Evaluating Large-Eddy Simulations of Boundary-Layer Cloud Response to Climate Change using MAGIC Observations

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Abstract

Over the cool waters off California, a persistent and extensive deck of low-lying clouds forms atop a shallow, turbulent layer of moist air extending 500-2000 meters above the ocean, above which the air is much warmer and drier. Its west edge varies with weather and season and is typically half way to Hawaii. This cloud deck and similar cloud decks elsewhere reflect sunlight back to space, cooling the underlying ocean and indeed the entire planet. They must be accurately represented by a climate model to correctly simulate our current climate or future global warming. Most climate models suggest these cloud decks will thin and break up in a warmer CO_2-enriched climate, so extra sunlight would reach the ocean surface and amplify warming worldwide. But these models have difficulty accurately simulating the cloud thickness and extent because the turbulent cloud-forming air currents are much too small to be simulated by their coarse computational grid.

In 2012-2013, the DOE Atmospheric Radiation Measurement MAGIC program instrumented a container ship transiting between California and Hawaii to observe clouds and rain, small particles (aerosols), and weather conditions. Data were obtained from 20 4-6 day cruises in each direction. This study tested whether a sophisticated 'large-eddy simulation' (LES) of the turbulent air motions that create the clouds in this region accurately predicts the variations in cloud properties seen across the different cruises. If so, that model is more believable for predicting cloud changes in this region in a future warmer climate. Our LES used a numerical mesh over a 6.4x6.4 km region with 50 m horizontal and 5 m vertical grid spacing to simulate the cloud-forming eddies and the sharp overlying transition between moist and dry air. To better compare with MAGIC observations, we configured our model to simulate a region that moved along with the ship. We used a weather forecast model to specify effects of the large-scale air flow. We compared our results with balloon ascents, a radar and other instruments pointed upward at the clouds, measurements of downward sunlight and infrared radiation, aerosols, and weather variables for all suitable cruise periods. Our LES was remarkably skillful in predicting the cloudiness variations measured by the ship. MAGIC also sampled mesoscale cells, regions of cloud thickening and thinning over distances of 10-50 km. An LES run over a larger region 100 km on a side shows these cells form spontaneously, enhanced by strong radiative heat loss at the cloud tops.

Acknowledgements

At the University of Washington, graduate research assistant Jeremy McGibbon, research scientist Dr. Peter Blossey, and postdoctoral associate Dr. Xiaoli Zhou collaborated with the PI to conduct key aspects of the research described below. Dr. Ernie Lewis (Brookhaven National Laboratory) led MAGIC from start to finish, ensuring high-quality data was gathered and advising us and others. Dr. Maike Ahlgrimm (ECMWF) helped us with numerous technical issues with the ECMWF numerical weather analyses used by our large-eddy simulations.

Introduction

Our results will be summarized using the abstract of each of the three papers supported by this funding (slightly reworded where necessary for clarity) along with three key figures from each paper (with captions reworded to provide more context). The References provide links to the full papers. The Appendix lists workshop/conference presentations of the funded work.

Paper 1 (McGibbon and Bretherton 2017): *Skill of ship-following large-eddy simulations in reproducing MAGIC observations across the Northeast Pacific stratocumulus to cumulus transition region*

