Use of Near Real-Time CALIPSO and CloudSat Observations to Assess the Performance of a Numerical Weather Prediction Model

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Abstract – The Centre for Australian Weather and Climate Research (CAWCR) is developing the Australian Community Climate and Earth System Simulator (ACCESS), a global, coupled atmosphere-ocean climate model based on the Unified Model of the U.K. Met. Office. A high-resolution atmosphere-only version combined with a 4DVAR assimilation system is being used for numerical weather prediction. Validation of the various aspects of the model is underway. Here we focus on the temporal and spatial distribution of clouds in the Australian region.

We report on a cloud and convection mask created from data from Cloud Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) and from CloudSat's radar. The combination gives a complete map of the vertical distribution of clouds along the satellites' ground track.

By comparing the observed cloud fields with forecasts, we are able to assess the model's predictive skill.

Keywords: atmosphere, climate, weather, LIDAR, space

1. INTRODUCTION

Clouds, through their interactions with radiation entering and leaving the Earth's atmosphere, play an important part in influencing the Earth's climate and lack of knowledge about these interactions remains the largest source of uncertainty in the predictions of the climate in the future (e.g. Dufresne and Bony, 2008). In addition, the accuracy of Numerical Weather Prediction (NWP) model forecasts, especially of rainfall from deep convective systems, is strongly influenced by the representation of those clouds in the models (e.g. Jakob, 2002).

The Centre for Australian Weather and Climate Research is developing a global, coupled atmosphere-ocean climate model, the Australian Community Climate and Earth System Simulator (ACCESS), based on the Unified Model of the U.K. Met. Office (UKMO). CAWCR is using a high-resolution, atmosphere-only version, combined with a 4DVAR assimilation, for numerical weather prediction. While validation of the various aspects of the model is underway, in this work we focus on the temporal and spatial distribution of clouds in the Australian region. Australia's remote location, surrounded by oceans, and sparsely distributed population over most of the continent limits the available validation data. While the horizontal distribution of clouds can be assessed using passive remote sensing satellites, the assessment of the vertical distribution has, until recently, been more problematical.

Fortunately, global measurements of the 3-D distribution of clouds, starting June 2006, are now available from the two active remote sensing satellites flying as part of the A-Train constellation. We report on a cloud and convection mask created from lidar data from the Cloud Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) satellite, which measures laser backscatter profiles from the more tenuous clouds and aerosols, and from CloudSat's radar, which penetrates into the denser clouds. The combination of the lidar and radar data gives a complete 2-D map of the vertical distribution of clouds along the satellites' ground track. As there are up to ten overpasses by the satellites of the region of interest per day, there is adequate opportunity to assemble useful statistics on the comparison of the observed cloud fields with forecasts. We present results of the comparisons of various parameters as a function of cloud height, latitude band (tropical, mid-latitude and Southern Ocean), season and forecast lead time.

2. THE OBSERVATIONAL DATA SET

2.1 CALIPSO

CALIPSO (Winker et al., 2010) carries a dual-wavelength lidar. There are three detector channels, one at 1064 nm, and two at 532 nm, one for each of the polarizations aligned parallel and perpendicular to the transmitted polarisation. This polarization sensitivity allows CALIPSO to distinguish between irregularly shaped particles, as found in ice clouds, and the spherical droplets found in water clouds. In contrast to passive remote sensing instruments (with the exception of limb scanners), which cannot measure heights of atmospheric clouds and aerosol layers directly, CALIPSO's lidar measures the range-resolved backscatter from a short pulse of laser light as it travels down through the atmosphere, thus providing a profile of the height and thickness of all layers encountered by the pulse. Operating at visible wavelengths, CALIPSO can measure backscatter from small aerosol particles and air molecules. This high sensitivity, however, means that the signal is fully attenuated within the first 100 m or so in dense water clouds because of the greater amount of scattering in these clouds.

CALIPSO lidar data are processed in several stages by a number of linked algorithms that perform the tasks of calibration, feature detection, cloud and aerosol discrimination, cloud and aerosol subtyping, and extinction retrieval. Details of these algorithms were recently published in the Journal of Atmospheric and Oceanic Technology. An overview of the algorithms was provided by Winker et al. (2009).

In this work we use the CALIPSO data product called the Vertical Feature Mask (Powell et al., 2010) which contains a map of all the layers detected by CALIPSO's feature finding algorithm, along with an identification of feature type (e.g. cloud or aerosol), subtype, ice-water phase, horizontal averaging resolution required for detection, and quality assessment (QA) flags for each of the relevant variables.

