Channel Compression of High Resolution Infrared Spectra with Using Hypothetical Channel System

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Abstract

A method has recently been shown by Aoki (2004) to compress the number of channels of trace gas remote sounder preserving almost all the information content that the original data has. In this method the weighting function of the original channels is expanded with empirical orthogonal functions (EOFs), and a set of hypothetical radiances, whose weighting functions are the EOFs, are used for the analysis. It has been shown that the radiance data of 240 original channels, which is obtained by the above trace gas sounder, can be compressed to 3 or less channels of hypothetical radiances, losing negligible information content.

In the present paper, the performance of this method is examined for the simulated radiance data of high spectral resolution in the thermal infrared region that is used for the remote measurements of temperature and humidity vertical profiles. The number of hypothetical channels that is required for preserving the information content of original data has been examined for two different spectral resolutions, 0.1 and 0.3 cm^{-1} . The present study showed that the radiance data of 1200 channels of high spectral resolution 0.1 cm^{-1} is compressed to less than 23 hypothetical channels with negligible loss of information content in the case of wavenumber region 640–760 cm^{-1} , which is used for the temperature soundings. For the low resolution 0.3 cm^{-1} , the number of hypothetical channels needed becomes smaller than this. In the case of the humidity sounding from the region 1300–1600 cm^{-1} with the spectral resolution 0.1 cm^{-1} , 3000 channels are compressed to less than 20 hypothetical channels.

1. Introduction

It has been recognized through the last decade that for the efficient use of vertical sounder data in numerical weather prediction, it is desired to directly incorporate the observed radiances rather than the retrieved physical parameters such as temperature and humidity into the assimilation scheme (Eyre 1993; Coutier et al. 1994; Andersson et al. 1994; Coutier et al. 1998). The difficulty of using radiance data

of high spectral resolution is the consumption of much computation time and the usage of large memory due to the large number of channels. In the three dimensional or four dimensional variational method of meteorological field assimilation, the iteration of the assimilation is generally repeated for several ten times or more (Coutier et al. 1994). For the modern satellite sounder, the number of the spectral channel has been increased by two orders larger than that of TOVS (TIROS Operational Vertical Sounder) of NOAA's satellites. The IMG (Interferometric Monitor of Greenhouse gases) on board Japanese Earth observation satellite ADEOS (Advanced Earth Observing Satellite), a Fourier Transform Spectrometer (FTS), has channels of more than 50 thousand (Kadokura et al. 1994; Kobayashi 1999). AIRS

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(Atmospheric InfraRed Sounder), a grating spectrometer boarded on the satellite AQUA, has 2378 channels of infrared thermal radiance (Aumann et al. 2000). IASI (Infrared Atmospheric Sounding Interferometer) is also a FTS containing 8461 channels in the thermal infrared region.

Since the incorporation of all channels into an assimilation scheme is not possible at the present computer ability, only a limited number of channels of Earth observation sensor are selected and used in the actual analysis of the atmosphere field. The data of all other channels are discarded. Various methods of channel selection have been proposed (Kadokura et al. 1994; Kadokura et al. 1996; McMillin and Goldberg 1997; Kobayashi 1999; Huang et al. 2001; Lerner et al. 2002; Rabier et al. 2002; Fourrié and Thépaut 2002). With these methods, the selection is made for those channels that are most sensitive to the retrieval of atmospheric parameters concerned, and the number of channels to be used is reduced to a level that is manageable in the assimilation scheme. Currently, a few to several hundred channels are selected for AIRS and IASI out of 2378 (AIRS) or 8461 (IASI) original channels (Huang et al. 2001; Lerner et al. 2002; Rabier et al. 2002; Fourrié and Thépaut 2002). McMillin and Goldberg (1997) also selected a similar number of AIRS channels under the context of “supper channels”. In IMG data processing, 4000 channels are adopted out of over 50000 channels (Kadokura et al. 1994; Kadokura et al. 1996; Kobayashi 1999). Thus, with these methods, about 90% of observational data is abandoned. However, many of the abandoned channels have the sensitivity of similar magnitude as those selected. They at least contribute to reduce the measurement error and, in turn, contribute to increase the information content of the measurements (Aoki 2004).

Aoki (2004) proposed a method to reduce the effective number of channels that are used in the atmospheric field analysis, preserving almost all the original information content. In this method a set of hypothetical channels is constructed, whose weighting functions are the empirical orthogonal functions (EOFs). The EOFs are the eigenvectors of a symmetry matrix, made from weighting functions of original channels. The radiances of the hypothetical

channels are obtained from a linear combination of original radiances. The performance of this method has been examined by applying the simulated radiance data of channels of TERSE (Tunable Etalon Remote Sounder of the Earth) that observes the solar radiation reflected at the Earth surface to measure the amount of the greenhouse gases (Aoki et al. 1993; Aoki et al. 2002). It has been shown that the radiance data of 240 original channels, which is obtained by TERSE, can be compressed to 3 or less channels of hypothetical radiances with losing negligible information content. In the present paper, a study will be carried out on the performance of this method for the simulated radiance data of high spectral resolution in the thermal infrared region that is used for the remote measurements of temperature and humidity vertical profiles.

2. Radiative transfer in the thermal infrared region

The radiance of the m -th channel of the infrared vertical sounder, which is centered at the wavenumber ν_m , is written as

$$I_m(\nu_m) = C \int_{\nu_1}^{\nu_2} d\nu \Phi(\nu_m, \nu) \times \left\{ \int_0^\infty \frac{\partial \tau(\nu, z)}{\partial z} B(\nu, T(z)) dz + \varepsilon_s B(\nu, T_s) \tau(\nu, 0) \right\}, \quad (1)$$

where C is the constant, $\Phi(\nu_m, \nu)$ is the normalized instrument function at the wavenumber ν . In the present paper the Gaussian shape for $\Phi(\nu_m, \nu)$ is assumed. ν_1 and ν_2 are the lower and upper wavenumber limits of the function Φ , respectively. $\tau(\nu, z)$ is the transmittance of the atmospheric path from the height z to the satellite at wavenumber ν . $B(\nu, T)$ is the Planck function at ν and temperature T . ε_s and T_s are the emissivity and temperature of the surface, respectively. In Eq. (1), for simplicity, the reflected radiation of the downward flux at the surface has been omitted. The radiation source due to the scattering of the radiation by aerosols and clouds has also been omitted, however, the emission and absorption of thermal radiation by them is taken into account in the formulation.

