Observations of decoupled boundary layers in the South Eastern Pacific during VOCALS using aircraft, ship and model data.

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1 Introduction

Aircraft observations (NCAR C130, FAAM BAe146, ASRF Dornier 228), and radiosonde ascents (RHB research vessel) are used to probe the structure of the Boundary Layer (BL) of the South Eastern Pacific (SEP) during the VOCALS-Rex field campaign, during austral spring 2008. Decoupled boundary layers, and the representation of them in the UK Met Office Unified Model (hereafter MetUM) are examined as a function of longitude and diurnal cycle. The MetUM ran in forecast model in a Local Area Model format over the SEP, with a grid box resolution of 17km, and 38 vertical levels, from 14 Oct 2008 to 19 Nov 2008. For further details on the model set-up see Abel *et.al.* (2010). The MetUM incorporates the Lock *et.al.* (2000) BL scheme, which controls turbulent mixing parameterisations.

2 Stratocumulus, Decoupling and the Met Office Unified Model

Stratocumulus (Sc) cloud topped boundary layers typically become more decoupled during the day as long wave radiative cooling from cloud top is offset by short wave heating of the cloud layer, with the possibility that Cumulus (Cu) clouds form below (Rogers 1995). Cloud Top Radiative Cooling (CTRC) will lead to a rise in cloud top height, and a consequent increase in Liquid Water Path (LWP). The Lock Boundary Layer Scheme in the MetUM makes decisions about how to parameterise boundary layer turbulent transport. Thermodynamic profiles are analysed and classified according to type. In the SEP there are three major types of interest, shown in Figure 1: T3-Well Mixed, possible Sc topped; T4-Decoupled Sc without Cu; and T5-Decoupled with Cu. In less than 5% of cases, and always far from the coast T6: Cumulus, was diagnosed. For this study T4, T5 and T6 were grouped into "Decoupled", and T3 classed as "Well Mixed". Turbulent Mixing Height (TMH) is calculated by the boundary layer scheme, and typically represents the top of the stratocumulus layer. Boundary Layer Depth (BLZ) essentially represents the height of a surface driven buoyant eddy, although the particular definition is boundary layer type dependant. TMH and BLZ are free to take sub-grid scale values

Figure 2 shows a composite of fractional occurance of boundary layers types diagnosed by the MetUM between 19.5 and 20.5 South, throughout the diurnal cycle as a function of longitude along 20S. The coast is at 72W, and the region between here and 78W shows that predominantly well mixed boundary layers are forecast, with some increase in the forecast of decoupling occurance just prior to local sunrise between 6UTC and 10UTC (sunrise), and possibly just after sunrise between 12UTC and 14UTC. Beyond 85W we see that decoupled boundary layers dominate the forecast. An interesting effect is noted in the region between 80W and 85W, where there is a clear diurnal cycle of boundary layer type. Following sunrise the region tends to be well mixed, with an increase in decoupling becoming apparent from approximately 6 hours prior to sunrise at the western edge of the region, and slightly later further to the east. This region is a transition region between the well mixed stratocumulus capped boundary layer to the east and a decoupled regime, with some characteristics of the well mixed boundary layers, and some characteristics of a more Cu below Sc regime.

Figure 3 shows the same type of plot for the variables TMH and for the non-convective element of Liquid Water Path (LWP). TMH is driven primarily by Cloud Top Radiative Cooling (CTRC), and so at night with enhanced cooling driving entrainment, the cloud top tends to rise. This is indeed seen in the left panel of Figure 3. There is some evidence that decoupling in the model varies with TMH, something that would seem to be physically reasonable. A double peak is visible in the model LWP, something observed in this region by O'Dell 2008. As decoupling increases the TMH is seen to decrease. Once decoupling is underway, the moisture supply to cloud may be reduced or removed, leading to a breakup or thinning of cloud due to entrainment of free tropospheric air from cloud top. Once the Sc has fragmented the CTRC will then be driven from the Cu top. The cycle of LWP closely follows that of TMH. Only non-convective LWP is considered here. Future study of the convective liquid water path may help to illuminate the decoupling process. It is one hypothesis that the drizzle efficiency in the model is too high for a given liquid water path. This will be more important in the SEP away from the coast where actual aerosol number concentrations may be lower in reality than in the model, where $N_{d(model-ocean)}$=100.

