

This work was written as part of one of the author's official duties as an Employee of the United States Government and is therefore a work of the United States Government. In accordance with 17 U.S.C. 105, no copyright protection is available for such works under U.S. Law.

Public Domain Mark 1.0

<https://creativecommons.org/publicdomain/mark/1.0/>

Access to this work was provided by the University of Maryland, Baltimore County (UMBC) ScholarWorks@UMBC digital repository on the Maryland Shared Open Access (MD-SOAR) platform.

Please provide feedback

Please support the ScholarWorks@UMBC repository by emailing scholarworks-group@umbc.edu and telling us what having access to this work means to you and why it's important to you. Thank you.

AIRS impact on precipitation analysis and forecast of tropical cyclones in a global data assimilation and forecast system

Y. P. Zhou,^{1,2} K.-M. Lau,¹ O. Reale,^{1,2} and R. Rosenberg^{1,3}

Received 23 October 2009; revised 25 November 2009; accepted 14 December 2009; published 29 January 2010.

[1] The impact of assimilating quality-controlled Atmospheric Infrared Sounder (AIRS) temperature retrievals obtained from partially cloudy regions is assessed, with focus on precipitation produced by the GEOS-5 data assimilation and forecasting system, for three tropical cyclones: Nargis (April 27 - May 03, 2008) in the Indian Ocean, Wilma (October 15–26, 2005) and Helene (September 12–16, 2006) in the Atlantic. It is found that the precipitation analysis obtained when assimilating AIRS cloudy retrievals (AIRS) can capture regions of heavy precipitation associated with tropical cyclones much better than without AIRS data (CONTRL) or when using AIRS clear-sky radiances (RAD). The precipitation along the storm track shows that the AIRS assimilation produces larger mean values and more intense rain rates than the CONTRL and RAD assimilations. The corresponding precipitation forecasts initialized from AIRS analysis show reasonable prediction skill and better performance than forecasts initialized from CONTRL and RAD analyses up to day-2. **Citation:** Zhou, Y. P., K.-M. Lau, O. Reale, and R. Rosenberg (2010), AIRS impact on precipitation analysis and forecast of tropical cyclones in a global data assimilation and forecast system, *Geophys. Res. Lett.*, 37, L02806, doi:10.1029/2009GL041494.

1. Introduction

[2] Recent developments in high resolution global atmospheric forecast models have enabled horizontal resolutions of a few tens of kilometers. Such high resolutions have made possible the representation of tropical cyclones (TCs) within a global modeling framework [e.g., *Atlas et al.*, 2005; *Reale et al.*, 2007] in a variety of operational and experimental settings. However, while there is measureable progress in hurricane track prediction from a high-resolution global modeling perspective, quantitative precipitation forecasting of TCs is still very problematic. TC-induced floods, even at great distance from landfall, cause larger loss of life than wind alone. It is therefore imperative to improve precipitation forecasts associated with these events.

[3] Accurate TC predictions are not only dependent on a model's resolution and physical parameterizations [*Henderson-Sellers et al.*, 1998] but also on the quality of

the data assimilation system and the accuracy of the produced analyses, which provide the initial conditions for numerical weather forecasts. The representation of both the large-scale circulation and the position/structure of TCs are crucial requirements for good forecasts of TCs in global models. In particular, a large TC displacement error in the initial conditions can severely undermine a model's capability of producing a good forecast track.

