Final Report

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Project Title: An Investigation of Aerosol-Cloud-Precipitation Interactions in the South-East Pacific Using DOE G-1 Data and WRF/Chem Large Eddy Simulations

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Summary

Under this grant, we investigated marine boundary layer clouds, their properties, behavior, and response to human activity and climate change, with a focus on scales and processes that cannot be studied with climate models. Investigated topics and results are summarized in this section. Detailed information are given in subsequent sections, followed by a list of resulting publications.

Interaction of cellular cloudiness and surface sensible heat and moisture fluxes

Marine stratocumulus clouds arrange themselves in characteristic cellular patterns (closed and open cells) which are associated with different boundary layer dynamical states. Boundary layer dynamics co-determines the surface moisture and sensible heat fluxes from the ocean, which in turn affect cloud properties. Climate models do not resolve cellular cloud structure and the associated boundary layer dynamics. In this investigation (Kazil et al., 2014), we investigated the feedback between cloud structure, boundary layer dynamics, surface fluxes, and cloud properties. We found that marine boundary layer cellular cloudiness imposes its horizontal spatial structure on surface air temperature and water vapor, and, to a lesser degree, on the surface sensible and latent heat flux from the ocean. More importantly we found that the open-cell cloud state creates conditions conducive to its maintenance by enhancing the surface sensible heat flux. This finding suggested that the transition from high- to low cloud fraction cloud fields may be more likely to occur than the reverse transition, a hypothesis that was investigated subsequently by this group of researchers.

Wind speed response of marine non-precipitating stratocumulus clouds

Independent observations have identified increasing ocean surface wind speeds in the course of the 20th century. Notably, satellite observations showed a general trend towards higher ocean surface wind speeds in the period 1991-2008 by up to 1.5 % per year. Climate simulations project ocean surface wind speed trends for the 21st century in the range of -10% to 10% at the locations of large marine stratocumulus decks. A cloud response to the observed and projected changes in large scale wind speed would constitute a cloud-climate feedback mechanism with the potential to impact Earth's radiation budget, the formation of precipitation, and the effect of aerosol on clouds. The response of marine stratocumulus clouds to wind speed and a resulting change in the cloud radiative effect are currently undetermined and unresolved by climate models.

In this investigation (Kazil et al., 2015), we found that marine boundary layer clouds and the associated cloud radiative effect (CRE) are sensitive to changes in wind speed. Observed and projected changes in ocean wind speed and the associated cloud response therefore constitute a cloud-climate feedback mechanism. We explained the processes by which wind speed acts on the evolution of boundary layer growth, entrainment, and decoupling, and quantified the response of marine straticumulus clouds to wind speed over the diurnal cycle. In addition, we explained the role of buoyancy- and shear-driven dynamics for boundary layer growth, entrainment, decoupling, and for marine stratocumulus cloud properties. Finally, we added to basic understanding of marine stratocumulus clouds: we found that in sufficiently thick stratocumulus clouds, a moistening of the boundary layer does not strengthen dynamics by enhanced cloud-top long-wave cooling. Instead, it is cloud updrafts which strengthen boundary layer dynamics in response to additional boundary layer moistening, and thereby lead to additional boundary layer growth and entrainment.

Cloud radiative forcing and cloud radiative properties for assessing indirect effects

We have developed a new approach to estimating aerosol-cloud radiative forcing that involves diagnosing the direct change in cloud radiative forcing to aerosol using highly accurate measurement of the surface radiation budget. The approach by-passes the need for using highly uncertain retrievals of cloud microphysical properties and relating them to radiative properties, and takes advantage of long-term, continuous, datasets of surface radiation that exist in far more locations than the active remote sensing required for microphysical retrievals.

The effect of elevated smoke layers on the stratocumulus to cumulus transition

Aerosol emissions from man-made wildfires in southern Africa affect the regional radiation budget directly and indirectly by affecting the low-level cloud response either through the above-cloud stabilization induced by the absorption of shortwave radiation, or through microphysical smoke-cloud interactions (Johnson et al., 2004; Adebiyi and Zuidema, 2015). We have conducted a pilot model study in preparation for field campaigns in the South-east Atlantic targeting effect role of biomass burning emissions on marine boundary layer clouds. A key result of our work is that the transition from stratocumulus to cumulus is delayed in the presence of smoke (Yamaguchi et al., 2015).

The transition between closed and open cellular convection in the marine boundary layer

The transition from high cloud fraction, closed cell cloud fields to low cloud fraction, open-cell cloud fields has been studied both in field campaigns and model studies. In this investigation we explored the reverse transition, from the open-cell cloud state to the closed-cell cloud state. This investigation identified that the transition is asymmetric: It proceeds more readily in the direction from closed- to open cells, compared to the opposite direction. The primary cause of the asymmetry is a much reduced cloud water content, reduced cloud top cooling, and reduced boundary layer turbulence in the open cell state. The reverse transition is possible but requires a very strong injection of aerosol particles into the system..

