In-cloud turbulence structure of marine stratocumulus

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[1] This study quantifies the level of turbulence inside the marine stratocumulus cloud deck over Pt. Reyes, CA, during the Marine Stratus Radiation, Aerosol, and Drizzle Experiment (MASRAD) in July 2005, and identifies the dominant sources of turbulent kinetic energy. We used vertical velocity data from a 3 mm wavelength (94-GHz) vertically pointing Doppler radar in combination with collocated radiosonde data. The results show that the stratocumulus observed at Pt. Reyes behaves differently from that expected on the basis of previous studies due to the modified marine environment that exists there. In particular, we found a decrease of turbulence levels with height within the cloud both during day and during night. The analysis highlights that for the conditions of our study longwave radiative cooling at cloud top was compensated by a number of mechanisms, resulting in the observed profiles. The production of turbulent kinetic energy is dominantly driven by wind shear. **Citation:** Ching, J., N. Riemer, M. Dunn, and M. Miller (2010), In-cloud turbulence structure of marine stratocumulus, *Geophys. Res. Lett.*, *37*, L21808, doi:10.1029/2010GL045033.

1. Introduction

[2] The life cycle and the structure of stratocumulus clouds are closely related to the in-cloud turbulence and its interactions with the surrounding environment [e.g., *Driedonks and Duynkerke*, 1989]. Previous observations found longwave radiative cooling at cloud top to be the dominant mechanism in generating turbulent kinetic energy [*Lilly*, 1968] either through the whole boundary layer [e.g., *Nicholls*, 1989], or within the cloud layer [*Frisch et al.*, 1995]. During the day time, shortwave warming from solar radiation approximately compensates cloud top cooling [*Slingo et al.*, 1982], inducing strong diurnal variations of turbulence in the stratocumulus. Other observational and modeling studies pointed out that rather than longwave cooling at the cloud top, shear could be the dominant mechanisms in generating turbulence [*Brost et al.*, 1982a, 1982b; *Moeng*, 1986]. The characteristics of the radiatively driven and shear driven boundary layer could be significantly different from each other.

[3] In recent years millimeter-wavelength radars have been successfully used to provide information about in-cloud motion by tracking the movement of cloud droplets [*Kollias and Albrecht*, 2000; *Kollias et al.*, 2007; *Babb and Verlinde*, 1999; *Albrecht et al.*, 1995]. Cloud radars have the advantage of providing vertically resolved data that are continuous in time, thus enabling the study of diurnal variation of cloud properties.

[4] In this paper we present a study of marine stratocumulus clouds at Pt. Reyes, CA, for July 2005 using data of vertical velocity obtained by a 3 mm vertically pointing cloud radar. The radar was deployed during the Marine Stratus Radiation, Aerosol and Drizzle Experiment (MASRAD), operated by the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Program. Compared to other studies, [e.g., *Frisch et al.*, 1995; *Albrecht et al.*, 1988] the cloud deck under investigation was thin, with cloud thicknesses ranging from 50 m to 350 m. This fact, combined with a low cloud base between nearly 0 m to 200 m above ground and strong wind shear made this a unique study of stratocumulus clouds. In Section 2 we outline the method for quantifying the spatial and temporal evolution of turbulence inside the marine stratocumulus cloud deck. In Section 3 we present the overall statistics for the month of July. For a specific day (July 5) we show the vertical profiles and diurnal variation of turbulence activity. Section 4 discusses the possible mechanisms that lead to the observed spatial and temporal development of turbulence kinetic energy within the cloud. We conclude our findings in Section 5.

2. Data and Methodology

[5] We used 3 mm-wavelength radar data from the whole month of July 2005, consisting of vertical velocity time series in cloudy air at various levels. The vertical velocity data have a temporal resolution of about 2 seconds, and a vertical resolution of 30 m. The uncertainty of the vertical velocity measurements is less than 5 cm s^{-1} [*Kollias and Albrecht*, 2000]. Radiosonde soundings, released four times daily at the same location as the cloud radar were also used in the analysis.

