

Space Science and Engineering Center
University of Wisconsin-Madison

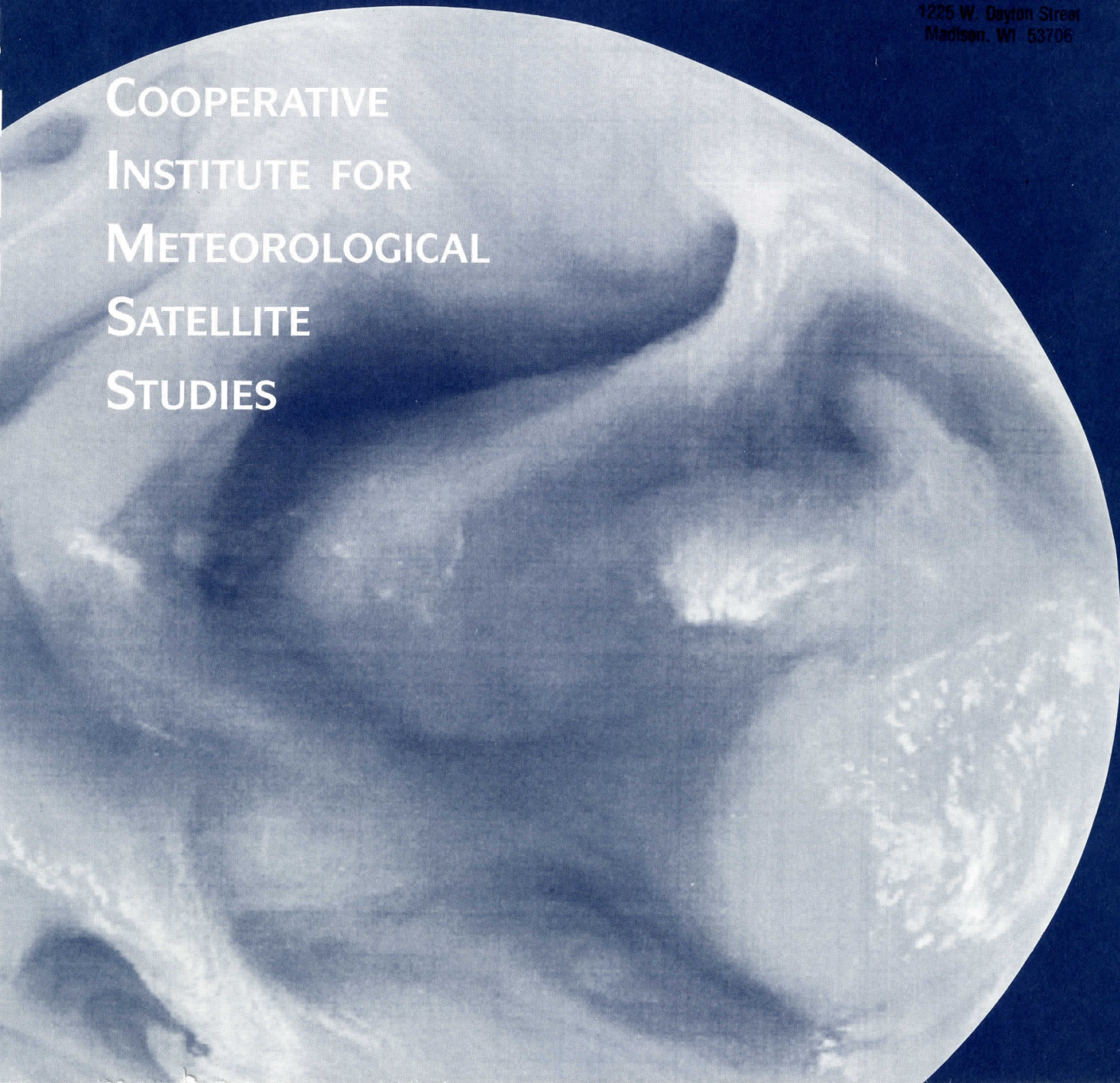
UW-Madison.
SSEC Publication No.97.12.S1.

Final Report for NOAA Grant NA36GP0481; Global Water Vapor
Covering the period 9/1/93-2/29/96

A REPORT from the

COOPERATIVE
INSTITUTE FOR
METEOROLOGICAL
SATELLITE
STUDIES

THE SCHWERDTFEGGER LIBRARY
1225 W. Dayton Street
Madison, WI 53706



THE SCHWERDTFEGER LIBRARY
1225 W. Dayton Street
Madison, WI 53706

**Final Report for NOAA Grant NA36GP0481; Global Water Vapor
Covering the period 9/1/93-2/29/96**



SPACE SCIENCE AND ENGINEERING CENTER

UNIVERSITY of WISCONSIN – MADISON
1225 West Dayton Street
Madison, Wisconsin 53706-1695

2 December 1997

Mr. Michael J. Coughlan/
Ms. Irma DuPree
NOAA Office of Global Change
1100 Wayne Avenue
Suite 1210
Silver Spring, MD 20910

Re: NA36GP0481 Reports


Dear Mr. Coughlan and Ms. DuPree:

Enclosed please find the reports which you requested on the Cooperative Agreement referenced above. The project is titled: "Global Water Vapor: A Core Proposal for an Approach to Reliable Observation and Understanding". The investigators are Professors William L. Smith and Donald R. Johnson.

The reports are for the periods of: 1) 1 September 1994 - 30 September 1995;
2) 1 October 1995 - 29 February 1996; 3) the final, covering the entire project of
1 September 1993 - 29 February 1996.

If you have any questions or concerns, please contact me at (608)262-0985 or Polly Ruff at (608)263-3037.

Sincerely,



John P. Roberts
Assistant Director

Enc.

cc: 3550
144DX09
T. Achtor
M. Pittman, Grants

k:\admin\3550rpt.doc

**Final Report for NOAA Grant NA36GP0481; Global Water Vapor
Covering the period 9/1/93-2/29/96**

This final report summarizes the UW-Madison studies of global water vapor issues, including modeling studies, software development and participation in the ASHOE/MAESA (Airborne Southern Hemisphere Ozone Experiment / Measurements for Assessing the Effects of Stratospheric Aircraft) field program. The grant to UW-Madison consisted of two separate activities; one activity supported software development for and the participation of the High resolution Interferometer Sounder (HIS) aboard the ER-2 aircraft in the data gathering campaign. The second activity supported global hydrologic cycle modeling and onsite forecasts of isentropic atmospheric structure and circulation in support of the ER-2 flights. Results of all activities are summarized below with additional information included as attachments. Attachment #1 contains the Annual Reports for both activities of this grant. There have been numerous publications of results from this grant; several of these are cited in the reference list at the end of this report.

1. HIS software development and field program participation during ASHOE/MAESA

Initial work for this grant included software development to improve the vertical water vapor profile retrievals from the HIS instrument radiance spectra, using data obtained from previous field experiments. Two key issues were the spectroscopic uncertainties and the non-linearity of the algorithm. Spectroscopic uncertainties refer to errors in the basic absorption line parameter and continuum approximations used to calculate the spectrum of atmospheric transmittance as a function of water vapor concentration. The algorithm non-linearity refers to methods to overcome the difficulties when using inverse solution methods to the radiative transfer equation. Mathematical techniques were developed with support from this grant to create a robust, non-linear solution for the HIS retrieval algorithm. Considerable work was done in these areas, as detailed in attachment #1 (first year Interim Report) and described below.

ASHOE/MAESA was sponsored by NASA, NOAA, NSF and others to address questions about the causes of the year round mid latitude ozone loss observed in the Southern Hemisphere (S.H.) in the last 15 years. A major goal of these programs was to gain an understanding of the composition of the lower stratosphere and its consequent effects on the radiative balance of the atmosphere. To support this and other requirements, flights of the NASA ER-2 high altitude aircraft were conducted to provide observations from which to diagnose the chemistry, physics and motion of the air in the lower stratosphere and troposphere. Measurements were made at four separate time periods; March, June, August and October to capture the seasonal cycle of S.H. circulation.

The UW-Madison HIS instrument participated in all four phases of the dynamics and radiation field campaign aboard the ER-2 aircraft. Table 1 summarizes the data gathering flights made from Christchurch, New Zealand (NZCH), primarily flying south into the polar vortex.

This grant provided support in years two and three for the deployment of the HIS science and technical support team to Ames Research Center for pre-experiment instrument checkout and to Christchurch, New Zealand on four separate occasions for the measurement campaign. Partial support to CIMSS for deployment in the field phase of ASHOE/MAESA was also provide by NASA.

**Annual Report for NOAA Grant NA36GP0481
Covering the period 9/1/94-9/30/95**

This annual report summarizes the UW-Madison participation in the ASHOE/MAESA (Airborne Southern Hemisphere Ozone Experiment / Measurements for Assessing the Effects of Stratospheric Aircraft) field program, supported by NOAA Grant NA36GP0481. There were two separate activities supported by this grant; one activity supports the participation of the High resolution Interferometer Sounder (HIS) aboard the ER-2 aircraft in the data gathering campaign, and the other activity supports onsite forecasts of isentropic atmospheric structure and circulation in support of the ER-2 flights and modeling the global hydrologic cycle.

1. HIS field program participation during ASHOE/MAESA

ASHOE/MAESA was sponsored by NASA, NOAA, NSF and others to address questions about the causes of the year round mid latitude ozone loss observed in the Southern Hemisphere (S.H.) in the last 15 years. A major goal of these programs was to gain an understanding of the composition of the lower stratosphere and its consequent effects on the radiative balance of the atmosphere. To support this and other requirements, flights of the NASA ER-2 high altitude aircraft were conducted to provide observations from which to diagnose the chemistry, physics and motion of the air in the lower stratosphere and troposphere. Measurements were made at four separate time periods; March, June, August and October to capture the seasonal cycle of S.H. circulation.

The UW-Madison HIS instrument participated in all four phases of the dynamics and radiation field campaign aboard the ER-2 aircraft; the first three phases were during the period covered in this report. Table 1 summarizes the data gathering flights made from Christchurch, New Zealand (NZCH), primarily flying south into the polar vortex.

Summary of UW HIS Experiment Data Collection Flights during ASHOE/MAESA

<u>Date</u>	<u>Launch – Return time</u>	<u>Flight Location</u>	<u>Mission</u>
04/13/94	1930 - 0330 UTC	NZCH - 68S	Antarctic vortex
04/15/94	0052 – 0350 UTC	NZCH – 38S	Volcano overflight
06/05/94	2000 - 0200 UTC	NZCH – 68S	Antarctic vortex
06/08/94	2000 – 2100 UTC	NZCH – 45S	Test flight
08/08/94	2200 – 0620 UTC	NZCH – 69S	Antarctic vortex
08/10/94	2100 – 0430 UTC	NZCH – 67S	Antarctic vortex
10/03/94	2130 – 0530 UTC	NZCH – 68S	Antarctic vortex
10/05/94	2100 – 0445 UTC	NZCH – 65S	Antarctic vortex

This grant provided support for the deployment of the HIS science and technical support team to Ames Research Center for pre-experiment instrument checkout and to Christchurch, New Zealand on four separate occasions for the measurement campaign. Partial support to CIMSS for deployment in the field phase of ASHOE/MAESA was also provide by NASA.

