Drizzle Evaporation in the Stratocumulus-Topped Boundary Layer and its Relationship with Sub-Cloud Turbulence

by

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Abstract

A prominent cloud structure that exists over the Atlantic is the marine stratocumulus (Sc) cloud, which affects the Earth's radiation budget due to their varying albedo – therefore it is important to understand the turbulent fluxes of energy and moisture that regulate these cloud properties. Previous experiments have shown that drizzle is an important factor in modulating cloud structure, but no long-term experiments have been conducted in the past. The Atmospheric Radiation Management's (ARM) Eastern North Atlantic (ENA) site has provided observations in the summers of 2016 and 2017 to understand the effect that drizzle has on these clouds. Observations have revealed that, on average, the presence of drizzle seems to decrease the TKE profile. Further separating the daytime and nighttime averages reveals that during daytime, TKE seems to decrease with the intensity of drizzle. The nighttime average is more complicated, with light drizzle increasing the TKE profile and heavier drizzle having varying effects on the TKE profile. Further measurements and observations are required to understand better the effect of drizzle on Sc regimes.

1. Introduction

The Atlantic Ocean covers approximately 20% of the Earth's surface, and the atmosphere above is home to a complex array of clouds. A prominent cloud structure that exists over the Atlantic is the marine stratocumulus (Sc) cloud, favored in subsiding regions of mid-latitude baroclinic systems (such as the downward branches of large-scale circulations; i.e. Hadley or Walker circulations). Coverage of marine Sc over midlatitude oceans can be 25%-40%. (Wood 2012; Figure 1a), and they constitute a large fraction of all low-clouds (Figure 1b), which makes them extremely important in both Numerical Weather Prediction (NWP) and climate modeling. The Earth's radiation budget and hydrologic cycle are also affected by marine Sc through subtle pathways that include cloud-scale process interactions that are not well understood. One such interaction involves the interplay between evaporating precipitation and the turbulent transport of moisture into marine Sc cloud layers, which is one theme of this thesis.

Atmospheric models of all varieties must represent clouds. Other than the highest resolution models, which are known as large eddy simulations, clouds occur on spatial and temporal scales that are not explicitly resolved in most models and are often referred to as a "sub-grid-scale" phenomena. Accordingly, their impacts must be captured using formulations called parameterizations, which are equations designed to represent the net effects of clouds without the necessity of representing each cloud or cloud layer individually. General Circulation Models (GCMs) and NWP models represent boundary-layer clouds by multiple interacting parameterizations. Some examples of these parameterizations include representations of turbulent mixing in the boundary layer, shallow moist convection, cloud and precipitation microphysics, and radiation.

Many GCMs and Reanalysis Products (RPs) fail to accurately reproduce observed marine stratocumulus and trade wind cumulus properties. This is a critical shortcoming because, as noted previously, marine Sc clouds play a prominent role in the climate system, and more specifically, the radiation budget. For example, they have a large effect on incoming solar radiation, as characterized by their high albedo, but a minimal effect on outgoing longwave radiation. Hence, radiation from the Earth’s surface is readily lost to space at the top of a layer of marine Sc and, since little compensating solar radiation is received due reflection, marine Sc typically have a strong negative net radiation flux. Globally, they act to cool the Earth’s surface.

The delicate mix of processes that serve to create and maintain marine Sc clouds over long periods of time and over vast areas of ocean are thus an important driver of global climate. Of particular importance is the nature of the vertical turbulent fluxes of energy and moisture that regulate stratocumulus cloud properties, and accordingly, the representation of these fluxes in models.

A wealth of valuable research has been conducted on marine Sc clouds over the past thirty to forty years, mostly driven by the need to understand potential changes in this sensitive cloud system in a changing climate. Particularly potent research results were gleaned from a series of experiments in the early 1990’s. One experiment in this collection was the Atlantic Stratocumulus Transition Experiment (ASTEX), which was conducted over the northeastern Atlantic Ocean during June 1992 (Albrecht et al., 1995). The scientific goal of ASTEX was to determine the mix of processes that lead to the evolution of vast, solid sheets of marine Sc in the mid-latitudes into broken cloud elements, known as trade cumulus, toward the tropics. The experiment produced an unprecedented data set that was used to better understand the formation, maintenance, and dissipation of marine stratocumulus clouds, and to improve the cloud parameterizations in various models.