[4] The Atmospheric Infrared Sounder (AIRS) instrument is one of the six instruments onboard NASA's EOS Aqua satellite launched in May 2002. AIRS, and its partner instrument, the Advanced Microwave Sounding Unit (AMSU-A), represent the most advanced atmospheric sounding system ever deployed in space. With 2378 spectral channels, AIRS provides very detailed information on the vertical moist thermodynamic structure of the atmosphere. By assimilating clear-sky radiances alone, AIRS has been shown to improve the NCEP operational system's analyses and forecast skill [*Le Marshall et al.*, 2006]. Using AIRS retrieved temperature and humidity profiles obtained in clear conditions, *Wu et al.* [2006] have shown improvements in hurricane mesoscale simulations and *Wu* [2009] has validated AIRS temperature and moisture profiles against campaign measurements. By assimilating quality-controlled AIRS temperature retrievals under partially cloudy conditions, described by *Susskind* [2007], *Reale et al.* [2008] have shown a positive impact on mid-latitude forecast skill in the NASA Goddard Earth Observing System (GEOS-5) global assimilation and forecast system. *Reale et al.* [2009] hereafter RA09, have applied the same techniques to a higher-resolution version of GEOS-5 on the analysis and track prediction of TC Nargis, which devastated Myanmar (former Burma) in May 2008, showing a stronger impact from the AIRS cloudy retrievals than from the clear-sky radiances. In this paper, it will be shown that the AIRS retrievals also improve the precipitation analyses and forecasts for TCs in the GEOS-5 system. Three recent TCs are selected for this study: Nargis (April 27 – May 03, 2008) in the Indian Ocean, Wilma (October 15–26, 2005) and the genesis stage of Helene (September 12–16, 2006) in the Atlantic Ocean. The analysis will be mainly focused on Nargis, with similar results from the other two TCs briefly discussed, and figures shown in the auxiliary material.⁴

2. Data Assimilation System, Forecast Model, and Experiment Design

[5] The GEOS-5 Data Assimilation System (DAS) is based on the GEOS-5 Atmospheric General Circulation

¹Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

²Goddard Earth Sciences and Technology Center, University of Maryland Baltimore County, Catonsville, Maryland, USA.

³Science Applications International Corporation, Beltsville, Maryland, USA.

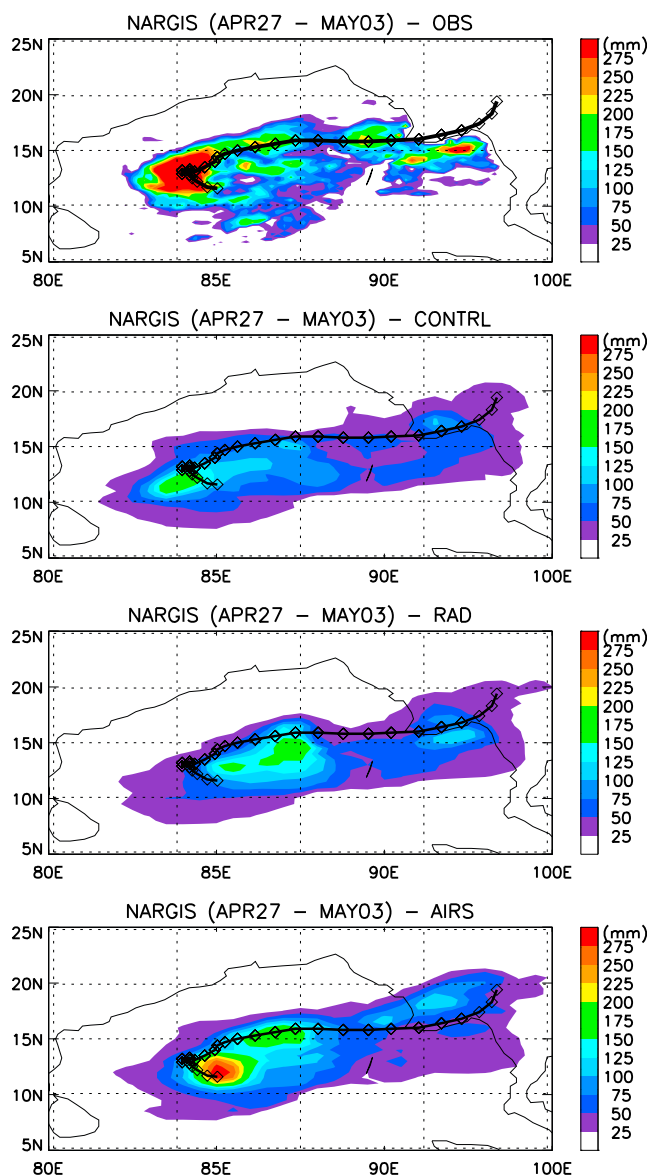


Figure 1. Precipitation accumulation associated with tropical cyclone Nargis from April 27 to May 3 from observations and CONTRL, RAD, and AIRS analyses.

