PVES: Powered Visualizer for Earth Environmental Science

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***Abstract*—In this paper, we propose a powered visualizer for earth environmental science (PVES) which can accommodate three-dimensional (3-D) datasets. Though a data integration system called the Information Fusion Reactor for Earth Environmental Science (IFRES) is being developed at the Institute of Industrial Science at the University of Tokyo, PVES is a part of the IFRES contribution to the Global Earth Observation System of Systems (GEOSS). Three key functions are implemented. The first is a rather naive function that allows users to visualize 3-D raw data through Virtual Reality Modeling Language. Second, the user can specify an arbitrary curve over the 3-D dataset and then visualize its cross section. This has been proven to be very powerful for 3-D analyses of flow phenomena. Third, users can easily specify various kinds of related data in IFRES to overlay on the cross section. This function also helps users to understand the flow phenomena deeply through the fusion of information. Atmospheric Infrared Sounder (AIRS) data and its reanalysis data are provided as examples of applicable data in this paper; AIRS data is a satellite sensor product, and reanalysis data is a type of model outputs. We also present some observations extracted with the PVES and confirm effectiveness and usefulness of PVES.**

***Index Terms*—Information fusion, three-dimensional (3-D) data, virtual reality, visualization.**

I. Introduction

THE agreement that created the ten-year implementation plan for the Global Earth Observation System of Systems, known as GEOSS, was reached by participating countries and organizations of the ad hoc Group on Earth Observations (GEO) at the Third Earth Observation Summit held in Brussels in February 2005. As a contribution to GEOSS, the Information Fusion Reactor for Earth Environmental Science (IFRES) is being developed at the Institute of Industrial Science at the University of Tokyo. IFRES provides various functions related to data archiving, data management, data quality assurance, data integration analysis, data visualization, and data mining [1]–[3]. IFRES is indispensable for improving current earth monitoring, increasing the understanding of earth processes, and enhancing predictions of the earth system's behavior.

Already, several components of IFRES have been presented in published literature. The first is a centralized data archive system for the Coordinated Enhanced Observing Period (CEOP). This system was constructed to make CEOP data more available and easier to use. This system manages all of the data, including metadata. Various data such as *in situ* data, satellite data, and model output data are archived and stored in a database management system (DBMS) [1], [2]. The second system is a data analysis module attached to the CEOP centralized data archive system. This system provides users with a menu-based, integrated graphical user interface for data retrieval and analysis. Users can access all kinds of data through the same interface without considering data type [2]. The third is a Web-based quality assurance system for CEOP reference data. Through this quality assurance system, the person responsible for the observing system can easily check whether the sensed data are reasonable and can add different flags to data [3].

IFRES archives various data sets such as *in situ*, ocean, satellite, and simulation data. These data are one-dimensional (1-D), two-dimensional (2-D), or three-dimensional (3-D) data that include time series. Using this data in first analyses requires visualizing the data, which is one of the important functions of GEOSS. Although many systems have been developed already for 1-D and 2-D data, sophisticated tools for 3-D data have not been well explored for environmental research. This is because large quantities of 3-D data did not exist until recently, and analyses involving the vertical direction were not common before. There are many 3-D visualization techniques, especially in medical science. The visualizer is good at displaying fluid and shape of the object. However, the conventional 3-D visualizer cannot express the earth environmental data proficiently because the display target is not a solid. Moreover, researchers in earth environment want to view not the shape but the value of variables on a cross section along phenomena. The conventional 3-D visualizer cannot apply to earth environment research because the display object and the display method are different. As a result, users researching earth processes do not have easy-to-use tools for visualizing and analyzing 3-D data. However, a great deal of 3-D data is presently being produced, and a highly rewarding visualization system that can improve research efficiency is needed. To create such a system, the visualization engine operating in IFRES is indispensable. We expect that this powered visualization system will speedily retrieve necessary data from a collectively managed database, carry out visualizations under the specified conditions, and display the results.

In this paper, we propose a powered visualizer for earth environmental science (PVES), whose target is 3-D data. PVES is a part of the IFRES contribution to GEOSS. Users can access this system through the Internet and receive visualization results using a Web browser. The aim of this project is to create an ef-

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ficient analysis environment for 3-D earth observation data that is unparalleled.

This paper begins by describing IFRES's ability to archive and uniformly manage various types and large quantities of data. Next, three functions of the PVES's 3-D visualization are concretely described. First, the 3-D product is displayed as a lattice using Virtual Reality Modeling Language (VRML) in 3-D space. Second, an arbitrary curved cross section is cut out from the 3-D data and displayed in 3-D space. Third, the cross section and its related meteorological data are overlapped flexibly. These three functions are developed based on two primary considerations. Users would like to view the 3-D data along geographical features or meteorological conditions so that PVES must be able to clip arbitrary curved cross sections. Furthermore, users would like to view 3-D data and the related meteorological data simultaneously and understand the phenomenon so that PVES must be able to overlap arbitrary curved cross sections and meteorological data such as reanalysis data or model outputs in 3-D space.

Although PVES can accommodate various types of 3-D data, AIRS data and reanalysis data are used in this paper as examples of target data for the system. AIRS is one of the six instruments onboard the Aqua Satellite, and it can measure quantities both horizontally and perpendicularly [4]. The system can manage reanalysis data output from meteorological models, and JRA-25 data and NCEP/NCAR reanalysis data are used here to demonstrate this [5], [6]. Finally, sample visualizations from PVES are described, and we review information about the usefulness and effectiveness of PVES that was acquired during development.

II. IFRES

Earth observation data are different from document data and numeric character data handled by general databases, because files of earth observation data are very large and numerous. For example, the gross amount of earth observation data managed by NASA's Earth Observing System Data and Information System (EOSDIS) up to fiscal year 2005 was 4.3 PB (1 PB is 1000 TB) [7], [8]. In addition, the amount of reanalysis data and climate simulation output available is huge.

For creating a highly useful, highly valuable visualizer for phenomenon analysis, it is very important to archive the many kinds and large quantities of data, manage the data collectively, retrieve the data from vast storage spaces, and generate a variety of functions. These functions include data handling, conversion processing, data clipping, and high-performance visualization processing for easy viewing. In order to satisfy the above-mentioned requirements, the IFRES for data integration was constructed to contribute to GEOSS [1], [2].