During the Marine ARM GPCI Investigation of Clouds (MAGIC) in October 2011 to September 2012, a container ship making periodic cruises between Los Angeles, CA, and Honolulu, HI, was instrumented with surface meteorological, aerosol and radiation instruments, a cloud radar and ceilometer, and radiosondes. Here large-eddy simulation (LES) is performed in a ship-following frame of reference for 13 four day transects from the MAGIC field campaign. The goal is to assess if LES can skillfully simulate the broad range of observed cloud characteristics and boundary layer structure across the subtropical stratocumulus to cumulus transition region sampled during different seasons and meteorological conditions. Results from Leg 15A (Fig. 1.1), which sampled a particularly well-defined stratocumulus to cumulus transition, demonstrate the approach. The LES reproduces the observed timing of decoupling and transition from stratocumulus to cumulus and matches the observed evolution of boundary layer structure, cloud fraction, liquid water path, and precipitation statistics remarkably well (Fig. 1.2). Considering the simulations of all 13 cruises, the LES skillfully simulates the mean diurnal variation of key measured quantities, including liquid water path (LWP), cloud fraction, measures of decoupling, and cloud radar-derived precipitation (Fig. 1.3). The daily mean quantities are well represented, and daily mean LWP and cloud fraction show the expected correlation with estimated inversion strength. There is a -0.6 K low bias in LES near-surface air temperature that results in a high bias of 5.6 W m^{-2} in sensible heat flux (SHF). Overall, these results build confidence in the ability of LES to represent the northeast Pacific stratocumulus to trade cumulus transition region.

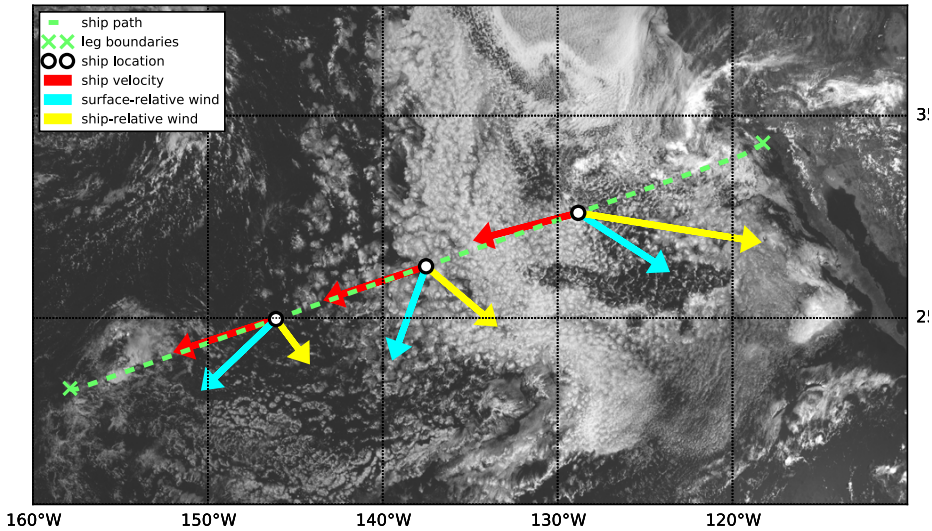

Fig. 1.1 (Fig. 1 of paper): Visible GOES image from 22 July 2012 at 1800 UTC from the middle of MAGIC leg 15A, showing a transition from broken cumulus clouds near Hawaii to stratocumulus clouds further east, off the California coast. The path of the ship is shown as a green dashed line; the LES models the cloudy boundary layer following the ship, which moves at approximately 10 m s^{-1}. At the ship location (indicated by white circles) at this time, and 1 day before and after, the near-surface vector wind (cyan) and the ship motion (red) are shown, together with their resultant, the ship-relative wind (yellow) used to calculate LES horizontal advective forcings.

