

STC Technical Report 2833

**REPRODUCIBLE CONTAINS
COLOR ILLUSTRATIONS**

Production of Long-Term Global Water Vapor and Liquid Water Data Set Using Ultra-Fast Methods to Assimilate Multi- Satellite and Radiosonde Observations

Annual Report

**Thomas H. Vonder Haar
David L. Randel
Donald L. Reinke
Graeme L. Stephens
Mark A. Ringerud
Cynthia L. Combs
Thomas J. Greenwald
Ian L. Wittmeyer**
Science and Technology Corporation-METSAT
Fort Collins, Colorado

Prepared for
Headquarters
National Aeronautics and Space Administration
Washington, D.C.
Under Contract NASW-4715
Technical Representative: Dr. James C. Dodge

June 1994



Science and Technology Corporation
101 Research Drive, Hampton, Virginia 23666-1340

FOREWORD

Science and Technology Corp. (STC)-METSAT is pleased to submit this annual report entitled "Production of Long-Term Global Water Vapor and Liquid Water Data Set Using Ultra-Fast Methods to Assimilate Multi-Satellite and Radiosonde Observations," by Dr. Thomas H. Vonder Haar, Dr. David L. Randel, Donald L. Reinke, Dr. Graeme L. Stephens, Mark A. Ringerud, Cynthia L. Combs, Thomas J. Greenwald, and Ian L. Wittmeyer of the STC-METSAT office, Fort Collins, Colorado. The work was performed under NASA contract NASW-4715 of the same title. The period of performance covered by this annual report was July 1993 through July 1994.

The new global data sets have been very well received by the science community. In order to extend the initial 5-year data set (1988-1992) to meet the EOS period, STC-METSAT will propose an additional 5 years (1993-1997) of processing and merging of DMSP, NOAA, and rawinsonde data using the same methods developed under the current project.

STC-METSAT gratefully acknowledges the support and helpful discussions provided during the course of this work by Dr. James C. Dodge, NASA Technical Representative. Special thanks are extended to Bill Elliot, NOAA Air Resources Laboratory, and to John Bates, NOAA CIRES, for discussions and access to some of their data sets.

ACRONYMS

ARL	Air Resources Laboratory
CD-ROM	Compact Disk–Read Only Memory
CIRES	Cooperative Institute for Research in Environmental Science
DAAC	Data Active Archive Center
DSC	Data Source Code
ECMWF	European Centre for Medium-Range Weather Forecasts
EOS	Earth Observing System
ETAC	Environmental Technical Applications Center (USAF)
GEWEX	Global Energy and Water Cycle Experiment
GVaP	GEWEX Water Vapor Project
HDF	Hierarchical Data Format
ISCCP	International Satellite Cloud Climatology Project
LWC	liquid water content
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
PWC	precipitable water content
POT	percent of total
SSM/I	Special Sensor Microwave/Imager
TOVS	TIROS (Television and Infrared Operational Satellite) Operational Vertical Sunder
USAF	United States Air Force
WMO	World Meteorological Organization

CONTENTS

	Page
FOREWORD	ii
ACRONYMS	iii
LIST OF FIGURES	v
1. INTRODUCTION	1
2. BACKGROUND—GLOBAL WATER VAPOR DATABASE	1
3. YEAR TWO PLAN REVIEW	2
4. YEAR TWO PROGRESS	3
4.1 INPUT DATA SETS	3
4.2 VERSION 2 TOTAL PWC MERGED PRODUCTS	5
4.3 VERSION 2 MERGE LAYERED PWC PRODUCTS	7
4.4 LWC PRODUCTS FROM SSM/I	9
4.5 PAPERS AND PRESENTATIONS	9
4.6 LIST OF COLLABORATING SCIENTISTS CURRENTLY REVIEWING THE OUTPUT PRODUCTS	12
5. FUTURE PLANS	13
6. REFERENCES	14
APPENDIX A	A-1
APPENDIX B	B-1

LIST OF FIGURES

	Page
Figure 1. ISCCP TOVS retrieval of PWC for July 1, 1989.	4
Figure 2. NESDIS retrievals of PWC for July 1, 1989.	4
Figure 3. Version 2 Merged produced, PWC for July 1, 1989.	6
Figure 4. Data Source/Quality Index codes, PWC merge for July 1, 1989.	6
Figure 5. Global averaged PWC from daily averages from the Version 2 merged product.	8
Figure 6. TOVS vs. Radiosonde comparison of the fraction of the total PWC measured by each in the lowest layer from the surface to 700 mb.	8
Figure 7. Percent of the observed PWC from the surface to 700 mb. July 1, 1989. ...	10
Figure 8. PWC for the lowest layer-surface to 700 mb. July 1, 1989.	10
Figure 9. PWC for the middle layer-700 mb to 500 mb. July 1, 1989.	11
Figure 10. PWC for the upper layer-500 mb to 300 mb. July 1, 1989.	11

1. INTRODUCTION

This document is the annual report for Year Two of the National Aeronautics and Space Administration (NASA) Contract #NASW-4715, entitled "Production of Long-term Global Water Vapor and Liquid Water Data Sets Using Ultra-fast Methods to Assimilate Multi-Satellite and Radiosonde Observations." Included in this report is a brief review of the project, progress in the second year, and a timeline for completing the project in the third year.

As Year Three of this project begins, STC-METSAT is well on the way to completing the proposed water vapor and cloud liquid water tasks. STC-METSAT personnel have incorporated an improved TIROS (Television and Infrared Operational Satellite) Operational Vertical Sounder (TOVS) retrieval data set from the National Environmental Satellite, Data, and Information Service (NESDIS), incorporated a new quality-controlled radiosonde data set produced at the National Oceanic and Atmospheric Administration/Air Resources Laboratory (NOAA/ARL), and derived the first 2 years of a three-layered global precipitable water product. These newest features were not originally proposed but have greatly improved the final global data set products. STC-METSAT fully intends that completion of the first 5 years (1988-1992) of integrated (e.g., total column) precipitable water content (PWC) will be on schedule during summer 1994, the multi-layered products will be finished within 6 months, and the last of the proposed tasks will be finished in the first 6 months of next year by including data formatting, archival submission, and documentation preparation.

2. BACKGROUND—GLOBAL WATER VAPOR DATABASE

The need for improved knowledge of the global water vapor distribution is well documented [e.g., international Global Energy and Water Cycle Experiment (GEWEX) reports, World Meteorological Organization (WMO), Geneva]. The majority of large-scale water vapor climatological studies have, to date, relied wholly upon analysis of radiosonde data (Bannon and Steele, 1960; Oort, 1983). Data collected at each site may not be representative of the surrounding atmospheric conditions as significant humidity gradients exist between the limited resolution of stations. Analyses of such data sets tend to smooth out mesoscale gradients, which are important to the cloudiness, precipitation, and the radiation balance fields. These fields are under special study by many scientists because of

their central role in the climate system. Data gaps over the oceans and even some land areas limit the extent to which inferences may be made about the nature of the global water vapor distribution. The newest additional data sources, such as infrared and microwave satellite data sets, can greatly enhance the global coverage on a daily basis.

To satisfy these needs, STC-METSAT is producing a pre-GEWEX Water Vapor Project (GVaP) 5 year global water vapor data set for use by the scientific research community using the best available existing satellite and *in situ* data. As a companion data set for analysis—especially because the best global climate models now contain liquid water as an explicit variable—a global (over ocean only) cloud liquid water data set is being prepared for NASA archives.

3. YEAR TWO PLAN REVIEW

The work plan for Year Two of this project included the following tasks:

- (1) Process the remaining global data sets for the last 4 yr (January 1989–December 1992) of the 5 year pilot study.
- (2) Create a Version 2 merge integrated PWC product.
- (3) Produce a Version 2 "Quality Index" product.
- (4) Produce a sample, layered PWC merged product.
- (5) Produce a 5 year cloud liquid water content (LWC) product using Special Sensor Microwave/Imager (SSM/I).
- (6) Examine the use of "over-land" algorithms for LWC retrievals from SSM/I.

In the following section the specific progress made toward each of these goals is discussed. As more is learned about the limitations of each of the input data sets during the course of research, different data and improved methodologies have been incorporated in order to produce a better merged PWC product.

4. YEAR TWO PROGRESS

The second year of this three-year contract is close to completion. This section will describe the progress made in the past year. Significant improvements have been made in the input data sets over those originally proposed, and this section will detail those modifications. An additional Year 2 task was to develop an algorithm for multi-layered PWC. The layered process has been successfully implemented and the results are currently being tested. This process is described later in this section.

4.1 INPUT DATA SETS

Processing of all 60 months of "Wentz-formatted" SSM/I tapes continues, and simultaneous retrievals of LWC and PWC from these satellite measurements are being completed. Two months still contain bad data and needed to be replaced: December 1991 and March 1992. In addition, an updated list of bad scan lines/bad navigation lines is being constructed so that these may be removed from the current retrievals. To improve retrievals in the North Atlantic and other regions, an interpolation scheme was incorporated with the $2^\circ \times 2^\circ$ SST data set (Reynolds, 1988) and a $1^\circ \times 1^\circ$ gridding routine. Major computer upgrades at STC-METSAT have allowed a significant decrease in the SSM/I processing time. These processing jobs are run after hours in the off-peak use time for these new systems. Processing time has been decreased from a high of 40 hours per SSM/I month to just under 2 clock hours/month. Additional modifications were made to the LWC retrieval to incorporate the latest algorithms from Greenwald (1994) and Greenwald et al. (1994).