To consider the possibility, and assess the benefits, of assimilating CALIPSO and CloudSat data into ACCESS in the future, and as a related project requires near-real-time data, we choose to use CALIPSO's so-called "expedited" data product rather than the "nominal" data product. The expedited data are available within 8 – 24 hours of acquisition, whereas the nominal data are only available after some days. The trade off in using the expedited data though is that they are produced using the most recently assimilated (up to 2 days prior) meteorological data rather than the actual meteorology along the orbit tracks. This may increase the possibility of layers being missed or incorrectly classified, although, because of their less tenuous nature and stronger backscatter, it is thought that this is less likely to be a problem with clouds than with aerosol layers.

2.2 CloudSat

CloudSat flies in formation with CALIPSO as part of the A-Train constellation of satellites (Stephens et al., 2002) and carries a 94-GHz cloud profiling radar. The longer wavelength compared with CALIPSO means that, although it is less sensitive to small particles, crystals and droplets than is CALIPSO, it has excellent sensitivity to larger droplets and precipitation while producing a recoverable signal in all but the heaviest precipitation.

CloudSat data are processed using a variety of algorithms and several useful data products are available. Here we use the 1B-CPR-FL product, which contains arrays of backscattered power and radar system information that permit the calculation of radar reflectivity. Note that, although a combined CloudSat-CALIPSO hydrometeor mask (2B-GEOPROF-LIDAR) is available from the Cooperative Institute for Research in the Atmosphere (CIRA), its several-week latency does not suit our current application.

2.3 The CALIPSO-CloudSat Near Real-Time Cloud and Precipitation Mask

CALIPSO and CloudSat fly in tight formation with such precise mutual alignment that CALIPSO's footprint on the ground is usually totally enclosed within CloudSat's rather larger footprint and the same atmospheric volume is sampled by both instruments with only a few seconds separation. This permits the creation of a combined cloud and precipitation mask that includes both the high thin cirrus and low stratus and stratocumulus detected by CALIPSO and the dense, convective water cloud and precipitation measured by CloudSat.

Our combined cloud and precipitation mask is created using expedited data from CALIPSO and CloudSat following the recommendations of Mace et al. (2009). The procedure is detailed in Protat et al. (2010). Briefly, the process begins by creating the CloudSat mask from the calculated radar reflectivities, then the radar reflectivity profiles are merged with the highest vertical resolution cloud base and top heights derived from the CALIPSO data to produce a combined CloudSat-CALIPSO hydrometeor mask. Finally, for comparison with the model described below, the vertical and horizontal resolutions are degraded to the model values to compute a "model-equivalent" hydrometeor mask and fraction. (e.g. Illingworth et al., 2007)

3. THE NWP FORECAST MODEL: ACCESS-A

In this study we use model outputs from the Australian regional mesoscale model (ACCESS-A), which is based on the UKMO Unified Model system. The model domain studied here covers the latitudes 55°S to 4.73°N and longitudes 95°E to 169.7°E with a horizontal resolution of 11 km and 30 height levels up to 18 km. Details of the cloud microphysics scheme can be found in Wilson and Ballard (1999). Convection is produced by a mass flux scheme based originally on Gregory and Rowntree (1990), but with major modifications including convective momentum transport based on a flux gradient relationship, separate deep and shallow schemes, and inclusion of a simple radiative representation of anvils. Non-precipitating clouds and precipitation profiles are separated in the same way in the CALIPSO-CloudSat observations and model simulations. The altitude of the 0°C isotherm is estimated from the ACCESS-A model temperature, and it is assumed that all CALIPSO-CloudSat hydrometeor returns from above the 0°C altitude are from ice clouds and below are from liquid clouds. Following this separation, if more than 90% of the profile below the 0°C altitude contains liquid water (for the model) or a signal (from the observations), then the whole profile is classified as "precipitation", otherwise it is classified as "cloud". The 90% threshold is used (as opposed to 100%) to allow for the observed total extinction of the CloudSat beams before reaching the ground in the most intense storms. It is noteworthy that our results are not sensitive to a change in percentages ranging from 70 to 100%. For the model simulations, a threshold of 100% is naturally used because there is no such total extinction effect.

4. ANALYSIS

The long-term aim of this project is a thorough statistical analysis of the performance of the model forecasts when compared with the observations interpolated to the model grid over the whole model domain. However, as a first stage in this assessment, we are comparing the forecasts with the observations only along the satellite ground tracks. We are, in effect, comparing the model 2-D (height versus along-track distance) cloud masks with the observed cloud masks.

The assessment, reported here, is for various forecast lead times centred on the four lead-time groups: T1 = (5±3) hours, T2 = (17±3) hours, T3 = (29±3) hours, and T4 = (41±3) hours. These lead times are a consequence of the combination of the timing of the forecasts at 0000 UTC and 1200 UTC and the times of the satellite overpasses of the model domain.