[6] We used the radiative model RRTM (Rapid Radiative Transfer Model) [*Mlawer et al.*, 1997; *Clough et al.*, 2005] to determine the magnitude of radiative cooling at the cloud top with the atmospheric profiles, cloud liquid water path (LWP) and effective radius (r_e) as model input. Measurements of LWP were made by the microwave radiometer profiler deployed by ARM. Representative values of r_e were taken from *Daum et al.* [2007], where r_e was determined by aircraft measurements as part of the Marine Stratus Experiment (MASE) campaign over Pt. Reyes.

[7] Similar to previous studies [*Frisch et al.*, 1995; *Kollias and Albrecht*, 2000; *Babb and Verlinde*, 1999; *Hignett*, 1991], we used the standard deviation of the vertical velocity to quantify the turbulence inside the cloud. We determined an appropriate averaging period, so that the turbulent scales are included, but the mesoscale scales are excluded, by calculating the power spectra of the vertical

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Table 1. Mean of σ_w, $\overline{\sigma}_w$, in m s^{-1} for July 2005 During Day and Night Separated Into Four Vertical Layers With Layer 1 Being the Lowest

	$\overline{\sigma}_w$ day	$\overline{\sigma}_w$ night
Layer 4	0.56 ± 0.30	0.56 ± 0.30
Layer 3	0.58 ± 0.26	0.59 ± 0.25
Layer 2	0.63 ± 0.21	0.62 ± 0.25
Layer 1	0.68 ± 0.23	0.62 ± 0.19

velocity time series. The results for various time series (day, night, various height levels) showed that 24 min is the time interval that separates the mesoscale and the turbulent scale. We therefore divided the vertical velocity time series in successive intervals of 24 min and calculated for each interval the mean, $\overline{w}$, the standard deviation, σ_w, and the skewness, S_w. These statistical quantities are functions of time and height. For our analysis we generally removed data whenever drizzle was reported (see auxiliary material for the details of this procedure).[1] For the day of our case study, July 5 2005, we selected a day without drizzle.

3. Results

3.1. Overview of Pt. Reyes Stratocumulus Clouds During July 2005

[8] During the month of July 2005, there were 21 cloudy days. Among those cloudy days, 12 days were reported to have drizzle, usually associated with thicker clouds. The cloud thickness showed a pronounced diurnal cycle being thickest (200–250 m) during the early morning (03:00–08:00 local time (LT)) and becoming gradually thinner during the day, with the cloud frequently dissipating in the afternoon.

[9] To investigate the vertical variation of σ_w during July 2005, we separated the cloud in four vertical compartments and calculated σ_w-averages, $\overline{\sigma}_w$, for each compartment separating day time and night time as shown in Table 1. For both day and night $\overline{\sigma}_w$ decreased with height although there was considerable variation, as can be seen by the large standard deviations for $\overline{\sigma}_w$.

[10] This is contrary to many previous studies on marine stratus, which showed a maximum of standard deviation close to the cloud top during the night due to longwave radiative cooling [e.g., *Nicholls*, 1984], and a characteristic diurnal cycle in the turbulence levels due to shortwave warming from solar radiation that reduced the turbulence at the cloud top by compensating the longwave cooling [*Frisch et al.*, 1995]. To investigate the reasons for our results in more detail we analyzed a specific day, July 5 2005.

3.2. Case Study for July 5 2005

[11] July 5 was chosen because of the persistent deck of stratocumulus without the occurrence of drizzle. Regarding the in-cloud motion it was a typical day for the month of July, i.e., the vertical profiles of σ_w on July 5 were comparable to the July averages. The wind direction was from the northwest. In Figure 1, the time-height cross-sections of σ_w (Figure 1, left) and S_w (Figure 1, right) show that the cloud formed at 22:00 LT on July 4, thickened during the morning of July 5 to about 250 m thickness at 10:00 LT, and dissipated during the afternoon, which is a typical cloud development during the month of July. At cloud top σ_w was consistently low with values of about 0.4 m s^{-1} compared to 0.7 m s^{-1} at the cloud base. The corresponding time-height sections of S_w were predominantly positive at cloud top indicating more intense and narrower updraft than downdraft in this region of the cloud.