For Version 1 of the merged product, discussed in the previous annual report, the International Satellite Cloud Climatology Project (ISCCP) TOVS gridded products were included as the infrared retrieval input to the merge. One serious inherent problem with this data set was the ISCCP grids on a $2.5^\circ \times 2.5^\circ$ grid spacing versus the final output product of the merge on a $1^\circ \times 1^\circ$ grid. When these data were included in the merge, it caused blockiness of the data due to all points within the 280 km box (almost a 9×9 merged data points area) having the same value. The ISCCP TOVS global grid for July 1, 1989 is shown in Fig. 1. The decision was made that this was unacceptable and an investigation into other sources of TOVS infrared retrievals was started. Other members of the GVaP science community provided quality controlled 8-mm tapes of the NOAA/NESDIS TOVS retrievals. These data were not gridded but included total and 3-layered PWC for approximately 15,000

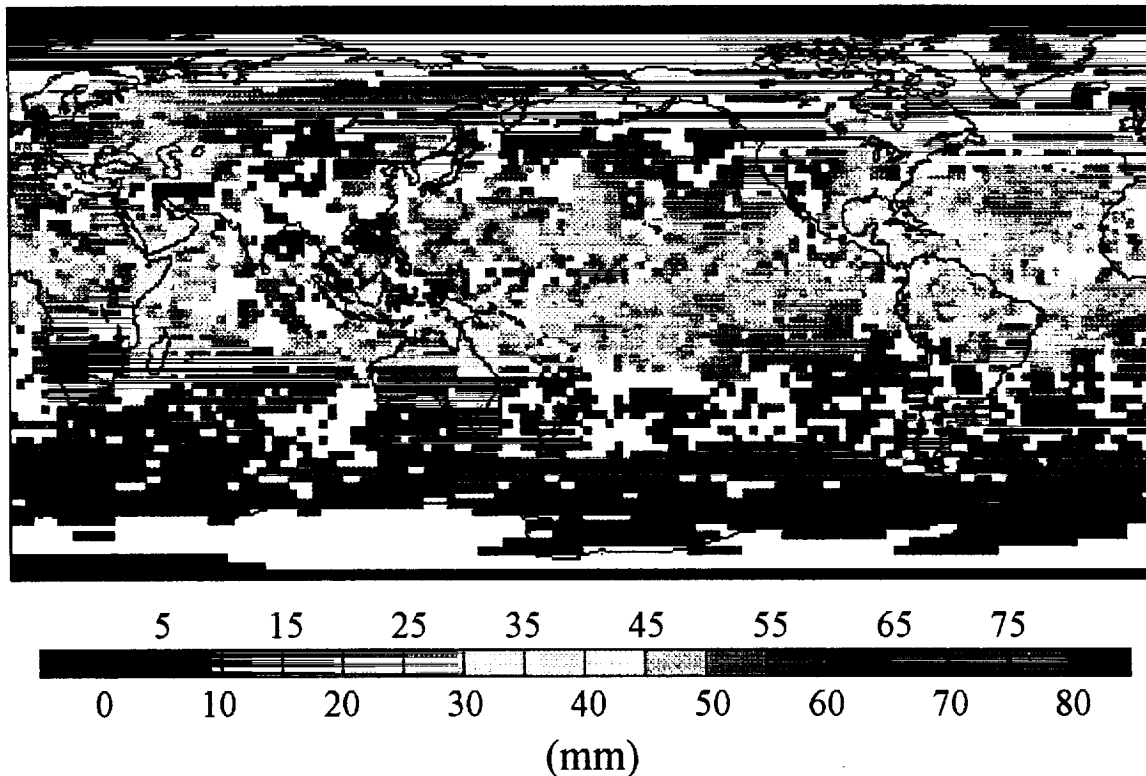


Figure 1. ISCCP TOVS retrieval of PWC for July 1, 1989

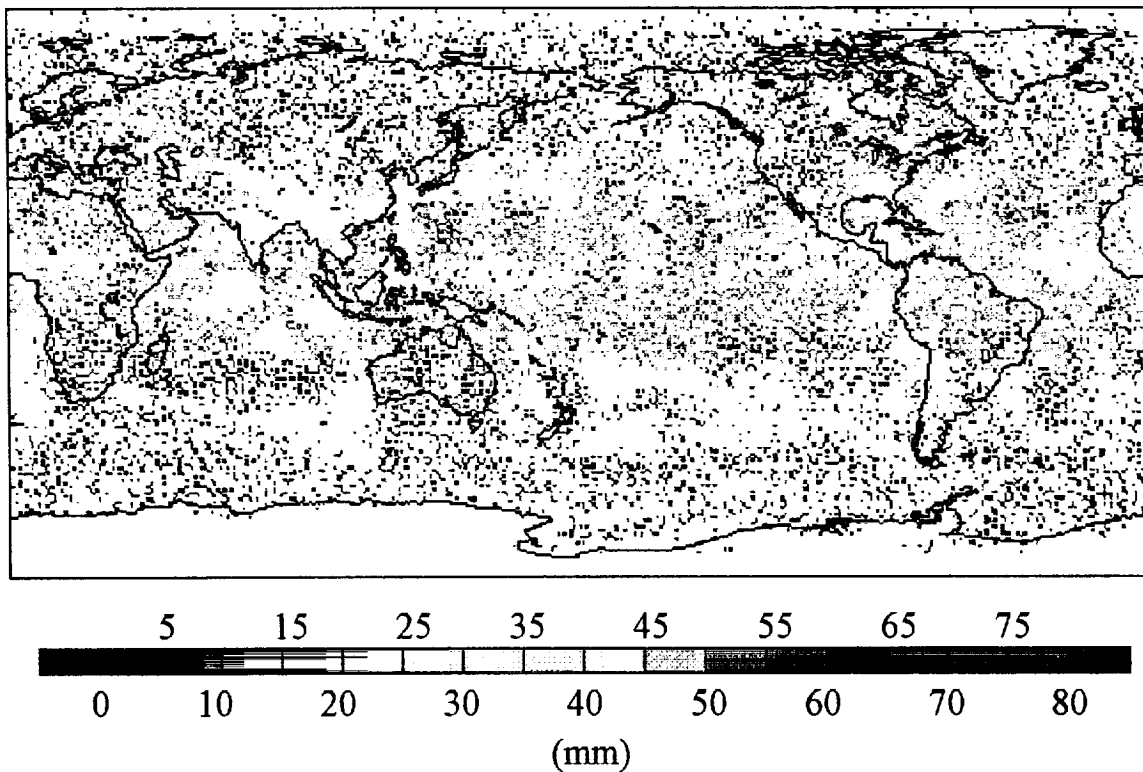


Figure 2. NESDIS retrievals of PWC for July 1, 1989

retrievals per day. After these new data were gridded (see Fig. 2) and compared with the old ISCCP results, it was decided to use them in the final merged product. This means an additional processing and gridding effort not originally planned; however, it will fit into current data ingest efforts. Processing of the first 3 years of the new TOVS is currently being finished and completion of the entire 5 years is expected by July 1, 1994.

The Version 1 merge radiosonde data set reported last year was a minimally quality-controlled United States Air Force (USAF) Environmental Technical Applications Center (ETAC) product. These data were organized in a station-ordered sequence, by year. This format created an arduous task to ingest the stations, calculate the total and layered PWC and then bin the products into daily grids. In addition, the level of quality control was poor, causing the data validation of the radiosonde PWC product to be a time-limiting factor in the entire merged process. Therefore radiosonde data sets have been changed in favor of the excellent quality-controlled set provided by a GVaP scientist from NOAA/ARL. These data were reformatted to STC-METSAT specifications and received in May 1994. Gridding and additional quality control was performed at STC-METSAT and the data were included in the latest Version 2 merged total and layered products.

4.2 VERSION 2 TOTAL PWC MERGED PRODUCTS

It is fully expected that the Version 2 merged product will be released in full next year without additional major improvements. There were many major modifications to the previous merge, which prompted the version number increment, the most critical improvements being the input data sources mentioned in the previous section. These included the change from ISCCP TOVS gridded products to the NESDIS TOVS individual retrievals, and the inclusion of the NOAA/ARL radiosonde data set. Since the area coverage of the NESDIS TOVS is less than the old ISCCP data (see Figs. 1 and 2), spatial filling and interpolation routines needed modification. Another major addition to Version 2 was the incorporation of time-averaged data for filling in missing data after the spatial filling. There was a concern that using time-interpolated data would void the use of the daily data for time variability studies. This prompted an additional flag in the data source code grids to identify the time interpolated filled data. If these studies are performed, the time-interpolated data can be easily identified and removed. An example of the Version 2 merged product and the data source code field for July 1, 1989 is presented in Figs. 3 and 4. The current data source code grid holds the following codes in order of increasing confidence:

