Reproducing cloud and boundary layer structure observed in MAGIC campaign Using ship-following large-eddy simulations

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Goal: Compare LES initialized with MAGIC soundings with observations at later times

(1) Can a Large Eddy Simulation (LES) capture the observed cloud variability during MAGIC?

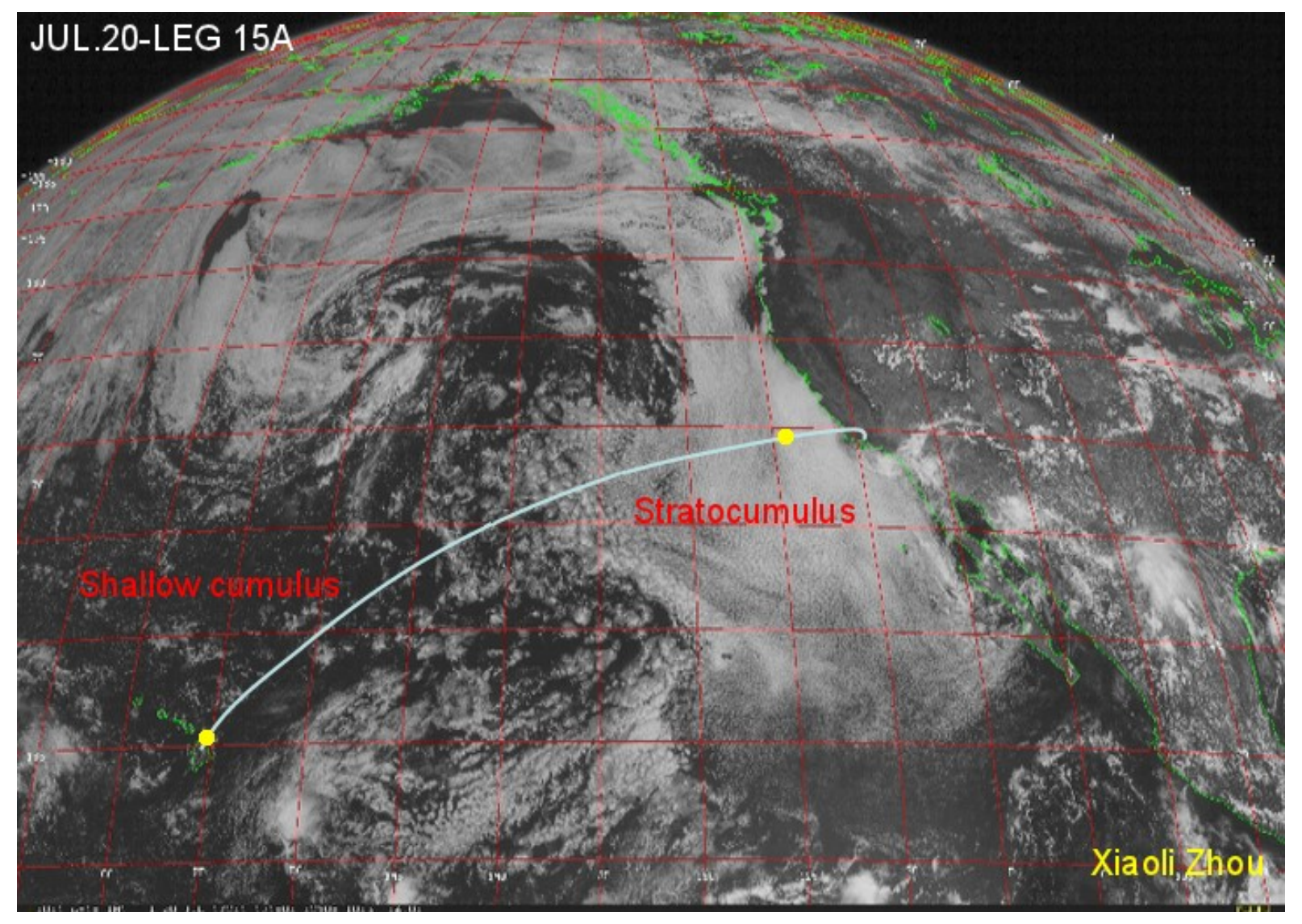
(2) Can this test the credibility of LES for simulating PBL cloud response to climate perturbations?