From the HIS measurements taken during the ASHOE/MAESA field campaign, software developed under year 1 funding was applied to the HIS radiance spectra to calculate temperature, moisture and ozone structure in the upper troposphere and lower stratosphere. The vertical profiles below the ER - 2 are computed from the HIS radiance observations using a retrieval method which is totally independent of contemporary meteorological data and as such the results are totally independent of the numerical model analyses which are to be validated. HIS temperature and water vapor profile data were used to validate the thermodynamic characteristics of global data assimilation / forecast models that provide the global circulation patterns used to analyze the transport of the constituents associated with the Ozone depletion process. HIS temperature and moisture retrievals were also used to calculate atmospheric cooling rates, which were compared to cooling rates calculated using input from global forecast models. As the time period for this report covers the field phase of ASHOE/MAESA, results of the data analysis efforts will be provided in the final report.

2. Isentropic model forecast support during ASHOE/MAESA

As part of the 1994 Airborne Southern Hemisphere Ozone Experiment /Measurement for Assessing the Effect of Stratospheric Aircraft (ASHOE/MAESA) program under the direction of Dr. Adrian Tuck of the NOAA Aeronomy Lab, the UW θ - σ modeling group under Professor Donald Johnson's direction was deployed to provide onsite forecasts of isentropic atmospheric structure and circulation in support of ER-2 flights carried out from Christchurch, New Zealand during the four Intense Observation Periods (IOPs). Daily 0 to 84 hour forecasts of tropospheric/stratospheric winds, temperature, water vapor, potential vorticity and corresponding transport processes were provided to determine the most beneficial flight path for each mission.

Several events during the IOPs were selected for scientific study. Emphasis was placed on investigating the Southern Hemisphere hydrologic cycle and the role of amplifying baroclinic waves on the meridional transport of water vapor, ozone and other trace constituents. Comparisons were made with corresponding forecasts from the nominally identical UW sigma coordinate model in order to investigate the impact of the vertical coordinate on simulation of atmospheric circulation and hydrologic processes.

An experiment was initiated to examine the relative capabilities of isentropic and sigma coordinate models to conserve joint distributions of potential vorticity (PV) and trace constituent transport for an ASHOE IOP using simulations from the UW θ - σ and σ coordinate models and the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM2). An initial proxy distribution of ozone (O_3) was specified analytically as a function of the initial PV on each model level. The capability of a model to retain a correlation of unity through the integration is a measure of its predictability of transport processes within the atmospheric continuum. At and above 370 K, the UW θ - σ model correlations remained above 0.99 throughout the 10-day simulation while correlations in the UW σ model simulation decreased to 0.50 by day 10 in the lower stratosphere. The corresponding correlations in simulations from CCM2, a state of the art climate model, decreased to near 0.95 in the low stratosphere at day 10. The correlations in the upper troposphere were further reduced in CCM2 compared to the UW θ - σ model with some decreasing to 0.6. These results, presented in Zapotocny et al. (1996a), document the superior conservation characteristics in the upper troposphere and lower stratosphere of models based on isentropic coordinates.

**Annual Report for NOAA Grant NA36GP0481
Covering the period 10/1/95-2/29/96**

This annual report summarizes the UW-Madison participation in the ASHOE/MAESA (Airborne Southern Hemisphere Ozone Experiment / Measurements for Assessing the Effects of Stratospheric Aircraft) field program, supported by NOAA Grant NA36GP0481. There were two separate activities supported by this grant; one activity supports the participation of the High resolution Interferometer Sounder (HIS) aboard the ER-2 aircraft in the data gathering campaign, and the other activity supports onsite forecasts of isentropic atmospheric structure and circulation in support of the ER-2 flights and modeling the global hydrologic cycle.

1. HIS field program participation during ASHOE/MAESA

The UW-Madison HIS instrument participated in all four phases of the dynamics and radiation field campaign aboard the ER-2 aircraft, the fourth and final phase occurred during the period covered in this report. The October HIS flights were included in order to characterize the polar vortex during the period of maximum ozone depletion. Table 1 summarizes the data gathering flights made from Christchurch, New Zealand (NZCH), primarily flying south into the polar vortex.

Summary of UW HIS Experiment Data Collection Flights during ASHOE/MAESA

<u>Date</u>	<u>Launch - Return time</u>	<u>Flight Location</u>	<u>Mission</u>
04/13/94	1930 - 0330 UTC	NZCH - 68S	Antarctic vortex
04/15/94	0052 - 0350 UTC	NZCH - 38S	Volcano overflight
06/05/94	2000 - 0200 UTC	NZCH - 68S	Antarctic vortex
06/08/94	2000 - 2100 UTC	NZCH - 45S	Test flight
08/08/94	2200 - 0620 UTC	NZCH - 69S	Antarctic vortex
08/10/94	2100 - 0430 UTC	NZCH - 67S	Antarctic vortex
10/03/94	2130 - 0530 UTC	NZCH - 68S	Antarctic vortex
10/05/94	2100 - 0445 UTC	NZCH - 65S	Antarctic vortex

HIS measurements taken during the final phase of ASHOE/MAESA used software developed under year 1 funding, applying the HIS radiance spectra to calculate temperature, moisture and ozone structure in the upper troposphere and lower stratosphere. HIS temperature and water vapor profile data were then used to validate the thermodynamic characteristics of data assimilation models that provide the global circulation patterns used to analyze the transport of the constituents associated with the Ozone depletion process. HIS temperature and moisture retrievals were also used to calculate atmospheric cooling rates, which were compared to cooling rates calculated using input from global forecast models. Results of the ASHOE/MAESA data analysis are provided in the final report.

2. Isentropic model forecast support during ASHOE/MAESA

Research over this five month period investigated the global hydrologic cycle with emphasis on the Southern Hemisphere circulation. The focus was to understand the underlying reasons for the relatively limited progress being made in the prediction of the atmosphere's hydrologic processes, cloudiness and energy exchange. The consensus of modelers utilizing σ coordinates is that with improved parameterization and increased resolution, the predictability of both weather and climate will improve. However, attempts to improve simulations through improving parameterizations have had limited success and the results from climate models with resolutions greater than T42 (or T63) do not demonstrate the expected improvements.

As a continuation of this effort, a second experiment examined the conservation capability of models to appropriately conserve properties. In a series of simulations, this experiment which is extremely pertinent to the hydrologic cycle compared the UW θ - σ and σ models, and the NCAR CCM2 abilities to conserve equivalent potential temperature (θ_e) during 10 day integrations under both dry and reversible moist adiabatic processes. Non-conservation of θ_e constitutes an error that seriously degrades a model's ability to simulate the full range of the atmosphere's hydrologic processes. The initial θ_e distribution from ASHOE IOP data was inserted as a trace constituent in each model. The models were then integrated to 10 days and conservation examined. The correlations remain higher in the UW θ - σ model than in the other two models. The results of these numerical experiments documented inherent advantages of modeling hydrologic processes in isentropic coordinates and demonstrated the potential for advancing the understanding and modeling of the hydrologic cycle, energy exchange and regional climate. Results from this experiment are presented in Zapotocny et al. (1996b).

Summary of UW HIS Experiment Data Collection Flights during ASHOE/MAESA

<u>Date</u>	<u>Launch - Return time</u>	<u>Flight Location</u>	<u>Mission</u>
04/13/94	1930 - 0330 UTC	NZCH - 68S	Antarctic vortex
04/15/94	0052 - 0350 UTC	NZCH - 38S	Volcano overflight
06/05/94	2000 - 0200 UTC	NZCH - 68S	Antarctic vortex
06/08/94	2000 - 2100 UTC	NZCH - 45S	Test flight
08/08/94	2200 - 0620 UTC	NZCH - 69S	Antarctic vortex
08/10/94	2100 - 0430 UTC	NZCH - 67S	Antarctic vortex
10/03/94	2130 - 0530 UTC	NZCH - 68S	Antarctic vortex
10/05/94	2100 - 0445 UTC	NZCH - 65S	Antarctic vortex

From the HIS radiance measurements, several products were created for and delivered to the ASHOE/MAESA data archive. Attachment 2 contains a summary of the HIS data collected, quality controlled and delivered to the ASHOE/MAESA science office. Data records include: aircraft altitude (m) and navigation data, HIS brightness temperatures (K), and retrieved temperature (K), water vapor mixing ratio (g/kg), ozone mixing ratio (ppMV), cooling rate (K/day), potential temperature (K), and surface skin temperature (K).

HIS Spectra

The base measurement from HIS is radiance spectra from 600 to 2600 wave numbers (3.8 to 16 microns). Figure 1 shows an example of the HIS brightness temperature spectra from 8 August 1994. Atmospheric absorption bands and window regions are noted. Figure 2 is a detail of this spectra in the ozone absorption band, indicating the large brightness temperature difference between 48 S latitude (New Zealand) and 66S latitude, which is well within the polar vortex and the Southern Hemisphere ozone hole. Figure 3, a detail of the CO₂ absorption band and adjoining atmospheric window, shows the effects on the HIS measurements from 'regular' and very thick cirrus clouds.

Temperature and Moisture Retrieval

From the HIS measurements taken during the ASHOE/MAESA field campaign, software developed under year 1 funding was applied to the HIS radiance spectra to calculate temperature, moisture and ozone structure in the upper troposphere and lower stratosphere. The vertical profiles below the ER - 2 are computed from the HIS radiance observations using a retrieval method which is totally independent of contemporary meteorological data and as such the results are totally independent of the numerical model analyses which are to be validated. Attachment 3 is a summary of the HIS thermodynamic retrieval algorithm, much of the work completed during year 1 of this grant. Figure 4 shows a cross section of HIS derived temperature along the ER-2 flight path from Christchurch, New Zealand toward Antarctica and returning to Christchurch for two days in August 1994. Of importance here is the rapid expansion of cold air in the upper troposphere from day 220 to day 222 (note the northward movement of the 216K and 220K

contours as depicted by the HIS temperature retrieval. Figure 5 is an example of the HIS temperature and water vapor mixing ratio retrieval from day 222. Note the ability of the HIS data and retrieval algorithm to depicted water vapor structure through a deep layer of the atmosphere. These retrievals were performed without selection of cloud free views or cloud clearing techniques, but display good skill down to the cloud top. The presence of low cloud layers is evidenced by isothermal retrievals in these regions. Figure 6 is a comparison for days 220 and 222 between a radiosonde temperature sounding and the nearest HIS retrieval (in space and time). HIS captures the strong cooling taking place throughout the troposphere with the expansion of the polar vortex (indicated in figure 4).