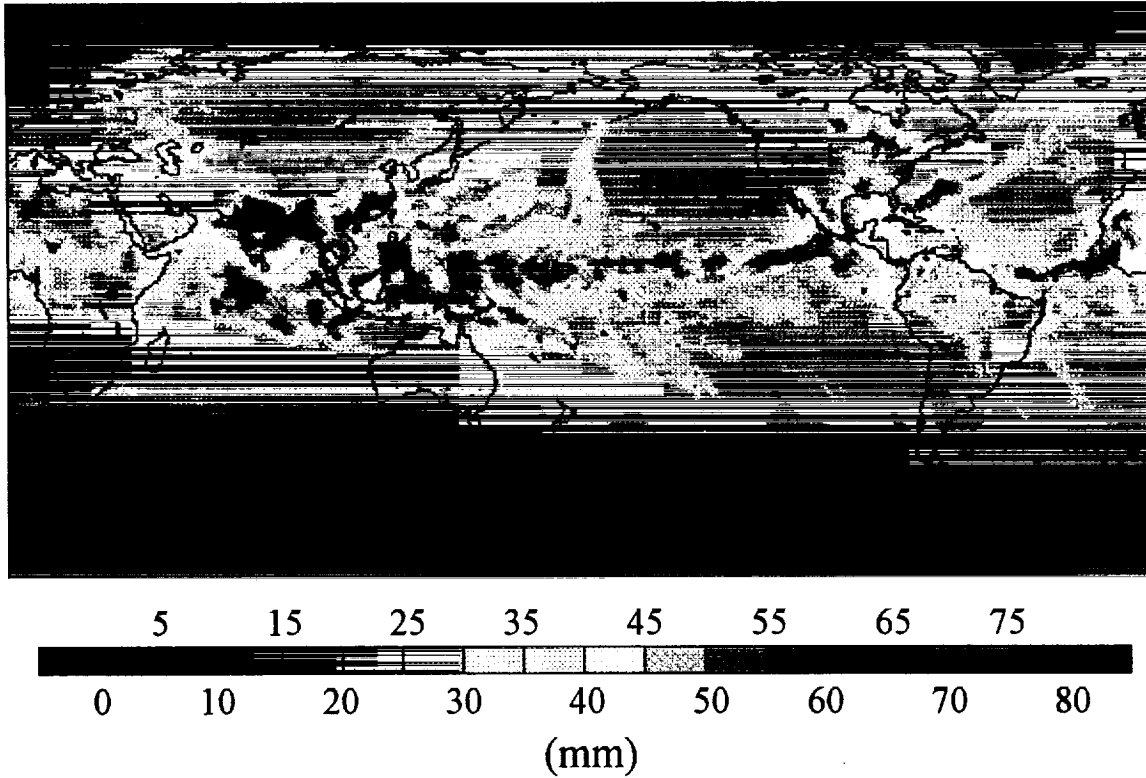


Figure 3. Version 2 Merged product, PWC for July 1, 1989

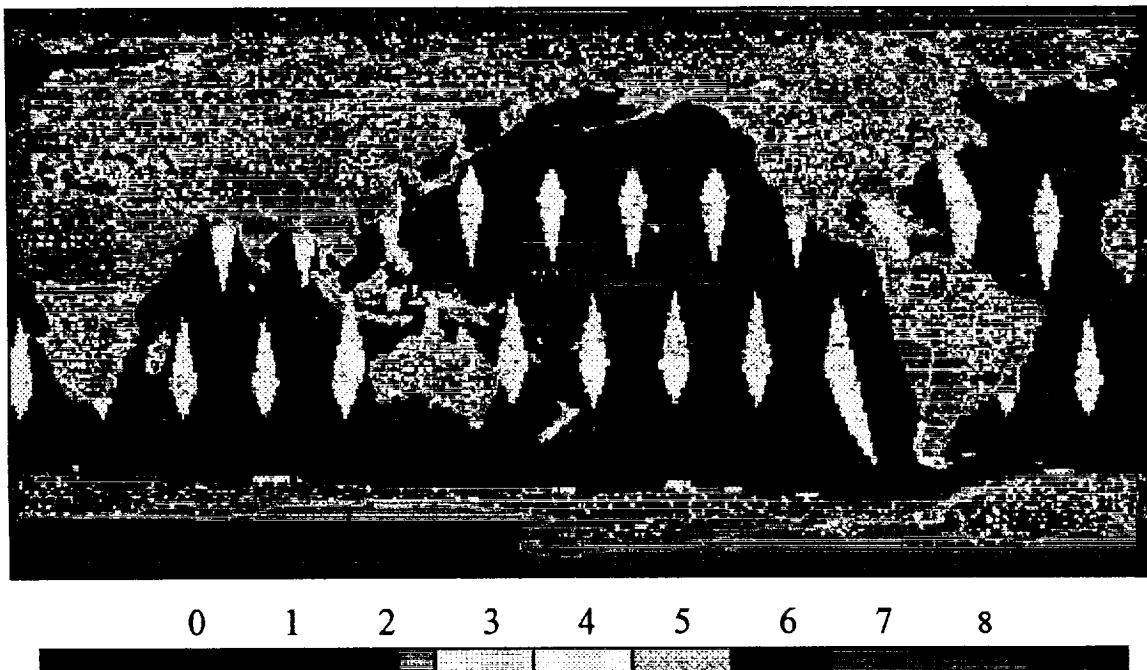


Figure 4. Data Source / Quality Index codes, PWC merge for July 1, 1989.
See text for code definitions.

DATA SOURCE CODE FLAGS

- 0 - Missing
- 1 - Time interpolated
- 2 - Spatially interpolated
- 3 - TOVS only
- 4 - SSM/I interpolated
- 5 - SSM/I interpolated - TOVS combination
- 6 - SSM/I only
- 7 - SSM/I - TOVS combination
- 8 - Radiosonde only

Figure 5 shows the annual cycle of the global averages from the Version 2 merge. The maximum in late July is 26.4 mm, and is in good agreement with previously published results. Also, one can see that the annual cycle is not symmetric, and the Northern Hemisphere summer dominates.

4.3 VERSION 2 MERGE LAYERED PWC PRODUCTS

An additional Year Two task of this proposal was to develop a method for creation of layered products as well as actually producing sample global fields. The problem addressed here was that the data set which is felt to be most reliable (SSM/I), included only the integrated column PWC. The two other input data sets, radiosonde and TOVS, did have layer information which can be used for this task. The NESDIS TOVS retrievals include three-layer PWC; therefore, these layers were used for the first layered products. These layers are: surface-700mb, 700-500mb, 500-300mb. The radiosonde data were then reprocessed to create global fields of PWC for each of these layers. At this time some basic assumptions on the global PWC distribution were made in order to progress with the next processing step. These included the assumption that while the TOVS may not give as accurate total PWC as SSM/I, the fraction of total column PWC in each layer is believed to be relatively accurate. Also, while the total PWC may change rapidly in space and time the fraction of the total PWC in each layer changes much more slowly. These two assumptions led to the creation of three global grids of percent of total (POT) PWC in each of the three layers using the combination of radiosonde and TOVS retrievals. The relationship between POT of the radiosondes and TOVS retrievals is shown in the scatter plot of Fig. 6. When the



Figure 5. Global averaged PWC from daily averages from the Version 2 merged product.

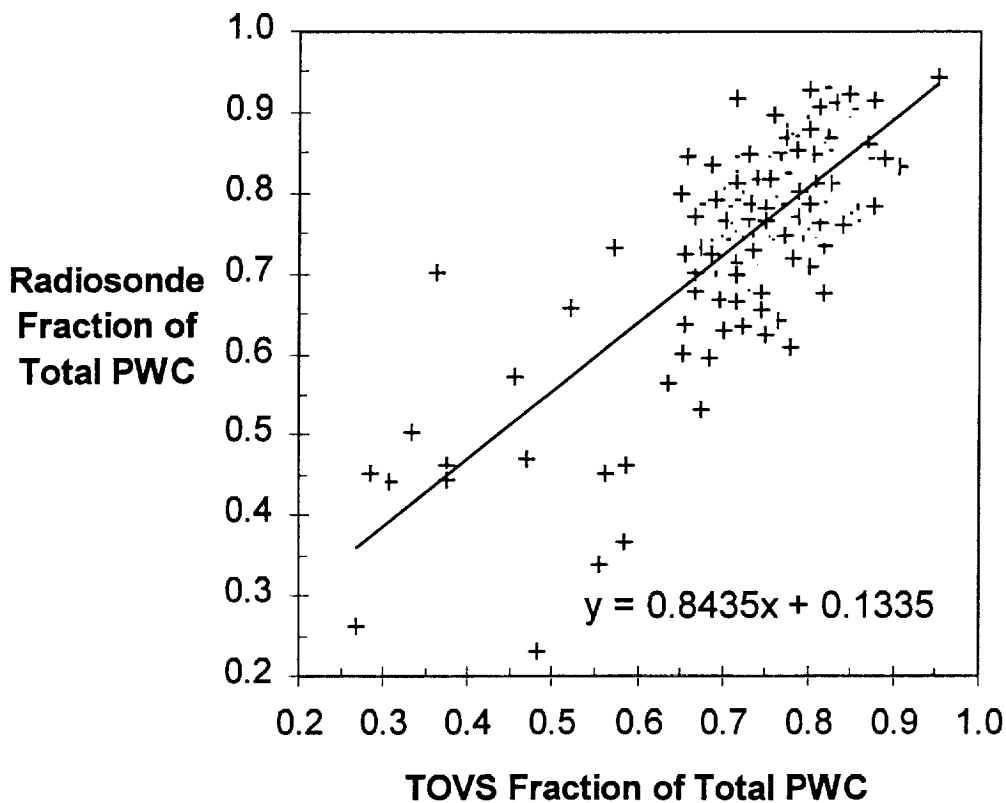


Figure 6. TOVS vs. Radiosonde comparison of the fraction of the total PWC measured by each in the lowest layer from the surface to 700mb.

fraction is low, the points tend to deviate from the best fit line. For most points the difference is less than 10 percent. The POT grids were spatially and temporally interpolated and an example for the lowest layer on July 1, 1989 is shown in Fig. 7. In oceanic areas roughly 75–85 percent of the total PWC is in this lowest layer. For elevated terrain roughly 50 percent of the PWC is in this layer. In some locations the surface may even be above 700 mb, such as over the Tibetan highlands, in which case the POT for this layer is zero. Simple multiplication of the three POT fields to the total integrated PWC merged product produced the three-layered PWC fields shown in Figs. 8–10. Note the scale change for each of the layered examples.

In summary, STC–METSAT has developed a technique whereby one can use the layered information from the TOVS and radiosondes and apply these to oceanic areas that have the highest confidence SSM/I retrievals. An additional review of the layered products should allow their release concurrently with the total integrated PWC merged fields.

4.4 LWC PRODUCTS FROM SSM/I

The SSM/I processing is complete for 5 years with the exception of 2 months. Global daily grids of LWC using the Greenwald et al. (1994) method are output and ready to format for distribution.

4.5 PAPERS AND PRESENTATIONS

In the past year, several presentations on the results of this work have been made by STC–METSAT personnel in large and small scientific sessions. In August 1993, Dr. Thomas H. Vonder Haar presented "A Pilot Study Blended Column Vapor Product for GEWEX" at the GVaP Meeting in Breckenridge, Colorado. In November 1993, Dr. Vonder Haar presented a paper (see Appendix A) to the Cloud Impacts on DoD Operations and Systems 1993 Conference (CIDOS-93). "Global Water Vapor and Cloud Liquid Water Analyses" by Vonder Haar et al. describes the background for this project, the production, and some of the first year results. Dr. David Randel presented the equivalent material at the Surface Radiation Budget Workshop in Williamsburg, Virginia in November 1993. This led to the workshop recommendation to use this data set for future SRB modeling.

