Validation of the IASI Temperature and Water Vapor Profile Retrievals by Correlative Radiosondes

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ABSTRACT

The METOP-A satellite Infrared Atmospheric Sounding Interferometer (IASI) Level 2 products comprise retrievals of vertical profiles of temperature and water vapor. The L2 data were validated through assessment of their error covariances and biases using radiosonde data for the reference. The radiosonde data set includes dedicated launches as well as the ones performed at regular synoptic times at Lindenberg station (Germany). For optimal error estimate the linear statistical Validation Assessment Model (VAM) was used. The model establishes relation between the compared satellite and reference measurements based on their relations to the true atmospheric state. The VAM utilizes IASI averaging kernels and statistical characteristics of the ensembles of the reference data to allow for finite vertical resolution of the retrievals and spatial and temporal non-coincidence. For temperature retrievals expected and assessed errors are in good agreement; error variances/rms of a single FOV retrieval are $<1K$ between 800 – 300 mb with an increase to ~1K in tropopause and ~2K at the surface, possibly due to wrong surface parameters and undetected clouds/haze. Bias against radiosondes oscillates within $\pm 0.5K$ between 950 – 100 mb. As for water vapor, its highly variable complex spatial structure does not allow assessment of retrieval errors with the same degree of accuracy as for temperature. Error variances/rms of a single FOV relative humidity retrieval are between 10 - 13% RH in the 800 – 300 mb range.

Keywords: Atmospheric, validation, remote sensing, retrieval, radiosonde network

1. INTRODUCTION

Atmospheric sounders, i.e. systems remotely measuring atmospheric thermodynamic parameters and constituents, are important sources of data for numerous practical and scientific applications such as Numeric Weather Prediction (NWP), climate studies, etc. To be usable the data from satellite sounders must be validated in the sense that their relation to the true state of the atmosphere is known with statistically estimated error [1, 2]. Thus, we define the validation as an activity whose purpose is to estimate the error of the sounder during its operation.

In the context of current work the term atmospheric sounder implies a satellite-borne measurement system comprising a sensor and subsequent data processing. The sensor receives and transforms the upwelling radiance, and the data processing generates calibrated spectra and retrievals of atmospheric parameters. In the process of designing, pre-launch testing, and calibration of a measurement system, modeled (nominal) relations between the true state and measurement results are established. Following Clive Rodgers [1] we call this characterization and error analysis. After launch the actual errors of measurements in the real atmosphere may differ from the errors established during pre-launch analysis. That may be caused by various factors such as changes in the instrument performance, inaccuracy in atmospheric radiative transfer

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modeling, etc. Thus, special efforts should be made to validate the sounding results during the in-orbit phase of the satellite system.

One of the ways to validate the satellite data is to perform a proper comparison of the data with an independently acquired reference data set. The reference (validating) system can be air-borne in situ, e.g. radiosondes [3, 4], air-borne remote [5], or space-borne [6, 7]. Because a remote sounder measures some function of the atmosphere-surface state [1], the ideal validation would be a straightforward comparison of the data from the system to be validated with the data from a validating system that samples exactly the same atmospheric state and has identical characterization but negligible errors. Unfortunately, on many occasions this approach is not feasible. As a rule, the systems have different characteristics, non-negligible errors, and perform their measurements at close but different times and locations. These types of measurements we will call correlative measurements.

Rodgers and Connor demonstrated [8] that even when two different systems perform the measurements on the same state of the atmosphere, a sensible comparison cannot be reduced to a simple straightforward point-by-point analysis of differences. Proper statistical methods should be used instead. The developed approach has been applied to validation of the MIPAS ozone [4] and MOPITT carbon monoxide [9] satellite measurements.

In practice, the situation is more complex than considered in previous research [1, 8], i.e. two factors must be taken into account: (i) the systems perform their measurements at different times and locations; and (ii) the systems have different characteristics, i.e. they sample the atmosphere differently on vertical and horizontal scales. Both factors cause additional error and must be accounted for. The error caused by the first factor we will call state non-coincidence error; it is caused by scenes' spatial nonuniformity and temporal variation. The error caused by the second factor we will call characteristic difference error; it is associated with the difference between the system's hardware and processing.

The goal of this work is twofold: (i) Scientific/Methodological – Testing of NPP CrIS Validation Assessment Model by its application to validation of IASI L2 data against radiosondes; the model takes into account state non-coincidence error, characteristic difference error as well as finite accuracy and precision of the system; (ii) Scientific/Utilitarian – Assessment of the IASI temperature and water vapor retrieval errors in the form that can be utilized by the community – regionally specific covariance and bias. We will mostly follow the terminology and notations used by Rodgers [1, 8, 10, 11]. In particular, bold lower case symbols denote column vectors, upper case bold typeface is used for matrices, and regular italicized typeface is reserved for scalars.