Fig. 1 shows the concept of the IFRES. It has multiple tiers of storage, file systems, data management, common software, and applications. Each tier has various components. Different kinds of earth observation data (such as *in situ,* ocean, satellite, and simulation data) are archived into the hierarchical file system using a tape library system and disk arrays. This file system has a space of the petabyte scale. The IFRES manages all of the data, including metadata, collectively. Namely, 1-D data are stored in a DBMS, and the metadata of 2-D and 3-D data are stored in DBMS. Though the server uses a tape library system and disk arrays for storage, the location of the data is hidden from users,

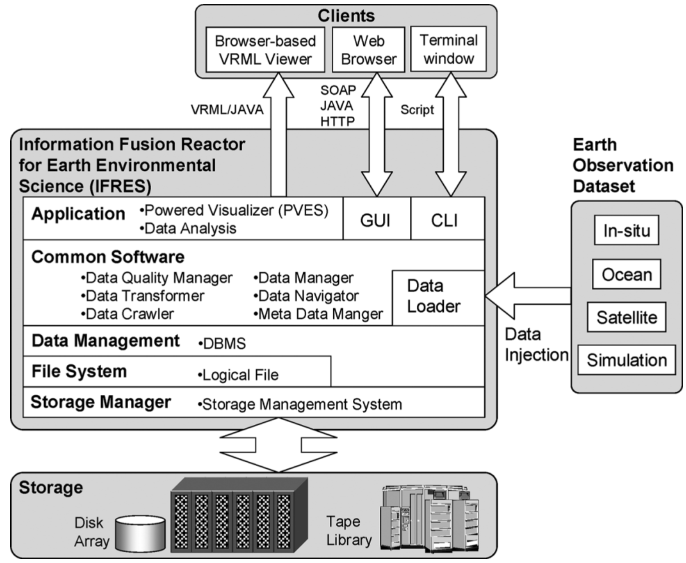


Fig. 1. Architecture of the IFRES.

so users can retrieve data without considering its location [1], [2].

In the common software tier are a data analysis system and a Web-based quality assurance system. The data analysis system provides users with a menu-based integrated graphical user interface for data retrieval and analysis. Users can access all kinds of data through the same interface without considering data type. Depending on data dimensions, users can view the retrieved data in graphic charts or bitmapped images. Some analyses such as average, difference, correlation, and so on can be applied to one or more retrieved data items on the server through the graphical user interface (GUI) [2]. Through the Web-based quality assurance system, the person who maintains the observing system can easily check whether sensed data are reasonable and can add various kinds of flags to data. Users have reported that data quality checking can be done much more efficiently with our system than with other methods. The system is able to show various kinds of sensor data simultaneously so that users can easily check intercorrelations. This correlation-assisted quality checking mechanism has proven to be quite effective [3].

The PVES described in this paper belongs to the application tier of the IFRES. Data are retrieved from the DBMS by a user's search conditions, the data are processed on a higher tier, the different kinds of processed data are integrated, and the visualization result is displayed in a virtual reality space. This system frees users from annoying and time-consuming tasks such as data collecting, data handling, data cutting, and data visualizing. In short, the time for phenomenon analysis increases and research efficiency improves. In the following, the details of the PVES are described.

III. Construction of PVES

A. Design Guideline of PVES

Recently, the popularization of the Internet has made the Web available for not only computer science researchers but also earth environmental engineering researchers. With this system, they use the Web for retrieving 3-D data. Users can set parameters such as the time and type of 3-D products, and they then retrieve the data of interest from the retrieval window. In order to perform flexible visualization on the retrieved 3-D data, three key functions are included in constructing the system. Although PVES can handle various kinds of 3-D data, AIRS data and reanalysis data (NCEP/NCAR and JRA-25) are used as examples of target data in this paper for simplicity. Details about each type of data are described in the next section.

1) 3-D Naive Display for 3-D Data: Users want to view 3-D data in 3-D space. However, it is difficult to naively display values without processing them in 3-D space using currently available viewers. Each pressure level can be divided into two dimensions and displayed, but users cannot easily view values in the vertical direction because the connections between each pressure level are lost. A visualization function that can naively display each 3-D product value in 3-D space must be developed. In order to display 3-D products, VRML is used [9]. Also, in order to plainly display the relationship between 3-D products and geographical features, the digital elevation model (DEM) is used.

2) Cutting Out and Displaying the Arbitrary Cross Section of 3-D Data: Users also want to cut out arbitrary curved surfaces from 3-D data and get desired images. In general, users do not utilize 3-D data as-is for analysis, but they use only the parts along the geographical features of interest. However, software with functions to enable this does not exist on the market. It is an onerous job for users to cut out the desired arbitrary cross section from 3-D data. Furthermore, they must also repeat the same job on a great deal of data for time-series analyses, so that analysis time is wasted and the analysis is not efficient. Therefore, an arbitrary cross-section slicer is developed here. In the proposed function, the desired part of an arbitrary cross section is cut out from 3-D data, and the results are displayed in 3-D space using VRML.

3) Overlapping and Displaying the Arbitrary Cross Section and the Related Data: A new function is added to the second function described above. In the actual data analysis, users view not only one kind of 3-D product but also related data, and the integrated analysis is carried out while users view those data simultaneously. For example, AIRS data and reanalysis data can be combined; overlapping the reanalysis data and AIRS data will improve analysis efficiency. New functions such as related meteorological data handling, data visualizing, and overlapping in 3-D space must be developed. For this example, geopotential height, wind, and specific humidity associated with the pressure level data in the NCEP/NCAR reanalysis data and the JRA-25 data are used for the related meteorological data. These and the AIRS data are all 3-D. Outputs show the geopotential height as a contour chart, the wind as arrows, and the specific humidity as a shaded chart. For each analysis, users can select the kind of reanalysis data they wish to overlap on the data selection page. This example shows that if all pressure levels of reanalysis data are overlapped in 3-D space, users cannot easily compare the data. Therefore, the pressure level and the color of the reanalysis data that is displayed can be chosen. The color should be selected automatically for beginners, and can be manually selected by expert users. These automatic- or manual-selection functions are developed for coloring the reanalysis data to improve the flexibility in 3-D data visualization.