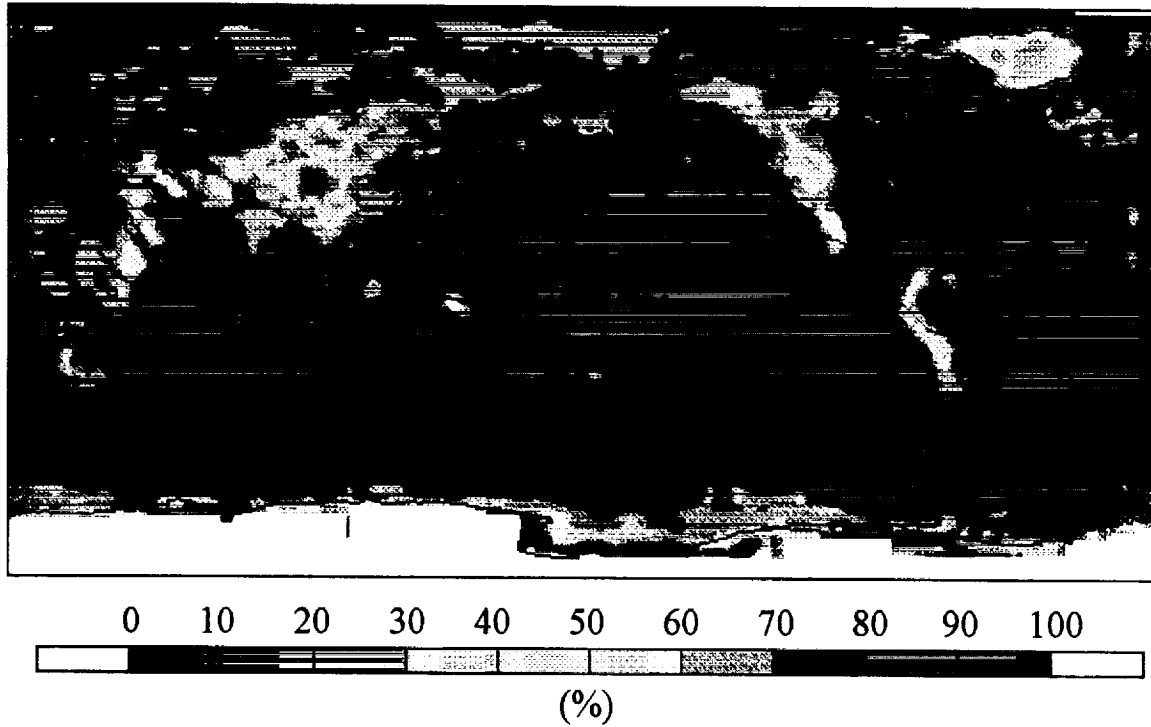


Figure 7. Percent of the observed PWC from the surface to 700mb. July 1, 1989

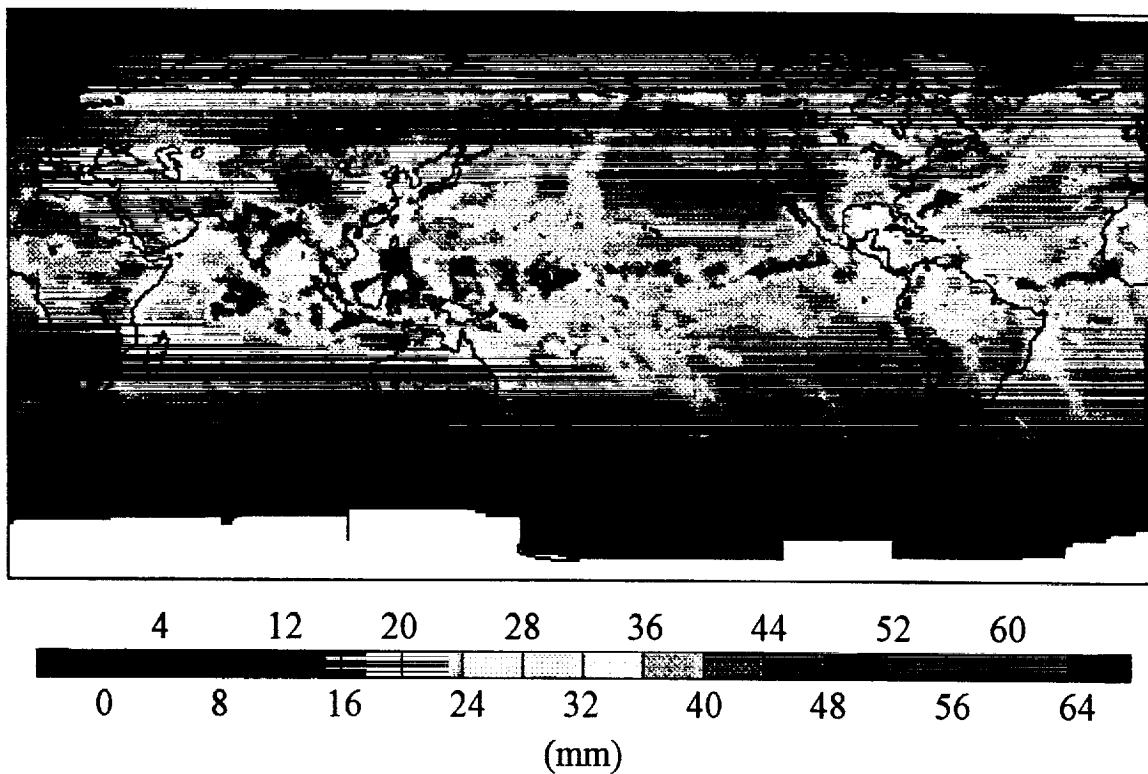


Figure 8. PWC for the lowest layer - surface to 700mb. July 1, 1989

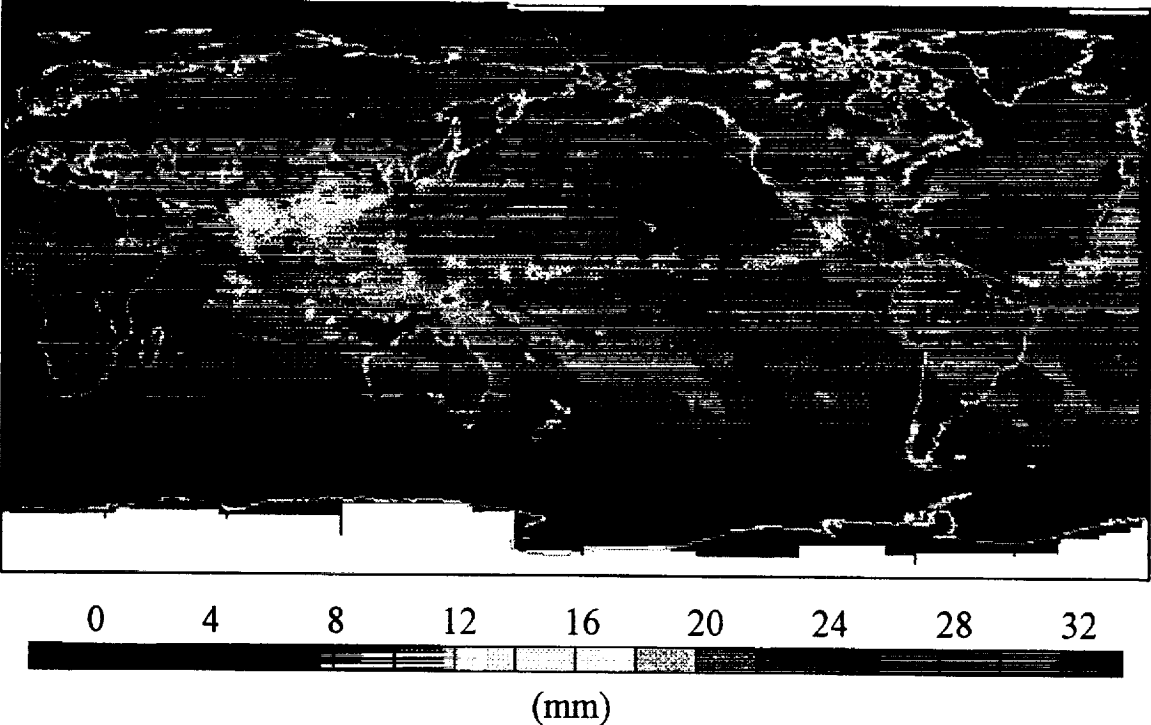


Figure 9. PWC for the middle layer - 700mb to 500mb. July 1,1989

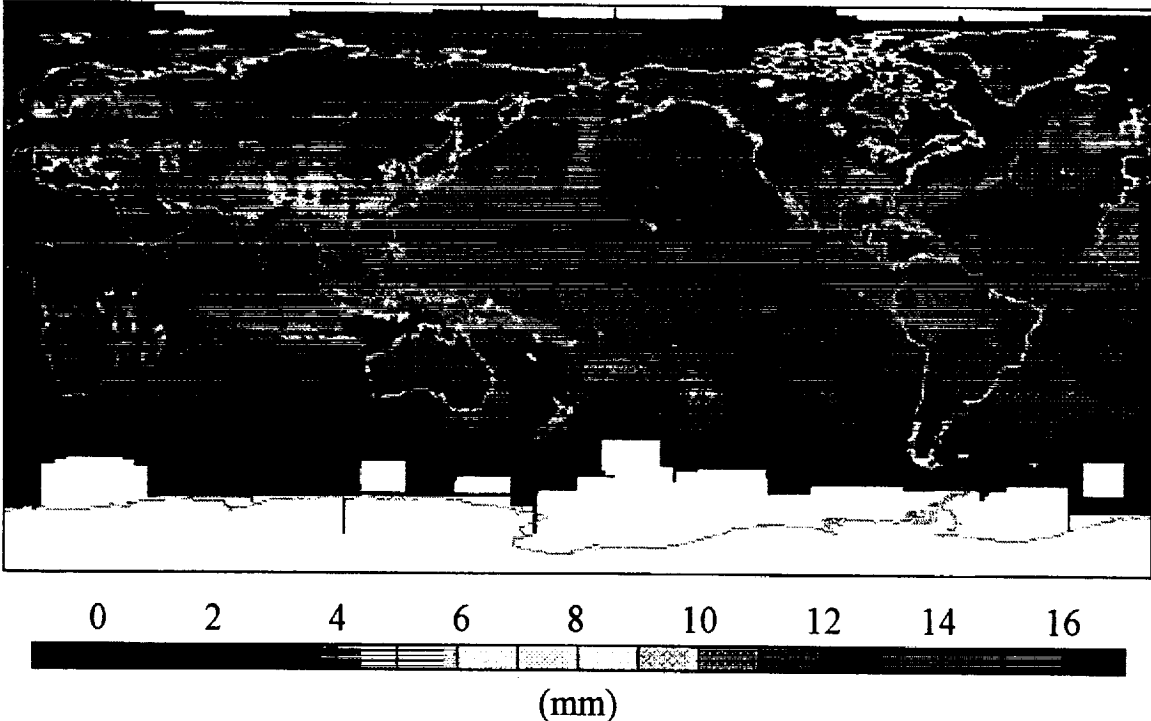


Figure 10. PWC for the upper layer - 500mb to 300mb. July 1,1989

In January 1994, a presentation was made at the American Meteorological Society (AMS) Radiation Conference in Nashville, Tennessee. "Observational Investigation of the Water Vapor distribution and the Water Vapor Forcing Effect" (Ganse et al., 1994) included results from the Version 1 merged PWC data for 1988 over the continental United States.

