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Improving forecast skill by assimilation of quality-controlled AIRS temperature retrievals under partially cloudy conditions

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[1] The National Aeronautics and Space Administration (NASA) Atmospheric Infrared Sounder (AIRS) on board the Aqua satellite is now recognized as an important contributor towards the improvement of weather forecasts. At this time only a small fraction of the total data produced by AIRS is being used by operational weather systems. In fact, in addition to effects of thinning and quality control, the only AIRS data assimilated are radiance observations of channels unaffected by clouds. Observations in mid-lower tropospheric sounding AIRS channels are assimilated primarily under completely clear-sky conditions, thus imposing a very severe limitation on the horizontal distribution of the AIRS-derived information. In this work it is shown that the ability to derive accurate temperature profiles from AIRS observations in partially cloud-contaminated areas can be utilized to further improve the impact of AIRS observations in a global model and forecasting system. The analyses produced by assimilating AIRS temperature profiles obtained under partial cloud cover result in a substantially colder representation of the northern hemisphere lower midtroposphere at higher latitudes. This temperature difference has a strong impact, through hydrostatic adjustment, in the midtropospheric geopotential heights, which causes a different representation of the polar vortex especially over northeastern Siberia and Alaska. The AIRS-induced anomaly propagates through the model's dynamics producing improved 5-day forecasts.
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1. Introduction

[2] The Aqua satellite containing the Atmospheric Infrared Sounder (AIRS) and the Advanced Microwave Sounding Unit (AMSU-A) was launched in May 2002 by NASA to become the most-advanced polar orbiting integrated infrared and microwave atmospheric sounding system to this day [*Pagano et al.*, 2003]. The basic 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, has been described previously [*Susskind et al.*, 2003, 2006]. The post-launch algorithm, referred to as AIRS Version 4 [*Susskind et al.*, 2006] has been used by the NASA Goddard Distributed Active Archive Center (DAAC) to generate AIRS retrieval products. AIRS unprecedented vertical resolution allows a more detailed depiction of the thermal structure of the atmosphere with respect to other data sets such as reanalyses. For example, *Tian et al.* [2006] investigated the Madden Julian Oscillation and documented that AIRS-derived products improve the representation of the vertical moist thermodynamic atmospheric structure in the tropics.

[3] *Le Marshall et al.* [2006] have shown an improvement of the NCEP operational system's forecasting skill resulting from the assimilation of AIRS radiance observations unaffected by clouds. *Wu et al.* [2006] found a specific impact on hurricane simulation by assimilating retrieved AIRS temperature and humidity profiles derived in clear conditions, which produce a more accurate representation of the Saharan Air Layer. However, the improved representation of the atmospheric structure discussed in these studies is limited by the use of AIRS data only in areas not contaminated by clouds. *Atlas* [2005] and *Chahine et al.* [2006] present preliminary results obtained by making some use of AIRS data also in cloudy areas.

[4] *Susskind* [2007] describes some of the capabilities of the AIRS Version 5 retrieval algorithm now being used operationally at the DAAC. A key element of the new system is the ability to generate accurate case-by-case level-by-level error estimates and also use them for quality control. In this work, we assimilate quality-controlled AIRS Version 5 temperature soundings, using the medium quality control described by *Susskind* [2007].

2. Model and Data Assimilation System

[5] The global data assimilation and forecasting system used is the NASA GEOS-5, which combines the Grid-point Statistical Interpolation (GSI) analysis algorithm co-developed by the National Centers for Environmental Predictions (NCEP) Environmental Modeling Center (documented by *Wu et al.* [2002]), with the NASA atmospheric global forecast model [*Bosilovich et al.*, 2006], which shares the same dynamical core [*Lin*, 2004] with the so-called finite-volume General Circulation Model

