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AIRS impact on the analysis and forecast track of tropical cyclone Nargis in a global data assimilation and forecasting system

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[1] Tropical cyclones in the northern Indian Ocean pose serious challenges to operational weather forecasting systems, partly due to their shorter lifespan and more erratic track, compared to those in the Atlantic and the Pacific. Moreover, the automated analyses of cyclones over the northern Indian Ocean, produced by operational global data assimilation systems (DASs), are generally of inferior quality than in other basins, partly because of asymmetric data distribution and the absence of targeted observations inside cyclones. In this work it is shown that the assimilation of Atmospheric Infrared Sounder (AIRS) temperature retrievals under partial cloudy conditions can significantly impact the representation of the cyclone Nargis (which caused devastating loss of life in Myanmar in May 2008) in a global DAS. Forecasts produced from these improved analyses by a global model produce substantially smaller track errors. The impact of the assimilation of clear-sky radiances on the same DAS and forecasting system is positive, but smaller than the one obtained by ingestion of AIRS retrievals, probably due to poorer coverage. **Citation:** Reale, O., 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.

1. Introduction

[2] Approximately 15% of the tropical cyclones of the world occur in the northern Indian Ocean, predominantly concentrated before and after the monsoon season [e.g., *Asnani*, 2005]. Some of these events are known to have caused enormous loss of life, and some of the countries affected, such as Bangladesh, are considered among the world's foremost disaster prone countries. Forecasts are being issued, among others, by the India Meteorological Department (IMD), and by the Joint Typhoon Warning Centers (JTWC), relying upon a combination of global and regional models, observational tools and subjective forecasts. *Vijaya Kumar et al.* [2006] discuss the performance of the Super-Ensemble methodology on the Bay of Bengal. Despite the relatively good forecasts issued for these systems, for a variety of reasons (partly related to data distribution geometry and lack of targeted operational flights into the areas of disturbed weather such as the US Hurricane Hunter flights) global operational data assimilation systems (DASs) often produce analyses of observed tropical cyclones over the northern Indian Ocean which are of lower quality than for other basins. Poor initial conditions may negatively affect the forecast skill of global and regional models, regardless of the good quality of the model.

[3] The Aqua satellite was launched in May 2002 by the National Aeronautics and Space Administration (NASA). It contains, among others, the Atmospheric Infrared Sounder (AIRS) and the Advanced Microwave Sounding Unit (AMSU-A), and is the most-advanced polar orbiting integrated infrared and microwave atmospheric sounding system to date [*Pagano et al.*, 2003]. Data from AIRS are becoming increasingly important in operational weather forecasting and have been proven beneficial in identifying the fine thermal structure of the atmosphere in a number of studies. Among these, *Tian et al.* [2006] demonstrate that AIRS-derived products improve the representation of the vertical structure of the tropical atmosphere, *Le Marshall et al.* [2006] show positive impact on the NCEP operational system's forecasting skill resulting from the assimilation of AIRS clear-sky radiances, and *Wu et al.* [2006] show improvement in hurricane simulations by assimilating retrieved AIRS temperature and humidity profiles derived in clear conditions. However, the use of data by these researchers only in regions unaffected by clouds is a limitation because of discontinuous coverage and because cloudy regions are likely to be more dynamically active. The theory used to analyze AIRS/AMSU/HSB data in the presence of clouds (called the 'at-launch' algorithm, and that used in a post-launch algorithm, also known as AIRS version 4), was described by *Susskind et al.* [2003, 2006]. *Susskind* [2007] documents the AIRS Version 5 retrieval algorithm now being used operationally at the Goddard Distributed Active Archive Center (DAAC) to generate AIRS retrieval products. These retrievals make use of information coming from partly cloudy areas. *Reale et al.* [2008] is the first study demonstrating the impact of AIRS Version 5 temperature retrievals under partial cloudy conditions on a global data assimilation and forecasting system. In this work we show that the same AIRS version 5 data can substantially improve the analysis of a devastating northern

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Indian Ocean tropical cyclone: Nargis, which hit Myanmar on 12z 2 May 2008.