In February and March 1994, Dr. Vonder Haar presented "Progress in Global Water Vapor and Cloud Liquid Water Data Sets" with some of the early Year Two results (layered products) at the Science Steering Group of GEWEX and at the Fifteenth Session of the Joint Scientific Committee for the World Climate Research Programme in Geneva, Switzerland. Mr. Mark Ringerud presented a paper (see Appendix B) to the AMS Seventh Conference on Satellite Meteorology and Oceanography in Monterey, California during June 1994. "Total and Layered Global Water Vapor Data Set" describes the multi-layer merged PWC production and results essentially included in this report.

4.6 LIST OF COLLABORATING SCIENTISTS CURRENTLY REVIEWING THE OUTPUT PRODUCTS

The following is a list of researchers/scientists currently examining test data sets from the first year of Version 1 products.

- (a) Teng Kui Lim. NASA Goddard Space Flight Center. Comparing the merged water vapor data set with other satellite derived products. Sent daily merged product and data access code global grids for July 1988.
- (b) Jim Knowles. NASA Ames Research Center. For example, on-line data for March 20, 1988. Sent PWC, LWC and data source code files.
- (c) Wayne Darnell and Nancy Ritchey. NASA Langley Research Center. Sent single day July 1, 1988 Version 1 merged PWC and DSC files for comparison with other data sets including model output.
- (d) Rachel Pinker. University of Maryland. Sent all July 1988 Version 1 merged PWC for inclusion and testing with the Pinker surface radiation budget processing.

- (e) Jack Ganse. Colorado State University. Complete year of 1988 and 1989 Version 2 merged products. Investigations into water vapor climatology over the GCIP region of the United States.
- (f) David Randel and Tom Vonder Haar. Cooperative Institute for Research in the Atmosphere, Colorado State University. Studies using Version 1 merge of global radiative effect of water vapor.
- (g) Tony Hollingsworth, European Centre for Medium-Range Weather Forecasts (ECMWF), Shinfield Park, United Kingdom. Incorporation of new water vapor data into global model studies.

5. FUTURE PLANS

Embarking on the final year of this 3-year proposal, STC-METSAT is well situated to complete all the required tasks. Under the original proposal Year Three work includes the finishing of quality control of the input data sets, the completion of the 5 years of Version 2 merge, the creation of standard output formats for general use, and finally finishing the complete documentation for the project. Since the new TOVS and radiosonde data sets were incorporated in the past year, more data set quality control was needed than expected. The schedule is still on track for completion of this task at the end of summer 1994. Completion of the Version 2 merge, including quality control, is expected by September 1994.

The output format decision is still under study. Application will be made to the NASA Data Active Archive Center (DAAC) at the Marshall Space Flight Center to include the complete merged 5-year PWC and LWC data sets in the first quarter of the third year. Under study are other possibilities for data dissemination including CD-ROM creation or Internet delivery from STC-METSAT. The decision on output formatting will depend on which mode of data delivery is selected. This may be a simple gridded data format if over Internet or HDF for the NASA DAAC or CD-ROM.

The final documentation will include all relevant information on the merge process as well as error analysis of the input data sets and merged products. In addition to the final

merged grids the three input data sets are also to be released. This will allow other researchers to easily apply their own merge algorithms.

Overall the project is well on schedule and additional data sets are expected to be released to selected researchers for review throughout the year. There are no apparent problems that will impede the successful completion of this project within the specified time schedule.

In view of the very strong scientific interest in both the PWC and LWC data sets, their interannual variation (just now becoming evident), and their central role in climate studies—and thus NASA's Mission To Planet Earth Program, STC-METSAT plans to propose to NASA to use STC-METSAT's existing methods and experiences to process an additional 5 years of data for 1993–1997. This addition to global climate data sets would then connect with the Earth Observing System (EOS) period. The work is proposed for the July 1995 to April 1998 period.

6. REFERENCES

- Bannon, J.K. and L.P. Steele, 1960: Average Water Vapor Content of the Air. Geophysical Memoir No. 102, British Met. Office, London.
- Ganse, H.J., D.L. Randel, and T.H. Vonder Haar, 1994: Observational investigation of the water vapor distribution and the water vapor forcing effect. Presented at American Meteorological Society Radiation Conference, Nashville, Tennessee, January.
- Greenwald, T.J., 1994: Satellite microwave remote sensing of oceanic cloud liquid water: application to the Earth radiation budget and climate. Ph.D. Dissertation, Colorado State University, June.
- Greenwald, T.J., G.L. Stephens, and T.H. Vonder Haar, 1994: Observations of the global characteristics and radiative effects of marine cloud liquid water. Submitted to *J. Climate*, 4/94.

Oort, A.H., 1983: Global Atmospheric Circulation Statistics, 1958–1973 NOAA professional paper No. 14, 180 pp. + microfiche.

Reynolds, R.W., 1988: A real-time global sea surface temperature analysis. *J. Climate*, 1, 7.

APPENDIX A



Specializing in METeorological SATellite Systems and Related Computer Technology

93-107

GLOBAL WATER VAPOR AND CLOUD LIQUID WATER ANALYSES

by

Thomas H. Vonder Haar, Donald L. Reinke, David L. Randel, Graeme L. Stephens,
Cynthia L. Combs, Mark A. Ringerud, Ian L. Wittmeyer and Thomas J. Greenwald
STC-METSAT
Fort Collins, Colorado, U.S.A.

November, 1993

This paper was presented at the CIDOS-93 Conference held in Fort Belvoir, Virginia,
November 16-19, 1993.

TABLE OF CONTENTS

	Page
Abstract	1
1.0 Introduction	2
2.0 Data Processing	3
3.0 Results	4
4.0 Acknowledgements	7
6.0 References	7

ABSTRACT

STC-METSAT is producing for NASA, a 5-year, global, 1° x 1° resolution, precipitable water and cloud liquid water analysis from satellite and radiosonde observations for scientific research. This unique project will provide daily composite analyses as well as monthly mean values. The product will allow an analysis of total atmospheric column water vapor amount and three dimensional distribution on a global scale that has not been previously available.

The precipitable water (PWC) product is a weighted merge of DMSP Special Sensor Microwave/Imager (SSM/I) microwave retrievals, NOAA TIROS Operational Vertical Sounder (TOVS) infrared retrievals, and radiosonde data. The initial analysis scheme takes advantage of SSM/I over water, TOVS in cloud-free regions over land and water, and radiosonde over land (with limited soundings over water) to produce an assimilated global product.

The cloud liquid water (CLW) product is also vertically integrated based upon the bi-spectral polarization – corrected method of Greenwald *et al.* (1993). At the present time it covers ocean areas only. Quantitative CLW values have numerous applications.

A video loop of daily scenes from the first year of the global water vapor product (1988) has been produced. This loop shows striking features in both the seasonal and daily variations of water vapor fields that have not been viewed before. Future plans include determination of the vertical variation of water vapor as the data set is expanded to a five-year period.

1.0 INTRODUCTION

The development of a complete and accurate global water vapor data set is critical to the adequate understanding of the Earth's climate system. Examples of climate research which are dependent on accurate water budget data include, but are not limited to: poleward energy transports, general circulation model (GCM) verification, and global change baseline measurements. During the next decade, many programs and experiments under the Global Energy and Water Cycle Experiment (GEWEX) (WCRP, 1990) will utilize present day and future data sets to improve our understanding of the role of moisture in climate, and its interaction with other variables such as clouds and radiation. An important element of GEWEX will be the GEWEX Water Vapor Project (GVaP), which will eventually initiate a routine, real-time assimilation of the highest quality, global water vapor data sets including information gained from future data collection systems, both ground and space based.

The need for improved knowledge of the global water vapor distribution is well documented. The majority of large-scale water vapor climatological studies have, to date, relied wholly upon analysis of radiosonde data (Bannon and Steele, 1960 and Oort, 1983). Data collected at each site may not be representative of the surrounding atmospheric conditions as significant humidity gradients exist between the limited resolution of stations. Analysis of such data sets tend to smooth out mesoscale gradients, which are important to the cloudiness, precipitation, and the radiation balance fields. Data gaps over the oceans and even some land areas limit the extent from which inferences may be made about the nature of the global water vapor distribution. Additional data sources, such as infrared and microwave satellite data sets, can greatly enhance the global coverage on a daily basis.

To satisfy these needs, STC-METSAT is producing a pre-GVaP, comprehensive, five year global water vapor data set for use by the scientific research community using a combination of ground-based radiosonde data, and infrared and microwave satellite retrievals. These data are needed to provide the desired foundation from which future GEWEX-related research, such as GVaP, can build upon.

2.0 DATA PROCESSING

Three main steps are followed to produce the merged daily product for water vapor for the designated five year period. Input data is gathered and accessed in their raw form for step one. Processing to generate individual total column water vapor and quality control is done in step two. The final major processing task involves utilizing the individual output products as well as associated estimates of data quality in the generation of merged products. A combination of methods are used to generate the hybrid output global data set for water vapor.

We create this product by combining all three of the main input data sets, using a hierarchical weighting scheme. This algorithm uses radiosonde data when available as truth, and then applies a weighting scheme to the TOVS and SSM/I. Finally linear interpolation routines are run to fill missing data points. The final products from the processing are: complete global fields of liquid water content over the oceans from SSM/I, the merged precipitable water content from TOVS, SSM/I, and radiosonde, and a data origin map which is ordered by estimated data error in the merged field.

The data origin code map contains numbers representing, in order of lowest to highest confidence: Missing data; interpolated and filled; TOVS Monthly climatology; TOVS only; SSM/I interpolated; SSM/I interpolated/TOVS combination; SSM/I only; TOVS/SSM/I combination; radiosondes.