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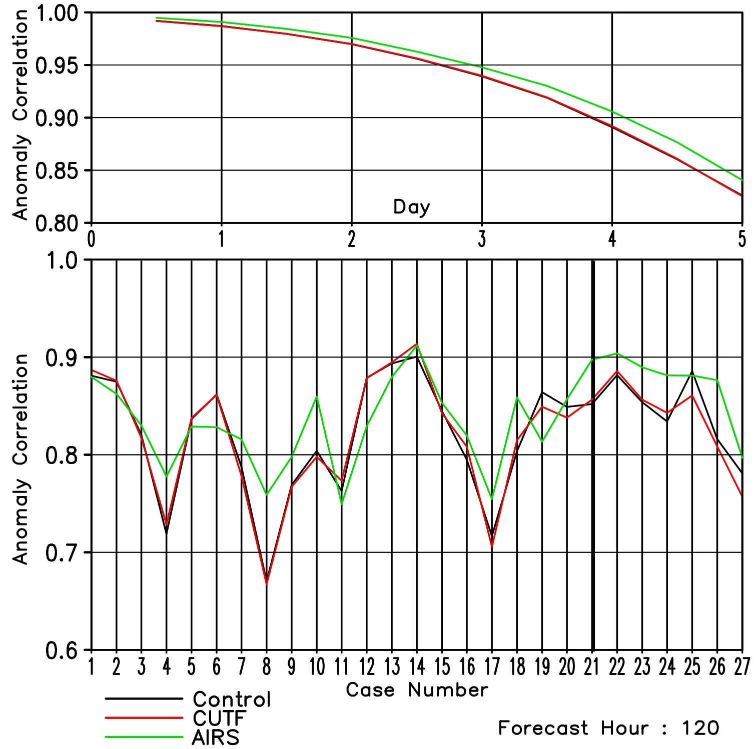

Figure 1. (top) The 500 hPa geopotential height anomaly correlation for the Northern Hemisphere Extratropics, north of 30°N. Green is AIRS, red is CUTF, and black is CNTRL. (bottom) Time series of 500NHAC. The numbers refer to individual forecasts. Case 1 corresponds to January 5th. The thick line on 21 corresponds to the selected case of January 25th.

(fvGCM), used in several studies focused on tropical cyclones [e.g., *Atlas et al.*, 2005; *Shen et al.*, 2006]. The GEOS-5 however contains a newer version of the fvGCM, differing in many aspects but most notably in the physical parameterizations, partly developed by the NASA Global Modeling and Assimilation Office (GMAO).

3. Experiments

[6] Three 31-day assimilation experiments, starting at 00z 1 January 2003, have been performed with the GEOS-5 DAS run at a spatial horizontal resolution of 1°. In all three experiments conventional and satellite observations used operationally at NCEP at that time are assimilated, with the exclusion of AIRS data in the first run, which we define CNTRL. AIRS temperature profiles with medium quality control, and the same AIRS data only above 200 hPa (so as to assess the significance of withdrawing tropospheric temperature information derived under cloudy conditions) are assimilated in the experiments named AIRS and CUTF respectively. The first four days are discarded to allow spin-up. From the three sets of analyses, three corresponding sets of 27 five-day forecasts (CNTRL, AIRS and CUTF) are produced and verified against operational NCEP analyses.

4. Results

[7] Figure 1 shows the anomaly correlation (*AC*) plot for 500 hPa geopotential height in the northern hemisphere extratropics, comparing 3 sets of 27 5-day forecasts: CNTRL, AIRS and CUTF. The AC at day 5 (AC_5) is about .82 for the CNTRL, and a significant impact of AIRS can be seen throughout the integration, with AIRS AC_5 being about .85. The CUTF *AC* is virtually identical to that of the CNTRL, thus suggesting that most of the impact during boreal winter originates from AIRS data within the troposphere.

[8] The daily variation of CNTRL AC_5 between 5 and 31 January 2003 for the northern hemisphere ranges between a minimum of about .67 to a maximum of .91 (Figure 1). The CUTF AC_5 does not differ remarkably from the CNTRL whereas the AIRS maintains an overall superior skill, with only 5 days over 27 in which the CNTRL is better. In particular, AIRS minimum and maximum AC_5s range from .76 to .91, suggesting that ingestion of AIRS profiles makes the GEOS-5 system more stable.