As a first step in this current assessment, a composite file is created for each day in which both the observational data and the forecasts at the different lead times are stored along the satellite tracks at the horizontal and vertical resolution of the model. These data are then analysed and binned according to altitude, latitude band, and season and statistics produced. We report here on the three latitude bands: tropical (north of the Tropic of Capricorn –23.5°S), Southern Ocean (south of 45°S), and midlatitude (the latitudes between 23.5°S and 45°S).

5. RESULTS

As a sample of our results, we now present height distributions of non-precipitating clouds and precipitating clouds in the three latitude bands: tropics, midlatitudes and Southern Ocean, for two seasons. Data and forecasts for January and February 2010 are used to represent summer while winter is represented by July 2010. The frequencies at each height were calculated by summing the number of detections or forecasts at that height and latitude region and normalising by dividing by the number of valid samples in that latitude region.

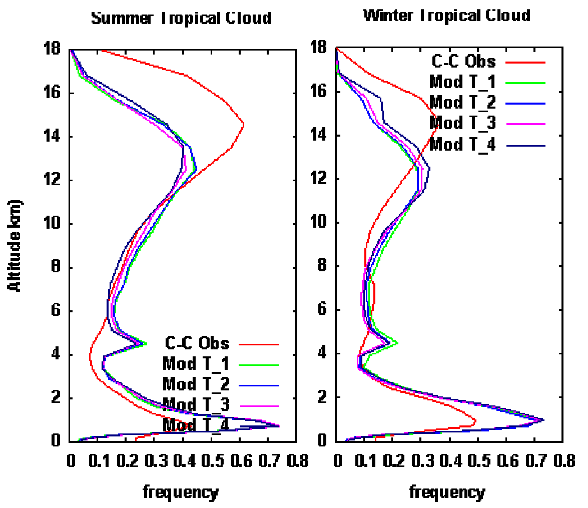

Figure 1. Tropical cloud height distributions

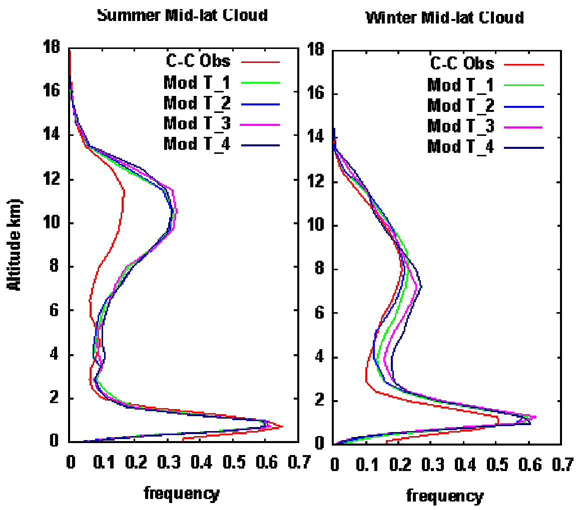

Figure 2. Mid-latitude cloud height distributions

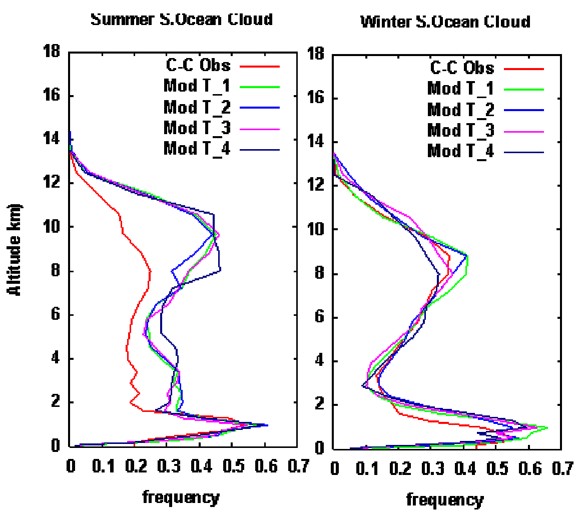

Figure 3. Southern Ocean cloud height distributions

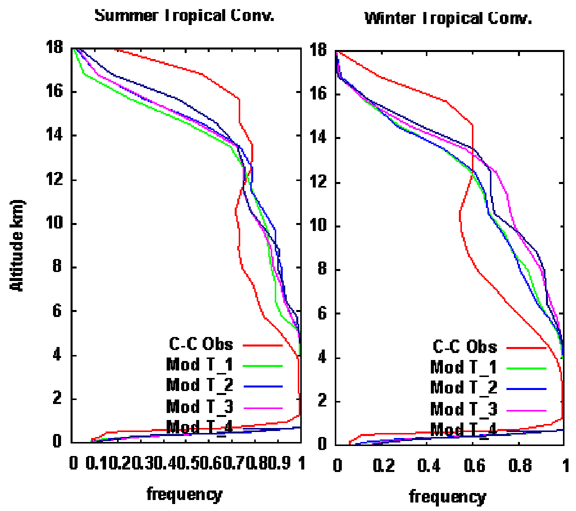

Figure 4. Tropical precipitation height distributions

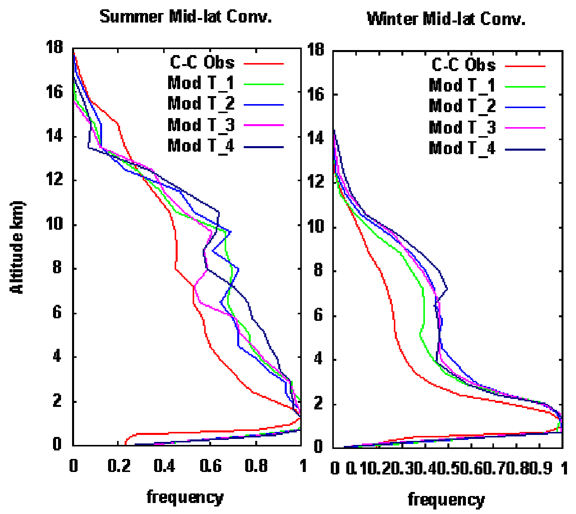

Figure 5. Mid-latitude precipitation height distributions

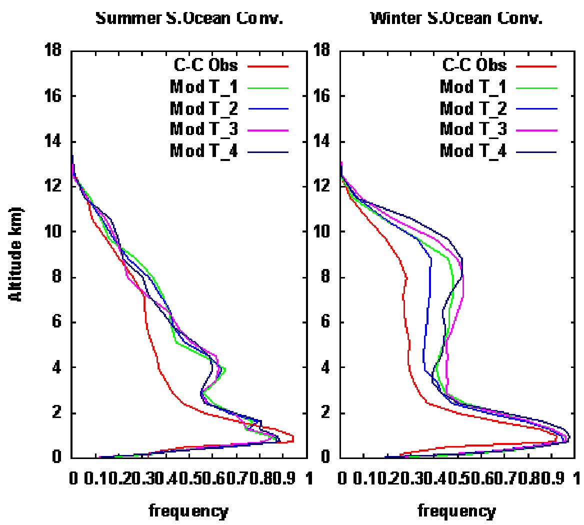

Figure 6. Southern Ocean precipitation height distributions

5.1 Clouds

The height distributions for clouds in the tropics, midlatitudes and Southern Ocean are presented in Figures 1 to 3 respectively. CALIPSO-CloudSat Observations are indicated in the figure keys by “C-C Obs” while the four model forecast lead-time groups are indicated by “T_1” to “T_4” respectively. The results are interpreted in terms of any differences in the heights of the clouds between the forecasts and the observations as well as differences in the relative proportions in the column of high, middle and low clouds.