3.0 RESULTS

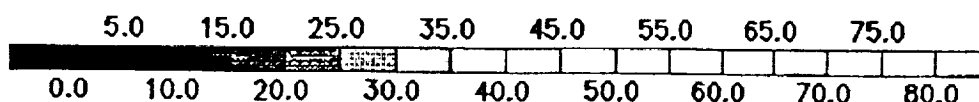
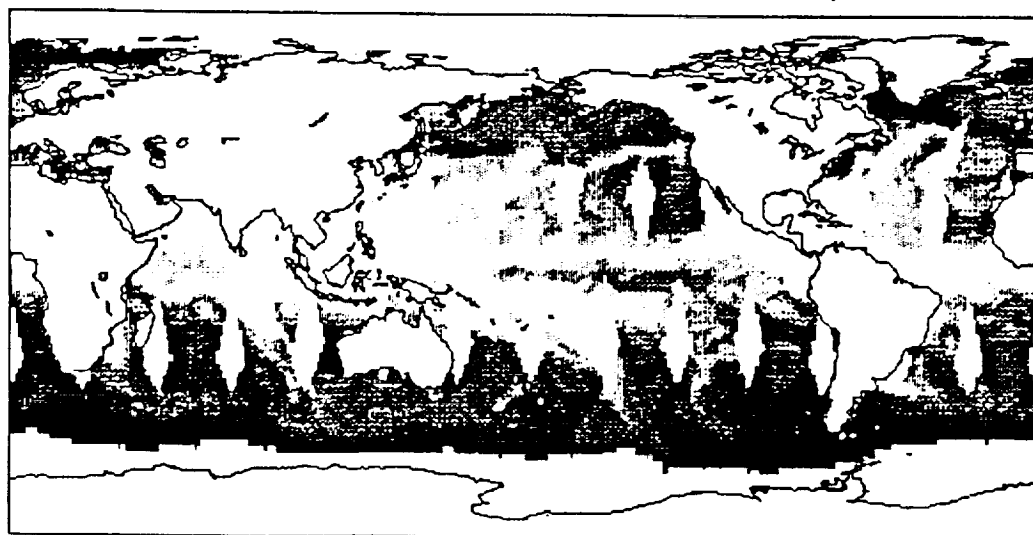
We have produced up to this point, two years of merged PWC data products, 1988 and 1989. Figure 1 shows the global distribution of the available SSM/I PWC for July 1, 1988. Figures 2 and 3 respectively, show the global TOVS and radiosonde data sets for the same date. Figure 4 shows the global water vapor merged product for July 1, 1988. Figure 5 shows the cloud liquid water content for July 1, 1988, over the oceans from SSM/I data.

Each of the individual input data sets has significant limitations. Microwave retrievals are presently feasible only over oceans (Figure 1). Infrared satellite techniques only work in absence of significant cloud cover (Figure 2). And radiosonde measurements are made primarily over land (Figure 3) and are distant points, not showing small scale water vapor variations. A comprehensive global data set must draw upon the strengths of each of these methods, and use the advantages of each for all meteorological and geographical scenarios. The result (Figure 4) is a combined effort far better than any one single input data set. High values of PWC are evident in the Intertropical Convergence Zone (ITCZ) and in the Indian Monsoon region. Values range up to 80 mm which may be contaminated by high rain rates.

A video loop of daily scenes from the first year of the global water vapor product (1988) has also been produced. This loop of the merged product shows striking features in both the seasonal and daily variations of water vapor fields that have not been viewed before. Prominence of the ITCZ, the subtropical jet reaching into the mid-latitudes, and tongues of dry air transported out of the polar regions are easily seen.

This complete data set is scheduled to be delivered to NASA by the summer of 1995.

Figure 1.



SSM/I PWC data for July 1, 1988 (mm)

Figure 2.

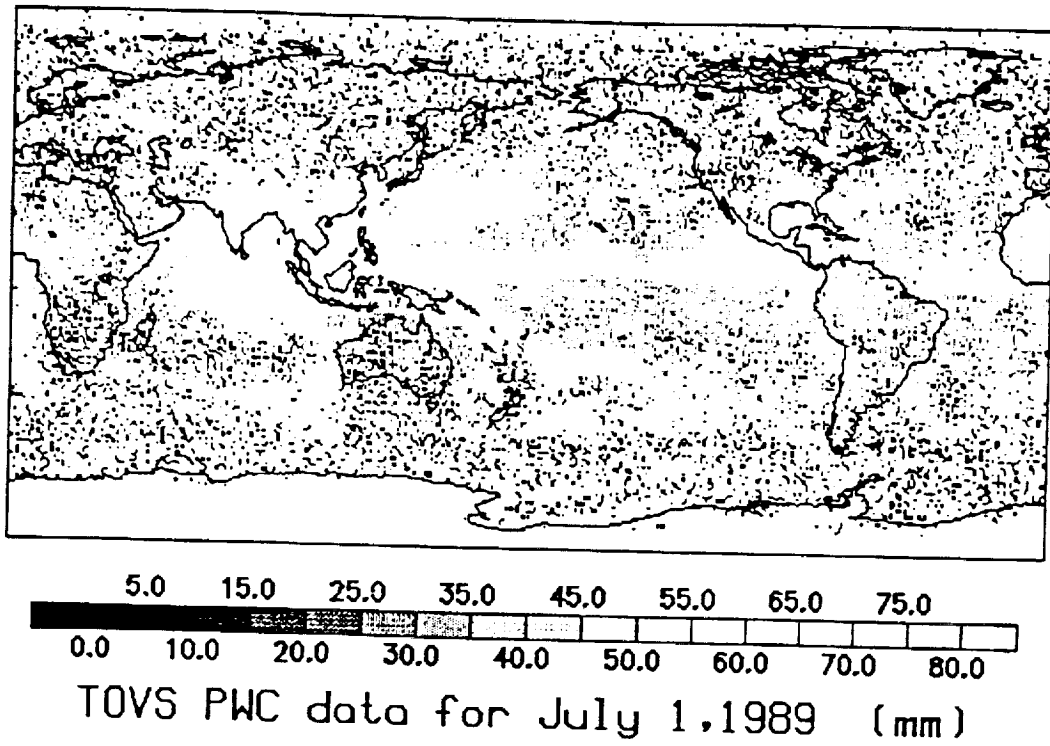


Figure 3.

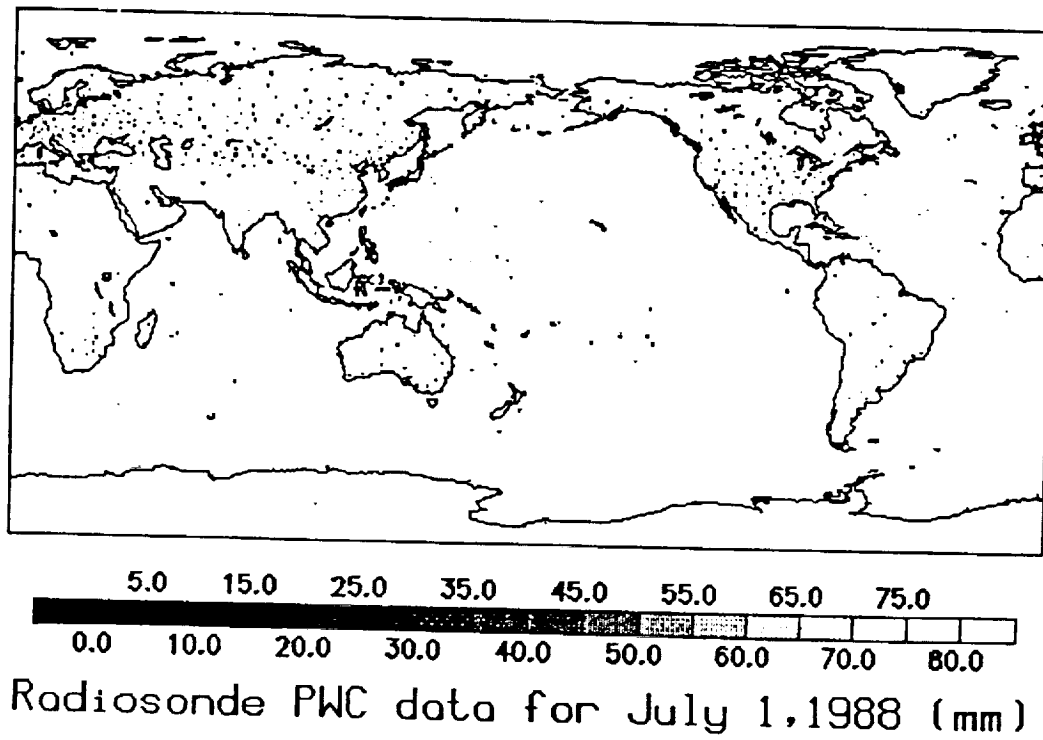
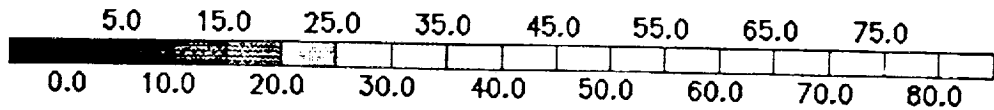
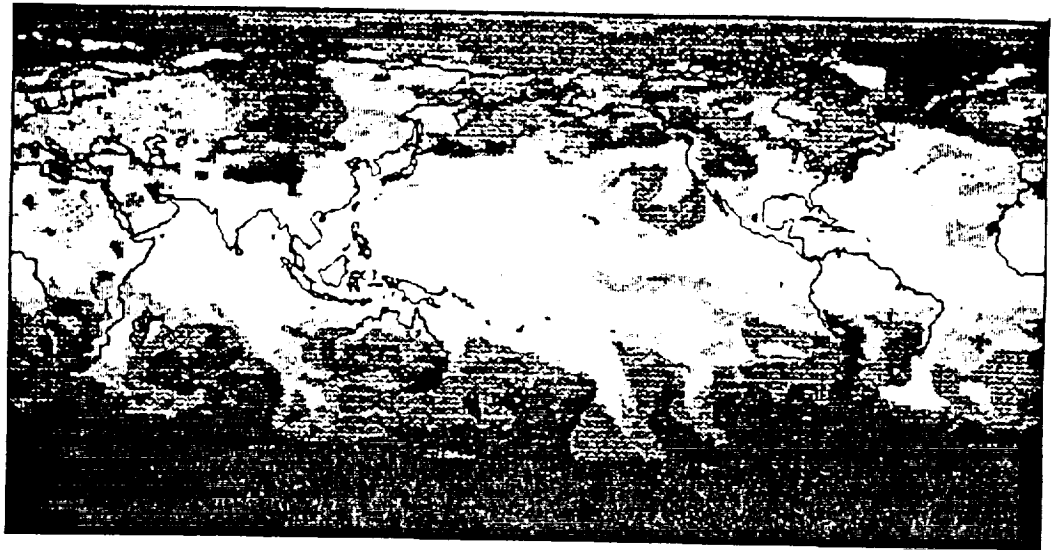


Figure 4.