1.1 Statement of the Problem

Consider physical quantity q, which depends on the state of the atmosphere-surface and itself is a function of altitude h, horizontal coordinate $\mathbf{z}$, and time t. In this work the measured quantity is presented in vector form $\mathbf{q}$ and may be either spectrum of radiance or atmosphere-surface state parameters such as temperature, concentration of atmospheric constituent, e.g. water vapor concentration, etc. We consider the true state $\mathbf{x}$ in the vector form as a function of coordinate $\mathbf{z}$ and time t: $\mathbf{x} = \mathbf{x}(\mathbf{z}, t)$.

Consider a satellite system performing measurement $\hat{\mathbf{q}}$ on the true state $\mathbf{x}$

$$\hat{\mathbf{q}} = \mathbf{q}(\mathbf{x}) + \boldsymbol{\varepsilon} \tag{1.1}$$

where function $\mathbf{q}(\mathbf{x})$ returns the expected modeled measurement given the true state and is known from the pre-launch characterization and calibration of the measurement system. Term $\boldsymbol{\varepsilon}$ represents an unmodeled component of the measurements and is considered the combined measurement error of all origins. The error can be statistically characterized by its mean value $E\{\boldsymbol{\varepsilon}\} = \boldsymbol{\Delta}$ (bias) and covariance $E\{\boldsymbol{\varepsilon}\boldsymbol{\varepsilon}^T\} = \mathbf{S}_{\boldsymbol{\varepsilon}}$ (measurement noise). From the pre-launch error analysis of the system we have a priori ${}^{\mathbf{a}}\mathbf{S}_{\boldsymbol{\varepsilon}}$, and we presume that the nominally performing system is bias-free: ${}^{\mathbf{a}}\boldsymbol{\Delta} = \mathbf{0}$.

The validation of a satellite sounder returns estimates of $\mathbf{\Delta}$ and $\mathbf{S}_{\varepsilon}$ based on the analysis of real in-orbit measurements $\hat{\mathbf{q}}$ performed under conditions when some knowledge about modeled measurement $\mathbf{q(x)}$ at the moment of observation is available. *Thus, the validation problem can be considered complementary to the sounding one in the sense that in the sounding we estimate the state of the atmosphere or its function assuming some knowledge about the measurement error, whereas in the validation we estimate the error based on some knowledge of the errorless measurement.*

In practical validation, the measurement $\mathbf{q(x)}$ is known with finite nonzero error $\boldsymbol{\varepsilon}_{\mathbf{val}}$, i.e.

$$\mathbf{q(x)} = \widehat{\mathbf{q(x)}} + \boldsymbol{\varepsilon}_{\mathbf{val}} \tag{1.2}$$

and the equation for validation is:

$$\hat{\boldsymbol{\varepsilon}} = \hat{\mathbf{q}} - \widehat{\mathbf{q(x)}} = \boldsymbol{\varepsilon} + \boldsymbol{\varepsilon}_{\mathbf{val}} \tag{1.3}$$

We consider the validation error a random variable characterized by its mean value $\overline{\boldsymbol{\varepsilon}}_{\mathbf{val}}$ and covariance $\mathbf{S}_{\mathbf{val}}$. The validation error $\boldsymbol{\varepsilon}_{\mathbf{val}}$, with its statistics $\overline{\boldsymbol{\varepsilon}}_{\mathbf{val}}$ and $\mathbf{S}_{\mathbf{val}}$, determines attainable accuracy and precision of a given validation scenario.

One of the validation approaches consists of using so called correlative measurements to acquire the estimate $\widehat{\mathbf{q(x)}}$. In this approach a validated satellite system (system sub-index 1) performs measurement $\hat{\mathbf{q}}_1$ (see equation (1.1)) on the ensemble of true states $\mathbf{X}_{\mathbf{v}}\{\mathbf{x}_{\mathbf{v}} = \mathbf{x}(\mathbf{z}, t)\}$ (ensemble sub-index **v**). The ensemble is characterized by its mean $\overline{\mathbf{x}}_{\mathbf{v}} = E\{\mathbf{x}_{\mathbf{v}}\}$ and covariance $\mathbf{S}_{\mathbf{v}} = E\{(\overline{\mathbf{x}}_{\mathbf{v}} - \mathbf{x}_{\mathbf{v}})(\overline{\mathbf{x}}_{\mathbf{v}} - \mathbf{x}_{\mathbf{v}})^T\}$.