2. Tropical Cyclone Nargis

[4] Tropical Cyclone Nargis originated from an area of disturbed weather close to the Nicobare island and was classified by the Indian Meteorological Department (IMD) as a depression at 03z April 27 2008. Nine hours later, the Joint Typhoon Warning Center (JTWC) classified it as TC 01B. The system underwent intensification, was upgraded to Cyclonic Storm Nargis at 05z 28April and to a 'very severe cyclonic storm' by the IMD early on April 29th. Initial forecasts were predicting landfall over Bangladesh. After a temporary but substantial loss of intensity the system underwent rapid intensification, recurved sharply eastward and made landfall at 12z 02 May 2008. Advisories, track and intensity information are available online at http://weather.unisys.com/hurricane/.

3. Model and Data Assimilation System

[5] The global data assimilation and forecasting system used is the NASA GEOS-5, which combines the Gridpoint Statistical Interpolation (GSI) analysis algorithm co-developed by the National Centers for Environmental Predictions (NCEP) [e.g., *Wu et al.*, 2002], with the NASA atmospheric global forecast model, documented by *Bosilovich et al.* [2007]. The forecast model shares the same dynamical core [*Lin*, 2004] with the so-called finite-volume General Circulation Model (fvGCM), which has performed very well in studies focused on tropical cyclones [e.g., *Atlas et al.*, 2005; *Shen et al.*, 2006]. The GEOS-5 however contains a more recent version of the fvGCM, with a different set of physical parameterizations, partly developed by the NASA Global Modeling and Assimilation Office (GMAO). The model is almost the same version as used by *Reale et al.* [2008] but at higher horizontal resolution ($0.5° \times 0.67°$) and with 72 vertical levels.

4. Experiments

[6] Three 31-day assimilation experiments, starting at 00z 15 April 2008, are performed with the GEOS-5 DAS. In all three experiments conventional and satellite observations used operationally at NCEP at that time are assimilated, with the exception that AIRS data are excluded in the first run, which we define as CNTRL. In the second and third assimilation runs two additional sets of data are assimilated: AIRS quality-controlled [*Susskind*, 2007] temperature retrievals from the DAAC (experiment named AIRS), AIRS clear-sky radiances in the other (experiment RAD). From the three sets of analyses, three corresponding sets of 30 five-day forecasts (CNTRL, AIRS and RAD) are produced and verified against operational NCEP analyses: global anomaly correlation at day 5, computed on 500 hPa geopotential, is about 0.8 for the CNTRL. The AIRS global impact is positive in the tropics and southern hemisphere, nonnegative in the northern hemisphere (not shown).

5. Results

[7] Figure 1 shows the observed track of Nargis and the 5-day forecast tracks from the CNTRL experiments for all the runs initialized at 00z between 27 April and 3 May. The distance, of the order of 50–100 km or more, between the first point of the forecast tracks (corresponding to the analysis) and the observed track, arises out of a substantial mis-representation of the cyclone location and structure present in almost all analyses. Instead of a closed, tight circulation, the DAS produces a broad area of low pressure, or occasionally even an open circulation. From these poor analyses the forecast model cannot improve the displacement error at subsequent times, and for two simulations (initialized at 00z 28 and 29 April) the predicted cyclone dissipates without ever making landfall. The forecasts initialized at 00z 27 April and 01 May produce a landfall displacement error of 300 km or more: a poor performance, if compared with the standard of current operational forecasts or by subjective forecasts issued by the IMD for this particular storm. However, this is a run in which no AIRS information is assimilated.