In the practical calculation, the vertical integral in Eq. (1) is replaced by the sum as follows:

$$I_m = C \int_{\nu_1}^{\nu_2} d\nu \Phi(\nu_m, \nu) \times \left\{ \sum_{j=1}^{N_0-1} B(\nu, T_j) \Delta\tau(\nu, z)_j + \epsilon_s B(\nu, T_s) \tau(\nu, 0) \right\}, \quad (2)$$

where $N_0 - 1$ is the number of layers. In the present work, the number of the layer increases upward. $\Delta\tau(z)_j$ is the difference between the transmittances at the j - and $(j+1)$ -th vertical level of the atmosphere (i.e., the lower and upper boundary of the j -th layer):

$$\Delta\tau(z)_j = \tau_{j+1} - \tau_j. \quad (3)$$

$\tau(\nu, 0)$ is the transmittance from the surface to the satellite, being given by $\tau(\nu, 0) = \tau_1$.

Since for the high spectral resolution the transmission function of the aerosols and cloud can be assumed constant in the narrow wavenumber range between ν_1 and ν_2 , the approximation can be made for the transmittance as follows:

$$\tau(\nu, z) = \tau^c(z) \tau^M(\nu, z), \quad (4)$$

where τ^c is the transmittance of the aerosols and clouds. It will formally be written as

$$\tau^c(z)_j = \exp \left[-\mu \sum_{n=j}^{N_0-1} \Delta u_n \right], \quad (5)$$

where μ is the reciprocal of cosine of zenith angle of the satellite, θ , and Δu_n is the optical depth of aerosols and cloud in the n -th layer. In the present work the atmosphere is divided into 29 layers ($N_0 = 30$).

$\tau^M(\nu, z)$ is the transmission function of the atmospheric molecules being given by:

$$\tau^M(\nu, z)_j = \exp \left[-\mu \sum_{n=j}^{N_0-1} \Delta z_n \sum_g k_{g,n}(\nu) \rho_{g,n} \right], \quad (6)$$

where Δz_n is the geographical thickness of the n -th layer. $k_{g,n}$ and $\rho_{g,n}$ are the absorption coefficient and the density of gas species g at the n -th layer, respectively.

In the method of the present paper, the weighting function is expanded with EOFs and a set of hypothetical channels is constructed, which is independent of the wavenumber. The numerical values of weighting function vary depending on the definition of the unit of output of channels, which is, in general, the radi-

ance or the brightness temperature. The radiance value of Planck function is different for different wavenumbers for the same temperature, whereas the numerical value of the brightness temperature is the same. Thus, in the following simulation, the brightness temperature T_{Bm} rather than the radiance I_m will be used as the observed quantity. The quantities T_{Bm} and I_m are related with each other by the equation

$$B(\nu_m, T_{Bm}) \equiv I_m, \quad (7)$$

or

$$T_{Bm} = B^{-1}(\nu_m, I_m), \quad (8)$$

where B^{-1} is the inverse function of B .

Expanding T_{Bm} around its initial value T_{Bm}° a linear system is obtained between T_{Bm} and the unknown variables as

$$T_{Bm} = T_{Bm}^\circ + \sum_{j=1}^{N_0-1} \left[\frac{\partial T_{Bm}}{\partial x_{Tj}} x_{Tj} + \sum_g \frac{\partial T_{Bm}}{\partial x_{gj}} x_{gj} + \frac{\partial T_{Bm}}{\partial x_{uj}} x_{uj} \right] + \frac{\partial T_{Bm}}{\partial x_{T0}} x_{T0}, \quad (9)$$

where the unknown variables are defined as follows:

$$x_{Tj} = T_j - T_j^\circ \quad (j \geq 1), \quad (10)$$

$$x_{T0} = T_s - T_s^\circ, \quad (11)$$

$$x_{gj} = \frac{\rho_g(z_j)}{\rho_g^\circ(z_j)} - 1, \quad (12)$$

$$x_{uj} = \frac{\Delta u_j}{\Delta u_j^\circ} - 1, \quad (13)$$

where the parameters attached by the superscript $^\circ$ is the initial value of them.

The partial derivative of T_{Bm} by x is given by

$$\frac{\partial T_{Bm}}{\partial x} = \frac{dT_{Bm}}{dI} \frac{\partial I}{\partial x}, \quad (14)$$

where the partial derivative of I by, e.g., temperature is written as

$$\frac{\partial I}{\partial x_{Tj}} = \frac{\partial I}{\partial T_j} = C \int_{\nu_1}^{\nu_2} d\nu \Phi \left[(\tau_{j+1} - \tau_j) \frac{\partial B}{\partial T_j} + \sum_{j'=1}^{N_0-1} B(T_{j'}) \frac{\partial}{\partial T_j} (\tau_{j'+1} - \tau_{j'}) \right]. \quad (15)$$

By using Eq. (4) it becomes that

$$\begin{aligned} \frac{\partial I}{\partial T_j} = C & \left[(\tau_{j+1}^c \bar{\tau}_{j+1} - \tau_j^c \bar{\tau}_j) \frac{\partial B}{\partial T_j} \right. \\ & \left. + \sum_{j'=1}^{N_0-1} B(T_{j'}) \left(\tau_{j'+1}^c \frac{\partial \bar{\tau}_{j'+1}}{\partial T_j} - \tau_{j'}^c \frac{\partial \bar{\tau}_{j'}}{\partial T_j} \right) \right], \end{aligned} \quad (16)$$

$$\bar{\tau}_j = \int_{\nu_1}^{\nu_2} d\nu \Phi \tau_j^M(\nu), \quad (17)$$

$$\frac{\partial \bar{\tau}_{j'}}{\partial T_j} = \int_{\nu_1}^{\nu_2} d\nu \Phi \frac{\partial}{\partial T_j} \tau_{j'}^M(\nu). \quad (18)$$