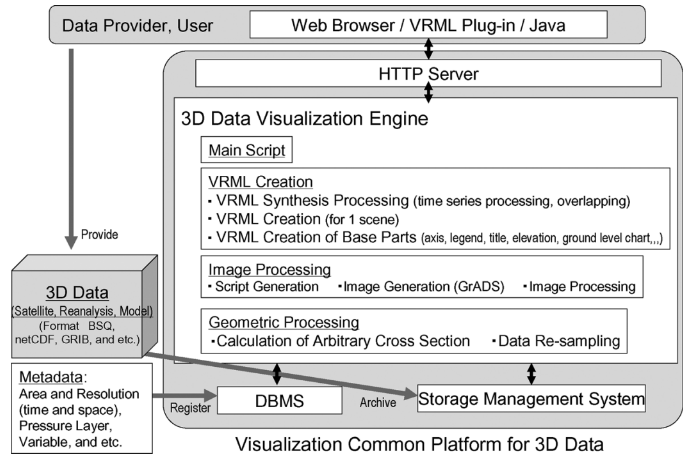


Fig. 2. Architecture of the PVES.

TABLE I
PVES SPECIFICATIONS

Hardware	SGI Onyx4 UltimateVision (MIPS R14000A 600MHz *10, 4GB Mem.)
Software	OS: IRIX64 6.5 Web server: Apache 1.3.37 The other software: csh, c, java 1.6, vrml2.0

B. Structure of PVES

The PVES which is a part of the IFRES is developed based on the design guidelines in the foregoing paragraph. Fig. 2 shows the concept of the PVES which is a visualization common platform for 3-D data. The PVES has storage management system, DBMS, 3-D data visualization engine, and an http server. Each processing in the 3-D data visualization engine is a module. Because the handling module has various format libraries, various kinds of 3-D datasets (such as satellite, reanalysis, and model output) can be applied to the PVES. Another visualization processing module that will be developed in the future can be embedded in the PVES. 3-D data is archived into the storage management system and the file information is registered in DBMS beforehand. When users request 3-D data in data retrieval page using Web browser, SQL is created and 3-D data is retrieved from DBMS. Using the visualization parameters of user's request, VRML files are created on the visualization engine and sent to users. A virtual reality space using VRML files is driven by Open Graphics Library (OpenGL) and the visualization results are displayed on Web browser. OpenGL is an application programming interface (API) for developing 2-D and 3-D computer graphics applications. Because the graphics cards on client PCs support OpenGL, almost all users can use the PVES. Time-series display is carried out by JavaScript in VRML files.

The proposed PVES is constructed using the hardware and software listed in Table I. For the Web browser, Internet Explorer 5.5 or later on Windows 2000 or later is necessary on the client side. The Java 2 Platform (version 1.2 and later) and a VRML plug-in conforming to VRML 2.0 are also necessary.

In the following, details of the PVES visualization engine are described.

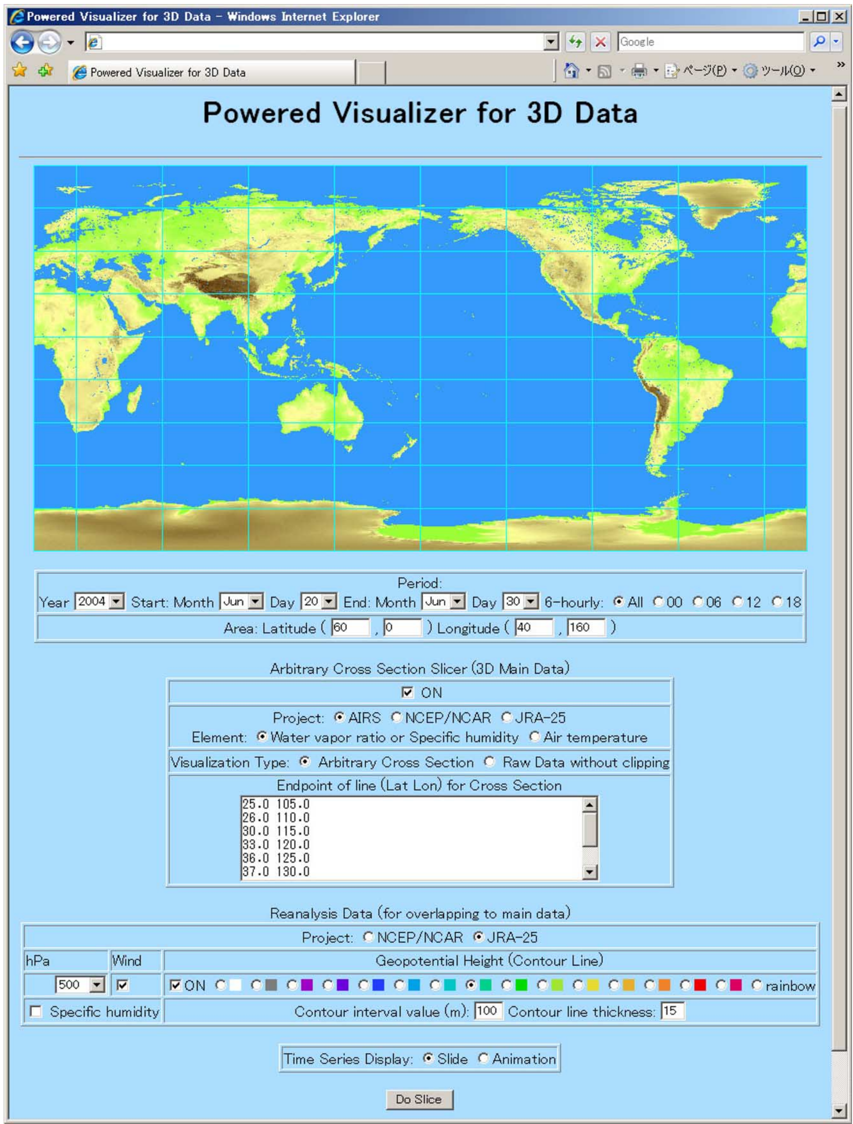


Fig. 3. Data retrieval page of the PVES.

C. How to Use PVES

The processing method of the PVES developed based on the design guidelines in the foregoing paragraph is described below. The Web-based data retrieval page has been reproduced in Fig. 3. In order to easily specify the latitude–longitude of the interested area, a global map with gridlines is shown. On this page, it is possible to specify conditions such as the time period, the area, the main data, the visualization method of the main data, the reanalysis data for overlap, and the time-series display method. The area is the space of interest. In our example, the main data are the AIRS data or the reanalysis data, from which arbitrary cross sections can be clipped, or raw data can be displayed without naive clipping. The visualization method of the main data allows selection of arbitrary cross-section display or raw unclipped data. Users can select points defining the arbitrary cross section and write the latitude–longitude pairs in the text field. The selection of reanalysis data for overlap allows the project (here, NCEP/NCAR or JRA-25) and the variable (e.g., air temperature, specific humidity, geopotential height or wind) to be selected for overlap with the main data. If the reanalysis data are selected for overlap, the visualization method (arrow, contour, or shading) is automatically determined. It is possible to select whether the time series will be displayed in slides or animations. It is also possible to specify the line thickness and the interval of the contour chart.