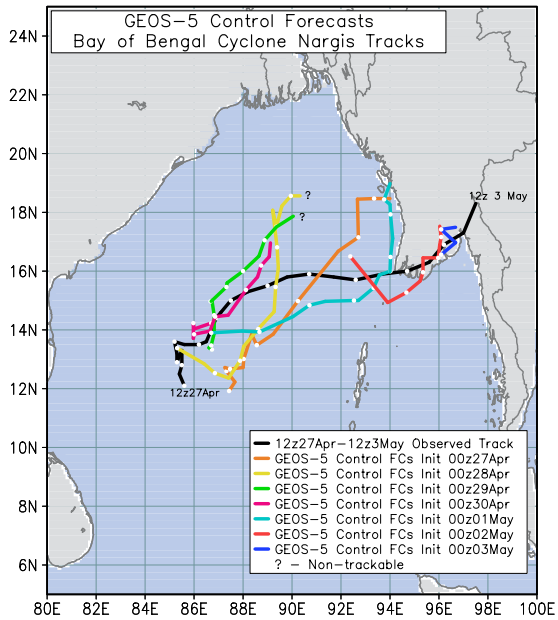

Figure 1. Nargis track in the GEOS-5 CNTRL simulations. Black line: observed. Position every 12 hours.

[8] In the RAD simulation, which is very close to the operational version of the GEOS-5, AIRS radiances are assimilated only in regions totally unaffected by clouds, and the improvement is small. Figure S1[1] shows the corresponding tracks for the RAD runs. Unlike the CNTRL, no cyclone dissipation occurs in these runs, but the forecast initialized on the 30th does not make landfall, and 2 forecasts (initialized at 00z 27 May and even as late as 00z 01 May) make landfall at least 300 km to the north of the observed landfall point.

[9] Figure 2 shows the corresponding tracks produced by the AIRS experiment and compares them with the observed track. The performance is very different from the CNTRL: with the exception of two outliers (runs initialized on April 27th and April 30th), 5 over 7 forecast tracks are packed together with a displacement error at landfall of 50 km or less, which corresponds approximately to the model's horizontal resolution.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL037122.

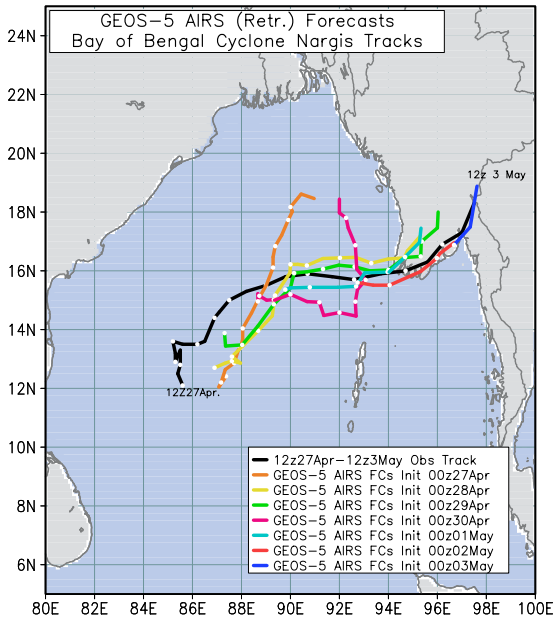

Figure 2. Nargis track in the GEOS-5 AIRS simulations. Black line: observed.

[10] Figure 3 compares the CNTRL and AIRS forecasts for one particular integration, initialed at 00z 28 April. The CNTRL 6-hour forecast, very close to the initial conditions of the 00z 28 April analysis, does not show a closed circulation but only a broad open trough expanding approximately from 11°N to 16°N and from 84°E to 88°E. On Figure 3 the AIRS 6-h forecast initialized at the same time is shown. A dramatic difference exists between the forecast initialized from the CNTRL and the one initialized from the analysis containing the AIRS temperature retrievals under partial cloudy conditions: the AIRS 6h forecast produces a well-defined low at approximately 12.9°N and 87.3°E against the observed center at 13.3°N and 85.5°E. The displacement error in the 00z analysis (not shown) and the 06 h forecast (about 200 km) is still very large for operational standard over other basins, such as the Atlantic, yet with the confined circulation and well-defined low the GEOS-5 large-scale forcing can somewhat correct a less-then-optimal initialization and produce an exceptionally good 108-hour forecast in the AIRS case. In fact, the displacement error at landfall time (12z 2 May 2008) is less than 50 km, being the coordinates of the storm at that time 16.44°N, 94.7°E in the AIRS run, against the observed of 16.00°N, 94.7°E. Importantly, the forecast initialized from the CNTRL does not produce a trackable cyclone throughout the forecast. In fact, the cyclone is off-course by 200 km north of the observed track and dissipates completely after May 1st. With the ex-

