INVESTIGATION OF CLOUD PROPERTIES AND ATMOSPHERIC STABILITY WITH MODIS

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TASK OBJECTIVES

MAS TOGA-COARE Data Evaluation. The MAS (MODIS Airborne Simulator) data gathered during the TOGA-COARE (Tropical Ocean Global Atmosphere - Coupled Ocean Atmosphere Response Experiment) in Townsville 6 Jan to 23 Feb 1993 will be evaluated. Spectral channels were reconfigured to enhance cloud investigations with longwave CO2 channels (out to 13.9 microns). Fifteen successful missions were flown in varying cloud conditions (including Tropical Cyclone Oliver). Data should should be evaluated for instrument performance and meteorological information content.

Participation in SCAR. Plans for a SCAR (Smoke, Clouds, Aerosol, and Radiation) experiment will be finalized for Jul-Aug 1993 over the eastern United States. The MAS will be flown in coordination with AVIRIS on the ER-2 out of Wallops Island, VA to collect radiance measurements over thin cirrus clouds and aerosol haze.

Algorithm Definition. Using the MAS and HIRS (High resolution Infrared Radiation Sounder) data from FIRE (First ISSCP Regional Experiment) in Nov-Dec 1991, TOGA-COARE in Jan-Feb 1993, CEPEX in Mar 1993, and SCAR in Jul-Aug 1993, the algorithms for specifying cloud parameters (temperature, phase, height, and amount) and total ozone column will continue to be investigated. The physical retrieval of profiles of temperature and moisture with MODIS infrared data will be added to the study. The appropriate adjustments for signal noise, spatial resolution, and spectral resolution will be determined. Studies with the MAS and HIRS data are intended to yield the best preflight MODIS algorithms within the next year. A first draft of the Algorithm Theoretical Basis Document will be completed (one for cloud properties; another for atmospheric profiles and integrated column products).

Global Cloud Study. Pre-MODIS cloud studies should continue via the global cloud census with HIRS data.

MODIS Instrument Review. Tradeoffs between product accuracy and MODIS infrared calibration and spectral selection will continue to demand attention Simulations of MODIS products with MAS and HIRS data should continue to guide instrument developers.

WORK ACCOMPLISHED

MAS in SCAR. Plans for the Smoke, Clouds, Aerosol and Radiation (SCAR) experiments were finalized in the a two day meeting 27-28 April 1993 in Greenbelt, MD. Paul Menzel and Chris Moeller attended. The first phase was conducted 12-28 July 1993 from Wallops Island, VA; the second phase will take place August-September 1995 in Brazil. The goal is to study aerosol and cloud properties associated with biomass burning from airborne sensors and to compare with in situ measurements.

From 12-28 July, MAS on NASA's ER-2 aircraft flew a total of 7 data missions (July 12, 14, 16, 20, 22, 25, and 28) as part of the SCAR - America (SCAR-A) field campaign. The MAS instrument was supported on site by Chris Moeller of UW and Mike King of GSFC from July 9 - 23, and Liam Gumley (GSFC) from July 20 - 28. MAS data was collected over clear land, boundary layer cumulus, multilayer, and cirrus clouds. Flights were directed over automated sun-photometer sites (for aerosol optical depth estimates) and industrial sites such as power plants. Special flights were coordinated with Landsat (July 12, 28) and NOAA-11 (July 14, 22) overpasses, capturing both clear and cloudy scenes. The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) was also onboard the ER-2, collecting approximately one hour of data during each flight. The University of Washington C-131 aircraft coordinated with the ER-2 aircraft during portions of most data flights. On site data evaluation showed the MAS performed well, with instrument noise (10 bit data) of .3, .3, 1.3, and .3 K for the 8.6, 11.0, 13.2, and 12.0 micron channels respectively. Initial investigations will focus on the July 14 and 22 data sets, which are rich in cirrus and multilayer clouds.

<u>MAS Data Flights during CEPEX</u>. The MAS flew 11 successful data missions on the NASA ER-2 on March 3, 9, 12, 15, 16, 17, 21, 23, 25, 28, 31. For these missions MAS was configured with an ozone channel, CO_2 channels for cloud height, cloud particle phase channels, and cirrus detection channels (1.83 or 1.88 microns). The data set has many cloud scenes (optically thick and thin, single layer and multilayer) for CO_2 cloud height and tri-spectral studies. Thin cirrus scenes will be of particular interest for algorithm development; clear scenes will also be used to evaluate instrument performance.