Precipitation susceptibility as a constraint on the lifetime effect

Climate models continue to exhibit strong sensitivity to the representation of aerosol effects on cloud reflectance and cloud amount. We embarked on a study using large eddy simulations (LES) of marine stratocumulus and trade wind cumulus clouds to show that these two cloud regimes exhibit qualitatively different relationships between the aerosol-cloud interaction and precipitation susceptibility. We identified diverging behavior in these quantities in our simulations that also differs from that derived from climate model simulations of oceanic clouds aggregated over much larger spatial scales. We explored possible reasons for variability in these relationships.

Closed to open cell transitions and the role of the spatial distribution of rain

Precipitation is considered a necessary but not a sufficient prerequisite for the transition from the closed cell- to the open cell stratocumulus cloud state. Hence factors in addition to precipitation likely exist that govern the occurrence of the transition. We tested the hypothesis that the spatial distribution of precipitation co-determines the closed-to-open cell transition. A central finding of this investigation was that even substantial precipitation (order few mm d^{-1}), when restricted to a small area, does not initiate the transition. Distributing sufficiently strong precipitation over larger areas, on the other hand, initiates the transition.

Interaction of marine boundary layer cellular cloudiness and surface heat fluxes

Motivation

In this investigation, the interaction of marine boundary layer cellular cloudiness and the surface fluxes of sensible and latent heat was studied and characterized. The investigation was motivated by observations of cold and moist pools with elevated wind speeds in the open-cell cloud state (Jensen et al., 2000; Comstock et al., 2005; Stevens et al., 2005; Comstock et al., 2007; Wood et al., 2011). Cold/moist pools with higher wind speeds have the potential to produce different surface fluxes of sensible and latent heat as well as of sea spray aerosol in the open-cell cloud state, relative to the closed-cell cloud state. A feedback mechanism could exist in the open-cell cloud state in which the cloud state drives surface fluxes, which in turn determine the properties and lifetime of the cloud state. Different surface fluxes between the open- and closed-cell cloud state could also provide an explanation for the frequently observed transition from the closed- to the open-cell cloud state, but the less frequent observation of the reverse transition: The reverse transition could be prevented by the tendency of the surface heat

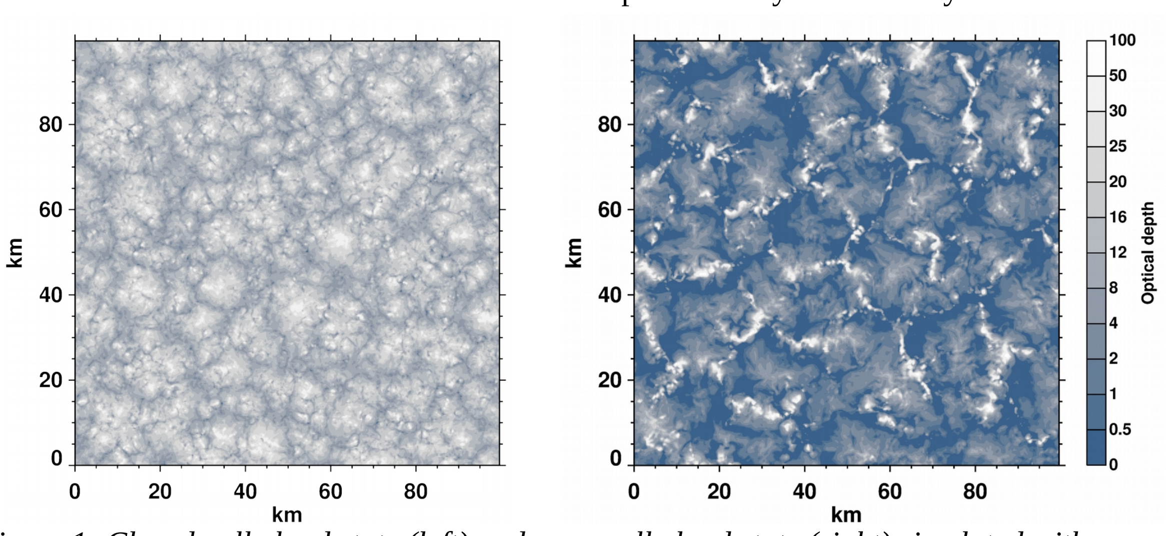

Figure 1: Closed-cell cloud state (left) and open-cell cloud state (right) simulated with WRF/Chem, after 12 h of simulation (Fig. 2 a, c in Kazil et al., 2014).

fluxes to preserve the open-cell state. Such a mechanism could hinder proposed geo-engineering methods that aim at generating large amounts of sea-spray aerosol to convert open-cell cloudiness to closed-cell cloudiness, to increase cloud fraction and radiative cooling of the planet.

