

Novel method of drizzle formation observation at large horizontal scales using multi-wavelength satellite imagery simulation

IGOR STEPANOV

Herman Russchenberg

Delft University of Technology

I.Stepanov@tudelft.nl

Abstract

The observations of on-board satellite imaging radiometers are representative of a far-reaching two-dimensional cloud top properties, however with a cutback in the capacity of profiling the cloud vertically. A combination of simulated radiances calculated at the top of the cloud in the near-infrared (IR) and thermal infrared part of the spectra, is used as a proxy to estimate in-cloud droplet growth stage and ongoing precipitation intensity at the water cloud base. We present a drizzle observational technique that is built on simulated satellite imaging radiometry via the EarthCARE SIMulator (ECSIM). A period of 40 hours of the modeled cloud field evolution (using Dutch Atmospheric Large Eddy Simulator - DALES) for the case study during the Atlantic Stratocumulus Transition Experiment campaign (ASTEX) is used to create a series of cloud scenes of a transitioning Sc into a Sc topped Cumulus (Cu) fields. Drizzle appears throughout the cloud evolution, evaporating on its way to the surface, depleting the cloud droplets at the cloud base. Longwave radiation model from ECSIM is applied to the ingested three-dimensional cloud scenes of a Stratocumulus evolution. The cloud top brightness temperatures are calculated using a three-dimensional, Monte Carlo, long-wave Radiative Transfer Model (RTM). The simulated Brightness Temperatures Difference (BTD) between the channels 3.9 and 11 μ m is then used to highlight the cloud top droplet size spatial variability, during the production of drizzle near the cloud base. The observed correlation of the BTD with the droplet size variability is used to interpret the conditions at which the precipitation at the cloud base is triggered or went through a change in the intensity. Tracking the process of evolution of the cloud droplet into a precipitating drop is likely due to the sensitivity of the 3.9 μ m channel to the particle size and cloud phase, near the cloud top. A comparison of the observed BTD with the vertically averaged cloud droplet size from the imported cloud scene is done. It is used to examine if a single pixel value of BTD from the cloud top (as retrieved via RTM) can be representative of the inhomogeneous microphysical vertical structure of a Sc deck and the potential precipitation intensity at the cloud base. A range in BTD for the two infra-red channels, between 0 and 2K is correlated to the presence of effective radius of the cloud droplets larger than 15 μ m, treated as drizzle drops in this paper.

I. Introduction

I.1 Climatological Stratocumulus properties

The incoming amount of the solar energy that gets absorbed, (re)transmitted or scattered in the atmosphere, is a major factor in Earth's global radiative balance. The presence of absorbing elements that cause local heating and reemission of heat includes atmospheric abundant gases such as ozone, molecular oxygen and water vapor, whereas the major source of variability in the scattering comes from the presence of clouds. In particular, the low, liquid, water clouds have a predominant influence on radiation by cooling the atmosphere (with an exception in the high latitudes), due to their thickness that reflects most of solar energy. The temperature that they radiate at is close to the one of the surface beneath, which is the reason they are not influencing the IR radiation amount emitted upwards. This cooling effect was quantified using GCM (Global Climate Model) and presented in details in a modeling experiment by [Slingo, 1990]. It was shown that the warming of the troposphere gained by doubling the levels of CO₂ is balanced by 15-20% increase in low clouds amount, globally. This quantification motivates the need for further understanding low cloud formation as well as its influence on radiation.

I.2 Uncertainty in models related to Sc cloud fields

The Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5) has shown the multi-model-mean bias as the difference between the CMIP5 (Coupled Model Intercomparison Project) multi-model mean and the climatology from ECMWF (European Centre for Medium range Weather Forecast) reanalysis of the global atmosphere and surface conditions (ERA)-Interim (see Figure 1). Biases peaks appear mainly above the oceans, along the western coasts of the southern hemisphere continents. This location in the mid-latitudes, where climate model uncertainties are shown as the highest, is the most typical for formation of the drizzling Sc cloud, due to the air mass subsidence as a part of the Hadley cell circulation.