[12] To quantitatively evaluate the evolution of turbulence levels with respect to time of the day and relative height, Figure 2 shows profiles of σ_w and S_w for the night (Figure 2, top), the morning (Figure 2, middle), and the afternoon (Figure 2, bottom). Figures 2 (top), 2 (middle), and 2 (bottom) each contains five profiles that together span a period of about 2 hours, displayed as function of relative height with respect to cloud base. The five profiles in each group were chosen so that the third one coincides in time with the soundings discussed later in this paper.

[13] Generally, σ_w decreased with height during both nighttime and daytime. The magnitude of σ_w decreased from night to morning for all the four layers of the cloud by about 0.2 m s^{-1}. From morning to afternoon, in the lower part of the cloud, σ_w stayed at the same magnitude of about 0.75 m s^{-1}, however in the upper part of the cloud, the magnitude increased by 0.2 m s^{-1}, leading to a decrease in the gradient of σ_w. The panels for S_w show that there were predominantly positive values throughout almost the whole cloud deck for both daytime and nighttime of about 0.3, except for some negative values in the bottom part of the cloud. The skewness profiles in the afternoon were more variable compared to the other two profiles.

4. Discussion

4.1. Radiative Cooling at Cloud Top

[14] Several previous studies on marine stratus found cloud top radiative cooling as the dominant mechanism to cause turbulent mixing in the cloud layer, especially during night time [*Frisch et al.*, 1995; *Hignett*, 1991]. In this case predominantly negative S_w as well as a maximum of σ_w are expected at cloud top. To estimate the magnitude of the cloud top radiative cooling for our case during the night (04:27 LT) and the afternoon (16:33 LT) we carried out RRTM model calculations as described in Section 2. The LWP is 50 g m^{-2} and 70 g m^{-2} for day and night, respectively, and the effective radius is estimated as 6 μm. The resulting net longwave radiative flux at the cloud top reached about 83 W m^{-2} during the day and about 69 W m^{-2} during the night, which is on the same order of magnitude as those given by *Slingo et al.* [1982] and *Ackerman et al.* [1995] for their studies on marine stratus. Hence, we conclude that longwave radiative cooling did take place. To reconcile this finding with the observed variation of σ_w, we conclude that there were mechanisms in place that compensated the negative buoyancy generated by cloud top radiative cooling.

4.2. Mechanisms Compensating Cloud Top Cooling

[15] The positive values of S_w (compare Figures 1 and 2) suggest that strong updraft motions occurred inside the cloud. The sources of energy for such updrafts are usually latent heat release above the lifting condensation level and sensible heat from the lower part of cloud and the surface.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL045033.

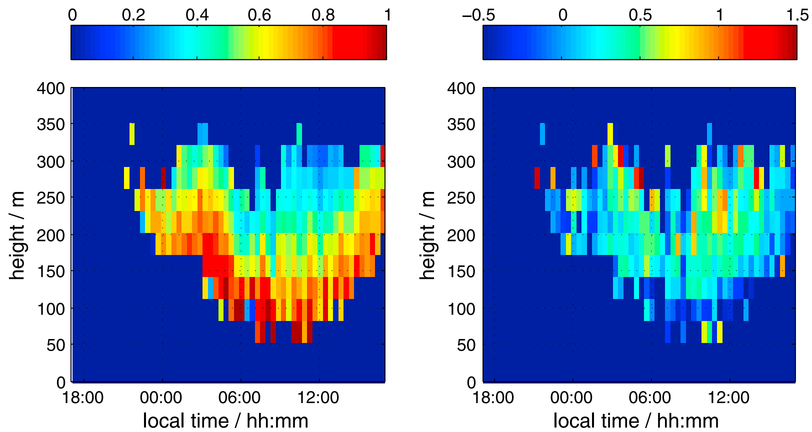

Figure 1. (left) Time-height plot of σ_w in cm s^{-1} for July 4th and 5th, 2005. The color scale is capped at 1 cm s^{-1} for better resolution. (right) Time-height plot of S_w for July 4th and 5th, 2005. The color scale is capped between −0.5 and 1.5 for better resolution. Vertical velocity measured by the 3 mm cloud radar.

