AEROSOL OPTICAL PARAMETER RETRIEVAL FROM SATELLITE DATA

Yasuyuki Kimura, Toshiaki Izumiya and Yoshiyuki Kawata

Environ. Infor. Research Lab.,Kanazawa Institute of Technology,
Ogigaoka 7-1, Nonoichi, Ishikawa 921-8501, Japan

ABSTRACT

The satellite image data, measured by ADEOS/POLDER, ADEOS/OCTS and NOAA/AVHRR, were used to retrieve aerosol optical parameters. We examined two methods for retrieving local aerosol optical parameters using the ADEOS/POLDER data by comparing with the validation data. The first method is based on a R-P(Reflectance-Polarization) algorithm using both multi-directional reflectance and multi-directional polarization information in 865nm band. The second method is based on a R-R(Reflectance-Reflectance) algorithm using only multidirectional reflectance information in two infrared bands(670nm and 865nm). We found that the former gives better agreement with the measured sky validation data than the latter. Furthermore, the retrieval results by the R-R algorithm using the mono-directional reflectance data of ADEOS/OCTS and NOAA/AVHRR were compared with those of ADEOS/POLDER, based on the R-P algorithm. Although we had a relatively good agreement in the aerosol optical thickness among these algorithms, we found that the retrieval results of Ångström exponent are not reliable in the cases of the R-R algorithm using the reflectance data alone.

1. INTRODUCTION

The POLDER and OCTS were on board of the same ADEOS and they have nearly six identical spectral bands. POLDER was an imaging sensor with nadir ground resolusion of 7 km, whereas OCTS was a scanning sensor with that of 0.7 km. They had collected global data sets for about 8 months during the ADEOS's operational period (launched in August 1996 - ended in June 1997). Since the POLDER had unique capabilities of measuring both multi-directional radiance in 8 wavelength bands(443, 490, 565, 670, 763, 765, 865, and 910[nm]) and linear polarization in 3 bands(443, 670, and 865[nm]) reflected by the Earth's atmosphere-surface system, the retrieval of aerosol's three optical parameters(i.e., real part of refractive index, optical thickness, and Ångström exponent) may be possible. by using POLDER's mult-directional information. However, it is difficult to retrieve aerosol's real part of refractive index from the reflectance data by OCTS and NOAA/AVHRR, because they collects the radiance reflected by the target from only a mono-direction.

2. BASIC BACKGROUNDS

The incident solar flux vector in Stokes vector representation is given by Eq.(1).

$$\pi\mathbf{F}=\pi[f\ 0\ 0\ 0]^t \qquad (1)$$

where a superscript represents the matrix transposition. In this notation we assume an incident solar flux vector $\pi\mathbf{F}$ illuminates a zenith angle θ_0 and the solar azimuth angle ϕ_0, respectively. In the right side πf equals to the extraterrestrial irradiance per unit area normal to the direction of solar rays, E_s[W/m²]. Then, the upwelling Stokes vector at the top of the atmosphere (TOA) in the direction of (μ, ϕ), $\mathbf{I}(\tau_{at}, \mu, \mu_0, \phi-\phi_0) = [I\ Q\ U\ V]^t$ can be expressed by Eq.(2) in terms of the reflection matrix of the atmosphere-ocean system $\mathbf{R}_{at+sf}$.

$$\mathbf{I}(\tau_{at}, \mu, \mu_0, \phi-\phi_0) = \mu_0 \mathbf{R}_{at+sf}(\tau_{at}, \mu, \mu_0, \phi-\phi_0)\mathbf{F} \quad (2)$$

As for the components of Stokes vector, I is the radiance, Q and U are related to the degree of linear polarization and angle of polarization, and V to the circular polarization. In the Earth's atmosphere the circular polarization can be ignored. By using the adding method[1], $\mathbf{R}_{at+sf}$ can be expressed in terms of the reflection matrix, the transmission matrix, of the atmosphere and the reflection matrix of the sea surface, $\mathbf{R}_{at}$, $\mathbf{T}_{at}$, and $\mathbf{R}_{sf}$, respectively. For the basic formulations of these matrices for a single atmospheric layer with a Gaussian type ocean surface (Cox-Munk model [2]), refer to our previous paper [3].
The reflectance R and degree of linear polarization P in the reflected radiation at the top of the atmosphere are given by Eq.(3) and Eq.(4), respectively.

$$R = \pi I / \mu_0 E_s \quad (3)$$

$$P = (Q^2+U^2)^{1/2}/I \quad (4)$$

For simplicity, we shall call the degree of linear polarization the polarization in this paper.

