P3.12 EVALUATING WATER VAPOR AND CLOUD RETRIEVALS FROM MODIS OVER ANTARCTICA

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1. INTRODUCTION

The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments, onboard the National Aeronautics and Space Administration (NASA)'s Earth Observing System (EOS) Terra and Aqua platforms, is a scanning spectroradiometer with 36 visible, near infrared, and infrared (IR) spectral bands between 0.645 and 14.235 µm (King et al. 1992). IR retrievals of atmospheric temperature, moisture and ozone are possible using most of the channels and are typically generated at 5-km spatial resolution. The wide spectral range, high spatial resolution and near-daily global coverage enable MODIS to observe the Earth's atmosphere and continuously monitor changes. Retrievals of atmospheric water vapor and temperature from MODIS radiances will, hopefully, allow scientists to better understand the role played by energy and water cycle processes that influence the Earth's weather and climate. In addition, MODIS observations may prove to be useful to numerical weather prediction models in the regions where conventional meteorological observations are sparse. The convergence of orbital tracks over the poles results in excellent spatial and temporal coverage over those regions.

Scientists at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) have used MODIS radiances as input to existing retrieval algorithms to generate profiles of temperature and moisture in addition to integrated products. Recently, MODIS radiances have been used to retrieve total precipitable water (TPW) in clear 5 by 5 fields-of-view (FOV) yielding a horizontal resolution of 5 kilometers. Cloud detection is also possible at this resolution. Cloud-top pressures (CTP) are retrieved using a standard CO_2 intercept approach. These retrievals have been evaluated against co-located measurements at the Atmospheric Radiation Measurement Program's Cloud and Radiation Testbed (ARM/CART) site in Oklahoma.

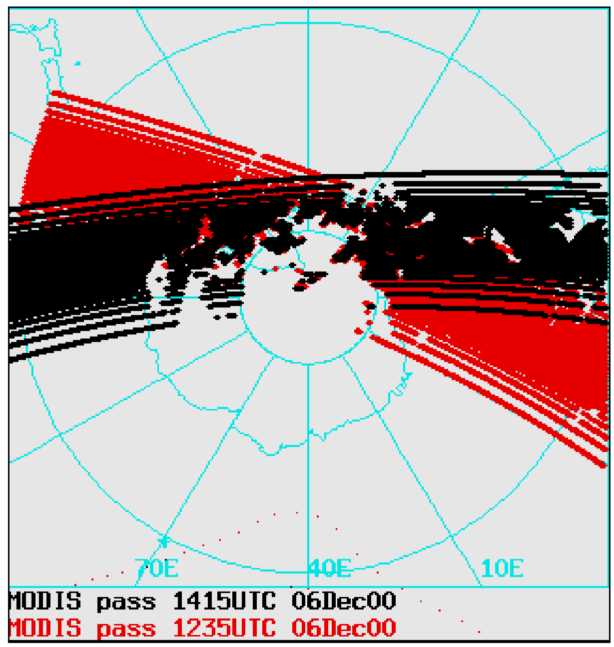

Fig. 1. Retrieval locations from 2 MODIS orbits crossing the pole at 12:35 UTC and 14:15 UTC. Every 20th retrieval location is plotted.

Results have been encouraging for a number of snow covered cases at this location. It has yet to be determined whether the same retrieval algorithms can be used at high latitudes to provide useful information to forecasters and numerical models.

In this study retrieved TPW and CTP from MODIS AM (Terra) are being evaluated over the Antarctic region using a Four Dimensional Data Assimilation (FDDA) approach. Retrievals are generated for each MODIS pass over the South Pole

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and inserted continuously into a numerical prediction model as it integrates forward in time. A 24-hour insertion period is used. Each insertion is evaluated for compatibility with respect to the model background. Information in the water vapor and cloud fields of the forecast model is tracked and reassessed as updated retrievals are obtained.