Comparison to Operational Forecast Models

The HIS temperature and water vapor profiles were then used for comparison/validation of forecast models that provide the global circulation patterns used to analyze the transport of the constituents associated with the Ozone depletion process. In the Southern Hemisphere there are few radiosonde measurements. Upper air forecast model analysis relies heavily on retrievals from the NOAA TOVS. Figures 7 is an example of the data; the upper panel of Figure 7 depicts the HIS and TOVS retrieved temperature for day 222/223 along the ER-2 flight line. The days are different due to the varying times of TOVS overpasses; this being the closest NOAA pass in time. Noteworthy is the increased detail of the upper air temperature structure from the HIS, compared to the TOVS. Also note the similarity of the independent HIS temperature retrieval to the ECMWF (European model) and GASP (Australian model) thermal structure on day 222/23, and also the increased detail from the HIS analysis. While the models tend to smooth out features, the HIS more accurately depicts the cold upper tropospheric vortex described above. Additional detail is provided in Attachment #4, which is a conference report on these activities.

HIS radiance measurements and retrieval methods also produce ozone mixing ratio profiles along the ER-2 flight path. Figure 8 clearly shows the Southern Hemisphere Ozone hole (minimum) as the ER-2 entered the polar vortex circulation. Figure 9 shows comparisons for four days between HIS derived total ozone retrieval and in situ ozone measurements from the ER-2 ozone dual beam UV photometer. This data is a real vertical profile along ER-2 ascending and descending tracks. Of note is the similarity of the profile characteristics between the independent measurements from HIS and the UV instrument.

Cooling Rates

HIS temperature and moisture retrievals were also used to calculate atmospheric cooling rates, which were compared to cooling rates calculated using input from global forecast models. Cooling rates were calculated for ASHOE/MAESA in order to understand the transport dynamics of ozone poor air and relate the cooling rates to circulations about the Southern Hemisphere circumpolar vortex (see the Attachment #5, a conference preprint by Lee, et. al. for details). Figure 10 shows the layer mean cooling rate attributed to various atmospheric constituents. These calculations indicate that water vapor is the dominant constituent contributing to heat flux in the upper troposphere. Even in the lower stratosphere, where water vapor only exists in small quantities the CO₂ cooling rate is relatively large, indicating the cooling from water vapor is important. Since the global forecast models tend to underestimate the amount of water vapor in the region, these models also under represent the cooling rates. Finally, Figure 11 shows the spectral cross sectional cooling rate from the seven optically active infrared gasses, as measured by the HIS

Summary of HIS activities

The UW-Madison CIMSS activities for NOAA Grant NA36GP0481 provided for research and field campaign activities in support of global water vapor and ozone measurements. Research into advanced algorithm development provided for improved atmospheric retrieval of temperature, moisture, ozone, and cooling rates, and thus allow a validation of the accuracy of global forecast models along the ER-2 flight path. Support for the field phase of ASHOE/MAESA enabled the HIS instrument team to participate in the all phases of the program, collect and quality control the data, and do post-experiment data analysis. The final data sets were provided to the ASHOE/MAESA program office.

2. Isentropic model forecast support during ASHOE/MAESA

The principal goals of research under NOAA grant NA36GP0481 were to: (1) provide onsite forecasts of isentropic atmospheric structure and circulation in support of ER-2 flights during the Intense Observation Periods (IOPs) of the 1994 Airborne Southern Hemisphere Ozone Experiment / Measurement for Assessing the Effect of Stratospheric Aircraft (ASHOE/MAESA) program, (2) simulate and analyze the global atmospheric hydrologic cycle including the transport of dehydrated polar air into lower latitudes and the intrusion of tropospheric water vapor into the stratosphere, and (3) investigate the capabilities of numerical models based on different numerical schemes and coordinate systems to conserve atmospheric properties, especially water vapor.

Summary of Research Results

The above goals were addressed primarily through use of the University of Wisconsin (UW) hybrid isentropic-sigma (θ - σ) coordinate numerical weather prediction model. The UW θ - σ model utilizes sigma coordinates to describe the lowest 150 millibars (mb) of the atmosphere and isentropic coordinates to describe the free atmosphere. A hemispheric version of the UW θ - σ model was developed for use in support of the ASHOE/MAESA field program. During the IOPs of ASHOE/MAESA, the UW θ - σ model provided 0 to 84 hour forecasts of isentropic atmospheric structure and processes in support of ER-2 flights for operational activities in Christchurch, New Zealand. Predictions of the tropospheric/stratospheric distributions of winds, temperature, water vapor, potential vorticity (PV) and corresponding isentropic transport processes were provided daily.

A series of numerical experiments were undertaken to investigate various aspects of the atmospheric hydrologic cycle. The first experiment examined water vapor exchange between Southern Hemisphere polar and subtropical latitudes in an effort to understand the extent to which dehydrated air within the Antarctic vortex reaches subtropical latitudes during baroclinic wave amplification. In this experiment the UW θ - σ model simulated the Southern Hemisphere stratospheric vortex and meridional transport of a trace constituent within the vortex to subtropical latitudes via filament generation. ECMWF assimilated data from 0000 UTC 24 July 1987 was used as initial data to simulate the exchange of water vapor confined inside the Southern Hemisphere winter polar vortex. An idealized, initially specified water vapor distribution is 2 ppm wherever isentropic potential vorticity (IPV) $> 7.5 \times 10^{-6} \text{ K m}^2 \text{ kg}^{-1} \text{ s}^{-1}$ (7.5 IPV units) and 4 ppm elsewhere. Figure 1 shows the 60-, 80-, 100-, and 120-hr forecast distributions on the 370 K model surface. Light color represents locations where the water vapor is 2 ppm, while the darker green

represents 4 ppm. At 60-hr the drier air in southern hemisphere high latitudes is generally circular and confined to latitudes higher than 45°. In Figs. 1b and c, baroclinic wave amplification between South America and Africa transports drier air equatorward and moist air poleward. Figure 1d, shows that a narrow filament of drier air has been transported to 25°S west of Africa and that moist air has penetrated as far as 60°S over the southern Indian Ocean. The penetration of very dry air to relatively low latitudes occurs in conjunction with intense tropospheric cyclone development. The meridional transport of inert trace constituent across the "container wall" of the stratospheric polar vortex within an extruded filament is modeled with a high degree of accuracy in the θ - σ model. Such accuracy extends to the simulation of stratospheric - tropospheric exchange of ozone, IPV and other trace constituents.

A second set of experiments was initiated to examine the relative capabilities of isentropic and sigma coordinate models to appropriately conserve atmospheric properties. The first experiment examined the models' capabilities to conserve joint distributions of potential vorticity (PV) and trace constituent transport for an ASHORE IOP using simulations from the UW θ - σ and σ coordinate models and the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM2). An initial proxy distribution of ozone (O_3) was specified analytically as a function of the initial PV on each model level. The capability of a model to retain a correlation of unity through the integration is a measure of its predictability of transport processes within the atmospheric continuum. At and above 370 K, the UW θ - σ model correlations remained above 0.99 throughout the 10-day simulation while correlations in the UW σ model simulation decreased to 0.50 by day 10 in the lower stratosphere. The corresponding correlations in simulations from CCM2, a state of the art climate model, decreased to near 0.95 in the low stratosphere at day 10. The correlations in the upper troposphere were further reduced in CCM2 compared to the UW θ - σ model with some decreasing to 0.6. These results, presented in Zapotocny et al. (1996), document the superior conservation characteristics in the upper troposphere and lower stratosphere of models based on isentropic coordinates.

The final experiment, which is extremely pertinent to simulation of the atmospheric hydrologic cycle, examined the ability of models to preserve an initial relationship between equivalent potential temperature (EPT) and a source-free inert trace constituent identical to the respective initial distributions (hereafter tEPT). Non-conservation of EPT constitutes an error that seriously degrades a model's ability to simulate the full range of atmospheric hydrologic processes. The results of this experiment provide an estimate of error, which is directly related to how accurately a model will simulate hydrologic processes resulting from the long-range transport of water vapor.

Figure 2a shows the initial one to one relationship between EPT and tEPT for all models of this study. Under the isentropic conditions prescribed for this experiment, each model should preserve the initial one to one relationship, reflected as a line in panel (a). Examination of the day 10 scatter plots between tEPT and the thermodynamically predicted EPT from the UW hybrid model (panel b), UW sigma model (panel c), T42 CCM2 (panel d), T63 CCM2 (panel e) and T42 CCM-S (panel f) reveals that the one to one relationship was not preserved by any model. However, scatter in the UW hybrid model's distribution is less than those from the other four models. Specifically, at day 10 the largest scatter between EPT and tEPT in the UW hybrid model is slightly less than 5 K for EPT values between 270 K and 340 K. For the same range of EPT, the UW sigma model shows more than twice as much scatter. Both CCM2 models display even more scatter, and have a tendency to produce scatter asymmetrically around the dashed line. In both CCM2 models, tEPT values generally exceed EPT for temperatures less than 330 K, while EPT values generally exceed

tEPT values for equivalent potential temperatures greater than 330 K. The CCM-S results show less scatter and are more symmetrically distributed around the dashed line than the CCM2 results. However, the scatter exceeds 100 K at some Gaussian grid points. Inspection of the CCM-S results for individual layers indicates that the grid points with the largest scatter are in the lowest two model layers near orography.

These experiments, examining the accuracy of transport processes in five models, illustrate that the UW θ - σ model simulates processes involving the long-range transport of trace constituents, including water vapor, to a higher degree of accuracy than the four models based on sigma coordinates. Proper simulation of water vapor transport, cloud production, precipitation and surface energy balance requires accurate simulation of the joint distributions of mass, potential temperature and water vapor. The EPT versus tEPT experiment clearly identifies the UW θ - σ model as superior in conserving these properties. As discussed in detail in Zapotocny et al. (1997), the difficulty in simulating trace constituent transport in sigma coordinate models arises from the inherent need for and complexity of resolving three-dimensional transport in the vertically sheared structure of flow within amplifying baroclinic waves.

Publications and Conference Presentations

Lee, S. C., H. Revercomb, R. Knuteson, and W. Smith, 1996: Cooling rate calculations for the Airborne Southern Hemisphere Ozone Experiment (ASHOE) using MODTRAN3. 19th Annual Review Conference on the Atmospheric Radiative Transfer Models and the HITRAN Database, Hanscom AFB, MA, June 1996.