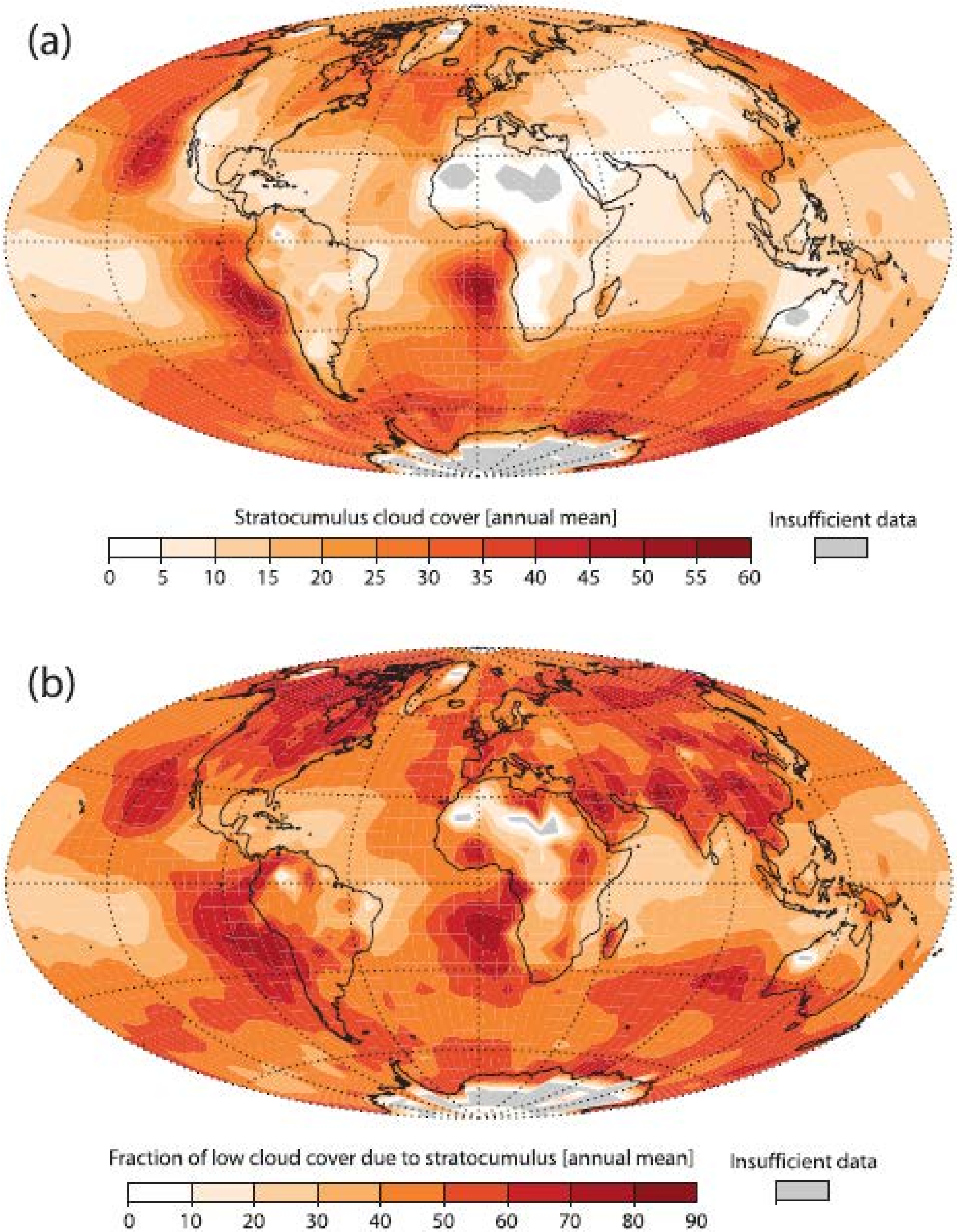

Figure 1: (a) Annual mean coverage of stratocumulus clouds. (b) Fraction of annual mean low-cloud cover associated with stratocumulus (Wood et al,, 2012)

Prior to ASTEX it was known that marine Sc undergo a diurnal metamorphosis driven by the radiative balance at cloud top (Nicholls, 1984, Hignett et al., 1992). Because these clouds are driven from the top down by radiative cooling at cloud top, any reduction in this cooling can lead to a disconnection between the ocean surface moisture source and the cloud layer. This disconnection, termed "decoupling", was shown to occur as a result of the offset of cloud-top radiative cooling by solar heating at cloud top during the day. The resulting decoupling caused the marine Sc to thin or even dissipate during the daytime. A new, fundamental understanding derived from ASTEX was that drizzle evaporation in the subcloud layer could also lead to decoupling (i.e. the process in which the boundary layer is not homogeneously mixed anymore, described in further detail at the end of this section) and cloud transitions.

Drizzle is a widespread feature of the marine stratocumulus cloud systems, particularly at night (Figure 2a,b; Leon et al., 2008). A plethora of scientific questions persists regarding the exact physics that lead to drizzle formation in marine Sc, and its impacts once it forms. Marine Sc are inherently thin clouds having limited vertical extent and possessing smaller amounts of total liquid water than clouds that exhibit significant vertical extent, such that drizzle can easily deplete cloud liquid water in the absence of continuous resupply of water vapor from the ocean surface below and cloud droplet formation. Measurements from ASTEX analyzed by Gerber (1996) were used to investigate the drizzle process by examining interdependencies between the cloud droplet size distribution and other microphyscial variables such as the "effective" cloud droplet radius, r_e, which governs cloud reflectivity, the profile of cloud liquid water content (LWC), droplet spectral broadening, the horizontal variability of LWC near cloud top, and the occurrence of heavy drizzle. A notable finding of this study was the presence of two distinct drizzle modes: 85% of the marine

Sc had a LWC of droplets less than 0.01 g m^{-3}, while the rest had a LWC much larger than 0.01 g m^{-3}. Gerber (1996) concluded that marine Sc over the northeastern Atlantic produced predominantly light drizzle, which was similar in quantity to other marine Sc regions, and approached "classical" behavior since the measured and adiabatic profiles of LWC were similar.