Model (AGCM) integrated with the Gridpoint Statistical Interpolation (GSI) Analysis developed by the National Centers for Environmental Prediction (NCEP). The GEOS-5 AGCM retains the finite-volume dynamics [Lin, 2004] used for GEOS-4 [e.g., Bloom *et al.*, 2005] which demonstrated good skill in TC forecasting [Atlas *et al.*, 2005]. This dynamical core is integrated with various physics packages under the Earth System Modeling Framework (ESMF) [Rienecker *et al.*, 2008].

[6] Three one-month-long assimilation experiments are conducted with the GEOS-5 DAS at $0.5^\circ \times 0.67^\circ$ horizontal resolution and 72 vertical levels for the following periods: 04/15–05/15/2008, 10/15–11/15/2005, and 08/10–09/16/2006 to cover TC Nargis (April 27–May 3, 2008), Wilma (October 15–25, 2005) and the initial development stages of TC Helene (September 12–16, 2006). For each

experiment, three assimilation runs are performed: a control run (CONTRL) assimilating all the operational (conventional and satellite) data used by NCEP, with the exception of AIRS data; a radiance run which adds AIRS clear-sky radiances (RAD) in a fashion similar to operational analyses; and a retrieval run in which AIRS temperature retrievals under partially cloudy conditions (AIRS) are assimilated in place of AIRS radiances. From each of the three one-month long sets of analyses, corresponding sets of daily (00z) five-day forecasts are produced (CONTRL, RAD, AIRS). From the assimilation runs, a product named ‘precipitation analysis’ (PA) is extracted. This is not an analysis in a strict sense, because no precipitation data are assimilated. It is instead precipitation originated from the so-called ‘corrector sequence’, i.e., a set of very-short term precipitation forecasts produced by the DAS, averaged over three-hour time intervals. However, in the precipitation forecast (PF) produced by the forecasting model, PA has a strong memory of all the assimilated data, including AIRS, and it is therefore considered as an approximate ‘precipitation analysis’. In this work we will use GEOS-5 PAs, as well as the PFs, to assess the impact of AIRS data on the precipitation fields.

3. Data and Methodology

[7] Several precipitation data sets are used to estimate precipitation associated with TCs and to validate the response of GEOS-5 precipitation analyses and forecasts to different initializations. Precipitation estimates from microwave instruments can be obtained from Remote Sensing Systems (<http://www.ssmi.com>) for a range of current flying instruments including Special Sensor Microwave Imager (SSM/I) (F13, F14, F15), Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) and AMSU-E. All the retrievals are based on the Wentz and Spencer [1998] algorithm and modified versions. Most of the instruments overpass the storm region twice a day with partial coverage so that single measurements are not very representative of the precipitation associated with TCs. We produced a daily mean precipitation at 0.25° spatial resolution (denoted as MWR) using daily products of the 5 instruments mentioned above (maximum of 10 instantaneous measurements for a grid). In addition, we used TRMM TMI and Precipitation Radar (PR) daily gridded products at the same spatial resolution for comparison.

[8] In this study, we calculate the TC-related rainfall using the 6-hourly best storm track data from the National Hurricane Center and the Joint Typhoon Warning Center for the north Atlantic and Indian Ocean TCs, respectively. Following Larson *et al.* [2005] and Lau *et al.* [2008], we define TC-rain as rain that falls within a 500 km radius from the center of a TC. Because analyses and forecasts of instantaneous rainfall by global models are still problematic, we use rainfall accumulation as a means of validating model outputs against observations.