3 RHB Sonde Launches

Observations of data from aircraft and the RHB are presented., in order to understand the performance of the model. Two periods are considered, when the RHB was stationary at either the DART buoy (75W) or the IMET buoy (85W) for a number of days. Sondes were released at 3 hourly intervals during these periods. The thermodynamic profiles from the sondes were composited according to launch time. Some individual structure is lost through this process, but the simplified output serves as a guide to the behaviour of the boundary layer at the two locations. MetUM model output was recovered for the closest grid box and time point. Combining data from adjacent grid boxes had little effect on the mean or spread of the forecast output. Figure 4 shows a composite diurnal cycle for each period, 85W – left and 75W - right. With time of launch on the x-axis, and vertical height on the y-axis. The color-bar shows the mean profile of the radiosonde potential temperature, the solid white line shows is presented to indicate the shape of the mean profile. The dash-dotted white line is the mean profile of the MetUM output for comparison. Crosses joined by a dotted line show the model estimate of TMH, diamonds joined by dotted line show the model estimate of BLZ. The two rows of numbers at the top of each plot show the relative fraction of Well Mixed and Decoupled Boundary Layers. Here we have included Type 6 Cumulus capped BL. A consequence of the packing resolution of the model archive compression algorithm is to allow for fractions greater than 1.0 to occur.

In the west the observations show that the boundary layer deepens through the hours of darkness, with some increase in decoupling through the day. Decoupling inversions are present in the mean profiles, and may be the result of individual profiles influencing the mean. Presenting profiles normalised by boundary layer depth may improve this. The TMH increases slightly through the night, and falls rapidly during the day. BLZ is fairly constant, and always very low. The model has the boundary layer most well mixed at the end of the day, with a 50% occurance of Well Mixed boundary layer type. Throughout the night the BL is always decoupled, even thought the observations look well mixed. It will be necessary to look at individual profiles, as the compositing will smooth the profiles.

In the region around 75W the observations are much more well mixed, and the boundary layer is much lower in general. The fractional occurance of diagnosed well mixed boundary layers is much higher, and a similar diurnal cycle in both TMH and BLZ is apparent, with both reaching maxima at 04z, mid way through the night, and 15z, sometime after local noon. The TMH value is much lower than the height of the stratocumulus.

It is thought that part of the low bias may be related to vertical resolution around the boundary layer top. Re-runs of the MetUM are underway, with 70 levels in the vertical (compared to 38 previously), and the output will be studied to look for any improvement.

4 LCL and Cloud Base Height

Following on from analysis by De Szoeke, the LCL and Cloud Base Height (CBH) (LIDAR) from all sub-cloud legs of the C130 aircraft and plotted against one another in a density plot. Figure 5 shows this for two regions, west of 80W (left), and for locations between 80W and 73W (right), with the colour being scaled by number of occurrences. The data were all collected along 20S, at an altitude of 500ft. This is well within the surface mixed layer at any location along 20S. There are more observations to the east of 80W, and the flights were biased to look for decoupled boundary layers, and so the results presented are not intended to represent a climatology for these regions. A bias in LCL, most likely from the temperature probe leads to differences between LCL and CBH in well mixed cases of up to 100m, or ~1K of adiabatic ascent. The right panel shows that the majority of observations are of well mixed boundary layers, with LCL=CBH (within instrumental uncertainties). A small percentage of data points are outside this regime. The left panel shows that more complex behaviour is present to the west of 80W. We see a high intensity region with a 1:1 relation for LCL:CBH in the range 700-800m, identified by a red circle on the left plot. This is due to the aircraft flying through eddies under Cumulus cloud. A more diffuse region is apparent (purple CIRCLE) where CBH is constant between 1100-1200m, not a function of LCL which varies from 600-1200m. The aircraft could be flying through surface generated eddies with an LCL at cumulus cloud base, but in a downdraught, or otherwise cumulus cloud-free region, and so LIDAR will see straight up to the Sc cloud base. Some occurance of well mixed Sc layers can be identified by the grey circle region, where the higher LCL between 1100 and 1300m equates to the Sc cloud base in a well mixed region.