2. RETRIEVAL METHODS

Two retrieval algorithms were used in this study. For cloudy FOVs cloud top pressure was retrieved using a CO_2-slicing approach. For clear FOVs a statistical approach was used to derive total column water vapor. Each method uses a 5 by 5 pixel footprint resulting in a 5-km retrieval spacing, extending 675 km either side of nadir. Figure 1 shows the coverage from 2 orbits crossing the pole at approximately 12:35 UTC and 14:15 UTC. Every 20th retrieval location is plotted. Gaps in the coverage result from the algorithm returning a retrieval failure flag.

The MODIS CO_2-slicing algorithm generally follows that of Menzel et.al. (1983), and is very similar to that of the GOES and HIRS CO_2-slicing algorithms used at CIMSS. The two main differences are: all clear-sky radiances are calculated from temperature and moisture profiles using a forward radiative transfer model, and clear sky pixels are pre-determined by the MODIS cloud mask. Background temperature and moisture profiles (final analysis fields) are acquired from NCEP at 6-hour intervals (00, 06, 12, 18 UTC) and have a spatial resolution of 1 degree. The MODIS cloud mask algorithm performs a series of spectral tests designed to detect clear-sky regions and is clear-sky conservative. MODIS long wave IR data have a native spatial resolution of 1-km but CO_2-slicing retrievals are performed on 5x5 pixel squares for better signal-to-noise characteristics. Observed ("cloudy") radiances are averaged over the 5x5 regions and compared to calculated ("clear") values from the nearest (in space and time) NCEP profile. The temperature and moisture profiles are interpolated to 50 levels in the vertical but are not interpolated spatially or temporally. Even though there is a clear/cloudy determination for each of the 25 MODIS pixels in the 5x5s, *all* 25 are averaged in computing the observed radiances. The 5x5s are treated as though they were single footprints. If 4 of the 25 pixels in a given 5x5 are cloudy (pre-determined by the cloud mask), then the CO_2-slicing algorithm is invoked.

The first step in the cloud height determination is to compute a "window channel" cloud height. This is simply a process where the observed 11µm brightness temperature is compared to temperatures from successively lower levels in the appropriate NCEP profile. The first pressure level reached with a temperature warmer than the observed is the lowest possible solution. A choice is made between this level and the next higher one based on the proximity of the observed brightness temperature. Except in cases of missing or invalid data, the window channel cloud height will always be available to the user. Next, the appropriate radiative transfer calculations are made, using the NCEP profile data as input, to determine the clear-sky upwelling radiances, as well as the right-hand-side (RHS) of the CO_2-slicing equation for each of the 50 pressure levels in the 11, 13.3, 13.6, 13.9, and 14.2 µm bands (31, 33-36). Observed minus calculated values, the left-hand-side (LHS) of the CO_2-slicing equation, which is equivalent to cloudy minus clear, are computed for each of the above bands. If the cloudy minus clear 11µm radiance difference is greater than a threshold value (currently -2.5 radiance units), CO_2-slicing is not performed and only the window channel cloud height is reported. If this test is passed, however, cloud heights are calculated using each of the following channel ratios: 36/35, 35/34, 35/33, and 34/33, provided the cloudy minus clear radiance differences are less than threshold values for both channels in any given ratio. (For example, both the LHS and RHS of the CO_2-slicing equation for band 36 are divided by corresponding band 35 values, then equated.) In addition, if the 5x5 is composed of mainly ice clouds (mean 8.5-11 µm T_{bb} > 2.0K), a cloud height is calculated using the 33/31 ratio. The pressure level at which the values of the LHS ratios and RHS ratios are closest is reported as the cloud top pressure for each pair of channels. Note that no solutions are permitted which are lower in altitude (higher in pressure) than the previously calculated window channel height. Next, effective cloud amounts at 11 µm are computed for each of the cloud heights from the previous step. Then, these cloud amounts are used to determine the squared error for each solution (residual from the difference between the LHS and RHS of the CO_2-slicing equation for a single channel) where the errors are summed over bands 31 and 33-36. The solution giving the least error is reported in the output array. An index is provided in the data set indicating which cloud pressure was chosen.