3. SIZE DISTRIBUTION MODEL OF AEROSOL

As for aerosol size distribution models, Junge type power law model was only considered as a base-line and it is given by Eq.(5).

$$n(r) = \begin{array}{ll} C\cdot 10^{\nu+1} & 0.02\mu m \le r \le 0.1\mu m \\ C\cdot 10^{-(\nu+1)} & 0.1\mu m \le r \le 10\mu m \\ 0 & r < 0.02\mu m, r > 10\mu m \end{array} \quad (5)$$

where n(r) is the number density whose particle size is between r and r+dr. C is a constant which is determined to satisy

$\int_{r_{min}}^{r_{max}} n(r)dr = 1$, where r_{min} =0.02 [mm]and r_{max} =10.0[mm]. The index n in Eq.(5) can be used as a measure of the size of aerosol particles. As a measure of aerosol optical thickness, we shall use the aerosol optical thickness τ_{500} at 500[nm] in this study. The aerosol optical thickness τ_λ at any wavelength λ[nm] can be expressed by Eq. (6) interms of τ_{500}.

$$\tau_\lambda = \tau_{500}(\frac{\lambda}{500})^{-\alpha} \quad (6)$$

where α is Ångström exponent and it is approximately related to Junge's index n as follows: $\alpha = \nu - 2$. Since Ångström exponent is commonly used, we shall use a as a measure of the size of aerosol particles, hereinafter, instead of n. In other words, we considered here 5 different cases of α, namely, α = 0.5, 1.0, 1.5, 2.0 and 2.5. The small and large values of a correspond to large and small aerosol particle size cases, respectively. As for aerosol refractive index, we considered 8 cases of refractive index, i.e., m=1.30 -i0.0, 1.33 -i0.01.35 -i0.0, 1.40 -i0.0, 1.45 -i0.0, 1.5 -i0.0, 1.55 -i0.0 and 1.60 -i0.0, where we ignored absorbing aerosol cases. In addition, we used the optical thicknesses of Rayleigh molecules, computed by the formulae in Hansen and Travis's paper[1]. We computed Look Up Tables (LUTs) of the space reflectance and polarization for a given aerosol model with 11 different parameterized aerosol optical thicknesses of τ_{500} from τ_{500} = 0.0 to 1.0 with an increment of $\Delta\tau_{500}$ = 0.1, for 33 different zenith angles of the incident and viewing direction and 72 different azimuthal angles of $\phi-\phi_0$. The LUTs were computed at 670 and 865[nm] by the adding and doubling radiative transfer code, including polarization, for 40 aerosol models (5 cases of a x 8 cases of m). In the computation, we assumed a homogeneous atmosphere(mixture of aerosol and Rayleigh particles) bounded by an isotropic Gaussian type ocean surface with a wind speed of V=5.0 [m/s].

As for the validation of aerosol optical parameter retrieval, the simultaneous solar attenuation measurements were made by the skyradiometer (POM-01: PREDE made) with 4 wavelength channels of 400, 500, 870, and 1040[nm] at Uchinada Agricultural Experiment Center in Ishikawa Prefecture in Japan, very close to the study site A in Fig.1.

4. MULTI-DIRECTIONAL R-P ALGORITHM

The use of multi-directional R-P(Reflectance-Polarization) diagram in a single infrared band was originally proposed by our previous study[4] . We presented a parametrized R-P diagram in 865[nm] at a viewing condition of (Scene 35:θ_0 =29.14, θ =55.87, $\phi-\phi_0$=88.25; scattering angle Θ=118.5) for m=1.45-i0.0 in Fig.2. From the diagram in Fig.2, we can find easily an appropriate parameter solution, i.e., (τ_{500} =0.241, α =1.77) from a location of X in the case of m=1.45-i0.0, where X satisfies both observed reflectance and polarization values by POLDER. These estimated values agree very well with the measured values of τ_{500} (obs) =0.248, α(obs) =1.63) by sky observation near the target A on April 26, 1997. We found parameter solutions with slightly different values for other viewing conditions for m = 1.45-i0.0. Appropriate aerosol parameters at the target A should be computed by taking an average over multi-angle conditions. Since we found no appropriate parameter solution for m=1.30-i0.0, m=1.35-i0.0, and m= 1.60-i0.0 , we can reject these three cases of m. There existed an appropriate paremeter solution for m = 1.40-i0.0, 1.45-i0.0, 1.50-i0.0 and 1.55-i0.0. Because the sum of relative difference S(m_j) between the model and observation in the case of m = 1.40-i0.0 is the smallest among four possible cases of m, we can adopt the case of m=1.40-i0.0 as the best case. The definition of S(m_j) is given by Eq.(9). Finally, an appropriate set of aerosol parameters at the target site A, based on the above arguments, was found to be (τ_{500} =0.245, α=1.20, m=1.40-i0.0) which was close to the measured ones (τ_{500} [obs]=0.248, α [obs]=1.63).

