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ADVANCING CLOUD LIFECYCLE REPRESENTATION IN NUMERICAL MODELS USING INOVATIVE ANALYSIS METHODS THAT BRIDGE ARM OBSERVATIONS OVER A BREADTH OF SCALES

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ABSTRACT

From its location on the subtropics-midlatitude boundary, the Azores is influenced by both the subtropical high pressure and the midlatitude baroclinic storm regimes, and therefore experiences a wide range of cloud structures, from fair-weather scenes to stratocumulus sheets to deep convective systems. This project combined three types of data sets to study cloud variability in the Azores: a satellite analysis of cloud regimes, a reanalysis characterization of storminess, and a 19-month field campaign that occurred on Graciosa Island. Combined analysis of the three data sets provides a detailed picture of cloud variability and the respective dynamic influences, with emphasis on low clouds that constitute a major uncertainty source in climate model simulations. The satellite cloud regime analysis shows that the Azores cloud distribution is similar to the mean global distribution and can therefore be used to evaluate cloud simulation in global models. Regime analysis of low clouds shows that stratocumulus decks occur under the influence of the Azores high-pressure system, while shallow cumulus clouds are sustained by cold-air outbreaks, as revealed by their preference for post-frontal environments and northwesterly flows. An evaluation of CMIP5 climate model cloud regimes over the Azores shows that all models severely underpredict shallow cumulus clouds, while most

models also underpredict the occurrence of stratocumulus cloud decks. It is demonstrated that carefully selected case studies can be related through regime analysis to climatological cloud distributions, and a methodology is suggested utilizing process-resolving model simulations of individual cases to better understand cloud-dynamics interactions and attempt to explain and correct climate model cloud deficiencies.

RESULTS AND DISCUSSION

The Azores region is characterized by a wide variety of cloud scenes, as evidenced by a weather state analysis performed on PC-TAU histograms obtained from ISCCP data. The vertical structure of these scenes was observed from the ground during a 19-month period in 2009–2010, as a wide variety of instruments were deployed on Graciosa Island for the CAP-MBL field campaign. Although low-level cloud structures predominantly feature in that region, storm-related scenes are also quite frequent, more so than in the main stratocumulus regions. This is caused by the Azores region located close enough to the midlatitude storm track, enabling storms to regularly influence the site, especially during winter months. The dynamic regime analyses performed here, established clear relationships between WS occurrence and the prevailing dynamic systems of the Azores region. It showed that the deep convective WS1 constitutes storm embedded convection, that the shallow cumulus WS8 occurs mostly in cold air outbreaks following cold front passages, and that the stratocumulus decks (WS9-11) occur outside storm influence mostly under trade wind conditions.

Measurements and retrievals from field campaigns are typically used to evaluate simulated clouds from cloud-resolving models and large-eddy simulations. However, the results of the present study indicate that the Azores site is also a good location to evaluate cloud simulations of global models, as it experiences most cloud regimes with frequencies similar to the ones found for the global domain. A comparison of the WS distribution from 10 climate models to the observed distribution shows that the models are capturing a large part of the variability of cloud regimes at that site, despite some obvious spread between the models. The main model biases appear to be related to the underprediction of WS5 and WS10 and the relative distributions of WS7 and WS8: all analyzed models exhibit a strong lack of WS8 (shallow cumulus fields), while all but one produced too much of WS7 (fair weather cloud fields). A possible explanation for this discrepancy could be that the models do not create enough shallow cumulus clouds to obtain the radiative signature of WS8, relegating these scenes to the WS7 category. Another scenario would be that the models create shallow cumulus structures but cannot sustain them long enough, treating them as a more transient state than it really is. In this case, evaporating cumulus clouds would again relegate these scenes to WS7. The analysis of frontal system passage and winds aloft indicate that the presence of WS8 is for the most part associated with cold-air outbreaks produced behind cold fronts, which can last long after the storm has passed. This result suggests that the models bias originates from a poor representation of cold-air outbreak conditions, either by not creating the right cloud regimes or by not sustaining them long enough. Note that previous studies have attributed climate model shortwave radiation biases over the Southern Ocean to the underprediction of clouds in the cold sector of baroclinic storms (e.g., Bodas-Salcedo et al. 2012; 2014, Williams et al. 2013).