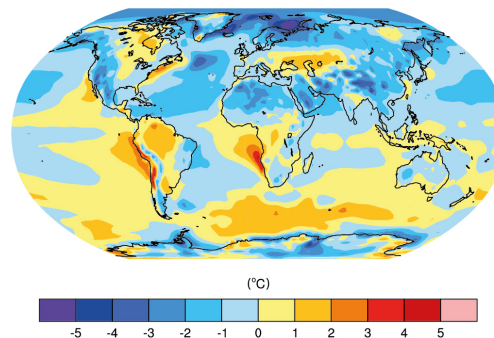


Figure 1: IPCC AR5 Multi Model mean bias, adapted from [Dee et al., 2011]

A possible explanation for the bias peaks in these areas is parameterization of the Sc clouds drizzle process in the climate models, for two reasons: 1) this process occurs on the subgrid scale of the model, therefore the need for it to be parameterized and 2) the Sc formation processes are not understood well to be included in the resolving part of the model, even if the resolution would be sufficiently high enough, to cover a domain large enough to describe Sc sheets evolution. Hence, further studies are needed from the remote sensing side, to interpret the physical meaning of this process, in different meteorological conditions.

II. Satellite observations of Sc structure

II.1 In-cloud droplet growth

When cloud droplets grow large enough, via diffusion and coalescence processes (close to droplet radius of $14\text{--}16\mu\text{m}$), drizzle occurs near the cloud base. It is known to deplete the cloud's liquid water content over a period of several hours, leaving behind a cellular cloud structure (as seen from satellite imagers). This transformation has been modeled in [Savic-Jovicic and Stevens, 2008] and [Wang and Feingold, 2009] and referred to in the literature as Pockets of Open Cells (POCs). Two ways for a part of a cloud to disappear or to dislodge itself from the whole, and consequently change its radiative character locally, is to evaporate or by precipitating. Drizzling in local areas of Sc clouds is a slow (up to 1mm/h rate) process that acts as a sink of the cloud's liquid water content [Faloona et al., 2005]. Its effect discloses itself leaving behind POCs, a cellular structure stretching across the restricted areas of Sc clouds. This behavior that can last for hours has been modeled using Large Eddy Simulations (LES) and described by [Savic-Jovicic and Stevens, 2008] and [Wang and Feingold, 2009].

II.2 Pockets of Open Cells as a drizzle proxy

[Stevens et al., 2005] used the observations from Geostationary Operational Environment Satellite (GOES) imagery, channels at $3.9\mu\text{m}$ and $11\mu\text{m}$ wavelength, to describe the areas of low reflectivity and cellular pattern, embedded in stratiform cloud fields. They interpreted low values of BTDR (assumed POC location) according to the modeling study made by [Pérez et al., 2000]. It corresponded to either a change in the

effective radius from 12 to $6\mu m$, with a fixed cloud optical depth, or a change in cloud optical depth, due to light scattering of cloud droplets (e.g. Figure 1 in [Pérez et al., 2000]. This means that places where POCs are observed, would have favorable conditions for formation of larger cloud droplets, compared to the surrounding environment. This in turn, means favorable conditions for precipitating drops to form, depleting the cloud over a period of several hours (with assumed rainfall rate at the cloud base of $1mmh^{-1}$).

II.3 Satellite microphysical retrievals as proxy to drizzle

The method used operationally for estimation of the cloud droplets size weighted near the upper part of the cloud, and precipitation from MSG is described by [Roebeling et al., 2006], using the Spinning Enhanced and Infrared Imager (SEVIRI). The values retrieved for cloud droplet size and precipitation rate could also be used a proxy to the drizzle intensity. This method uses the satellite reflectance measurements at 0.6 and $1.6\mu m$ wavelength channels in a step-wise process. Firstly, classification is done of the level of cloud contamination within every pixel by comparing the observed reflectance at $0.6\mu m$ to the simulated reflectance for clear sky conditions and over the cloned surface. Secondly, droplet size and Cloud Optical Thickness (COT) in the cloudy pixels are determined from comparison of the reflectance at $0.6\mu m$ and $1.6\mu m$ to the Look Up Tables (LUT) of simulated reflectance for a specific droplet radius and COT values. Once the cloud phase is classified using the threshold value of 265K of the Cloud Top Temperature (using $10.8\mu m$ brightness temperatures), an estimate of the droplet size is given via the effective radius parameter:

$$r_{eff} = \frac{\int_0^\infty r^3 n(r) dr}{\int_0^\infty r^2 n(r) dr} \quad (1)$$