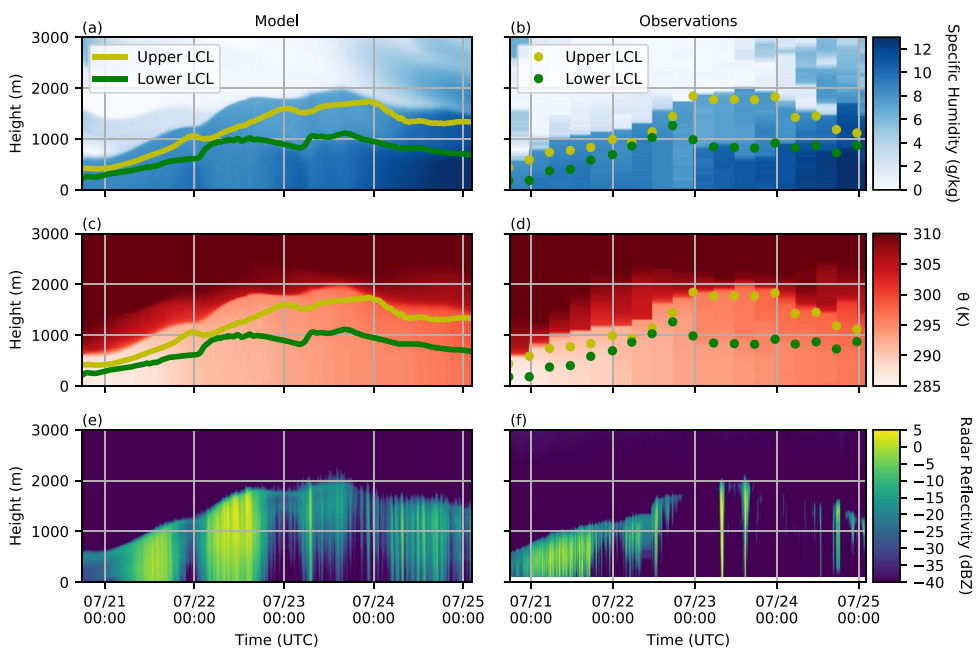

Fig. 1.2 (Fig. 5 of paper): A time-height section of the LES domain-averaged humidity, potential temperature, and simulated radar reflectivity (left) compared to leg 15A radiosonde and WACR cloud radar observations, showing good consistency. Green and yellow lines/dots indicate near-surface lifting condensation level and stratocumulus base, respectively.

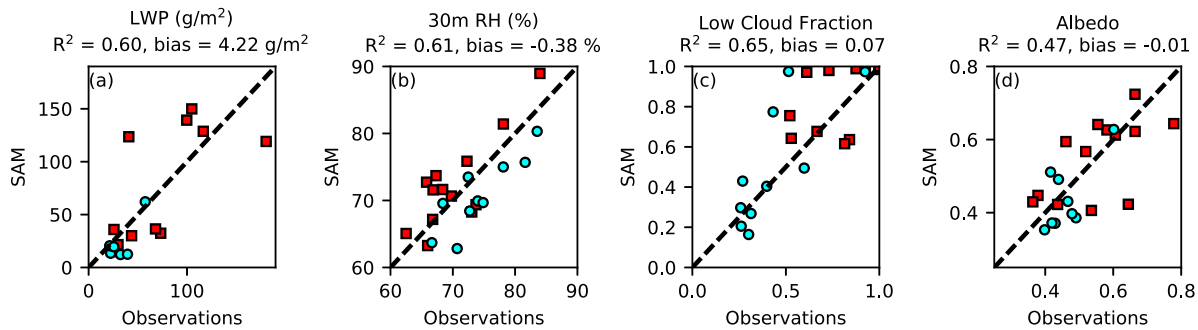

Fig. 1.3 (Fig. 13 of paper): Scatterplot of daily mean cloud statistics from LES of all MAGIC outbound cruise legs vs. the ship measurements, showing good agreement with little bias. Blue and red squares correspond to climatological cumulus and stratocumulus regions, respectively.

Paper 2 (Bretherton and Blossey 2017): *Understanding mesoscale aggregation of shallow cumulus convection using large-eddy simulation*