Since the cloud deck was rather thin, it seems likely that the latent and sensible heat flux reached the cloud top. This explains why we did not find a spatial separation between the two sources of turbulence generation, the cooling at the cloud top and the latent heat and sensible heat warming from the bottom, which was for instance given by *Frisch et al.* [1995], but rather an overall compensation of cloud top cooling.

[16] In Figure 3 the radiosonde data show that above the top of the stratocumulus, in the temperature inversion layer, the mixing ratio of water vapor increased with height during both day and night. (Note that the atmospheric profile of the morning is not shown as the sounding was not guaranteed to pass through the cloud.) These local maxima of water vapor mixing ratio could be due to advection of moist air or due to detrainment of saturated cloudy air by in-cloud updraft into the cloud top. The latter is supported by the observed pos-

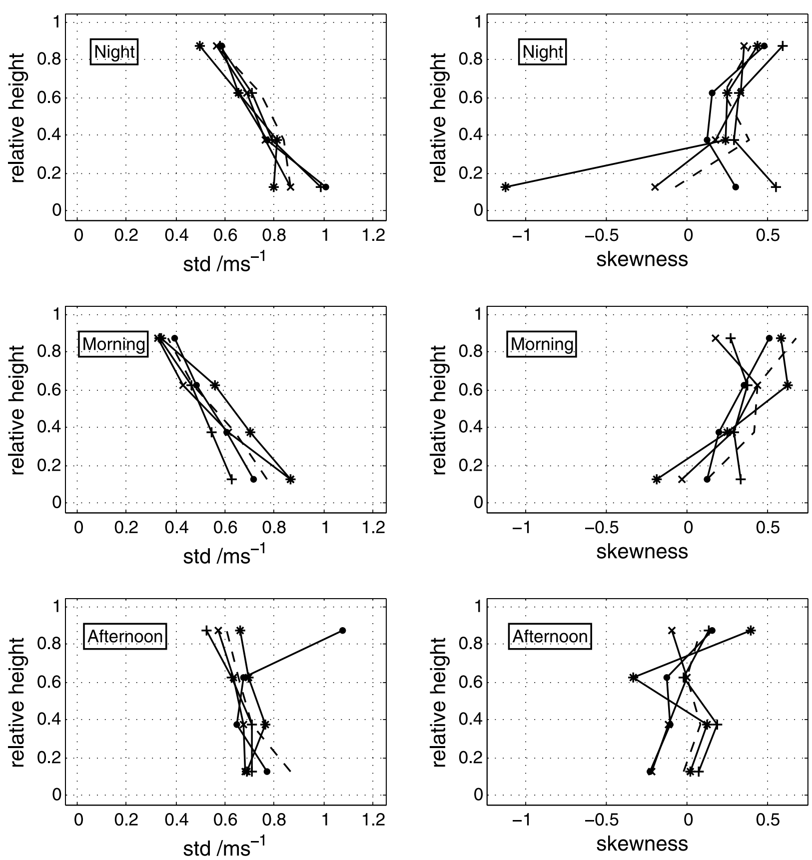

Figure 2. (left) Profiles of σ_w for 5 July, (top) night (03:24–05:24 LT), (middle) morning (09:24–11:24 LT) and (bottom) afternoon (15:24–17:24 LT). (right) Profiles of S_w for the same three periods of time. In each panel, the plus, dash, cross, dot and star represent the first to the fifth 24 min interval, respectively. Vertical velocity measured by the 3 mm cloud radar.

