Validating IASI Temperature and Moisture Sounding Retrievals over East Asia Using Radiosonde Observations

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ABSTRACT

Temperature and moisture profiles retrieved from Infrared Atmospheric Sounding Interferometer (IASI) data are evaluated using collocated radiosonde data from September 2008 to August 2009 over East Asia. The level-2 products used in this study were provided by the National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service. By using radiosonde observations as a reference, the bias and root-mean-square error (RMSE) of the temperature and water vapor profiles are obtained to examine the performance of the IASI retrievals depending on surface types and the degree of atmospheric moisture. Overall, retrievals over the land or under drier atmospheric conditions show degraded performance for both the temperature and the moisture, especially for the boundary layer temperature. It is further shown that the vertical distributions of the RMSEs and the biases of the IASI retrievals resemble the variability pattern of the radiosonde observations from the mean profiles. These retrieval aspects are thought to be related to the surface emissivity effect on the IASI retrieval and the difficulties of accounting for large atmospheric variability in the retrieval process. Although the retrieval performance appears to degrade under cloudy conditions, cloudy- and clear-sky retrievals show similar statistical behaviors varying with surface type and atmospheric moisture. Furthermore, the similar statistical behaviors between first guess and final retrievals suggest that error characteristics inherent to the first guess were not sufficiently resolved by the physical retrieval process, leaving a need to improve the first guess for the better retrieval.

1. Introduction

With the advent of satellite technology, hyperspectral measurements at several thousand channels over the infrared (IR) spectral band are now possible. For example, the Atmospheric Infrared Sounder (AIRS) on board the Aqua satellite covers 3.74–4.61, 6.20–8.22, and 8.8–15.4 μm with 2378 IR channels (Chahine et al. 2006). The Infrared Atmospheric Sounding Interferometer (IASI) in the MetOp satellite provides measurements at 8461 channels over the IR spectral region of 3.7–15.5 μm, with a spectral resolution of 0.25 cm⁻¹ (Blumstein et al. 2004). Observed hyperspectral measurements are routinely used to produce atmospheric temperature and moisture profiles over both the land and the ocean, with a very high vertical resolution, by applying various retrieval algorithms (Li et al. 2000; Aires et al. 2002; Goldberg et al. 2003; Susskind et al. 2003; Carissimo et al. 2005; Smith et al. 2005; Liu et al. 2009).

The retrieved high-resolution atmospheric profiles obtained from AIRS and IASI measurements over the globe lead to significant improvements in numerical weather forecasting (e.g., Reale et al. 2008a,b; Singh et al. 2008; Hilton et al. 2009) and enhance our understanding of our climate system (e.g., Gettleman et al. 2006; Tian et al. 2006; Dessler et al. 2008; Stubenrauch et al. 2010). The sounding retrievals are also used for...
improving the hurricane and typhoon forecasts (Li and Liu 2009; Liu and Li 2010). Although the retrieved outputs are now routinely used for weather forecasting and climate studies, it is essential to validate the derived products using common in situ measurements such as radiosonde data across various climate regimes in order to assess their quality. The validation efforts will pave the way to an improved version of the retrieval algorithm by revealing where potential problems might exist. There have been efforts to validate the profiles retrieved from hyperspectral IR sounders. Validation studies using radiosonde data (Divakarla et al. 2006) and Atmospheric Radiation Measurement Program (ARM) data (Tobin et al. 2006) reported that the National Aeronautics and Space Administration (NASA) AIRS science team level-2 retrievals over the ocean show good performance with accuracies close to the requirements—that is, 1 K in 1-km layers for temperature and 20% (goal of 10%) in 2-km layers for water vapor in the troposphere. However, poorer performances of AIRS temperature and moisture retrievals were indicated over land.