The validating system (sub-index 2) performs the correlative measurement

$$\hat{\mathbf{q}}_2 = \mathbf{q}_2(\mathbf{x}_{\mathbf{c}}) + \boldsymbol{\varepsilon}_2 \tag{1.4}$$

on the ensemble of true states $\mathbf{X}_{\mathbf{c}}\{\mathbf{x}_{\mathbf{c}} = \mathbf{x}(\mathbf{z} + \mathbf{d}, t + \tau)\}$ (sub-index **c**; see Figure 1). The ensemble is also characterized by its mean $\overline{\mathbf{x}}_{\mathbf{c}}$ and covariance $\mathbf{S}_{\mathbf{c}} = E\{(\overline{\mathbf{x}}_{\mathbf{c}} - \mathbf{x}_{\mathbf{c}})(\overline{\mathbf{x}}_{\mathbf{c}} - \mathbf{x}_{\mathbf{c}})^T\}$, and correlation between the true states is described by cross-covariance $\mathbf{S}_{\mathbf{vc}} = E\{(\overline{\mathbf{x}}_{\mathbf{v}} - \mathbf{x}_{\mathbf{v}})(\overline{\mathbf{x}}_{\mathbf{c}} - \mathbf{x}_{\mathbf{c}})^T\}$. The bias $\mathbf{\Delta}_2 = E\{\boldsymbol{\varepsilon}_2\}$ of the correlative measurements and its error covariance $\mathbf{S}_{2\varepsilon} = E\{(\mathbf{\Delta}_2 - \boldsymbol{\varepsilon}_2)(\mathbf{\Delta}_2 - \boldsymbol{\varepsilon}_2)^T\}$ are considered known. Thus, the problem of the validation by correlative measurements can be formulated as follows: Given correlative measurements $\hat{\mathbf{q}}_2$ on the ensemble $\mathbf{X}_{\mathbf{c}}$ and the statistical characteristics of the ensembles as described previously, estimate the modeled measurement of the satellite validated system performed on the ensemble $\mathbf{X}_{\mathbf{v}}$

$$\widehat{\mathbf{q}_1(\mathbf{x}_{\mathbf{v}})} = \mathbf{f}(\hat{\mathbf{q}}_2, \overline{\mathbf{x}}_{\mathbf{v}}, \overline{\mathbf{x}}_{\mathbf{c}}, \mathbf{S}_{\mathbf{c}}, \mathbf{S}_{\mathbf{v}}, \mathbf{S}_{\mathbf{vc}}, \mathbf{S}_{2\varepsilon}) \tag{1.5}$$

Equations (1.1) - (1.5) illustrate this general approach to the validation of atmospheric sounders by correlative measurements. Formulated this way the validation problem comprises elements of the forecast and inverse problem as it is considered in remote sensing. If $\mathbf{X}_{\mathbf{v}} \equiv \mathbf{X}_{\mathbf{c}}$ then the validation is reduced to the general problem of remote sensing, i.e. given measurements $\hat{\mathbf{q}}_2 = \mathbf{q}_2(\mathbf{x}) + \boldsymbol{\varepsilon}_2$ estimate the function of the true state $\mathbf{q}_1(\mathbf{x})$. In his classical book Rodgers [1] examined the inverse problem comprehensively. In particular, he demonstrated that generally it is an ill-posed inverse problem and may have an infinite number of solutions; therefore, the notions "estimate" or "best estimate" do not have an absolute meaning but depend on chosen criteria instead. In the current work we use those terms in the sense of expected values. In cases when validated and correlative systems perform their measurements on different states, we need the forecast model for the true states, i.e. the model that allows estimating the state $\mathbf{x}_{\mathbf{v}} = \mathbf{x}(\mathbf{z}, t)$ given the correlative state $\mathbf{x}_{\mathbf{c}} = \mathbf{x}(\mathbf{z} + \mathbf{d}, t + \tau)$.

Pougatchev [12] has developed the linear mathematical model for validation by correlative measurements - Validation Assessment Model (VAM). Namely, the model allows estimating the nominal measurements of the validated system in the form

$$\widehat{\mathbf{q}_1(\mathbf{x}_v)} = \mathbf{B}\hat{\mathbf{q}}_2 + \mathbf{b} \tag{1.6}$$

where matrix $\mathbf{B}$ and vector $\mathbf{b}$ are some functions of statistical characteristics of the ensembles $\mathbf{X}_v$ and $\mathbf{X}_c$ and characteristics of the measurement systems. The model also provides the estimate of the validation error $\boldsymbol{\varepsilon}_{val}$, i.e. its mean value $\overline{\boldsymbol{\varepsilon}}_{val}$ and covariance $\mathbf{S}_{val}$. In the following sections we will use the VAM to construct specific **B** and **b** and estimated the IASI temperature and relative humidity retrieval errors.