A flowchart of the visualization following parameter selection is shown in Fig. 4. First, the data of interest are retrieved from the IFRES [Fig. 4(a)]. Next, the VRML file is created using the retrieved data in a process shown in Fig. 4(b). Fig. 4(b) details the processes enclosed in the left-hand dashed-line box in Fig. 4(a). Retrieved data are handled using the library of GRIB [10] and netCDF [11] formatted data. The processes of file seeking, file reading, and data clipping are carried out using the specified conditions of the period, the area, the variable, and the pressure level.

The clip processing has the following three functions. Arbitrary cross sections are clipped from each dataset of interest and processed as follows. A continuous curved surface is calculated using the latitude–longitude pairs input by users. The original

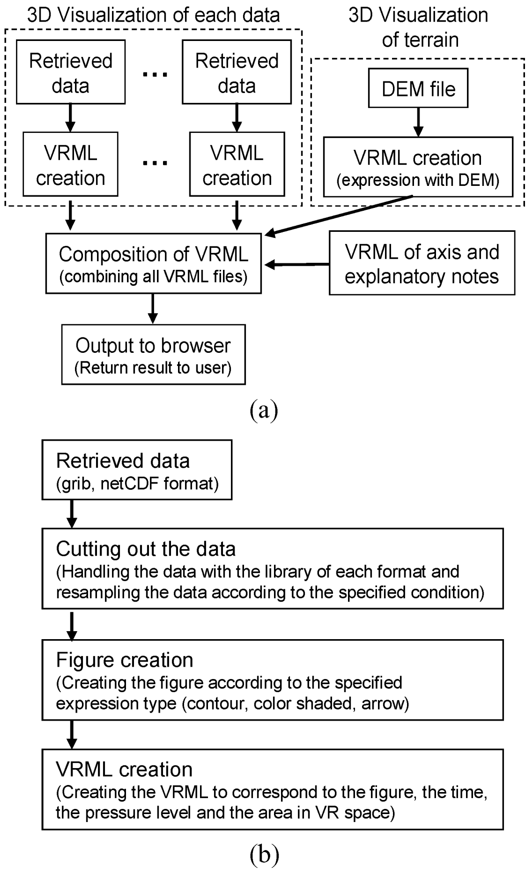


Fig. 4. Flowchart of the visualization. (a) Entire flowchart. (b) Detail of VRML creation.

data are resampled along the curved surface using the calculated result, and the resampled data are converted to 2-D data [12]. The horizontal axis of the 2-D data is the map track, and the vertical axis is the pressure level. The hexahedron of the latitude–longitude axis and pressure level is clipped using the specified condition of latitude–longitude area. A rectangle is clipped from the 3-D reanalysis data using the specified pressure level and horizontal plane area that will later be overlapped with the main data.

According to the expression type (shaded, contour, or arrow) specified by users, the clipped 2-D data are converted to a color image using GrADS software [13]. Last, the clipped 3-D data are converted to VRML. To do this, the voxel (volumetric pixel) of each value is expressed using a sphere with a specific color and size. The VRML file is created so that the aforementioned components correspond to time, area, and pressure level in virtual reality space. The VRML file returns to the flow shown in Fig. 4(a) when this processing is ended.

In the 3-D terrain-visualization step shown in Fig. 4(a), the DEM file is included, and the VRML file is created using height and square grid. The axis and the explanatory notes are also expressed in VRML. After each VRML file is created, the parent file that includes all VRML files is produced. This visualization result is displayed on the user's Web browser, and the visualization processing ends.

IV. Target 3-D Dataset for Visualization

In the following, the target 3-D data used for the visualization, including AIRS data, reanalysis data, and topography data, is described.

A. AIRS Data

AIRS is one of six instruments onboard Aqua, a satellite that is part of NASA's Earth Observing System (EOS). The heart of the instrument is an array-grating spectrometer operating over the range of 3.74–15.4 μm at a spectral resolution of $(\lambda/\Delta\lambda)$ 1200. The method requires no moving parts for spectral encoding and provides 2378 spectral samples, all measured simultaneously in time and space. AIRS is also outfitted with a 4-channel (0.4–1.0 μm) visible/near-infrared imaging module [14]. The 3-D data of the AIRS Standard Retrieval Product consist of retrieved estimates such as TAirStd (retrieved atmospheric temperature profile) and H2OMMRStd (retrieved water vapor mass mixing ratio). This 2-D data consist of retrieved estimates such as surface skin temperature, surface air temperature, total water, and total ozone [15].

B. Reanalysis Data

The data assimilation uses observational data to improve numerical model predictions. Observation data that may be imperfect, inhomogeneous, or of different kinds become integrated grid data after data assimilation, which makes it easy to treat the data. The acquired dataset, matched in space and time, is called reanalysis data. Variables such as air temperature, specific humidity, horizontal wind, and geopotential height are very important in water cycle analyses. Specific humidity is the mass of water vapor per unit mass of air, including water vapor. Geopotential height is the height of a given point in the atmosphere in units that are proportional to the potential energy of a unit mass (geopotential) at this height relative to sea level. Geopotential height is used for meteorological analyses using the upper air chart. The reanalysis data is produced by many organizations worldwide, and the specifications of output variable, period, spatial resolution, and accuracy are all different.

1) JRA-25: This paper uses the Japanese 25-year Reanalysis Project (JRA-25) data for a sample reanalysis dataset. JRA-25 lasted for a five-year period from 2001 to 2005 and was the product of a collaboration between the Japan Meteorological Agency (JMA) and the Central Research Institute of Electric Power Industry (CRIEPI). The analysis dataset covers the period from 1979 to 2004. Six-hour data assimilation cycles were performed, producing atmospheric analysis and forecast fields of various physical variables. The global model used in JRA-25 has a spectral resolution of T106 (equivalent to a horizontal grid size of around 120 km) and a maximum of 40 vertical layers. The variables used here, such as air temperature, specific humidity, horizontal wind, and geopotential height, are 3-D data [5], [16].