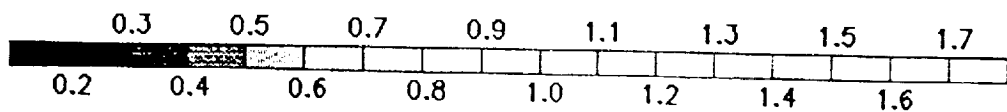
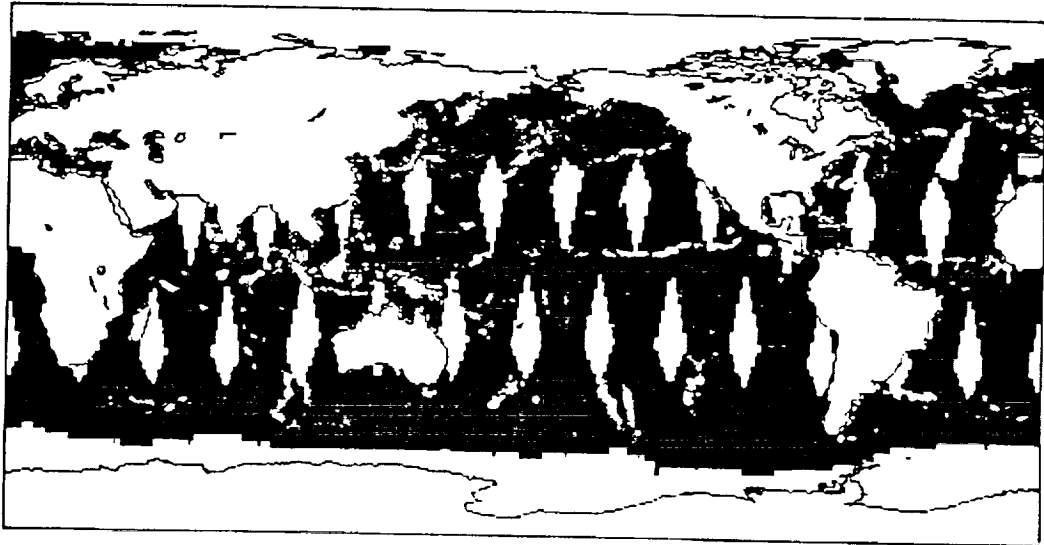


Integrated Precipitable Water (mm)

July 1, 1988

from: TOVS SSM/I Radiosonde

Figure 5.



Total Integrated Liquid Water (mm)

July 1, 1988

from SSM/I

4.0 ACKNOWLEDGMENTS

Data collection and processing for this project is currently sponsored by the National Aeronautics and Space Administration (NASA) (Contract No. NASW-4715).

5.0 REFERENCES

- Bannon, J.K. and L.P. Steele, 1960: Average Water Vapor Content of the Air. Geophysical Memoir No. 102, British Met. Office, London.
- Greenwald, T.J., G.L. Stephens, T.H. Vonder Haar, D.L. Jackson, 1992: A physical retrieval of cloud liquid water over the global oceans using SSM/I observations. J. Geophys. Res., Vol. 98, pp. 18,471-18,488.
- Oort, A.H., 1983: Global Atmospheric Circulation Statistics, 1958-1973 NOAA professional paper No. 14, 180 pp. + microfiche.
- Oort, A.H. and E.M. Rasmusson, 1971: Atmospheric Circulation Statistics. NOAA Professional Paper No. 5, Stock Number 0317-0045, 323 pp.
- Reynolds, R.W., 1988: A Real-Time Global Sea Surface Temperature Analysis. J. of Climate, Vol. 1, p. 7.
- World Climate Research Program, 1990: Scientific plan for the global energy and water cycle experiment, WMO/TD - No. 376, WMO, Geneva.

APPENDIX B



STC - METSAT
A division of Science and Technology Corp.

515 South Howes • Fort Collins, CO 80521
Phone (303) 221-5420 • Fax (303) 493-3410

Specializing in METeorological SATellite Systems and Related Computer Technology

94-101

FA 2.3 TOTAL AND LAYERED GLOBAL WATER VAPOR DATA SET

by

Thomas H. Vonder Haar, Donald L. Reinke, David L. Randel, Graeme L. Stephens,
Cynthia L. Combs, Mark A. Ringerud, Ian L. Wittmeyer and Thomas J. Greenwald
STC-METSAT
Fort Collins, Colorado, U.S.A.

June 1994

This paper was presented at the AMS Seventh Conference on Satellite Meteorology and Oceanography, Monterey, California, June 6-10, 1994.

TABLE OF CONTENTS

	<u>Page</u>
1.0 Introduction	1
2.0 Data Processing	2
3.0 Multi-Layer Water Vapor	3
4.0 Results	4
5.0 Conclusions	7
6.0 Acknowledgments	8
7.0 References	8

1.0 INTRODUCTION

The development of a complete and accurate global water vapor data set is critical to the adequate understanding of the Earth's climate system. Examples of climate research which are dependent on accurate water budget data include, but are not limited to: poleward energy transports, general circulation model (GCM) verification, and global change baseline measurements. During the next decade, many programs and experiments under the Global Energy and Water Cycle Experiment (GEWEX) (WCRP, 1990) will utilize present day and future data sets to improve our understanding of the role of moisture in climate, and its interaction with other variables such as clouds and radiation.

The need for improved knowledge of the global water vapor distribution is well documented. The majority of large-scale water vapor climatological studies have, to date, relied wholly upon analysis of radiosonde data (Bannon and Steele, 1960 and Oort, 1983). There are a number of new projects currently ongoing to better define the global water vapor climatology from both infrared and microwave space-based retrievals. Satellite based observations are critical to this climatology effort because the data collected at each radiosonde site may not be representative of the surrounding atmospheric conditions as significant humidity gradients exist between the limited resolution of stations. Analysis of such data sets tend to smooth out mesoscale gradients, which are important to the cloudiness, precipitation, and the radiation balance fields. Data gaps over the oceans and even some land areas limit the extent from which inferences may be made about the nature of the global water vapor distribution. Additional data sources, such as infrared and microwave satellite data sets, can greatly enhance the global coverage on a daily basis.

To satisfy these needs, STC-METSAT is producing a pre-GVaP, comprehensive, five year, 1x1 degree resolution, global water vapor data set of daily composites for use by the scientific research community using a combination of ground-based radiosonde data, and infrared and microwave satellite retrievals. These data are needed to provide the desired foundation from which future GEWEX-related research, can build upon.

The precipitable water (PWC) product is a weighted merge of DMSP Special Sensor Microwave/Imager (SSM/I) microwave retrievals, NOAA TIROS Operational Vertical Sounder (TOVS) infrared retrievals, and radiosonde data to produce an assimilated global product. The cloud liquid water (CLW) product is also vertically integrated based upon the bi-spectral polarization -- corrected method of Greenwald *et al.* (1993). At the present time it covers ocean areas only.

2.0 DATA PROCESSING

Three main steps are followed to produce the merged daily product for water vapor for the designated five year period. Input data is gathered and accessed in their raw form for step one. Processing to generate individual total column water vapor and quality control is done in step two. The final major processing task involves utilizing the individual output products as well as associated estimates of data quality in the generation of merged products. A combination of methods are used to generate the hybrid output global data set for water vapor.

This product is created by combining all three of the main input data sets, using a hierarchical weighting scheme. This algorithm uses radiosonde data when available as truth, and then applies a weighting scheme to the TOVS and SSM/I. Finally linear and temporal interpolation routines are run to fill missing data points. The final products from the processing are: complete global fields of liquid water content over the oceans from SSM/I, the merged precipitable water content from TOVS, SSM/I, and radiosonde, and a data origin map which is ordered by estimated data error in the merged field.

The data origin code map contains numbers representing, in order of lowest to highest confidence: Missing data; spatially interpolated, temporally interpolated; TOVS only; SSM/I interpolated; SSM/I interpolated/TOVS combination; SSM/I only; TOVS/SSM/I combination; radiosondes.

3.0. MULTI-LAYER WATER VAPOR

In order to study the important energy transport processes we need layer information as well as the total integrated water. We have developed a method to divide the total PWC into three layers. For the total PWC merged product, we use three input data sources, TOVS, radiosonde, and SSM/I retrievals. Two of these contain level information which can be used for multi-layer water vapor processing. TOVS PWC retrievals are reported at 3 layers: Surface - 700mb, 700mb - 500mb, and 500mb - 300mb. The global radiosondes PWC retrievals are divided to match these same layers. For each day, 3 global grids are formed of the Percent-Of-the-Total (POT) PWC in each of the three layers. Spatial and temporal interpolations are used to fill in missing data points. The assumption used in this method is that while the total and layered PWC can change rapidly, the POT in each layer is much more stable. The variability in the POT is a strong function of latitude and season and doesn't vary spatially as fast as the PWC. These POT fields are multiplied by the total PWC created in the SSM/I, TOVS, and radiosonde merged process and output as layered PWC global grids. Figure 1 shows a scatter plot of concurrent radiosonde and TOVS data points represented as the percentage of the total water vapor for the lowest layer for July, 1988. The scatter shows a good fit for combining the two data sets. From the general slope of the scatter we see that the TOVS data does not show as much lowest layer PWC as the radiosonde when there are high PWC values.

4.0 RESULTS

A total integrated PWC product for 1988 has been produced along with the three vertical levels of PWC products. Figure 2 shows the daily composites of the global average for the total PWC in millimeters over the entire year. It also shows the northern and southern hemispheric averages over the entire year. Figure 3 combines the global average total PWC with the three levels of global averages. Figure 4 has the total PWC plus the three level averages for the northern hemisphere (NH) and Figure 5 for the southern hemisphere (SH).