Lee, S. C., R. O. Knuteson, H. E. Revercomb, W. L. Smith, 1997: Atmospheric cooling rate calculations for the Airborne Southern Hemisphere Ozone Experiment using MODTRAN3. OSA Winter Topical Meeting on Optical Remote Sensing of the Atmosphere, Santa Fe, NM, 10-12 February 1997. (Attachment #5)

Smith, W. L., H. E. Revercomb, H. L. Huang, X. L. Ma, H. B. Howell, H. M. Woolf, R. G. Dedecker, R. Herbsleb, F. Best, and R. O. Knuteson: HIS - Validation of NWP Model Performance during ASHOE, Airborne Southern Hemisphere Ozone Experiment Workshop, Melbourne, Australia, September 28-30 1994. (Attachment #4)

Zapotocny, T. H., A. J. Lenzen, D. R. Johnson, F. M. Reames, P. A. Politowicz and T. K. Schaack, 1996a: Joint distributions of potential vorticity and inert trace constituent in CCM2 and the UW θ - σ model simulations. *Geophys. Res. Let.*, **23**, 2525-2528.

Zapotocny, T. H., D. R. Johnson, T. K. Schaack, A. J. Lenzen, F. M. Reames, P. A. Politowicz and Z. Yuan, 1996b: Simulations of tropospheric distributions in the UW θ - σ model and CCM2. *Geophys. Res. Let.*, **24**, 865-868.

Collaboration on publications from ASHOE/MAESA which used HIS results:

Anderson, Gail P., Frank X. Kneizys, James H. Chetwynd, Lawrence S. Rothman, Michael L. Hoke, Alexander Berk, Lawrence S. Bernstein, Prabhat K. Acharya, Hilary A. Snell, Eli Mlawer, Shepard A. Clough, Jinxue Wang, Szu-Chia Lee, Henry Revercomb, Tatsuya Yokota, Lucy M. Kimball, Eric P. Shettle, Leonard W. Abreu, John E. A. Selby, 1996: Reviewing atmospheric radiative transfer modeling: New developments in high and moderate resolution FASCODE/FASE and MODTRAN. SPIE Annual Meeting, Denver, CO, 4-9 August 1996.

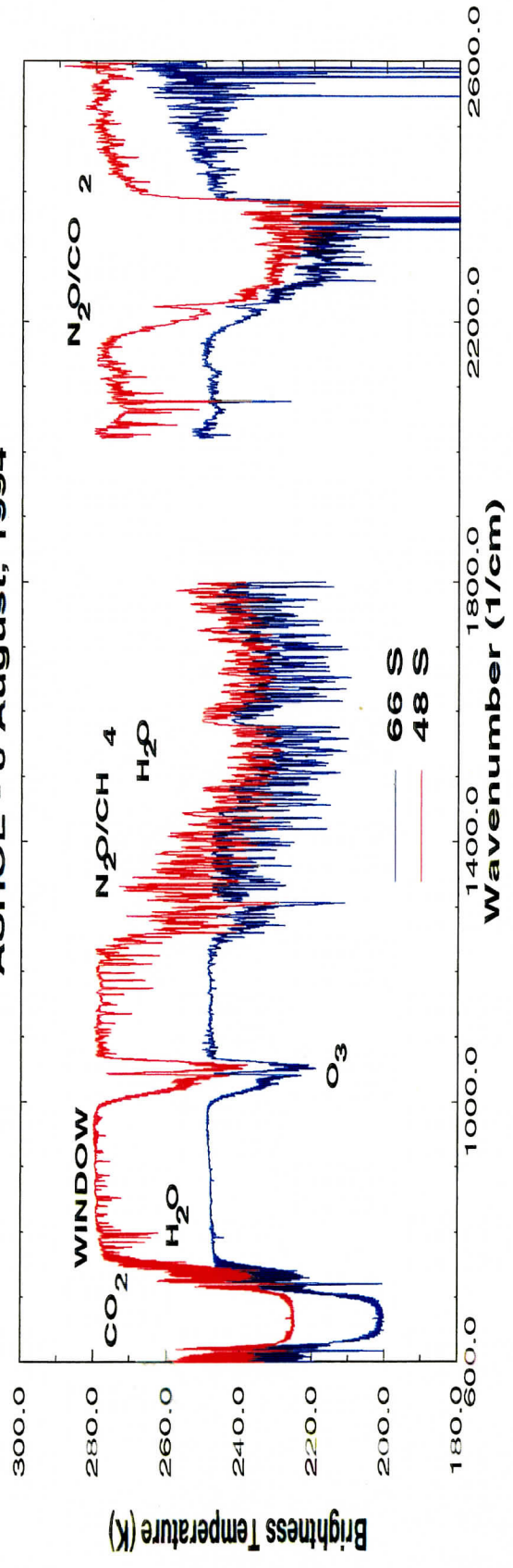
Tuck, A. F., D. Baumgardner, K. R. Chan, J. E. Dye, J. W. Elkins, S. J. Hovde, K. K. Kelly, M. Loewenstein, J. J. Margitan, R. D. May, J. R. Podolske, M. H. Proffitt, K. H. Rosenlof, W. L. Smith, C. R. Webster, and J. C. Wilson, 1997: The Brewer-Dobson circulation in the light of high altitude in situ aircraft observations. *Q. J. R. Meteorol. Soc.*, 123, 1-69.

Tuck, A. F., K. K. Kelly, C. R. Webster, M. Loewenstein, R. M. Stimpfle, M. H. Proffitt, and R. K. Chan: Airborne chemistry and dynamics at the edge of the 1994 Antarctic vortex, *J. Chem. Soc. Faraday Trans.*, 91, 3063-3071, 1995.

Attachments:

1. Annual Reports for NOAA Grant NA36GP0481
2. Summary of HIS data delivered to ASHOE/MAESA science team
3. HIS retrieval algorithm summary
4. Conference Report: Validation of NWP Model Performance during ASHOE, Airborne Southern Hemisphere Ozone Experiment Workshop, Melbourne, Australia, September 28-30 1994
5. Conference Report: Atmospheric cooling rate calculations for the Airborne Southern Hemisphere Ozone Experiment using MODTRAN3. OSA Winter Topical Meeting on Optical Remote Sensing of the Atmosphere, Santa Fe, NM, 10-12 February 1997.

HIS Brightness Temperature Spectra ASHOE - 8 August, 1994



btspb129.sriv(.ps)