2) NCEP/NCAR Reanalysis Data: This paper also uses data from the NCEP/NCAR Reanalysis Project, a joint project between the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). The analysis covers the period from 1948 to the present. The global model used in the NCEP/NCAR reanalysis data has a spectral resolution of T62 (equivalent to a horizontal grid size of around 209 km) and 17 pressure levels. The variables here, such as air temperature, specific humidity, horizontal wind, and geopotential height, are 3-D data [6], [17], [18].

C. GTOPO30

GTOPO30 is a global DEM with a horizontal grid spacing of 30 arc seconds (approximately 1 km) that was developed through a collaborative effort led by staff at the U.S. Geological Survey's EROS Data Center (EDC). This data was derived from several raster and vector sources of topographic information. The root mean square error (RMSE) accuracy is within about 100 m [19]. GTOPO30 is used widely in the environmental fields. GTOPO30 (2 bytes, grid data, binary data without the header) is used to generate the terrain display of the 3-D visualization, overlapped with AIRS data and reanalysis data.

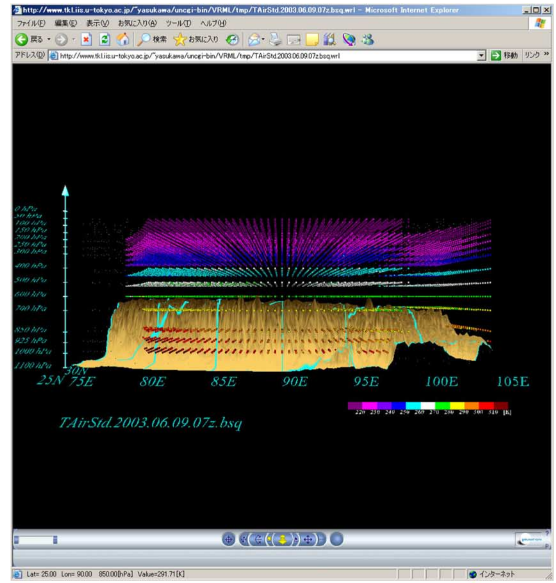
D. Data Installation

In order to construct a 3-D data visualization tool in this project, AIRS data and reanalysis data are installed in the system. Because the total size of earth observation data is very large and large-scale storage systems are required for archiving the data, those data are archived into the IFRES and only the minimum of clipped data is provided to users. AIRS data are downloaded from the GES Distributed Active Archive Center [15], the format is recognized (BSQ), the data is re-sampled to a latitude/longitude coordinate system, and it is archived into the IFRES shown in Fig. 1. The data covers Asia (70°E–150°E, 10°N–50°N), with a spatial resolution of 0.25° and 28 pressure levels. The water vapor ratio and atmospheric temperature data products from January 2003 to the present are used, and the total size of the products used is over 50 GB (4 bytes/pixel, float type). JRA-25 data, in GRIB [11] format, are downloaded from JMA and installed in the IFRES. Geopotential height and wind are used from 1979 to 2004. The total volume of all elements is about 7.5 TB (4 bytes/pixel, float type) [5]. NCEP/NCAR reanalysis data, in netCDF [12] format, are downloaded from the NOAA-CIRES Climate Diagnostics Center and installed in the IFRES. Geopotential height and wind are used, from January 1980 to the present, and the total size is about 225 GB (4 bytes/pixel, float type) [6]. Although the data volume treated in this paper is not large now, the gross volume of the data will exceed 20 TB in the future, as AIRS products and related data (such as reanalysis data and simulation outputs) are added, and the area and period of interest are expanded.

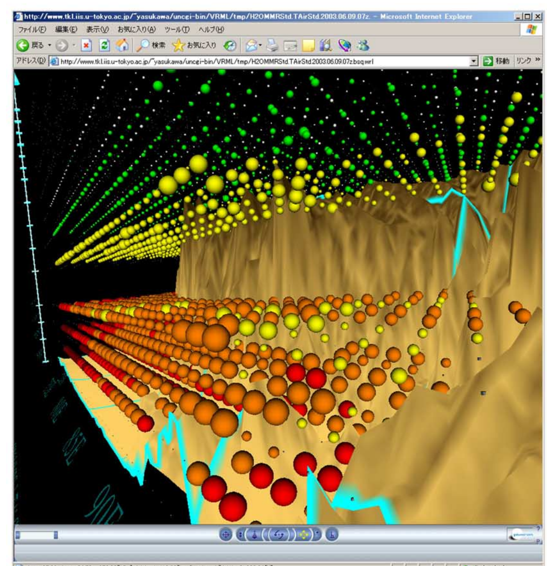
V. Examples of 3-D Data Analysis Through PVES

A. 3D Display

To display AIRS raw data in 3-D space naively using VRML, users can first select the arbitrary cross-section slicer in Fig. 3 and select the terms of the project, the variables, and the "Raw Data" of the visualization type. They can also select the period and the area of interest. The selected data are visualized by the server, the VRML file set is produced, and the visualization results are displayed on the user's Web browser as shown in Fig. 5. The data are displayed as a lattice along the axes of latitude–longitude and pressure level.



(a)



(b)

Fig. 5. 3-D display of AIRS data (7:00AM, 9 June 2003). (a) Overview of retrieval result. (b) Change of view and display of multiple products. CPU time for visualization is 2.5 s. The size of the VRML file is 1.8 MB and the size of the original 3-D data is 11 MB.

To interact with AIRS data, users can place the mouse cursor on each lattice. This displays the value of AIRS products on the status bar of the Web browser, and users can understand details in the virtual reality space. Because the DEM is also overlapped in this space, the AIRS data are expressed along geographical features. Thus, users can visually confirm the relationship between the AIRS data and geographical features. Because users can walk through and change the viewing angle and distance in virtual space using VRML, they can freely approach the area of interest and confirm the data, as shown in Fig. 5(b). It is also possible to display multiple products at the same time while utilizing the advantages of virtual reality. For example, if water vapor ratio is the size of the lattice and atmospheric temperature is the color of the lattice, the two products are displayed at