5. Mechanism: Temperature Structure at the High Latitudes

[9] The most relevant aspect of the AIRS data impact on the forecast is a substantially different representation of the lower midtropospheric temperature structure over the Arctic region, northeastern Asia and northern Alaska. This is observed in most of the cases in which AIRS AC_5 is higher than the CNTRL. One case is selected, initialized on January 25th, in which the difference AIRS minus CNTRL is particularly remarkable (larger than .05) and where the CNTRL performance is already satisfactory (CNTRL AC_5 = .85). In other words, a case is chosen in which the ingestion of AIRS data further improves a reasonably good forecast.

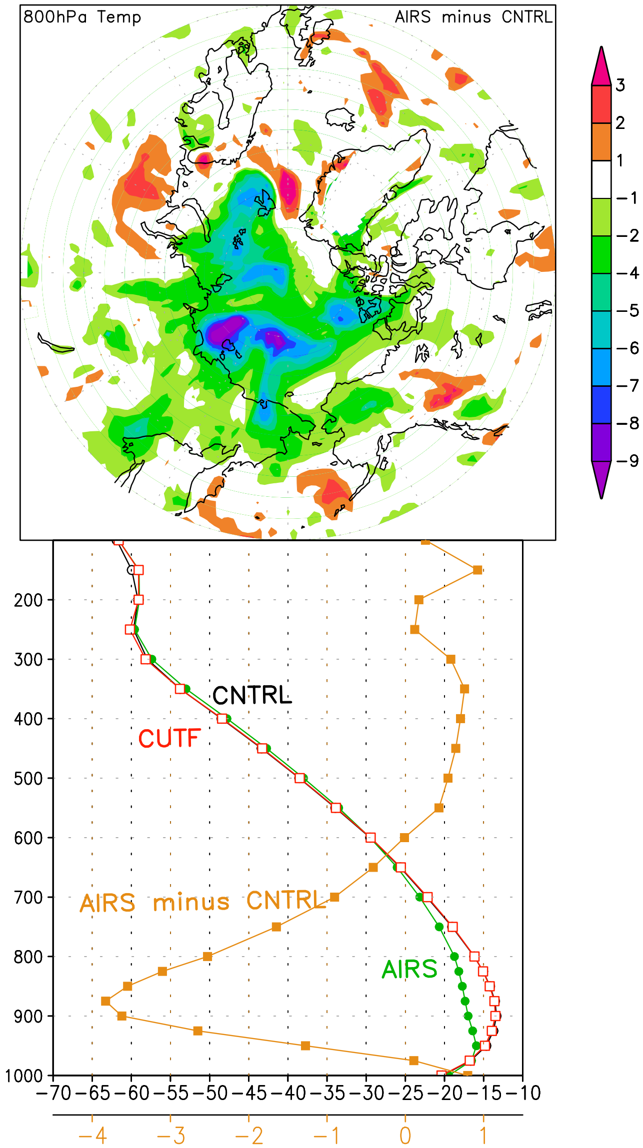

Figure 2. (top) Temperature anomaly analyses (AIRS minus CNTRL, °C) at 800 hPa and (bottom) area-averaged (70°–90°N) temperature (°C) vertical profiles from analyses at 00z 25 January. CUTF and CNTRL virtually indistinguishable below 200 hPa. Upper horizontal axis refers to CNTRL, AIRS, and CUTF; lower horizontal axis in red refers to AIRS minus CNTRL.

[10] Figure 2 shows the 800 hPa temperature difference between AIRS and CNTRL analyses at 00z 25 January 2003: a large asymmetric temperature anomaly, slightly displaced towards Asia, dominates the Polar regions, with the AIRS analysis colder than the CNTRL of about 2°C over a large portion of the Arctic and Northeastern Siberia. This remarkable temperature difference is entirely caused by AIRS data. In the same figure, the area-averaged temperature profiles for AIRS, CUTF, CNTRL and the difference AIRS minus CNTRL are computed for latitudes between 70°N and 90°N. The CUTF profile is virtually indistinguishable from the CNTRL up to 200 hPa, confirming that most of the AIRS impact is in the troposphere. The largest difference between AIRS and CNTRL is of more than 2.5°C between 925 hPa and 800 hPa, reaching almost 4°C at 875 hPa, and goes to zero at about 600 hPa.