The algorithm for retrieving atmospheric temperature, moisture, and total column ozone is the operational MODIS algorithm. It performs clear sky retrievals globally over land and ocean for both day and night. The algorithm is based on a regression and has an option to follow the statistical retrieval with a nonlinear physical retrieval. The regression coefficients are determined from an extension of the NOAA-88 data set containing more than 8400 global radiosonde measurements of atmospheric temperature, moisture and ozone profiles. Evaluation of atmospheric products is performed by a comparison with data from ground-based instrumentation, geostationary infrared sounders, and polar orbiting microwave sounders. MODIS moisture products are in general agreement with the gradients and distributions from the other satellites, while MODIS depicts more detailed structure with its improved spatial resolution. The advantage of MODIS for retrieving atmospheric profiles is its combination of shortwave and longwave infrared spectral bands (3 – 14.5µm) useful for sounding and its high spatial resolution suitable for imaging (1km at nadir). The increased spatial resolution of MODIS measurements delineates horizontal gradients of moisture, temperature, and atmospheric total ozone better than companion instruments, however, as MODIS has broadband spectral resolution, there is only modest information content regarding vertical profiles.

The retrieval process involves applying the regression coefficients to the actual MODIS measurements to obtain the estimated atmospheric profiles; integration yields the total precipitable water or total column ozone. The advantage of this approach is that it does not need MODIS radiances collocated in time and space with atmospheric profile data; it requires only historical profile observations. However, it involves the radiative transfer calculations and requires an accurate forward model in order to obtain a reliable regression relationship. Any uncertainties (e.g., a bias of the forward model) in the radiative calculations will influence the retrieval. To address model uncertainties, radiance bias adjustments have been implemented in the retrieval algorithm.

The statistical regression algorithm has the advantage of computational efficiency, numerical stability, and simplicity. However, it does not account for the physical properties of the radiative transfer equation (RTE). After computing atmospheric profiles from the regression technique, a non-linear iterative procedure (Li et.al., 2000) can be applied to the RTE to further improve the profile solution. Combining a first-guess profile derived by the statistical regression with a direct physical solution of the RTE often improves the retrieval accuracy. Because of computer limitations, the operational MODIS MOD07 retrieval algorithm includes only the regression retrieval. A version of the MOD07 algorithm with the physical retrieval will be available for MODIS direct broadcast processing as part of the International MODIS/AIRS Processing Package (IMAPP) developed at the Space Science and Engineering Center (SSEC) at the University of Wisconsin-Madison.

MODIS atmospheric and surface parameter retrievals require clear sky measurements. The operational MODIS cloud mask algorithm (Ackerman et al. 1998) is used to identify pixels that are cloud free. The MODIS cloud mask algorithm determines if a given pixel is clear by combining the results of several spectral threshold tests. A confidence level of clear sky for each pixel is estimated based on a comparison between observed radiances and specified thresholds. The operational retrieval algorithm requires at least 5 of the 25 pixels in a 5x5 field-of-view area to be assigned a 95% or greater confidence of clear by the cloud mask. The retrieval for each 5x5 field-of-view area is performed using the average radiance of those pixels that were considered clear. Since the decision to perform a retrieval depends on the validity of the cloud mask algorithm, cloud contamination may occur if the cloud mask fails to detect a cloud, or the retrieval may not be run if the cloud mask falsely identifies a cloud.