Once input from the WS analysis establishes which cloud regimes are more difficult to reproduce in models, as described above, then selecting case studies when the identified WSs dominate the region makes it possible to employ cloud process models and field study data to study in detail cloud formation and dissipation processes. Two examples are presented in Fig. 1 where visible imagery acquired by the MODIS onboard the Aqua satellite while flying over the Azores region are shown with the WS numbers from the ISCCP analysis superimposed on each image.. These images were selected at a time instant when WS8 dominates the region (11/13/2009, left) and one when WS10 is the dominant regime (11/22/2009, right). The figure also shows a few hours of the AMF W-band radar observed reflectivity with the lidar-derived cloud base, as well as the MCMS analysis of Sea Level Pressure and storm area of influence around the time of the satellite images. It can be seen that the WS8-dominated time period is characterized by the presence of an extended broken-cloud field consisting of open cell clouds that are commonly characterized as shallow cumulus clouds in the literature. The radar image also illustrates the intermittency of the cloud field and shows that individual cells have high water contents and are, for the most part, precipitating with the rain reaching the ground. The presence of much weaker cells can also be noted at times. Further, the MCMS analysis reveals the presence of a cold-air outbreak in the aftermath of a strong storm located to the north of the site. On the other hand, for the WS10-dominated time period, the satellite image shows a more consistent cloud deck that is characteristic of marine stratocumulus decks. The radar image confirms that the cloud deck is persistent, with moderate water content amounts, and indicates some drizzle below the cloud base that, for the most part, does not reach the ground. For this case, the MCMS analysis exposes the influence on the site of a well-defined Azores high-pressure system. The two cases presented here are therefore representative of cold-air outbreak shallow cumulus and high-pressure dominated stratocumulus conditions and can be used in process studies utilizing cloud-resolving or large-eddy simulation (LES) models to better understand the prevailing cloud processes.

The combined inspection of satellite and radar images shows that the WS cluster analysis captures well the low cloud regimes and allows us to generalize the conclusions of case study analyses over the Azores site. This study also demonstrates that regime-based methods applied to in-situ and satellite observations can be used to study cloud processes and evaluate models ranging from process resolving to global climate ones. Future studies will benefit from the upcoming expansion of both the satellite and the in-situ data sets, since the ISCCP analysis is being extended to years beyond 2009, providing a full overlap of the 19-month field campaign, and a permanent site is under development near the field campaign site that will include similar instruments. The presence of a permanent site will provide a wealth of data to study a wide range of cloud fields and their environment. Together, these will enhance the work presented here, allowing for a better characterization of climatological values (by reducing the impact of inter annual variability) and storm influences. The present study demonstrates that all the tools are now in place to perform process-resolving LES/SCM simulations of CAP-MBL individual cases and, using the cloud regime analysis, to generalize the case study results and attempt to explain whether major GCM cloud deficiencies relate to the poor representation of atmospheric dynamics mechanisms or to issues related to the parameterization of cloud microphysics processes.