2. VALIDATION METHODOLOGY

2.1 Basic Relations

We assume that the validated IASI sounder performs its measurements on the ensemble of true states $\mathbf{X}_v$ which has mean value $\overline{\mathbf{x}}_v$ and covariance $\mathbf{S}_v$ .The retrieved profile $\hat{\mathbf{x}}$ in linear approximation is related to the true state $\mathbf{x}_v \in \mathbf{X}_v$ as follows

$$\hat{\mathbf{x}} = \mathbf{x}_a + \mathbf{A}(\mathbf{x}_v - \mathbf{x}_a) + \boldsymbol{\varepsilon} \tag{2.1}$$

where $\mathbf{x}_a$ is the a priori profile (linearization point); $\mathbf{A}$ is the averaging kernel matrix (Freché derivatives); and $\boldsymbol{\varepsilon}$ is the error that we will assess through validation. The retrieval error may be caused by various factors, in particular, by inevitable noise in the radiances measured by the sounder. This component is called retrieval noise, and it gives the lower estimate of the error. The other way to look at the problem is to estimate the difference between the true and retrieved profiles - total retrieval error:

$$\boldsymbol{\varepsilon}_{tot} = \hat{\mathbf{x}} - \mathbf{x}_v = (\mathbf{I} - \mathbf{A})(\mathbf{x}_a - \mathbf{x}_v) + \boldsymbol{\varepsilon} \tag{2.2}$$

We present the total retrieval error in the following form:

$$\begin{aligned} \boldsymbol{\varepsilon}_{tot} = (\mathbf{I} - \mathbf{A})(\mathbf{x}_a - \mathbf{x}_v) \quad & \text{smoothing error } \boldsymbol{\varepsilon}_{sm} \\ + \boldsymbol{\varepsilon}_n \quad & \text{retrieval noise} \\ + \boldsymbol{\varepsilon}_r \quad & \text{residual/unmodeled error} \end{aligned} \tag{2.3}$$

From pre-flight instrument testing and algorithm characterization we know expected averaging kernels $\mathbf{A}$ and retrieval noise covariance $\mathbf{S}_n$, hence, given the covariance of the ensemble of true states $\mathbf{S}_v$ the covariance of the expected error $\mathbf{S}_e$ is

$$\mathbf{S}_e = (\mathbf{I} - \mathbf{A})\mathbf{S}_v(\mathbf{I} - \mathbf{A})^T + \mathbf{S}_n \tag{2.4}$$

In the process of validation we will assess covariance of the total error - $\mathbf{S}_{tot}$ and compare it to the expected error - $\mathbf{S}_e$.

In this context the term $\mathbf{x}_a + \mathbf{A}(\mathbf{x}_v - \mathbf{x}_a)$ in equation (2.1) represents the expected retrieval. We will estimate it from correlative radiosonde measurements using the VAM.

We assume that the radiosonde performs correlative measurement on the ensemble of true states $\mathbf{X}_c$ and returns profile $\mathbf{x}_s$, which is related to the true state $\mathbf{x}_c \in \mathbf{X}_c$ as follows:

$$\mathbf{x}_s = \mathbf{x}_c + \boldsymbol{\varepsilon}_c \tag{2.5}$$

The correlative ensemble has mean value $\overline{\mathbf{x}}_c$ and covariance $\mathbf{S}_c$.

Following the formalism from [12], we can write

$$(\mathbf{x_v} - \overline{\mathbf{x}}_\mathbf{v}) = \mathbf{B_x}(\mathbf{x_c} - \overline{\mathbf{x}}_\mathbf{c}) + \boldsymbol{\xi} \tag{2.6}$$

where correlation matrix $\mathbf{B_x}$ and random error $\boldsymbol{\xi}$ depend on temporal and spatial non-coincidence between satellite and sonde measurements. Using $\overline{\mathbf{x}}_\mathbf{v}$ as the linearization point in equation (2.1) and expression (2.6) we can write:

$$\boldsymbol{\delta} = \hat{\mathbf{x}} - \mathbf{AB_x x_s} = (\overline{\mathbf{x}}_\mathbf{v} - \mathbf{AB_x}\overline{\mathbf{x}}_\mathbf{c}) + \mathbf{A}\boldsymbol{\xi} - \mathbf{AB_x}\boldsymbol{\varepsilon}_\mathbf{s} + \boldsymbol{\varepsilon} \tag{2.7}$$