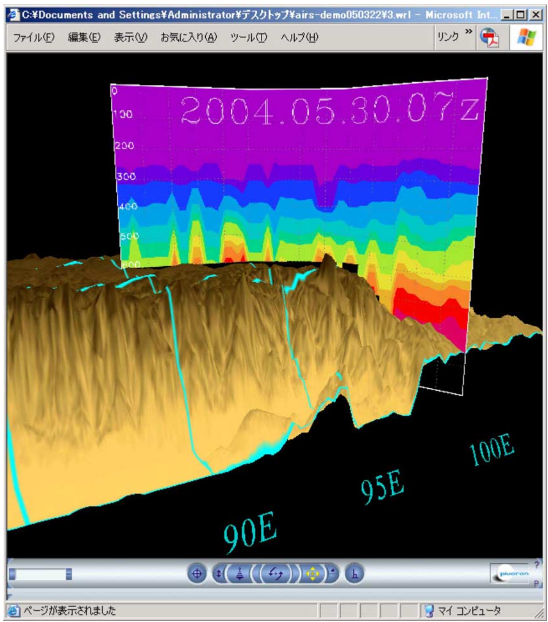


Fig. 6. Arbitrary cross section for water vapor ratio of AIRS data. Time series of arbitrary cross section is displayed (12 scenes, 25–30 May 2004.). CPU time for visualization is 5.3 s. The size of the VRML file is 1.5 MB and the size of the original 3-D data is 67 MB.

the same time as in Fig. 5(b). This is useful for analyzing correlations between the different products.

B. Arbitrary Cross-Section Slicer

To display an arbitrary clipped cross section of 3-D AIRS data in virtual reality space using the PVES, users begin by switching on the arbitrary cross-section slicer shown in Fig. 3 and selecting the terms of the project, the variables, and the "Arbitrary Cross Section" of the visualization type. They can also select the period and area of interest. They then select the data of interest by describing an arbitrary cross section by typing the latitude–longitude pairs in the text field. The server visualizes the selected data, produces the VRML file, and displays the visualization result on the user's Web browser, as shown in Fig. 6. Because the cross section and geographical features overlap, users can view and discuss the relationship between geographical features and data points. Using the system to display time series of AIRS data results in several curved surfaces being cut out, which are combined into an animation and displayed, as in Fig. 6. Then, users can effectively view and understand changes in the time series.

C. Overlapping Between AIRS Data and Reanalysis Data

Users select data as described above and select the terms of reanalysis data for overlap with the AIRS arbitrary cross section shown in Fig. 3. A contour chart of geopotential height, wind arrows, or a shaded image of specific humidity is produced for the specified pressure level. The AIRS data and the reanalysis data are overlapped on geographical features in virtual reality space using VRML, as shown in Fig. 7. The contour chart provides a transparent background to minimize interference with other data. Wind characteristics are expressed using the following convention: arrow direction indicates wind direction, arrow length indicates wind strength, and color (blue/red) indicates stream direction (descending/ascending). To enable the system to handle various analysis situations, time series may be displayed using slides or animations.

Because this tool uses VRML and users can walk through and change the virtual-space viewing angle and distance using the pointing device, it is useful for regional meteorological analyses. For example, overlapping AIRS data and reanalysis data such as geopotential height and wind shows moisture flow trends along the arbitrary cross section. For viewing this time series, slides show moisture structure details in the area of interest, yet animations catch the movement of moisture in the area of interest.

Though AIRS data and NCEP/NCAR reanalysis data are overlapped in Fig. 7, overlapping AIRS data and JRA-25 data is also possible. Fig. 8(a) shows the overlap of an arbitrary cross section of AIRS water vapor ratio and a horizontal section of JRA-25 specific humidity. We can view the perpendicular spread of water vapor and the horizontal distribution of specific at the same time. This display is useful for validation and checking of the reanalysis data.

Moreover, an arbitrary cross section of the reanalysis data can be cut out. Fig. 8(b) shows the overlap of an arbitrary cross section of JRA-25 specific humidity, the JRA-25 wind arrows, and the JRA-25 geopotential height contour. This figure is useful for understanding meteorology, reanalysis data validation, and monsoon occurrence analyses.

PVES was developed so that users' requests could be met and a flexible method could be developed to visualize the overlap between 3-D data and related meteorological data. This system enables easy selection of the kind of products, the overlap pressure level, the visualization color, and the time-series display method. This 3-D environment for the analysis of phenomena is now ready to release to users.

D. Practical Applications

Developing the PVES provided insight into some atmospheric phenomena, described below.

1) Moisture Flow in Tibetan Plateau: The Asian summer monsoon is one of the important factors influencing water resource management in the Asian region, but its seasonal development is not fully understood. Fig. 9 shows the horizontal global distribution of specific humidity in the summer 500-300 hPa layer when a great deal of moisture exists over the Tibetan plateau. This moist air is the source of primary rivers in Asia and a source of latent heating over the Tibetan plateau. Atmospheric heating over the Tibetan plateau has been thought to be a major factor in driving the Asian summer monsoon and the latent heat release accompanied by cloud activity. First, the moisture current around the Tibetan plateau was investigated using the temporal variation of 2-D moisture distributions, and three main patterns of moisture flow were found. The first is moisture from the west transported by the westerly jet. The second is moisture flow from the southwest after the onset of Indian summer monsoon. The third is moisture from the Bay of Bengal. From only 2-D moisture distributions, these flow patterns could not be determined to be caused by flows of the atmospheric upper layer or by flows of the ground-level vicinity.

Using the PVES to visualize the AIRS cross-sections of the three moisture flow patterns, we confirmed the layer in which