Methodology

We used the WRF/Chem model to run simulations of the closed- and open-cell cloud states (Fig. 1). The simulations were performed for the conditions observed during the Second Dynamics and Chemistry of Marine Stratocumulus field study Research Flight 2 (DYCOMS II RF02, Stevens et al., 2003, 2005) In these simulations, the cellular cloud states interact with the surface fluxes of sensible and latent heat, as well as with the surface flux of sea spray aerosol. The surface fluxes are driven by the total wind speed, which is the sum of a (constant) geostrophic component and a residual component. Tests revealed significant numerical diffusivity of the WRF/Chem dynamical core when applied to the total wind speed. The WRF/Chem model was developed so that the dynamical core acts only on the residual wind speed. In the resulting simulations, the (constant) geostrophic wind speed is added to the residual wind speed, which yields the correct results in the calculation of the surface fluxes. As a side effect, the cloud field remains stationary (except for motion caused by the Coriolis effect) in the model domain, which facilitates the analysis of horizontal structures such as closed and open cells. In the original implementation of the dynamical core, the cloud field would be advected through the domain at the speed of the geostrophic wind.

Results

We found that the dynamics of the open-cell state, which leads to the formation of cold and moist pools with surface wind divergence, determines surface air temperature, surface water vapor, and drives the surface sensible and latent heat flux. In particular, open-cell cloud state dynamics is responsible for a higher surface sensible heat flux relative to the closed cell cloud state (Fig. 2). The higher surface sensible heat flux in the open-cell state, relative to the closed-cell state (Fig. 2) is required for the maintenance of the open-cell state. For this, open-cell simulations were conducted with prescribed surface heat fluxes from the closed-cell state. When the open-cell state was driven by both (sensible and latent) heat fluxes from the closed-cell state, the open-cell state collapsed. When the open-cell state was driven by the open-cell

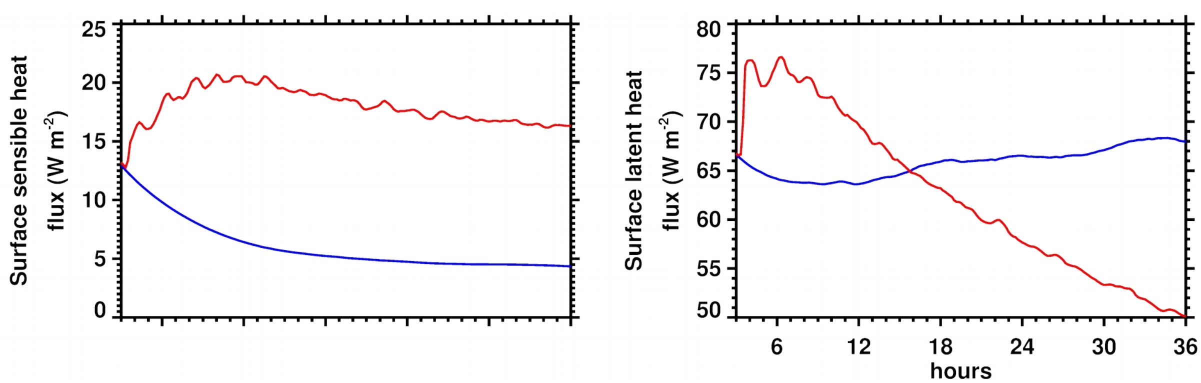

Figure 2: Surface sensible (left) and latent (right) heat flux (Fig. 3 d, e in Kazil et al., 2014). Closed-cell cloud state fluxes are denoted by blue, open-cell cloud state fluxes by red curves. Notice the higher sensible heat flux in the open-cell cloud state (red curve in left panel).

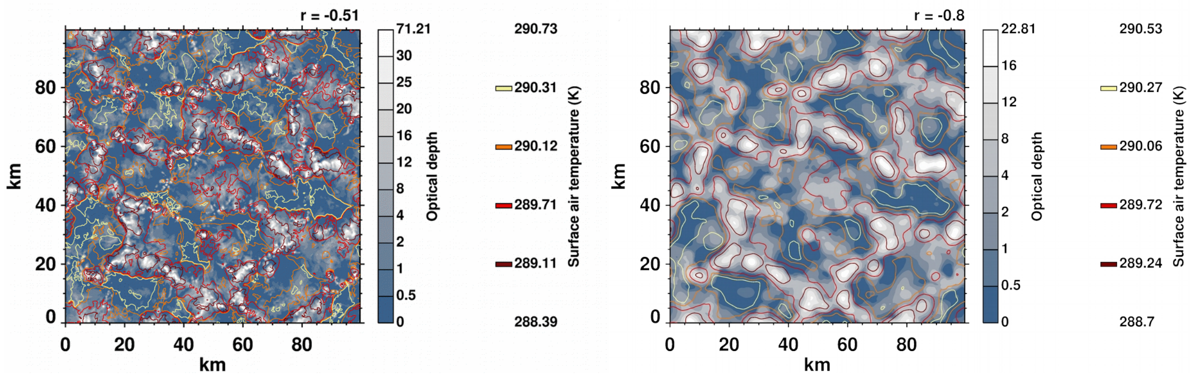

Figure 3: Spatial correlation of cloud optical depth and surface air temperature in the open-cell state (left), and after filtering with a low-pass filter (∅ = 4.5 km, right) (Fig. 11 b and supplemental material Fig. A3 b in Kazil et al., 2014). Surface air temperature is shown with a delay of 30 minutes relative to cloud optical depth. This delay, at which the spatial correlation peaks with r=-0.51 and r=-0.8, respectively, reflects the time between formation of rain in the cloud and the formation of surface cold pools when the rain reaches the surface.