The covariance of the difference $\boldsymbol{\delta}$ is:

$$\mathbf{S}_{\boldsymbol{\delta}} = \mathbf{AS}_{\boldsymbol{\xi}}\mathbf{A}^T + (\mathbf{AB_x})\mathbf{S}_{\boldsymbol{\varepsilon}_\mathbf{s}}(\mathbf{AB_x})^T + \mathbf{S}_{\boldsymbol{\varepsilon}} \tag{2.8}$$

The estimate of the total retrieval error (see equation (2.3)) is:

$$\begin{aligned}\mathbf{S_{tot}} &= (\mathbf{I} - \mathbf{A})\mathbf{S_v}(\mathbf{I} - \mathbf{A})^T + \mathbf{S}_{\boldsymbol{\varepsilon}} \\ &= (\mathbf{I} - \mathbf{A})\mathbf{S_v}(\mathbf{I} - \mathbf{A})^T + [\mathbf{S}_{\boldsymbol{\delta}} - \mathbf{AS}_{\boldsymbol{\xi}}\mathbf{A}^T - (\mathbf{AB_x})\mathbf{S}_{\boldsymbol{\varepsilon}_\mathbf{s}}(\mathbf{AB_x})^T]\end{aligned} \tag{2.9}$$

The equations (2.7) - (2.9) constitute the algorithm for the VAM; in the following section we discuss the actual values of the input parameters such as $\mathbf{A}, \mathbf{B_x}, \mathbf{S}_{\boldsymbol{\xi}}, \mathbf{S_v},$ and $\mathbf{S}_{\boldsymbol{\varepsilon}_\mathbf{s}}$.

2.2 Inputs for the VAM

Averaging kernel matrix $\mathbf{A}$ has been provided by EUMETSAT for the v. 4.3 of the temperature and water vapor retrieval [13, 14]. The rows of the matrices are presented in Figure 1. The width of the curves can be taken for a measure of the vertical resolution. The sum of diagonal elements of the matrices gives the upper limit of the number of independent pieces of information in the retrieved profiles. In our case it is 14 for temperature and 10 for relative humidity.

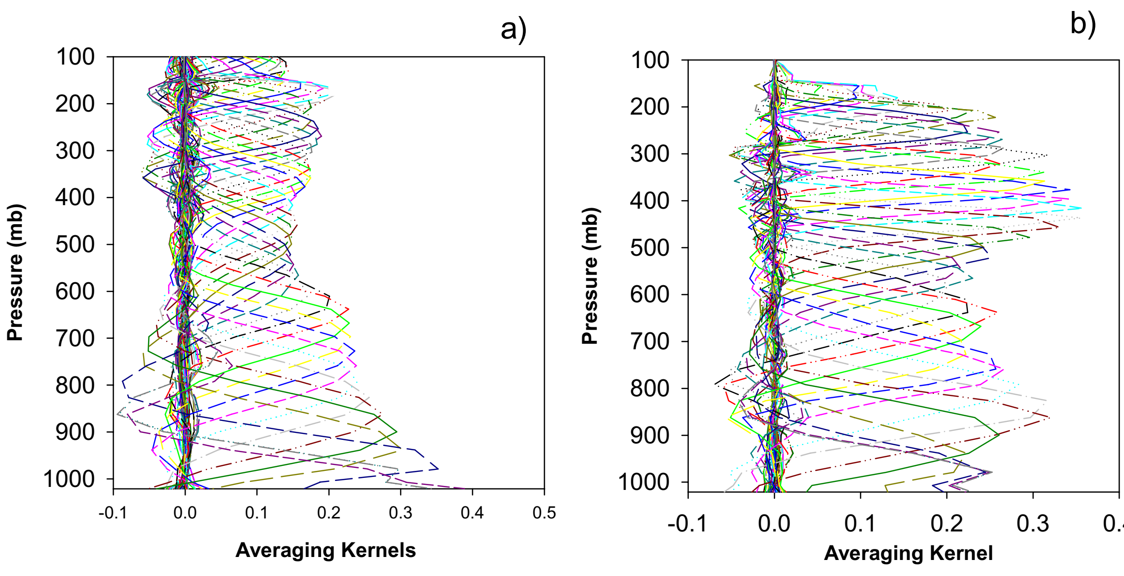


Fig. 1. Averaging kernels for temperature - **a)** and relative humidity - **b)** retrievals.