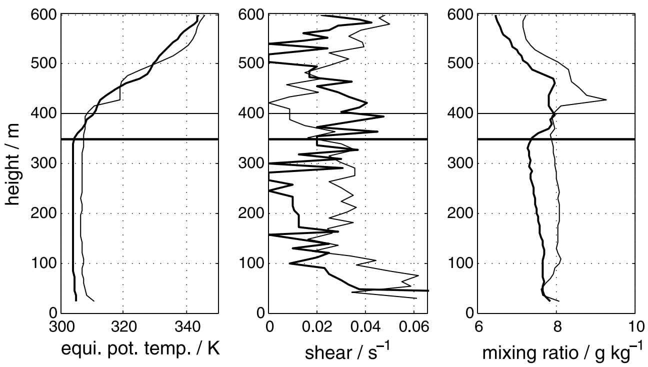

Figure 3. (left) Equivalent potential temperature. (middle) Wind shear. (right) Water vapor mixing ratio. Variables calculated are based on radiosonde data. The horizontal lines are cloud top heights from radiosondes for afternoon and night on 5 July. Thick: 5 July night; Thin: 5 July afternoon.

itive skewness at cloud top and is consistent with model simulations by *Sorooshian et al.* [2007] who found that, during MASE, a significant fraction of the aerosol mass concentration above cloud can be accounted for by evaporated droplet residual particles. Regardless of the causes of the moisture maximum, if this moist air is re-entrained, evaporative cooling at cloud top is limited.

[17] The wind shear calculated from radio sonde measurements at Pt. Reyes ranged from 0.01 to 0.04 s^{-1} (Figure 3). This is about a magnitude larger than the values given by *Frisch et al.* [1995], which ranged from 0.002 to 0.01 s^{-1}. The greater magnitude of wind shear is consistent with larger σ_w values compared to other studies [*Frisch et al.*, 1995]. The stronger wind shear inside the cloud and at the cloud top during both day and night has two effects. First, it generates turbulence and enhances entrainment of moist, warm air (compared to in-cloud air) at the cloud top. Second, with stronger turbulence, the latent heat and sensible heat is distributed more effectively from the bottom upwards and therefore compensates the cloud top radiative cooling.

4.3. Temporal Evolution of σ_w

[18] While σ_w decreases with height during both day and night, there are slight changes in the absolute magnitude of σ_w on July 5. During morning and afternoon, shortwave radiative warming from solar radiation contributes by compensating the longwave cooling at cloud top. This is consistent with overall smaller values of σ_w during the morning compared to the night as seen in Figure 2. In the afternoon, the gradient of the σ_w profile decreases, most likely due to increased wind shear (Figure 3), which promotes mixing in the in-cloud atmosphere. The overall small temporal variation in σ_w suggests that the in-cloud turbulence over Pt. Reyes is not dominantly radiatively driven, but rather by wind shear and by surface fluxes.

5. Conclusions

[19] Our analysis showed that for the marine stratocumulus at Pt. Reyes during July 2005 the standard deviation of vertical velocity, σ_w, decreased with height, both during day and during night, in contrast to other stratocumulus studies. This suggests that for the prevailing conditions the cloud top longwave cooling, while still present, was compensated by several simultaneously operating mechanisms. The cloud deck was on average only 200 m thick and close to the ground. These facts, in conjunction with the strong in-cloud wind shear, would enable effective transport of latent heat and sensible heat from the lower part of the cloud to the upper part, partly offsetting the radiative cooling at cloud top. Moreover, the air with a local maximum of water vapor mixing ratio above the cloud top did not cause much evaporative cooling when re-entrained. It may therefore have helped offsetting the radiative cooling at the cloud top even further. The cloud top cooling being compensated by these mechanisms thus did not produce strong turbulent motion at the top. Hence, the vertical profiles of σ_w for both day and night generally decreased with height and varied only slightly in magnitude. In contrast to the lack of diurnal cycles in the profiles of σ_w, the cloud thickness did show a pronounced diurnal cycle, which is most likely explained by daytime surface heating over land causing daytime entrainment.

