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LOOKING FOR EVIDENCES OF DRIZZLE−INDUCED DECOUPLING IN THE STRATOCUMULUS−TOPPED BOUNDARY LAYER

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1. INTRODUCTION

Stratocumulus clouds are a prominent feature of the subtropical high pressure systems, forming over cold waters, under large−scale subsidence, covering broad areas over the eastern Pacific and Atlantic oceans. Because of their long residence time, stratocumuli (Sc) are capable of substantially modifying Earth's surface energy balance. A great amount of uncertainty is attributed to those clouds in a global climate change scenario. Based on the strong influence of those clouds on the planetary albedo (Kogan et al. 1995 point out that Sc are responsible for a 30 to 50% increase in this quantity), Randall et al. (1984) estimated that a mere 4% increment in the areal coverage by Sc would compensate for a temperature rise due to a doubled carbon dioxide concentration. In addition, Charlson et al. (1992) suggested that an increase in the droplet number concentration in marine stratiform clouds could neutralize or at least mitigate the greenhouse warming. However, predictions on the final result of a combination of an enhanced greenhouse effect and an increased aerosol concentration remain inconclusive.

A better understanding of Sc physics, including their formation, maintenance and dissipation, would help to quantify their role in cloud−radiation−surface feedbacks, as well as contribute a greater skill in weather prediction over regions under their influence.

A number of physical processes act over stratocumulus clouds, including longwave radiative cooling at the cloud top, which drives turbulence; shortwave absorption throughout the cloud layer; entrainment of warm, dry air from the free atmosphere and microphysical processes (condensation / evaporation, drizzle formation). Due to their complex nature, Sc dynamics is probably influenced by several environmental characteristics. Some researchers proposed that entrainment can be a factor causing Sc to breakup (Lilly 1968, Randall 1980, Deardorff 1980), or at least a necessary condition to their dissipation (Kuo and Schubert 1988). On the other hand, drizzle was addressed as one of the mechanisms resulting in boundary−layer decoupling (used in a "weak sense", i.e., as a local reduction of turbulent fluxes, as in Stevens et al. 1998) by other scientists.

The later hypothesis is sustained by both observational and modeling studies. The effect of drizzle was verified in the field since the observations described by Brost et al. (1982) and Nicholls (1984). Recently, Feingold et al. (1999) analyzed radar echoes during the Atlantic Stratocumulus Transition Experiment (ASTEX) and concluded that all stratocumulus−topped boundary layers (STBL) showing drizzle exhibited a negative correlation between radar reflectivity and vertical velocity variance in the sub−cloud layer. Aircraft measurements from the 2nd Aerosol Characterization Experiment (ACE2) analyzed by Durand and Bourcy (2001) showed that non−polluted STBL were typically decoupled whereas coupling between the mixed layer and the cloud layer was found in a continental/polluted environment. The influence of drizzle was also investigated via numerical simulations by Wang and Wang (1994) and Stevens et al. (1998), who concluded that Sc driven by radiative cooling cannot persist in the presence of heavy drizzle.

In the present paper, turbulence and microphysics data from ACE2 CLOUDYCOLUMN are presented and a possible connection between drizzle formation and boundary−layer decoupling is investigated. The field campaign is briefly described in Section 2 and data from six flights are presented in Section 3. A discussion on the mechanisms leading to decoupling in the STBL is shown in Section 4, followed by a summary and concluding remarks, in Section 5.

2. ACE2 CLOUDYCOLUMN

The 2nd Aerosol Characterization Experiment (ACE2) was designed to measure and characterize atmospheric aerosols and held from 15 June to 31 July 1997 over the North Atlantic Ocean, off the European coast. In that region, the dominance of marine, polluted (primarily from Europe) and continental aerosols (mainly from the Sahara desert) alternate.

One of the six field projects in ACE2 was the ACE2 CLOUDYCOLUMN (Brenguier et al., 2000), dedicated to study indirect climatic effects of aerosols, especially changes in cloud properties due to changes in cloud condensation nucleus (CCN) characteristics. CLOUDYCOLUMN also aimed at improving parameterizations of physical processes in cloudy boundary layers.

Meteorological, radiation, turbulence, aerosol and microphysics data were collected on board Météo−France's Merlin IV. Some of the instruments are listed in Table 1.

