Organization of shallow and deep convection

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Keynote Speakers

Locally generated convections over land and their driving mechanisms: Inferences from observations

Yunyan Zhang – Lawrence Livermore National Laboratory

Continental shallow cumulus clouds, their transition to deep convection, and their interactions with land surface are very important processes affecting radiative balance and hydrological cycle in the climate system. Over decades, the diurnal evolution associated with these processes, such as growth and dissipation of clouds, timing and intensity of precipitation, and maintenance and organization of convection, still pose great challenges for simulations by global climate models, including the emerging global convection permitting or cloud resolving models at the resolution of several kilometers. In this study, comprehensive ground-based ARM observations and high-resolution GOES-R satellite measurements are used to investigate the characteristics and the driving mechanisms of the locally generated surface-forced shallow cumulus and deep convection. This study consists of two parts, which not only advance our physical understanding but also provide process-oriented perspectives on model diagnosis.

During summertime shallow cumulus days at US Southern Great Plains, we found that cloud occurrence shows strong preferences over heterogeneous land cover types, e.g., the largest cloud fraction over the urban area and the least over the lakes. In general, there is more cloud formation over forest regions than over grasslands. This is supported by the surface observations, in which much larger sensible and latent heat fluxes are found over forest regions and lead to faster PBL development and lower lifting condensation levels. On the other hand, the cloud difference between forest and grassland increases with the heterogeneity patch size and decreases with the wind speed. Moreover, such heterogeneity patch size preference shifts from smaller scales (< 9km) during midday to larger scales (>9km) in early afternoon. This observational evidence supports the theory in which convection is enhanced by secondary circulation, which is driven by differential heating over adjacent patches of forest and grassland and such differential heating intensifies with the diurnal variation of surface heat fluxes from morning to early afternoon.

Using 2-year GoAmazon observations from the scanning precipitation radar, cloud radars and satellite data, the diurnal cycles of tropical continental convections are successfully categorized into regimes including shallow cumulus, congestus, local deep convections, and propagating mesoscale convective systems. In addition, four modes are discovered for local afternoon deep convections regarding precipitation timing and pulse numbers, which include days with early-onset single pulse, early-onset double pulses, late-onset single pulse, and late-onset double pulses. Free troposphere humidity plays a dominant role in controlling the regime transition, e.g., the 4-7 km troposphere humidity is found most different between early-onset and late-onset days, while the humidity difference at 2-4 km is more pronounced between early-onset single-pulse and early-onset double-pulse days. Comparing the first pulse of early-onset double-pulse days with the early-onset single pulse, although with the same onset timing, scanning radar statistics shows that precipitation is attributed to shallow convection at 25% versus 10%, to congestus at 55% versus 40%, to deep convection at 20% and 50%. While the radar statistics of the second pulse of early-onset double days is pretty similar to those of the early-onset single pulse. This supports that the majority population of shallow and congestus convections during the first pulse leads to less consumption of atmospheric instability and their development and dissipation during the first pulse fosters a favorable environment for the second pulse, thus maintain the convection into late afternoon. A further analysis with the tracking algorithm on scanning radar data shows a strong connection between the first and second pulses regarding the evolution of convective clusters. For example, the survival rate of the larger clusters (>10 km) during the second pulse is 1/3 due to aggregation and 1/5 due to natural growth of the clusters back tracking to the first pulse. Such results suggest the importance of convective cell interactions which should be represented in model developments.

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Mesoscale Organisation of Shallow Cumulus Convection: an Qverview.

Pier Siebesma – Delft University of Technology

It has become clear over the last decade that marine shallow cumulus convection has a strong tendency to develop a rich variety of spatial extended cloud structures.

It is particular challenging to simulate these mesoscale cloud patterns. On the one hand, it requires turbulence resolving resolutions to resolve the vertical convective mixing processes while at the same time domains of several hundreds of kilometres are required to represent the resulting large mesoscale cloud structures. It is only recently that the computational capability is allowing us to simulate these richand fascinating structures

In this overview we will address a number of current questions and challenges related to the organisation of shallow cumulus convection:

- how well can we simulate the observed modes of cloud organisation?
- what are the key internal and/or external processes that drive cloud organisation?
- can we parameterise or conceptualise cloud organisation?
- to what extent does it matter for cloud-climate feedback?

Understanding the physical processes governing the iris effect: Precipitation efficiency, upper-tropospheric stability, and possible roles of shallow convection

Hirohiko Masunaga – ISEE, Nagoya University

The iris hypothesis suggests a cloud feedback mechanism that a reduction in the tropical anvil cloud fraction in a warmer climate may act to mitigate the warming by enhanced outgoing longwave radiation. Two different physical processes, one involving precipitation efficiency and the other focusing on upper-tropospheric stability, have been argued in the literature to be responsible for the iris effect. In this work, A-Train observations and reanalysis data are analyzed to assess these two processes. Major findings are as follows: (1) the anvil cloud fraction changes evidently with upper-tropospheric stability as expected from the stability iris theory, (2) precipitation efficiency is unlikely to have control on the anvil cloud fraction but is related to mid- and low-level cloud fractions, and (3) the day and nighttime cloud radiative effects are expected to largely cancel out when integrated over a diurnal cycle, suggesting a neutral cloud feedback.

The iris hypothesis and other theories on tropical anvil feedbacks (e.g., thermostat and FAT/PHAT hypotheses) involve different mechanisms to link deep convection with the anvil clouds it produces. A potentially important element of the cloud radiation interactions in the tropics that has yet to be explored further is shallow convection. Deep convection is a self-destructive system in that deep circulation exports moist static energy from the atmospheric column. Shallow convection, by contrast, has a tendency to grow on its own by importing moist static energy, capable of eventually developing into deep convection. The key role of shallow convection has been hinted at by satellite observations of tropical convection intensifying at ITCZ edges. The effects of shallow convection are discussed as a possible player of the tropical cloud radiation interaction. The potential relevance of the present findings to convective aggregation will be also discussed.

Oral Presentations

Cloud organization, cold pools and water isotopes in large eddy simulations of EUREC4A

Peter Blossey – University of Washington

In trade wind regions over tropical oceans, shallow cumulus cloud cover often dominates. These clouds, which are difficult to represent in global models, were a focus of the EUREC4A/ATOMIC field campaign that took place on and near Barbados in January and February 2020. The field campaign included several ships and aircrafts as well as an island-based cloud observatory, which provide a wealth of in situ and remote sensing observations. A main interest of the field campaign was the organization of shallow clouds and the ways in which clouds and circulations interact to produce the patterns of cloudiness observed from space. These patterns of organization and the processes which give rise to them have been explored in large-domain large eddy simulations of boundary layer air masses as they approach Barbados along quasi-Lagrangian trajectories. (The trajectories are quasi-Lagrangian because they are designed to follow the winds at only one height.) Trajectories are chosen to coincide with periods of intense observations from ships, aircrafts close to Barbados and to correspond to different patterns of organization. They are simulated in three different models, CASIM, DALES and SAM, using domains that are large enough (about 50-100 km square) to permit some cloud organization. These simulations are compared to each other as well as in situ and remote sensing observations. The simulations are also interrogated to understand the physical processes that drive cloud organization.