Temporal non-coincidence error covariances and correlation matrices for different time intervals were estimated from analysis of radiosonde profiles as described in [12]. Spatial non-coincidence error covariance and retrieval noise were estimated from analysis of retrieval small sample repeatability covariance as a function of effective radius of the sample $\mathbf{S_{rep}}(r_{eff})$. Then extrapolation to $r_{eff} = 0$ gives an estimate of retrieval noise $\mathbf{S_n} = \mathbf{S_{rep}}(0)$. For the current study we analyzed the IASI retrievals within one hour about sonde launch time ($\tau_{av} = 0.5$ h) and $\pm 1^{\mathrm{o}}$ about the Lindenberg launch site, which corresponds to an effective radius of $r_{eff} = 80$ km. We assume that non-coincidence errors caused by time difference and spatial mismatch are statistically independent; then the total non-coincidence error covariance matrix $\mathbf{S}_{\mathbf{non}}$ can be estimated as follows:

$$\mathbf{S}_{\mathbf{non}} = \mathbf{A}\mathbf{S}_{\xi}(\tau = 0.5\,\mathrm{h})\mathbf{A}^{T} + \mathbf{S}_{\mathbf{rep}}(r_{eff} = 80\mathrm{km}) - \mathbf{S}_{\mathbf{rep}}(r_{eff} = 0\,\mathrm{km}) \qquad (2.10)$$

Square roots of diagonal elements of matrix terms in equation (2.10) are plotted in Figure 2.

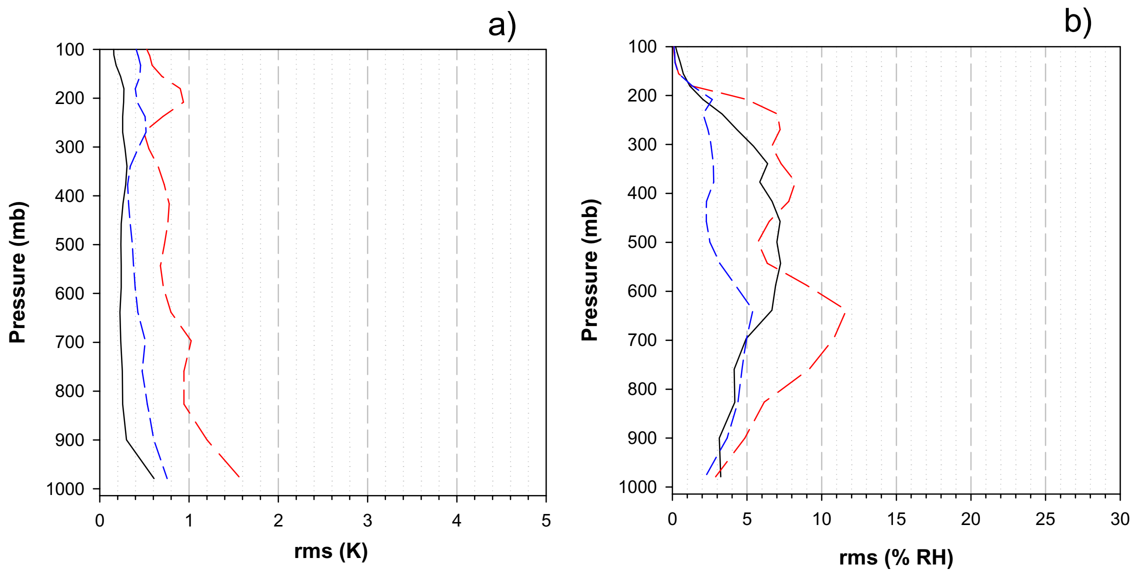


Fig. 2. Validation non-coincidence rms errors and noise for temperature - a) and relative humidity - b) retrievals. Variances (square roots of diagonal elements) of: temporal 0.5 hour non-coincidence - solid black line; effective 85 km spatial non-coincidence - red dashed line; and retrieval noise - blue dashed line.

Given radiosondes and satellite measurements only, the correlation matrix can be directly calculated for temporal non-coincidence only - $\mathbf{B}_{\mathbf{x}}(\tau)$ [12]. In the current study we have to account for both temporal and spatial non-coincidence; therefore, the effective $\mathbf{B}_{\mathbf{x}}$ -matrix was calculated by linear interpolation on the family of precalculated $\mathbf{B}_{\mathbf{x}}(\tau)$. The interpolation contains two steps: first - for each $i-th$ altitude level, effective time non-coincidence τ_i was calculated so that the diagonal element of the total non-coincidence matrix $s_{ii\,\mathbf{tot}}$ is equal to the corresponding diagonal element of the temporal non-coincidence matrix $\tau_i : s_{ii\,\mathbf{tot}} = s_{ii\xi}(\tau_i)$. Then we assigned the elements of the $\mathbf{B}_{\mathbf{x}}$ -matrix $b_{ij} = b_{ij}(\tau_i)$.