6. Changes in the Polar Vortex and Baroclinic Waves

[11] Ingestion of AIRS data produces major height hydrostatic adjustments causing negative AIRS minus CNTRL 500 hPa geopotential height anomalies, on the order of several tens of meters, over the entire Arctic and a fraction of northeastern Siberia and Alaska (Figure 3). This difference is not found for the CUTF case which is almost identical to the CNTRL (not shown).

[12] The geopotential anomaly, originated mostly in the Polar regions, propagates through the model forecast also in the mid-latitudes and can be followed with the aid of a Hovmøller diagram (Figure 4), which shows the 500 hPa geopotential AIRS minus CNTRL difference, latitudinally averaged between 40° and 80°N. The small negative initial anomaly between 160°E and 150°W over northeastern Siberia and Alaska corresponds well to Figure 3, and appears to undergo dispersion and amplification, producing a wave packet affecting most of North America and the northern Atlantic at day 5. In the same figure the difference between the corresponding verifying NCEP analyses and the CNTRL between 100°W and 0° is in qualitative good agreement with the impact induced by AIRS.

[13] In Figure 5 the 5-day 500 hPa height forecast difference between AIRS and CNTRL is compared with the difference between the verifying corresponding NCEP analysis and the CNTRL. A good correspondence can be observed over most of the western part of the northern hemisphere and over Europe, in agreement with Figure 4. The suggested explanation is that AIRS data modify the representation of the high latitude low and mid-tropospheric temperature structure, leading to a substantially changed polar vortex, particularly on the side of Siberia, where troughs and ridges are altered. These changes in the initial conditions affect in turn baroclinic wave production and propagation in the GEOS-5 forecast. Similar patterns are noted in other cases in which the AIRS AC_5 is larger than the CNTRL (not shown).

[14] It is important to stress that the Arctic and northeastern Siberia are almost void of conventional data and are not covered by geostationary data: therefore polar orbiting observing systems are particularly beneficial. In our case, the data coverage provided by AIRS over these regions is very dense (not shown). Low-level stratus cloud coverage over the Arctic peaks in summer but a non-negligible coverage of about 18% is also documented in winter [*Klein and Hartmann*, 1993]. The capability of deriving accurate quality controlled temperature profiles in partly cloudy condition allows a significantly improved lower tropospheric spatial coverage compared to that obtained from the use of clear-sky data only.

[15] The few cases in which AIRS AC_5 is smaller than the CNTRL are associated with asymmetric data sampling over highly dynamically active regions. We select case 12 from