The EUREC4A campaign also included extensive sampling of water vapor isotopes, in part because water vapor in the marine boundary layer is the starting point for much of the water stored in ice cores and other climate records. In addition, mesoscale phenomena like cloud organization and cold pools --- both observed during EUREC4A --- can be expected to have isotopic signals that reflect the history of condensation, evaporation and mixing in an air parcel. One large eddy simulation model, SAM, includes water isotopes in water vapor, clouds and precipitation, and performed simulations along the quasi-Lagrangian trajectories . This model is used to simulate the evolution of the marine boundary layer and the isotopic composition of vapor, cloud and rain along the Lagrangian trajectories described above. Initial and boundary conditions for the water isotopic composition are drawn from an isotope-enabled GCM, LMDZiso. In addition to comparing the isotopic fields against observations, and the simulations are also analyzed to understand the isotopic signals associated with cloud organization, rain evaporation and cold pools. Cold pools display an isotopic signature and are enriched in the heavy water isotope, HDO. The sub-cloud-layer mass, moisture and isotopic budgets of the sub cloud layer are examined to understand the relative contributions of updrafts, downdrafts and entrainment of cloud layer air in fixing the moisture and isotopic content of sub cloud layer air.

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Cold pool, CAPE, and organization of squall lines: An analytic analysis

Minghua Zhang – Stony Brook University

Mesoscale convective systems (MCS) contribute about half of the world's precipitation and create much of the extreme weather events, but they are poorly parameterized in current climate model. Here, I present a theoretical model of squall lines. The formulations of the model show that given the environmental profiles of wind and the Convective Available Potential Energy (CAPE), the following global properties are all determined if the cold pool strength is known: the propagation speed, the mass fluxes of the front-to-real ascending flow, the overturning circulation and the backside descending, as well as the cold pool height. Implication of the results to parameterizations will be discussed.

Convective Organization and 3D Structure of Tropical Upper Tropospheric cloud systems from synergistic satellite observations and Machine Learning

Claudia Stubenrauch – Laboratoire de Météorologie Dynamique IPSL CNRS 6440

Upper tropospheric (UT) clouds play a crucial role in the climate system by modulating the Earth's energy budget and heat transport. These clouds are most abundant in the tropics, where they often form as cirrus anvils from convective outflow, building mesoscale systems. The radiative heating of the cirrus anvils may be critical to cloud climate feedback.

CIRS (Clouds from IR Sounders) data, retrieved from IASI (Infrared Atmospheric Sounding Interferometers) and AIRS (Atmospheric Infrared Sounder) measurements, which are sensitive to cirrus, provide a horizontal structure of cloud height and emissivity. A cloud system approach allows to link convective core to anvil properties and has been successfully employed to evaluate bulk ice schemes in the LMDZ climate model (Stubenrauch et al., 2019). For a complete 3D view, we need also the vertical structure information, which is given by active radar and lidar from the CloudSat and CALIPSO missions, but only along successive narrow nadir tracks, separated by about 2500 km.

In order to get a more complete instantaneous picture, required for process studies, Stubenrauch et al. (2021) demonstrated that the radiative heating rate profiles derived along these nadir tracks (CloudSat FLXHR-lidar) can be horizontally extended by neural network regression models applied on cloud properties retrieved from CIRS and atmospheric and surface properties from meteorological re-analyses (ERA-Interim provided by ECMWF). The 15-year time series reveal a connection of the heating by mesoscale convective systems in the upper and middle troposphere and the (low-level) cloud cooling in the lower atmosphere in the cool regions, with a correlation coefficient equal to 0.72, which consolidates the hypothesis of an energetic connection between the convective regions and the subsidence regions.

By completing our dataset by the vertical extent, probability of thin cirrus layers above, and lower clouds below as well as rainy areas within the cloud systems and even latent heating rates, we will gain further insight how these anvils evolve, under different environmental conditions, and how they may influence their environment. Therefore we have again used Machine Learning, trained on CIRS data collocated with CloudSat-CALIPSO (GEOPROF-lidar and PRECIP-COLUMN) and with TRMM (Tropical Rainfall Measuring Mission) data. The latter provide the latent heating profiles. These optimized non-linear regression and classification models have then been applied to the time series of CIRS-AIRS and CIRS-IASI data. Furthermore we have determined a convective organization index from the horizontal arrangement of the rainy areas within the UT clouds.

Selected results on the relation between horizontal and vertical structure of the convective systems and on temporal anomalies are presented.

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Disentangling Diurnal and Lagrangian Influences on the Evolution of Trade Wind Mesoscale Morphologies

Isabel McCoy – University of Miami & UCAR

We investigate the evolution of sub-cloud dynamics on diurnal and Lagrangian scales as a function of shallow convective organizational structures in the winter-time trade-winds. Trade-wind mesoscale cloud morphologies have been grouped by their distinct appearance and size into four categories: Sugar, Gravel, Flowers, and Fish (Stevens et al. 2019). Previous studies have examined diurnal (Vial et al. 2021) and multi-day Lagrangian (Schulz et al. 2021) influences on the relative occurrence frequency of these organizational structures and, thus, the overall cloudiness of this radiatively important region. We utilize a synergistic, multi-platform observational dataset developed during the 2020 EUREC4A-ATOMIC joint campaign to further investigate and disentangle these influences. We focus on two multi-day periods: a Sugar-dominated case at the beginning of February and a Gravel-dominated case in mid-January. Large-scale environmental differences between these two morphology-dominated periods are consistent with the 19-year statistics from Bony et al. (2020): lower stability and surface temperatures with higher surface wind speeds during the Gravel-period compared to the Sugar-period. Motion-stabilized Doppler-lidar data allows us to examine updraft, cloud fraction, and cloud base mass fluxes across the diurnal cycle in these two periods. Observations from downwind platforms are anticipated to provide insight into the Lagrangian evolution of these cloud morphologies, including as a function of the environmental conditions expected to influence cloud organization and development (e.g., surface wind speeds, energy and moisture fluxes, stability, and both large- and meso-scale subsidence).

Increased large-scale convective aggregation in CMIP5 projections: implications for tropical precipitation extremes

Martin Singh – Monash University

Convective aggregation refers to the clustering of convective events and occurs on a wide range of spatial scales. It has been suggested that the behaviour of convective aggregation may change under global warming, with potential implications for future changes in precipitation extremes. Building on recent idealised studies, we develop a robust method to quantify large-scale convective aggregation in an ensemble of global climate models that is comparable across models. Applying three separate indices for aggregation, it is found that large-scale convective aggregation increases in 17 of the 19 analyzed models under future warming. However, aggregation is found not to be correlated with tropical-mean precipitation extremes, either climatologically or with respect to the sensitivity to warming. The large model spread in aggregation indices across the ensemble suggests the possible utility of large-scale convective aggregation as a target for model evaluation.