4. Results

4.1. Precipitation Analysis From GEOS-5 DAS for TC Nargis

[9] TC Nargis, which was the focus of RA09, was an exceptional pre-monsoon Bay of Bengal storm that underwent initial slow development from an area of intense but

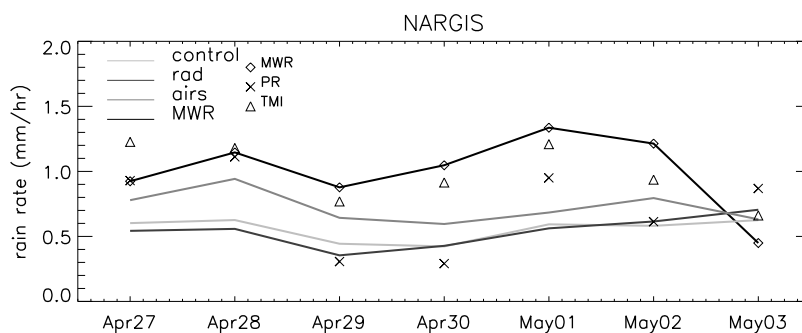


Figure 2. Daily averaged precipitation intensity along the storm track of Nargis from observations and analyses.

disorganized convection in the southeastern Bay of Bengal, and became a depression on April 27. It was a particularly difficult system because it underwent intensity fluctuations and rapid intensification with a sharp eastward recurvature just before making landfall at 12UTC May 2, 2008.

[10] Figure 1 shows observed and assimilated precipitation associated with Nargis, accumulated during April 27 to May 3 along the storm track. There is a region of observed heavy precipitation accumulation of over 250 mm in the area of (83–86°E, 11–14°N), which is due to Nargis lingering in the area for more than two days. Neither the CONTRL nor RAD analyses show precipitation maxima in this area. However, the AIRS analysis does capture an area of heavy precipitation of 250 mm, displaced only about 1 degree to the east of the track center.

[11] The improvement in AIRS analysis is also evident in the daily accumulated precipitation along the storm track (Figure 2). The precipitation analysis from AIRS is slightly larger and closer to the MWR observations than either CONTRL or RAD analyses. The probability distribution function (PDF) of precipitation amount associated with Nargis is shown in Figure 3 from both the observations and the analyses. All data are converted to the same spatial resolution. The PDF of MWR observations indicates that rain rates greater than 10mm/hr contribute to more than 10% of the total rainfall. The GEOS-5 analyses show few heavy rain-rates greater than 10 mm/hr. In the RAD and CONTRL analyses only 10% of precipitation comes from rain rates greater than 3 mm/hr. However, the AIRS analyses show a substantial improvement, with rain rates greater than 3 mm/hr contributing to 25% of the total. Overall, the GCM is still unable to produce strong instantaneous rain rate as found by *Wilcox and Donner* [2007], but roughly the right accumulated amount for a large domain over a period of time.

4.2. Precipitation Forecast From GEOS-5 for TC Nargis

[12] RA09 shows strong improvement in the forecast track initialized from AIRS analyses, compared to CONTRL and RAD analyses. The improvement comes from a more confined and better placed low-level circulation due to adjustments to the upper-tropospheric thermal structure induced by the assimilation of cloudy AIRS retrievals. Although the storm is displaced slightly to the east of the observed location, the improved circulation in the AIRS case produces substantially more precipitation than in the

CONTRL and RAD cases. Figure S1 shows the precipitation accumulations over the period April 27 to May 3 from observations and from forecasts initialized with AIRS analysis from Day-(1,2,3) forecasts. (Day-N forecast is defined as the precipitation accumulated over the Nth day of the forecast, i.e., the April 27 Day-1 forecast was initialized at 00UTC April 27, and the April 27 Day-2 forecast was initialized at 00UTC April 26, etc.) It is shown that AIRS forecasts have considerable skill in Day-1 and Day-2 forecasts but deteriorate for Day-3 and longer forecasts.

[13] Figure 4 illustrates the impact of AIRS analysis on hurricane precipitation forecasts in the GEOS-5 system by comparing the ratios of the three precipitation forecasts against observations. It is shown that the precipitation accumulations along the storm track in the AIRS forecasts are significantly better (~30%) than the CONTRL and RAD Day-1 forecasts. The AIRS Day-2 and Day-3 forecasts are also superior to the Day-2 and Day-3 RAD and CONTRL forecasts except in the first two days of the storm's lifecycle. Assimilation of AIRS radiances improves the Day-2 and Day-3 forecasts over the CONTRL, but the magnitude of that improvement is still only half that of the AIRS forecasts.