Marine shallow cumulus convection, often mixed with thin stratocumulus, is commonly aggregated into mesoscale patches. The mechanism and conditions supporting this aggregation are elucidated using 36 h large-eddy simulations (LES) on a 128x128 km doubly periodic domain, using climatological summertime forcings for a location southeast of Hawaii. Within 12 h, mesoscale patches of higher humidity, more vigorous cumulus convection, and thin detrained cloud at the trade inversion base develop spontaneously. Mesoscale 16x16 km subdomains are composited into quartiles of column total water path and their heat and moisture budgets analyzed. The weak temperature gradient approximation is used to explain how apparent heating perturbations drive simulated mesoscale circulations, which in turn induce relative moistening of the moistest subdomains, a form of gross moist instability. Self-aggregation is affected by precipitation and mesoscale feedbacks of radiative and surface fluxes but still occurs without them. In that minimal-physics setting, the humidity budget analysis suggests self-aggregation is more likely if horizontal mean humidity is a concave function of the horizontal-mean virtual potential temperature, a condition favored by radiative cooling and cold advection within the boundary layer.

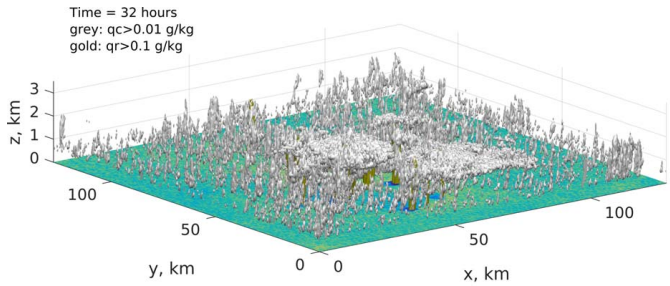

Fig. 2.1 (Figure 4 of paper): Perspective plot of the cloud field (q_c > 0.01 g/kg) and rain (q_r > 0.1 g/kg, gold shading) at 32 h in the control simulation. Sea-surface color shading indicates the virtual temperature anomaly at the lowest grid level.