Mesoscale Convective System Cloud Shield Expansion Rates and Connection to Convective Latent Heating

Gregory Elsaesser – Columbia University & NASA GISS

Mesoscale Convective System (MCS) stratiform anvil cloud shields have significant impacts on atmospheric radiation and water budgets. However, across the spectrum of MCSs, knowledge is limited regarding how convective area, depth, and convective core profiles quantitatively connect to stratiform anvil cloud shield time tendencies. In this presentation, we discuss work on improving our understanding of these cloud shields at the system scale via development of a simple source – sink model for MCS cloud shield areas applied to observed tropics-wide systems. Growth occurs when detrained convective mass (newly inferred from satellite-estimated vertical gradients of convective latent heating and temperature lapse rates) and/or generation of convective area exceeds a sink term whose magnitude is proportional to the current cloud shield size. The model works well for systems over land and ocean, and for systems characterized by varying degrees of convective organization and duration, and further reveals that during the decaying stages of system lifecycles, less organized convective clusters within a given cloud shield more readily sustain overall cloud shields, potentially extending cloud shield longevity. The simple model may serve as a useful foundation for improved understanding of processes driving changes in convective system cloud shields, and further supports conceptual development and evaluation of prognostic climate model MCS stratiform anvil area parameterizations, which at present are lacking in many coarse-resolution climate models.

Open-Cell Convection in Marine Cold-Air Outbreaks with Snow

Steven Krueger – University of Utah

Dramatic cloud patterns are typically evident in satellite imagery of winter-time cold-air outbreaks over the the Greenland and Norwegian Seas. The cellular cloud structure usually evolves from closed-cell to open-cell as the air masses traverse the open ocean. Our recent studies suggest that the open-cell structure is a result of a convective cell life cycle that includes the formation of cold pools by snow sublimation with new cells growing at the cold pool edges. Our analyses are based on large-eddy simulations, scanning radar, and polar-orbiting-satellite imagery. Feingold et al. (2010) noticed essentially the same life cycle in subtropical open cell shallow cumulus fields with warm-cloud microphysics. It appears that this type of open cell life cycle has not been previously reported when the surface precipitation is in the form of snow. When the surface precipitation is snow, the open-cell structure is not very evident from satellite imagery or scanning radar because ice hydrometeors obscure the underlying and embedded narrow updrafts. This is evident in the 2D fields from a simulated cold-air outbreak which show the liquid water path associated with narrow updrafts and ice water path associated with broad regions of detrained hydrometeors. Our large-eddy simulation was performed using SAM (System for Atmospheric Modeling) in a 64-km by 64-km Lagrangian domain with a 100-m horizontal grid size. We used the Morrison et al. (2005) two-moment ice-phase microphysics scheme.

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Squall lines orientation and its impact on extreme precipitations

Sophie Abramian – Laboratoire de Météorologie Dynamique

Squall lines are the consequence of the interaction of low-level shear with cold pools associated with convective downdrafts, and beyond a critical shear, squall lines tend to orient themselves. It has been shown that this orientation has the effect of reducing the incoming wind shear to the squall line and maintains equilibrium between wind shear and cold pool spreading (Abramian et al 2021).

While the mechanisms behind squall line orientation seem to be increasingly well understood, few studies have focused on the implications of this organization. However, Roca & Fiolleau 2020 shows that mesoscale convective systems, including squall lines, are disproportionately involved in rainfall extremes in the tropics. One may then question whether the orientation of squall lines has an impact on the rainfall extremes, and if so, then how and why.

Using a CRM, we perform simulations of tropical squall lines by imposing a vertical wind shear in radiative convective equilibrium. Our results show that the extreme precipitation in the squall lines is more intense in the critical organized case. With a scaling of the precipitation extremes (Muller & Takayabu 2019, Da Silva et al 2021), we show that the condensation rates control the precipitation extremes in tropical squall lines. It seems that the critical case is also optimal for the vertical dynamics, a hypothesis that we further investigate here.

The Organization and Vertical Structure of Shallow Convection in Marine Cold-Air Outbreaks, based on Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE): Developing the Framework for an Intercomparison Modeling Study

Timothy Juliano – NCAR

The Arctic's complex atmospheric environment remains a challenge for numerical weather prediction (NWP) models across a range of scales, especially during cold-air outbreaks (CAOs). Under CAO conditions, cold air passes over the much warmer open ocean, leading to strong, positive heat fluxes and a subsequent growth of the convective boundary layer depth with increasing fetch. Moreover, CAO events are typically accompanied by intricate cloud structures that transition from narrow cloud streets or helical rolls near the ice edge to cellular convection downstream. To study the CAO cloud regime at high-latitudes, the Cold-air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) was conducted from December 2019 to May 2020. Measurements taken at a coastal site near Andenes in northern Scandinavia, more than 1000 km downstream of the Arctic ice, reveal the frequent presence of an open-cellular cloud structure defined by regions of strong up- and down-drafts associated with enhanced turbulence and liquid water production, in addition to high cloud tops (reaching up to ~5 km MSL). An exemplary case occurred on 12-13 March 2020, when the synoptic scale conditions led to an intense CAO that was observed at the Andenes site.

Results from preliminary numerical simulations of the event using a Lagrangian large-eddy simulation (LES) approach suggest that the transition from convective rolls to cells is reasonably well captured in a qualitative sense. Nonetheless, we find that discernable differences in parameters important to the radiation energy budget and water cycle (e.g., liquid/ice water partitioning and cloud fraction) arise among two different modeling platforms (the Weather Research and Forecasting, or WRF, model and the System for Atmospheric Modeling, or SAM). Given the wealth of COMBLE data, including value-added products, available at the Andenes site, we are motivated to initiate a community-wide intercomparison modeling study of the 12-13 March 2020 CAO case. This presentation will first highlight initial results from our simulations of the CAO event, including model sensitivities to microphysical parameters (e.g., cloud condensation nuclei and ice nucleating particles), as well as strength of surface forcing (e.g., sea surface temperature). Then, we will provide overarching goals and plans for the proposed intercomparison study in an effort to solicit interest from various modeling groups using approaches including, but not limited to, Lagrangian LES, single-column, or limited-area.

The ubiquity of shallow circulations in the trades

Geet George, presented by Bjorn Stevens – Max Planck Institute for Meteorology

We find an abundance of low-level, mesoscale circulations in the atmosphere below the trade-wind inversion layer based on observations of the mesoscale atmospheric circulation taken during the EUREC4A campaign. Over time-means of 3-6 hours, the mean sub-cloud divergence anomaly correlates negatively with the mean divergence anomaly in the cloud layer. Here, the term anomaly means the deviation from the EUREC4A-wide month-long mean of divergence at the corresponding altitude. Additionally, sub-cloud divergence anomaly correlates negatively with specific humidity anomaly in the sub-cloud and cloud layers, indicating moist, convergent regimes and dry, divergent regimes. We hypothesise that the presence of shallow circulations below the inversion layer explains these associations. Our proposed mechanism of shallow circulations is that regions of ascending air are balanced by neighbouring cells of subsidence, thus creating and maintaining moist and dry regions, which reinforce the shallow circulations. We use mixed-layer theory to estimate the time-scales at which the sub-cloud layer moisture would respond to such divergence patterns. The observed relationships are also evident in reanalysis data, which further reinforce that these are indeed mesoscale features and not large-scale signals captured by the observations.