<u>MAS TOGA Data Studies</u>. Chris Moeller and Paul Menzel were on site in Townsville, Australia to support MAS deployments in January and early February. The MAS flew successful data missions on the ER-2 on January 9, 12, 18, 19, 26 and February 1, 4, 7, 8, 10, 21, 22 and 23. Data collection included thick and thin cirrus, multilayer clouds, convective cumulus, and scenes over tropical storm Oliver. Inflight NEdT (noise equivalent temperatures) from January 26 data were .78, .24, .32, .51, 1.76, and 4.51 for the 3.7, 8.6, 11.0, 12.0, 13.2, and 13.9 micron channels respectively, confirming that the instrument was performing as expected during the deployment. MAS 1.83 micron data was verified to be doing a good job of discriminating high cirrus. A MAS TOGA-COARE Cloud Catalogue has been started; it will include low, middle, high and total cloud fraction, cloud top height and temperature, albedo, connectivity, and multilayering. A multispectral cloud classification was attempted for the MAS data from an adaptation of the GOES bi-spectral algorithm. Visible and infrared window data were used initially and the cloud albedo calculation was added through a bidirectional model and estimation of low reflectance cloud coverage (i.e. thin cirrus); clear sky scenes from the January 26 flight were used to define a visible clear scene threshold value, which is increased by about 5% to distinguish partly clouds scenes in an oceanic reflectance model. However, sunglint is posing problems for the cloud fraction determination.

Tri-spectral Algorithm Developments. The relationship between cloud parameters (type, amount, and phase) and the three infrared channels at 8, 11 and 12 microns was refined in several case studies using MAS, HIS (High resolution Interferometer Sounder), AVHRR (Advanced Very High Resolution Radiometer), and HIRS data. An automated algorithm has been tested for several different scenes. A technical paper describing this work is in final review for publication in the Journal of Applied Meteorology. See comments in section on Data/Analysis.

Global Cirrus Study with HIRS. Four year trends in global upper tropospheric semi-transparent cirrus cloud cover have been tracked using NOAA polar orbiting HIRS multispectral infrared data. Cloud occurrence, height, and amount have been determined with the CO2 slicing technique on four years of data (June 1989 - May 1993). Results indicate that there is a global preponderance of semi-transparent high clouds, presumed to be cirrus; 42% on the average. In the ITCZ a high frequency of cirrus (greater than 50%) is found at all times; a modest seasonal movement tracks the sun. Large seasonal changes in cloud cover occur over the oceans in the storm belts at midlatitudes; the concentrations of these clouds migrated north and south with the seasons following the progressions of the subtropical highs (anticyclones). More cirrus is found in the summer than in the winter in each hemisphere. The changes in cirrus cloud cover from year 1 to year 2 were insignificant, but the changes from year 2 to year 3 were very noticeable. Opaque cloud cover reduced by 7% globally, while cirrus cloud cover (most of it having effective emissivities less than 0.50) increased by 9%. Year 4 remained similar to year 3. While 1991 saw the eruption of Mt. Pinatubo and a significant El Nino event in the eastern Pacific, the cirrus has persisted well past this ENSO and volcanic period. A paper by Don Wylie, Paul Menzel, Harold Woolf, and Kathleen Strabala on this work has been submitted to the Journal of Climate. Present support for this work comes primarily from non-MODIS funds.

CO2 Slicing with MAS Data. The CO2 slicing heights (using the MAS 11, 13.3, and 13.9 micron channels) were compared to airborne lidar data (received from Jim Spinhirne) for 2335 UTC 17 Jan 93 during TOGA-COARE. Lidar height of thin cirrus was reported at 250 mb. Infrared window heights (unable to correct for the cloud semi-transparency) ranged from 355 to 590 in thick to thinner cirrus. CO2 heights in thick to thin cirrus ranged from 240 to 280 mb with effective emissivities of 77% to 42%. The comparison was very encouraging; further MAS CO2 investigations will be conducted before the algorithm is used routinely to process all TOGA-COARE data.

CO2 Slicing Tested in Two Layer Clouds. A two cloud layer CO2 slicing algorithm was developed and tested with HIRS data. Verification with lidar data and overlapping single cloud layers was accomplished. A five day global cloud census with and without the two cloud layer algorithm enhancement was processed and studied. Jason Li finished his Masters Thesis on this work. See comments in section on Data/Analysis.

