the upward transport of moisture in the cumulus updraughts.

Our data are different from those shown by Wang and Lenschow (1995) in that there was little change in buoyancy from the updraught region to the surrounding area. Traces of the virtual potential temperature (not shown) indicated no change as the aircraft penetrated the updraught region. This is a puzzling result given the fact that updraught speeds of over 3 m s⁻¹ were recorded.

We do not have a convincing explanation for the organization of the convection. One possibility is that wind shear played a role: Fig. 3 shows that the convective line extended roughly from the west-north-west to the east-south-east (from 290° to 110° direction). Given the wind shift from 270° in the layer close to the surface, to 330° in the stratocumulus cloud near the inversion, the line was oriented roughly perpendicular to the wind-shear vector and in the direction of the vorticity vector generated by the wind shear. Clearly, this type of organization is an effective means of supplying the upper stratiform layer with water, which is necessary to balance the downward flux of liquid due to precipitation. Another possibility is that this type of cloud layer allows for the occurrence of mesoscale instabilities. Fiedler (1984) demonstrated that boundary layers covered by uniform cloud layers may be subject to such instabilities in which fluctuations in temperature and moisture are reinforced by fluctuations in entrainment, setting up cloud convective patterns with cell sizes of 20 to 100 km across. Although this paper reports on only one of those crossings (right in the middle of the flight legs), video images indicate that a second line existed at the southern end of the flight legs separated from the first one by about 15 km. With the boundary-layer depth approximately 1.5 km, this would suggest an aspect ratio of 10:1, at the lower end of the range that may exist according to Fiedler (1984).

5. Conclusion

We have sampled an updraught region embedded in an extensive stratocumulus cloud shield. Sampling at different levels indicated substantial modifications of the microphysical structure in the upper part of the cloud when compared with the lower part.

The observations shed light on the transport of moisture into a stratiform cloud that was decoupled from the ocean surface. The moisture transport appeared to be organized into convective lines. The updraught regions were apparently driven in part by a mesoscale
circulation. Little or no buoyancy differences were found between the updraught regions and their surroundings.

Once the moisture from the convective regions entered the upper stratiform deck, the formation of precipitation particles together with mixing of the convective region with the stratocumulus region rapidly reduced the droplet number concentration to about one-third of its value in the convective region. This process needs to be studied further, but on first principles can be seen to have a profound impact on the albedo of the clouds.

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