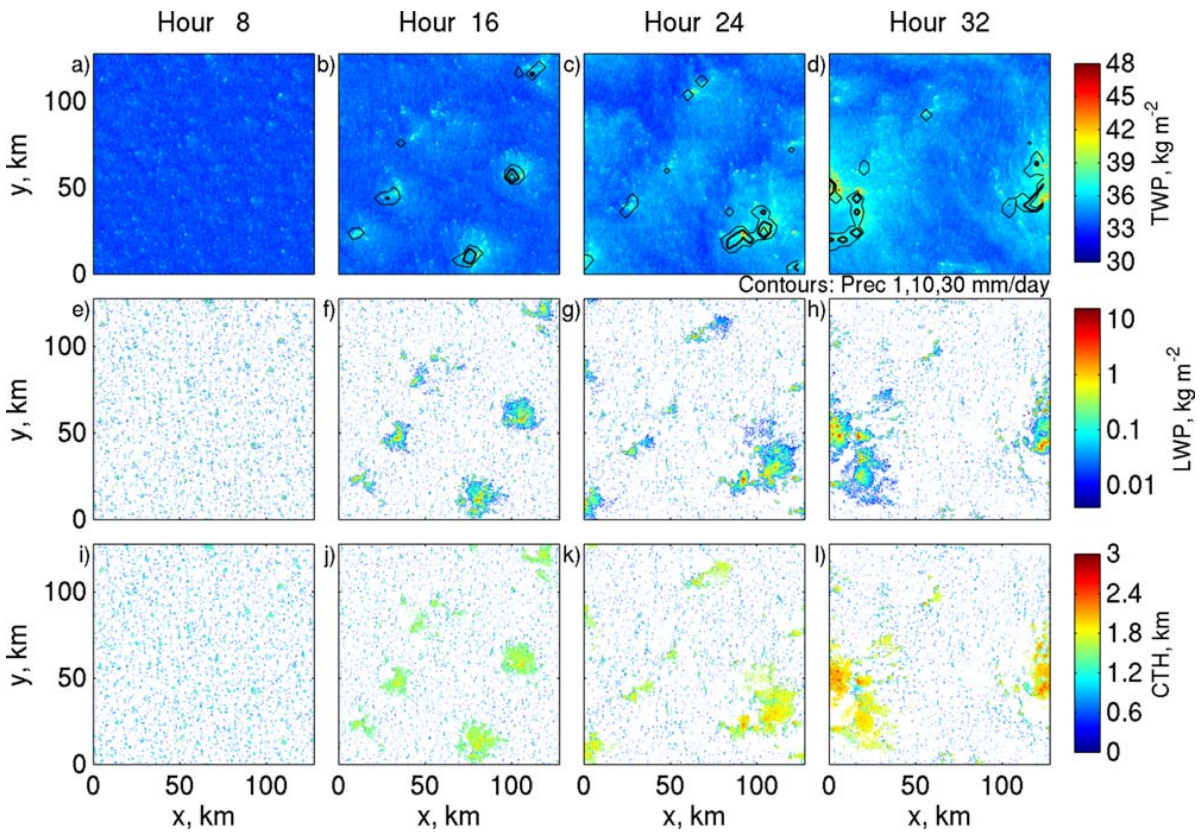

Fig. 2.2 (Fig.3 of paper): (a–d) Total water path, (e–h) liquid water path, and (i–l) cloud top height in the control simulation at 8 h, 16 h, 24 h, and 32 h.

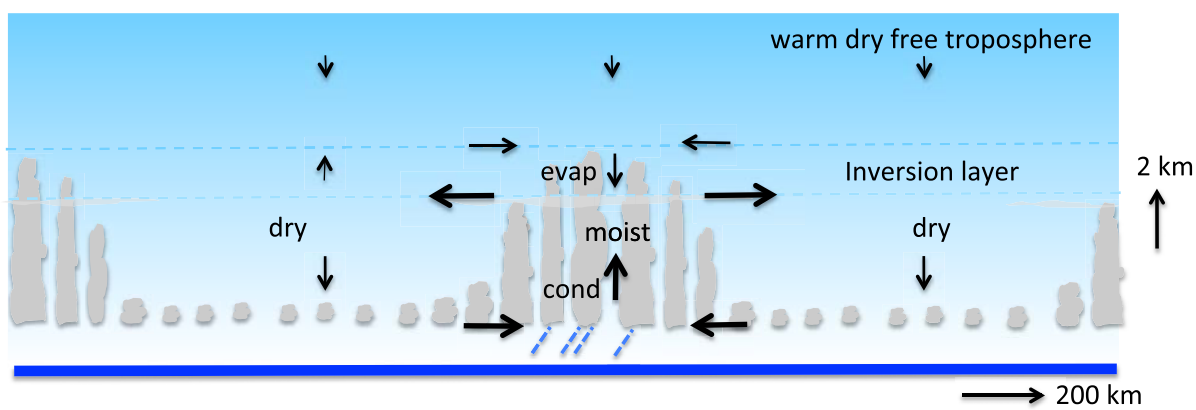

Fig. 2.3 (Fig. 10 of paper): Schematic of processes accompanying shallow convective aggregation. On mesoscales, the virtual temperature remains flat on mesoscales but moist and dry patches develop. The moist patches support deeper and more vigorous cumulus convection, driving condensational heating and mesoscale ascent in the conditionally unstable layer and penetrative entrainment-induced evaporative cooling and mesoscale subsidence in the overlying inversion layer. The moist patches become moister via low-level humidity convergence but dry from penetrative entrainment and precipitation.

Paper 3 (Zhao and Bretherton 2018, in review): *Simulation of mesoscale cellular convection in marine stratocumulus. Part II: Non-drizzling conditions.*

Large-eddy simulations are carefully analyzed to better understand the mechanism of mesoscale closed-cell cellular organization (MCC) in non-drizzling marine stratocumulus. We use a 'hard nudging' approach which maintains fixed horizontal-mean temperature and humidity profiles for a well-mixed boundary layer with a constant boundary layer depth. For the case studied, closed cells develop and grow by 32 h to a 25:1 aspect ratio, consistent with satellite observations. Simulations indicate that the closed-cell MCC is driven by the feedback from cloud-induced mesoscale perturbations of longwave radiative cooling. These reinforce horizontal mesoscale flows along the inversion that preferentially warm and moisten the mesoscale regions that are already warm and moist.