, where $n(r)$ represents the DSD. The interpretation of the visible channel during the night is disadvantage of this method for detection and tracing of small precipitation droplets, as well as low sensitivity to the particle size.

The Brightness Temperature Difference (BTD) from thermal infrared channel at 3.7 and a mid-IR channel at $10.8\mu m$, which are more sensitive to the cloud phase and the particle size, was introduced to highlight the cloud droplets size, from space in [Han et al., 1995], [Ferek et al., 2000] and [Pérez et al., 2000]. In their work [VanZanten et al., 2005], it is argued that moving into thermal infrared part of the spectra is needed for drizzle observations because of non existing night-time retrievals of the effective radius.

Brightness Temperature method to characterize cloud properties (including cirrus and deep tropical convective clouds) was used in the previous study by [Otkin et al., 2009], where they used WRF model to estimate BT and validate them compared to BT derived from SEVIRI (for a different set of IR wavelengths).

The combination of using multiple channels from satellite borne imagers was initially proposed by [Arking and Childs, 1985]. They describe how each wavelength can be used to retrieve one type of cloud property from the Advanced Very High Resolution Radiometer (AVHRR); for example, the visible channel reflectance at $0.73\mu m$ is corresponding to optical thickness, near infra-red at $3.7\mu m$ is sensitive to particle size and shape or cloud phase and the far infra-red at $10.8\mu m$ wavelength is used to estimate the cloud top temperature.

II.4 Brightness Temperature Difference as a proxy

[VanZanten and Stevens, 2005] analyzed the RF02 flight during DYCOMS-II and found that it suffices to use a condition of BTD being less than 1.5K to flag satellite imagery areas as POCs. The post flight analysis where BTD depressions collocated with the radar-based drizzle rate along the flight path are capable of indicating not only whether there is drizzle, but also that the BTD is a parameter that can classify whether it is light or heavy drizzle (as in Figure 5 in [VanZanten and Stevens, 2005]).

Analyzing the data from DYCOMS-II, the second research flight (RF02) [VanZanten et al., 2005] looked into the structure of Sc boundary layers with precipitation reaching the surface. Using the collocated GOES data, they found that the observed BTD values lower than 2K are collocated with areas of heavy drizzle, during the RF02 flight in DYCOMS-II. The temperature difference threshold is derived from a series of

observations flights (RF01-RF08) made during this campaign, where N , estimated cloud depth H , BTD and the radar derived drizzle rate were compared. The analysis showed that larger drops are associated with lower number of drops and higher drizzle rates. Including the GOES imagery BT data at thermal IR channels during these flights, a proxy of $0.25K < \delta T < 2K$ was found to match the rainfall rate of $R > 1mmday^{-1}$, and used for retrievals.

The method of using the IR channels of $3.7\mu m$ and $10.8\mu m$ to delineate the transition between the suspended cloud droplets and drops with a positive terminal velocity, using droplet radius as a proxy, in Sc clouds, was shown in [Lensky and Rosenfeld, 2003]. They correlated the BTD at the top of the cloud with the cloud vertical profile (assuming vertical homogeneous) in terms of optical thickness and the droplet size, for every processed horizontal pixel (see Figure 2(a) in [Lensky and Rosenfeld, 2003]). [Rosenfeld et al., 2012] found that a potential indicator for the rain initiation, is at the range of 12 to $14\mu m$ threshold in the droplet radius parameter, observed near the cloud top. Using a Large Eddy Simulation (LES) mode of the Weather Research and Forecasting (WRF) model they concluded that the cloud water gets rapidly depleted only after the rain intensity exceeds $0.1mmh^{-1}$. This event is triggered after the cloud top effective radius reaches $14\mu m$, in their simulation. At this stage, not only that the drizzle is initiated, but also if the effective radius continues increasing, the drizzle becomes heavy. In this work we are going to use the proposed channel BTD to estimate if the retrieved correlation to the effective radius near the cloud top can be used as an indicator of the vertical structure in the Sc, particularly the cloud base drizzle rate.