Motivation

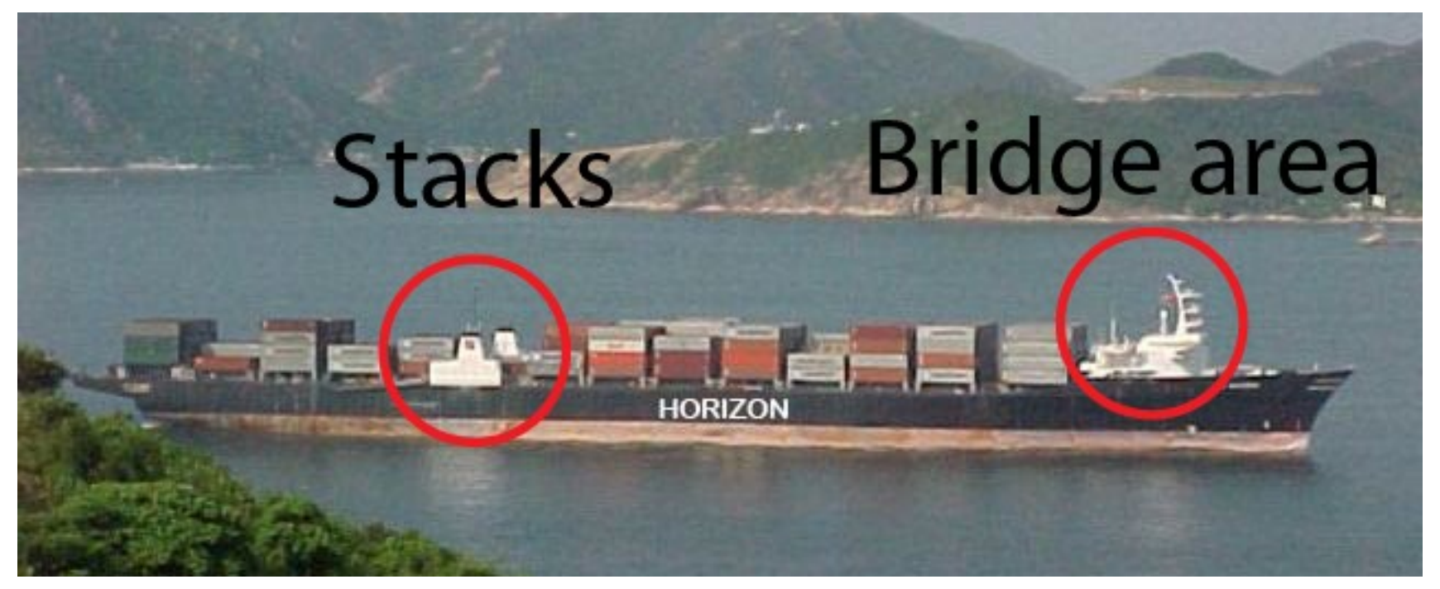
- Cloud feedbacks are currently the largest source of uncertainty in climate sensitivity of GCMs
- This is partly due to inadequate observational constraints on cloud parameterizations
- We can compare cloud parameterizations to LES, but this requires the results of LES to be credible
- The MAGIC dataset may provide a good test of how well LES can simulate cloud properties in the stratocumulus to trade cumulus transition

Model Configuration

- LES used was System for Atmospheric Modeling (SAM)
- Prescribed time-varying cloud droplet number concentration based on linear fit of hourly median ship CCN measurements to GOES cloud droplet number concentration
- 3D model with 128x128 horizontal grid, 288 vertical levels. Horizontal domain of 6.4km by 6.4km, vertical domain of 23.8km
- Horizontal grid spacing of 50m, variable vertical grid spacing of 20m below 1km, 5m from 1.3 to 1.8km, increasing to about 60m at 3km and to a maximum of 1000m at 23.8km
- RRTMG radiative transfer with translating domain position, double-moment microphysics (Morrison et al. 2005) with ice microphysics disabled, 5th-order ULTIMATE_MACHO (Yamaguchi et. al., 2011) advection scheme for non-uniform vertical grid
- Initial profile of temperature and moisture determined by second balloon sounding of leg (balloon soundings nominally occur every 6 hours)
- Thermodynamic profile nudged weakly (2 day timescale for moisture, 1 day for temperature) to sounding profiles below 3000m, and strongly above 3000m. This ensures inversion height stays in agreement with sounding profiles
- Forcings used were in a Lagrangian (ship-following) frame, using ship-relative winds, eg. $\left(\frac{dT}{dt}\right)_{adv} = (\vec{u} - \vec{u_{ship}}) \cdot \nabla T$
- Advective tendencies of q and T, large scale vertical velocity, and geostrophic winds were determined from ECMWF MAGIC dataset. Dataset has horizontal resolution of 0.5 degrees, and was smoothed in the horizontal with a Gaussian kernel of standard deviation 2 degrees prior to calculating forcings.
- SST prescribed from ship observations
- Time-varying cloud droplet number concentration prescribed from linear fit of hourly median ship-observed CCN concentration to GOES cloud droplet number concentration