Infrared Cloud Mask. An initial set of tests to screen for clouds in the infrared was forwarded to John Barker. The IR cloud mask is for single field of view (without consistency checks with nearest neighbors) over ocean; it must evolve to more sophisticated algorithms. Six multispectral cloud detection algorithms are suggested; all should be satisfied for clear determination. The first three attempt to correct window channel for moisture contamination, the fourth looks for broken or cirrus cloud, and the last two screen for cirrus. Over land these algorithms need corrections for surface emissivity; which will be addressed later.

MODIS Infrared Calibration Discussed. An initial set of measurements required to characterize the infrared calibration of the MODIS was presented at the Calibration Team Meeting. The ground testing must provide the following information: (1) spectral response for each IR detector/spectral channel combination, (2) calibration tests with several instrument thermal configurations, (3) stray radiation as a function of view angle, and (4) non linear response and measurement repeatability. This data will be used to calculate R=a+bC+qC2 for each thermal configuration for each detector for each spectral channel. In the process there will be an attempt to characterize changes in the nonlinearity of the calibration equation as a function of instrument temperature (q(T)) and to correlate with foreoptics temperatures. The cal algorithm mean and RMS errors with respect to the external target will also be calculated as a measure of cal performance. With enough data available, half the data will be used to specify the cal algorithm and the other half will be used to determine cal performance.

MODIS Algorithms Listed. The list of algorithms and products from the atmosphere group was reviewed once more at the March 1993 Science Team Meeting. Cloud top properties now refer to the cloud top pressure, cloud effective amount, and cloud top temperature which are all products from the same algorithm. Atmospheric profiles of temperature and moisture have been added to the product list; they will be produced by the same software that generates atmospheric stability, total ozone, and total precipitable water vapor. The initial guess field of surface temperature and pressure as well as vertical temperature and moisture profiles will be accessed from the operational National Meteorological Center global models. Data from the AIRS as available will be used for enhancement.

Processing Load Sized. An initial estimate of data input and output volumes was forwarded to SDST; additionally, a the number of Mflops required to process the 5 x 5 km data sets was sized from present experience using the McIDAS (Man computer Interactive Data Access System) at the University of Wisconsin. More iterations on these estimates will be necessary.

MAS Processing transferred to McIDAS-X RISC Environment. Chris Moeller has moved most of the algorithms for processing MAS data from the McIDAS mainframe to the McIDAS-X RISC environment. MAS calibration and navigation software are in place on the RISC. The transfer of existing MAS applications software to the RISC is nearly complete. This move will save considerably in mainframe CPU charges over the next 12 months.

DATA\ANALYSIS

Tri-spectral Study Accomplishments. Kathleen Strabala tested the tri-spectral technique on several MAS TOGA flight tracks. The simple thresholds of brightness temperature differences (8um - 11um, 11um - 12um), determined from the FIRE data over mid-latitude winter atmospheres, had to be adjusted for tropical atmospheres. A clustering analysis was added to improve cloud identification within the scatter diagram of these brightness temperature differences; it assisted considerably in identification of clear regions. The normalized 11 um brightness temperature was also added to the clustering analysis to further define cloud properties.

The problem of clear sky identification in the tri-spectral scatter diagram was further addressed via the development of regressions of the 8-11 micron and the 11-12 micron brightness temperature differences versus precipitable water (PW). The amount of PW in the atmosphere greatly affects the clear sky threshold due to differential water vapor absorption in the three bandwidths. Given an estimate of the PW, which can be related to the sea surface temperature (SST), the threshold can be adjusted for differing climate regimes. The regressions are based on results from globally processed HIRS data. An outline of the tri-spectral technique algorithm for implementation on MODIS data has been drafted. Work has begun on the final software development.

Zenith angle corrections were performed on TOGA MAS infrared data to determine the magnitude of water vapor absorption effects in the tropical atmosphere. Radiance differences of from 3.5 to 5 mW/(m^2 ster cm^{-1}) were found from nadir to limb (43 degree scan angle) on a clear scene from 18 January 1993. These tropical data sets must either be limb corrected or limited to near nadir scenes for use with the tri-spectral method. MAS FIRE data single sample noise for the tri-spectral channels (8, 11 and 12 microns) from 5 December 1991 at roughly 300 K were evaluated to be .64, .43 and .74 K NEDT (noise equivalent temperatures). Previous investigations indicated that cloud parameter delineation became possible when the data was averaged over a 5 x 5 box. This lowers the NEDT values to .13, .09 and .15 K for the 8, 11 and 12 micron data. The MODIS NEDT specifications for these infrared bandwidths at 300 K are .05 K. Based on these results, it appears that little or no averaging will be necessary for distinct cloud properties to become apparent when applying the tri-spectral technique to MODIS data.