5 Aircraft Observations of Decoupling along 20S

Two cases are presented here showing how the cloud and boundary layer thermodynamic structure varies as a function of longitude along 20S in both observations and model output, from two case study days involving the C130, BAe146 and Dornier aircraft. The left panel of Figure 6 shows an example of well mixed conditions on 31st October 2008, and the right panel shows a decoupled day on the 23rd October 2008. CTH from C130 RADAR (black) and Dornier LIDAR (grey) is seen to increase away from the coast on both days, typical but not exclusive behaviour. The CTH is much higher on the decoupled day. Cloud Base Height (CBH) from the C130 LIDAR is in green, and shows that cloud deepens to the west in the well mixed case, and stays a uniform thickness or even thins to the west in the decoupled case. Leg-mean LCL is calculated from sub cloud legs of the C130 (stars) and BAe146 (dots) with the standard deviation given by the bars. The well mixed case is defined by these LCL values being at the same height as cloud base. The values increase away from the coast, as cloud base does. There is good agreement between LCL values where coincidence occurs between C130 and BAe146 legs. In the decoupled case, the LCL does not increase away from the coast, as the air parcel is defined by surface properties, and so is related to the sea surface temperature. The spread around the mean increases away from the coast in the decoupled case. The model output of TMH (purple) and BLZ (blue) is shown on the plot, taken from the nearest time point to the passage of the aircraft. In the well mixed case there is some indication the TMH increase follows reality, whilst the BLZ does not seem to increase, limited by the way it is defined. The decoupled case shows the TMH increasing away from the coast, although generally a 100-200m too low. The spikes occur as a result of breaks in cloud. TMH is related to CTRC, and so without cloud the is no CTRC. The breaks in cloud may or may not be realistic in the model, and are sometimes simply associated with a step up in model level. The BLZ tracks the trend of the LCL in this case, again some 100-200m too low.

6 Probability Density Functions of LCL to determine decoupling from flight level observations

Decoupling has been observed using in-situ measurements and LIDAR and RADAR. In the absence of remote sensing instrumentation it is still possible to assess the state of decoupling by looking at a profile of the Probability Density Function (PDF) of the LCL obtained from a sub-cloud leg, flown in the mixed layer. In a truly well mixed layer, over an extended horizontal scale a PDF of LCL would resemble a delta function at the height of the Sc cloud base. In reality a mono-modal PDF with a finite distribution will be observed. Any additional modes that may be present below this Sc mode can be attributed to some occurance of decoupling. In Figurex7 we see an example of a typical PDF of LCL obtained from a 100km sub-cloud leg (in red). We see a dominant mode at 1200m associated with the Sc. Two secondary modes are present below this at 750, and 950m. These are related to surface generated eddies, or cumulus convection reaching lower altitudes than the Sc. Here a manual split has determined the cut off between the two regimes. Integration of the area under these two curves then gives some assessment of the state of decoupling along the flight leg. An example of a well mixed mono-modal distribution in shown in blue for comparison.

7 Summary

MetUM captures the board features in the SEP BL such as general increase in Sc height away from the coast, and an increase in decoupling occurance. TMH and BLZ are generally lower than in observations, possible due to lower vertical resolution at the height of the inversion. There is a diurnal cycle in the thermodynamics of the boundary layer in both observations and the model output, and work is needed to understand this behaviour. The model appears to be out of phase with observations, possibly as a result of to high drizzle efficiency (a function of LWP) and aerosol number in the model.