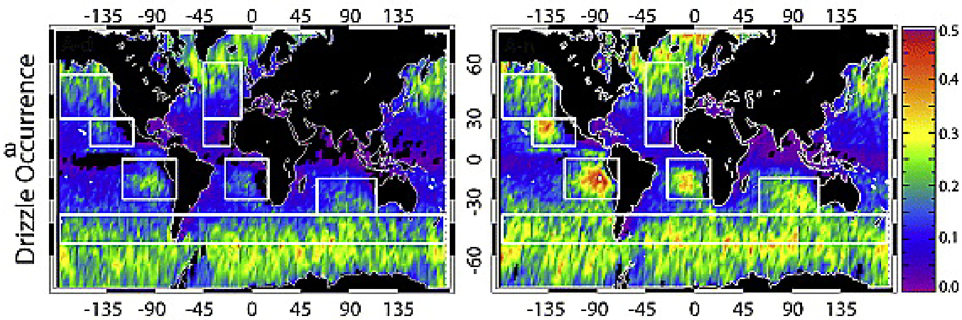

Figure 2: Drizzle occurrence in the major stratocumulus regions for (a) daytime and (b) nighttime (Leon et al., 2008)

Modeling studies have been designed to investigate the potential role of drizzle in shaping the macroscale marine Sc cloud configuration. It has long been known that the marine Sc cloud system exhibits mesoscale variability and two predominant modes have been identified (Agee et al., 1973): open and closed cellular convection. These two structures are characterized by cells that resemble hexagons but differ in their internal circulation geometry. Open cellular convection is characterized by clear center with a cloud band surrounding the periphery and closed cellular convection being exactly the opposite. Wang and Feingold (2009) used the three-dimensional Advanced Research WRF (ARW) model to show that drizzle plays a critical role in the formation and evolution of open cells in marine Sc clouds. Their study implies that there is a strong connection between drizzle occurrence and the macroscale cloud configuration, which has important consequences for the radiation budget in marine Sc regions. It also amplifies the importance of drizzle as one primary modulator of cloud structure. However, there has been very limited research on the role of drizzle in the marine boundary layer and the general applicability of the Wang and Feingold (2009) findings are unknown. A major research limitation has, until recently, been the lack of relevant observations from which to validate model results.

Recognizing the need for statistically significant observations of marine Sc and the processes that operate therein, the United States Department of Energy (DOE) conducted the Cloud, Aerosol, and Precipitation in the Marine Boundary Layer (CAP-MBL) in 2009-2010 (Wood et al., 2015) from the northern shore of Graciosa Island in the Azores archipelago, west of Portugal. Leveraging the success of CAP-MBL, the DOE's Atmospheric Radiation Measurement (ARM) program installed a permanent Eastern North Atlantic (ENA) Climate Research Facility on Graciosa in 2014. This ENA site, which includes a substantially upgraded instrument package from that used during CAP-MBL is providing an unparalleled data set from which to conduct process-level investigations of the marine Sc over the northeastern Atlantic Ocean. It is rare to find a marine stratocumulus dataset that has a sufficient duration to be used in research. This site, which has been measuring different variables using a state-of-the-art surface-based measurement system, is the origin of the dataset that will be employed in this project.

It can be seen in observations that most marine boundary layer clouds produce drizzle. In many cases, the drizzle evaporates before it reaches the ocean surface, as it falls through the subcloud layer. In other cases, it reaches the ocean surface, so liquid water is thus removed from the system. One hypothesis is that evaporation of drizzle stabilizes the subcloud layer and leads to decoupling, which discourages turbulent eddies from transporting water vapor from the ocean surface into the cloud layer, as previously noted. This attenuated vapor transport could thin the overlying clouds, or possibly affect cellular convection in the marine boundary layer. Multiple Large Eddy Simulations have suggested that this drizzle-induced decoupling is an important feedback mechanism in the marine boundary layer, but there are limited observations to support these findings.

Transport of water vapor in the boundary layer is a consequence of turbulent motions. These motions are rather uniform through the depth of the well-mixed boundary layer, but exhibit vertical gradients when it is decoupled. Signatures of decoupling include minor gradients in the thermodynamic and water vapor profiles and gradients in the profile of Turbulent Kinetic Energy (TKE). Thermodynamic and water vapor profiles are available from radiosonde ascents, but these occur periodically on the scale of hours. Profiles of vertical velocity in the subcloud layer are available every second from Doppler Lidar (DL), enabling diagnoses of decoupling every one-half hour. In the summer of 2017, data collected at the ENA site included DL profiles, from which TKE profiles were computed. Availability of continuous TKE profiles is a new and unique element in marine stratocumulus research. While ASTEX collected important data via aircraft in the 1990s, these new instruments enable detailed analysis of the physical properties of marine Sc clouds and the marine boundary layer.

In this thesis, we examine the relationship between evaporating drizzle beneath single-layer marine stratocumulus clouds and ocean surface vapor coupling, in both broken and unbroken marine stratocumulus. Vertical moisture will be measured throughout the sub-cloud layer using radiosonde profiles. A DL will be used to compute TKE profiles with half-hour resolution during drizzling and non-drizzling periods.

2. Instruments and Methods

I. Site Location

As mentioned above, the Eastern North Atlantic (ENA) atmospheric observatory islocated on the northern shore of the Graciosa Island in the Azores archipelago. The Azores are located in the northeastern Atlantic Ocean west of Portugal. ENA is the newest permanent measurement site established by the ARM Climate Research Facility. This site was chosen for a variety of reasons, but most importantly it is located within a major stratocumulus belt and is positioned in an area where the International Satellite Cloud Climatology Project (ISCPP; Figure 3) and the associated Earth Radiation Budget Experiment (ERBE), along with other satellite studies, have shown a multitude of different boundary layer cloud structures, a large fractional coverage of stratocumulus, and a significant net radiative cloud forcing. The ENA site is also located on a sharp cloud-coverage boundary often referred to as a stratocumulus transition region because individual cumulus elements are found just to the south of the Azores.