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Tropical Oceanic Cold Pools in a High-Resolution DYAMOND-ICON Simulation

Piyush Garg – Argonne National Laboratory

In recent years, global kilometer-scale convection-permitting models have shown promising results in producing realistic convection and precipitation. Cold pools, which can be represented by km-scale models, are identified as one of the significant mesoscale processes responsible for modulating the life cycle of mesoscale organized convection. However, there is still a lack of understanding about cold pool properties across the spatio-temporal scales, as well as their representation in models. In this study, a 2.5 km global Icosahedral Nonhydrostatic (ICON) model simulation run for 40 days (06 UTC 01 Aug - 23 UTC 10 Sep 2016) from the Dynamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) initiative is used to identify thermal cold pools (using Tv) over the tropical oceans. The diurnal cycle of simulated thermal cold pools is compared against NASA's RapidScat-observed gradient feature (GF) frequency and IMERG precipitation. ICON and IMERG exhibit morning peaks in cold pool activity similar to RapidScat GF frequency but miss the RapidScat-observed afternoon peak. EUMETSAT's Advanced Scatterometer (ASCAT) and RapidScat GF spatial climatology is also compared to ICON cold pools, where ICON shows more cold pools over the Indo-Pacific and western Atlantic basins. ICON TF size and precipitation percentiles are validated with ASCAT and RapidScat GF size and precipitation, and the simulated cold pool properties depict similar regional variability in cold pool properties with a smaller order of magnitude. Random forest regression is applied to identify critical environmental properties with column water vapor found out to be most important for controlling cold pool number, size, and intensity. Regional differences between cold pool properties are explored, where easterly waves dominate the eastern Pacific and Atlantic cold pool activity. The western Pacific and the Indian Ocean cold pools are controlled by local mesoscale forcing and intra-seasonal oscillations. Thus, a holistic conceptual framework is established to explain the simulated cold pool characteristics over tropical oceans.

Tropical precipitation extremes in global storm-resolving simulations

Jiawei Bao – Max Planck Institute for Meteorology

Precipitation extremes have been found to be closely linked to the behavior of convective organization in idealized storm-resolving simulations of radiative-convective equilibrium. However, such a relationship is not supported by global climate models with a resolution of ~100km. In this study, we investigate with a global storm-resolving model (GSRM) whether tropical precipitation extremes are sensitive to convective organization. When performing these simulations, we have accidentally produced a small ensemble of simulations with very different ITCZ structure: some simulations show very pronounced double-ITCZ structure while one simulation shows a single ITCZ peaking over the equator. The distinct ITCZ structure suggests varying large-scale circulation. Despite the different large-scale conditions, we have identified, across all the simulations, that mean precipitation and convective organization as the two main factors affecting precipitation extremes. Extreme precipitation can be predicted using mean precipitation and organization of convection. They together explain most of the variance of extreme precipitation. When mean precipitation is fixed, the dependency on organization is larger. Such a relationship is highest in data that is coarsened to 0.2 degree, suggesting on the horizontal scales (20 km) that organization impact mostly manifests.

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Unified Boundary Layer and Convection Parameterizations in Global Models

Joao Teixeira – JPL/Caltech and UCLA, presented by Mikael Witte – Naval Postgraduate School

The parameterization of turbulent and convective mixing in global atmospheric models has been a major challenge in weather and climate research for several decades. In particular, different parameterizations are used, and often patched together artificially, for different types of convection: dry or moist, within the boundary layer or in the full troposphere. For example, the eddy-diffusivity (ED) approach has been relatively successful in representing the properties of neutral and stable boundary layers, and surface layers in general. The Mass-Flux (MF) approach, on the other hand, has been often used for the parameterization of shallow and deep moist convection. Recently, higher-order turbulence closures have been implemented in global models to represent boundary layer and shallow convection mixing. However, a fully unified parameterization of turbulence and convection (including deep convection) has never been successfully developed and implemented in atmospheric models.

In this presentation, we discuss recent approaches based on optimal combinations of the ED and MF parameterizations (EDMF), and of higher-order closures with the multi-plume MF approach, as potential solutions for the full unification of turbulence and convection in atmospheric models. We focus on cloud transitions that are critical for weather and climate prediction, such as the stratocumulus to cumulus transition, and the diurnal cycle of convection (from shallow to deep) over tropical land. We discuss the latest results from the recent developments and implementations of these unified approaches in the National Center for

Atmospheric Research (NCAR), the Geophysical Fluid Dynamics Laboratory (GFDL), and the U.S. Department of Energy (DOE) climate models, that culminate in the first fully unified representation of turbulence and convection in global atmospheric models.

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Poster Presentations

CO56 – A new global satellite database of deep convective cloud systems to explore cloud system organization, microphysics and links to atmospheric thermodynamic structure

Eric Wilcox – Desert Research Institute

Deep convective clouds systems span a broad range of scales from isolated convective cells to immense mesoscale convective complexes. A number of factors can be observed to strongly influence the spatial coverage of deep convective clouds systems, and hence the magnitude of their radiative forcing. Furthermore, the total precipitation, and hence latent heating of the atmosphere, increases with increasing cloud system horizontal scale. Factors influencing the horizontal scale of cloud systems include convective aggregation, the level of mesoscale organization of individual cloud systems, the convective available potential energy (CAPE) and vertical shear of the horizontal wind in the cloudy environment, and the microphysics of the cloud. Here we present results from a database of millions of deep convective cloud systems observed by the NASA A-Train of satellite sensors over the entire global tropics, where cloud boundaries have been objectively determined by analysis of infrared satellite observations that identifies deep convective cores and associates them with related anvil cloudiness. The spatial coverage of isolated deep convective clouds, as well as the combined coverage of the core-anvil structure of large mesoscale convective cloud systems, is related to CAPE, shear and the distribution of cloud particle size and phase within cloud boundaries. We describe geographic variations in these relationships and offer observational constraints on these relationships suitable for evaluating climate model parameterizations of the convection and clouds that strongly influence the radiative forcing of tropical climate. A global database of tropical deep convective clouds spanning the record of the MODIS-Aqua satellite's lifetime will be made publicly available as part of this project. We illustrate some applications of the resulting database that relate cloud system scale and structure to regional radiative forcing, convective organization, extreme events and potential evidence of aerosol effects on convective cloud systems.

CO57 – A Study of AR-, TS-, and MCS-Associated Precipitation and Extreme Precipitation in Present and Warmer Climates

Ming Zhao – GFDL/NOAA

Atmospheric rivers (ARs), tropical storms (TSs), and mesoscale convective systems (MCSs) are important weather phenomena that often threaten society through heavy precipitation and strong winds. Despite their potentially vital role in global and regional hydrological cycles, their contributions to long-term mean and extreme precipitation have not been systematically explored at the global scale. Using observational and reanalysis data, and NOAA's Geophysical Fluid Dynamics Laboratory's new high-resolution global climate model, we quantify that despite their occasional (13%) occurrence globally, AR, TS, and MCS days together account for ∼55% of global mean precipitation and ∼75% of extreme precipitation with daily rates exceeding its local 99th percentile. The model reproduces well the observed percentage of mean and extreme precipitation associated with AR, TS, and MCS days. In an idealized global warming simulation with a homogeneous SST increase of 4 K, the modeled changes in global mean and regional distribution of precipitation correspond well with changes in AR/TS/MCS precipitation. Globally, the frequency of AR days increases and migrates toward higher latitudes while the frequency of TS days increases over the central Pacific and part of the south Indian Ocean with a decrease elsewhere. The frequency of MCS days tends to increase over parts of the equatorial western and eastern Pacific warm pools and high latitudes and decreases over most part of the tropics and subtropics. The AR/TS/MCS mean precipitation intensity increases by ∼5%/K due primarily to precipitation increases in the top 25% of AR/TS/MCS days with the heaviest precipitation, which are dominated by the thermodynamic component with the dynamic and microphysical components playing a secondary role.