sensible heat flux and the closed-cell latent heat flux, the open-cell state persisted. The conclusion is that the sensible heat flux that is driven by the open-cell cloud state is conducive to the maintenance of the open-cell cloud state. Finally, we found that the closed-cell cloud state imposes its horizontal spatial structure on surface air temperature and water vapor, and, to a lesser degree, on the surface sensible and latent heat flux. The responsible mechanism is the entrainment of dry free tropospheric air into the boundary layer. In the open-cell cloud state, cloud formation, cloud optical depth and liquid water path, and cloud and rain water path were identified as good predictors of the horizontal spatial structure of surface air temperature and sensible heat flux, but not of surface water vapor and latent heat flux. Fig. 3 shows the spatial correlation of cloud optical depth and surface air temperature in the open-cell state.

Impact

This work established basic understanding of the mechanisms proceeding in the transition between closed- and open-cell stratocumulus clouds over the oceans.

Wind speed response of marine non-precipitating stratocumulus clouds

Motivation

An understudied cloud-clime feedback is the response of marine boundary layer clouds to wind speed. The mechanism by which wind speed acts on cloud properties proceeds through the effect of wind speed on the surface fluxes of heat, moisture, horizontal momentum (shear), and sea spray aerosol. The investigation is motivated by observed increasing trends in ocean surface wind speeds in the course of the 20th century. Young et al. (2011) identified, using satellite radar altimeter wave heights, a global increase in ocean surface wind speed by up to 1.5 % per year in the period 1991-2008 (Fig 4.). Hande et al. (2012) found an increasing surface wind speed trend spanning nearly four decades in radiosonde data at a location in the Southern Ocean. Bertin et al. (2013) identified a significant increase in wave height (driven by wind speed) in the North Atlantic Ocean over the 20th century, and Servain et al. (2014) found an intensification of trade winds in the tropical Atlanic over the period 1964-2012 that

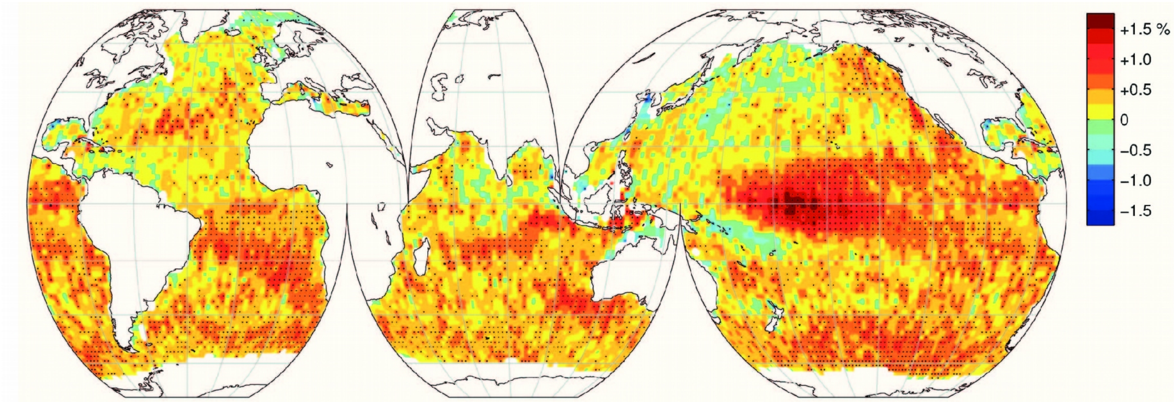

Figure 4: Annual mean 10 m wind speed trend 1991 – 2008, from satellite altimeter data (Young et al., 2011)

accompanied an observed warming trend in sea surface temperature. These trends in large scale wind speed are not necessarily a consequence of climate change, but could arise from internal climate variability (Dobrynin et al., 2015). Additional motivation derives from projected changes in ocean wind speeds and wave heights in the course of the 21st century (McInnes et al., 2011; Hemer et al., 2013). Together with an associated cloud response, the observed and projected changes in large scale wind speed would constitute a cloud-climate feedback mechanism with the potential to impact Earth's radiation budget, the formation of precipitation, and the effect of aerosol on clouds. The response of marine boundary layer clouds to the observed and projected wind speed changes and the resulting effects on Earth's radiative forcing are unknown because climate models do not resolve the effect of wind speed on marine boundary layer dynamics and cloudiness.

Methodology

We conducted cloud-system resolving simulations with the WRF/Chem model, varying large scale wind speeds. The observed wind speed during the Second Dynamics and Chemistry of Marine Stratocumulus field study Research Flight 1 (DYCOMS II RF01, Stevens et al., 2005) served as a reference for a ±25 % faster and slower large scale wind speed, respectively. We chose this variation because the associated variation in 10 m wind speed averaged over a diurnal cycle in our simulations (-18 %/+21 %) is comparable to the peak values of the 1991-2008 change in ocean surface wind speed at the location of the north-east Pacific coastal stratocumulus deck (Young et al., 2011). The different wind speeds drive different surface fluxes of sensible heat, moisture, and momentum in the simulations. We focused on the dynamical rather than the microphysical response of the stratocumulus-topped boundary layer to changes in wind speed, and excluded the effect of wind speed on surface aerosol production and loss. The simulations were initialized with a boundary layer state that closely reproduces DYCOMS II RF01 observations.