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References

Ackerman, A., O. Toon, and P. Hobbs (1995), A model for particle microphysics, turbulent mixing, and radiative transfer in the stratocumulus-topped marine boundary layer and comparison with measurements, *J. Atmos. Sci.*, *52*, 1204–1236.
Albrecht, B., S. Randall, and S. Nicholls (1988), Observations of marine stratocumulus clouds during FIRE, *Bull. Am. Meteorol. Soc.*, *69*, 618–626.
Albrecht, B., C. Bretherton, D. Johnson, W. Schubert, and A. Frisch (1995), The Atlantic Stratocumulus Transition Experiment-ASTEX, *Bull. Am. Meteorol. Soc.*, *76*, 889–904.
Babb, D. M., and J. Verlinde (1999), Vertical velocity statistics in continental stratocumulus as measured by a 94GHz radar, *Geophys. Res. Lett.*, *26*, 1177–1180.
Brost, R., C. Wyngaard, and D. Lenschow (1982a), Marine stratocumulus layers. Part I: Mean conditions, *J. Atmos. Sci.*, *39*, 800–817.
Brost, R., C. Wyngaard, and D. Lenschow (1982b), Marine stratocumulus layers. Part II: Turbulence budgets, *J. Atmos. Sci.*, *39*, 818–836.
Clough, S., M. Shephard, E. Mlawer, J. Delamere, M. Iacono, S. B. K. Cady-Pereira, and P. Brown (2005), Atmospheric radiative transfer modeling: A summary of the AER codes, *J. Quant. Spectrosc. Radiat. Transfer*, *91*, 233–244.
Daum, P., Y. Liu, R. McGraw, Y. Lee, J. Wang, G. Senum, and M. Miller (2007), Microphysical properties of stratus/stratocumulus clouds during the 2005 marine stratus/stratocumulus experiment (MASE), *Rep. BNL-77935-2007-JA*, Brookhaven Natl. Lab., Upton, N. Y.
Driedonks, A., and P. Duynkerke (1989), Current problems in the stratocumulus-topped atmospheric boundary layer, *Boundary Layer Meteorol.*, *46*, 275–303.
Frisch, A., D. Lenschow, C. Fairall, W. Schubert, and J. Gibson (1995), Doppler radar measurements of turbulence in marine stratiform cloud during ASTEX, *J. Atmos. Sci.*, *52*, 2800–2808.
Hignett, P. (1991), Observations of diurnal variation in a cloud-capped marine boundary layer, *J. Atmos. Sci.*, *48*, 1474–1482.
Kollias, P., and B. Albrecht (2000), The turbulence structure in a continental stratocumulus cloud from millimeter-wavelength radar observations, *J. Atmos. Sci.*, *57*, 2417–2434.
Kollias, P., E. Clothiaux, M. Miller, B. Albrecht, G. Stephens, and T. Ackerman (2007), Millimeter-Wavelength radars new frontier in atmospheric cloud and precipitation research, *Bull. Am. Meteorol. Soc.*, *88*, 1608–1624.
Lilly, D. K. (1968), Models of cloud-topped mixed layers under a strong inversion, *Q. J. R. Meteorol. Soc.*, *94*, 292–309.
Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough (1997), Radiative transfer for inhomogeneous atmospheres: RRTM, a

validated correlated-k model for the longwave, *J. Geophys. Res.*, *102*, 16,663–16,682.
Moeng, C. (1986), Large-eddy simulation of a stratus-topped boundary layer. Part I: Structure and budgets, *J. Atmos. Sci.*, *43*, 2886–2900.
Nicholls, S. (1984), The dynamics of stratocumulus: aircraft observations and comparisons with a mixed layer model, *Q. J. R. Meteorol. Soc.*, *110*, 783–820.
Nicholls, S. (1989), The structure of radiatively driven convection in stratocumulus, *Q. J. R. Meteorol. Soc.*, *115*, 487–511.
Slingo, A., S. Nicholls, and J. Schmetz (1982), Aircraft observations of marine stratocumulus during JASIN, *Q. J. R. Meteorol. Soc.*, *108*, 833–856.
Sorooshian, A., M.-L. Lu, F. Brechtel, H. Jonsson, G. Feingold, R. Flagan, and J. Seinfeld (2007), On the source of organic acid aerosol layers above clouds, *Environ. Sci. Technol.*, *41*, 4647–4654.

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