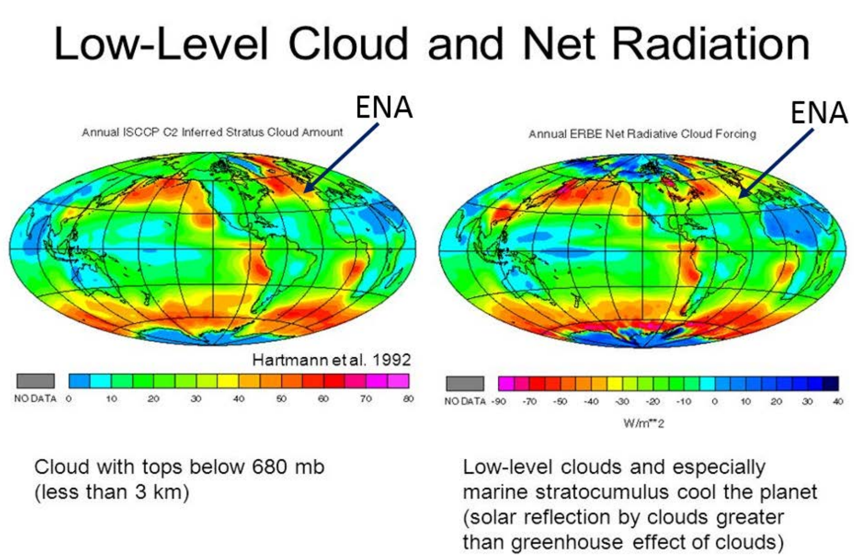

Figure 3: (a) Frequency of cloud-tops below 680 mb and (b) net radiation impact on the earth. Graphic by D. Hartmann and M. Michelsen, University of Washington.

The location was also chosen because two previous field deployments in the region, ASTEX and CAP-MBL, provide additional information about the cloud structures that exist there. Logistics was another important consideration in that Graciosa Island has an airport and a seaport, which are necessary for transporting large systems and scientists to and from the island.

Figure 4: The location of the ENA site in the North Atlantic Ocean, a high-frequency region for Sc clouds

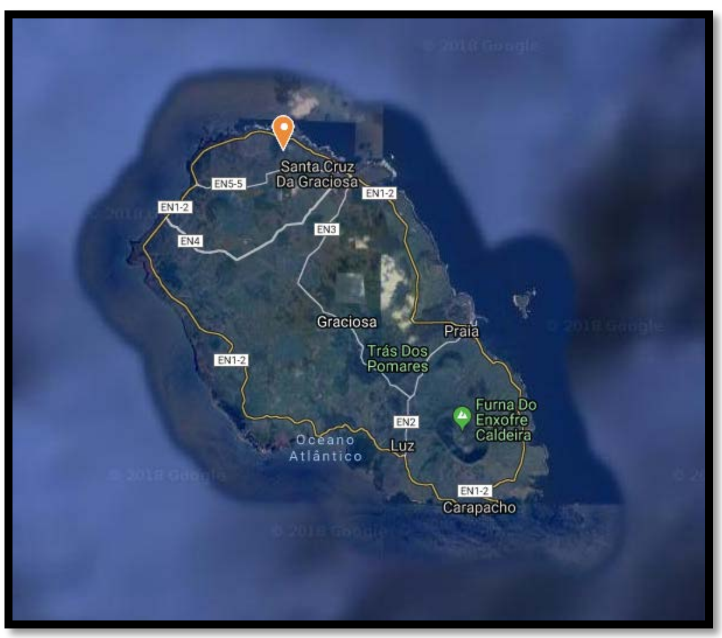

Figure 5: A map of Graciosa Island, showing the ENA site on the northern shore.

II. Instrument Descriptions

The DL is a pulsed active sensor with a temporal resolution of about one second and range resolution of 30 m, with a minimum range of less than 100 m (typically 75 m) and a maximum range of 9600 m. The DL operates in the near-IR at a wavelength of 1.5 μm making it sensitive to atmospheric aerosols that move with the wind. Using its Doppler capabilities, it measures wind velocities under clear-sky and lightly precipitating conditions. The DL is able to scan the horizon, but the data analyzed in this thesis were measured exclusively when the DL was pointed towards the zenith. This zenith orientation makes these data ideal for providing the height- and time-resolved measurements of vertical velocities requited to compute TKE. Once the laser pulse reaches the optical cloud base, which is defined as the initial region in which cloud droplet sized particles have sufficient number density to disperse the laser pulse, it cannot penetrate the cloud. However, the range at which the return from the transmitted pulse is no longer detectable represents the cloud base height and the top of the subcloud layer. Knowledge of the cloud base height is required to provide a means to normalize all profiles collected by the DL, as will be discussed in the section that follows.

A means to detect the presence of drizzle in the subcloud layer is also required and a Ka-band Zenith-pointing Radar (KAZR) is used for this purpose. The KAZR and other radars that operate with wavelengths less that approximately 8.5 mm are known collectively as "cloud radars" because their short wavelength enables them to be extremely sensitive to cloud and drizzle-sized droplets (4-300 μm), but less useful when rainfall becomes moderate and droplet sizes approach 1000 μm. The KAZR used in this study operates at a frequency of 35 GHz and possesses a range resolution of 30 m through a maximum range of up to 20 km. One limitation of all cloud radars, particularly those operating at a frequency greater than 35 GHz is that the transmitted signal suffers significant absorption by oxygen and water vapor molecules along the beam trajectory. A unique aspect of this site is the fact that the KAZR provides vertical profiles of clouds by measuring the first three Doppler moments: reflectivity, radial Doppler velocity, and spectra width (this information is available in the ENA Radar Handbook).