CO59 – An A-Train Convective Object Database for Studying Atmospheric Convective Processes

Juliet Pilewskie – University of Wisconsin-Madison

Atmospheric convective systems influence the Earth's Energy Budget and Water Cycle through their cloud radiative effects and precipitation. As the Earth warms, convective organization may change leading to high cloud feedbacks that alter how convection contributes energetically to the climate. One of the key challenges facing the climate prediction community is constraining the high cloud feedback owing to incomplete understanding of the environmental factors that contribute to convective organization. This is, in part, due to the challenge of acquiring global-scale observations that capture convective behavior at fine spatial and temporal scales. The A-Train, despite only twice-daily sampling, is able to determine the cloud properties, precipitation, and radiative effects of convection on a nearly global scale. Using a global database of convective objects (COs) generated from four years of A-Train measurements, we document the intensity, size, precipitation, and radiative effects of storm systems globally. We leverage the day and night sampling of instruments on board the A-Train to contrast the character of early afternoon and nighttime convection, and extrapolate the seasonal cycles of the most intense storm systems observed. Results suggest that the population of the most intense storms resides over the Amazon and the Congo, yet these storms tend to be smaller than those found in Southeast Asia and the tropical East Pacific Ocean. On a global scale, COs contribute a net cooling effect but individual storms exert a wide range of radiative impacts with many storms actually warming their environment. The A-Train observations also allow the number of distinct convective cores in each system to be distinguished providing insights into the structural dynamics of storm development. CO size increases as the number of distinct convective cores in a CO increases, which is due an increase in non-convective rain and anvil cloud area. Despite the large greenhouse effect of extensive anvils, cooling only slightly weakens for COs that have an increased number of cores and anvil extent. This emphasizes the importance in understanding the role that anvil thickness plays in influencing net cloud radiative effects, as well as how convective cloud features and precipitation vary in response to differing environments.

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CO61 – Causes of bias in cloud size distributions

Thomas DeWitt – University of Utah

Cloud area distributions, while being an important component in global climate model parameterization, are surprisingly complex to determine from satellite data due to the fractal nature of clouds. While clouds are generally accepted to be power-law distributed in area, previous studies have found inconsistent parameters and evidence for scale breaks at different sizes. We show results from a “first guess” determination of cloud sizes using images from multiple space-based instruments including MODIS, POLDER, EPIC, and GOES-ABI, which are highly inconsistent in the location of a scale break and the parameters of the distribution. To explain the differences, we investigate two effects that are found to bias results that are previously under-studied.

The first source of bias is the treatment of clouds that touch the edge of the image. While previous studies give little or no mention to decisions made about these clouds, we show that these decisions can both affect the distribution and create behavior that could be misinterpreted as a scale break. We also investigate the effects of increasing pixel size across the image, which can further bias the measured size distributions. To differentiate these measurement effects from actual features of cloud fields, we examine several simple physical models that create 2-D binary images akin to cloud fields: the Ising model of a ferromagnet and a simple model of liquid percolating through a lattice. Both models are well studied and are known to produce power-law size distributions. Using these models, we show that the treatment of clouds on the edges of the image as well as the variation of pixel sizes across the image can produce inconsistencies of a similar magnitude to those seen in the satellite images. Finally, we propose methods to identify and account for the bias accrued due to these effects with direct applicability to clouds seen from satellites as well as fractals in other fields.

CO63 – Convective Momentum Transport in Organised Shallow Cumulus Fields

Alessandro Savazzi – Delft University of Technology

In winter, the north Atlantic trade wind region is characterised by shallow convective cumulus clouds and persistent easterly winds. These clouds and their organization have the potential to greatly influence Earth's radiation balance and climate sensitivity. Recent studies have shown that near surface wind speed is one of the factors that correlates with the type of organization.

In this study we investigate on the one hand, how convection (in differently organised states) may influence winds via convective momentum transport (CMT) and on the other hand, how CMT may help regulate convective organization. To improve our understanding of this interplay between winds and clouds, we make use of model experiments and measurements from the EUREC4A field campaign. This is the largest observational campaign of the coupled atmosphere-ocean system, it took place in a region eastward of Barbados between January and February 2020. EUREC4A provided unique measurements of wind profiles and wind divergence at the mesoscale for a prolonged period of time

Observations suggest that in early February, deeper convection and larger cloud structures are associated with a different profile of eddy momentum flux divergence than days with shallower convection. Using large eddy simulation hindcasts and a mesoscale weather model, this study investigates the profiles of eddy momentum flux associated with turbulence, convection, and mesoscale flows during the EUREC4A field campaign.

Within EUREC4A, we select a ten-day period for which the Dutch Atmospheric Large-Eddy Simulation (DALES) is run on a 150 km x 150 km domain with a resolution of 100 m. Its boundaries are forced hourly with dynamical tendencies from the mesoscale weather model (HARMONIE), which is initialised every 24 hours from ERA5. HARMONIE is also run in a climatological mode on a 3200 km x 2000 km domain with 2.5 km resolution, in runs with shallow convective momentum transport on and off.

After addressing how well the simulations capture the observations, we answer the following questions:

How is eddy momentum flux divergence carried by flows at different scales? Do mesoscale circulations accompanying convective cloud systems significantly impact the mean wind? And what is the role of CMT on the organization of the cloud field?

The model simulations also allow us to address ECMWF forecast wind biases, which we already showed are linked to biases in the momentum budget. By decomposing the eddy momentum flux divergence introduced on various spatial and temporal scales: from small-scale turbulence to cloud- and meso-scale circulations, we will test our hypothesis that the IFS misrepresents momentum tendencies introduced by convection in the cumulus layer.

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CO64 – Ensemble of Radiative-Convective Equilibrium Simulations near the Marginal Boundary between Aggregated and Scattered Regimes

Ching-Shu Hung – University of Tokyo

An ensemble of ten radiative-convective equilibrium (RCE) simulations near the sharp transition zone between scattered and aggregated states are examined in a square-domain cloud-resolving model. Surprisingly, the occurrence of self-aggregation is not deterministic near the boundary line of the two states, with six runs reaching an aggregated state and four runs returning to scattered states. A spatial autocorrelation length analysis reveals that the development of moisture contrast in the boundary layer (BL) is the key indicator for self-aggregation. To reach an aggregated RCE state, a part of the BL needs to be dry and extensive sufficiently to suppress convection triggered by collisions of intruding cold pools. Furthermore, the relation between moisture aggregation and convective organization is elucidated. In a shorter time-scale, convective organization is governed by cold pool dynamics. Meanwhile, large-scale moisture determines the region of active convection for time-scale longer than 2 days.