The theoretical basis of the National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite, Data, and Information Service (NESDIS) IASI retrieval algorithm is similar to that of the NASA AIRS science team algorithm (Susskind et al. 2003), and thus, we expect similar or better retrieval accuracies from IASI measurements since their calibration accuracies are comparable to each other (Hillger and Schmit 2010). However, given the fact that there are some several differences between the AIRS and IASI level-2 retrieval algorithms, arising from the different instrument characteristics (NOAA/NESDIS 2008), it is necessary to examine the quality of the IASI products in order to demonstrate the capability of the IASI retrieval algorithm. Thus far, however, there have not been in-depth studies assessing the accuracies of IASI retrievals. Furthermore, it is of much interest to examine how the hyperspectral products are regionally different from one climate regime to another. In particular, East Asia is of much interest because diverse weather and climate conditions are present over geographically diverse surface conditions. Ocean-influenced warm moist conditions are prevalent during the summer, in contrast to continent-influenced cold dry conditions during the winter. The arid and semiarid regions located in the northwest contrast the warm oceans located in the southeast, implying diverse surface conditions. Therefore, validation study over diverse atmospheric and surface conditions such as East Asia should improve our understanding of general retrieval problems.

In this study, we focus on the assessment of quality of IASI retrievals of temperature and moisture. We conduct validation studies using radiosonde observations across these diverse temporal and geographical conditions over East Asia region. In doing so, IASI temperature and moisture retrievals obtained from NOAA/NESDIS are taken and compared to radiosonde observations. This study intends to provide insights on what factors should be considered and thus where improvements might be made for better retrieval of atmospheric temperature and moisture profiles, particularly in the NOAA/NESDIS algorithm.

2. IASI-raob collocated data

IASI temperature and moisture retrievals used in this study are from the Comprehensive Large Array-Data Stewardship System (CLASS; http://www.class.necdc.noaa.gov) of NOAA/NESDIS. The algorithm used for the retrieval is theoretically equivalent to the NASA AIRS team retrieval algorithm (Chahine et al. 2007) originally designed for AIRS. The retrieval algorithm uses an iterative physical inversion procedure (Susskind et al. 2003) starting with the initial guess obtained from a regression retrieval method (Goldberg et al. 2003). Since microwave measurements are also used for cloud clearing capabilities, NOAA/NESDIS IASI level-2 retrievals are performed in an IASI field of regard (FOR) collocated to the Advanced Microwave Sounding Unit-A (AMSU-A) and Microwave Humidity Sounder (MHS) FORs. The IASI FOR consists of a $2 \times 2$ matrix of circular fields of view (FOVs) with a 12-km diameter at nadir, and the FOVs are sampled with a 25-km interval at nadir. Detailed differences between the AIRS and IASI retrieval systems, arising from different instrument characteristics, can be found in the Algorithm Theoretical Basis Document (ATBD) of NOAA/NESDIS (2008). The atmospheric profiles produced by NOAA/NESDIS are provided at 100 pressure levels from 1100 to 0.0161 hPa.

Raob profiles extracted from the NOAA/Earth System Research Laboratory (ESRL) database are used as a reference for validating the IASI temperature and moisture retrievals. The raob data include temperature, humidity, and wind profiles at 22 mandatory levels (including surface) and various significant levels. According to Miloshevich et al. (2004, 2006), the measurement errors of radiosonde water vapor are substantial and complicated in the upper troposphere and lower stratosphere because of the slow sensor response to the humidity changes at low temperatures; therefore, validation results obtained from the upper-level humidity should be interpreted with caution.

The collocated IASI and radiosonde data are constructed over a 1-yr period from September 2008 to August 2009 over East Asia ($0^\circ$–$55^\circ$N, $90^\circ$–$150^\circ$E; Fig. 1
for the geographical location of the study domain). For collocation, data are kept if the time and spatial differences between the radiosonde observations and the satellite measurements are within 3 h and 1°, respectively.

Since the MetOp satellite passes around 0100 and 1300 UTC over East Asia, we use raob observations collected at 0000 and 1200 UTC at 130 stations whose locations are given in Fig. 1. Stations near oceans hold relatively larger sampling numbers (around 1800 samples over the Philippines, the Indochina area, southeast China, South Korea, and the southern Japanese islands). The sampling number tends to decrease when the station is located farther inland and decreases further to around 200 over the northwest arid region.