8 References

Abel ***et. al.*** **2010** Evaluation of stratocumulus cloud prediction in the Met Office forecast model during VOCALS-Rex **ACPD 2010,** *16797-16835*
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O'Dell ***et. al.*** **2008** Cloud Liquid Water Path from Satellite-Based Passive Microwave Observations: A New Climatology over the Global Oceans **JC 2008** *1721-1739*
Rogers ***et. al.*** **1995** Diurnal Evolution of the Cloud-Toped Marine Boundary Layer,. Part 1. Nocturnal Stratocumulus Development **JAS 1995** *2953-2966*

9 Thanks

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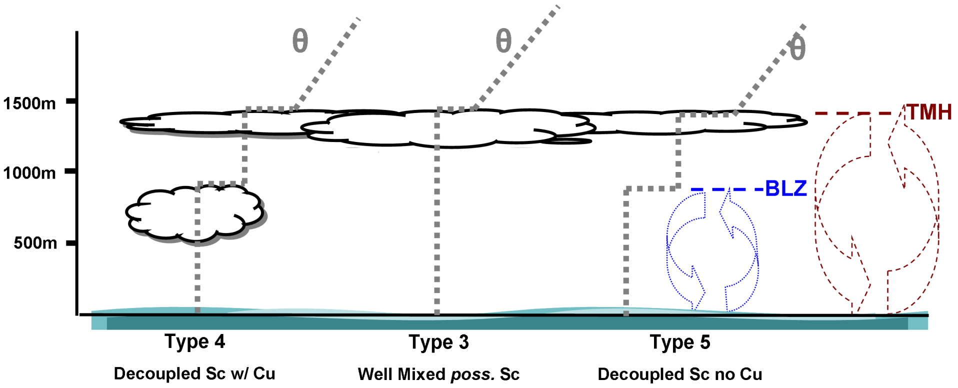
Dave Leon (University of Wyoming) for Wyoming Cloud RADAR and LIDAR data
Simon de Szoeke (Oregon State University) for Ron H. Brown radiosonde data.