According to Brenguier et al. (2000), the experimental strategy for the Merlin IV during CLOUDYCOLUMN consisted of square flight trajectories containing:

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1. Constant altitude legs, during which turbulent fluxes, aerosols in the sub−cloud layer or hydrometeors in the cloud layer were sampled;

2. Zig−zag segments from above to below the cloud layer, sampling vertical microphysical profiles, as well as cloud top and base heights;

An example of a square flight−track, with vertical zig−zag segments and horizontal straight legs is shown in Figure 1, which depicts the Merlin IV trajectory during the 19 July 1997 flight.

Measured Parameter	***Sensor (s)***
Temperature	Rosemount 102E2AL
Static Pressure	Static ports on fuselage + transducer Rosemount 1201
Dynamic Pressure	Total pressure port on radome and static pressure port on fuselage + transducer Rosemount 1221F
Attack and sideslip angle	Pressure ports on radome + 2 transducers Rosemount 1221F
Latitude and Longitude	Intertial navigation system Sagem ULIS 45I
Altitude above the surface	Radioaltimeter TRT ERT900
Specific humidity	Lyman alfa AIR LA1
Dew−Point Temperature	General Eastern 1011B
Liquid Water Content	Johnson Williams CT43
Aerosols	2 Condensation nucleus counters CN TSI−3760A, Passive Cavity Aerosol Spectrometer Probe PCASP−100X, Cloud condensation nucleus counter WYO−CCNC, Forward Scattering Spectrometer Probe FSSP−300
Hydrometeors	Fast−FSSP, Optical Array Probe OAP−200X

Table 1 − Instrumentation on board Météo−France's Merlin IV

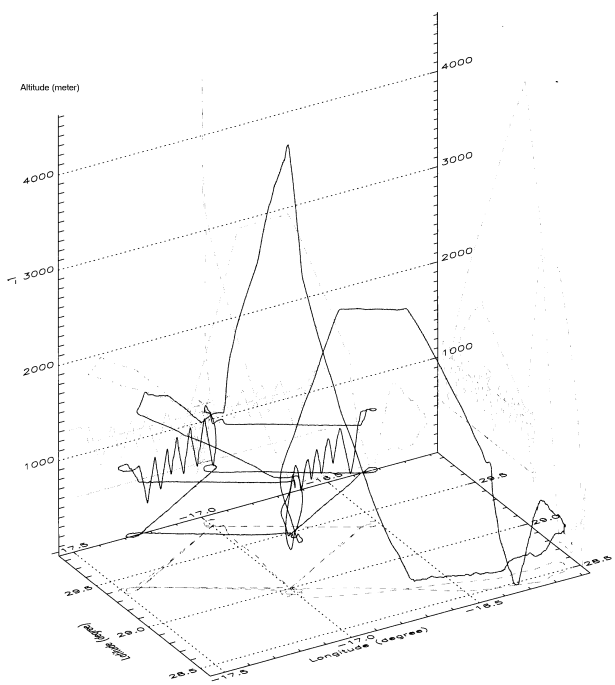


Figure 1 − Merlin IV flight trajectory for 19 July 1997, from 0913 to 1234 UTC.

3. DATA

3.1 *26 June 1997*

On that day, observations suggested the existence of a broken stratocumulus layer (as suggested by Figure 2) and a possible stratocumulus−to−cumulus transition. In the flight region, under a relatively small value of sea−level pressure (~1017 hPa), the boundary−layer extended up to 1500 m, where a marked inversion was found. Low−level potential temperature and water vapor mixing ratio were 293 K and 10 g.kg−1, respectively. A slightly increasing trend was found in the potential temperature as time progressed.