For quality control of the radiosonde data, the observed profiles are checked to see whether temperature and dewpoint depression are within two standard deviations of the 3-yr (September 2006–August 2009) mean profiles at any given pressure level from the surface to 100 hPa. The quality of the IASI profiles are also checked using the quality flags that are included in the level-2 products. The IASI 100-level temperature and moisture profiles are interpolated to 21 mandatory pressure levels used for radiosonde observations. Because water vapor retrievals from satellites and radiosondes above 200 hPa are not reliable because of the difficulty in measuring humidity under cold conditions, statistics for water vapor are restricted to below 200 hPa.

### 3. Validation results for clear-sky retrievals

First, we examined the IASI clear-sky-only retrievals depending on surface types and the degree of atmospheric moisture. Examination of the retrieved products under cloudy conditions will be discussed in section 4. The outputs are considered clear-sky retrievals if the cloud fractions (also available in the IASI level-2 data) are smaller than 1%. The obtained results are separately presented in terms of surface type and degree of atmospheric moisture.

#### a. Statistics classified by surface types

To examine the performance of the IASI retrievals, we first separate the surface types into land, coastal region, and ocean. For each type, biases of the retrievals from the raob measurements are calculated at each level, and their corresponding root-mean-square errors (RMSEs) are determined (Fig. 2). The bias and RMSE for all observations are also shown in Fig. 2. For the relative humidity, the normalized RMSE is plotted separately after normalizing against the mean radiosonde value. The number of samples used for calculating the statistics and mean precipitable water up to the 300-hPa level [referred to as total precipitable water (TPW)] are given in parenthesis. The number of samples used for land, coast, and ocean are 35312, 6341, and 17950, respectively, and their respective TPW values are 25.9, 34.8, and 39.0 kg m⁻².

Figure 2 shows that the mean biases and RMSE values for each surface type are significantly different from the total mean values, indicating that the retrieval accuracies depend on the surface types. Indeed, retrievals over land appear less accurate as compared to those for other surface types (coast or ocean). The dependency of the retrievals on the surface type is obvious near the surface, where the temperature bias and RMSE are also increased, particularly over the land.

It is well known that surface emissivity varies with surface conditions, temperature, time, and wavelength. Since the land surface conditions have a large variability in space and time, the degradation of IASI retrievals over the land, especially near the surface, is thought to be related to the inhomogeneity of the land surface and its accompanied emissivity variations. These results suggest that the specification of accurate full spectral emissivity is necessary for a better estimation of temperature and moisture profiles from hyperspectral measurements. In fact, the results are consistent with recent findings showing that physical retrieval getting IR emissivity and profiles simultaneously can improve the retrieval accuracy, particularly in the boundary layer (Li et al. 2007; Yao et al. 2011). The surface emissivity is included in
both the regression and physical retrieval processes of the NOAA/NESDIS IASI retrieval scheme; however, the degraded retrieval results over land, especially near the surface, suggest that the current IASI scheme cannot fully utilize the information on IR surface emissivity spectrum over land. Because the current surface emissivity regression is performed only on three surface types of snow/ice, land, and ocean, it may need more specific classification of surface types in the regression retrieval for better accounting for the surface emissivity. It may also be worthwhile to investigate the impact of the infrared land surface emissivity data obtained from other measurement sources.

The relative humidity retrievals show positive biases in the boundary layer below the 800-hPa level, where temperature biases are also large and positive. Because a temperature profile is required for water vapor soundings from water vapor channel radiances, the moist bias shown in Fig. 2 may be attributed to the warm bias. The moist bias seems to be caused by a combination of water vapor mixing ratio bias and the layer’s mean Planck function. In the retrieval process, a more absorbing water vapor effect should be present to compensate for the higher emitting effect due to the warmer temperature. The normalized RMSEs of relative humidity increase with altitude, likely because of the general tendency of lower relative humidity in the upper layers, contributing to the larger relative error.