In Eq. (16) the averaging of the quantities τ^c , $\frac{\partial B}{\partial T}$ and B over the wavenumber is omitted and replaced by center values of them between ν_1 and ν_2 since the instrument function is very narrow in the present study. The temperature dependence of the transmission function of aerosol and cloud is also omitted. Equation (18) is further rewritten as

$$\begin{aligned} \frac{\partial \bar{\tau}_{j'}}{\partial T_j} = -\mu \int_{\nu_1}^{\nu_2} d\nu \Phi \sum_g \frac{\partial k_g(z_j)}{\partial T_j} \\ \times \rho_g(z_j) \Delta z_j \tau_{j'}^M(\nu) \quad (j > j'), \end{aligned} \quad (19)$$

$$= 0 \quad (j \leq j'). \quad (20)$$

In a similar manner, the derivatives of I by other parameter are obtained as follows:

$$\begin{aligned} \frac{\partial I}{\partial x_{T0}} = \frac{\partial I}{\partial T_s} = C \varepsilon_s \int_{\nu_1}^{\nu_2} d\nu \Phi \frac{\partial B(\nu, T_s)}{\partial T_s} \tau(\nu, 0) \\ = C \varepsilon_s \frac{\partial B(\nu_m, T_s)}{\partial T_s} \tau_1^c \bar{\tau}_1, \end{aligned} \quad (21)$$

$$\frac{\partial I}{\partial x_{gj}} = C \left[\sum_{j'=1}^{N_0-1} B(T_{j'}) \left(\tau_{j'+1}^c \frac{\partial \bar{\tau}_{j'+1}}{\partial x_{gj}} - \tau_{j'}^c \frac{\partial \bar{\tau}_{j'}}{\partial x_{gj}} \right) \right], \quad (22)$$

$$\frac{\partial \bar{\tau}_{j'}}{\partial x_{gj}} = \int_{\nu_1}^{\nu_2} d\nu \Phi \frac{\partial}{\partial x_{gj}} \tau_{j'}^M, \quad (23)$$

$$\frac{\partial I}{\partial x_{uj}} = C \left[\sum_{j'=1}^{N_0-1} B(T_{j'}) \left(\tau_{j'+1}^c \frac{\partial \tau_{j'+1}^c}{\partial x_{uj}} - \tau_{j'}^c \frac{\partial \tau_{j'}^c}{\partial x_{uj}} \right) \right]. \quad (24)$$

It should be reminded that although it is not shown here, for simplicity, similar relations as Eqs. (19) and (20) are applied to the derivative of transmittance by x_{gj} and x_{uj} .

From the above equations a linear system between the increment of the unknown parameter x and the increment of the brightness temperature, Y , is obtained as:

$$Y_m = T_{Bm} - T_{Bm}^o = \sum_{j=1}^N K_{mj} x_j, \quad (25)$$

$$K_{mj} = \frac{\partial T_{Bm}}{\partial x_j}, \quad (26)$$

$$(x_1, x_2, x_3, x_N) = (x_{T1}, x_{T(N_0-1)}, x_{T0}, x_{g1}, \\ x_{g(N_0-1)}, x_{u1}, x_{u(N_0-1)}), \quad (27)$$

where K_{mj} is the weighting function. N is the total number of the unknown parameter x . In the present work, only water vapor for gas species to be retrieved is considered. Since the number of the layer is $N_0 - 1$, N is given by

$$N = 3N_0 - 2. \quad (28)$$

However, in the following study, it is assumed that the amount and the vertical distribution of aerosols and cloud are fixed and known, and only the characteristics of weighting functions for the temperature and humidity will be examined. The purpose of the present study is to demonstrate the performance of the hypothetical channel system. Further, in the present paper, the study on the hypothetical channel system is carried out within the framework of the assumption that the retrievals of temperature (including the surface temperature), and water vapor are separately performed in the wavenumber regions 640–760 cm^{-1} and 1300–1600 cm^{-1} , respectively. As a result, in the present study, it becomes that $N = N_0$ for the wavenumber region 640–760 cm^{-1} , and $N = N_0 - 1$, for the wavenumber region 1300–1600 cm^{-1} , respectively. For simplicity, let's call the weighting functions in these wavenumber regions “temperature weighting function” and “humidity weighting function”, respectively.

3. Characteristics of temperature derivative of T_B

3.1 Magnitude of two components of weighting functions

As can be found in Eq. (16), the derivative of T_{Bm} by T_j is composed with two terms as

$$\frac{\partial T_{Bm}}{\partial T_j} = K_{mj}^1 + K_{mj}^2, \quad (29)$$

$$K_{mj}^1 = C \frac{dT_{Bm}}{dT_j} \left[(\tau_{j+1}^c \bar{\tau}_{j+1} - \tau_j^c \bar{\tau}_j) \frac{\partial B}{\partial T_j} \right], \quad (30)$$

$$K_{mj}^2 = C \frac{dT_{Bm}}{dT_j} \left[\sum_{j'=1}^N B(T_{j'}) \times \left(\tau_{j'+1}^c \frac{\partial \bar{\tau}_{j'+1}}{\partial T_j} - \tau_{j'}^c \frac{\partial \bar{\tau}_{j'}}{\partial T_j} \right) \right]. \quad (31)$$

The first term comes from the temperature dependence of the Planck function, and the second comes from the temperature dependence of the atmospheric transmission function. In line-by-line method, the second term has frequently been ignored. In this section, the magnitude of this term is examined in comparison with the first term in Eq. (16). The calculation has been carried out, as an example, for the model atmosphere of Midlatitude Winter used in LOW-TRAN 6 (Kneizys et al. 1983).