Results

We determined that marine stratocumulus clouds and their cloud radiative effect (CRE) are sensitive to wind speed. Observed and projected changes in large scale wind speed and the response of marine stratocumulus clouds therefore constitute a cloud-climate feedback mechanism. The response is caused by wind speed changing cloud liquid water path (LWP):

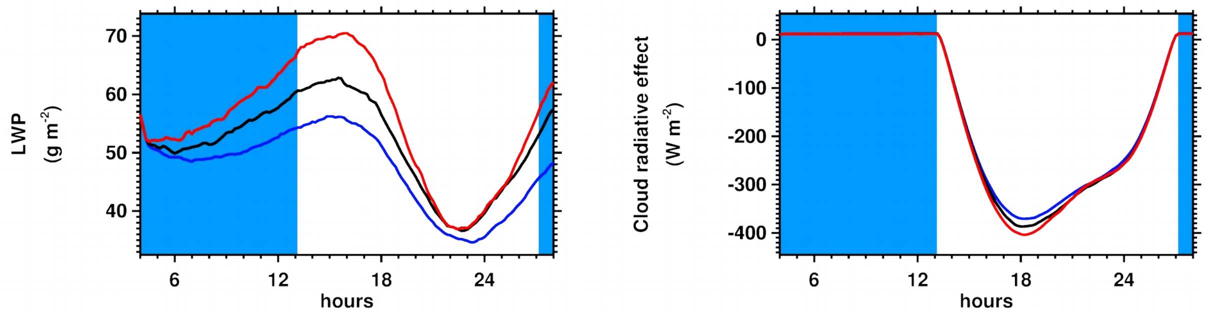

Figure 5: Liquid water path (top) and cloud radiative effect (bottom) for low (blue), reference (black) and high (red) wind speed, from WRF/Chem simulations (Fig. 4 a, c in Kazil et al., 2015). Blue shading indicates nighttime.

higher wind speed enhances LWP during the night and in the morning, and more strongly suppresses it later in the day (Fig. 5, top). Wind speed hence accentuates the diurnal LWP cycle by expanding the morning-afternoon contrast. Overall, higher wind speed results in higher LWP and a stronger diurnally averaged CRE. The CRE response to wind speed changes, however, in the course of the day: The CRE is most sensitive to wind speed at its peak shortly before noon, and becomes insensitive to wind speed later in the day (Fig. 5, bottom). As a consequence, the diurnally averaged CRE becomes less sensitive to wind speed with increasing wind speed.

In addition to identifying and quantifying the response of marine stratocumulus clouds to wind speed, a key outcome of this investigation was to explain the mechanism by which wind speed acts on the evolution of boundary layer growth, entrainment, and cloud properties. We found that the higher LWP at higher wind speed does not enhance cloud top cooling and drive additional turbulence, because in sufficiently thick clouds (LWP $\gtrsim$ 50 g m^{-2}), long wave emissions are very insensitive to LWP. Instead, higher wind speed leads to faster boundary layer growth and entrainment by enhanced buoyant production of turbulence kinetic energy (TKE) from latent heat release in cloud updrafts. Based on further analysis of our simulations we concluded that cloud updrafts are a key dynamical driver of boundary layer growth and entrainment.

Finally, we found that large scale wind plays an important role in modulating boundary layer decoupling. At nighttime and at low wind speed during daytime, it enhances decoupling in part by faster boundary layer growth and stronger entrainment, and in part because circulation driven by shear from large scale wind in the sub-cloud layer hinders vertical moisture transport between the surface and cloud base. With increasing wind speed, however, in decoupled daytime conditions, shear-driven circulation due to large scale wind takes over from buoyancy-driven circulation in transporting moisture from the surface to cloud base, and thereby reduces decoupling and helps maintain LWP.

Impact

This investigation established fundamental, previously unavailable understanding of marine boundary layer clouds and of their behavior, and thus helps understand the response of marine boundary layer clouds to climate change. With this it contributes to the knowledge required for the improvement of boundary layer cloud representations in climate models, and of climate simulations and projections.

Cloud radiative forcing and cloud radiative properties for assessing indirect effects

Typically, observational studies use measures of cloud microphysical properties and their relationship to some aerosol parameter to quantify aerosol-cloud interactions. In order to estimate an associated radiative forcing, the radiative properties associated with these microphysical properties must be determined. This requires knowledge of a chain of relationships for which observations are themselves uncertain. We have developed a new approach to estimating aerosol-cloud radiative forcing that involves diagnosing the direct change in cloud radiative forcing to aerosol using highly accurate measurement of the surface radiation budget. The approach by-passes the need for using highly uncertain retrievals of cloud microphysical properties and relating them to radiative properties, and takes advantage of long-term, continuous, datasets of surface radiation that exist in far more locations than the active remote sensing required for microphysical retrievals. We have currently analyzed 20 years of data from SGP and are planning on analyses at Manacapuru, the Pacific Ocean (Magic) and Eastern North Atlantic sites.