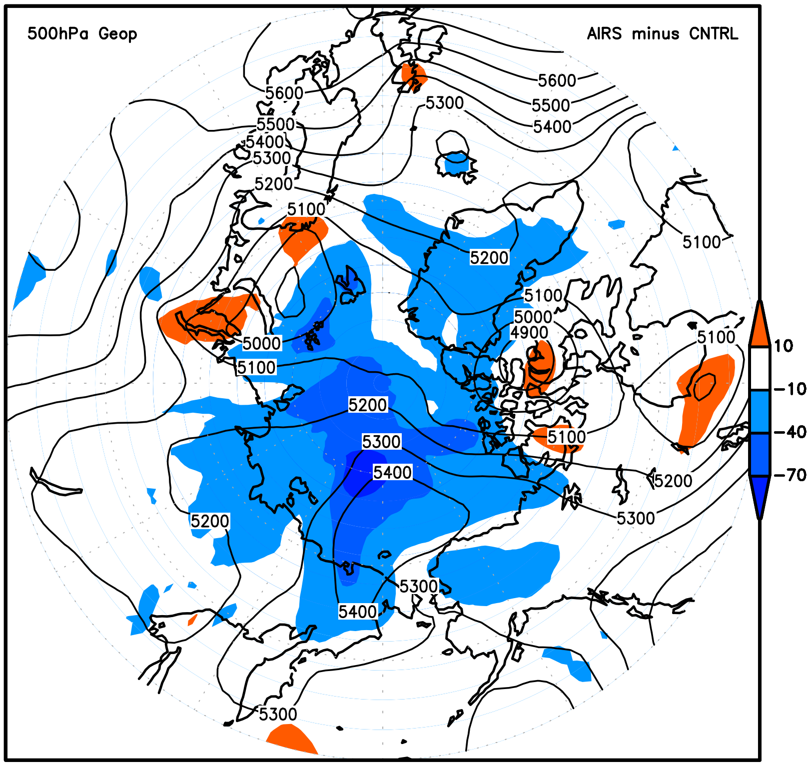

Figure 3. Geopotential height (*m*) anomaly analysis (AIRS minus CNTRL) at 500 hPa, 00z 25 January (shaded). CNTRL analysis is superimposed (solid contour).

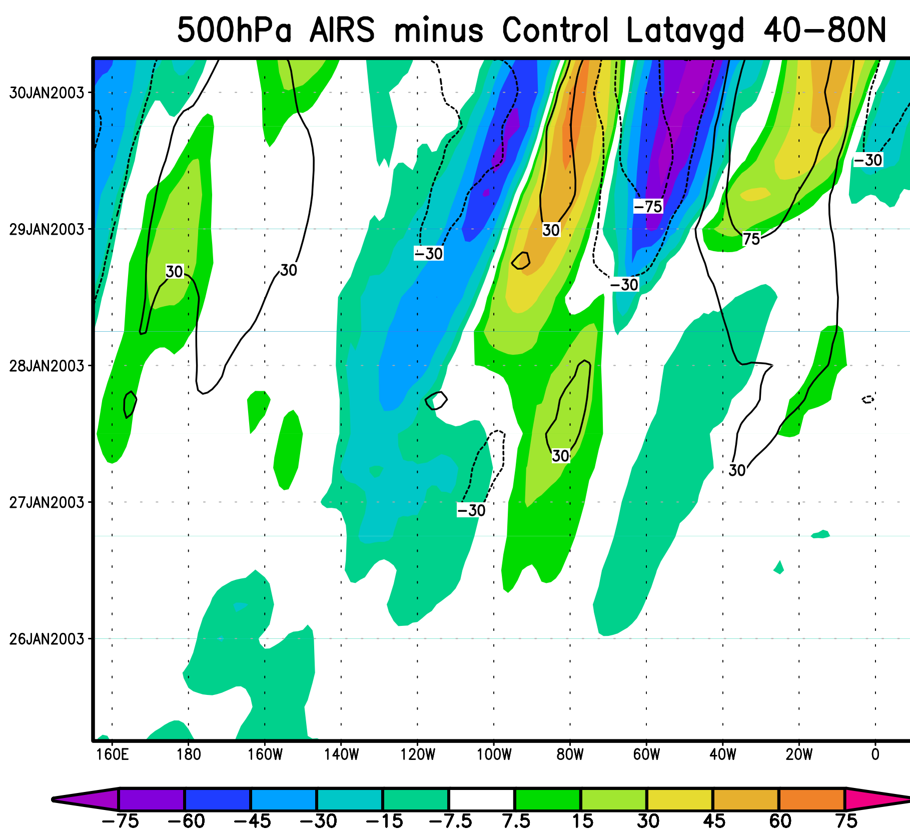

Figure 4. Hovmøller diagram of latitudinally-averaged (40°–80°N) 500 hPa height (*m*) anomaly forecast (AIRS-CNTRL) from 00z 25 January to 06z 30 January (shaded). Difference between NCEP verifying analyses and CNTRL forecast is superimposed (solid contour). Time upward.