III. Radiation modeling and cloud scenes

III.1 Synthetic cloud scenes

LES to ECSIM intervention parameterization: In the process of creating the DSD for a synthetic cloud scene, N needed to be assumed a fixed value in order to calculate the droplet effective radius (from LWC). Selected N value was $100\#/cm^3$, which is an approximation for ASTEX, according to the flight measurements range, as well as fitting in the maritime Sc standardly used value in models. DSD was modeled by choosing a generalized gamma distribution according to [Hu and Stamnes, 1993] (see Eq.2) Authors of this paper also conclude that the radiative properties of water clouds would be comparable as the gamma distribution. not change if the log-normal distribution were selected (possible ECSIM option when building the cloud scene).

$$N(r) = \frac{N}{R_m} \frac{1}{G(\gamma)} \left(\frac{r}{R_m}\right)^{\gamma-1} \exp\left(-\frac{r}{R_m}\right) \quad (2)$$

The used expression for effective radius is the inverse LWC equation, calculating the effective radius values on all grid box centers of LES data. This was required in order to construct the DSD of the synthetic scene, needed for running the forward model of simulated observations. The relationship used was:

$$R_m = \left(\frac{3q_l}{4\pi\rho N}\right)^{\frac{1}{3}} \quad (3)$$

$$r_{eff} = \frac{4}{3}(g+2)R_m \quad (4)$$

, where g stands for the distribution shape parameter.

After the DSD is created from the given parameters and scene creator model run, a three-dimensional scene is created. See Figure 2 and 3 for an example 3D-extinction and the Liquid Water Path (LWP) field, for cloud scene at the beginning of the hour 24 from the LES simulations initialization, used in this work.

III.2 EarthCARE Simulator

The EarthCARE (Earth Clouds, Aerosols and Radiation Explorer) satellite mission is scheduled to be launched in 2015. The mission payload itself will consist of 4 instruments:

- ▷ 94GHz Cloud Profiling Radar
- ▷ High Spectral resolution Lidar at 353nm
- ▷ Broadband radiometer
- ▷ Multiple Spectral Imager

The software developed for simulating the mission path and retrievals, EarthCARE SIMulator (ECSIM) [Voors et al., 2007] is also suitable for simulating the response of Meteosat Second Generation, for a given cloud field. BTDR in near-IR channels of a geostationary borne imager is simulated for drizzle evaluation in the cloud scene, imported into ECSIM.

ECSIM consists of connected models: scene creation, orbit, forward model, instrument and the retrieval model. When run in that consecutive order, they simulate how EarthCARE measurements from all 4 on board instruments would appear, for a predefined 2D or 3D cloud scene. An extensive description of models and algorithms used in ECSIM can be found in the models and algorithm documentation by [Donovan et al., 2008].

In this work, an LES model was used to reproduce Sc clouds evolution observed during the ASTEX campaign. The simulation starts at 0h UTC, for the day June 13th 1992, and lasts for 40 hours. Output is saved in the fields of liquid water content (LWC), at 2 hours interval. Input information imported from LES output contained mentioned LWC values stored in the centre of each model grid box. Resolution of the cloud scene is 50m and 15m in horizontal and vertical direction, respectively. Scene domain size is 25.6km x 25.6km in horizontal, and 2.75km in vertical direction (increased to 100km for RTM calculation of radiances at the top of the atmosphere).