The attached figure illustrates some of the properties of the tri-spectral technique. The MAS data from 00Z, 26 January 1993 contained 3 distinct cloud regimes; a cirrus cloud with varying emissivities (box A), a low level water cloud with 11 micron brightness temperatures between 280 and 285 K (box B), and a water cloud with a relatively higher level top as indicated by 11 micron brightness temperatures between 272 and 280 K, (box C). All three scenes were averaged over 10x10 MAS FOVs and plotted on a scatter diagram of 8-11 versus 11-12 micron brightness temperature differences (top right). The different cloud regimes separated into distinct regions on the scatter diagram. Water clouds have a stronger signal in the 11-12 micron differences, whereas ice clouds affect the 8-11 brightness temperature differences more. This is due to the basic properties of ice and water; the absorption coefficient of ice changes more between 8 and 11 microns than for water, while the opposite is true between 11 and 12 microns. The separation of the two water cloud layers in the scatter diagram, represent the potential for discerning multiple layers of similar phase cloud.

The tri-spectral technique has recently been compared to visible channel reflectance ratioing (1.6/.7 microns) in different cloud scenes. Results indicate that the visible ratioing performs best in single phase cloud scenes, while the tri-spectral infrared method distinguishes cloud phase more consistently in mixed cloud scenes. These results have been included in the paper "Cloud Properties Inferred from 8-12 micron Data", currently in final review for publication.

Developing a Two Cloud Layer CO2 Slicing Algorithm. The cloud forcing from two layers of clouds is greater than the cloud forcing from one layer; assuming only one cloud layer when two exist causes the CO2 solution to put the cloud between the two layers with larger effective emissivity. This suggests that, overall, global cloud parameter estimates using the one cloud layer CO2 slicing algorithm will be a little low in the atmosphere and with an effective emissivity a little too high. Work has progressed on determining cloud parameters in two layers of clouds. In a radiative model formulation the cloud amount and height for each layer is solved from radiance observations in the infrared window and the CO2 channels over clear and two cloud layer scenes. The two layer cloud forcing can be written as follows, where u indicates the upper cloud layer and l indicates the lower cloud layer,

$$R - R_{clr} = N_l E_l \, [1 - N_u E_u] \int_{p_s}^{p_{cl}} t \, dB + N_u E_u \int_{p_s}^{p_{cu}} t \, dB \,.$$

R is the observed radiance for the field of view, Rclr is a clear sky radiance, NE is effective emissivity of the fov, p_c is the cloud pressure, t is transmittance, and B is Planck function dependent on the temperature profile. Thus the two layer cloud forcing is characterized by four unknowns $N_l E_l$, $N_u E_u$, p_{cl}, and p_{cu}. Using the measured spectral cloud forcing in the CO2 channels, a solution for upper and lower cloud pressures and effective cloud amounts is calculated. The algorithm selects spectrally close pairs of CO2 channels. For each pair of cloud forcing measurements, all possible $N_l E_l$, $N_u E_u$ are calculated as a function of p_{cl}, p_{cu}. From this array of possible solutions, the selected solution best satisfies the radiative transfer equation for all spectral channels. Since four unknowns offer more degrees of freedom than two unknowns, the two layer solution is preferred over the one layer solution. Indication of when to use the two layer solution is sought through inspection of 4.0 micron versus 11.0 micron radiance scatter plots for the HIRS field of view (using AVHRR data). When radiances for the two spectral channels lie on two or more straight lines then the presence of two or more cloud layers is suggested. Constraints have been added to the two layer solution to keep the cloud layers 200 mb apart and to keep the upper layer thinner than the lower layer; the attempt is to highlight thin cirrus above lower opaque clouds. Verification with lidar data (from Jim Spinhirne) was accomplished; rms errors were 110 mb for the upper layer and 185 mb for the lower layer when the combined one and two layer algorithm was used. Considerably more development work remains, before the two layer solution can be incorporated into the cloud parameter algorithm.

Comparison of 1-layer and 2-layer CO2 solutions for five days of HIRS data spanning 17-21 April 1993 is shown in the following table. 71 % of the HIRS observations found cloud, and 43 % found semi-transparent cloud. Two layer solutions were preferred to one layer solutions for 21% of the semi-transparent clouds. The global cloud census with the two cloud layer enhancement showed 4% more high thin clouds and 3% more low thick clouds, at the expense of 3% fewer high thick clouds.