3. THE FORECAST MODEL

The model used in this evaluation is the polar version of the Cooperative Institute for Meteorological Satellite Studies (CIMSS) Regional Assimilation System (PCRAS), running at 60-km resolution (160 by 160, 32 levels). The CRAS was modified to run on a polar stereographic grid for this study. It incorporates a semi-implicit time scheme that includes advection equations for cloud and condensate mixing ratio (Raymond et. al. 1995). The model physics includes explicit cloud calculations with an ice phase similar to Sundqvist et.al. (1989), a long and short wave surface radiation calculations (Ackerman and Stephens, 1987), and surface flux calculations following Kondo et. al. (1990) and Lee and Pielke (1992). To control numerical noise the CRAS incorporates a selective sixth order filter in place of horizontal diffusion (Raymond, 1988). This reduces the artificial dispersion of moisture gradients and clouds. Turbulent mixing is accomplished using a simplified version of the non-local scheme of Raymond (1999). All sub-modules of the CRAS are designed to conserve moisture. Additional details can be found in Raymond (2000) and Raymond and Aune, (1998). The initial and horizontal boundary conditions for the PCRAS are interpolated from the one-degree resolution National Center for Environmental Prediction's (NCEP) Aviation model.

In this study total precipitable water (TPW) retrievals from MODIS were used to adjust the model background mixing ratio for clear FOVs. A summary of the assimilation procedure is as follows. First, TPW retrievals are mapped onto a model grid box. A recursive quality control is applied to the sample to identify "extreme" values. A mean TPW is calculated from the sample and compared to the model background after perturbations are removed from the column. The mean mixing ratio profile from the model background is then adjusted to reflect the observed mean TPW minus the perturbations using a vertically weighted structure function (power law). The mixing

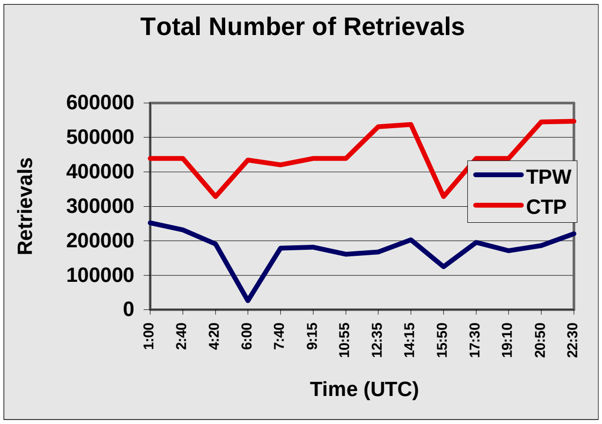

Fig. 2. MODIS Retrieval counts for cloud top pressure (red) and total precipitable water (blue) for the 24 hour period ending 07 Dec 2000.

ratio perturbations are then added to the adjusted mixing ratio profile completing the process. The TPW computed from the updated mixing ratio profile now reflects the observed mean TPW within a prescribed error tolerance. Vertical fluctuations in the mixing ratio lapse rate generated by the model physics are preserved. Super saturation checks are performed after each iteration of the adjustment process.

Cloud water adjustments are accomplished using a procedure similar to Bayler et.al. 2000. Cloud top pressures (CTP) and the corresponding effective cloud amounts (ECA) are mapped onto the model grid. Thresholds of .5 for ECA and 50% for area coverage are required for cloud building. Cloud clearing is performed when these thresholds are not met. CTP values generated by the CO2 slicing algorithm are used to build clouds above 600 hPa. Cloud top pressures from the "Window" cloud algorithm are not used because they reflect the model background used by the retrieval algorithm, in this case the NCEP Aviation model. They do indicate, however, that a cloud is present below 650 hPa. The CRAS model background is then used to estimate where the cloud layer is likely to be. Clouds are inserted with concentrations below the autoconversion limit and are assumed to be non-precipitating. The background relative humidity is then checked to make sure it does not fall below the cloud evaporation limit prescribed by the cloud physics used in the forecast model. If it does water vapor mixing ratio is increased so the observed clouds will not immediately vanish when the model integration continues.