CO65 – Environmental Factors Regulating Deep Convective Updraft Width across a Spectrum of Convective Modes

Jake Mulholland – Naval Postgraduate School

The width of deep convective cloudy updrafts is a critical cloud-scale property that influences updraft vertical mass flux, cloud dilution, and vertical velocity. Numerous environmental factors are hypothesized to influence updraft width. In this research we specifically address the impacts of variations in lifting condensation level (LCL) height on the width of unsheared updrafts and the influence of variations in vertical wind shear (hereafter “shear”) magnitude on the width of squall line updrafts. Using large-eddy simulations, we demonstrate that: (1) in unsheared environments, as the LCL is raised, updrafts become wider and (2) in sheared environments, as shear is increased, squall line updrafts become wider. In the unsheared simulations, higher LCLs allow dry thermals more time to grow wider as they ascend below the LCL, which sets the stage for wider moist updrafts above the LCL. In the sheared squall line simulations, stronger shear increased the total amount of inflowing air with nonzero convective available potential energy, and through a mass continuity argument, resulted in wider updrafts. In both simulated environments, wider updrafts displayed less entrainment-driven dilution of core buoyancy, which resulted in stronger and deeper updrafts. These results shed light on a subset of the numerous environmental factors that may impact updraft width and in turn cloud dilution and updraft strength.

CO66 – How well do large-eddy simulations capture the observed co-variability of trade-wind cloudiness and its environment?

Hauke Schulz – Max-Planck-Institut für Meteorologie

Recent observations revealed that meso-scale patterns of shallow convection in the downwind trades can be connected to specific atmospheric environments whose characteristics are not solely from within the trades but have traces from tropical or mid-latitudinal origin depending on the pattern. As a consequence of this co-variability of patterns and air-mass characteristics, a different feedback to a changing climate is anticipated and will be modulated by the observed, pattern-dependent net cloud radiative effects. By conducting large-eddy simulations we evaluate how well current climate models reproduce this co-variability in cloudiness and its environment and whether the meso-scale patterns are represented due to the observed mechanisms. To capture the full range of patterns and its processes these simulations are done on a large-scale domain with grid-spacings of 625m, 312m and 156m and focus on the EUREC4A field campaign time period for further observational process understanding.

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CO67 – Improving shallow convection in the DOE SCREAM model with the Stochastic Moist Multi-Plume Mass-Flux parameterization

Maria Chinita – University of California Los Angeles

Convection is still one of the largest sources of uncertainties in global circulation models partly due to the difficulty in correctly representing it. High-resolution modeling, such as cloud-resolving models, emerges as a way to reduce the climate sensitivity uncertainty associated with convection parameterizations by explicitly resolving deep convection. The Simple Cloud-Resolving E3SM Atmosphere model (SCREAM) is a high-resolution global model (in development) that aims to run globally at a resolution of 3 km offering the opportunity to finally reduce long-standing errors and uncertainties on climate modeling. Nevertheless, planetary boundary layer turbulence and shallow convection still need to be parameterized which in SCREAM is accomplished through the TKE-based Simplified Higher-Order Closure (SHOC)—a simplified version of the assumed doubled-Gaussian PDF method combined with a 1.5-order turbulence closure.

Here, we introduce the implementation into SCREAM of the Stochastic Moist Multi-Plume Mass-Flux (MF) parameterization which is coupled to SHOC, and we discuss its performance for shallow convection using single-column model results and reference large-eddy simulation (LES) data. Briefly, the results show that the coupling of SHOC and MF leads to a better representation of the thermodynamic quantities and their turbulent fluxes, and cloud macrophysics relative to the reference LES data. This is possible due to the MF scheme properties, i.e., MF represents the most energetic plumes capable to travel from the surface to the top of the cloud layer providing a source of countergradient transport without reducing the top entrainment flux needed for a proper convective boundary layer deepening.

CO68 – Investigating the Effect of Orography on Deep Convection Over Tropical Islands

Frank Robinson – Sacred Heart University

An examination of the Tropical Rainfall Measuring Mission (TRMM) satellite database (1994-2015) of 280 tropical islands, reveals an overall weakening of convection with increases in peak island elevation or surface wind speed. By running simulations with different surface fluxes, we find that to reproduce these trends in simulations, requires a weak solar heating combined with a sounding with a high Convective Available Potential Energy (CAPE). In the simulations, the key metric determining convective vigor is the size of the pre-convective reservoir of CAPE. The observations and simulations imply that, the strongest deep convective events occur for islands with 100-500m elevation and a weak diurnal cycle.

CO69 – Linking cloud-radiative feedbacks to precipitation extremes in the tropics

Brian Medeiros – National Center for Atmospheric Research

This study uses a hierarchy of climate model experiments to establish that cloud-radiative feedbacks contribute to extreme precipitation over tropical oceans. The experiments remove cloud-radiation interactions in two different ways: by making clouds transparent to longwave radiation (so-called "COOKIE" experiments), and by prescribing clouds to the radiation code of one model from a previous, independent simulation (the cloud-locking method). The COOKIE experiments are from the CFMIP archive, and include 5 models contributing experiments with realistic geography and four that also contributed zonally symmetric aquaplanet configurations. The cloud-locking experiments were conducted with CESM2 in both coupled and prescribed-SST configurations. In all cases, tropical extreme precipitation reduces without cloud-radiative effects. The reduced extreme precipitation without cloud-radiative feedbacks does not arise from changes in the mean climate. Rather, evidence is presented that cloud-radiative feedbacks enhance organization of convection, and therefore foster environments that lead to extreme precipitation. Moisture modes are suppressed in the absence of cloud-radiative feedbacks, and detection and tracking of individual events shows that in most cases the models produce fewer, but larger, convective events when cloud-radiative feedbacks are disabled. The impacts in the cloud-locking experiments are smaller than in the COOKIE experiments, hinting that the coupling between cloud-radiative effects and the convective atmosphere may play an important role in organizing convective events that produce extreme precipitation.

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CO71 – Observational Evidence for Dependencies of Cloud Properties and Radiative Fluxes by Cloud Types on Measures of the Degree of Convective Aggregation

Kuan-Man Xu – NASA Langley Research Center

Convective aggregation can increase the degree of convective organization, which includes a mode of self-aggregation phenomenon appearing in idealized radiative-convective equilibrium simulations from cloud resolving models and general circulation models under constant, uniform sea surface temperature, with humid clusters surrounded by dry patches. For aggregated convection, the domain-mean column water vapor (CWV) and column relative humidity (CRH) are lower, precipitation is stronger while outgoing longwave radiation is higher, compared to non-aggregated convection. Other characteristics of convective aggregation include a large subsidence fraction (or a small ascending fraction) and large variances of CWV or vertical motion. Can all of these measures and morphology-based aggregation indices provide a similar description of convectively aggregated states? In this study, we use observational data from Clouds and the Earth's Radiant Energy System's (CERES) flux-by-cloud-type (FBCT) data product and Modern-Era Retrospective analysis for Research and Applications (MERRA-2) data to address this question.