Schematic of ship path for Leg 15A with ship position at start and end of simulation



The Horizon *Spirit*

Leg 15A Case Study

- Model accurately reproduces peaks of LWP near start of run (Fig 2c)
- Boundary layer decouples and transitions into cumulus regime at correct times (Fig 1a-f, Fig 2a)
- Advective forcings mainly represent ship-relative advection of changes in inversion height (Fig 1g-h)
- Bulk surface fluxes are reasonable (Fig 2e)

Analysis

A total of 14 transects from Los Angeles, CA to Honolulu, HI were run. The first 6h of each run was discarded as spin-up time, and then each run was divided into 24h periods, discarding the period under 24h at the end of the run. Each period was divided into 3h segments, and any period with no observations for one of its segments was discarded. Means were then taken within each 3h period, and then among 3h periods for each 24h segment.

The resulting daily mean observations were compared with their corresponding daily mean model values. The results are in Table 1. All correlation coefficients were positive, and all fits apart from liquid water path were statistically significant.

Quantity	Observation source	Linear fit R^2	Bias in SAM mean
Low Cloud Fraction	Ceilometer	0.23	-0.051
Surface Longwave Radiation	Portable Radiation Package	0.42	1.5 W/m^2 upward
Surface Shortwave Radiation	Portable Radiation Package	0.55	21 W/m^2 downward
Precipitable Water Vapor	Microwave Radiometer (MWR) Retrieval	0.77	-0.0019 g/m^2 (0.072%)
Liquid Water Path	MWR Retrieval	0.04	-110 g/m^2 (-75%)
Latent Heat Flux	COARE-3 Bulk Fluxes	0.48	16.49 W/m^2 upward (15%)

Table 1: Squared correlation coefficients and mean biases for daily mean values between SAM and observations. See Analysis for details. All correlation coefficients were positive.