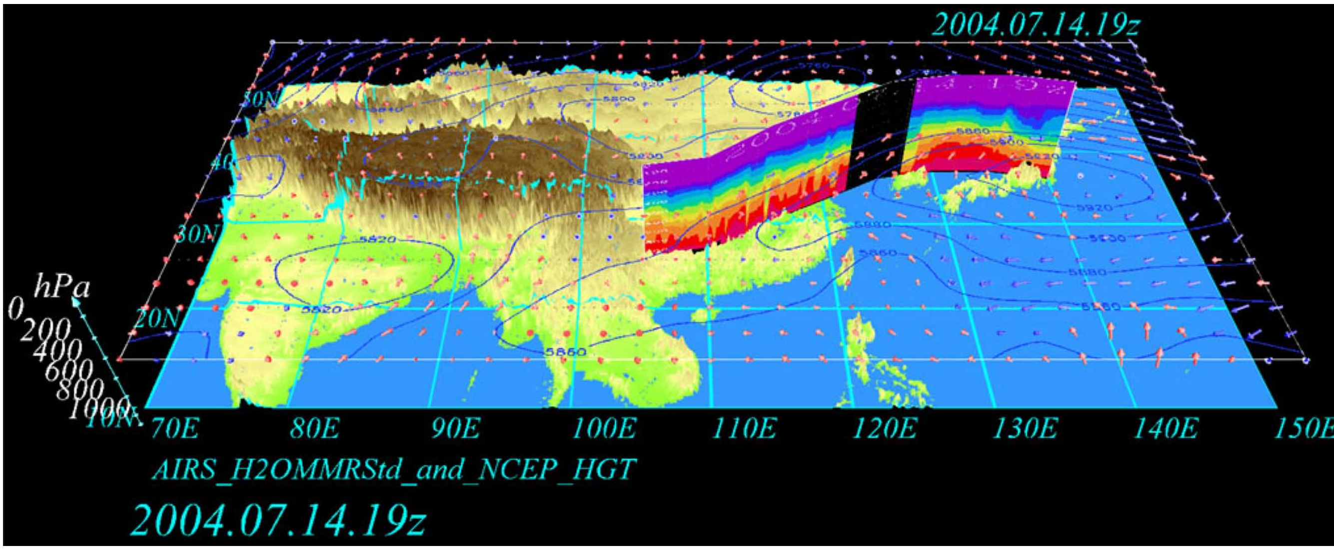
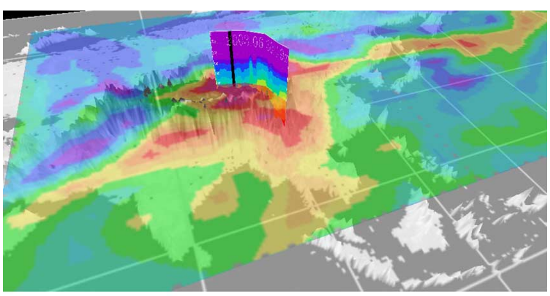
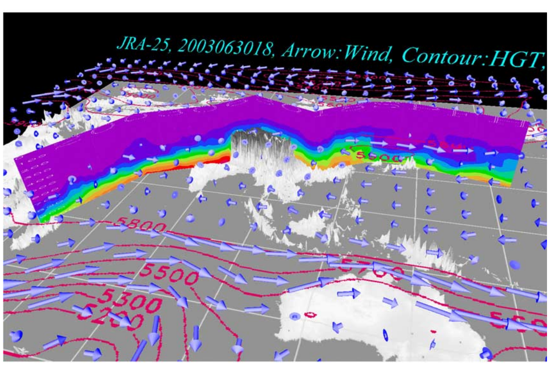


Fig. 7. Result of overlapping an AIRS data cross section and NCEP/NCAR reanalysis data. Time series is displayed (12 scenes, 9–14 July 2004.). CPU time for visualization is 15.5 s. The size of the VRML file is 6.6 MB and the size of the original 3-D data is 1066 MB.



(a)



(b)

Fig. 8. Examples of JRA-25 data overlapping. (a) Overlapping between water vapor ratio of AIRS data and specific humidity of JRA-25 (18:00, 30 June 2003). CPU time for visualization is 1.3 s. The size of the VRML file is 0.5 MB and the size of the original 3-D data is 14 MB. (b) Arbitrary cross section of JRA-25 specific humidity (18:00, 30 June 2003). CPU time for visualization is 1.8 s. The size of the VRML file is 2.4 MB and the size of the original 3-D data is 26 MB.

the moisture was transported. Fig. 10 shows the visualization result for moisture flow from the Bay of Bengal. Because PVES allows users to view the time series along a cross section and to approach the target cross section by changing the view and the angle, the results clearly show that much moisture climbed to the Tibetan plateau along the ground surface from the Bay of

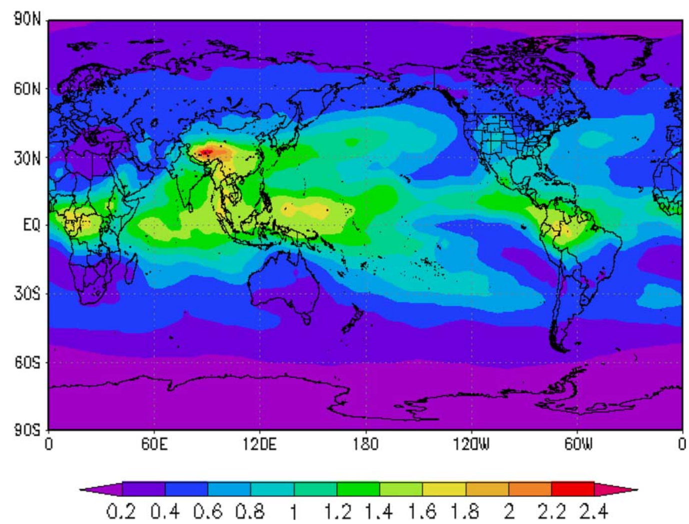


Fig. 9. Specific humidity (g/kg, NCEP/NCAR reanalysis) average on 500-300 hPa in Apr.–Aug. 2003.

Bengal. On the other hand, in the moisture flow from the southwest, the location of relatively high moisture is limited to the lower layer (Himalaya's southern edge) around May. However, a great deal of moisture was admitted to the upper layer after the middle of June, and moisture sometimes reached a height exceeding the Himalayas. Also, much moisture moved inland after the flow occurred. We received favorable reviews of the way in which the arbitrary cross-section display of our PVES showed the influence of topographic effects on moisture movement or atmospheric circulation.

2) Torrential Downpours in Niigata Prefecture and Fukui Prefecture in 2004: Japan is a country where floods and landslides occur because of torrential downpours every year, causing loss of life and property. As a result, studies that clarify torrential downpour-generation mechanisms, develop rainfall prediction models, and develop control methods for dams during heavy rains are pressing needs for security and safety. PVES

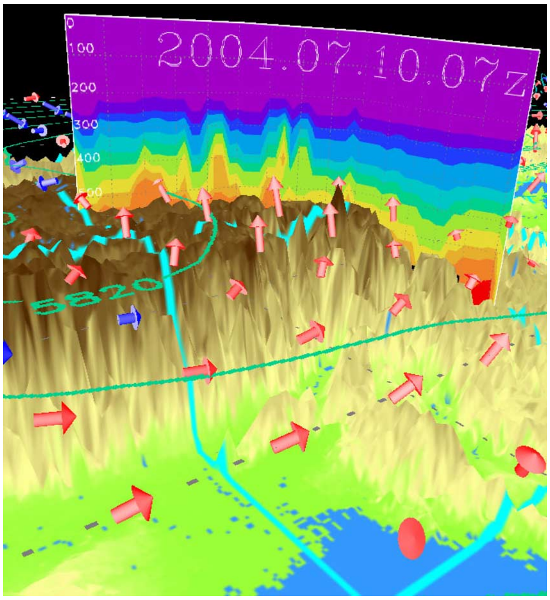


Fig. 10. Analysis of the moisture flow over the Tibetan plateau.