4. FIRST CASE STUDY: DECEMBER 6, 2000

The 24-hour period commencing December 6, 2000 was selected as the first study period. At this time of year intense springtime storms begin to push moisture southward toward the Antarctic continent generating strong frontal boundaries. During this 24-hour period Terra made 14 passes over the pole; each pass generated approximately 650,000 MODIS retrievals at 5-km spacing. During the 24-hour analysis period the forecast model is stopped when the Terra satellite is approximately over the South Pole. Four or five retrieval granules of five-minute duration each are then assimilated at the observation time of the granule nearest the pole. The total number of retrievals for the 14 MODIS passes is shown in Figure 2. The variation in the number of retrievals is a function of varying cloudiness and whether 4 or 5 granules were available for a particular pass. The reduced number of TPW retrievals at 6:00 UTC is due to 3 missing granules.

The cloud adjustment algorithm performs separate cloud adjustments for clouds detected with the CO2 algorithm or the window cloud algorithm (discussed in Section 3). The total number of each cloud type for the granules used in this study is shown in Figure 3. Clouds detected by the window algorithm (low clouds) generally outnumber those identified with

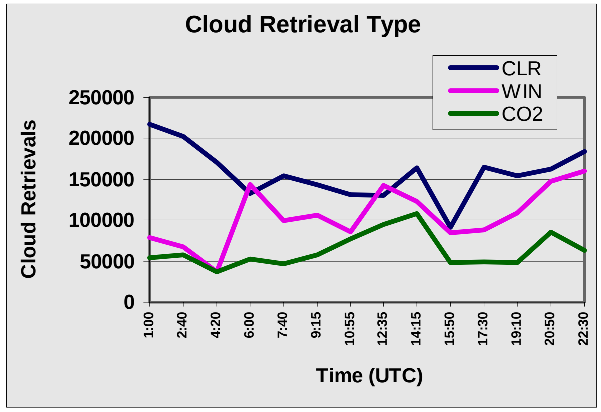

Fig. 3. Total number of clear (CLR) retrievals, CO2 retrievals (CO2), and window (WIN) retrievals for the 24-hour period ending 07 Dec 2000.

the CO2 technique (high clouds) which is typical for polar regions.

One indicator as to whether the MODIS observations are compatible with the forecast model is to track the number of adjustments to model grid points as the forecast advances through the analysis period. Figure 4 shows the number of grid column adjustments for each of the four possible cloud combinations: clear to clear (no change) cloud to clear (cloud removal), clear to cloud (cloud building) and cloud to cloud (cloud top adjustment, or no change). The number of gridcells with TPW adjustments is also shown. The clear gridcells matched with clear retrievals (red) is consistently the highest category for the cloud adjustment. The number of clear backgrounds that received cloud building (green) is second. Cloud to clear and cloud to cloud remain small throughout the

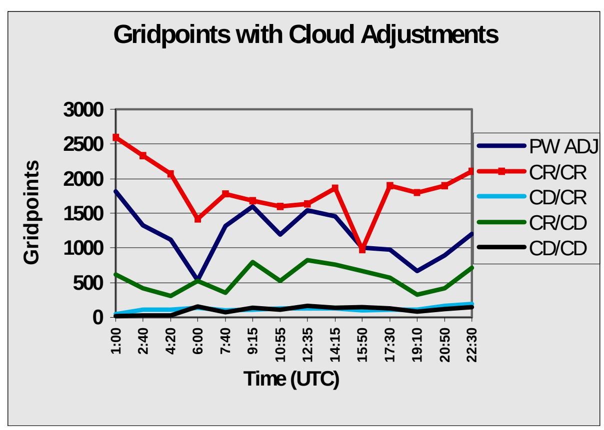

Fig. 4. Total number of grid points with cloud adjustments and mixing ratio adjustments for the for the 24 hour period ending 07 Dec 2000. Total gridcells = 25,600.