hcb1;2;3lobt.asc & hcb1;2;3hibt.ASC

Fig. 1

HIS Ozone Brightness Temperature Spectra

ASHOE - 8 August, 1994

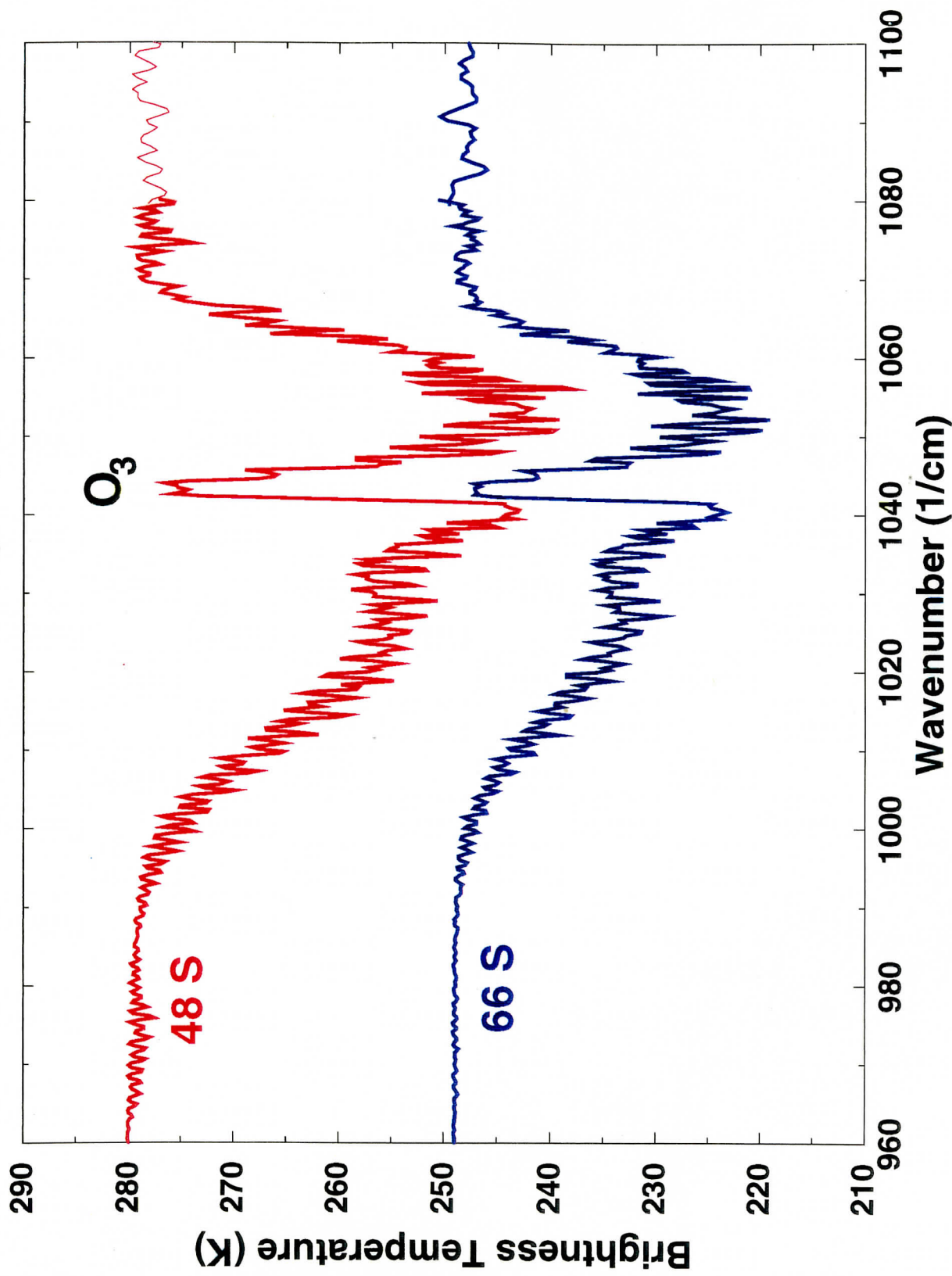


Fig. 2

HIS A/C Brightness Temperature Cirrus Spectra

AUGUST 8, 1994 - ASHOE

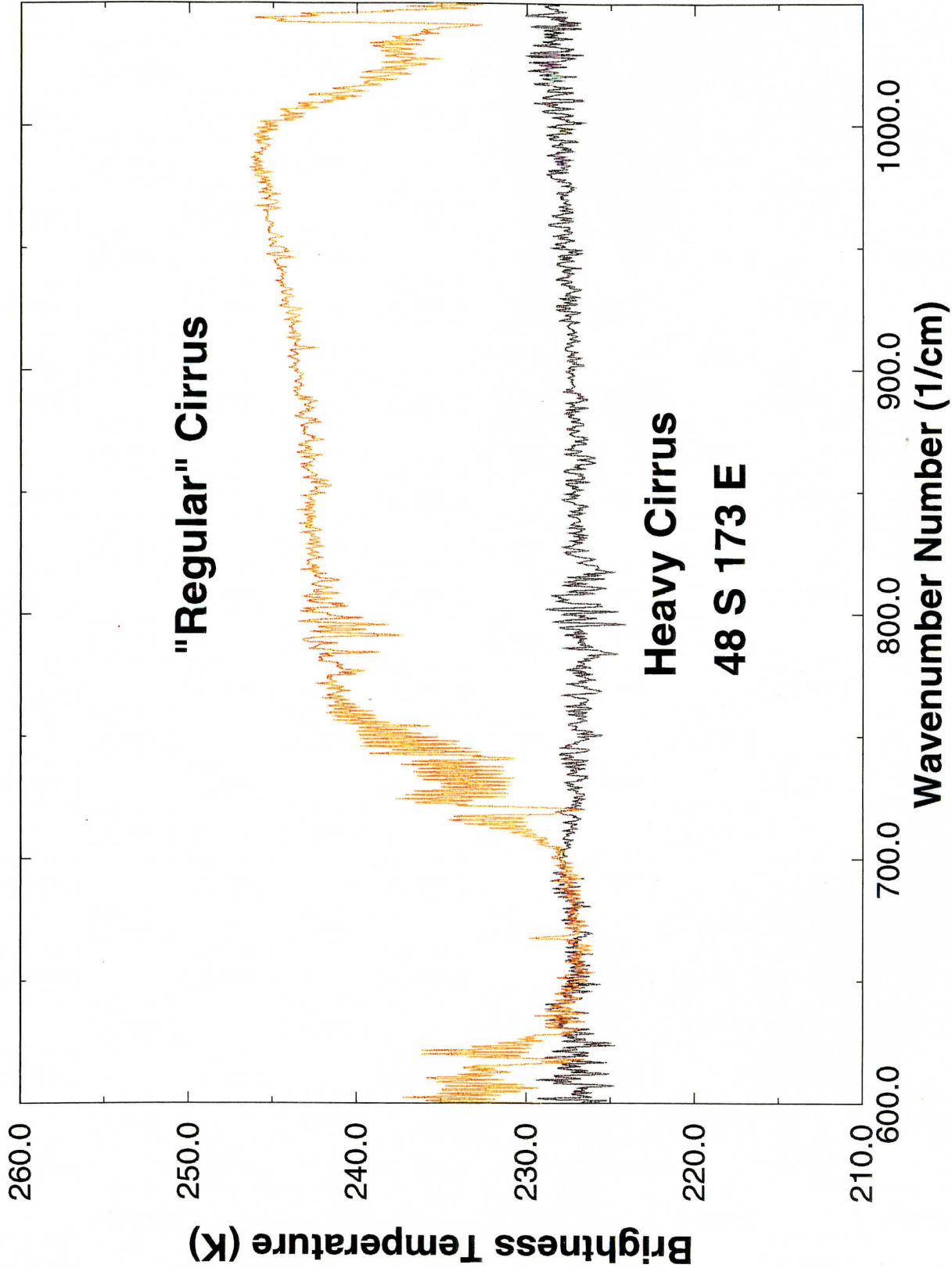
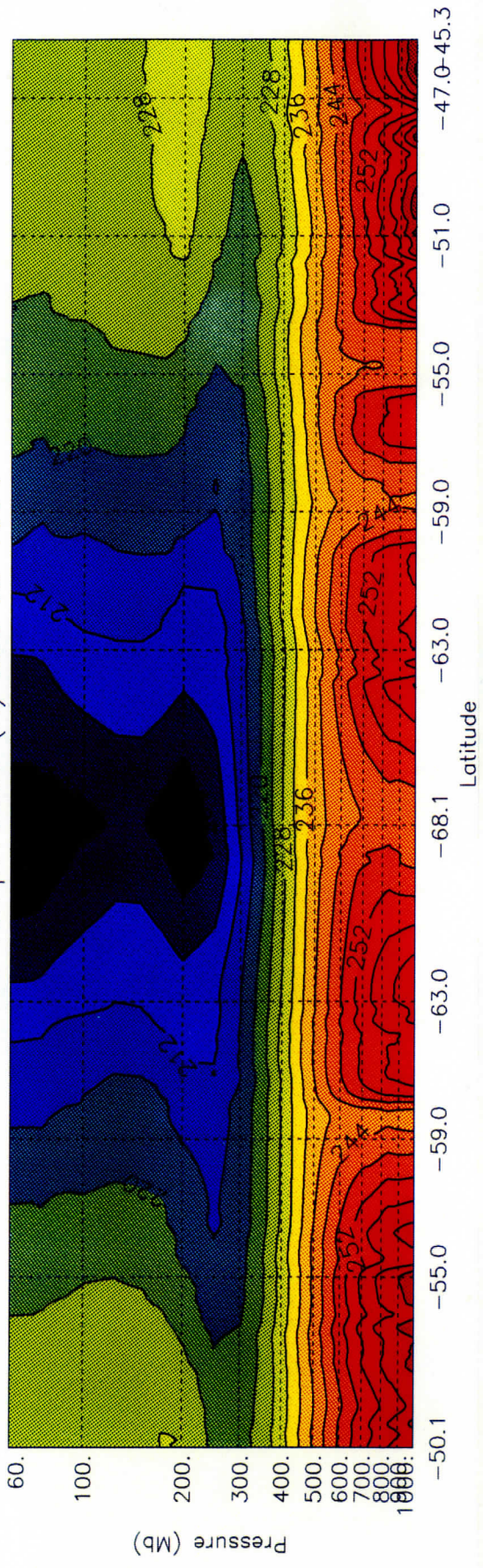


Fig. 3

HIS Temperature (K) 220 JD 1994



HIS Temperature (K) 222 JD 1994

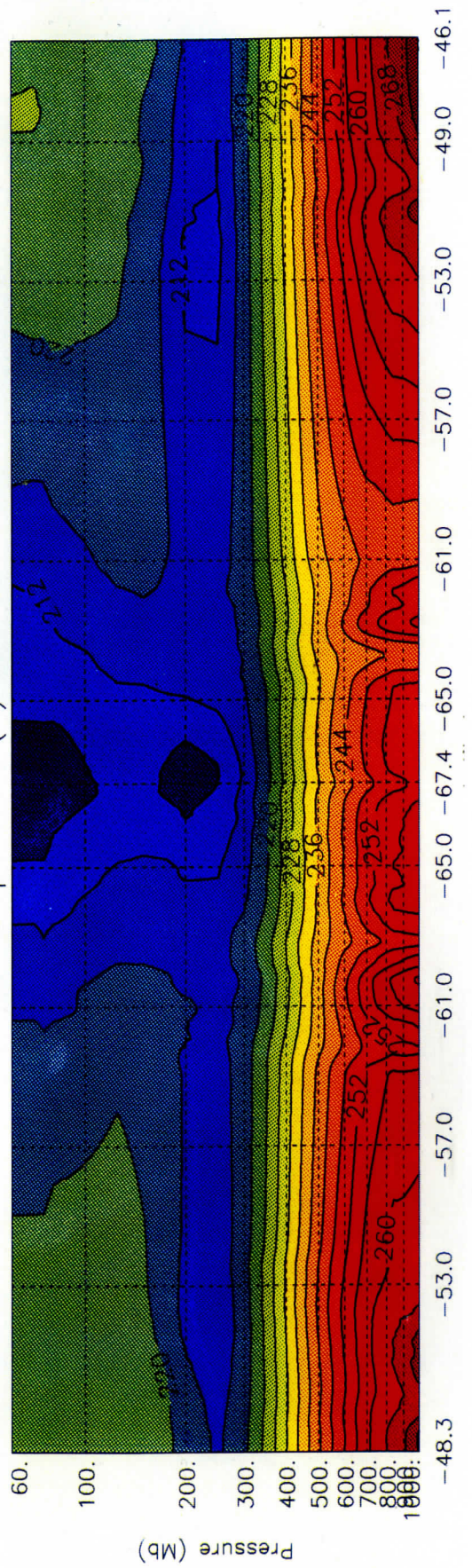
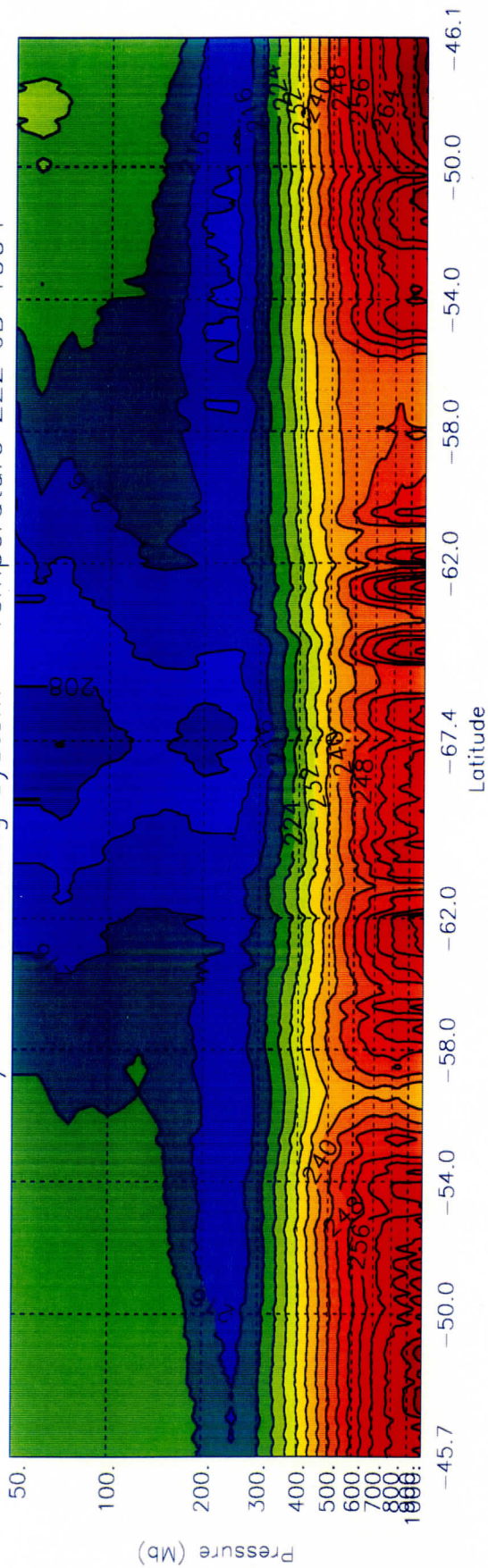