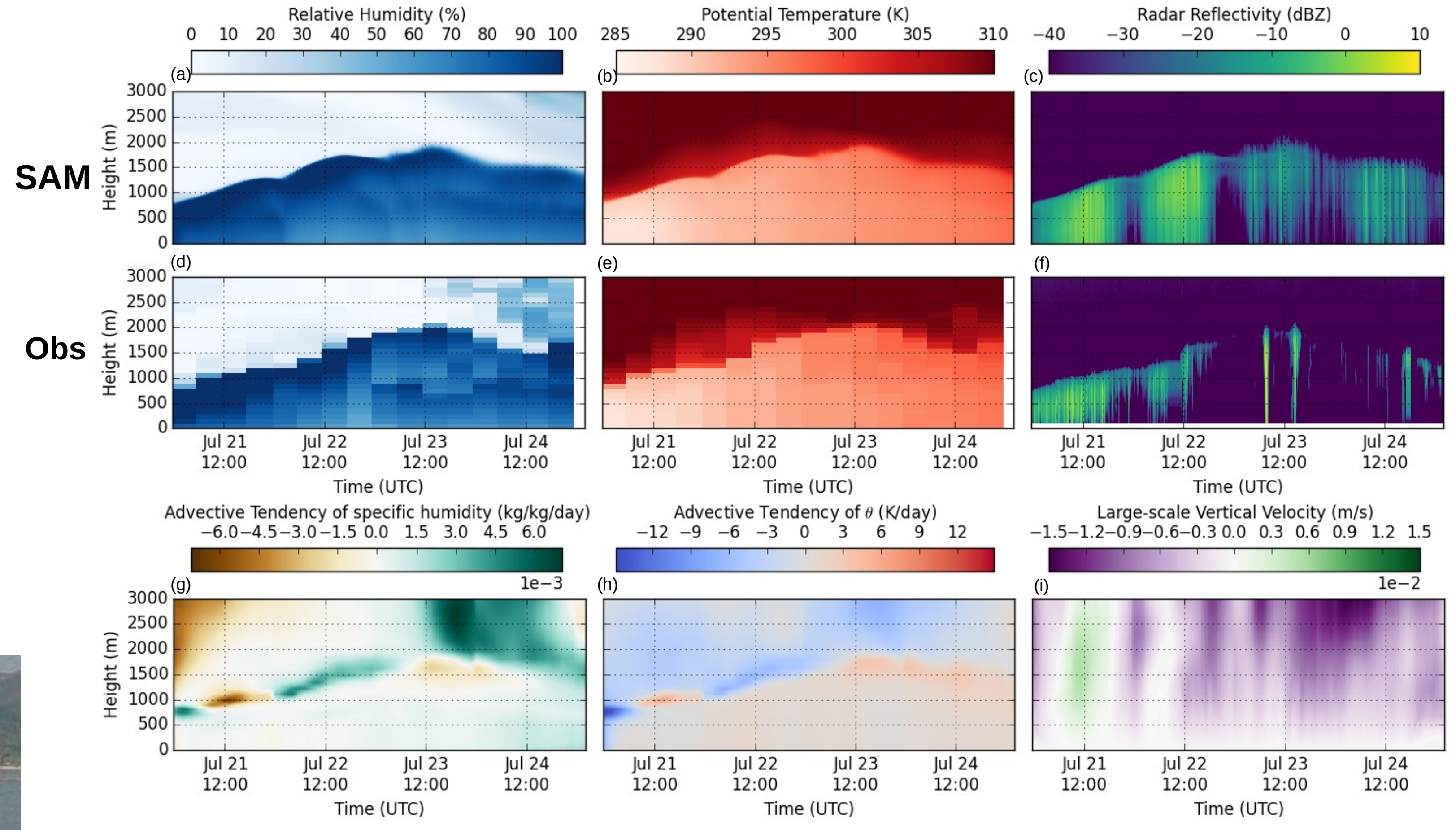


Fig. 1: Thermodynamic profiles and large-scale forcings forcings of Leg 15A ship-following run. Panels a-c: SAM horizontal mean relative humidity, potential temperature, and QuickBeam radar reflectivity. Panels d-e: radiosonde observed relative humidity and potential temperature. Panel f: WACR radar reflectivity. Panels g-i: Ship-relative advective tendencies of specific humidity and potential temperature, and vertical velocity derived from 2-degree smoothed ECMWF analysis and prescribed as forcing conditions in SAM.

Discussion

- Very large low bias in liquid water path, and no statistically significant correlation with observations
- Observational error in LWP during periods of precipitation
- Low bias in LWP agrees with surface radiation biases
- Statistically significant positive correlation of other cloud parameters
- Some runs are inaccurate due to high moisture in initial sounding not being captured by large-scale advective forcings
- Visual analysis of plots shows the Stratocumulus to Trade Cumulus transition is well-represented for four out of five Sc-Cu transition runs. Decoupling behaviors are also well-represented
- Fine 5m vertical grid only applied from 1.3 to 1.8km, while inversion heights ranged from 500m to 2km. Over-entrainment is expected to reduce liquid water path in the stratocumulus regime when vertical resolution is insufficient near the inversion
- Model may be over-precipitating, reducing liquid water path
- 6.4km by 6.4km horizontal domain cannot represent mesoscale convective features