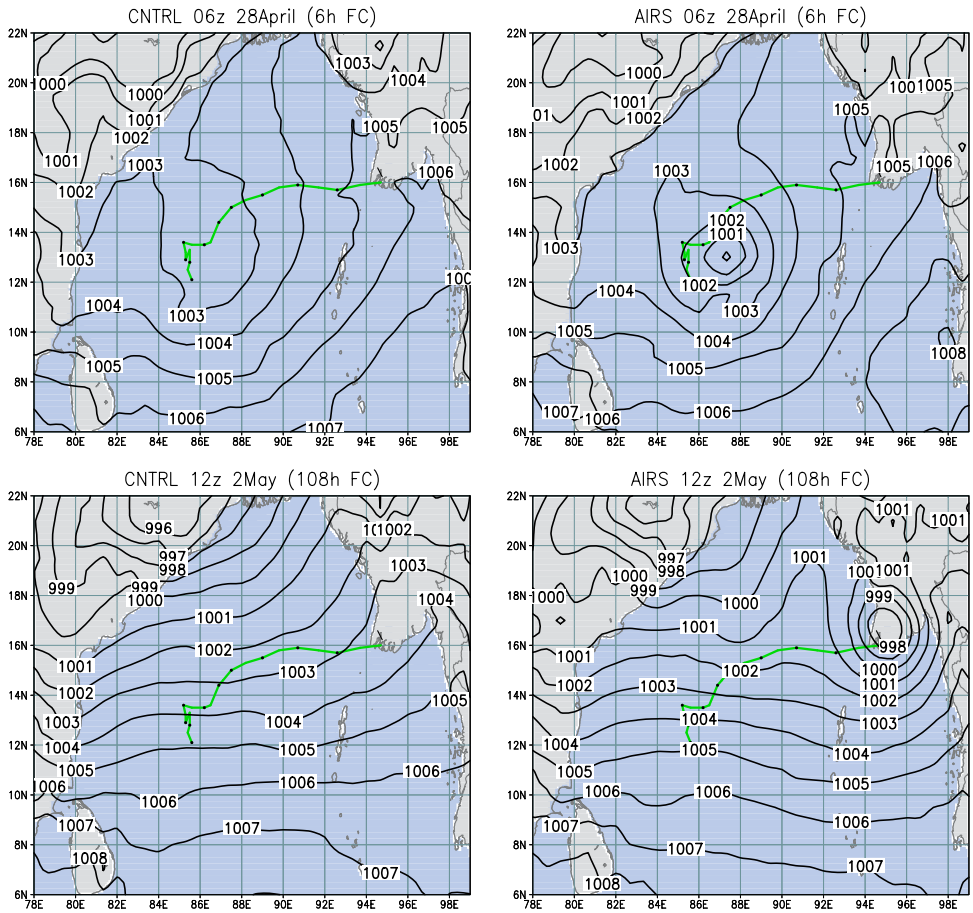

Figure 3. (top) 6-h forecast for slp (hPa) at 06z 28 April 2008. (bottom) 108 hour forecast slp (hPa) for 12z May 2008. Green line: observed track. (left) CNTRL, (right) AIRS.

ception of the forecasts initialized on April 27th and April 30th, all the other AIRS forecasts (Figure 2) are similar to the case of April 28th seen in Figure 3: the initialized vortex is quite distant from the observed track, yet the GEOS-5 model compensates for the deficient initialization and produces an error at landfall which is of the order of 50 km. On the contrary, lacking a well-defined circulation to represent cyclone Nargis in the CNTRL initializations, no possible improvement comes from the model forecasts (Figure 1).