At this point we have all the inputs for application of the VAM to a practical validation/error assessment of the IASI retrieval errors using correlative radiosondes. In the next section we will present and discuss the results.

3. RESULTS AND DISCUSSION

3.1 Data description

The correlative data set covers the time period from July 1 to August 31, 2007. The sondes were launched from Lindenberg station (52.21$^{\mathrm{O}}$ N, 14.21$^{\mathrm{O}}$ E, 125 m a.s.l.). The Vaisala RS80 radiosondes were launched at synoptic times 4:45 UTC, 10:45 UTC, 16:45 UTC, and 22:45 UTC as well as one hour and five minutes prior to IASI overpasses. In the current study we consider only the dedicated launches. Random rms error of the sondes is assumed ± 0.1 K for temperature and $\pm 2\%$ for relative humidity.

The IASI temperature and water vapor profile retrievals are v. 4.3 EUMETSAT Level 2 products. The profiles are on standard IASI 90 point pressure grid levels. For analysis we used only cloud clear retrievals (as reported by cloud flags in the product) within $\pm 1^{\circ}$ about the Lindenberg launch site. Additional filtering of the data was performed based on the repeatability of the temperature retrievals within a given overpass. The retrievals were rejected if the repeatability rms between 700 mb and 50 mb exceeded 1.8 K or if it exceeded 2.5 K between 980 mb and 700 mb. After that rigorous filtering, 29 overpasses (out of 113 total) and 55 corresponding sondes were selected for final analysis; on average, each selected overpass contains 13 retrieved profiles.

3.2 Error Assessment

The equations (2.7) - (2.9) of the Validation Assessment Model with the inputs described in Section 2.2 were applied to the data described in the previous Section 3.1. For temperature and relative humidity retrieval we estimated bias against radiosondes and total error covariance matrix.

For temperature the result are presented in Figure 3.

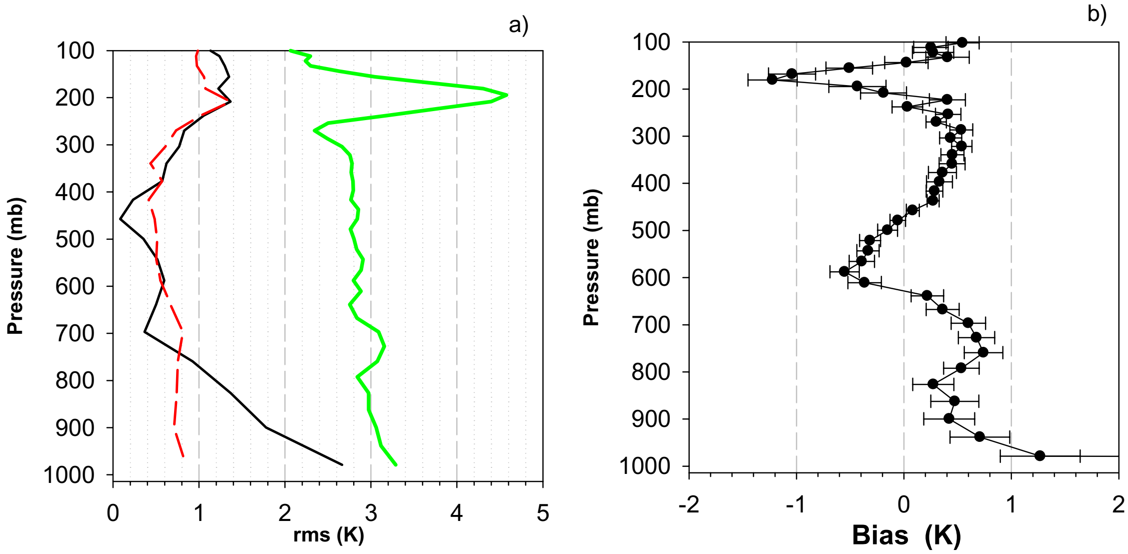
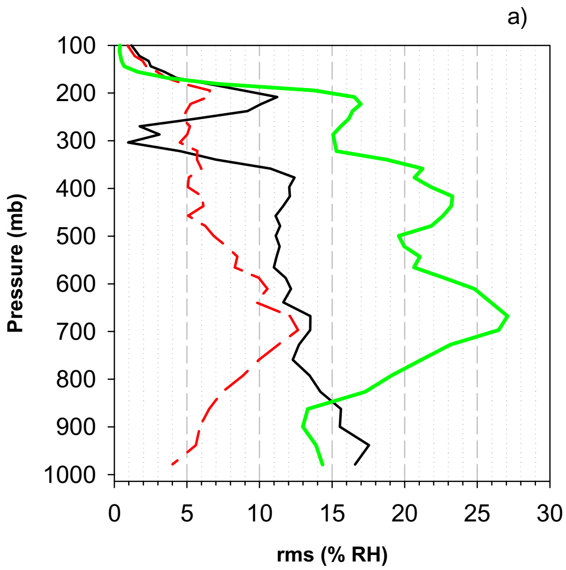