The simulated brightness temperature for the wavenumber region 640–760 cm^{-1} for this model atmosphere is shown in Fig. 1. The plot interval σ_v is 0.1 cm^{-1} so that the total channel number becomes 1200.

In the present work the atmospheric layer is divided in the constant interval of the parameter

$$\xi = p^\alpha, \quad (32)$$

where $\alpha = 0.2$ and p is the pressure in unit of the atmosphere ranging from 1 to 0.0000493. The values of $\xi = p^\alpha$, for example, are 0.986 and 0.155 for layer number 1 and 29, respectively. The value of the constant C was assumed to be unity. The Gaussian shape was assumed for the instrument function with the width of $\sigma_v/2$. Although the Gaussian shape tailed to the far distance from the center, the wavenumber integral over the instrument function for each channel is confined only within the range of $\pm \sigma_v/2$. Instead, the instrument function is normalized by its area within this range. The error by this kind of approximation will not be important for the discussion of the present study.

An example of the comparison of the two components of weighting function, K^1 and K^2 , is shown in Fig. 2 for 9 channels that is placed in

Fig. 1. An example of the brightness temperature spectrum in the wavenumber region including the range to be used for the temperature soundings.

Fig. 2. Weighting function components K^1 (solid lines) and K^2 (dotted lines) for 9 channels in the region 729–731 cm^{-1} with the resolution 0.1 cm^{-1} .

the wavenumber range from 729 to 731 cm^{-1} . The value of K^1 is positive and that of K^2 is mostly negative in this wavenumber range. It can be seen that the magnitude of K^2 is too large to neglect in comparison with the component K^1 .

The region where the component of K^2 has a significant value depends on the atmospheric layer and the wavenumber. The values of K^1

Fig. 3. The spectrum of weighting function component K^1 for every other layer from 1 to 29.

Fig. 4. The spectrum of weighting function component K^2 for every other layer from 1 to 29.

and K^2 are plotted for every other layers from 1 to 29 all together in Figs. 3 and 4, respectively. The value of K^1 is positive at any wavenumber, however, that of K^2 could be positive and negative depending on the wavenumber as seen in Fig. 4. This is because the absorption line intensity could change positively and negatively with temperature depending on the rotational quantum number of the line. It is found in Figs. 3 and 4 that in very broad range of the wavenumber, the term K^2 plays a very important role in constructing the weighting function.

3.2 Representation of the weighting function with EOFs

In this subsection it will be shown that the weighting functions are decomposed into a small number of EOFs by the method of Aoki (2004). Let's write the Eq. (25) in matrix form:

$$Y_i = \mathbf{K}_i X_i, \quad (33)$$

where Y_i is the vector of y , $\mathbf{K}_i$ is the matrix of K and X_i is the vector of x , for the i -th case of situation of zenith angle and atmospheric profile. By calculating the weighting functions for various situation of observational condition and atmospheric profile, a set of sample data of weighting function is gotten as:

$$\mathbf{K} = \begin{bmatrix} \mathbf{K}_1 \\ \mathbf{K}_2 \\ \mathbf{K}_3 \\ \vdots \end{bmatrix}, \quad (34)$$

where $\mathbf{K}_i$ ($i = 1, 2, 3, \dots$) is a block matrix of $M \times N$ dimension. In this work, for simplicity, only three sets of the weighting functions for different zenith angles ($\theta_{obs} = \theta_{Sun} = 20, 45, 60^\circ$) are used. That is, $\mathbf{K}$ is a $3M \times N$ matrix in this paper. For the pressure, temperature and humidity profiles, the US standard model atmosphere is used assuming the surface pressure to be 1013.25 hPa. It should be noted that in constructing a data set of $\mathbf{K}$, the vertical axis and layering of the atmosphere should be the same for all $\mathbf{K}_i$.

As the basis vectors for expanding the arbitrary weighting functions, the eigenvectors for the symmetry matrix $\mathbf{K}^t \mathbf{K}$ are used in the present work. The matrix ϕ , whose columns are composed with eigenvectors ϕ , should satisfy the following equation (see, e.g., Rodgers 1976)

$$\mathbf{K}^t \mathbf{K} \phi = \phi \Lambda, \quad (35)$$

where Λ is a diagonal matrix whose diagonal elements are the eigenvalues. Figure 5 shows the eigenvalues of $\mathbf{K}^t \mathbf{K}$ for the present data set of $\mathbf{K}$.

In Fig. 6 only seven eigenvectors are shown corresponding to the first seven eigenvalues that are shown in Fig. 5. The ordinate is the layer number. The first number corresponds to the lowest atmospheric layer and the number 29 is the top layer. In this paper the surface

Fig. 5. Eigen values for the matrix $\mathbf{K}^t\mathbf{K}$ of temperature weighting functions.

Fig. 6. Plot of the first seven eigen vectors for wave number region 640–760 cm^{-1} with the spectral resolution 0.1 cm^{-1} against the layer number. Attached numbers on the curves denote the corresponding order of eigenvalues starting from the highest value. The number 30 (top) corresponds to the surface temperature.

temperature is placed at the number 30. This is the reason that the magnitude of the eigenvectors at the number 30 in Fig. 6 is greatly different with those of number 29 and others. Attached numbers on the curves denote the corresponding order of eigenvalues counted from the largest value. It should be noted that the frequency of the oscillation of the curves in vertical direction increases with the increase of

the order number. If the component of the high frequency oscillation is large in weighting function, it means that the vertical resolution is good in that measurement system.