RTM was run in Monte Carlo (MC) mode [Barker et al., 2003] on for cloud scene during the hour 24, from the beginning of the model run time. At this point, the initially approximately horizontally homogeneous layer of Sc has developed a drizzling regime whilst breaking off into broken Cumuli clouds, hence more appropriate for a case study here. It is possible to run ECSIM in the 1-D RTM in Discrete Ordinates Radiative Transfer Program (DISORT) mode [Stamnes et al., 2000], however the difference in accuracy of treating the cloud scene near the column edges between the two modes proved to be too large for simple "box-cloud" scene (not shown here) to make use of DISORT, even though computation time would have been decreased.

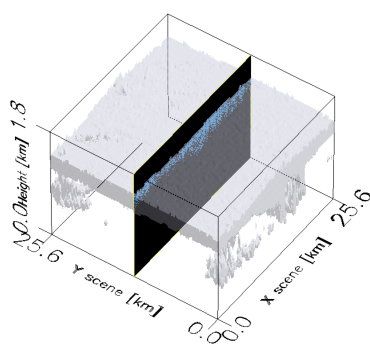


Figure 2: 3D extinction hour 24

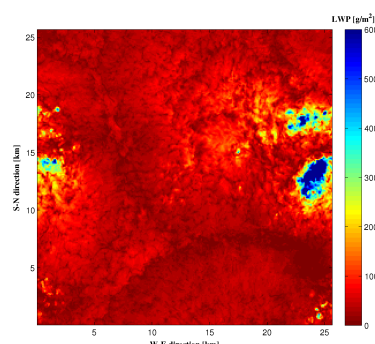


Figure 3: LWP hour 24 scaled

IV. Cloud top Brightness Temperature and drizzle relationship

In the work presented here, we used the mid-IR channel at $3.9\mu\text{m}$ and a thermal-IR channel at $10.8\mu\text{m}$, to further constrain the droplet effective radius, using BTD of these channels. The mid-IR channel at $3.9\mu\text{m}$ has a minor contribution from the solar reflectance during the daytime (see Figure 4). To avoid the solar reflectance contribution, this method can initially be applied only on night time cases, and in the later stage a correction for this contribution can be done. Another issue with the $3.9\mu\text{m}$ channel is that it is very close to the CO_2 absorption band, even though it is considered a window channel. $10.8\mu\text{m}$ acts also as a window channel with few absorption gases active around that wavelength, making it practical for cloud studies.

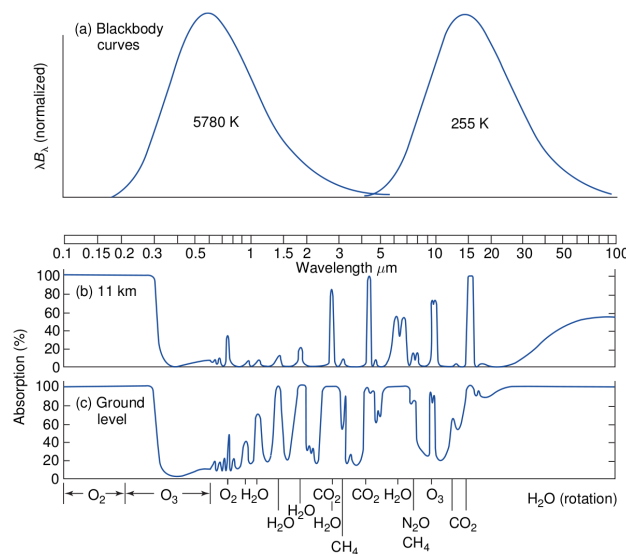


Figure 4: Wallace and Hobbs, atmospheric spectral radiative properties

IV.1 LES scenes Radiative Transfer Model

Once the LES cloud scene is imported into ECSIM, it is possible to use the utility extract quantity to extract the microphysical parameters of the scene, based on the DSD information. Figure 5a and b show the LWP to be sufficiently high for a drizzling type of Sc and the effective radius, vertically averaged for the entire domain. Figure 5c shows the BTD range (the same as in previously referenced studies) as a result of the long wave RTM, and the qualitative correlation to the 2 extracted microphysical parameters.