Table 1. Types of clouds found for one layer solution for 17-21 April 1993. hi (above 400 mb), mid (400 to 700 mb), low (below 700 mb), thin (NE < .5), thick (.5 < NE < .95), opaque (NE > .95).

	thin	thick	opaque
hi	19	14	2
mid	15	12	12
low	0	0	26

Table 2. Types of clouds found when one layer solution or two layer solution was used (59648 clouds)

	thin	thick	opaque
hi	22	11	1
mid	14	12	11
low	0	4	25

Table 3. Difference of Table 2 minus Table 1

	thin	thick	opaque
hi	3	-3	-1
mid	-1	0	-1
low	0	4	-1

Jason Li has completed his Masters Thesis on this work; the title is "A two layer model for altitude determinations from spaceborne infrared measurements". He is seeking employment with CSIRO in Australia.

ANTICIPATED FUTURE ACTIONS

Algorithm Definition. An initial version of the operational MODIS Airborne Simulator (MAS) cloud parameter code will be transferred to the Science Data Support Team this year. The atmospheric profile and integrated column software will take somewhat longer.

MAS/HIS Intercomparisons. The collocated HIS (High resolution Interferometer Sounder) data will be used for intercalibration of the two instruments (MAS and HIS) and for studying the spectral sensitivity of the cloud parameter algorithms.

Cloud Mask. Work will continue to refine cloud screening algorithms for different applications.

Investigating CO2 Slicing in Two Cloud Layers. The CO2 slicing algorithm will continue to serve as a test bed for modifications that will accommodate both single and multiple cloud layers. Several case studies of HIRS, AVHRR, and HIS data will be processed to converge on the best version of the algorithm.

PROBLEMS/CORRECTIVE ACTIONS

Telemail communications have mostly been reliable, with some notable exceptions (eg. reporting hardware plans for the next two years). If the issue is important enough, a fax message should supplement email to assure receipt of message and a timely reply.

The sizing of computer needs to process MODIS products needs to be an iterative dialogue between the team scientist and SDST. To date estimates have simply been forwarded. It may be useful for SDST to conduct a site visit to see the local processing environments and to clarify the sizing exercise.

PUBLICATIONS

Wylie, D. P., W. P. Menzel, H. M. Woolf, and K. I. Strabala, 1993: Four Years of Global Cirrus Cloud Statistics using HIRS. submitted to Jour. Clim.

Schreiner, A. J., D. A. Unger, W. P. Menzel, G. P. Ellrod, K. I. Strabala, and J. L. Pellet, 1993: A Comparison of Ground and Satellite Observations of Cloud Cover. submitted to Bull. Amer. Meteor. Soc.

Strabala, K. I., S. A. Ackerman, and W. P. Menzel, 1993: Cloud Properties Inferred from 8-12 micron Data. in final review by to Jour. Appl. Meteor.

Nieman, S. A., J. Schmetz, and W. P. Menzel, 1993: A Comparison of Several Techniques to Assign Heights to Cloud Tracers. accepted by to Jour. Appl. Meteor.

Menzel, W. P., D. P. Wylie, and K. I. Strabala, 1993: Trends in Global Cirrus Inferred from Three Years of HIRS Data. Technical Proceedings of the Seventh International TOVS Study Conference (Igls, Austria)

Li, J., 1993: A two layer model for altitude determinations from spaceborne infrared measurements. Masters Thesis (University of Wisconsin - Madison).