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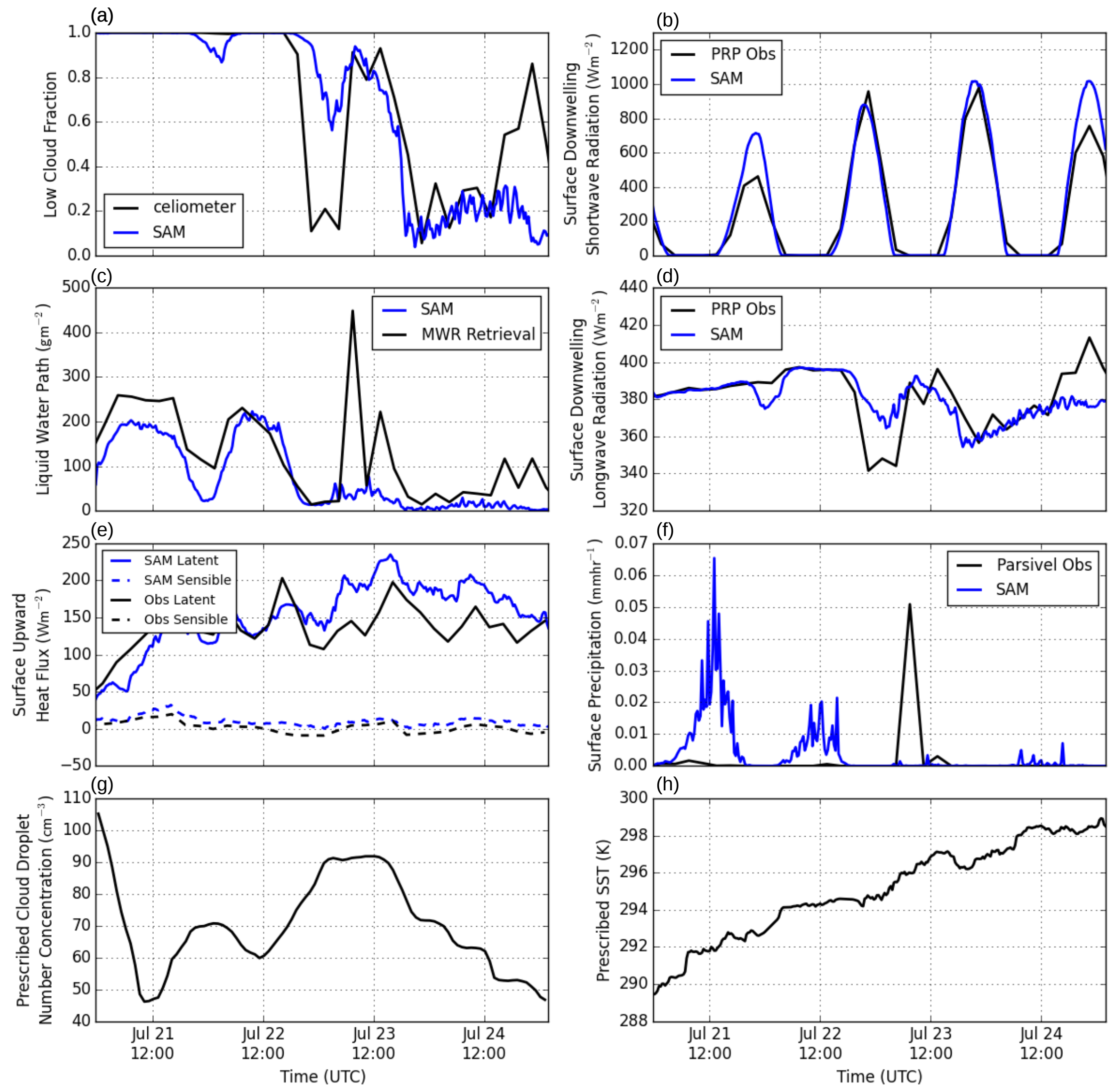

Fig. 2: Time-varying quantities for Leg 15A ship-following run. Panels a-f: Comparison of 3h-mean observed quantities with horizontal mean SAM quantities. PRP, MWR, SHF and LHF refer to Portable Radiation Package, Microwave Radiometer, sensible heat flux, and latent heat flux, respectively. Panels g-h: Prescribed cloud droplet number concentration and sea-surface temperatures. Cloud droplet number concentration determined from linear fit of hourly-median ship CCN measurements with GOES cloud droplet number concentration.

Future work

- Goal is to bring SAM's LWP in closer agreement with observations
- Repeat runs with 5m vertical resolution from 400 to 2100m
- Complete test runs with larger horizontal domain, sub-5mvertical resolution, and disabled autoconversion to assess the impact of resolution and precipitation on LWP and cloud regime
- Perform analysis using satellite-based liquid water path
- Mask MWR liquid water path for periods following precipitation
- Evaluate errors attributed to forcing conditions, and improve those forcing conditions or remove the cases from the analysis
- Ensure advective inversion height matches model inversion height

Conclusions

- SAM shows significant skill for several daily-mean cloud properties, and is able to produce reasonable simulations for several MAGIC legs
- However, SAM is not able to represent variability in observed daily mean liquid water path, and shows a large negative bias in liquid water path
- Further investigation is needed to determine the source of the model errors, and continue to reduce errors associated with model forcings