Consider an arbitrary situation of zenith angle and atmospheric profile X_a , which does not belong to the situations of data set that has been used to make the eigenvectors through Eqs. (34) and (35). Write the matrix of weighting function for this situation as $\mathbf{K}_a$, and write the corresponding vector for Y as Y_a . Let's assume this arbitrary weighting function can be expanded as follows

$$\mathbf{K}_a = \mathbf{A}_a \boldsymbol{\varphi}^t, \quad (36)$$

where $\mathbf{A}_a$ is the matrix of expansion coefficients and $\boldsymbol{\varphi}^t$ is the transpose of $\boldsymbol{\varphi}$.

Using the orthogonality relation $\boldsymbol{\varphi}^t \boldsymbol{\varphi} = \mathbf{E}$, where $\mathbf{E}$ is the unit matrix, $\mathbf{A}_a$ is given by

$$\mathbf{A}_a = \mathbf{K}_a \boldsymbol{\varphi}. \quad (37)$$

As a test of the accuracy and performance of the Eq. (36), let's apply this equation to the weighting functions calculated from the model atmosphere of Midlatitude Winter given in LOWTRAN 6 (Kneizys et al. 1983), which is not included in a population of Eq. (34). As has been shown in Aoki (2004), a full set of EOFs is not always needed in expanding the weighting function. Eq. (36) can be approximated with sufficient accuracy as

$$\mathbf{K}_a \cong \mathbf{A}_s \boldsymbol{\varphi}_s^t, \quad (38)$$

where $\mathbf{A}_s$ is a part of $\mathbf{A}_a$ only containing first M_Ψ columns of $\mathbf{A}_a$, and $\boldsymbol{\varphi}_s^t$ contains first M_Ψ rows of $\boldsymbol{\varphi}_a^t$.

This approximation is now applied to the weighting functions for the Midlatitude Winter atmosphere with the zenith angle $\theta_{obs} = 20^\circ$, using $\boldsymbol{\varphi}_s^t$ that has been obtained from weighting functions for the US Standard model atmosphere and three zenith angles shown before. Figure 7 shows the absolute values of the maximum error in the vertical profile of the approximated weighting function for the cases where the first 19, 23, 27 and 29 columns of $\mathbf{A}_a$ are used. In this figure the absolute values of the maximum of weighting function (peak value of weighting function) are also shown at the top in the panel. It can be seen that by using about 23 of EOFs (23 columns of $\mathbf{A}_a$), weighting functions are approximated, with the

Fig. 7. The absolute maximum errors of approximated weighting functions given in Eq. (38) in the case of spectral resolution 0.1 cm^{-1} . The curves assigned by the numbers 19, 23, 27 and 29 are the maximum of absolute error among approximated weighting functions for 29 atmospheric layers when the weighting functions are represented with using EOFs of these number. (The curve attached by 29 is the case where all the EOFs are used.) The top curve is the maximum of the absolute values of the weighting functions for 29 layers.

error of about 0.001 of the weighting function peak. When 29 columns of $\mathbf{A}_a$ are used (full set of EOFs) the error becomes the order of 10^{-15} , meaning that the approximated weighting function is almost exact.

Now consider a set of hypothetical channels whose weighting functions are just the EOFs, ϕ_s^t . The increment of the brightness temperature of such hypothetical channels for an increment X_a is given by

$$\Psi = \phi_s^t X_a. \quad (39)$$

This quantity corresponds to Y of real measurements given in Eq. (7), and it will be called hypothetical radiance or hypothetical brightness temperature. If the values of hypothetical radiances can be known by any procedure, it will be of great advantage for dealing with the satellite data, since the number of channels for this radiance is N at the maximum.

In the present paper, the values of Ψ will be obtained from real measurements Y by the

following procedure: Note that it is written, from Eqs. (38) and (39), as

$$Y_a = \mathbf{K}_a X_a \cong \mathbf{A}_s \phi_s^t X_a = \mathbf{A}_s \Psi. \quad (40)$$

We can look at this equation as the simultaneous linear system for solving Ψ from known values of Y_a since the coefficient $\mathbf{A}_s$ is known. Since the number of component of Y_a is much larger than that of Ψ , the estimate of Ψ , $\hat{\Psi}$, from Eq. (40) may be given by the least square method as

$$\hat{\Psi} = (\mathbf{A}_s^t \mathbf{A}_s)^{-1} \mathbf{A}_s^t Y_a = \mathbf{B} Y_a, \quad (41)$$

$$\mathbf{B} = (\mathbf{A}_s^t \mathbf{A}_s)^{-1} \mathbf{A}_s^t. \quad (42)$$

It should be noted that $\mathbf{B}$ and Y_a depends on the zenith angle but Ψ is independent of it. The characteristics of the errors in this relation will be examined in the next section.

3.3 Characteristics of the error in hypothetical brightness temperature

In this subsection the statistical characteristics will be examined about the error in vector $\hat{\Psi}$ that is derived from Y_a by Eq. (41). The hypothetical brightness temperature $\hat{\Psi}$ for the temperature increment $x_a = 2.0 \text{ K}$, which is assumed to be equal for all layers, is shown in Fig. 8 together with its error. Here, the error is the difference between the estimated $\hat{\Psi}$ and the true one $\phi_s^t X_a$:

$$\Delta \Psi = \hat{\Psi} - \phi_s^t X_a. \quad (43)$$

In Fig. 8, 23 of EOFs are used, which correspond to the top 23 eigenvalues. The values of error are multiplied by 1000 to see its fine structure. It is shown that the maximum error is about -0.001 K at channel number 23.

The error in the approximation given by Eq. (41) is thus negligible compared to the magnitude of $\hat{\Psi}$.