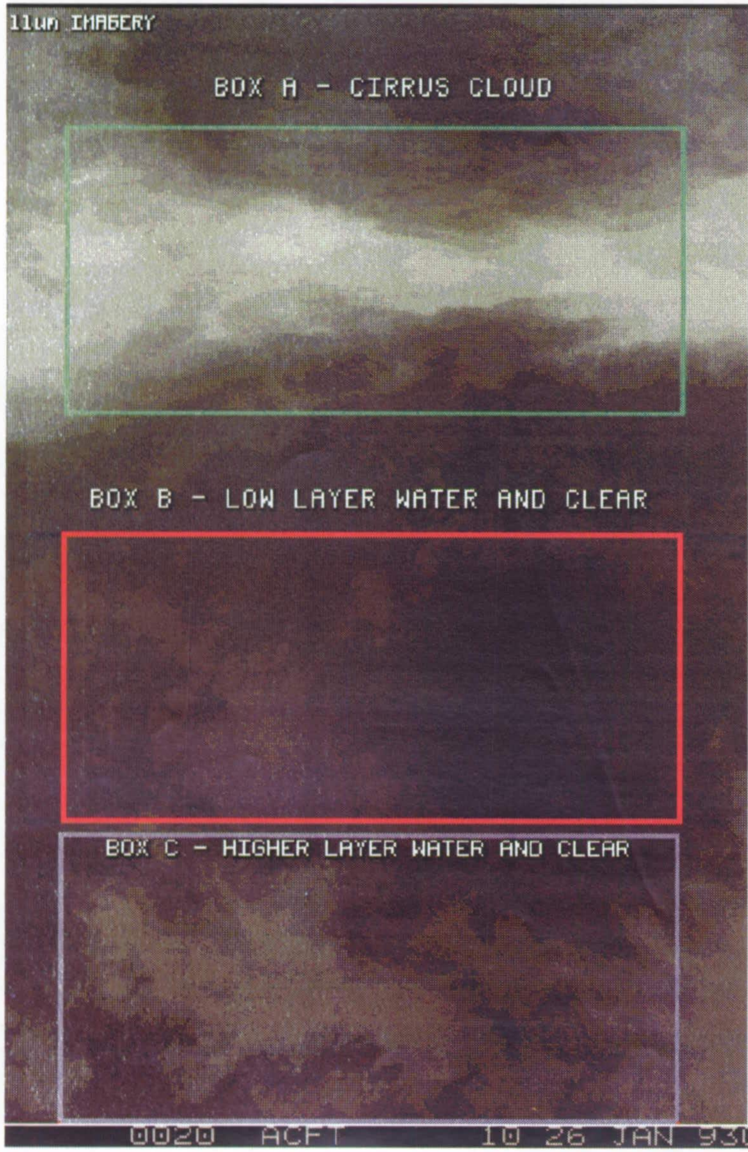
SEMINARS

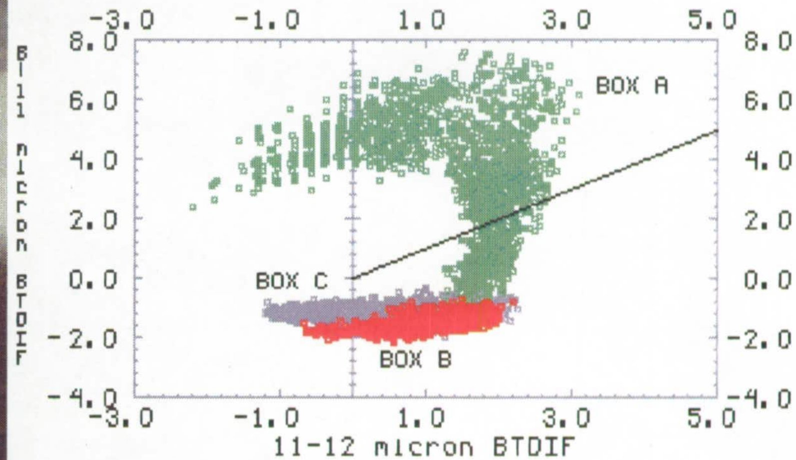
P. Menzel presented a paper on 11 February on "HIRS Cloud Studies" at the 7th International TOVS Study Conference in Igle, Austria

P. Menzel gave a seminar at GSFC on 28 April on "Trends in Global Cirrus Inferred from Four Years of HIRS Data".

P. Menzel gave a presentation on "HIRS/AVHRR Study of Clouds" on 29 June at the 6th European AVHRR Users Conference in Belgirate, Italy.

P. Menzel gave a seminar at the ECMWF on 20 July on "Trends in Global Cirrus Inferred from Four Years of HIRS Data".





MAS TRI-SPECTRAL

BRIGHTNESS TEMPERATURE DIFFERENCING

AS A MEANS OF CLOUD DETECTION

USING TOGA/COARE DATA
FROM 26 JAN 93 AT 00Z

* BOXES AT RIGHT CORRESPOND TO GROUPINGS ON SCATTER DIAGRAM ABOVE
* ICE CLOUD SIGNAL LARGER IN 8-11um BTDIF
* WATER CLOUD SIGNAL LARGER IN 11-12um BTDIF
* TWO DISTINCT WATER CLOUD LAYERS APPARENT IN SCATTER DIAGRAM