In parallel, we embarked on a large eddy simulation (LES) study to examine the sensitivity of cloud radiative forcing to both aerosol and meteorological drivers. Two sets of LES, each comprising about 100 simulations, and differing only in their sampling of the initial aerosol and meteorological conditions, demonstrated the primacy of the co-variability in these initial conditions for detecting aerosol effects on the radiative forcing of clouds (Feingold et al., 2015a). These results support the importance of routine LES at SGP (LASSO) for quantification of aerosol-cloud radiative forcing.

This work was an invited presentation at the National Academy of Sciences Sackler Colloquium on Aerosol-Cloud Interactions in June, and at the Gordon Conference for Radiation and Climate in July.

Impact

This work will provide an entirely new path to observational constraint on aerosol-cloud interactions and aerosol indirect effects in many different climatological regimes.

The effect of elevated smoke layers on the stratocumulus to cumulus transition

The transition from stratocumulus to cumulus has been the focus of significant DOE effort (e.g., MAGIC and the upcoming LASIC). In the classical transition, a combination of increasing sea surface temperature (SST) and weakening subsidence with westward distance from the continental coast results in transition. We have investigated the influence of smoke in the free atmosphere overlaying, but separated from the stratocumulus on this transition. Unlike the relatively homogeneous SST gradient, smoke is a source of heating that varies spatially through progressive dilution and removal, and diurnally with the solar zenith angle. Through a series of large eddy simulations we have shown that the key mechanisms via which well-mixed boundary layers transition to decoupled boundary layers with penetrative cumulus are modified by smoke (Fig. 6). The key result of our work is that the transition from stratocumulus to cumulus is delayed in the presence of smoke (Yamaguchi et al., 2015). Support for this finding can be found in a recent observational study (Adebiyi et al., 2015).

Impact

Field campaigns such as LASIC, CLARIFY, ONFIRE, and ORACLES will be an important data source and provide opportunities for the community to address and evaluate more fully the effect of biomass burning aerosol on the marine boundary layer cloud. If indeed the transition is delayed this could have important implications for aerosol-cloud radiative forcing.

The transition between closed and open cellular convection in the marine boundary layer

The transition from closed to open cellular convection is by now well studied with both observations and models. What has received far less attention is the two-way transition between closed and open cellular convection. In other words, how readily does open cell convection revert to closed cell convection, and what are the relative roles of the aerosol and other factor meteorological factors in that transition. The work is motivated by the observations of ship tracks filling in open cells and creating apparent closed cells.

As part of this research project we addressed the two-way transitions between these cloud states in an idealized cloud resolving modeling framework (Feingold et al., 2015b). A series of cloud resolving simulations shows that the transition between closed and open cellular states is asymmetrical, and characterized by a rapid ("runaway") transition from the closed- to the open-cell state, but slower recovery to the closed-cell state. We showed that the asymmetry in the two-way transition occurs even for very rapid drop concentration replenishment. The primary barrier to recovery is the loss in turbulence kinetic energy (TKE) associated with the loss in cloud water (and associated radiative cooling), and the vertical stratification of the boundary layer during the open-cell period. For this reason, although the aerosol is an essential part of the

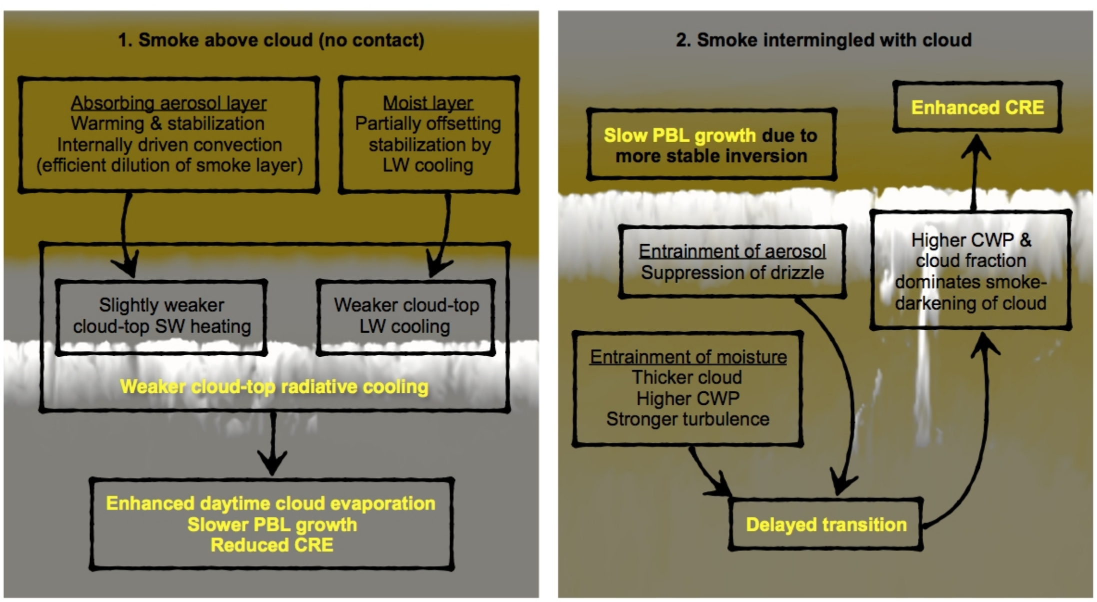

Figure 6: Schematic showing key effects of absorbing smoke on the transition from stratocumulus to cumulus. Left panel: smoke resides high above cloud; Right panel: smoke is intermingled with clouds. The gold colour is an indication of the smoke concentration. White indicates cloud. (From Yamaguchi et al., 2015, Figure 3.)