There is another error that is contained in $\hat{\Psi}$. It is the error transferred from the measurement error contained in Y_a through the Eq. (41). By denoting the vector of measurement error contained in Y_a as ε , the corresponding error in $\hat{\Psi}$ is written as $\mathbf{B}\varepsilon$. This quantity may be called the "measurement error" of $\hat{\Psi}$. Although the error in Eq. (41) includes not only the measurement error, but also errors such as the error in the weighting function calculation, it will symbolically be called the measurement error of the hypothetical radiance. The

Fig. 8. The values of $\hat{\Psi} = \mathbf{B}Y_a$ for $x_a = 2.0$ K, which is assumed to be the same for all layers, (solid line) and the discrepancy $\Delta\Psi$ between $\hat{\Psi} = \mathbf{B}Y_a$ and true value $\phi_s^t X_a$, (dotted line). $\Delta\Psi$ is multiplied by 1000.

covariance matrix of this error is given by

$$\mathbf{S}_{\varepsilon'} = \mathbf{B}\mathbf{S}_{\varepsilon}\mathbf{B}^t, \quad (44)$$

where $\mathbf{S}_{\varepsilon}$ is the covariance matrix of ε . In this study it is assumed that $\mathbf{S}_{\varepsilon}$ is diagonal and the diagonal elements are constant. In Fig. 9 the square root value of the diagonal elements of covariance matrix in Eq. (44) are shown for a case where $\varepsilon = 0.2$ K. It can be found that although the diagonal elements of $\mathbf{S}_{\varepsilon}$ are assumed to be constant, the diagonal elements of Eq. (44) are not constant with respect to the channel, but rapidly increase with the channel number as seen in Fig. 9. This result denotes the fact that the high frequency component of the vertical profile of density is difficult to be retrieved.

3.4 Information content of hypothetical brightness temperatures

In this subsection the minimum number of EOFs that is required to preserve the information content on the unknown parameter will be discussed, which is contained in the original measurements. In this study, the vector of the hypothetical radiances is used as the unknown parameter. The information content is calculated by comparing the error covariance of this quantity and that of the a priori knowledge on it.

Fig. 9. “Measurement error” of hypothetical channels transferred from the error of real measurements when the error of the original channels are all 0.2 K.

According to Rodgers (1976), the information content of a measurement is given by a change of the entropy such that

$$H(P_1) - H(P_2), \quad (45)$$

where $H(P_1)$ and $H(P_2)$ are the entropy of the probability density function P before and after the measurement. When the probability density function P is given by a Gaussian distribution with the covariance $\mathbf{S}$, the entropy of it is given by

$$H(P) = \frac{1}{2} \log_2 |\mathbf{S}|, \quad (46)$$

where $|\mathbf{S}|$ is the determinant of the error covariance of the estimation. In the study of preceding subsections, it has been demonstrated that 1200 channels of original brightness temperatures in the $640\text{--}760\text{ cm}^{-1}$ region are condensed into about 23 channels of hypothetical brightness temperatures. The change of the entropy by this action will be examined in the followings.

Using the relation $\hat{\Psi} = \mathbf{B}Y_a = \mathbf{B}\mathbf{K}_a X_a$ we can calculate the covariance matrix of the error in a priori information of Ψ as

$$\mathbf{S}_{\Psi} = (\mathbf{B}\mathbf{K}_a)\mathbf{S}_x(\mathbf{B}\mathbf{K}_a)^t, \quad (47)$$

where $\mathbf{S}_x$ is the covariance matrix of the error in the initial values of X . By making the “measurements” a better estimate for Ψ will be ob-

tained. According to Rodgers (1976), the error covariance of the maximum likelihood estimate becomes, after the measurement,

$$\hat{\mathbf{S}}_{\Psi} = (\mathbf{S}_{\Psi}^{-1} + \mathbf{S}_{\varepsilon'}^{-1})^{-1}, \quad (48)$$

where $\mathbf{S}_{\varepsilon'}$ is the measurement error of $\hat{\Psi}$ being given by Eq. (44). The information content is now given by

$$\Delta H = -\frac{1}{2} \log_2 |\hat{\mathbf{S}}_{\Psi} \mathbf{S}_{\Psi}^{-1}|. \quad (49)$$

As has been done in Aoki (2004), in this study too, the values of the elements of the matrix $\mathbf{S}_{\mathbf{x}}$ is given by a fairly arbitrary manner as:

$$S_{\mathbf{x}}(i, j) = \sigma_x^2 \exp \left[-\frac{(\xi_i - \xi_j)^2}{\delta_x^2} \right], \quad (50)$$

where σ_x is a constant representing the magnitude of the error in the initial value of x , and δ_x is a parameter giving the distance of the correlation between errors of x in different layers.

Figure 10 shows the relationship between the information content ΔH and the number of hypothetical channels for two cases of parameter set; $\varepsilon = 0.2$ K, $\sigma_x = 2.0$ K, $\delta_x = 0.03$ and $\varepsilon = 0.3$ K, $\sigma_x = 1.0$ K, $\delta_x = 0.03$. The results in Fig. 10 show that the number of the hypothetical channels to be used is sufficient with about 20 in the case where $\varepsilon = 0.2$ K, $\sigma_x = 2.0$ K and $\delta_x = 0.03$. In the second case, where $\varepsilon = 0.3$ K, $\sigma_x = 1.0$ K and $\delta_x = 0.03$ (worse measurement error and better initial value than the first case), it is sufficient with 10~15. Both the result obtained here and that in subsection 3.3 suggest that a full set of EOFs is not needed to deal with the observed spectral data.

In the rest of this subsection, a discussion will be made on the relationship between the information content and the number of original channels used in the analysis. Figure 11 shows the dependency of the information content on the number of channels of the original brightness temperature. The information content has been calculated by only using every 2^j ($j = 0, 1, 2, 3, 4, 5$) channels in 1200 of total original channels. The number of original channels used for these five cases becomes 1200, 600, 300, 150 and 75. It will be found that the information content changes in very clear manner with the number of original channels: It constantly decreases with the decrease of the

Fig. 10. Relationships between the information content and the number of hypothetical channels used in the case of wavenumber region 640–760 cm^{-1} . The solid line is for the case $\varepsilon = 0.2$ K, $\sigma_x = 2$ K and $\delta_x = 0.03$ and the dotted line is for $\varepsilon = 0.3$ K, $\sigma_x = 1$ K and $\delta_x = 0.3$, respectively, with the spectral resolution 0.1 cm^{-1} . The long dashed line is for the spectral resolution 0.3 cm^{-1} with the values of parameters ε , σ_x and δ_x same as the solid line.

number of original channels used. The reason for this is that the measurement error of hypothetical brightness temperature Ψ , i.e., $\mathbf{S}_{\varepsilon'}$ given by Eq. (44) increases with the decrease of the number of original channels.