Fig. 4

ASHOE -- A/C HIS Sounding System -- Temperature 222 JD 1994



ASHOE -- A/C HIS Sounding System -- Mixing Ratio (g/kg) 222 JD 1994

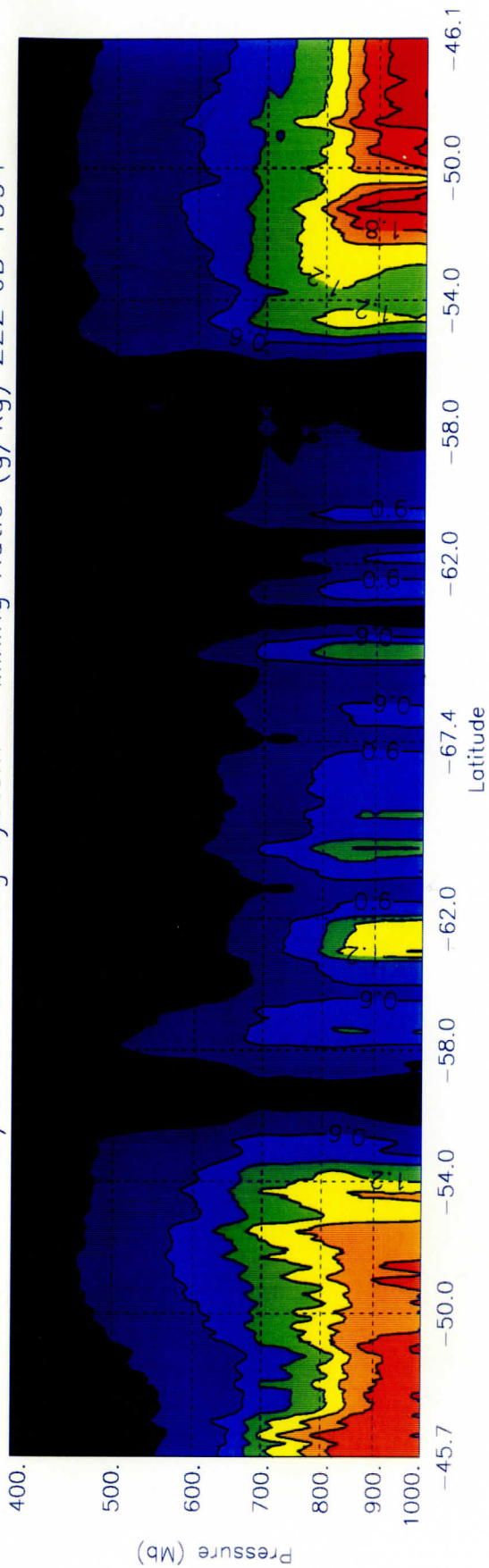


Fig. 5

ASHOE (August 9 & 11, 1994)

Radiosondes vs A/C HIS Retrievals

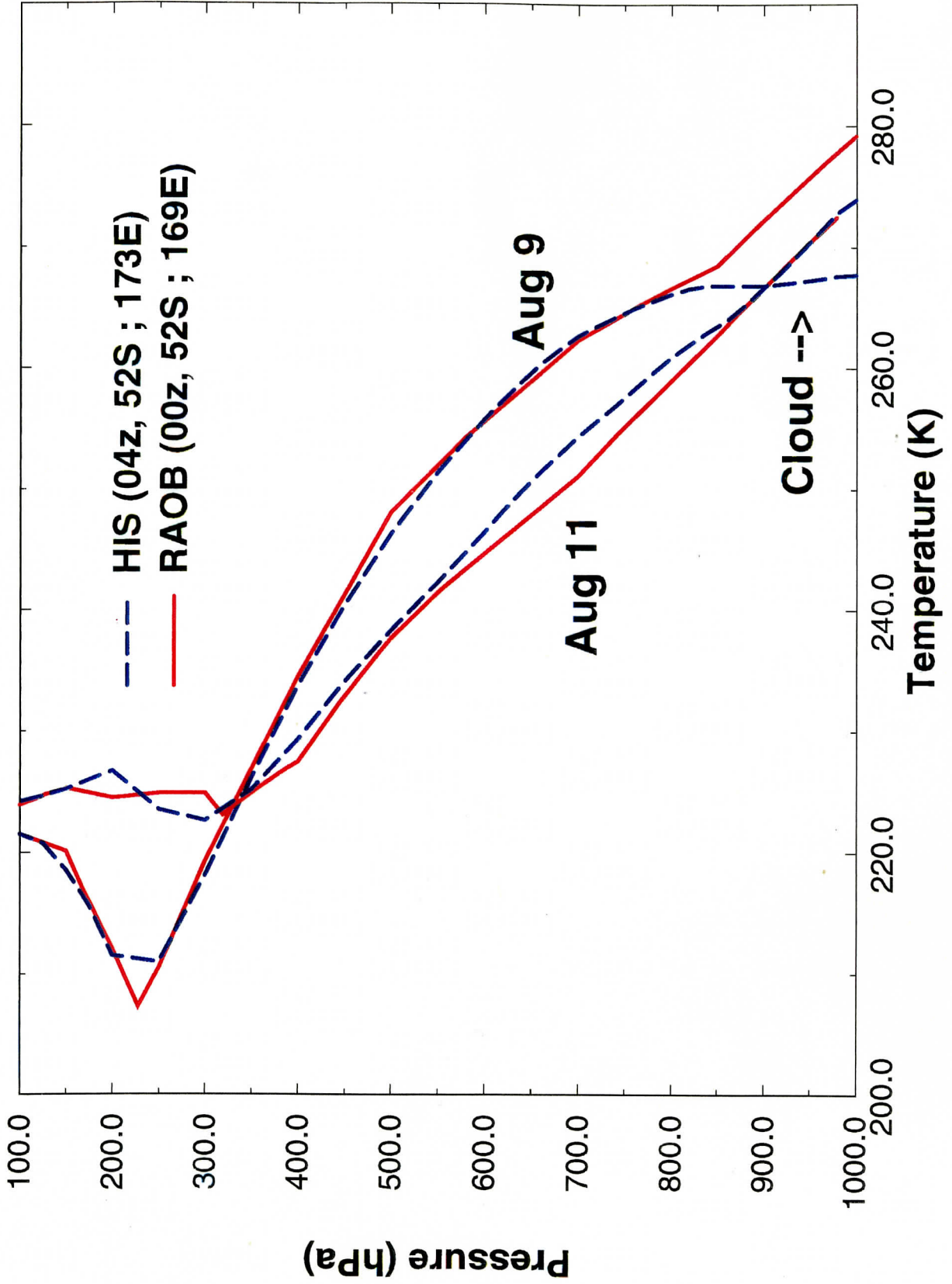


Fig. 6

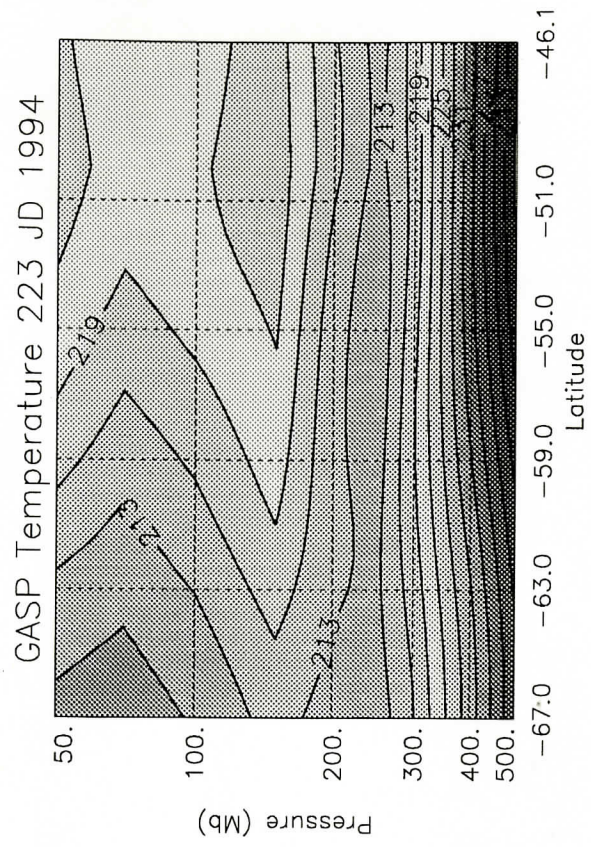
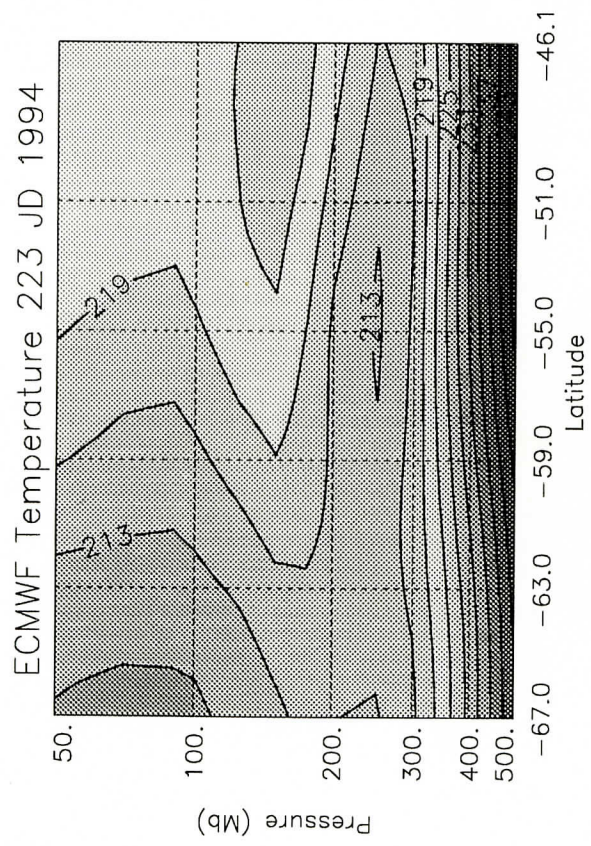
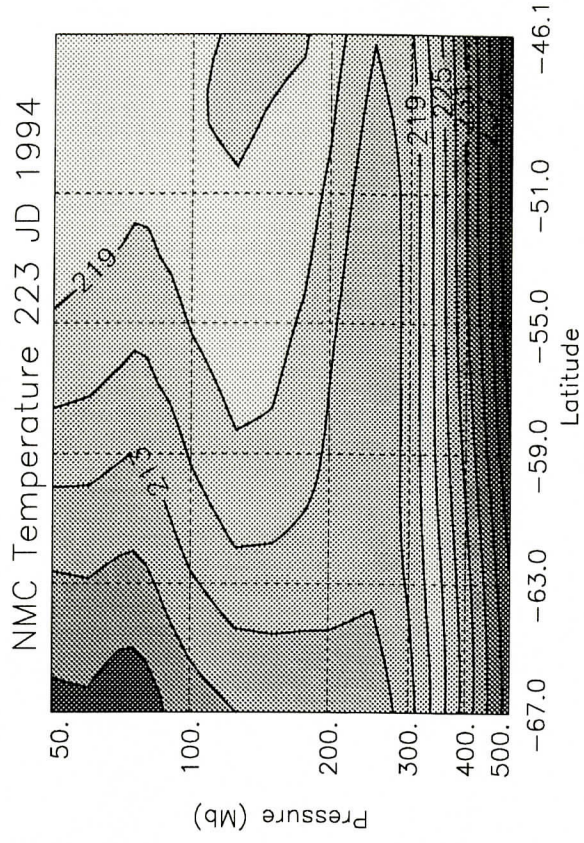
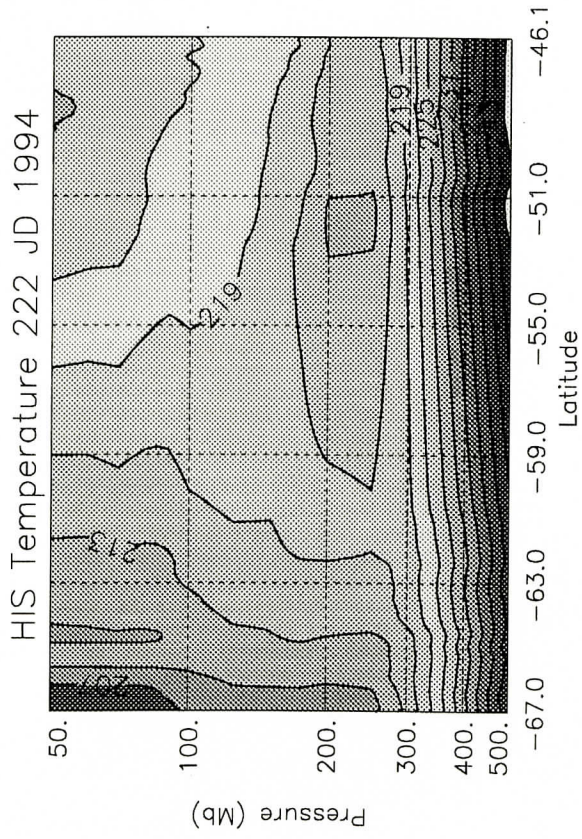