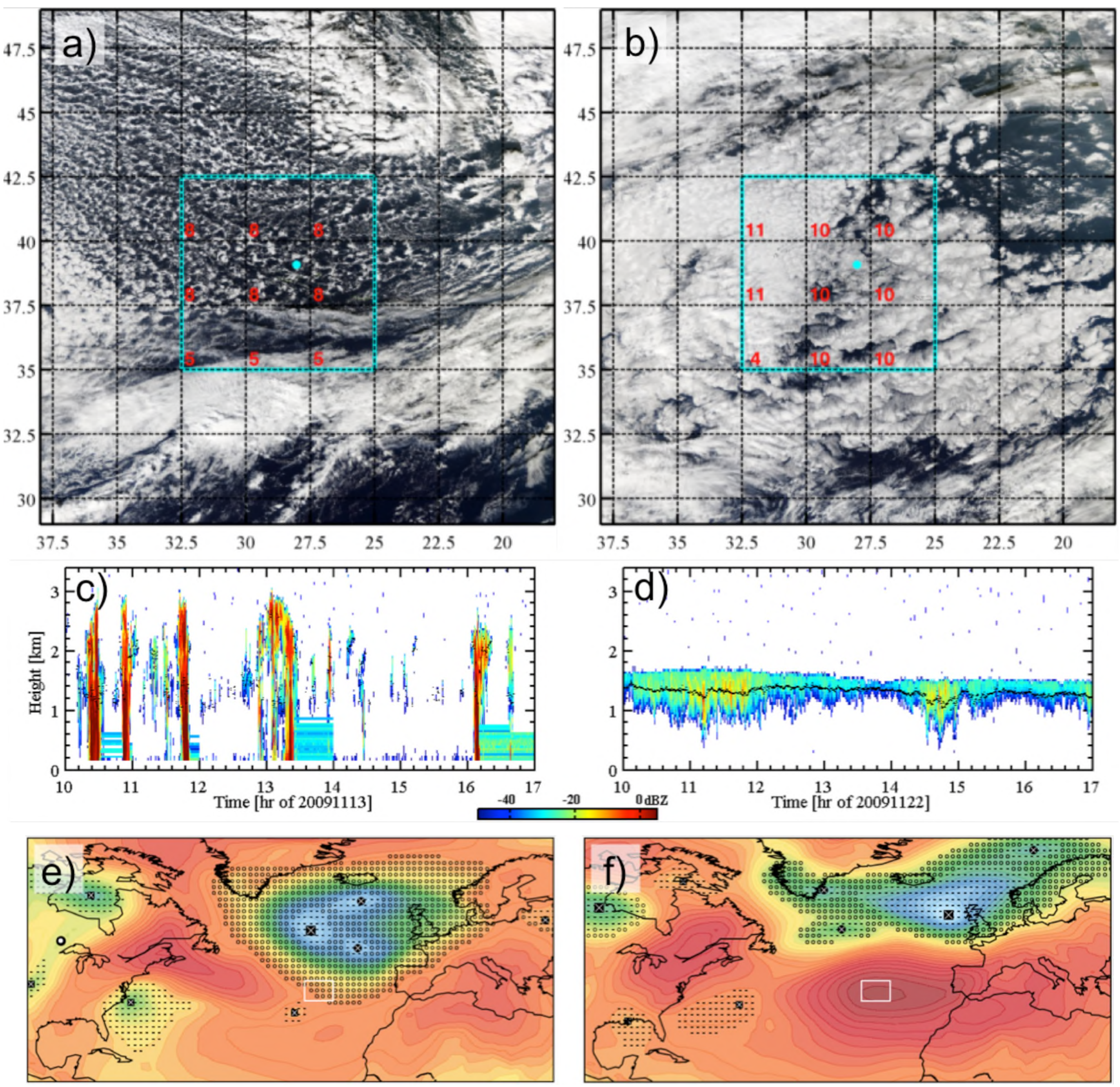

Figure 1: Examples of open and closed cell formation of low clouds, as seen from satellite imagery (a-b; Aqua MODIS amalgam provided by NASA/GFSC Rapid Response team, centered on Graciosa Island (blue dot) with the ISCCP-based WS indicated for the 9 closest cells), ground-based instruments (c-d; radar reflectivity with

lidar cloud base in black dots) and model reanalysis (e-f; field of sea-level pressure (colors) with the storms center and influence from MCMS (symbols and shaded regions respectively) and a white rectangle indicating the Azores region).