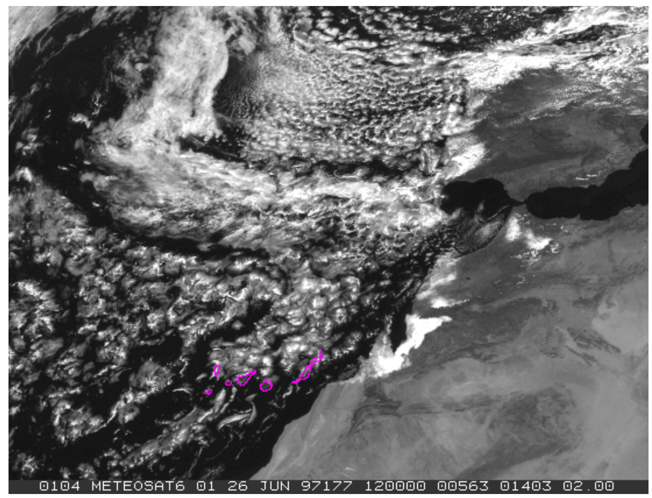


Figure 2 − Satellite image, 26 June 1997, 1200 UTC (visible channel). Canary Islands are marked.

Vertical profiles, as in Figures 3 and 4, suggest decoupling in the sub−cloud layer. Those figures depict profiles in airborne soundings at a cloud−free position and at a column containing both stratocumulus and cumulus clouds, respectively.

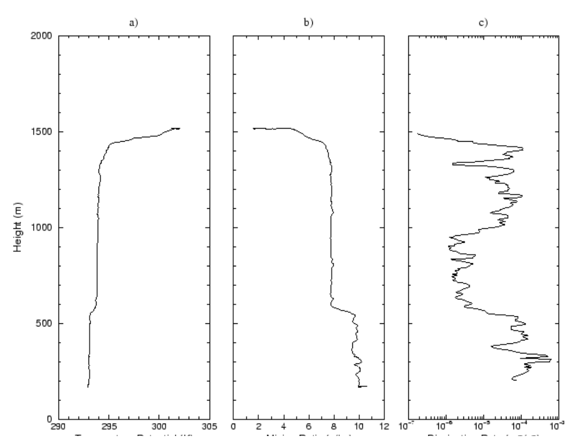


Figure 3 − Vertical profiles of (a) potential temperature, in K, (b) water vapor mixing ratio, in g.kg^{-1}, and (c) TKE dissipation rate, in m^{2}s^{-3}, 26 June 1997, sounding started at 1355 UTC.

As shown in panels 3a and 3b, a discontinuity occurred in both the potential temperature and water vapor mixing ratio profiles, approximately at the 550 m level. At that point, this height corresponds to the top of the mixed layer, way below the stratocumulus cloud base. A significant minimum in the turbulent kinetic energy (TKE) dissipation rate, which decreased more than 2 orders of magnitude, is found from 550 m up to 1000 m (panel 3c). Such a layer is characterized by warmer, drier air, and small turbulence activity.

Figure 4 illustrates a feature found in the 26 June flight, namely the presence of cumuli behind the stratocumulus layer. The thermodynamic, liquid water and turbulence structure of a "cumulus−under−stratus" sounding is depicted in Figure 4. The potential temperature still exhibits an increasing trend below the stratocumulus layer (panel 4a), but not as a sharp discontinuity, as in panel 3a. The jump in the water vapor mixing ratio profile is still prominent, but appears at the ~1100 m level (panel 4b), instead of at the 550 m height (panel 3b). This is probably due to a significant vertical transport by cumulus clouds. Those clouds formed with base at approximately 900 m and top below 1100 m (panel 4c). A decreased TKE dissipation rate is still present, however the separation between the well−mixed, near surface layer and the stratocumulus layer is less pronounced (panel 4d). Apparently the cumulus clouds worked as a discrete, intermitent connection between the mixed layer and the stratocumulus clouds.

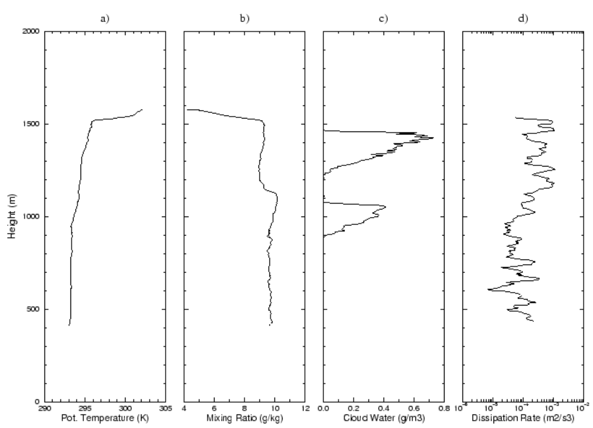


Figure 4 − Vertical profiles of (a) potential temperature, in K, (b) water vapor mixing ratio, in g.kg^{-1}, (c) cloud water content, in g.m^{-3}, and (d) TKE dissipation rate, in m^{2}s^{-3}, 26 June 1997, sounding started at 1336 UTC.