Fig. 7

A/C HIS Sounding System - Ozone Mixing Ratio (PHY)

ASHOE 276 JD 1994

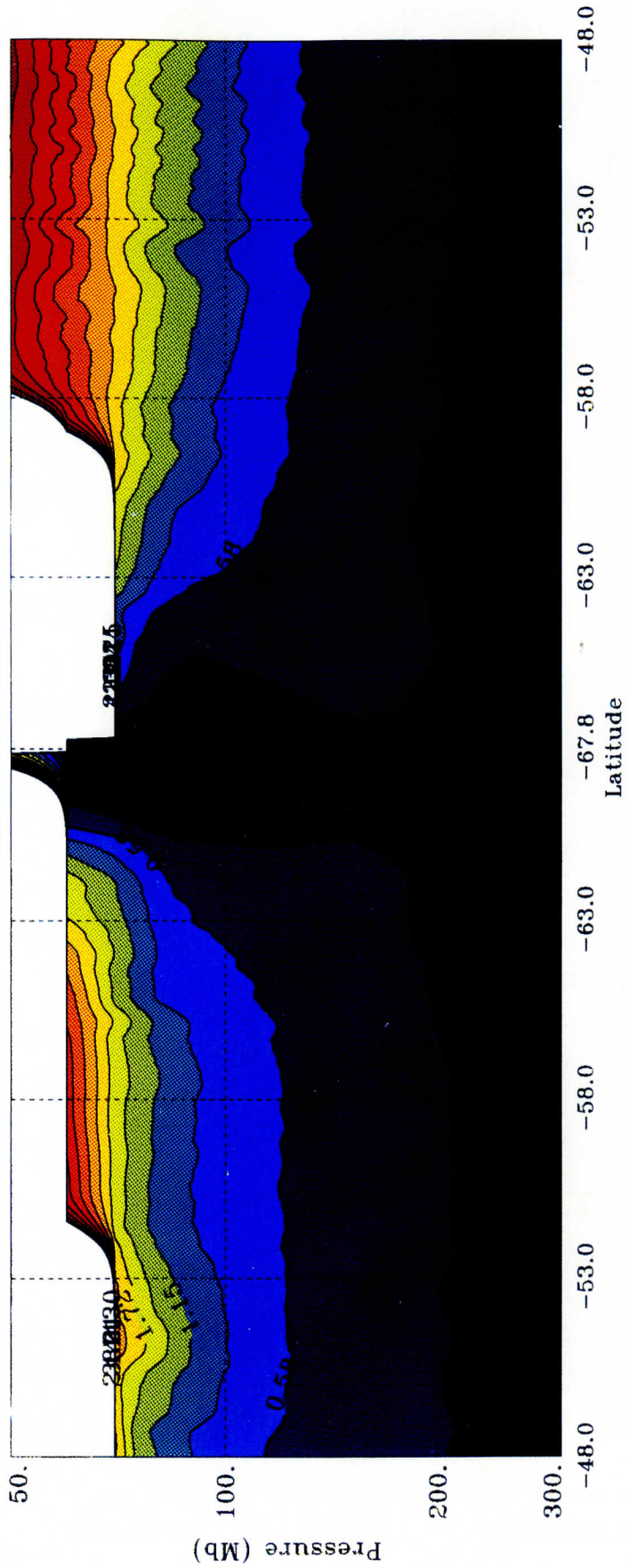


Fig. 8

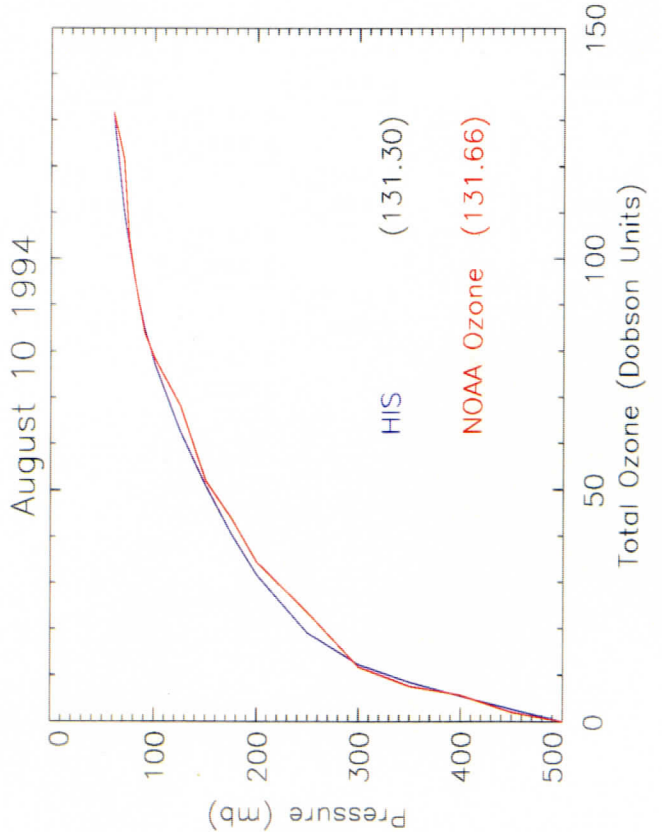
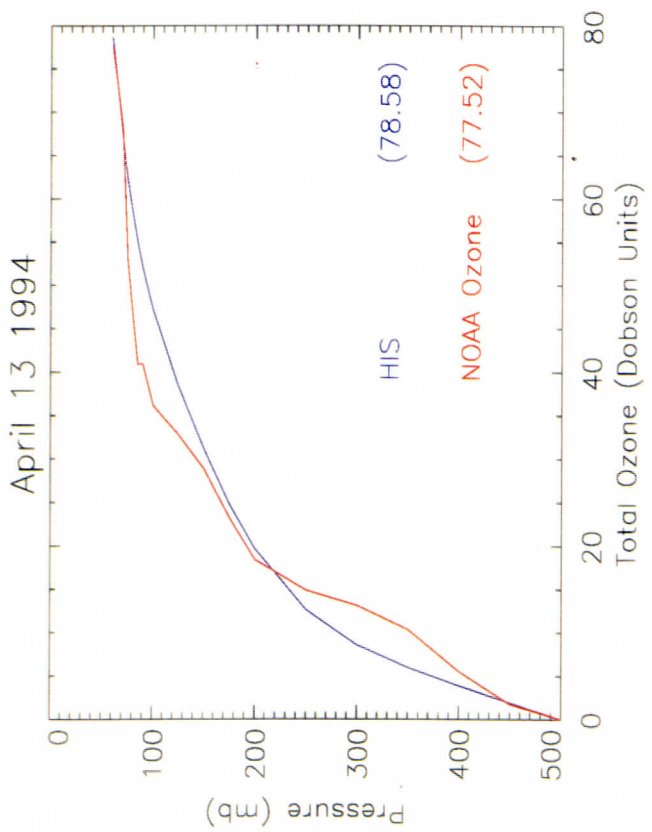
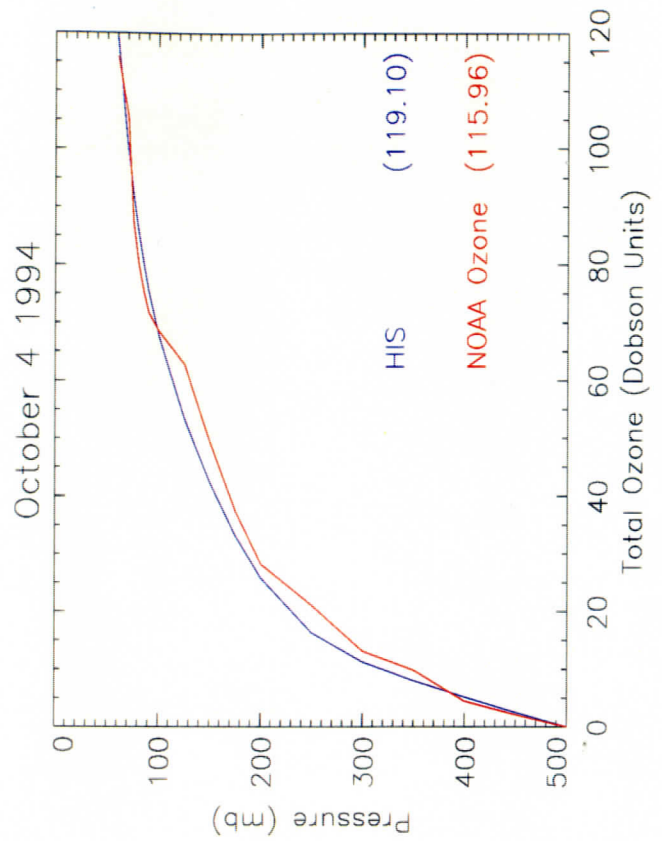
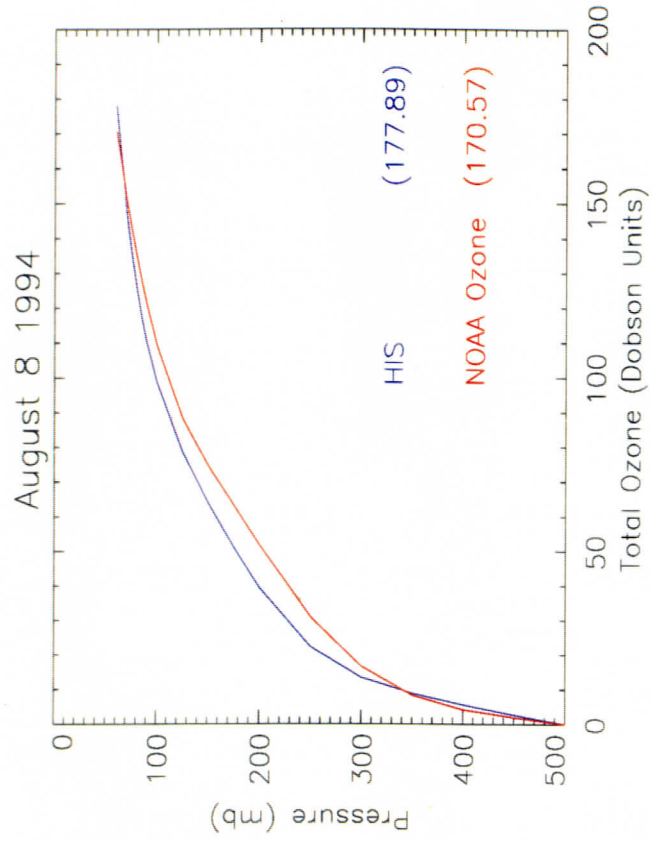