A conceptual model for closed-cell stratocumulus as a mesoscale wavelength hydrodynamic instability in which mesoscale moist and dry anomalies spontaneously grow is presented (Fig. 3.1).

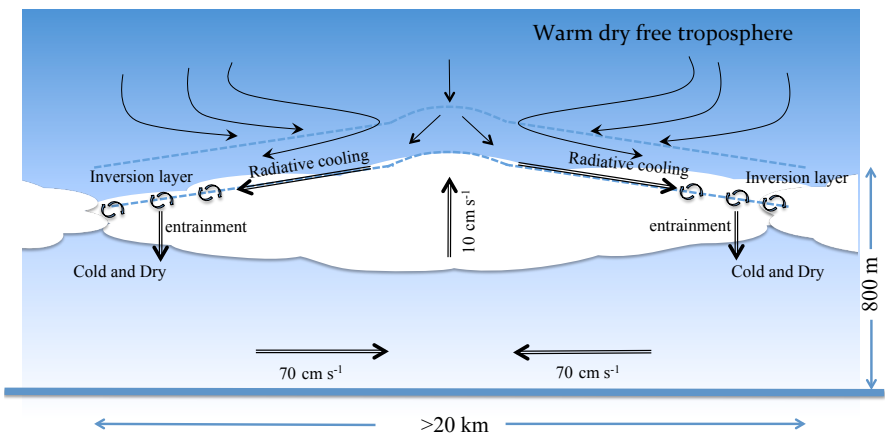

Fig 3.1 (Fig. 15 of paper): Key characteristics of a mesoscale closed cell developing in a well-mixed stratocumulus boundary layer as distilled from an LES composite. Air subsiding into the boundary layer is drawn toward the moist, cloudy cell center. It diverges along the sloping inversion at the top of the cloud layer, helped by strong radiative cooling, before entraining into the thinner cloud at the drier edge of the cell. This process can be regarded as a radiatively-driven instability of a horizontally uniform cloud sheet in which short-wavelength modulations grow fastest but long-wavelength modulations keep growing to larger amplitude.

In simulations in which long-wavelength sinusoidal moisture anomalies are initially imposed, these anomalies evolve into amplifying closed cells (Fig. 3.2). The cell structure is visualized with a compositing approach based on sorting grid columns by their mesoscale-smoothed total water path. A thermally direct mesoscale circulation pattern develops in the interior of the boundary layer with buoyant mesoscale updrafts, thicker cloud, and a slightly higher capping inversion in the moister columns. There is a mesoscale flow of above-inversion air down the slightly sloping capping inversion from the moist to the dry regions, reinforced by cloud-top radiative cooling. This flow fluxes radiatively cooled dry air horizontally from the moist regions to the dry regions, where it is entrained and spreads vertically throughout the boundary

layer. This reinforces the mesoscale anomalies that make the closed cells by preferentially cooling and drying the already dry regions. The sloping inversion flow is not driven as efficiently if the radiative cooling is artificially horizontally homogenized, partly disrupting this positive feedback and the resulting closed cell development (Fig. 3.3).