The FBCT data provide cloud fraction, frequency, cloud macrophysical and microphysical properties and radiative fluxes of each cloud type that is characterized by cloud optical depth and effective cloud pressure. The MERRA-2 reanalysis data are used to calculate measures of the degree of convective aggregation based upon either thermodynamic or dynamic variables. Most of these measures such as CRH and subsidence fraction are closely related to each other with lowly and highly aggregated sub-populations being segregated for each index. However, none of them is correlated with the morphology-based indices such as simple convective aggregation index (SCAI), modified SCAI (MCAI) and convective organization potential (COP). This is related to the fact that values of these indices have no preferrable geographic locations. But the MERRA-2 measures show that weakly aggregated states are located over the equatorial belt and strongly aggregated states are located over higher latitudes. We match these measures/indices over 10°x10° grids to the same regions in the FBCT data and divide the entire population (~30,000) into three equal-size sub-populations (i.e., low, moderate and strong aggregation) for a given measure or index. The analysis domain covers the tropical belt between 25°S and 25°N. Individual cloud systems identified from another CERES data product are used to calculate SCAI, MCAI and COP. The deviations of cloud and radiative properties by cloud type from those of the entire population are examined for each of low, medium and high aggregation sub-populations.

For SCAI, MCAI and COP, the deviations of cloud and radiative properties are mirror images to each other between the low and high aggregation sub-populations, with small magnitudes of deviations for the moderate aggregation sub-population. This is less true for MERRA2-calculated measures. For the high aggregation sub-population, there is a general trend of more frequent occurrence of optically thick clouds and less frequent occurrence of optically thin clouds for all measures/indices except for SCAI, which show less frequent occurrence of optically thick clouds. Both SCAI and MCAI show much higher frequencies of occurrence for optically-thin low-level clouds. The middle-level liquid clouds show less frequency of occurrence for SCAI/MCAI/COP, which is opposite to those of MERRA-2 measures, although the general trend is similar for ice clouds, i.e., less optically thin clouds but more optically thick clouds except for SCAI. The liquid/ice water path trends are largely similar, but liquid droplet radius and ice diameters have opposite trends for nearly all cloud types between the morphology-based indices and MERRA-2 measures, which likely contribute to the opposite trends in shortwave flux; that is, cooling for morphology-based indices but warming for MERRA-2 measures. Longwave flux trends are more similar, with warming for optically thin and low-level clouds and cooling for optically thick and high-level clouds. The magnitude of cooling is particularly large for MCAI and COP. The contrasting behaviors in SW and liquid droplet radius and ice diameters are attributed to the different locations of high aggregation states for different measures/indices.

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CO72 – Organization as an evolutionary game theory strategy

Brian Mapes – University of Miami

Convective motions of different scales and configurations are invigorated according to their success at lowering the center of mass, and evolve according to the laws of mass continuity and inertia. Harsher conditions like shear or congested microphysics or more top-heavy instability can disfavor the simplest strategies like plumes, allowing the energy resource to accumulate for more unlikely (low-entropy) configurations which for that reason take longer to develop from rest. We seek to illustrate the value, or ideally even the necessity, of such evolutionary interpretations to explain cloud-model experiments contrived to challenge them and to confound other interpretive frameworks.

CO73 – Quantitative analysis of cloud self-organization using Shannon's information entropy: Results from radiative convection equilibrium experiments

Takuya Jinno – The University of Tokyo

The intensity of precipitation and the radiative fluxes in and out of the atmosphere change intensely depending on the spatio-temporal distribution of clouds and have a significant impact on the global climate. To understand these changes physically, it is useful to isolate the complex mechanisms involved in the organization of clouds and precipitation into hierarchical processes. In this study, we used Shannon's information entropy, a measure corresponding to the clutter of spatio-temporal patterns, calculated from the orthogonal function expansion of spatio-temporal variability, as an index to quantify the degree of cloud self-organization. As a result of the analysis of the outward longwave radiation and precipitable water data obtained from the equilibrium experiment of radiative convection in the cloud-resolving model, it was found that each mode of variability, such as the drying trend of the entire experimental region and the appearance of moist regions with active convection, could be separated, and the value of the information entropy decreased in conjunction with the formation of cloud clusters. In addition, it was confirmed that the information entropy value decreases in conjunction with the formation of cloud clusters. The results suggest that the use of information entropy is useful for analyzing self-organization phenomena that appear under idealized conditions with high resolution.

CO74 – Shallow-to-Deep Convection Transition in Amazonia from GOES and GoAmazon 2014/5 Observations

Henrique Barbosa – UMBC

In tropical continental regions, atmospheric convection spans a wide range of spatial and temporal scales and is hardly properly captured by regional or global atmospheric models. The representation of shallow-to-deep (STD) convective transition is particularly challenging, which limits the confidence of modeled climate change impacts on the hydrological cycle.Here we make use of Cloud Top brightness Temperature (CTT) from GOES13 and ground observations from DOE/ARM deployment in the Amazon region (GoAmazon 2014/5) to study the STD transition. We identified 86 afternoon STD events from sep-2014 to aug-2015, and built composites centered at the time of minimum CTT (t_0) for various thermodynamic variables. Our results show the PBL (LCL) height rising from 250 m (200 m) at -12h to 800 m (600 m) a -4h, while the LFC is dropping from 1750 m to 750 m, and CAPE is increasingfrom 800 J/kg to 2200 J/kg. Warm (CTT > 0^oC) and cold (CTT < -38^oC) cloud fractions are rather constant during these first hours, around 25% and <3% respectively. We found that the rapid vertical development (STD transition) occurs when the LFC encounters the LCL. Thecongestus phase happens from -4h to -2h, when warm CF decreases to 15% and cold CFincreases to 15%. Congestus organize into deep towers from -2h to 0h, at the expense of quick CAPE consumption. During the whole process, CTT drops from 290 K to 220 K and PWV convergence amounts to +4 mm. Precipitation occurs from -30min to +30min, when warm CF reaches a minimum of 8% and cold CF a maximum of 60%. Results from previous studies for the dry season (Jun-Nov) indicate anomalously high PWV at begin of days with the STD transition. We found that this is not the case during the wet season (Dec-May), and we are currently investigating other possible mechanisms.

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CO75 – Simulating marine cloud morphology at operational scales

Joseph Olson – NOAA/GSL

Unorganized marine shallow cumuli are completely subgrid-scale clouds for most operational-scale (O(1-12 km)) models but organized structures become at least partially resolved within this window. The unorganized shallow cumuli are represented by the mass-flux portion of Eddy-Diffusivity Mass Flux (EDMF) scheme but the EDMF scheme must at some point hand off this representation to the resolved-scale model dynamics as structures become organized (resolved). This is an important and practical research topic for operational-scale modeling. The interplay between the local and nonlocal mixing and the resolved circulations is investigated for some EUREC4A/ATOMIC cases at grid spacing of $\Delta x = 12$, 3, and 1 km and compared to in-situ observations, satellite, and SAM LES using forcing from ERA5. The degree of success for each case varies, as determined by the mean PBL structure, vertical and horizontal cloud structures, and PDFs of cloud properties. Our focus, on both the successful and more challenging cases, is to (1) determine the sources of success and failure, (2) critique whether or not we are getting positive results for physically justifiable reasons, and (3) experiment with adjustments to the physical parameterizations in an attempt to improve the cloud morphology while always revisiting (1-2). We intend to present the results of our experiments with shameless transparency. The methods used for the most successful cases will be highlighted and reasons for failure will be open for ridicule.