Figures



After Lock. et. al. 2000

Figure 1 Lock 2000 Boundary Layer types important in the south eastern pacific

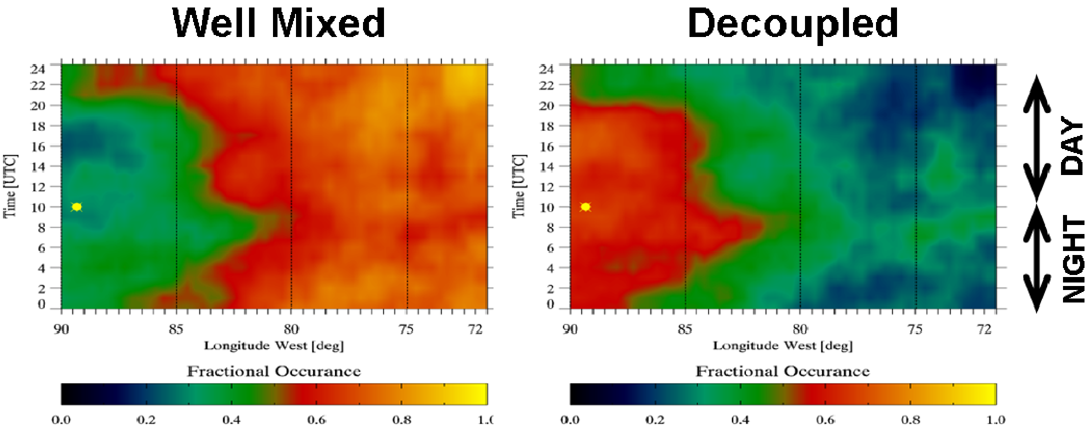


Figure 2 Diurnal cycle of composite of occurance BL types in MetUM along 20S

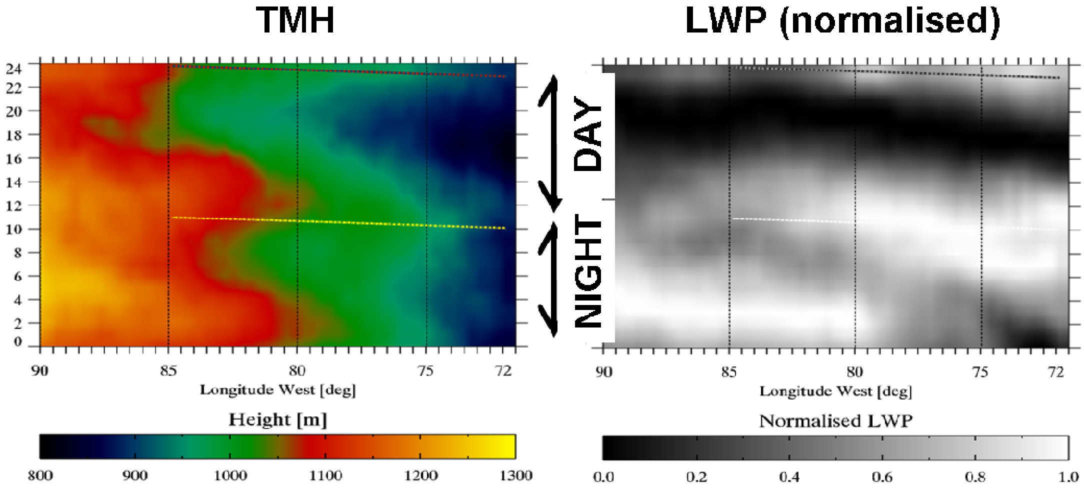


Figure 3 Diurnal cycle of composite of MetUM output of TMH and LWP along 20s

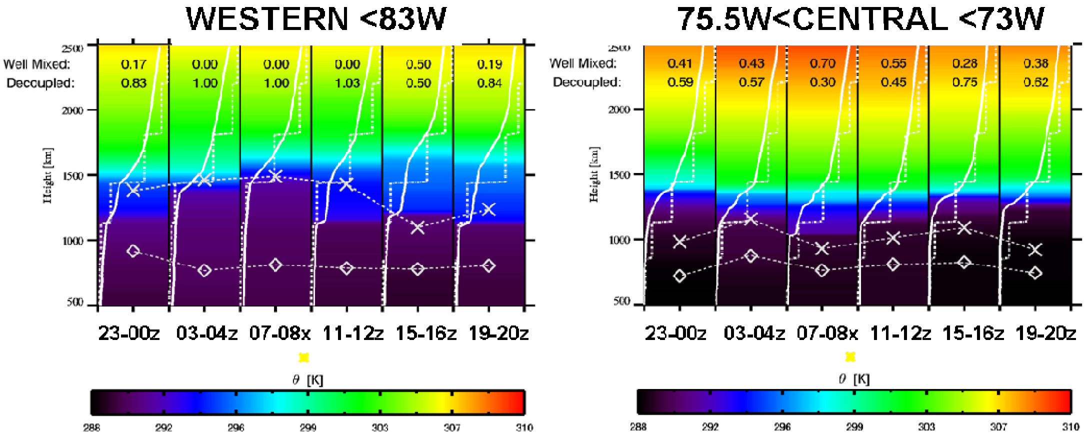


Figure 4 Comparison of thermodynamic structure of boundary layer from RHN radiosondes and MetUM