This result is suggestible to the current channel selection problem in that the channel selection can never appreciate the effect of noise reduction of $\mathbf{S}_{\varepsilon'}$ that would be the result when many channels are used. This, in turn, brakes improving the information content, that would be obtained through the relationship between $\hat{\mathbf{S}}_{\Psi}$ and $\mathbf{S}_{\varepsilon'}$ in Eq. (48). It should be noted, however, that in the current channel selection, the more efficient and sophisticated procedure is used to preserve much information content than has been done in the Fig. 11. As a result, in the actual channel selection method currently used, the curve in Fig. 11 more sharply increases with the channel number in the small number range. But even with such a sophisticated method the information content is lost by the channel selection, unless many numbers

Fig. 11. The relationship between the information content and the number of original channels in $640\text{--}760\text{ cm}^{-1}$ when the number of hypothetical channels is 23, $\varepsilon = 0.2\text{ K}$, $\sigma_x = 2\text{ K}$ and $\delta_x = 0.3$.

of the original channels are selected (see, e.g., Fourrié and Thépaut 2002; Rabier et al. 2002).

3.5 Eigenvectors and information content at spectral resolution 0.3 cm^{-1}

In the preceding subsections the studies have been made for the characteristics of EOFs and information content that results from weighting functions at the spectral resolution 0.1 cm^{-1} . At a reduced spectral resolution, the spectrum is smoothed out and the sharpness of the weighting function is degraded. Thus, at lower resolution the eigenvectors would become different from those in Fig. 6. To examine the effect of the spectral resolution, the weighting functions and eigenvectors have been recalculated at spectral resolution 0.3 cm^{-1} . Figure 12 shows the first seven eigenvectors at spectral resolution 0.3 cm^{-1} . It can be seen that shapes of eigenvectors are slightly different with those in Fig. 6, especially for rapid oscillation components.

The effect of spectral resolution degradation seems to appear most clearly in the relationship between information content and the number of hypothetical channels. This is shown by a long-dashed line in Fig. 10 under the same condition as the solid line in Fig. 10 for the parameters ε , σ_x and δ_x . By comparing the solid

Fig. 12. As in Fig. 6 except for the spectral resolution 0.3 cm^{-1} .

line and dashed line in Fig. 10 it is found that the increase of the information content with the number of hypothetical channel is saturated faster for the case of degraded spectral resolution: At spectral resolution 0.1 cm^{-1} the information content increases until about channel number 20, whereas at spectral resolution 0.3 cm^{-1} the significant increase ceases at about 15. In other words, at degraded spectral resolution we only need a smaller number of hypothetical channels than at higher resolution.

4. Characteristics of humidity derivative of T_B in the water vapor band

As has already been mentioned in section 2, in the present paper, it has been assumed that water vapor retrieval is performed using the radiance data of the wavenumber region $1300\text{--}1600\text{ cm}^{-1}$. In this section the characteristics of hypothetical channels for water vapor sounding will be examined using the spectral data from 1300 to 1600 cm^{-1} with the resolution 0.1 cm^{-1} . An example of the spectral data of the brightness temperature is shown in Fig. 13 for US Standard atmosphere. As in the case of temperature weighting function, the eigenvectors are obtained from the symmetry matrix $\mathbf{K}^t\mathbf{K}$ of humidity weighting functions for US Standard model atmosphere, and they are applied to the representation of the weighting functions for Midlatitude Winter model atmosphere. The

Fig. 13. The spectrum of brightness temperature for the water vapor band, where only the region $1300\text{--}1600\text{ cm}^{-1}$ has been used in the present study.

first seven eigenvectors are shown in Fig. 14. Most of them are confined in the lower atmospheric layer as compared with the case of temperature weighting functions. This is because the water vapor amount in the higher atmospheric layer is very small. However, in Fig. 14 we see that one component of eigenvectors has large amplitude in the higher altitude and a few other components have the weak amplitude there too. This may reflect the fact that some of very strong absorption lines of water vapor generate a significant absorption even in the higher altitude.

In Fig. 15 the error of approximated weighting functions is shown for the water vapor band when it is expanded with a limited number of EOFs, just as has been done in Fig. 7 for the temperature weighting functions. The result in Fig. 15 shows that around 20 of EOFs is required to approximate the weighting function in reasonable accuracy.

The study for the relationship between the information content, and the number of hypothetical channels, indicates that only about 15 hypothetical channels is sufficient to preserve the original information as shown in Fig. 16. Both the results in Figs. 15 and 16 again show that a full set of EOFs is not needed to deal with the observed spectral data in the water vapor band.

Fig. 14. First seven eigen vectors for the covariance matrix of humidity weighting functions.

Fig. 15. As in Fig. 7 except for the humidity weighting function.

5. The procedure for applying the method of the present study to the assimilation scheme

To incorporate the multi-spectral radiance data into three or four-dimensional variational scheme of meteorological field assimilation, only selected channels are currently used to reduce the computation time and other computer resources. But it has been shown in the preceding sections that the reduction of channels results in losing the information content. In addition, the number of the channels selected is

Fig. 16. Information content as a function of number of hypothetical channels used for the case of humidity weighting function in the wavenumber region 1300–1600 cm^{-1} with the spectral resolution 0.1 cm^{-1} .

the order of a hundred, being still larger than that of TOVS by several factors. The method of using hypothetical channels proposed by Aoki (2004) and shown in the preceding sections seems to give a solution to this problem, since it only loses a negligible amount of the information content by keeping the channel number small, which is comparable to that of TOVS.