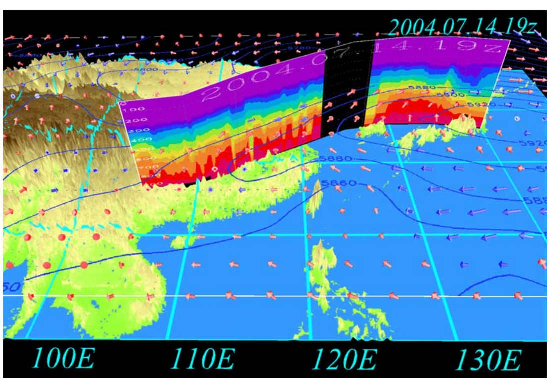


Fig. 11. Torrential downpours in Niigata Prefecture and Fukui Prefecture in 2004.

was used to clarify torrential downpour-generation mechanisms by analyzing the relationship between the Asian summer monsoon and the torrential downpours in July 2004 in the Niigata and Fukui prefectures in Japan. The flow of moisture supplying the torrential downpours was visualized, and the moisture path was traced using the water vapor ratio of the AIRS data. The cross section of the AIRS water vapor ratio is shown along the Bai-u Front in Fig. 11. The contours of the NCRP/NCAR reanalysis data geopotential height and wind arrows were overlapped with the cross section to show the weather situation. The moisture flow was confirmed by examining change of the water vapor ratio of the cross section during the time series.

The visualization showed that much of the upper level moisture was carried from southeastern China into Niigata and Fukui by the monsoon, causing torrential downpours. This new finding will be used to verify and improve meteorological models. Because PVES can visualize user-requested phenomena, we found that PVES is very useful for understanding the phenomena. Moreover, this analysis confirmed that PVES can perform highly valuable visualizations that lead to new findings.

VI. Discussion

In the following, the features of the developed PVES are discussed.

The PVES which is a part of the IFRES including storage system, DBMS, common software, and scientific application is a 3-D visualization system of server side. The PVES has a 3-D visualization engine with three visualization functions. Because each processing in the PVES visualization engine is a module, the PVES has extendibility and maintenance possibility. Another visualization processing module that will be developed in the future can be embedded in the PVES. Because the PVES is a system of the server side and the Web-based visualization environment, users need not install any pay software or much free software in the client PC and update the software. Using a Web browser, the PVES is free, needs no manuals, and provides users a convenient visualization environment. For the generality of 3-D visualization, visualization results using the PVES are described with VRML. If users have a PC in which a Web browser and VRML plug-in are installed, visualization results in virtual reality space are displayed using the OpenGL technique. The server transmits not streaming data but VRML files, and the transmission size of the visualization result is small and the network load is small. From the visualization experiment, it was confirmed that the transmission size of the visualization result is smaller than original data size in the case of three visualization examples. Also, the small processing time for visualization was confirmed. When users utilized the PVES actually, some new findings in atmospheric phenomena analysis were provided. Therefore, the effectiveness and usefulness of this system was clarified.

On the other hand, there are many 3-D visualization techniques, particularly in medical science. The visualizer is good at displaying fluid and shape of the object. However, the conventional 3-D visualizer cannot express the earth environmental data proficiently because the display target is not a solid. Moreover, researchers in earth environment want to view not the shape but the value of a variable on a cross section along the phenomenon. Then, the display object and the display method in medical science are different from those in earth environment research. The visualization tools that consider the above-mentioned concept do not exist in medical science. Though the existing earth environmental visualization system Vis5D [20] has various functions, cutting out a specified arbitrary cross section and displaying it are not possible. Almost all of the conventional 3-D visualization tools are standalone software, and data visualization processing on the client side requires a great deal of main memory and causes a large machine load. In order to analyze various phenomena using 3-D visualization, users might have to archive 3-D data of hundreds of terabytes and to manage that, if the visualizer is standalone software. Therefore, the conventional 3-D visualizer cannot apply to earth environment research. On the other hand, the machine load on the client side in PVES is small, because the minimum requirement of data is downloaded for display using VRML after visualization on the server side. Thus, the system requirements in PVES are low, and PVES is useful for researchers who only have limited computer resources. This online 3-D visualizer with enhanced functions, including clipping arbitrary cross sections along phenomenon, displaying cross sections using virtual reality techniques, and overlaying multiple datasets, is unparalleled. Because our 3-D visualization functions and the visualization service style of the PVES which contribute to GEOSS can promote the 3-D analysis of earth environment, the PVES can considerably contribute to standardization of 3-D visualization method and the visualization platform for earth environment data.

VII. CONCLUSION

In this paper, we propose using the PVES, a component of the IFRES, to contribute towards the GEOSS, for manipulating 3-D datasets. PVES has three functions: it displays the value of 3-D products in lattices using VRML in virtual reality space, it allows an arbitrary cross section to be cut out from 3-D data and displayed in virtual reality space, and it flexibly overlaps the arbitrary cross section and related meteorological data. Because this high-functioning system is driven by the IFRES, which can manage various kinds of large datasets, this system can be used to provide very informative visualizations.

The PVES is ready for release to users who need a 3-D analysis environment for 3-D data. This system allows users to analyze the structure and motion of phenomena along geographical features or in a variety of meteorological situations. To clarify the effectiveness and usefulness of this system, some of the new findings obtained using this system are introduced. The PVES has been proven to be very powerful for 3-D analysis and for helping users to understand phenomena deeply through information fusion. Though mainly AIRS data and reanalysis data were treated in this paper, this system can be applied to various 3-D data from other satellites, other reanalyses, and other model outputs. These results show that the PVES developed is useful for "better understanding of earth processes," which is one of the purposes of GEOSS.

In the future, a questionnaire regarding the functionality of the PVES will be circulated among users to improve this system. Finally, tools for verifying the accuracy of data and for visualizing the intermediate of the simulation calculations will be developed and added to this system.

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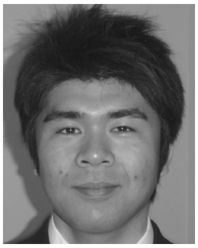

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