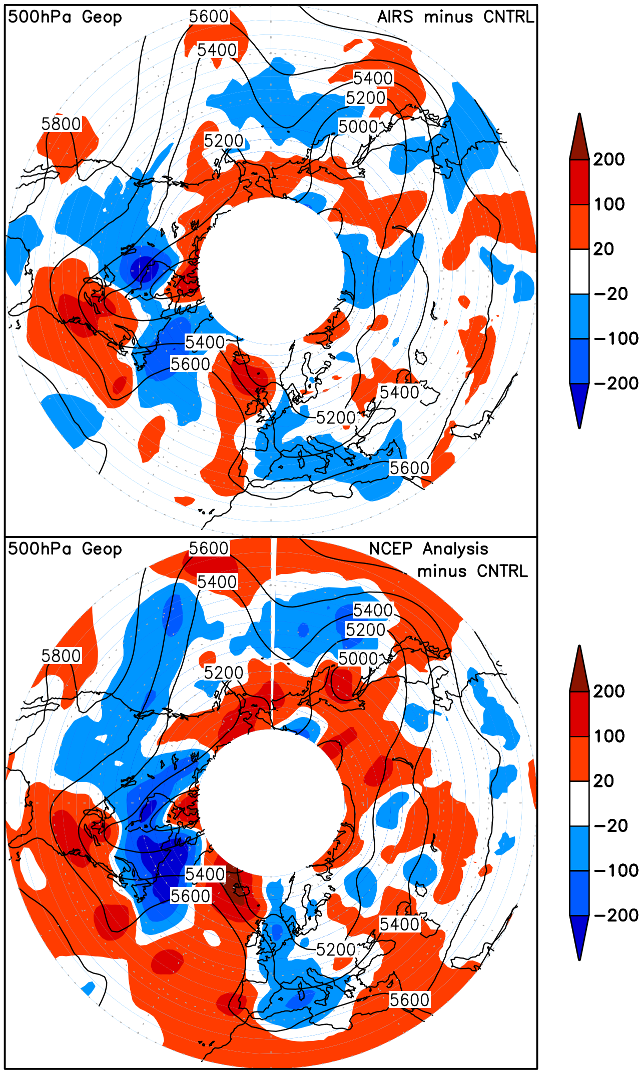

Figure 5. (top) The 500 hPa height (*m*) anomaly 120h forecast (AIRS minus CNTRL, shaded) and (bottom) NCEP verifying analyses minus CNTRL 120h forecast (shaded) at verifying time of 00z 30 January. On both panels the corresponding CNTRL 500 hPa geopotential 120h forecast (initialized at 00z 25 Jan, contour) is superimposed. Latitude range 25°–70°N for clarity.

Figure 1, corresponding to January 16th. Figure S1[1] shows the 500 hPa analysis at 00z 16 Jan 2003 (with a deep low to the west of Kamchatka and two strong shortwaves) and a Hovmøller illustrating the AIRS minus CNTRL growth. Figure S2 shows that AIRS coverage at 00z 16 Jan only exists on the eastern side of the system, creating an imbalance that propagates in the Hovmøller as an unrealistic stationary wave.

[16] The AIRS temperature retrieval methodology involves the determination and use of so-called "cloud-cleared" radiances $\hat{R}_i$ [*Susskind et al.*, 2003], that are in effect estimates of what AIRS would have measured had the scene been cloud free. These cloud-cleared radiances can be assimilated in an analogous manner to that used now with cloud free radiances. A comprehensive assessment of this approach will be the subject of a future article.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL033002.

7. Concluding Remarks

[17] In this article we emphasize that the use of AIRS soundings derived in cloud contaminated areas significantly increases weather forecast skill during midlatitude boreal winter conditions due to a substantially different representation of the low midtropospheric thermal structure over the Arctic region, northeastern Siberia and Alaska. The analyzed thermal anomaly induced by AIRS data ingestion causes hydrostatically related adjustments in the representation of the mid- and upper-tropospheric height fields, modifying particularly the geopotential gradients in dynamically active features such as troughs and ridges. The modified pattern of baroclinic waves over half of the northern hemisphere, caused by AIRS data ingestion, is verified against the NCEP operational analyses, and found to be more realistic than the control simulation without AIRS data. It is important to stress that the experiment in which AIRS data are excluded only below 200 hPa is virtually indistinguishable from the control and indicates that most of the AIRS impact is driven by a better depiction of the troposphere, especially beneath 600 hPa.

[18] **Acknowledgments.** Authors thank Don Anderson for support through grant MAP/04-0180-0070 and acknowledge use of NASA High-End Computing systems.

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