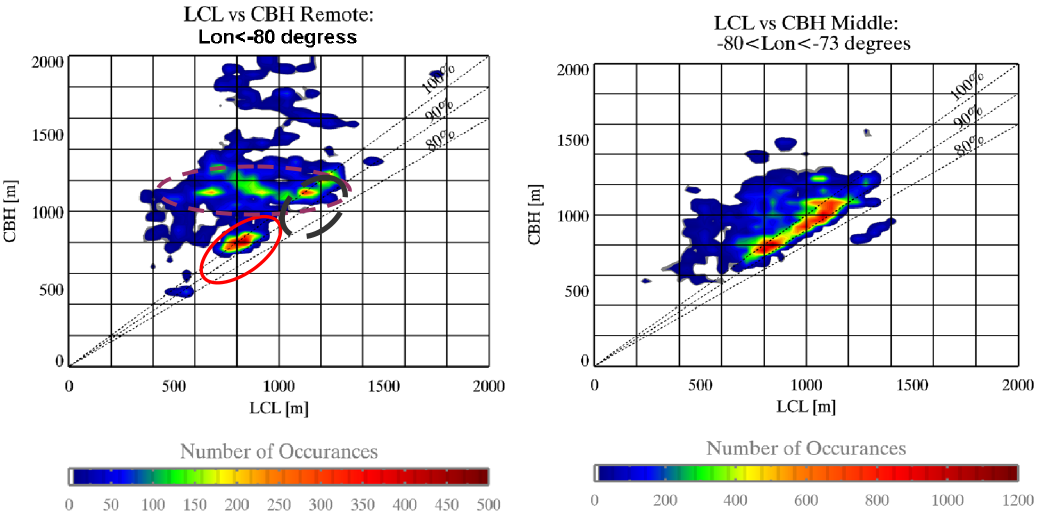


Figure 5 (after de Szoeke) LCL vs. CBH for two regions along 20S to look at occurance of decoupled boundary layers

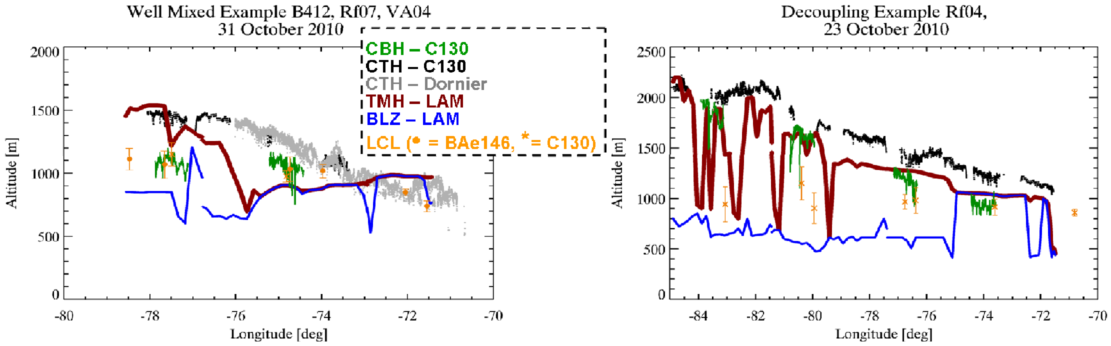


Figure 6 Aircraft cross sections of thermodynamic structure along 20S for a well mixed and decoupled case

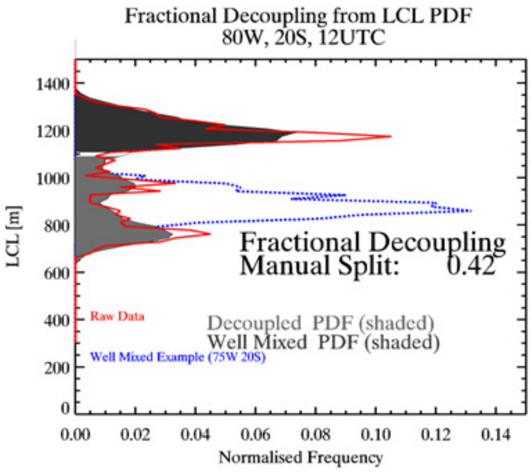


Figure 7 Profile of PDF of LCL for a 100km sub cloud leg in a decoupled boundary layer