The focus of the DL and KAZR data collected at ENA is marine boundary layer clouds. Thus, it is essential to minimize any influences on the data that might be a result of the location of the instruments on an island, even though the site is located directly adjacent the shoreline. Previous studies (Miller et al., 1995) have shown that it is possible to minimize the development of an island-generated internal boundary layer above the island surface by conditionally sampling according to a range of wind directions that represent a minimum acceptable fetch across the island surface. Winds in that study and in this study were analyzed using surface wind data from the ENA site and data from a 1236 MHz wind profiler. A range of 75º degrees either side of north were deemed to be acceptable as the fetch ranged from less than 200 m to ~500 m. Studies of the turbulent structure over the site have shown that the lower 50% of the boundary layer is subject to the turbulence enhancement due to the impacts of island surface heating during the daytime when cloud cover is 50% or less, but increasingly less influence as the cloud coverage increases to a complete overcast. Nighttime influences were found to impact only the lowest 10% of the turbulence profile over the site. Drizzling stratocumulus clouds represent complete overcast, which reduces solar heating at the island surface, and are demonstrably devoid of island effects on the turbulence profile above the lowest 10% of the turbulence profile over the site.

III. Analysis Techniques

The variable of interest in this study is the TKE. To calculate the TKE, the DL is used to measure the vertical velocity profile in the sub-cloud layer every second. Although TKE (e), is a three-dimensional field, we can relate the variance of vertical velocity, w', to e, by assuming that $\overline{w'^2} = k_f e$, where $k_f = 0.5$, and the overbar represents a half-hour average. By doing this, we are assuming the turbulence is isotropic (i.e. where velocity fluctuations are invariant to axis rotation and reflection). We then calculate e by computing the average w at each height for a period of 30 minutes, and then subtracting this average from each individual measurement of w to find w'. A specific TKE profile can be formed by calculating TKE at each DL range using $e = 0.5\,\overline{w'^2}$.

Marine boundary layer depth varies from hour to hour and from day to day, due to changing synoptic conditions and the radiative effects of solar heating upon entrainment at cloud top. Hence, it is necessary to normalize the sub-cloud TKE profiles to remove this variability such that all sub-cloud depths are reported as a fraction of the distance to the optical cloud base, as measured by the DL. This normalization relationship is given by

$$\eta(z) = 1 - \frac{z_{base} - z}{z_{base}}, \text{ where } 0 < \eta(z) < 1,$$

and it prescribes that the normalized depth be unity at cloud base and zero at the surface. All TKE profiles originating from acceptable wind directions were normalized using this procedure.

The goal of this study is to characterize changes in the TKE profile that are the result of evaporating drizzle, whereupon is necessary to characterize the intensity of sub-cloud layer drizzle. This particular aspect of the sub-cloud structure is difficult to quantify in an absolute sense, but can be characterized by the depth through which drizzle is detected below the optical cloud base. Visually, drizzle evaporating in the sub-cloud layer resembles virga, which is a term used to describe evaporating raindrops that are much larger and fall much faster than drizzle in decidedly deeper layers of the atmosphere.

Given that the sub-cloud evaporation is the root process, the length that drizzle falls before evaporating in the marine boundary layer has been recently referred to as the Drizzle Virga Depth

(DVD) and used as a surrogate for drizzle intensity: the greater the DVD, the greater the drizzle intensity is assumed to be. Radar analysis of drizzle events in the marine boundary layer has shown them to be quite variable during a half-hour period and not well characterized by an averaged, normalized DVD. The average geometric DVD better represents drizzle intensity and is used here. Given the average marine boundary layer depth at ENA of ~1100 m, subjective analysis of radar and DL data shows that DVD of at least 100 m may be classified as light, evaporating drizzle while DVD's which extend lower in the sub-cloud layer, to at most 250 m, may be classified as heavy, evaporating drizzle. When the DVD is greater than 250 m, there is a high probability that the sub-cloud drizzle will reach the surface before completely evaporating, which creates a partitioning complication, and is excluded in this study.

IV. Case Selection

Hourly data were examined from the summers of 2016 and 2017 (June-August) and cases were selected based on the conditions above: wind direction (to minimize island effect) and presence of marine stratocumulus clouds and drizzle. A computer code ran through each hour of the summer months mentioned above, collecting data on these factors.

As previously mentioned, we wanted to minimize an island effect on our data to keep the focus of the DL and KAZR data collected at ENA on the marine boundary layer. Since the ENA Climate Research Facility is located on the north side of the island, a range of 75º degrees either side of north was deemed acceptable as the fetch ranged from less than 200 m to ~500 m. This range was used to determine days where flow from the island was likely minimized, and all winds were coming from over the ocean. Thus, it is assumed that the TKE profiles analyzed in this thesis are relatively free from land influences, but some influence in the lowest levels cannot be dismissed.

Cloud structure was also examined determine cloud type. Marine cloud structure in the vicinity of the Azores is extremely complicated, featuring a mix of single-layer and multiple layer clouds, individual cumulus elements, and mixtures of all cloud types. To simplify our analysis, we restricted the case selection to include only single layer stratocumulus, broken or solid, with varying amounts of subcloud drizzle as determined by the KAZR and DL daily images. A condition code with parameters was used to ensure that the observations in this study came from marine stratocumulus clouds. The ceiling cloud fraction had to be greater than 75% to ensure that there was a sufficient amount of cloud to have an impact on TKE. The ceiling base height must have also been between 100 and 500 meters, with a mean height greater than 300 meters. This was enough in the code to trigger a “stratocumulus flag.”

To assess the drizzling status, the KAZR was used to assess the DVD. If the DVD was between 100 and 250 meters, this was considered “light drizzle.” If the DVD was greater than 250 meters, this was considered “heavy drizzle.”