The statistics associated with first-guess profiles are also analyzed in terms of the same surface-type classification. Because the statistics of the first guess and the final retrieval are very similar (not shown), the improvements of the final retrievals, in comparison to the first guess, are plotted in Fig. 3. Although some degradation of the IASI retrieval is noted in the temperature bias around the tropopause level and low-level humidity statistics, final retrieval errors both for temperature and relative humidity are generally reduced especially in the lower troposphere, implying that IASI retrievals were improved through the physical retrieval process. However, the similar statistical behaviors between the first guess and final retrieval strongly suggests that error
characteristics inherent to the first guess (e.g., degraded performance over land and sharply increasing errors near the land surface) were not much resolved by the current version of physical retrieval algorithm.

b. Statistics classified by TPW

Although the IASI retrieval quality dependency on surface types may be associated with the surface emissivity, they may be attributed to the influence of atmospheric moisture because the TPWs averaged for surface types show a gradual increase from the land to the ocean. Hence, we hypothesize that the IASI retrievals may depend on the degree of atmospheric moisture. To examine the possible dependency of the IASI retrieval accuracies on the degree of atmospheric moisture, the statistics of temperature and relative humidity profiles are classified with respect to TPW.

The results are shown in Fig. 4 for the different ranges of TPW (i.e., <10, 10–20, 20–30, 30–40, 40–50, 50–60, and >60 kg m\(^{-2}\)). The temperature biases seem small except at the surface boundary layer in which sizable biases are found in dry conditions. The bias of the IASI relative humidity against raob is relatively large for drier conditions in the boundary layer, which decreases with increased moisture. However, above the 700-hPa level, the humidity bias increases for the two largest cases (i.e., TPW > 50 kg m\(^{-2}\)). The normalized relative humidity shows similar behaviors to the ones shown in the relative humidity bias.

The temperature RMSEs appear to be comparable to those noted in the surface-type classifications, and much larger RMSEs and biases in the lower boundary layer are similarly obvious. In general, the RMSE values become larger in dry atmosphere, with a maximum RMSE for TPW < 10 kg m\(^{-2}\). At the same time, the normalized RMSEs for the relative humidity tend to increase with drier conditions, although the RMSEs for the extremely dry atmosphere (<10 kg m\(^{-2}\)) are smaller above the 700-hPa level than those for relatively moist conditions. However, given that such dry atmospheres may bring in more uncertainties in calculating the relative RMSEs, it is not easy to interpret the result that the
normalized RMSEs of the ISAI relative humidity become larger for drier conditions. It is also interesting to note that normalized relative humidity RMSEs become larger with altitude.

Because the degree of atmospheric moisture significantly varies with the season, the statistical behaviors varying with atmospheric moisture also implicitly convey the seasonal differences. By separating the temperature and moisture retrievals into seasons, larger retrieval errors are found in winter (not shown), which is similar to those found for the dry condition. Since a substantial number of the collocated samples come from Chinese radiosonde measurements, results shown in this study might be significantly determined by the use of Chinese instruments. However, the statistics sampled only over non-Chinese radiosonde stations show behaviors similar to those found only for the Chinese samples (not shown), implying that error characteristics varying with atmospheric moisture described above are a general aspect of IASI retrievals.

The TPW-classified statistics for the IASI first-guess field are also analyzed in order to compare the dependence of error statistics on the atmospheric moisture between first guess and final retrieval. Because the magnitude and behaviors of first guess and final retrieval statistics are similar, the differences between them are plotted in Fig. 5 in order to examine the degree of improvement. Although temperature bias shows complicated aspects, temperature RMSE is generally reduced through the physical retrieval process except for the moist case. For relative humidity, both bias and RMSE clearly indicate an improvement of the IASI retrievals compared to the first guess except near the surface. It is also of interest to note that first-guess and final retrieval errors show very similar statistical behaviors, varying with atmospheric moisture—that is, large moisture bias for both extremely dry and moist conditions, and increasing retrieval errors with decreased moisture (not shown here).