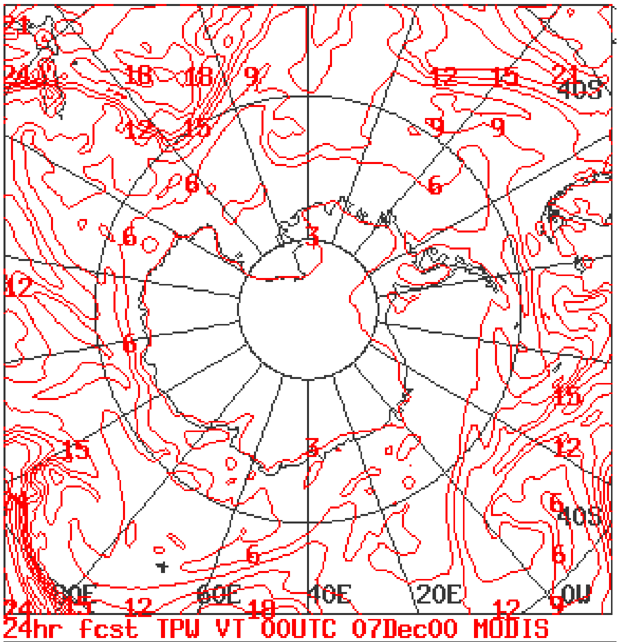

Fig. 5. PCRAS Total precipitable water (mm) after assimilating MODIS TPW/CTP (14 passes) valid 00 UTC December 7, 2000.

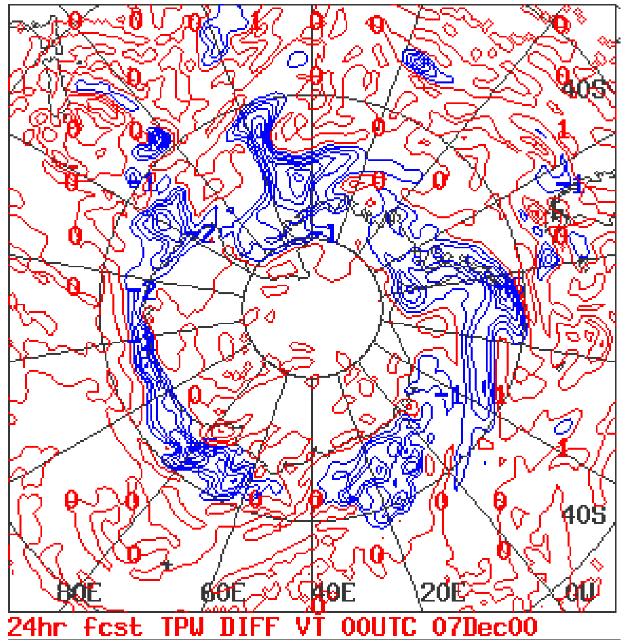

Fig 6. PCRAS total precipitable water differences (mm), MODIS TPW/CTP minus NOSAT, valid 00 UTC December 7, 2000.

period. All of the cloud adjustment combinations did not indicate any significant trends throughout the analysis period. All of the cloud adjustment combinations did not indicate any significant trends throughout the analysis period. The total number of mixing ratio adjustments did exhibit a slight decrease through the period implying that information in the mixing ratio field was being retained. A decrease in the total number of cloud adjustments is desirable as the model integrates forward. This would imply that the model dynamics and physics are tending toward a balanced cloud/moisture distribution that agrees with MODIS. It is not known at this time whether the PCRAS cloud physics is condensing too much cloud or