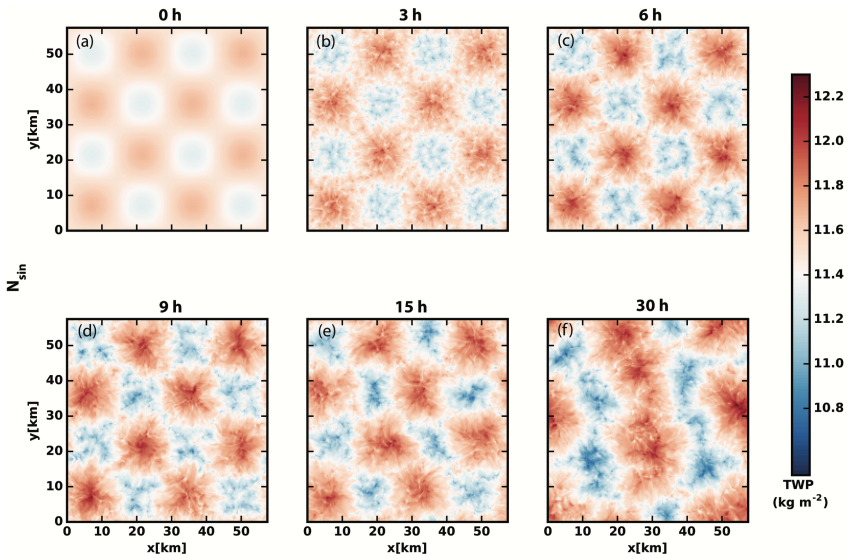

Fig. 3.2 (Fig. 4 of paper): Simulated closed-cell evolution starting from a mesoscale sinusoidal humidity modulation in the boundary layer (color shading; TWP = total (vapor + liquid) water path. The cells develop circulations and strengthen. Larger cells take over after 30 hours.

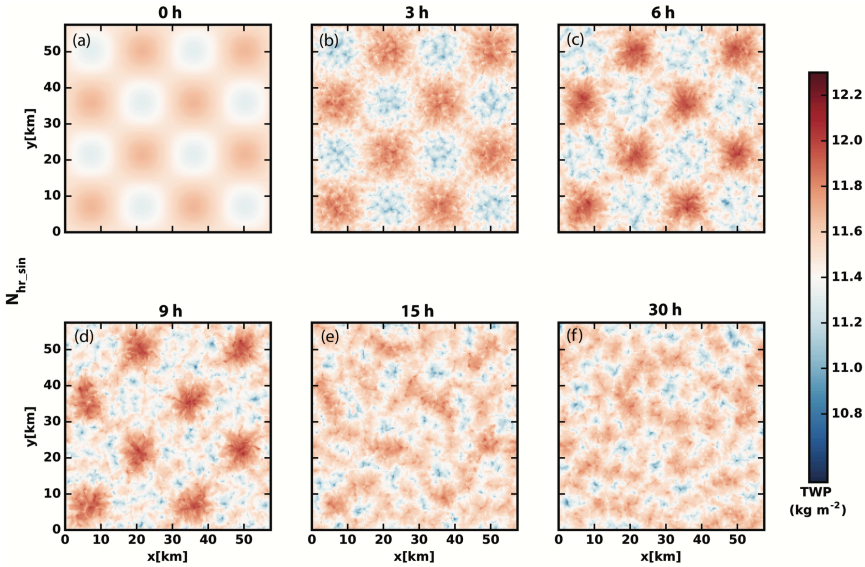

Fig. 3.3 (Fig. 5 of paper): Like Fig. 3.2, but with radiative cooling artificially homogenized in the horizontal. The cells barely strengthen and abruptly collapse after 15 h, indicating the importance of cloud-radiation interaction in sustaining closed-cell convection.

References

McGibbon, J., and Bretherton, C. S., 2017: Skill of ship-following large-eddy simulations in reproducing MAGIC observations across the Northeast Pacific stratocumulus to cumulus

transition region. *J. Adv. Model. Earth Syst.*, **9**, 810–831, https://doi.org/10.1002/2017MS000924.

Bretherton, C. S., and P. N. Blossey, 2017: Understanding mesoscale aggregation of shallow cumulus convection using large-eddy simulation. *J. Adv. Model. Earth. Syst.*, **9**, 2798–2821, https://doi.org/10.1002/2017MS000981.