Fig. 3 Temperature. a) - Variances of: total retrieval error (assessed) - solid black line; total retrieval error (expected) - dashed red line; temperature profile - solid green line. b) Estimated bias against radiosondes.

The assessed and expected total retrieval errors are in good agreement above the 800 mb level and significantly smaller than the temperature variance, which means that the IASI temperature measurements are very informative. Good agreement between assessed and expected errors is an indicator that the averaging kernels adequately characterize the retrievals and that they can be used for retrieval assimilation using Clive Rodgers' approach [1]. Increase of the error below 800 mb is probably caused by undetected clouds or haze and an inaccurate account of the surface radiative properties. It pertinent to note that the presented errors characterize the difference from the true atmospheric state on which the sounder is making its measurements. Estimated bias against radiosondes is within ± 0.5 K at most altitudes; error bars indicate standard error.

For relative humidity the result are presented in Figure 4.



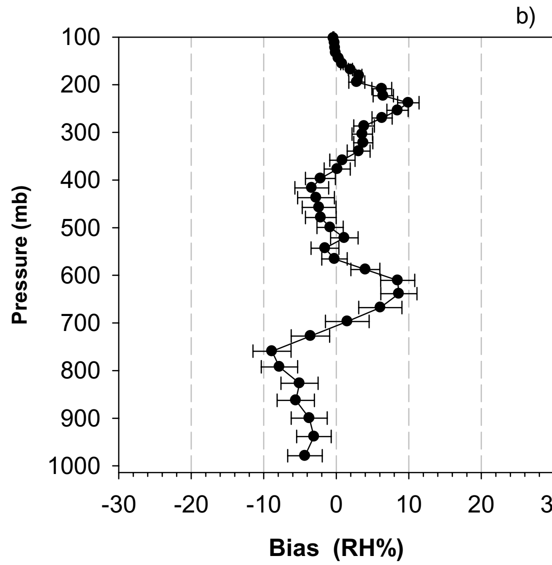


Fig. 4 Relative Humidity. a) - Variances of: total retrieval error (assessed) - solid black line; total retrieval error (expected) - dashed red line; relative humidity profile - solid green line. b) - Estimated bias against radiosondes.

Unlike for temperature, for relative humidity the assessed total retrieval error is noticeably larger than the expected one at almost all altitudes. The increase of the assessed error below 800 mb is consistent with the same tendency in the temperature error; that may be an indicator that they have the same cause. The kink on the assessed error curve around 300 mb needs additional analysis. Comparison of the retrieval errors with relative humidity profile variance shows that the sounding is informative in the troposphere above 800 mb. Estimated bias against radiosondes oscillates within $\pm 10\,\%$ at most altitudes with significant error bars indicating standard error.

4. CONCLUSIONS

The performed study demonstrates that the Validation Assessment Model can be efficiently used for accurate assessment of retrieval error with the presence of significant difference in characteristics of the compared systems and non-coincidence errors. Proper statistical characterization of the correlative data set allows accounting for the non-coincidence errors, and averaging kernels can be used to reconcile the vertical resolution.

For temperature retrievals, expected and assessed errors are in good agreement; error variances/rms of a single FOV retrieval are $< 1\mathrm{K}$ between 800 – 300 mb with an increase to ~1K in tropopause and ~2K at the surface, possibly due to incorrect surface parameters and undetected clouds or haze. Bias against radiosondes oscillates within $\pm 0.5\mathrm{K}$ between 950 – 100 mb. As for water vapor, its highly variable, complex spatial structure does not allow assessment of retrieval errors with the same degree of accuracy as for temperature. Error variances/rms of a single FOV relative humidity retrieval are between 10 - 13 % RH in the 800 – 300 mb range.

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