As shown by microphysical measurements, maritime conditions prevailed in this case, with a small average droplet number concentration on the order of 55 cm^{-3}. Figure 5 shows cloud water and rainwater content, each point representing a single measurement, at a 1 Hz rate. A two−layer cloud structure is clearly shown in panel 5a, again establishing the existence of cumulus clouds forming under the stratocumulus layer. A significant amount of drizzle formed, with rainwater content exceeding 0.1 g.kg^{-1} in many occasions (panel 5b).

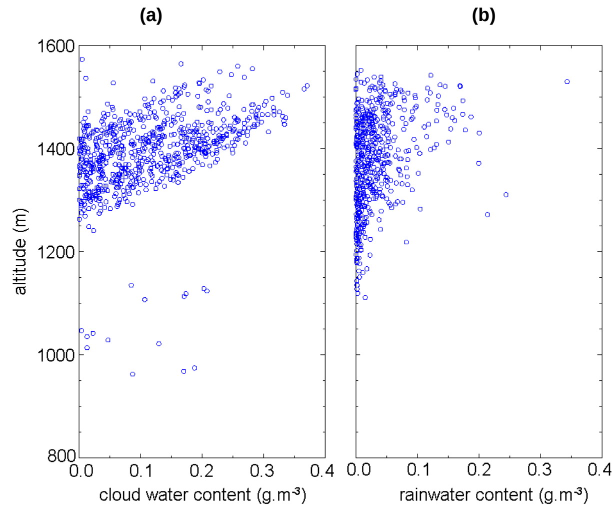


Figure 5 − (a) Cloud water content (from the Fast−FSSP) and (b) drizzle water content (from OAP 200−X), 26 June flight.

3.2 *08 July 1997*

A nearly solid stratocumulus deck formed off the northern African coast, north of the Canary Islands, as shown in the satellite image (Figure 6). The estimated sea level pressure was 1022 hPa (higher than in the previous case) and the boundary−layer height did not exceed 980 m. Low−level potential temperature and water vapor mixing ratio were 291 K and 10 g.kg^{-1}, which means that, although cooler, the atmosphere exhibited approximately the same moisture content found on 26 June.

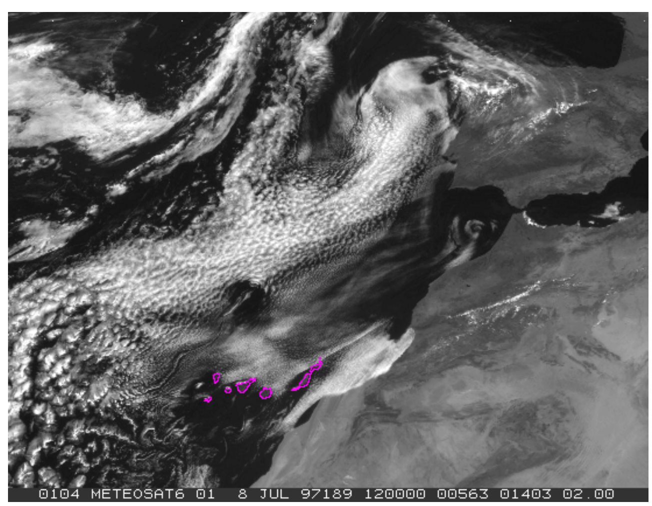


Figure 6 − Same as Figure 2, except for 08 July

Vertical profiles show the absence of discontinuity in the thermodynamic fields below the stratocumulus layer (panel 7a, potential temperature profile) and a relatively well−mixed boundary layer (panel 7b, TKE dissipation profile).

Although the cloud water content was similar to its counterpart on 26 June (panel 8a), drizzle was scarce (panel 8b), with rainwater content seldom exceeding 0.1

g.kg^{-1}. The limited conversion of cloud water into drizzle was associated with relatively high droplet number concentrations (196 cm^{-3} on average).