3. Results

Vertically oriented turbulence, which is quantified using TKE, transports scalar variables, such as water vapor, upward and downward in the marine boundary layer. If the TKE profile is constant with height, the implication is that mechanical mixing is uniform from one layer to the next and that the turbulent transport is uniform. If, on the other hand, there is a minimum in the TKE profile, this minimum acts as a mechanical bottleneck and, in a sense, regulator of turbulent transport. Minima in the TKE profile in the marine boundary layer are indicative of a "decoupling" across the depth of the sub-cloud layer in which regions above and below the TKE minimum are partially separated, from an energetic standpoint, and may evolve independently.

To diagnose the impact of drizzle on all single-layer stratocumulus cases analyzed, specific TKE profiles as a function of normalized sub-cloud depth are plotted for nighttime and daytime stratocumulus and the three different drizzle modes: no drizzle, light drizzle, and heavy drizzle. Evidently, light drizzle is associated with slightly elevated TKE in the sub-cloud layer. The profile shape in light drizzle is not radically altered and the "degree of decoupling", (quantified by the difference in TKE between the mid-layer TKE minimum and the surrounding maxima), is not significantly different, though the minimum is observed to be slightly higher in the sub-cloud layer. In the light drizzle mode, TKE seems to slightly decrease close to the cloud top, but then starts to increase slightly about one-third of the sub-cloud layer below the cloud base. The clearest impact on the sub-cloud layer occurs when there is heavy drizzle. In this case, specific TKE substantially decreases through the entire profile, with the exception of the lowest portion of the mixed layer.

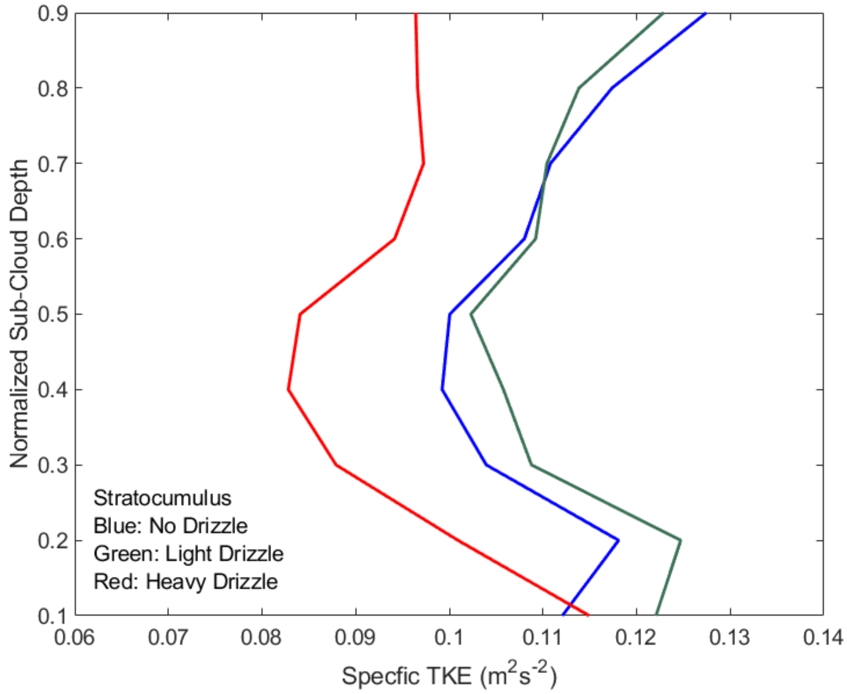

*Figure 6: Average specific TKE profiles (m**2 s**-2) under a normalized sub-cloud depth for three different drizzle modes. The blue line indicates no drizzle, the green line indicates light drizzle, and the red line indicates heavy drizzle.*

Consistent with theory is that there is a maximum of TKE at the cloud top when there is no drizzle and a positive TKE gradients is observed in the upper 50% of the sub-cloud layer (Figure 6). The top of the sub-cloud layer is influenced by negative buoyancy due to net longwave cooling, and this negative buoyancy acts as a destabilizing mechanism. When drizzle is added to the mix, the evaporative cooling of this drizzle evidently becomes a sink for TKE and slightly reduces the positive gradient associated with TKE generation at cloud top. As the drizzle intensity and DVD increase, a profound change in the TKE profile is observed in the upper 40% of the sub-cloud layer. The typical positive gradient associated with TKE production at the top of the cloud layer that stretches into the sub-cloud layer is no longer observed. Heavy drizzle appears to completely offset this production and significantly reduce the specific TKE beneath cloud base. The effect on the sub-cloud fluxes is not clear from this analysis because it is possible that the scalar thermodynamic gradients are altered by the heavy drizzle.

Radiative changes in the cloud structure in single-layer stratocumulus are known to modulate the production of TKE at cloud top through the diurnal cycle. Further understanding this relationship between drizzle and TKE can be done through separating nighttime and daytime situations. Figures 7 and 8 show the same variables, except for daytime and nighttime only, respectively. In Figure 7, it is clear that during the daytime, the presence of drizzle seems to decrease the TKE throughout the entire layer. The heavier the drizzle is, the larger the DVD, and the more that evaporative cooling will occur, thus giving a larger decrease in TKE. At the surface, however, there is very little difference between light drizzle and no drizzle, which could be a result of an island effect.