The surface emissivity effect could be one reason for the more degraded performances under drier conditions.
Since the drier regions are more predominant in land area, as indicated in Fig. 2, much drier classes in Fig. 4 in general represent drier land areas. Such interpretation is consistent with the results shown in Fig. 2. For dry atmospheres that may be more frequently observed during the winter season or over dry areas, the atmospheric transmittance of water vapor absorption channels can be large enough such that the radiances of the water vapor channels may be contaminated by the surface; thus, surface emissivity can be crucial to sensing temperature and moisture from the measured radiances. In contrast to the expected surface emissivity effect over land, the surface influence on retrieval over the ocean is expected to be minimal. However, the statistics sampled only over the ocean show similar error characteristics, particularly above the boundary layer (not shown), suggesting that the surface emissivity effect is not the only reason for explaining the degraded performance under dry conditions. Here, we suggest that the dependency of the IASI retrieval accuracies on the degree of atmospheric moisture could be attributed to the intrinsic difficulty of retrieving atmospheric parameters with large variability. The statistical significances depending on the atmospheric moisture and altitude appear to be similar to those found in the standard deviations of radiosonde-based temperature and moisture profiles (Fig. 6). The standard deviations are generally large under dry conditions, and their vertical variations with respect to TPW changes are similar to those found in the RMSE of Fig. 4. This positive relationship between the retrieval errors and the fluctuations of raob observations may be understood as an intrinsic problem of the retrieval process. The gross error of the initial guess field can be substantially reduced via iterative processes; however, the final outcomes resemble the climatology-based initial guess field, not fully accounting for the daily fluctuations. Therefore, the retrieval itself may be a challenging problem because information resolving small-scale variability may be necessary when the initial guess field is assigned.

The temperature and relative humidity anomaly profiles for seven TPW classes are shown in Fig. 7 to demonstrate the difficulties of accounting for diverse

![Fig. 5. As in Fig. 4, but for the improvement of IASI retrievals compared to first-guess profiles. The improvements represent the differences of bias magnitude and RMSE between the IASI final retrieval and first guess.](http://journals.ametsoc.org/doi/pdf/10.1175/JTECH-D-11-00078.1)
atmospheric moisture conditions. The anomaly profiles are calculated by subtracting the total mean profiles from the respective mean profiles for the seven TPW classes. Compared to the total mean climatology, the dry atmosphere is colder and drier in the troposphere while the moist atmosphere is warmer and moister. A notable point in the anomaly profiles is that the anomaly structures are similar to their respective biases in Fig. 4, with the reversed sign. This similarity emphasizes the difficulty in correcting the first guess field from climatology. For example, the lower-tropospheric dryness of the raob profiles in dry conditions may not be fully resolved by the iterative processes, and thus, the moist bias of the lower troposphere may be significant in the retrieval results. Conversely, a dry bias may be expected in the retrieval of humidity under moist conditions.

This lack of ability to retrieve the extreme conditions in the retrievals is thought to be due to limitations in
both the regression procedure used to generate the initial profile for the physical retrieval and in the physical retrieval itself owing to the use of a too-small channel subset of the radiances measured. The “first guess” NOAA/NESDIS linear regression algorithm is produced using a global, unstratified by moisture and cloudiness, statistical ensemble of radiance spectra and atmospheric profiles. Thus, because of the high degree of radiance nonlinearity with respect to moisture and cloud altitude, this linear regression will underestimate extreme variations of temperature and moisture from the mean conditions for the statistical ensemble. In principle, the physical and iterative nonlinear retrieval should alleviate this limitation, but the degree to which it can do so is highly dependent on the signal to noise of the radiances used for the physical retrieval. In the NOAA/NESDIS algorithm, only a small subset of the spectral channels available is sequentially used for the temperature (137 channels) and water vapor (79 channels) retrieval. As a result, the signal to noise of the system of radiances used for the physical retrieval could not be enough to retrieve extreme conditions of temperature and moisture. It is well known that the skill of profile retrievals is highly dependent on radiance information of signal to noise, which increases with the number of independent radiance observations used for the retrieval process (Smith et al. 2009). A priori error specification for the first-guess field is also known to play an important role in the physical inversion procedure by controlling the weight on the first guess. Based on the first-guess errors varying with atmospheric moisture, it is thought that the first-guess error specification accounting for the dependence on atmospheric moisture may contribute to the retrieval problems in extreme conditions.

4. Validation results for cloudy-sky retrievals

Figure 8 shows the statistics for the temperature and relative humidity profiles classified by different cloud-top fractions (i.e., 0.01–0.1, 0.1–0.3, 0.3–0.5, 0.5–0.7, and >0.7). Both the bias and the RMSE of the IASI temperature and moisture retrievals tend to increase with
the cloud-top fraction, although retrievals are likely to be contaminated by clouds are excluded in this analysis by using the IASI quality flags. This implies that the accuracy of the atmospheric temperature and moisture profiles degrades with an increase in the cloud amount; this result is consistent with the results of Susskind et al. (2006) for the AIRS level-2 retrievals. In fact, degraded performance under cloudy conditions is more evident with increasing cloud cover if the IASI quality control is not applied for the IASI–raob collocation (not shown).