Our new algorithm for retrieving aerosol's real part of refractive index, τ_{500} and α, is as follows:

(a) Find a solution of ($\tau(i,m_j)_{500}$, $\alpha(i,m_j)$) using the R-P diagram at the first pixel in POLDER scene under consideration at a given viewing condition, Θ_i, for fixed m=m_j, where i=1- 5 and j=1-8. As for Θ_i, we consider 6 cases of scattering angles Θ_i, namely, Θ_i:(i=1-5)=$123.5^\circ, 136.4^\circ, 150.8^\circ, 162.7^\circ, 163.0^\circ$ *and* 154.7° selected among POLDER'S 12-14 viewing conditions at each pixel. As for m_j, we consider 8 cases of real part of refractive index, namely, m_j=1.30 -i0.0, 1.33 -i0.0,1.35 -i0.0, 1.40 -i0.0, 1.45 -i0.0, 1.5 -i0.0, 1.55 -i0.0 and 1.60 -i0.0.

(b) Compute an average optical thickness $\tau_{av}(m_j)_{500}$ and Angstrom exponent $\alpha_{av}(m_j)$ for fixed m_j, as follows:

$$\tau_{av}(m_j)_{500} = \frac{1}{n_j}\sum_i \tau(i,m_j)_{500} \tag{7}$$

$$\alpha_{av}(m_j) = \frac{1}{n_j}\sum_i \alpha(i,m_j) \tag{8}$$

where n_j is the total number of existing solutions for fixed m_j. We reject the case of m_j as an inappropriate case, if no possible solution is found in the P-R diagram.

(c) Compute theoreatical reflectance $R_t(i)$ and polarization $P_t(i)$ at each pixel for Θ_i, using the values of $\tau_{av}(m_j)_{500}$ and $\alpha_{av}(m_j)$. Then, compute a sum of relative differences S(m_j) between the model (m=m_j) and observation, according to Eq.(9).

$$S(m_j) = \frac{1}{2}\sum_i \left[\frac{|R_{ob}(i) - R_t(i)|}{R_{ob}(i)} + \frac{|P_{ob}(i) - P_t(i)|}{P_{ob}(i)}\right] \tag{9}$$

where $R_{ob}(i)$ and $P_{ob}(i)$ are the observed reflectance and polarization values for Θ_i.

(d) Assign $m=m_k$ as an appropriate real part of refractive index at the pixel, where m_k satisfies Eq.(10).

$$S(m_k) = Min\{S(m_j): j = 1,2,..,8\} \tag{10}$$

Three values of m_k, $\tau_{av}(m_k)_{500}$ and $\alpha_{av}(m_k)$ are appropriate aerosol optical parameters at the pixel.

(e) Repeat steps (a) to (d) for all pixels in a series of POLDERscenes.

5. MULTI- AND MONO- DIRECTIONAL R-R ALGORITHMS

This is a method for retrieving aerosol optical parameters, using two band reflectance values alone. This method was originally used in the retrieval analysis of NOAA/ AVHRR data by Stowe et al.[5]. By using a parameterized diagram of theoretical reflectances in 670 and 865[nm] bands at a given angular condition, we can also estimate an appropriate set of (τ_{500} , α) which satisfies the observed reflectances at 670 and 865[nm]. The R-R (Reflectance-Reflectance) algorithm in two bands is applicable to POLDER's multi-directional reflectance data and the mono-directional reflectance data of OCTS and NOAA/AVHRR. We can retieve aerosol's three optical parameters from POLDER's reflectance data using the similar algorithm in the previous section, except using multi-directional R-R diagrams and the different definition of $S(m_j)$ given below.

$$S(m_j) = \frac{1}{2}\sum_i \left[\frac{|R^{670}_{obs}(i) - R^{670}_t(i)|}{R^{670}_{obs}(i)} + \frac{|R^{865}_{obs}(i) - R^{865}_t(i)|}{R^{865}_{obs}(i)}\right] \tag{11}$$

However, it is difficult to retrieve aerosol's real part of refractive index by the R-R diagram from the mono-directional reflectance data by OCTS and NOAA/AVHRR, because they collects the radiance reflected by the target from a mono-direction. In other words, we can retrieve only values of τ_{500} and α by using a mono-directional R-R algorithm.