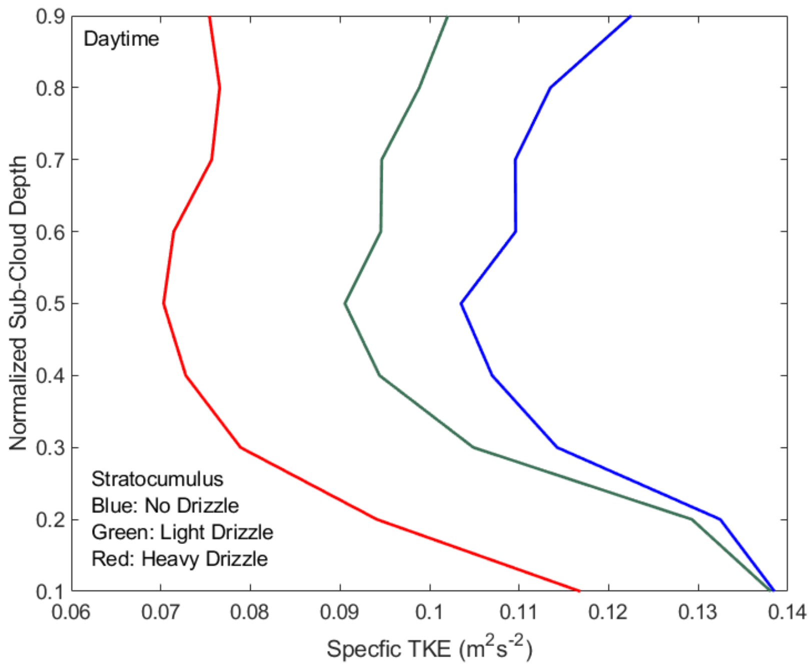

*Figure 7: Average specific TKE profiles (m**2 s**-2) under a normalized sub-cloud depth for three different drizzle modes, as in Figure 6. Daytime conditions only.*

Figure 8 is the same as Figure 7, except in the nighttime. Throughout the sub-cloud layer, light drizzle at night seems to increase the TKE. However, the presence of heavy drizzle at night does not change the TKE in a uniform way throughout the sub-cloud layer. Near the top of the sub cloud layer, heavy drizzle seems to decrease TKE. However, further down the sub-cloud layer, both heavy and light drizzle then seems to increase TKE. Then, from about 20% to 50% below the sub-cloud layer, heavy drizzle has minimal effect on TKE. The bottom tenth of the sub-cloud layer seems to increase in TKE in the presence of heavy drizzle. Clear differences between the three drizzle modes can be seen in Figure 9, where the results are separated by the different types of drizzle, rather than time of day.

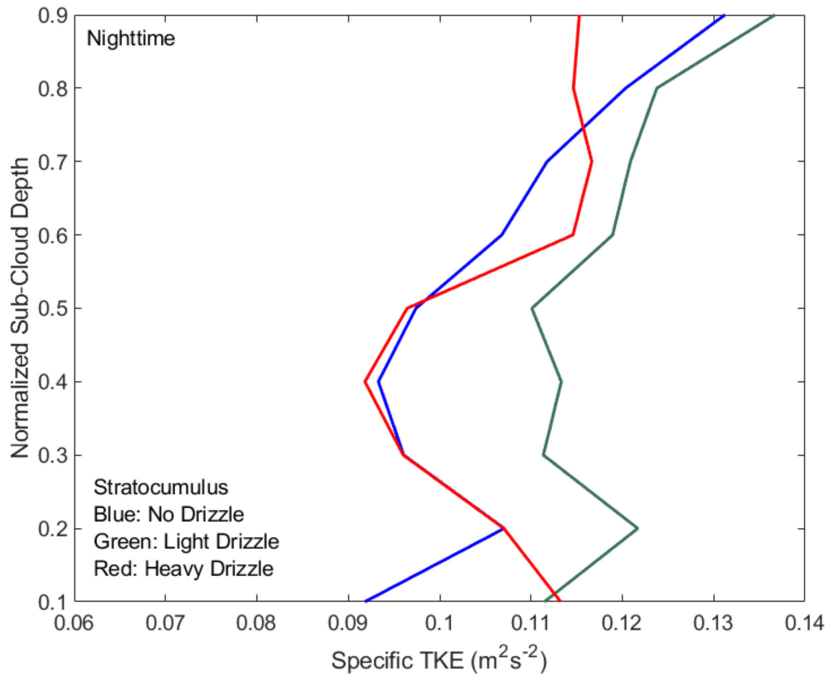

Figure 8: As in Figure 7, but nighttime conditions only.

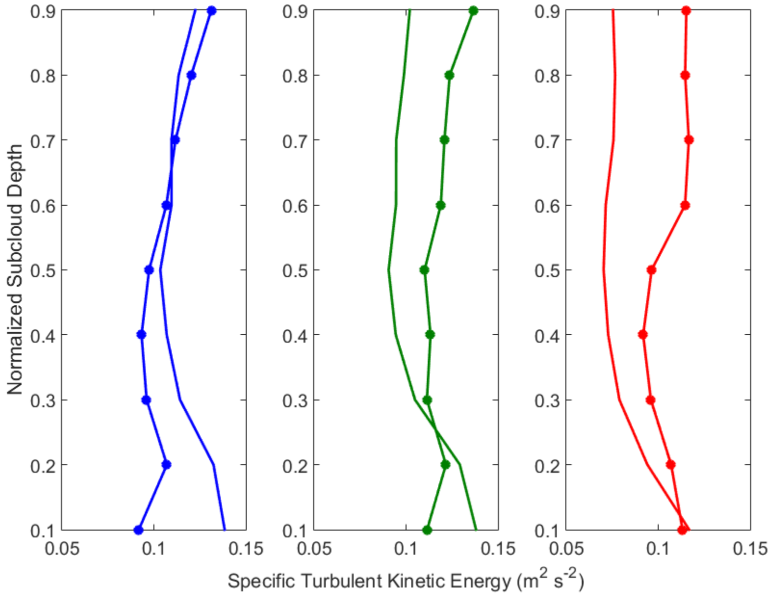

Figure 9: The difference in specific TKE in the sub-cloud layer of marine stratocumulus clouds between daytime (solid line) and nighttime (solid line with circles) for (a) no drizzle, blue (b) light drizzle, green, and (c) heavy drizzle, red).