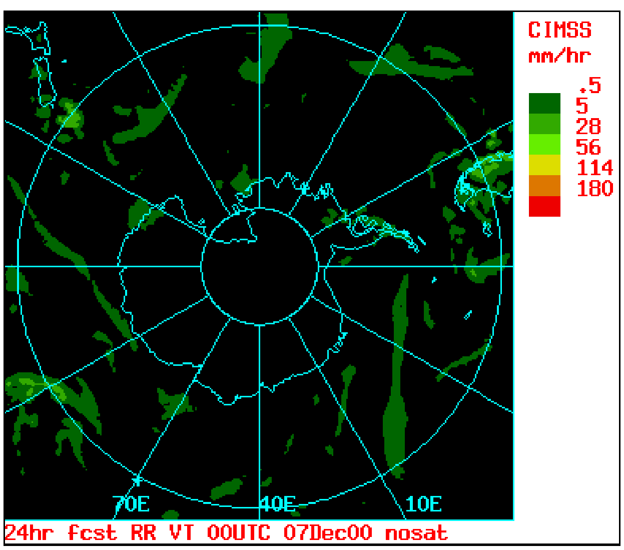

Fig. 7. 24 hour forecast instantaneous rain rate (mm/hr) from PCRAS (nosat) valid 00 UTC December 7, 2000.

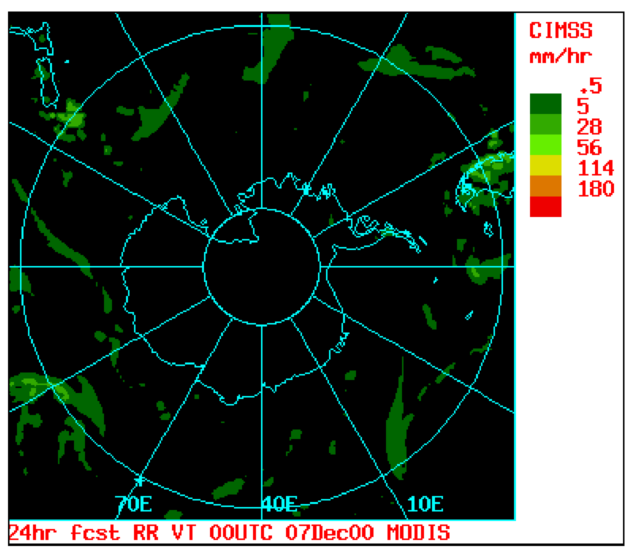

Fig 8. 24 hour forecast of instantaneous rain rate (mm/hr) from PCRAS with MODIS TPW/CTP (14 passes) valid 00 UTC December 7,2000.

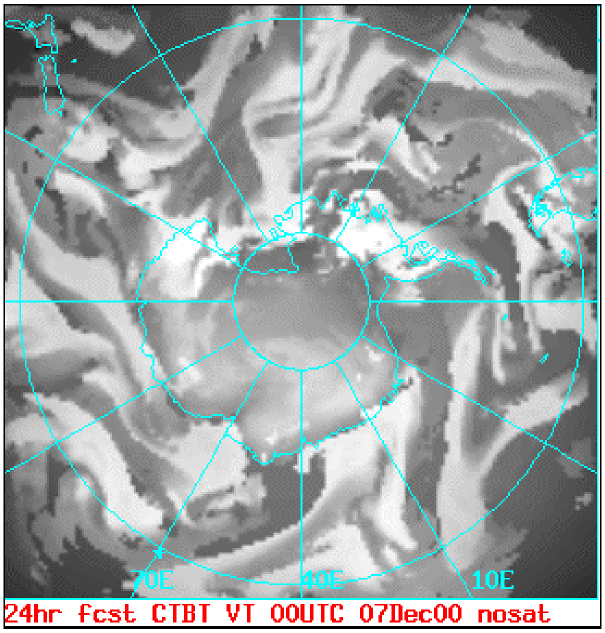

Fig 9. 24 hour forecast IR brightness temperature from PCRAS (nosat) valid 00 UTC December 7,2000.