6. COMPARISON OF RETRIEVED RESULTS

Retrieved distribution maps of aerosol parameters, namely, m=Nr-i0.0, τ_{500}, and α, from POLDER, OCTS, and NOAA/AVHRR aquired on April 26, 1997 were presented in Fig.3, Fig.4, and Fig.5, respectively. Here, Nr is the real part of refractive index. In these figures (a) and (b) represent retrieved results from POLDER data by the multi-directional R-P algorithm and multi-directional R-R algorithm, respectively. In addition, (c), (d) , and (e) represent those from the reflectance data of OCTS, AVHRR with 1.5 hours time-lag and AVHRR with 4 hours time-lag by the mono-directional R-R algorithm. The retrieved results at the validation site A are shown in Table 1. We can find that the multi-directional R-P algorithm gives the best agreement with the observation data among different algorithms. The retrieved map of the real part of refractive index cannot be made from OCTS and AVHRR data, because of their mono-directionality limitation. Fig.3-(a) shows that we have a large extended region of aerosols with Nr in a range of 1.40 to 1.45 from Asian Continent to Japanese islands, whereas we have regions of aerosols with that in a range of 1.30 -1.35 in the Pacific Ocean. Fig.4-(a) shows that the aerosol optical thickness (τ_{500} =0.0- 0.2) is much smaller in the Pacific Ocean than that (τ_{500} =0.4-0.5) in the Japan Sea. As for α, we have aerosol regions with α=0.5 (corresponds to large size particles: Oceanic Particles) in the Pacific Ocean, whereas we have a very large region with a =2.0-2.5 (corresponds to small size particles: Land Particles), which extends from Asian Continent toward the Pacific Ocean, as is seen in Fig.5-(a). All features by the mult-directional P-R algorithm were consistent and they agreed well with our general knowledge about the local atmospheric movement. We have strong Yellow dusts from Asian Continent (China) in spring and they are extending over Japan and the western part of the Pacific Ocean. Since most features in Fig.4-(b) , -(c), -(d) and-(e) are similar to those in Fig.4-(a), we can judge that retrieved results of τ_{500} from the reflectance data are qualitatively reliable, but not quantitatively. We should note that the retrieved results of τ_{500} and α from POLDER and OCTS data, based on either multi- or mono- directional R-R algorithms, are very close to each other, whereas they are very different in the case of AVHRR data. The reasons are not clear at present. There are many factors which were not taking into account in our dealing with the AVHRR data, such as the effect of water vapor absorption in wider band-width of AVHRR, the observation time-lag between ADEOS and NOAA, and others. As for α and m=Nr-i0.0, we can judge that results from the reflectance data may not be trusted, because we found that the computed polarization values, assuming the optical parameters based on the R-R algorithm, failed to satisfy the observed polarization values.

7. CONCLUSIONS

Conclusions of this study can be summarized as follows:

(1) For the first time, we showed that aerosol's real part of refractive index, together with aerosol optical thickness and Ångström exponent, can be retrieved systematically by the multi-directional R-P algorithm using POLDER's reflectance and polarization data.

(2)We found a good agreement between the retrieved and measured aerosol optical parameter values at the validation site.

(3)Retrieved maps of aerosol's toptical parameters by the proposed algorithm were compared with those by the multi-directional R-R algorithm and by the mon-directional R-R algorithm using the reflectance data of POLDER, OCTS and AVHRR.

(4)We found retrieved results from reflectance data seemed to be qualitatively correct in the estimation of τ_{500} , but not reliable in the estimation of m=Nr-i0.0 and α.

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Table 1. Retrieved aerosol optical parameters by different algorithms at validation site A.