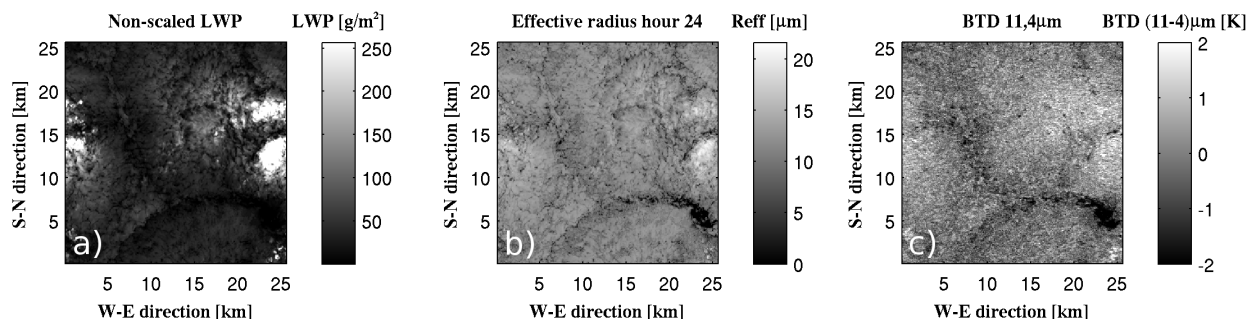


Figure 5: Extracted and simulated variables from LES scene for hour 24

Analysis of BTD correlation with the cloud microphysical parameters along a single vertical cross-section was done for the hour 24 of the LES simulation output, where POCs have appeared and layered cloud structure changed to broken clouds. The vertical cross-section of the effective radius is shown on Figure 6a, representing a typical structure of a low Sc cloud. The effective radius is calculated as an extinction

weighted, column average value. Overlay of the BTD and the effective radius on Fig. 6b and c shows that for the maximum of the droplet size, BTD is correlated within the range $0.25K < \delta T < 2K$ of the BTD, but also that the vertically averaged effective radius can be used as a proxy to indicate the vertical profile variability for a several hundred meters thick cloud deck structure. Averaging of both effective radius and BTD signals was done using the Savitzky Golay technique, in order to keep the raw signal as much as possible, so that the comparison is based more on the physical values, rather than statistical high order polynomial fitting. Similar concept for correlation of the effective radius and the BTD was shown by the schematics in [Lensky and Rosenfeld, 2003], where a transition from optically thin cloud was introduced with large droplets to optically thick cloud with larger droplet, in their Figure 2 a) and b). This was correlated to the modeled BTD at the same two near-IR and thermal-IR channels, as used here.

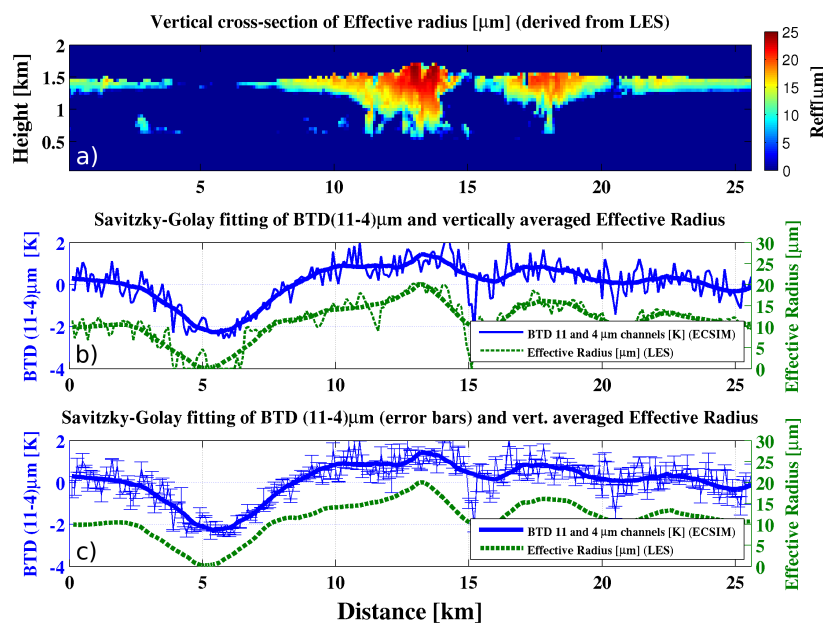


Figure 6: Top of the cloud observations (BTD) spatial correlation with cloud vertical cross-section microphysical properties.