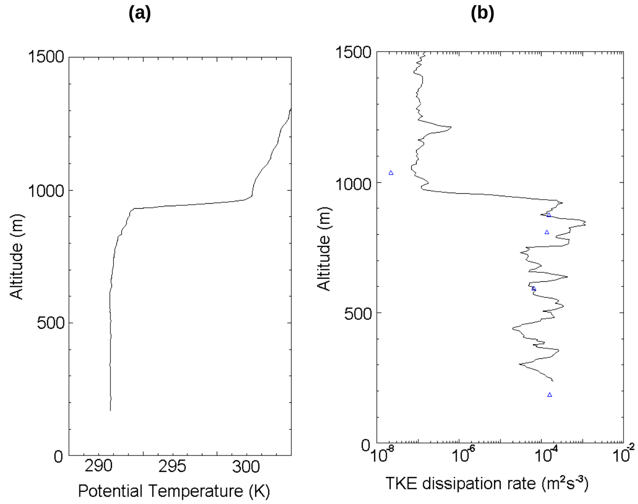


Figure 7 − Vertical profiles of (a) potential temperature and (b) turbulent kinetic energy dissipation rate, 08 July flight.

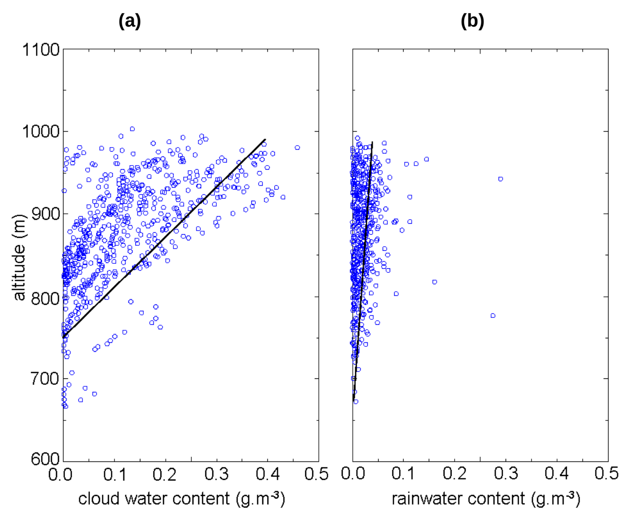


Figure 8 − Same as Figure 5, except for the 08 July flight

3.3 *09 July 1997*

During this flight, atmospheric conditions were akin to the ones found on 08 July. Sea−level pressure was about 1021 hPa, with a boundary−layer height of approximately 1000 m. A nearly−solid stratiform cloud deck formed again to the north of the Canary Islands on top of a well−mixed boundary−layer with no decoupling signature. Only a little amount of drizzle was present, in association with a mean droplet number concentration of 244 cm^{-3}, the greatest value among the five flights analyzed in this paper (Figures not shown).

3.4 *17 July 1997*

As on 08 June, satellite images (as in Figure 9) show the presence of broken Sc under a relatively weak surface pressure (~1019 hPa). The boundary−layer was typically warmer (mixed−layer potential temperature of 294 K) and moister (water vapor mixing ratio up to 13 g.kg^{-1} at near−surface levels) than in previous dates, the inversion located roughly at 1250 m. A significant mesoscale variability in the cloud fields was found, with cumuli being encountered to the northeast and an almost solid stratocumulus deck found to the northwest of the Canary Islands.

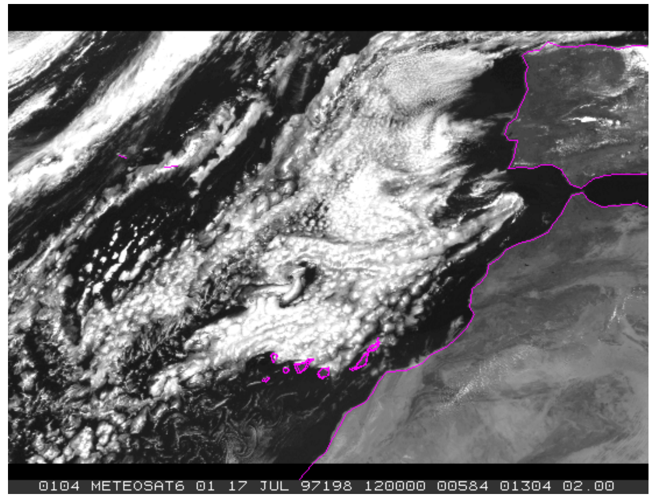


Figure 9 − Same as Figure 2, except for 19 July.