In the tropics (Figure 1) in both summer and winter the model forecasts a greater proportion of low clouds (below 2.5 km) than is observed. It also predicts a narrow band of cloud around 4.5 km that is not observed. The most noticeable difference is that the observed high cloud is about 1.5 km higher, and has a significantly greater relative frequency in summer than is forecast.

In both the midlatitudes and the Southern Ocean (Figures 2 and 3), the forecast winter cloud height distributions are comparable with the observations. However, in summer a greater proportion of high clouds is forecast.

While it is possible that the greater observed proportion of high clouds in the tropics is a result, in part, of the occasional, total attenuation of the radar and lidar signals by heavy precipitation at upper levels, and hence reduced detection of lower-level clouds, the greater forecast proportion of high clouds in the more southerly regions cannot be explained by this mechanism.

5.2 Precipitating Clouds

The height distributions for precipitating clouds are presented in Figures 4 to 6 in a manner similar to the cloud distributions in Figures 1 to 3.

As with the cloud height distributions just discussed, there is a greater proportion of observed precipitation at high levels in the tropics than is forecast and it is at a greater altitude. In the more southerly latitude bands, however, especially in winter, there is a greater forecast proportion of precipitation in the middle to high levels than is observed.

The model forecasts of the maximum height of the convective, precipitating clouds in both seasons and in all latitude bands is substantially in agreement with the observations.

Further analysis of our comparisons between the model forecasts and the observations by the satellite-borne active sensing instruments is in progress. In particular, we are processing data for a whole year in order to develop improved statistics of seasonal differences between forecasts and observations. The extra data will also enable a more detailed examination of differences as a function of latitude, longitude and altitude within the model domain.

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