The BTD field shown at the top of the Figure 6 is correlated to the effective radius values in a quantitative manner on the 7. The correlation for this case was 0.70 and shows a tendency that the vertically averaged radius of a non-homogeneous vertical profile could be used to reflect the radiative property of the pixel. The color coding for LWP values shows that the larger droplets are most likely to have higher values of LWP, which leads that the LES made cloud scenes can be used for drizzle approximation, when they include droplets larger than $14\text{--}16\mu\text{m}$.

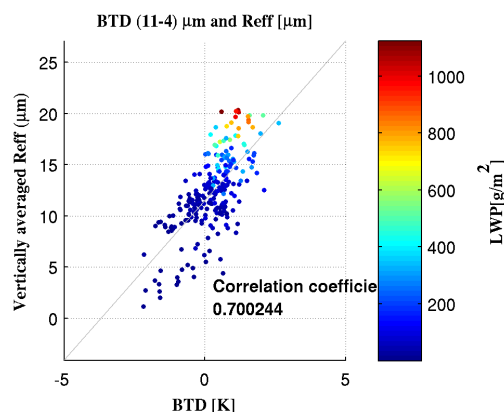


Figure 7: Top of the cloud observations (BTD) spatial correlation with cloud vertical cross-section microphysical properties.

V. Conclusion

The concept of relating the vertically averaged effective radius within the vertically variable structure of a typical geometrical thickness Stratocumulus cloud, as a proxy to drizzle has been described. Correlation of simulated BTM values that spatially match to POCs locations was tested to the values of the vertically averaged effective radius. As the satellite borne imagers using near-IR wavelengths can not penetrate deep into the cloud to reach the base, BTM can not be considered a direct indicator of drizzle intensity at the cloud base. However it has been shown that the information from the cloud top can be used to infer on the cloud base structure, for the LES cloud scene used here.

Further investigation will conclude if the visible channel in the non-absorbing wavelength, dependent on the cloud optical thickness can further constrain the criteria for POCs identification and a deeper cloud penetration depth, to categorize the intensity of drizzle at the cloud base.

REFERENCES

- [Arking and Childs, 1985] Arking, A. and Childs, J. D. (1985). Retrieval of cloud cover parameters from multispectral satellite images. *Journal of Climate and Applied Meteorology*, 24(4):322–333.
- [Barker et al., 2003] Barker, H., Goldstein, R., and Stevens, D. (2003). Monte carlo simulation of solar reflectances for cloudy atmospheres. *Journal of the atmospheric sciences*, 60(16):1881–1894.
- [Dee et al., 2011] Dee, D., Uppala, S., Simmons, A., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M., Balsamo, G., Bauer, P., et al. (2011). The era-interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656):553–597.
- [Donovan et al., 2008] Donovan, D., Voors, R., van Zadelhoff, G., Acarreta, J., SL, D. S., de Poniente, R., and Cantos, T. (2008). Ecsim model and algorithms document. *ESTEC Contract*, 20003(06).
- [Faloona et al., 2005] Faloona, I., Lenschow, D. H., Campos, T., Stevens, B., Van Zanten, M., Blomquist, B., Thornton, D., Bandy, A., and Gerber, H. (2005). Observations of entrainment in eastern pacific marine stratocumulus using three conserved scalars. *Journal of the atmospheric sciences*, 62(9).
- [Ferek et al., 2000] Ferek, R. J., Garrett, T., Hobbs, P. V., Strader, S., Johnson, D., Taylor, J. P., Nielsen, K., Ackerman, A. S., Kogan, Y., Liu, Q., et al. (2000). Drizzle suppression in ship tracks. *Journal of the Atmospheric Sciences*, 57(16):2707–2728.
- [Han et al., 1995] Han, Q., Welch, R., Chou, J., Rossow, W., and White, A. (1995). Validation of satellite retrievals of cloud microphysics and liquid water path using observations from fire. *Journal of the atmospheric sciences*, 52(23):4183–4195.
- [Hu and Stamnes, 1993] Hu, Y. and Stamnes, K. (1993). An accurate parameterization of the radiative properties of water clouds suitable for use in climate models. *Journal of climate*, 6(4):728–742.
- [Lensky and Rosenfeld, 2003] Lensky, I. M. and Rosenfeld, D. (2003). Satellite-based insights into precipitation formation processes in continental and maritime convective clouds at nighttime. *Journal of Applied Meteorology*, 42(9).
- [Otkin et al., 2009] Otkin, J. A., Greenwald, T. J., Sieglaff, J., and Huang, H.-L. (2009). Validation of a large-scale simulated brightness temperature dataset using seviri satellite observations. *Journal of Applied Meteorology and Climatology*, 48(8):1613–1626.
- [Pérez et al., 2000] Pérez, J. C., Herrera, F., Rosa, F., Gonzalez, A., Wetzal, M. A., Borys, R. D., and Lowenthal, D. H. (2000). Retrieval of marine stratus cloud droplet size from noaa-avhrr nighttime imagery. *Remote sensing of environment*, 73(1):31–45.