4. Conclusion

Marine Sc are extremely important in both NWP medium-range models and climate modeling. Their varying albedo (between thin and thick stratocumulus decks) affects Earth's radiation budget, but many GCMs and RPs fail to accurately reproduce this. The vertical turbulent fluxes of energy and moisture regulate stratocumulus cloud properties, and these fluxes need to be better understood and represented in climate models. Most marine boundary layer clouds produce drizzle, and when this drizzle evaporates before it reaches the ocean surface, previous modeling studies and a heretofore limited number of observations have suggested that it stabilizes the subcloud layer and leads to decoupling, discouraging turbulent eddies from transporting water vapor from the ocean surface into the cloud layer, which could thin or even destroy the clouds. Many studies conducted with Large Eddy Simulations (LES) have suggested that this drizzle-induced decoupling is an important feedback mechanism in the marine boundary layer, but apart from a limited number of aircraft profiles there has been scant observational support to confirm and quantify the nature of this decoupling. Findings presented herein represent a quantum leap the sophistication, continuity, and detail of the dynamic decoupling of the marine boundary layer when drizzle is present and when it is not. A statistical analysis of the average vertical profile

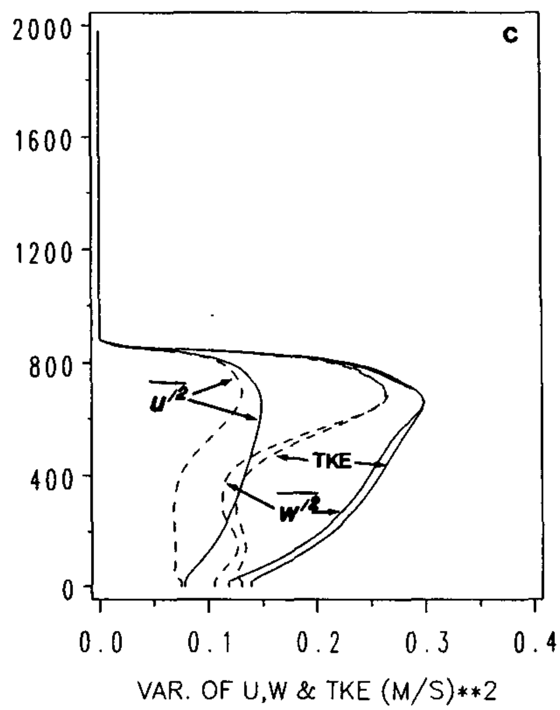

Figure 10: Reproduction of Figure 13c from Wang and Wang, 1995. The dashed and solid lines marked with a 'w' show the vertical component of TKE with no drizzle (solid) and moderate drizzle (dashed).

of TKE beneath single-layer stratocumulus on our dataset has revealed that on average, the presence of drizzle decreases the TKE as suggested by previous modeling studies using one-dimensional models (Wang and Wang, 1995) and LES (Zhou et al., 2017). The observed TKE reduction is more pronounced in the daytime and impacted the sub-cloud layer in a rather systematic way by steadily reducing TKE in the upper reaches of the sub-cloud layer and reducing the vertical TKE gradient there. The nighttime scenario is more complicated. Light drizzle seems to slightly increase the TKE, especially in the upper reaches of the sub cloud layer, while the effect of heavier drizzle varies throughout the TKE profile. Many modeling studies consider only nocturnal marine boundary layers, including the two studies referenced above. There is a remarkable correspondence in profile shape and magnitude of the TKE in the measured nighttime profile and the simulated profile from Wang and Wang (1995), which is shown in Figure 10. The drizzle- and non-drizzle TKE profiles in this simulation differ from those in Figure 8, comparison of the light and heavy drizzle profiles shows a strong correspondence. While this is a limited comparison and may not be a general result, this comparison seems to reinforce the fidelity of one-dimensional, third order closure models and a candidate for further study.

Many climate and NWP models connect cloud development with parameterized sub-cloud TKE, but do not account for TKE reductions due to evaporating drizzle (Bretherton and Park, 2009). Findings presented here, which are derived from the largest and most detailed date set to date, suggest that inclusion of this process could be important in GCMs and NWP models.

Further understanding of the role of drizzle in stratocumulus is likely required to improve their simulation in climate models. During daytime, outgoing longwave radiation acts to destabilize the top of the sub-cloud layer, but incoming solar shortwave radiation counteracts some of this destabilization. During nighttime, however, the incoming shortwave radiation is zero, and there is more negative buoyancy since there is no radiational heating to counteract it (this is why TKE tends to be at a minimum right as the sun rises). These radiation-driven structural changes in stratocumulus operate in the presence of drizzle.

Despite the detail in the observations presented herein, the inescapable truth is that the applicability of these results to other stratocumulus regions is unknown. Thus, additional observations are required to confirm these results for other regions of marine Sc-belts around the world. In addition, modes of cloud structure including multiple layers of stratocumulus were discarded in this analysis and remain fertile ground for future research.

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