Zhou, X., and C. S. Bretherton: Simulation of mesoscale cellular convection in marine stratocumulus. Part II: Non-drizzling conditions. *J. Adv. Model. Earth. Syst.*, **10**, https://doi.org/10.1029/2018MS001448.

Summary

Goal: Use MAGIC observations of NE Pacific cloud-topped boundary layer properties to test the fidelity of large-eddy simulations and their simulation of mean cloud statistics in varying environments, cloud mesoscale organization, and cloud-aerosol interaction.

Main findings:
(1) The SAM large-eddy simulation model skillfully reproduces the cloud and boundary layer properties across a variety of weather regimes and seasons, suggesting that it might also be trustworthy for simulating boundary-layer clouds in perturbed climates. Simulated cloud properties are not too sensitive to aerosol variations.

(2) Mesoscale organization of boundary layer clouds is ubiquitous over the MAGIC region and in marine boundary layers more generally. Large-eddy simulation on 100x100 km domains can reproduced observed characteristics of this variability and suggests that it is an instability of a horizontally uniform cloudy boundary layer in which mesoscale dry and moist patches spontaneously amplify due to positive feedbacks between circulations and clouds, amplified by cloud-radiation interaction and precipitation. This mesoscale organization usually has a surprisingly modest impact on the horizontal-mean cloud properties.

Questions for further study:

(1) Many LES studies have suggested that marine stratocumulus thickness and cloud fraction are strongly sensitive to aerosol concentrations. This study suggests differently. Can we reconcile the two points of view more clearly, possibly even with the ARM and other ground-based observations that we have?

(2) LES do much better than most climate model parameterizations at replicating the observed vertical structure of marine boundary layers and the associated clouds. How can we exploit this skill to produce better parameterizations?

Appendix: Presentations supported by this funding

MAGIC workshop, 5/14, BNL:

The Science of the Stratocumulus-to-Cumulus Transition (Bretherton, invited presentation)

Fall ASR Working Group Meeting, 11/14, Bethesda MD:

Challenges of Deriving Useful LES Forcings and Results for MAGIC Leg15A: A Status Report (Bretherton/McGibbon poster)

Are subtropical stratocumulus to cumulus transitions driven by dynamics or microphysics? (Bretherton, invited talk)

Spring ASR Meeting, 3/15, Tysons Corner, Virginia:

Ship-following large-eddy simulation of a Sc-Cu transition observed during MAGIC Leg 15A (McGibbon/Bretherton poster)

Fall AGU Meeting, 12/15, San Francisco CA:

Reproducing cloud and boundary layer structure observed in MAGIC campaign using ship-following large-eddy simulations (McGibbon/Bretherton poster)

DOE Atmospheric System Research Program Annual PI meeting, Vienna, MD, 5/16

Comparison of ship-following large-eddy simulations with cloud and boundary layer structure observed in MAGIC (Bretherton talk)

AMS Aerosol-Cloud Symposium, Seattle, WA, 1/17

Aerosol sensitivity in large-eddy simulations of subtropical boundary layer clouds observed in MAGIC (Bretherton talk)

DOE Atmospheric System Research Program Annual PI meeting, Vienna, MD, 3/17

Aerosol sensitivity in large-eddy simulations of subtropical boundary layer clouds observed in MAGIC (Bretherton invited talk)

Skill of ship-following large-eddy simulations in reproducing MAGIC observations (McGibbon/Bretherton poster)

Frontiers in mesoscale organization of boundary-layer clouds (Bretherton talk)

NAS BASC Boundary Layer Observations Workshop, Airlie, VA, 10/17

Bretherton Keynote Lecture: Boundary layer modeling and observation: Advancing together

AMS Cloud Physics and Radiation Conference, Vancouver, BC, 6/18

Bretherton Haurwitz Prize Lecture: Mesoscale cellular convection: fluid dynamics meets cloud physics and radiation (invited)

Understanding mesoscale organization of closed-cell marine stratocumulus using large-eddy simulation (Zhou talk)