4.3. Results for TC Wilma and Helene

[14] To obtain further confidence in these results, two additional TCs are investigated, Wilma (October 15–25, 2005) and Helene (September 12–14, 2006), chosen because of their profound differences. Wilma was a late-season

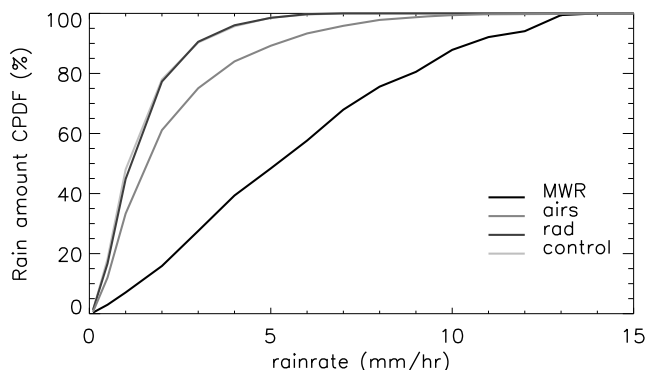


Figure 3. Cumulative probability distribution functions of precipitation amount along the Nargis track from April 27 to May 3, 2008, computed from daily data.

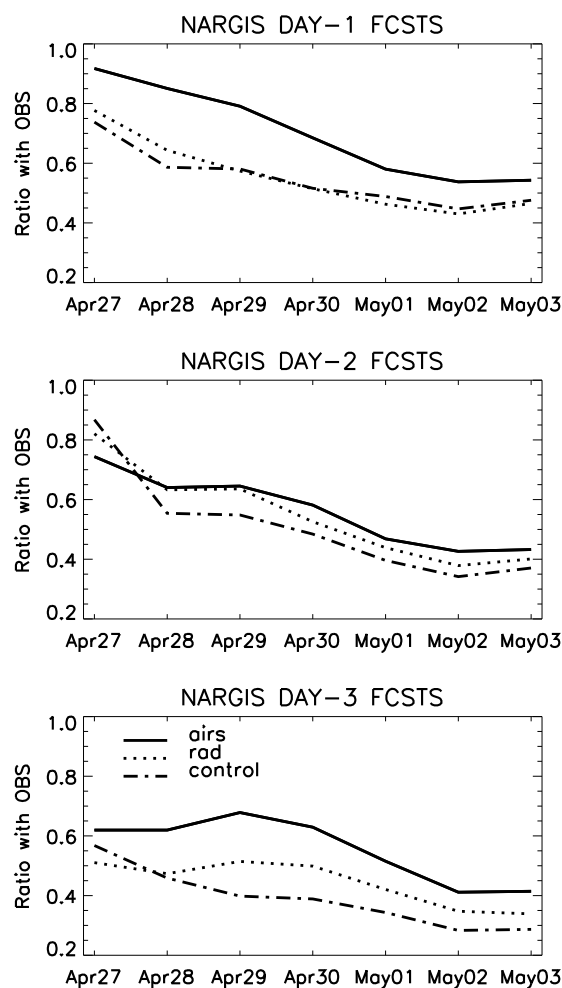


Figure 4. Ratio of precipitation accumulation from April 27 to date along the storm track from GEOS-5 forecasts using AIRS (solid line), RAD (dot line), and CONTRL (dash dot line) analyses versus observed precipitation accumulation.

Caribbean hurricane, and became the most intense Atlantic hurricane ever recorded. For a detailed synoptic description see http://www.nhc.noaa.gov/pdf/TCR-AL252005_Wilma.pdf. The storm track and the precipitation accumulations along the track from observations and from CONTRL, RAD and AIRS analyses are shown in Figure S2 (left).