Statistics for the IASI cloudy-sky retrievals are obtained in order to examine the retrieval quality dependencies on surface type or atmospheric moisture, as examined in the clear-sky retrievals. Figures 9 and 10 show the statistics for the temperature and relative humidity of the IASI cloudy-sky retrievals (i.e., cloud fraction > 0.01), but classified with surface type and TPW. In comparison to clear-sky retrievals (Figs. 2 and 4), cloudy-sky retrievals show similar statistical behaviors that vary with surface type and TPW. These similarities suggest that the degraded performance of IASI retrievals over land or dry areas can be understood as a general aspect of IASI retrievals. A moist bias of the lower troposphere under dry conditions and a dry bias of the midtroposphere in moist conditions are also found in cloudy-sky retrievals.

However, in contrast to temperature retrievals under clear-sky conditions, the statistics for the boundary layer temperature show much smaller changes according to the surface type or TPW. Because clouds obscure the radiation signal coming from the layer below the cloud top, cloudy-sky retrievals may be less dependent on the surface type or the moisture condition of the lower layers where most of the water vapor resides, leading to a lower dependency of the boundary layer temperature on the surface type and TPW. Thus, the uncertainties shown in the cloudy-sky retrievals seem to be largely due to the less accurate specification of the clouds.

5. Conclusions and recommendations

Temperature and moisture profiles retrieved from IASI measurements were evaluated using collocated radiosonde observations as a reference over East Asia.
Statistics classified by surface type and TPW reveal that temperature and moisture retrievals show less agreement with radiosonde observations over the land or under dry atmospheric condition. Although the retrieval performance appears to degrade proportionally with cloud fraction, both cloudy- and clear-sky retrievals show similar statistical behaviors, suggesting that the degrading performance over land or under dry atmosphere may be one aspect of the IASI retrievals under study. Although some notable improvements are made for relative humidity and for low-level temperature profiles through the physical retrieval process, the first-guess profiles also show similar statistical behaviors to those found in the final retrievals. Error statistics appear to be varying with surface type and atmospheric moisture. The similarity found in the comparison of statistics leads to a general conclusion that the first guess is an important factor in determining the retrieval error characteristics. The similarity also suggests that error characteristics inherent to the first guess are not fully resolved by current NOAA/NESDIS physical retrieval process.

Based on the statistical behaviors varying with surface type and atmospheric moisture, we addressed the issues regarding the surface emissivity effect and the difficulties in accounting for large atmospheric variability in the retrieval processes. Because surface emissivity and surface temperature have a larger variability over land and a stronger impact on the top-of-atmosphere radiance under dry conditions, a part of the degraded performance over land or under a dry atmosphere is thought to be attributed to the surface emission effect; therefore, an accurate specification of the hyperspectral emissivity spectrum along with the surface temperature seems important for retrieving the temperature and moisture profiles over land or under dry atmosphere. The dependency of the IASI retrieval accuracies on the degree of atmospheric moisture could also be related to the intrinsic difficulty in retrieving atmospheric parameters with large variability. The similarity between the RMSE (bias) of the retrievals and raob profile variability (anomaly) from the mean field suggests that the variability of the temperature and moisture profiles are not

Fig. 10. As in Fig. 4, but for cloudy sky.
fully resolved in the retrieval. As stated earlier, this is believed to be due to both the limitation of the linear regression used to generate the initial profile retrieval and the reduced input radiance signal to noise resulting from the use of only a small subset of the spectral channel radiances available for the physical retrieval.

In conclusion, it is recommended that improvements be made for accounting for land surface spectral emissivity variability and the radiance nonlinear dependence on clouds and moisture, which impacts the accuracy of the initial profile used in the physical retrieval. Also, the use of many more spectral channel radiances and the use of first-guess error specification varying with the atmospheric moisture for the physical retrieval should enhance the accuracy of the retrieval of extreme atmospheric conditions.

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