Satellite Data	Algorithm	τ	α
NOAA/AVHRR(1.5 hours later)	R-R Mono-angle	0.279	0.50
NOAA/AVHRR(4 hours later)	R-R Mono-angle	0.281	0.23
ADEOS/POLDER	R-R Multi-Angles	0.233	0.95
ADEOS/POLDER	R-P Multi-Angles	0.245	1.20
ADEOS/OCTS	R-R Mono-angle	0.219	0.93
Observed Data		0.248	1.63

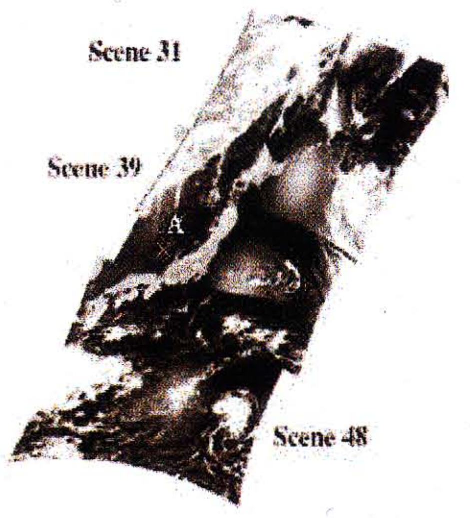


Fig.1. Sequential POLDER scenes on April 26,1997.

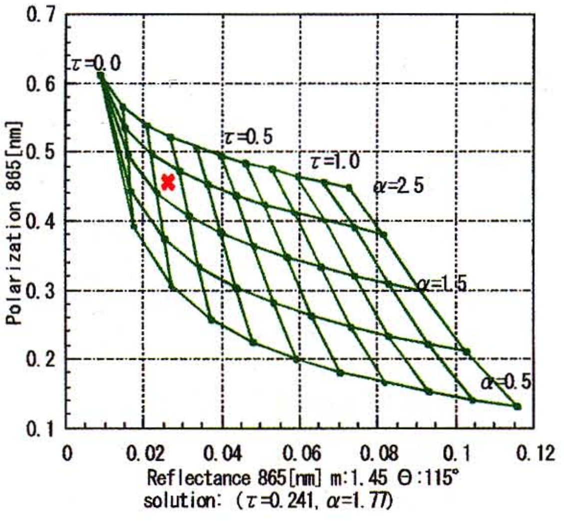
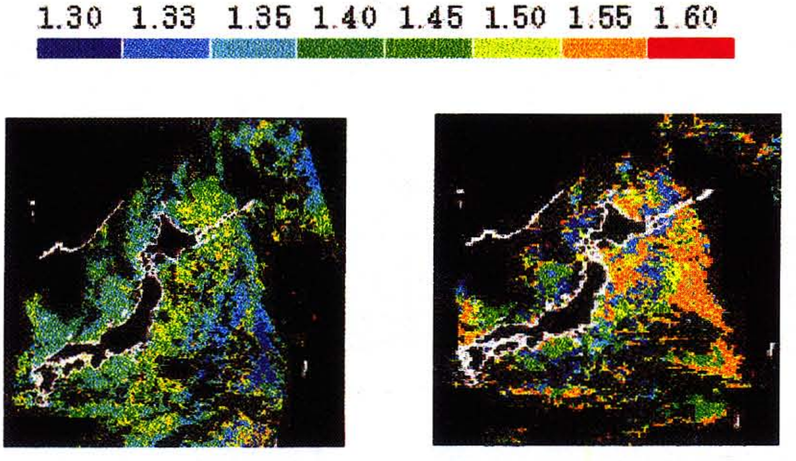


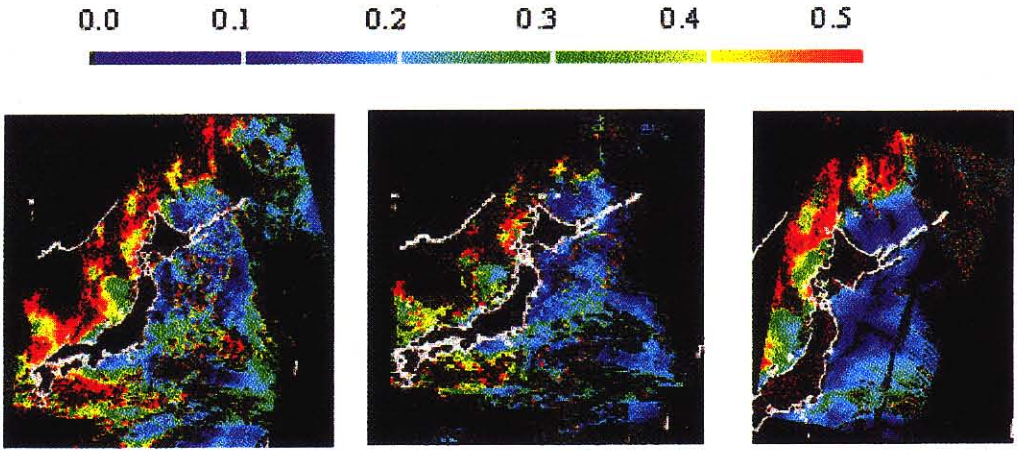
Fig.2. Directional P-R diagram . X represents a point satisfying observation values by POLDER