recovery, even very large infusions of particles do not result in rapid recovery. In transitioning from the open to the closed state, the system faces the task of replenishing cloud water fast enough to counter precipitation losses, such that it can generate radiative cooling and TKE. It is hampered by a stable layer below cloud base that has to be overcome before water vapor can be transported more efficiently into the cloud layer. A faster return to the closed-cell state may occur when the drop concentration increase is accompanied by significant dynamical forcing, e.g., via an increase in surface latent and sensible heat fluxes.

Impact

Whether the cloud state is closed (high reflectance) or open (low reflectance) has a significant impact on the cloud radiative effect. This work places the observed closing of open cells by ship effluent in perspective by showing that it likely occurs when aerosol intrusions are large, when contact comes prior to the heaviest drizzle in the early morning hours, and when the free troposphere is cloud-free.

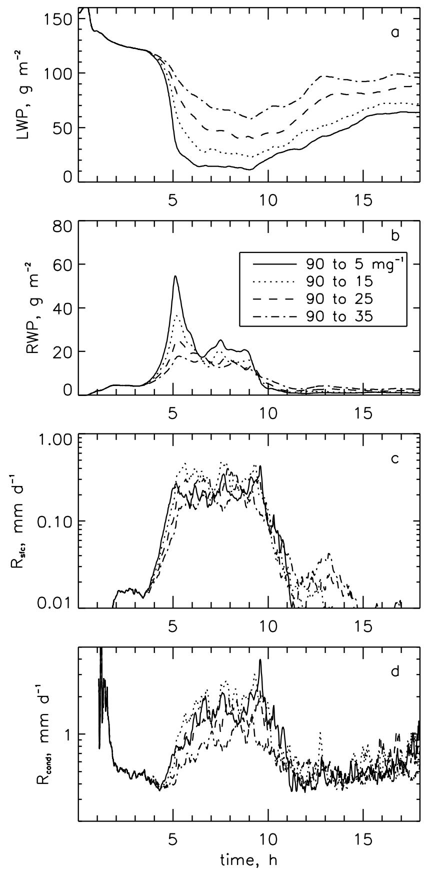

Figure 7: Time series of (a) LWP, (b) rain water path (RWP), (c) do- main mean surface rain rate R_{sfc}, and (d) surface rain rate condi- tionally sampled for $R \geq 0.1$ mm d^{-1} (R_{cond}) for the control case and for the various minimum N as in Fig. 1. Recovery becomes progressively more difficult with decreasing minimum N. The initial spike in surface Rcond is related to the fact that during the first hour of simulation, collision coalescence and sedimentation are not simulated (Fig. 3 in Feingold et al., 2015b).

Precipitation Susceptibility as a Constraint on the Lifetime Effect

Climate models continue to exhibit strong sensitivity to the representation of aerosol effects on cloud reflectance and cloud amount. We embarked on a study to evaluate a recently proposed method to constrain modeled cloud liquid water path (LWP) adjustments in response to changes in aerosol concentration N_a using observations of precipitation susceptibility. Recent climate modeling has suggested a linear relationship between relative LWP responses to relative changes in N_a ($\lambda = d\ln(LWP)/d\ln(N_a)$) and the precipitation frequency susceptibility S_{pop} which is defined as the relative change in the probability of precipitation for a relative change in N_a. Using large eddy simulations (LES) of marine stratocumulus and trade wind cumulus clouds, we showed that these two cloud regimes exhibit qualitatively different relationships between λ and S_{pop} in stratocumulus clouds, λ increases with S_{pop} while in trade wind cumulus, λ decreases with S_{pop}. The LES-derived relationship for marine stratocumulus is qualitatively similar, but quantitatively different than that derived from climate model simulations of oceanic clouds aggregated over much larger spatial scales. We