CO76 – Study of the organization of cumulus clouds and cold pools using LES simulation

Nicolas Maury – LMD UMR-8539

Trade wind cumulus clouds cover a significant part of the oceans, especially near the subtropics. Recent studies have shown that these cumulus clouds can organize at the mesoscale (Bony et al., 2020). During the EUREC4A (Elucidating the role of clouds-circulation coupling in climate) field campaign (Stevens et al., 2021), a case of transition between shallow cumulus clouds – denoted “sugar-type” cloud patterns in Bony et al., 2020 - and larger structures – denoted “flower-type” cloud patterns - was observed during the 2-3 February 2020 period. This transition case was simulated and analyzed using a Large Eddy Simulation (LES) in the study performed by Narenpitak et al., 2021.

Starting from this simulation and compared with data collected during the EUREC4A campaign, this study first focuses on the statistical properties of cloud objects, especially their number and size. Hence, the related thermodynamical properties of the subcloud layer are analyzed to interpret the transition from one type of mesoscale organization to another. The role of processes like thermals, cold pools and low-level convergence will be particularly investigated.

CO77 – The processes driving the organization of the trade-wind flower- and gravel-clouds transition

Thibaut Dauhut – CNRM/Météo-France

The trade-wind cumuli are a great source of uncertainty for the future climate as their net radiative effect is hardly represented in the global models. The spatial organization of these clouds, that drives their radiative effect, has been categorized into 4 major patterns: Sugar, Flower, Gravel and Fish (Bony et al. 2020). The processes governing their spatial organization and the relationships with the large scale environment remain however unclear. This study investigates the processes that shape the clouds organized as Flowers and Gravel observed east of Barbados, during the EUREC4A-ATOMIC campaign. These investigations are performed thanks to Large-Eddy Simulations using the Meso-NH model and a 100-m horizontal grid-spacing downscaled from the operational AROME model, and in synergy with high-resolution cloud observations. A particular attention is paid to the realism of the simulated clouds and clear sky patterns by comparison with airborne and spaceborne observations. For the Flower case, we show that the processes shaping the flower-clouds are wide cold pools below the clouds. At the edge of the cold pool, intense convergence of humidity drives the development of updrafts, organized in arcs. These updrafts shape the flower-cloud top and supply the cloud layer with water. For the Gravel case, ongoing investigations are led in order to determine the role and the characteristics of the cold pools, and how they contrast with the ones in the Flower case. Modifications of the initial fields are used to assess what ingredients are key for the mesoscale organization. The underlying processes that differentiate Flower from Gravel and their dependence on the environmental conditions are then proposed.

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CO78 – The role of vertical wind shear in the shallow-to-deep transition

John Peters – Naval Postgraduate School

Predicting the timing of the initiation of convection initiation (DCI) is a longstanding problem in global climate models. Parametrizations often assume DCI occurs once shallow updrafts overcome convective inhibition (CIN). However, an updraft overcoming CIN is a necessary-but-not-sufficient condition for the development of deep convection. Hence, I will explore how conditions other than CIN influence DCI, such as free tropospheric relative humidity (RH), initial sub-cloud updraft width (R), convective available potential energy (CAPE), and vertical wind shear.

I will first explore theory and large eddy simulations (LESs) of unsheared convection. My results indicate that larger values of R, RH, and CAPE generally promote stronger and deeper updrafts, increasing the probability of DCI. A sharp thresholding behavior occurs, whereby for a given RH and CAPE, very small increases in R result in commensurately large changes in cloud depth. Updrafts in drier environments and with narrow R are prone to a structural breakdown into individual updraft pulses, resulting in a thermal-like updraft; whereas, updrafts with large R and/or a moist environment are vertically continuous and plume-like.

I will then expand the theory and body of LESs to explore the influence of vertical wind shear on DCI. For fixed RH, CAPE, and shear, clouds with small R will generally experience suppressed growth rates via downward oriented shear-induced aerodynamic forces, and the probability of DCI is consequently reduced by shear. In contrast, clouds with large R in otherwise identical conditions will experience a positive feedback cycle, whereby they increase their widths, depths, and low-level inflow until reaching an organized steady-state. Hence, in this second outcome shear facilitates DCI. There is also a strong bifurcation between these two outcomes, with a change in R of merely 100 meters determining whether or not shear “helps or hurts” DCI.

CO79 – Using Perimeter Size Distributions to Evaluate Changes in Anvil Cloud Coverage

Corey Bois – University of Utah

Since the introduction of the Fixed Anvil Temperature (FAT) hypothesis (Hartmann & Larson, 2002), the radiative impacts of anvil clouds have been of primary interest in cloud-climate feedbacks. Despite numerous studies of anvil coverage, there is currently no widespread consensus on the sign or magnitude of anvil cloud feedbacks. Recent research has used 3D radiative-convective equilibrium (RCE) and global climate models to show that anvil coverage is likely to decrease with increasing sea surface temperatures; thermodynamic constraints have been derived to explain these results (Bony et al., 2016). Even if anvil coverage decreases in a warmer climate, the reduction may be accompanied by changes in low cloud coverage, further complicating our understanding of large-scale cloud field dynamics. Here we build upon our prior research to determine the organization of cloud coverage and how it may change in a warmer climate.

Convective clouds have been proposed to perform ‘buoyancy sorting’, where detrained cloudy air parcels move to their points of neutral buoyancy. A parcel’s saturation static energy (SSE) is defined as the threshold enthalpy where a parcel of air would become just saturated. The advantage of SSE is that it represents a point of neutral buoyancy at the interface of cloudy and clear air (Arakawa and Schubert 1974). Using this property of SSE, we provide evidence from simulations that the mean anvil cloud height occurs at the intersection of the vertical SSE profile and the domain-averaged SSE. Essentially, since SSE is a neutrally buoyant point for cloudy air, the height corresponding to the domain-average SSE represents the equilibrium level where maximum cloud coverage is likely to occur.

In order to better understand anvil coverage under different climate scenarios and how these changes may affect the prevalence of high and low clouds, we analyze the distributions of cloud perimeters versus cloud size using cloud-resolving RCE simulations with varying sea surface temperatures (SSTs). Garrett et al. 2018 demonstrated that by considering the small-scale mixing interactions along cloud edge, we can derive the large-scale relationship between cloud perimeters and cloud sizes. By building on this framework, we expect that an increase in upper tropospheric stability associated with higher SSTs (Bony et al. 2016) will lead to a larger total perimeter. How this increase in total perimeter affects total cloud coverage remains unclear.

We are interested in cloud perimeters because cloud edges act as the interface between clear environmental and cloudy convective parcels. Exchanges of energy and mass between the environment and a cloud occur across cloud perimeters. By viewing a cloud field as a perimeter distribution that varies in height and energy, rather than a spatial distribution of moisture and wind, a simple statistical organization of clouds emerges (Garrett et al. 2018). We take advantage of these statistical distributions to show how anvil coverage may change in a warming climate as well as any changes to cloud coverage at other heights.

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