- [Roebeling et al., 2006] Roebeling, R., Feijt, A., and Stammes, P. (2006). Cloud property retrievals for climate monitoring: Implications of differences between spinning enhanced visible and infrared imager (seviri) on meteosat-8 and advanced very high resolution radiometer (avhrr) on noaa-17. *Journal of Geophysical Research: Atmospheres* (1984–2012), 111(D20).
- [Rosenfeld et al., 2012] Rosenfeld, D., Wang, H., and Rasch, P. J. (2012). The roles of cloud drop effective radius and lwp in determining rain properties in marine stratocumulus. *Geophysical Research Letters*, 39(13).
- [Savic-Jovicic and Stevens, 2008] Savic-Jovicic, V. and Stevens, B. (2008). The structure and mesoscale organization of precipitating stratocumulus. *Journal of the Atmospheric Sciences*, 65(5):1587–1605.
- [Slingo, 1990] Slingo, A. (1990). Sensitivity of the earth's radiation budget to changes in low clouds. *Nature*, 343(6253):49–51.
- [Stammes et al., 2000] Stammes, K., Tsay, S.-C., Wiscombe, W., and Laszlo, I. (2000). Disort, a general-purpose fortran program for discrete-ordinate-method radiative transfer in scattering and emitting layered media: documentation of methodology. *Goddard Space Flight Center, NASA*.
- [Stevens et al., 2005] Stevens, B., Vali, G., Comstock, K., Wood, R., Van Zanten, M. C., Austin, P. H., Bretherton, C. S., and Lenschow, D. H. (2005). Pockets of open cells and drizzle in marine stratocumulus. *Bulletin of the American Meteorological Society*, 86(1).
- [VanZanten et al., 2005] VanZanten, M., Stevens, B., Vali, G., and Lenschow, D. (2005). Observations of drizzle in nocturnal marine stratocumulus. *Journal of the atmospheric sciences*, 62(1).
- [VanZanten and Stevens, 2005] VanZanten, M. C. and Stevens, B. (2005). Observations of the structure of heavily precipitating marine stratocumulus. *Journal of the atmospheric sciences*, 62(12):4327–4342.
- [Voors et al., 2007] Voors, R., Donovan, D., Acarreta, J., Eisinger, M., Franco, R., Lajas, D., Moyano, R., Pirondini, F., Ramos, J., and Wehr, T. (2007). Ecsim: the simulator framework for earthcare. In *Proc. SPIE*, volume 6744, page 67441Y.
- [Wang and Feingold, 2009] Wang, H. and Feingold, G. (2009). Modeling mesoscale cellular structures and drizzle in marine stratocumulus. part i: Impact of drizzle on the formation and evolution of open cells. *Journal of the Atmospheric Sciences*, 66(11):3237–3256.