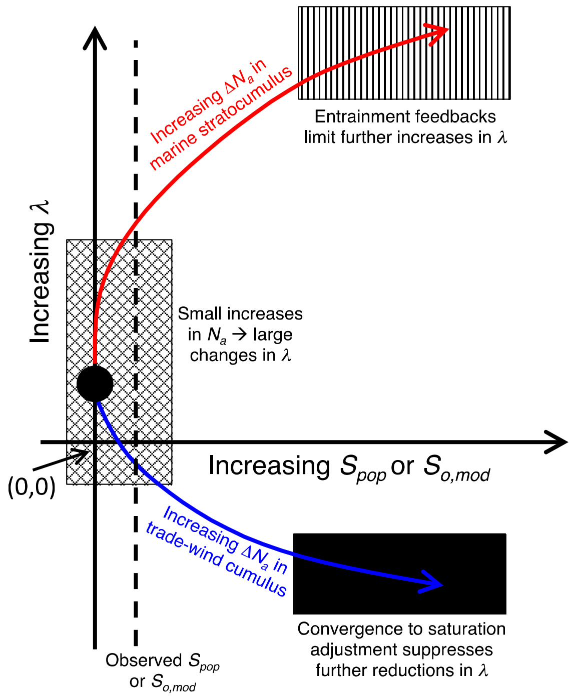

Figure 8: Summary schematic showing two different responses of the lifetime effect to S_{pop} (the susceptibility of the probability of rain (POP) to changes in aerosol).Note that unlike GCM-derived relationships, here two different regimes are identified. The red branch is for stratocumulus and the blue branch for cumulus (from Lebo and Feingold, 2014).

explored possible reasons for variability in these relationships, including the selected precipitation threshold and the various definitions of precipitation susceptibility that are currently in use.

Impact

Because aerosol-cloud-precipitation interactions are inherently small-scale processes, we recommend that when deriving the relationship between λ and S_{pop}, careful attention be given to the cloud regime, the scale, and the extent of aggregation of the model output or the observed data.

Closed to open cell transitions and the role of the spatial distribution of rain

Precipitation is generally thought to be a necessary but insufficient condition for the transformation of stratocumulus-topped closed cellular convection to open cellular cumuliform convection. We decided to test the hypothesis that the spatial distribution of precipitation is a key element of the closed-to-open cell transition (Yamaguchi and Feingold 2015). A series of idealized 3-dimensional simulations were conducted to evaluate the dependency of the transformation on the areal coverage of rain, and to explore the role of interactions between multiple rainy areas in the formation of the open cells. When rain is restricted to a small area, even substantial rain (order few mm day^{-1}) does not result in a transition. With increasing areal coverage of the rain, the transition becomes possible provided that the rain rate is sufficiently large. When multiple small rain regions interact with each other, the transition occurs and spreads over a wider area, provided that the distance between the rain regions is short. When the distance between the rain areas is large, the transition eventually occurs, albeit slowly. For much longer distances between rain regions the system is anticipated to remain in a closed-cell state.

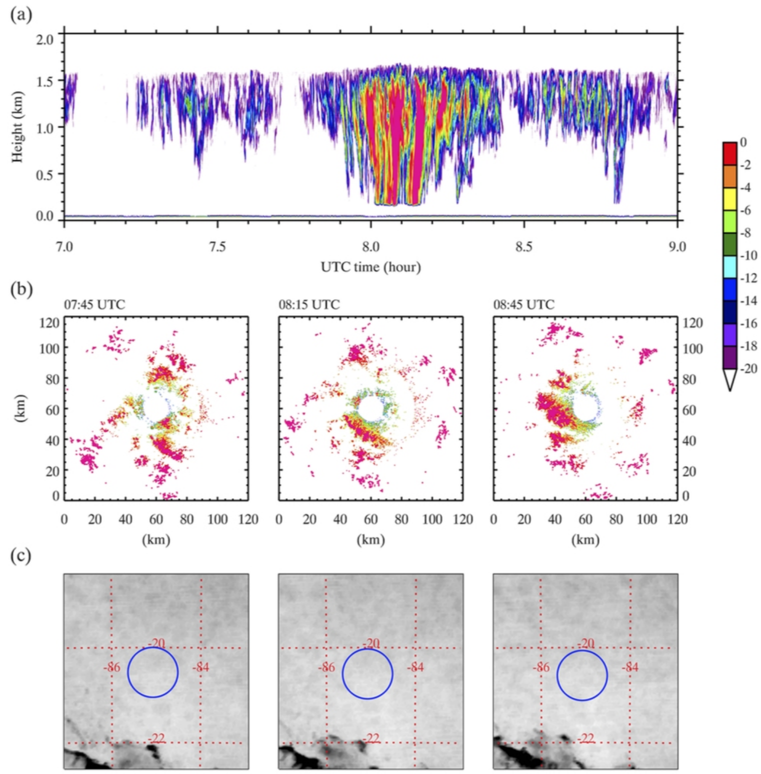

Figure 9: Ship- and satellite-based observations from VOCALS-REx between 07:00 and 09:00 UTC on 23 November 2008: (a) W-band radar reflectivity, (b) C-band radar reflectivity and (c) corresponding GOES infrared image (4 km resolution). The blue circle on each GOES image is the approximate range of the C-band radar. This figure serves as motivation for why spatial distribution of precipitation might be important for the closed to open cell transition. In the images shown here, precipitation is significant but localized and therefore does not induce transition (from Yamaguchi and Feingold, 2015).

Impact

Our results support the surface radar measurements from VOCALS from a particular day which showed significant local precipitation in a closed cell cloud state. These ideas can be combined with satellite remote sensing to gauge the climate relevant impact of closed and open cells.

Resulting publications

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