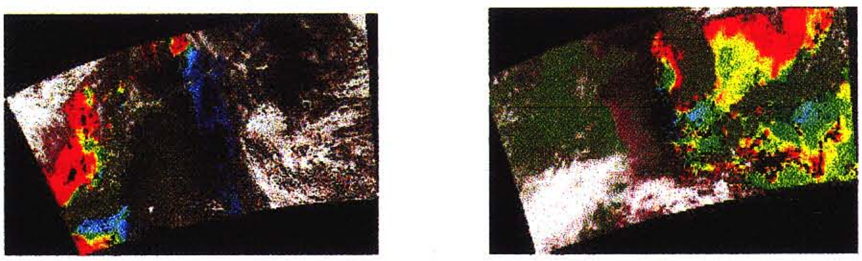
(a) Nr (POLDER: R-P)

(b) Nr (POLDER: R-R)

Fig.3. Retrieved distribution maps of aerosol's real part of refractive index

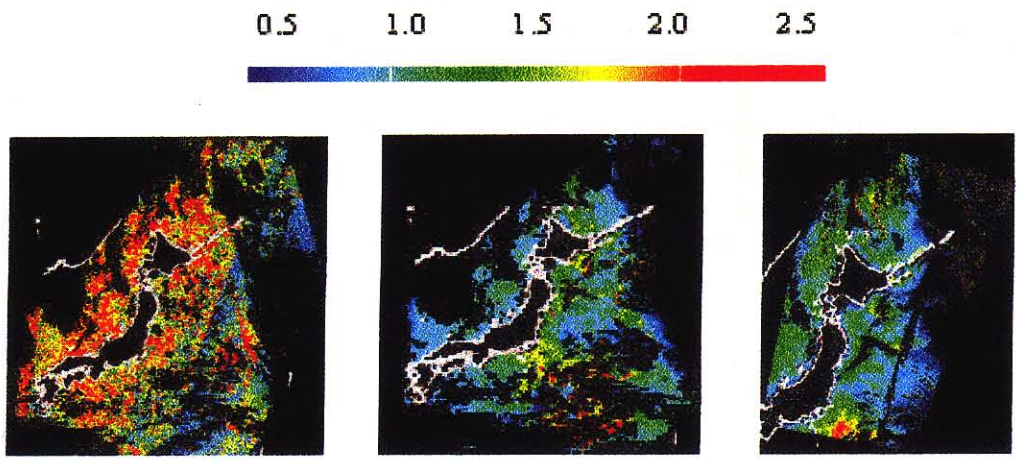


(a) τ_{500} (POLDER: R-P) (b) τ_{500} (POLDER: R-R) (c) τ_{500} (OCTS: R-R)

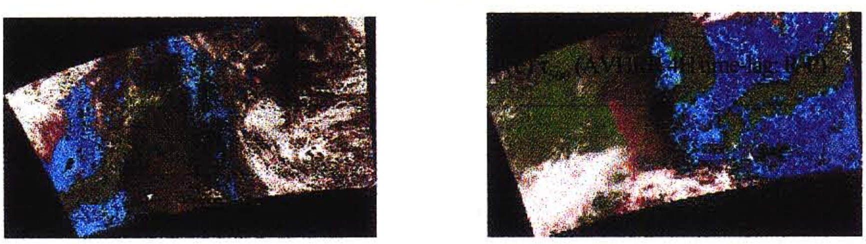


(d) τ_{500} (AVHRR 1.5 H time-lag: R-R) (e) τ_{500} (AVHRR 4H time-lag: R-R)

Fig4. Retrieved distribution maps of aerosol's optical thickness



(a) α (POLDER: R-P) (b) α (POLDER: R-R) (c) α (OCTS: R-R)



(d) α (AVHRR 1.5 H time-lag: R-R) (e) α (AVHRR 4H time-lag: R-R)

Fig.5. Retrieved distribution maps of aerosol's ÅngstrÕm exponent