3.5 *18 July 1997*

In this flight, a decoupled profile was found, with a ~1019 hPa surface pressure and near−surface values of 293 K and 12 g.kg^{-1} for the potential temperature and water vapor mixing ratio, respectively. The stratocumulus base was relatively high, varying from 900 to 1050 m. Cloud top was approximately located at a 1200 m height. The mean droplet concentrations was of the order of 128 cm^{-3}. A significant amount of drizzle was observed.

4. DATA ANALYSIS

If decoupling is present in the stratocumulus−topped boundary−layer, the turbulent kinetic energy decreases somewhere between the near−surface mixed−layer and the cloud layer. Such a decrease in turbulence activity is generally accompanied by changes in the thermodynamic and humidity profiles. For instance, in Figure 3, the potential temperature increases and the water vapor mixing ratio decreases as a result of decoupling.

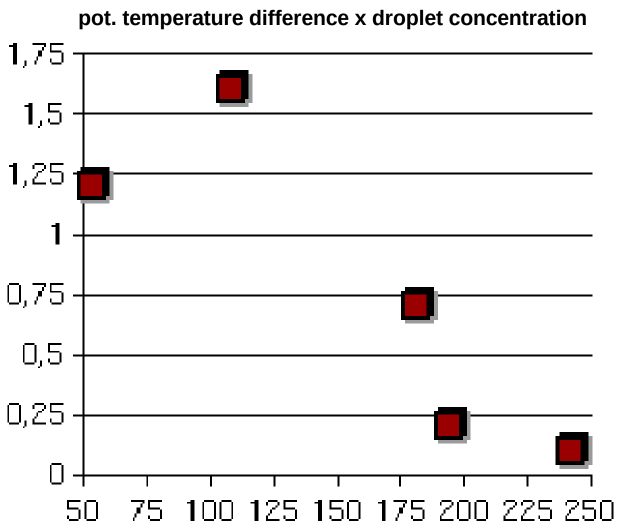
In order to investigate how changes in the potential temperature and mixing ratio profiles are associated with the formation of drizzle, the following quantities were defined:

$$\Delta\vartheta = \left|\vartheta_{z_b - 200m} - \vartheta_{z_0}\right| \quad (1)$$

$$\Delta q = \left|q_{z_b - 200m} - q_{z_0}\right| \quad , \quad (2)$$

variations in the potential temperature and water vapor mixing ratio, respectively. In equations (1) and (2), the subscript z_b−200m indicates a level 200 m below the cloud base, whereas z_0 indicates the lowest level in which aircraft observations were available. It is expected that both $\Delta\vartheta$ and Δq are dependent upon some parameter that regulates the drizzle formation, such as the droplet number concentration.

In fact, as depicted in Figure 10, flights in which the droplet concentration were low generally exhibited large values of $\Delta\vartheta$ and Δq whereas cloudy boundary−layers in which a high droplet concentration was present showed relatively small values of $\Delta\vartheta$ and Δq.



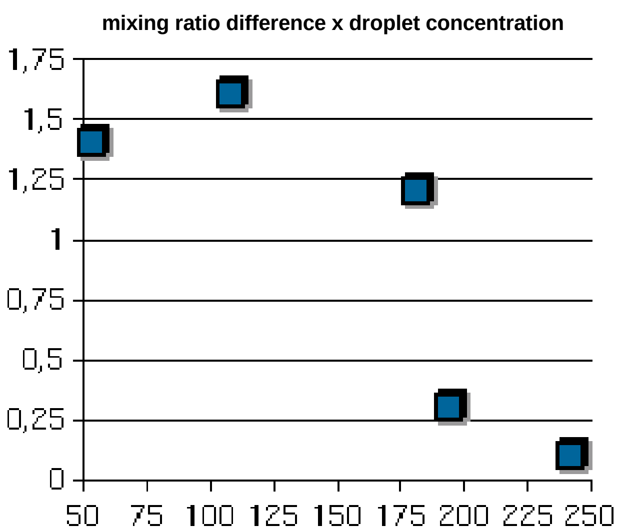


Figure 10 − $\Delta\vartheta$ (upper panel) and Δq (lower panel) as functions of the droplet number concentration, respectively.