6. Mechanism: Temperature Structure in the High Troposphere

[11] The suggested mechanism that allows the model to improve the forecast tracks for Nargis in the AIRS simulations is the different large-scale upper-tropospheric temperature structure that AIRS provides. This is consistent with the previous study by *Tian et al.* [2006] in which the impact of AIRS in improving the vertical structure of the tropical atmosphere was demonstrated. However, this work suggests that the rejection of all data from cloudy areas, which is being done by the clear-sky radiance approach, is indeed detrimental to the forecasts and the capability of retaining some data in partial cloudy areas, already proven beneficial by *Reale et al.* [2008] in the midlatitudes, appears to be important in the tropics as well. In particular, the net impact of AIRS noticed in this set of experiments is a slightly cooler upper troposphere except in the areas where organized convection is present. This creates a relative warm anomaly which helps the model dynamics, adjusting to the upper-level heating, to produce a vertically aligned column of lower geopotential values throughout the troposphere (and steeper surrounding gradients) in correspondence to the storm center, which in turn creates more confined tropical circulations.

[12] This fact has already been observed in the Atlantic (not shown) but has been found particularly beneficial in the case of Nargis. Figure S2 shows the AIRS impact on the temperature structure at 200 hPa at the same time shown in Figure 3: 06Z 28 April. The AIRS minus CNTRL temperature difference is superimposed on the AIRS minus CNTRL sea level pressure difference. The observed position of Nargis at that time is 13.3°N 85.5°E and Dvorak-based estimates give an intensity of 65 kts. The CNTRL, as shown in Figure 3, does not have a closed low, but ingestion of AIRS temperature retrievals induces a relative upper-tropospheric warming and a consequent, localized, sea-level pressure drop between 12°N–15°N and 85°–90°E, somewhat to the East of the observed storm, but sufficient to create the closed circulation seen in Figure 3 from which an extremely good forecast track is produced by the GEOS-5. In addition to the low-level closed circulation, the AIRS analysis also produces a strong, larger-scale, persisting anticyclonic circulation at 200 hPa, centered over Nargis, which improves the outflow and further enhances vertical motion. This circulation does not fluctuate but, together with a relative warm anomaly, appears on a 4-day mean (from 00z 27 April to 00z 1 May) obtained from the AIRS analyses across all the times in which Nargis lingers over the Bay of Bengal (Figure S3). This feature is much weaker in the simulations using clear-sky assimilated radiances (not shown). In other words, the impact of the clear-sky radiances for the particular case of Nargis simulation is positive, but lower than the retrievals, consistently with Figures 1 and 2. It is important to stress however that the coverage of retrievals with respect to radiances is substantially different around the cyclone, due to the presence of clouds. We do need to acknowledge that this is a case study based on only one storm. A more objective comparison on a global scale, with several cases, is underway and will be the subject of a future article.

[13] Finally, we need to emphasize that this study is centered on analysis improvement, and on consequent track forecast improvement, but does not address the issue of intensity forecast or tropical cyclone structure as produced by the model. Unlike its predecessor [e.g., *Atlas et al.*, 2005; *Shen et al.*, 2006] this particular version of the system does not yet have sufficient skill in intensity forecast to properly deal with these issues.

7. Concluding Remarks

[14] In this article we emphasize that the use of quality-controlled AIRS temperature soundings derived also in cloud contaminated areas significantly increases weather forecast skill during boreal spring conditions in a tropical region, greatly improving the forecast track of Tropical Cyclone Nargis. The improvement is due to a substantially different representation of the upper tropospheric thermal structure over actively convective regions, which helps the Data Assimilation System to create more confined and well-defined low-level circulations. The improved circulation interacts with the large-scale forcing produced by the GEOS-5 global forecast model and allows a very satisfactory forecast track.

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