[15] Helene was a long-lived Cape Verde-type hurricane that reached Category 3 as it crossed the central Atlantic. A Synoptic discussion is available online at http://www.nhc.noaa.gov/pdf/TCR-AL082006_Helene.pdf. In this work we focus on the precipitation analyses during the genesis and early development of Helene, from September 12–16 (Figure S2, right) when the AIRS-derived improvement is particularly significant.

[16] The improvement of the AIRS precipitation analysis over the CONTRL and RAD analyses is quite remarkable for both TCs, especially in the early stages of the storm, i.e., for Wilma near (15°N, 80°W) (Figure S2, left) and for Helene throughout the deepening phase (Figure S2, right). The daily precipitation accumulations along the storm track (Figure S3) and the PDFs of TC precipitation (Figure S4)

show that the AIRS analyses provide larger amounts of precipitation and more intense rain rates along the storm track, respectively, for both TCs. The precipitation forecasts initialized with AIRS analyses show much better Day-1 and Day-2 forecasts, and slightly better Day-3 forecasts (Figure S5). With the increase in forecast time, the impact on precipitation due to improved initial conditions becomes negligible.

5. Conclusions

[17] RA09 showed that assimilation of quality controlled AIRS temperature retrievals obtained under partially cloudy conditions significantly improved the representation of TC Nargis, (including position, upper-level outflow and low-level circulation) in the GEOS-5 analyses. As a consequence of the improved initialization, the GEOS-5 forecast produces a better track than when initialized from analyses in which clear-sky radiances or no AIRS data are assimilated.

[18] In this work, precipitation analyses and forecasts produced by the same experiment referred to in RA09 are examined, with the addition of two more experiments to investigate TCs Wilma and Helene. Thus 3 very different cyclones from 3 different years are studied. It is found that the precipitation analyses produced from the AIRS assimilations capture regions of heavy precipitation associated with each tropical cyclone much better than either CONTRL or RAD assimilations. The precipitation along the storm track shows that the AIRS assimilation produces larger mean precipitation and heavier rain rates within the storm radius than the CONTRL and RAD assimilations. The improvements caused by ingestion of AIRS cloudy retrievals occur for a number of reasons, partly discussed in RA09 for Nargis, and confirmed also in the additional cases discussed in the present work. In particular: (1) cyclone position, (2) compactness, (3) vertical alignment, (4) vorticity, and (5) upper tropospheric outflow are better represented in the AIRS experiments (not shown). A subsequent paper will illustrate the detailed impact of AIRS data on TC moist dynamics.

[19] In addition to the precipitation analysis, the precipitation forecasts initialized with AIRS analyses show reasonable skill (measured by precipitation accumulation) in one and two-day forecasts, and are substantially better (about 20–50% from Day-1 and 10–30% from Day-2 forecasts) than the corresponding CONTRL and RAD forecasts. The forecast skill is less affected beyond Day-3, the main reason being the dominant control exerted by the larger scale, and the inadequate resolution of the initialization, still incapable of resolving fine TC features such as bands. Although TC-related precipitation forecasting in a global modeling framework is still less than optimal, these results represent a considerable improvement and may have important implications on flood forecasting.

[20] **Acknowledgments.** The project is supported by NASA PMM project sponsored by Ramesh Kakar. The authors thank Tsengdar Lee and acknowledge use of NASA High-End computing resources.

References

- Atlas, R., O. Reale, B.-W. Shen, S.-J. Lin, J.-D. Chern, W. Putman, T. Lee, K.-S. Yeh, M. Bosilovich, and J. Radakovich (2005), Hurricane forecasting with the high resolution NASA finite-volume general circulation model, *Geophys. Res. Lett.*, 32, L03807, doi:10.1029/2004GL021513.