5. SUMMARY

Data from 5 ACE2 flights were presented and analyzed, with emphasis to the thermodynamic and moisture vertical profiles, turbulence and microphysical variables. The main purpose of this investigation was to found a relationship between drizzle formation and decoupling of the stratocumulus−topped boundary−layer during the aforementioned experiment.

The data provided evidences that the stratocumulus−topped boundary−layer off the African coast often alternates coupled and decoupled states, characterized by solid or near−solid stratocumulus decks and transitional states (e.g., cumulus−under−stratocumulus), respectively. Microphysical data analysis suggested that a significant variation in the cloud droplet concentration may also occur, mainly due to different aerosol transport regimes. While the presence of maritime air masses typically favor stratocumulus clouds with low number concentration and significant drizzle development, under the influence of continental (e.g., Saharan) and/or polluted air masses, the clouds tend to show higher droplet concentrations and little precipitation development.

The data also suggested that, in reality, the variability found in the microphysical structure of ACE2 marine stratocumuli was quite related to the changes in the boundary−layer vertical structure. In the five flights analyzed, as the droplet concentrations increased, favoring drizzle formation, decoupling between the near−surface layer and the cloud−layer tended to occur.

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REFERENCES

Brenguier, J. L., P. Y. Chuang, Y. Fouquart, D. W. Johnson, F. Parol, H. Pawloska, J. Pelon, L. Schüller, F. Schröder, and J. Snider, 2000: An overview of the ACE−2 CLOUDYCOLUMN closure experiment. *Tellus B*, **52**, 815−817.

Brost, R. A., D. H. Lenschow, J. C. Wyngaard, 1982: Marine stratocumulus layers .1. Mean conditions. *J. Atmos. Sci.*, **37**, 800−817

Charlson, R. J., S. E. Schwartz, J. M. Hales, R. D. Cess, J. A. Coakley, J. E. Hansen, and D. J. Hofmann, 1992: Climate forcing by anthropogenic aerosols. *Science*, **255**, 423−430.

Deardorff, J. W., 1980: Cloud−top entrainment instability. *J. Atmos. Sci.*, **37**, 131−147.

Durand, P. and T. Bourcy, 2001: Observations of the turbulence structure within two stratocumulus−topped, marine boundary layers. *Boundary−Layer Meteorol.*, **99**, 105−125.

Feingold, G., W. R. Cotton, S. M. Kreidenweis, and J. T. Davis, 1999: The impact of giant cloud condensation nuclei on drizzle formation in stratocumulus: Implications for cloud radiative properties. *J. Atmos. Sci.*, **56**, 4100−4117.

Kogan, Y. L., M. P. Khairoutdinov, D. K. Lilly, Z. N. Kogan, and Q. F. Liu, 1995: Modeling of stratocumulus cloud layers in a large−eddy simulation−model with explicit microphysics. *J. Atmos. Sci.*, **52**, 2923−2940.

Lilly, D. K., 1968: Models of cloud−topped mixed layers under a strong inversion. *Q. J. R. Meteorol. Soc.*, **94**, 292−,

Nicholls, S., 1984: The dynamics of stratocumulus − aircraft observations and comparisons with a mixed

layer model. *Q. J. R. Meteorol. Soc*., **110**, 783−820.
Randall, D. A., 1980: Entrainment into a stratocumulus layer with distributed radiative cooling. *J. Atmos. Sci*., **37**, 148−159
Randall, D. A., J. A. Coakley, C. W. Fairall, R. A. Kropfli, and D. H. Lenschow, 1984: Outlook for research on sub−tropical marine stratiform clouds. *Bull. Amer. Meteorol. Soc*., **65**, 1290−1301.
Stevens B., W. R. Cotton, G. Feingold, and C.−H. Moeng, 1998: Large−eddy simulations of strongly precipitating, shallow, stratocumulus−topped boundary layers. *J. Atmos. Sci*., **55**, 3616−3638.
Wang, S. P., and Q. Wang, 1994: Roles of drizzle in a one−dimensional 3rd−order turbulence closure−model of the nocturnal stratus−topped marine boundary−layer. . *Atmos. Sci*., **51**, 1559−1576.