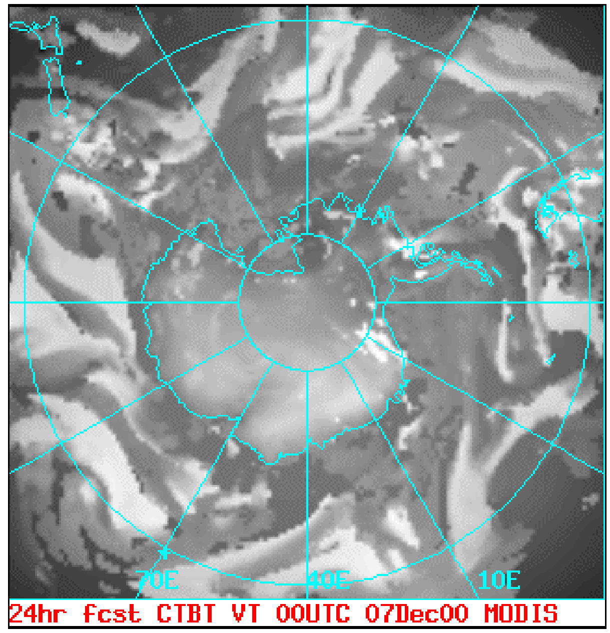

Fig 10. 24 hour forecast IR brightness temperature from PCRAS after assimilating TPW/CTP from MODIS valid 00 UTC December 7,2000.

the MODIS cloud mask is biased toward cloudy conditions. Figure 5 shows the TPW field valid 00 UTC December 7, 2000, after the MODIS adjustments. Figure 6 shows the TPW differences (MODIS minus nosat). This comparison indicates that the MODIS retrievals tend to dry the forecast model in the coastal regions surrounding Antarctica. Differences in the instantaneous rain rate at the end of the analysis period are also present as shown in Figures 7 and 8. A simple subjective method to monitor changes in the cloud distribution is to calculate a synthetic IR image from the model dependent variables. Figure 9 shows a 24-hour nosat forecast IR image valid December 7, 2000. The forecast IR image resulting from the MODIS adjustments is shown in Figure 10. Changes in the cloud field are evident throughout the domain. A composite IR image from NOAA polar orbiters valid near 00 UTC December 7, 2000 is included for comparison. The PCRAS appears to have simulated a number of the cloud systems present in the composite, however, others appear to have been over-forecast. Or missing. Clearly, further investigation is needed.

5. ADDITIONAL EXPERIMENTS

Additional cases are currently being processed. It is our intention to 1) validate the PCRAS forecasts using additional observing systems such as surface sites, NOAA AVHRR and HIRS, and radiosondes; 2) tune, if necessary, the PCRAS cloud physics for the arctic climate; and 3) to identify any seasonal variations in the adjustment statistics. With the launch of the Aqua platform, a second MODIS instrument will soon be online. This will double the amount of available retrievals. An experiment is planned to use combined Terra/Aqua retrievals. A horizontal resolution of 40 km is planned for this experiment.

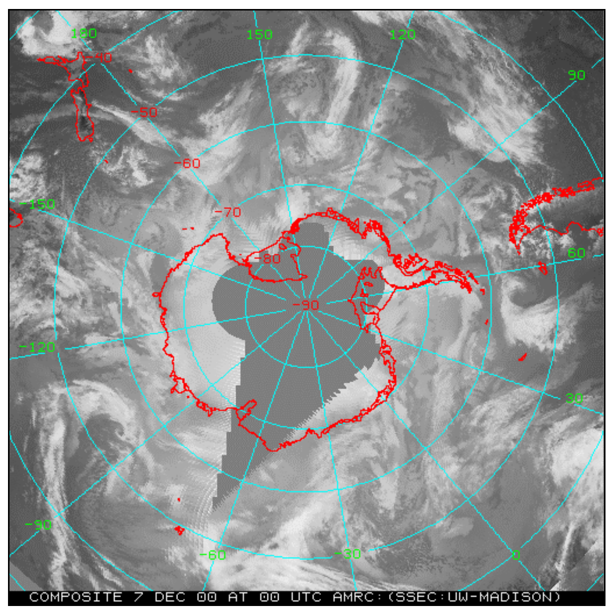

Fig 11. Composite IR image from NOAA polar orbiters valid near 00 UTC December 7,2000.

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