However, to incorporate the hypothetical channels in an actual assimilation scheme we have to construct a system different with the current method. In the current method of channel selection, a few or more times of radiative transfer calculation for all channels selected are carried out during the iteration of assimilation scheme to overcome the effect of the nonlinear characteristics between radiance and atmospheric parameters. In the system of hypothetical radiances proposed here, many number of original channels are used to calculate the hypothetical brightness temperature by Eq. (41), so that repeated calculation of radiances of these original channels greatly affects the computation time.

By this fact, the assimilation scheme using hypothetical channel system has to be carried out only within a range where the linear relationship is maintained between hypothetical brightness temperature and the atmospheric

Fig. 17. Conceptual diagram of the processing flow for the iterative assimilation scheme based on the hypothetical channel system.

parameters. To maintain such a linear relationship model atmospheres have to be prepared, which are used as the initial values, in sufficiently fine interval in the axes of temperature and other parameters. The assimilation system will become as in Fig. 17. In this system a massive look-up table is had that is composed with many boxes. Each box contains its own model atmosphere, and in addition to the values of X^o for the model atmosphere, it has the brightness temperature calculated for original channels, T^o_B , and conversion coefficient $\mathbf{B}$. In addition to these data, we have a table of eigenvectors Φ . It should also be noted that model atmospheres should also be prepared for various values of surface pressure. A sufficiently large number of model atmospheres should be prepared so as to give guarantee that the radiance for an arbitrary atmospheric profile can be given by a linear correction to the radiance of one of model atmospheres contained in the look-up table.

In the process of assimilation, first select a model atmosphere X^o in the look-up table that

is closest to the initial value of the atmospheric field X_0 , where X_0 may be given by the numerical prediction of weather forecasting. From the Y value that is calculated by Eq. (25) using the observed brightness temperatures T_B and T_B^o in the table, obtain the measured hypothetical brightness temperatures Ψ_{obs} by Eq. (41) using the coefficient $\mathbf{B}$. Meteorological parameters may be estimated by minimizing the cost function such as

$$(\phi^t X - \Psi_{obs})^t \mathbf{S}_\epsilon^{-1} (\phi^t X - \Psi_{obs}) + (X - X_0)^t \mathbf{S}_X^{-1} (X - X_0), \quad (50)$$

where $\mathbf{S}_X$ is the covariance matrix of the error in X_0 .

Saunders et al. (1999) noted that the non-linear effect on radiances of TOVS and AMSU (Advanced Microwave Sounding Unit) is less than 0.1 K for the temperature increment of -2 K for both the tropical and arctic atmospheric profiles. On the other hand, for the humidity, the increment of -50% of water vapor could result in the brightness temperature by 24.9 K including the non-linear contribution of 7.5 K for a channel of AMSU. This fact suggests that in our look-up table the distance between the temperature profiles of nearest neighbors could be about 2 K, and, for the humidity, profiles of neighboring atmospheric models should be much smaller than 50%. In general, the distance should be such that the fraction of the non-linear effect is negligible compared to the brightness temperature increment. Such a look-up table could become so massive as to give a great affect to the computer system.

As an example of this kind of look-up table of radiance and atmospheric profile, we know the TIGR (Thermodynamic Initial Guess Retrieval) data set of LMD (Laboratoire de Météorologie Dynamique) of France, which contains 2300 atmospheric situations (Chédin et al. 2002). In our case, for each atmospheric situation, the data of $\mathbf{B}$ is also included in addition to the atmospheric profile, brightness temperatures and some other parameters. If the look-up table is too large for the computer system, it is necessary to explore a method to correct the non-linear effect within a framework of hypothetical brightness temperature system, whereby the size of the look-up table is reduced by making the distance between profiles larger.

6. Summary and discussions

In the present work, it has been shown that the weighting function for the temperature soundings in the thermal infrared region, with the spectral resolution 0.1 cm^{-1} is expanded by about 23 or less EOFs with the error of about 0.001 K, where EOFs are the eigenvectors of the symmetry matrix of the weighting functions, $\mathbf{K}^t \mathbf{K}$. Based on this fact, a set of hypothetical brightness temperature is constructed, whose weighting functions are the EOFs. The maximum number of channels of hypothetical brightness temperature is the number of unknown parameters. The “observed” brightness temperatures of the hypothetical channels are obtained as a linear combination of the brightness temperatures of the original channels of real observation. The error covariance is also calculated from the error of real measurements of original observation. Despite the number of hypothetical channels is two order smaller than the original one, the information content that the original data set has is almost completely preserved.

Theoretically, the maximum number of the hypothetical channels is the number of the unknown variables. In practice, however, only smaller channels than this are needed for preserving the original information content. It has been shown that in case of spectral resolution 0.1 cm^{-1} , the number of hypothetical channels that is required to preserve the original information content, without losing significant amount of it, is about 20 for temperature soundings in the range $640\text{--}760 \text{ cm}^{-1}$, and 15 for humidity sounding in the range $1300\text{--}1600 \text{ cm}^{-1}$, where the number of the original channel is 1200 for the former and 3000 for the latter wavenumber ranges, respectively. For the degraded spectral resolution 0.3 cm^{-1} , the number of hypothetical channels needed to preserve the information content becomes smaller than these.

The method of the present paper can be applied to the data archiving: As shown in the previous sections, Y values of 1200 original channels can be compressed into about 20 hypothetical channel data losing negligible information content in the case of wavenumber region $640\text{--}760 \text{ cm}^{-1}$. In the range $1300\text{--}1600 \text{ cm}^{-1}$, 3000 of original channels are

compressed to about 20 or less hypothetical channels. Thus, the efficiency of data compression is drastic. However, to reconstruct the original brightness temperature T_{Bm} from $\hat{\Psi}$, the values of $\mathbf{A}_a$ for each model atmosphere, and a set of look-up table described in the preceding section, should also be available. The discussion of more details about this kind of application of the hypothetical channel system is, however, beyond the scope of the present work.

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