The seasonal variation of the global water vapor and some of the hemispheric differences is very evident in Figure 2. These variations were first reported by Wittmeyer and Vonder Haar (1994) using only the TOVS data. Basically, the global PWC averages have a sinusoidal maximum during June-July-August (JJA). The northern hemisphere values in Figure 2 has a maximum during its summer months, JJA, and minimum in the winter, December-January-February (DJF). The difference of the NH versus the southern hemisphere is significant. The range of NH averages is twice that of the SH, the summer maximum being much greater for the NH than the SH. This is mainly due to land/ocean differences – the NH contains most of the earth's land area. The large land areas produce much more of a seasonal temperature range than the oceans, colder in the winter and warmer in the summer. The amount of water vapor in the air is directly proportional to the temperature and availability thus helping to produce the larger NH seasonal range in combination with a strong summer seasonal maximum of convective clouds. Other factors include the severe summer monsoon season in India (NH) while the very cold and elevated Antarctic contributes very low water vapor concentrations in the SH.

The relative seasonal magnitudes of PWC is demonstrated in Figures 3, 4 and 5, at the three vertical levels. The plots show that more than 75% of the total PWC is below 700mb and more than 90% is below 500mb. The highest level shows more seasonal variability in the NH than the SH. The same with the mid level. Again, this would be due largely to the same northern and southern hemispheric differences mentioned above.

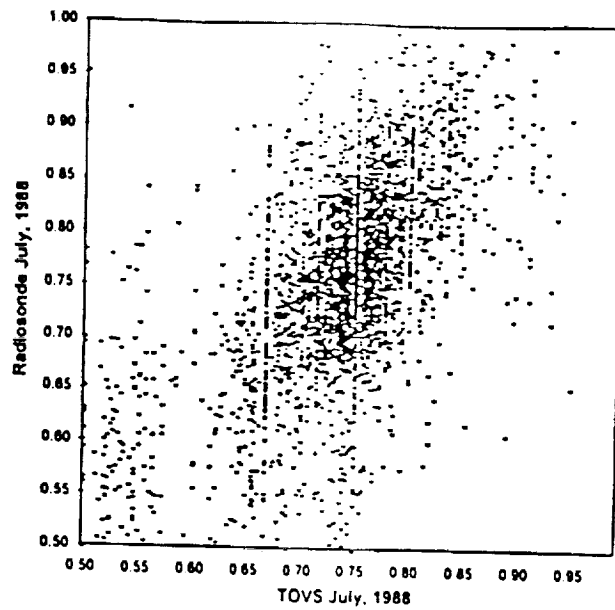


Figure 1. Surface-700mb Fraction of Total Precipitable Water Content.

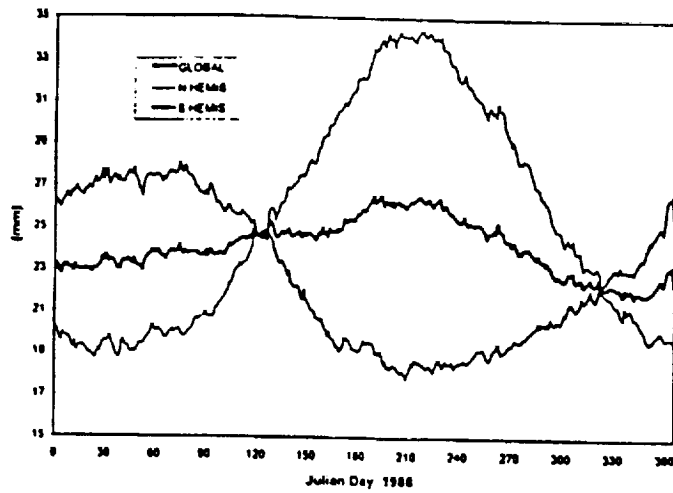


Figure 2. Total Precipitable Water (mm).

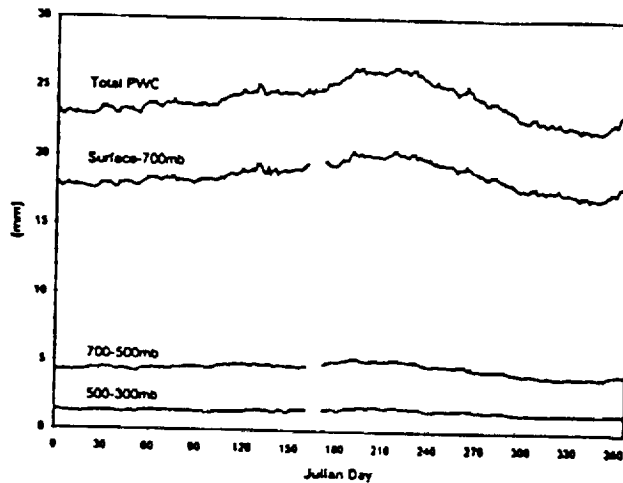


Figure 3. 1988 Global Average Precipitable Water Content.

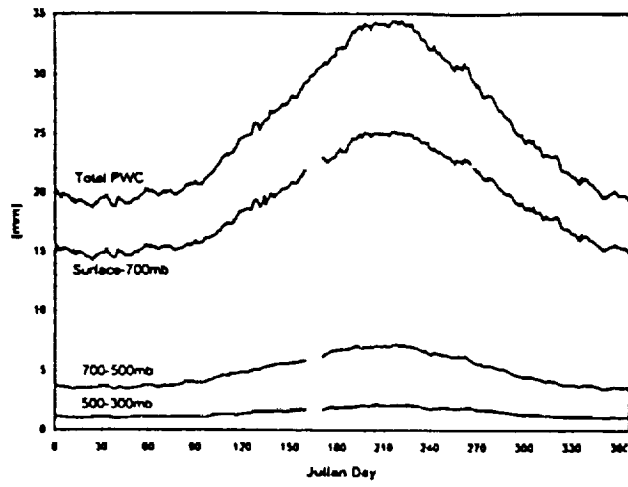


Figure 4. 1988 Northern Hemisphere Average Precipitable Water Content.

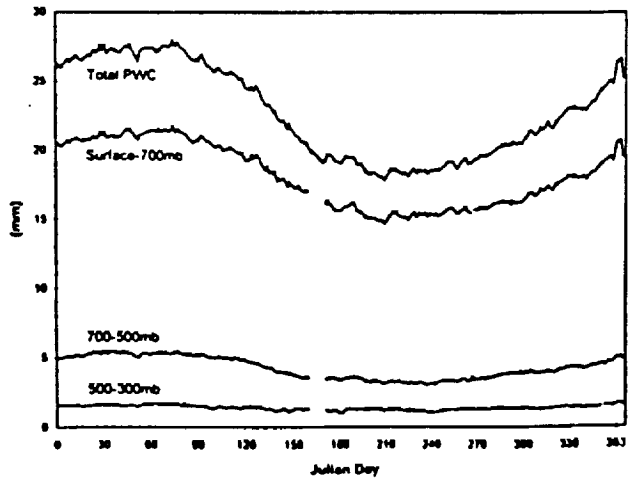


Figure 5. 1988 Southern Hemisphere Average Precipitable Water Content.

5.0 CONCLUSIONS

An exhaustive data set of global water vapor has been produced from three independent data sources. These products include total column integrated values and vertical layered values at three levels. Each of the individual input data sets has significant limitations: microwave retrievals are presently feasible only over oceans, infrared satellite techniques only work in absence of significant cloud cover, and radiosonde measurements are made primarily over land and are distant points, not showing small scale water vapor variations. A comprehensive global data set must draw upon the strengths of each of these methods, and utilize the advantages of each for all meteorological and geographical scenarios. The result is a combined product far better than any one single input data set. A method had been derived using the layered PWC from radiosondes and TOVS retrievals to create a 3-layer global PWC data set. By using this information along with the SSM/I PWC retrievals over ocean areas, we have produced an accurate global 3-layer data set. This complete five-year data set is scheduled to be delivered to NASA for use by climate researchers by the summer of 1995.

6.0 ACKNOWLEDGMENTS

Data collection and processing for this project is sponsored by the National Aeronautics and Space Administration (NASA) (Contract No. NASW-4715).

7.0 REFERENCES

- Bannon, J.K. and L.P. Steele, 1960: Average Water Vapor Content of the Air. Geophysical Memoir No. 102, British Met. Office, London
- Greenwald, T.J., G.L. Stephens, T.H. Vonder Haar, D.L. Jackson, 1992: A physical retrieval of cloud liquid water over the global oceans using SSM/I observations. *J. Geophys. Res.*, **98**, 18,471-18,488
- Oort, A.H., 1983: Global Atmospheric Circulation Statistics, 1958-1973 NOAA professional Paper No. 14, 180 pp. + microfiche
- Oort, A.H. and E.M. Rasmusson, 1971: Atmospheric Circulation Statistics. NOAA Professional Paper No. 5, Stock Number 0317-0045, 323 pp
- Wittmeyer, I.L. and T.H. Vonder Haar, 1994: Analysis of the global ISCCP TOVS water vapor climatology. *J. of Climate*, **7**, 325-333.
- World Climate Research Program, 1990: Scientific plan for the global energy and water cycle experiment, WMO/TD - No. 376, WMO, Geneva

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE June 1994	3. REPORT TYPE AND DATES COVERED Annual Report July 1993 - June 1994	
4. TITLE AND SUBTITLE Production of Long-Term Global Water Vapor and Liquid Data Set Using Ultra-Fast Methods to Assimilate Multi-Satellite and Radiosonde Observations		5. FUNDING NUMBERS Contract NASW-4715	
6. AUTHOR(S) Thomas H. Vonder Haar et al.			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Science and Technology Corporation-METSAT 515 South Howes Fort Collins, CO 80521		8. PERFORMING ORGANIZATION REPORT NUMBER STC Technical Report 2833	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546		10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION/AVAILABILITY STATEMENT		12b. DISTRIBUTION CODE	
<p>13. ABSTRACT (Maximum 200 words)</p> <p>In recent years climate research scientists have recognized the need for increased time and space resolution precipitable and liquid water data sets. This project is designed to meet those needs. Specifically, NASA is funding STC-METSAT to develop a total integrated column and layered precipitable water data set. This is complemented by a total column liquid water data set. These data are global in extent, 1° x 1° in resolution, with daily grids produced. Precipitable water is measured by a combination of <i>in situ</i> radiosonde observations and satellite derived infrared and microwave retrievals from 4 satellites. This project combines these data into a coherent merged product for use in global climate research.</p> <p>This report is the Year 2 Annual Report from this NASA-sponsored project and includes progress-to-date on the assigned tasks.</p>			
14. SUBJECT TERMS water vapor, TOVS, precipitable water content, liquid water content		15. NUMBER OF PAGES 41	16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT SAR