- Bloom, S., et al. (2005), Documentation and validation of the Goddard Earth Observing System (GEOS) Data Assimilation System—version 4, *NASA Tech. Memo., NASA/TM-2008-104606*, vol. 26, 181 pp.
- Henderson-Sellers, A., et al. (1998), Tropical cyclones and global climate change: A post-IPCC assessment, *Bull. Am. Meteorol. Soc.*, 79, 19–38, doi:10.1175/1520-0477(1998)079<0019:TCAGCC>2.0.CO;2.
- Larson, J., Y. Zhou, and R. W. Higgins (2005), Characteristics of land-falling tropical cyclones in the United States and Mexico: Climatology and interannual variability, *J. Clim.*, 18, 1247–1262, doi:10.1175/JCLI3317.1.
- Lau, K.-M., Y. P. Zhou, and H.-T. Wu (2008), Have tropical cyclones been feeding more extreme rainfall?, *J. Geophys. Res.*, 113, D23113, doi:10.1029/2008JD009963.
- Le Marshall, J., et al. (2006), Improving global analysis and forecasting with AIRS, *Bull. Am. Meteorol. Soc.*, 87, 891–894, doi:10.1175/BAMS-87-7-891.
- Lin, S.-J. (2004), A “vertically Lagrangian” finite-volume dynamical core for global models, *Mon. Weather Rev.*, 132, 2293–2307, doi:10.1175/1520-0493(2004)132<2293:AVLFDC>2.0.CO;2.
- Reale, O., J. Terry, M. Masutani, E. Andersson, L. P. Riishojgaard, and J. C. Jusem (2007), Preliminary evaluation of the European Centre for Medium-Range Weather Forecasts (ECMWF) nature run over the tropical Atlantic and African monsoon region, *Geophys. Res. Lett.*, 34, L22810, doi:10.1029/2007GL031640.
- Reale, O., J. Susskind, R. Rosenberg, E. Brin, E. Liu, L. P. Riishojgaard, J. Terry, and J. C. Jusem (2008), Improving forecast skill by assimilation of quality-controlled AIRS temperature retrievals under partially cloudy conditions, *Geophys. Res. Lett.*, 35, L08809, doi:10.1029/2007GL033002.
- Reale, O. J., W. K. Lau, J. Susskind, E. Brin, E. Liu, L. P. Riishojgaard, M. Fuentes, and R. Rosenberg (2009), AIRS impact on the analysis and forecast track of tropical cyclone Nargis in a global data assimilation and forecasting system, *Geophys. Res. Lett.*, 36, L06812, doi:10.1029/2008GL037122.
- Rienecker, M. M., et al. (2008), The GEOS-5 Data Assimilation System—Documentation of versions 5.0.1, 5.1.0, and 5.2.0, *NASA Tech. Memo., NASA/TM-2008-104606*, vol. 27, 97 pp.
- Susskind, J. (2007), Improved atmospheric soundings and error estimates from analysis of AIRS/AMSU data, *Proc. SPIE Int. Soc. Opt. Eng.*, 6684, 66840M, doi:10.1117/12.734336.
- Wentz, F. J., and R. W. Spencer (1998), SSM/I rain retrievals within a unified all-weather ocean algorithm, *J. Atmos. Sci.*, 55, 1613–1627, doi:10.1175/1520-0469(1998)055<1613:SIRRWA>2.0.CO;2.
- Wilcox, E. M., and L. J. Donner (2007), The frequency of extreme rain events in satellite rain rate estimates and an atmospheric general circulation model, *J. Clim.*, 20, 53–69, doi:10.1175/JCLI3987.1.
- Wu, L. (2009), Comparison of atmospheric infrared sounder temperature and relative humidity profiles with NASA African Monsoon Multidisciplinary Analyses (NAMMA) dropsonde observations, *J. Geophys. Res.*, 114, D19205, doi:10.1029/2009JD012083.
- Wu, L., S. A. Braun, J. J. Qu, and X. Hao (2006), Simulating the formation of Hurricane Isabel (2003) with AIRS data, *Geophys. Res. Lett.*, 33, L04804, doi:10.1029/2005GL024665.

K.-M. Lau, O. Reale, R. Rosenberg, and Y. P. Zhou, Laboratory for Atmospheres, NASA Goddard Space Flight Center, Code 613, Greenbelt, MD 20771, USA.