Fig. 9

Layer Mean Cooling Rates Polar Vortex (-67 deg), 3/4 October 1994

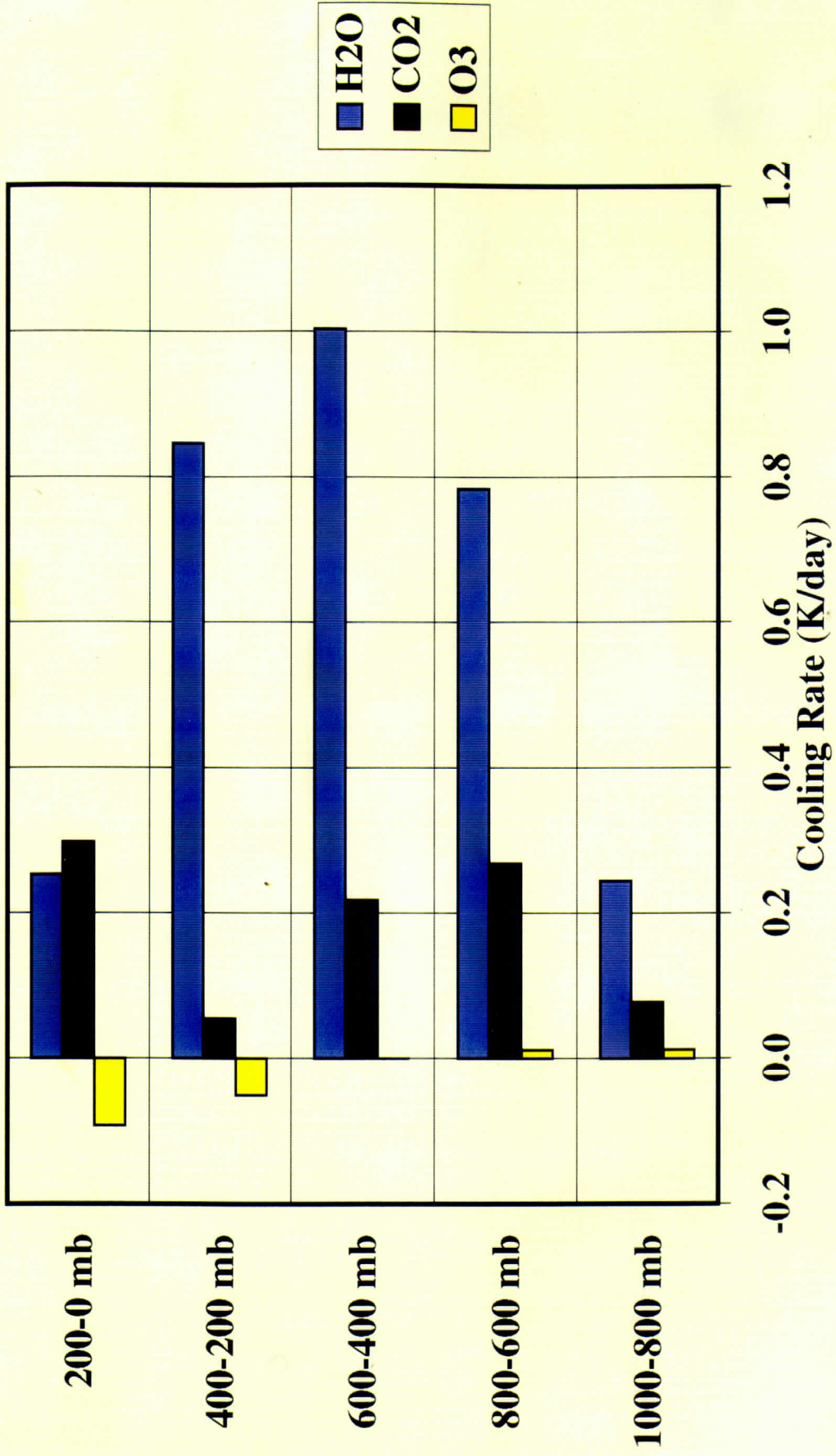


Fig. 10

Cooling Rate for ASHOE ac941004 Rec.40 (-67.7,172.2) - using MODTRAN3



Fig. 11

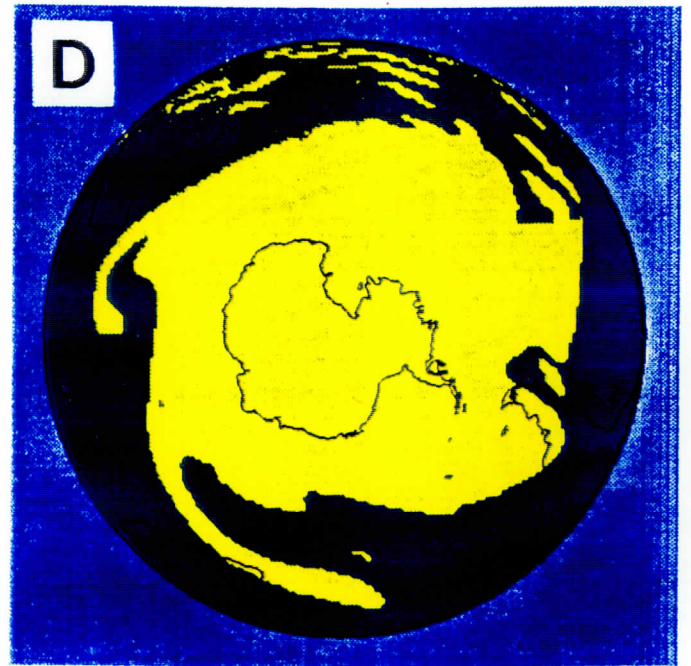
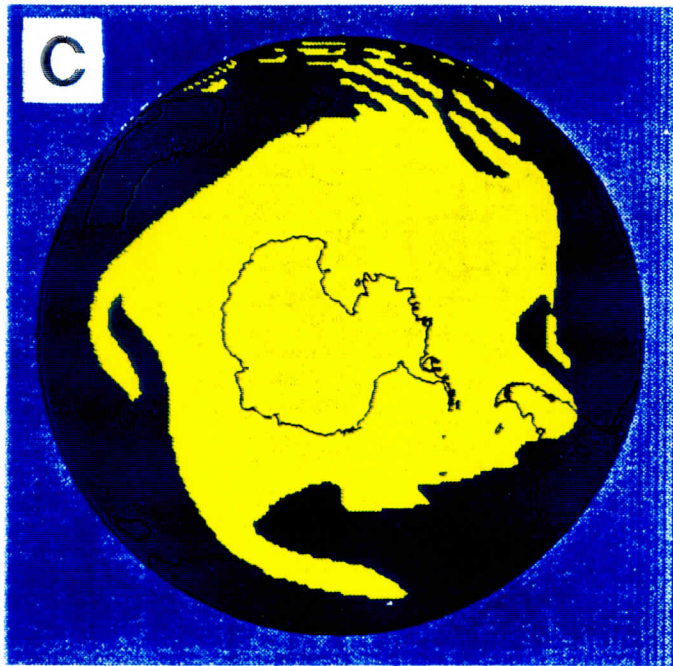
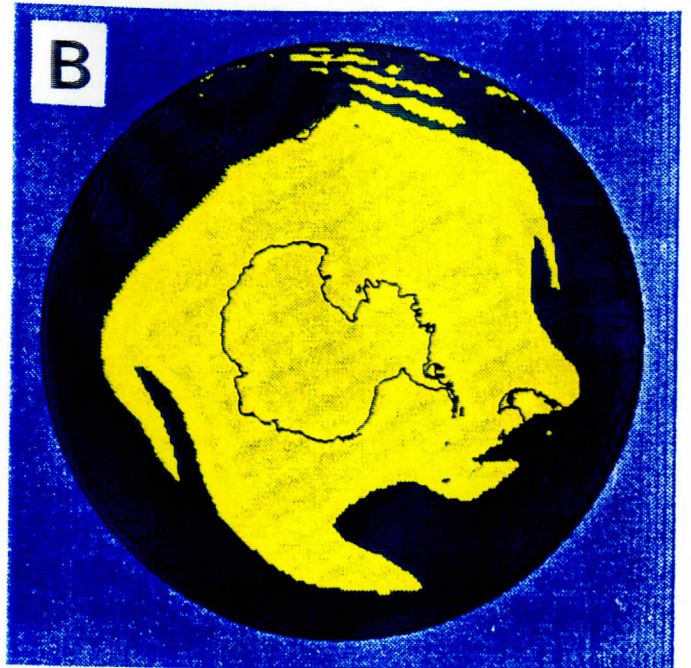
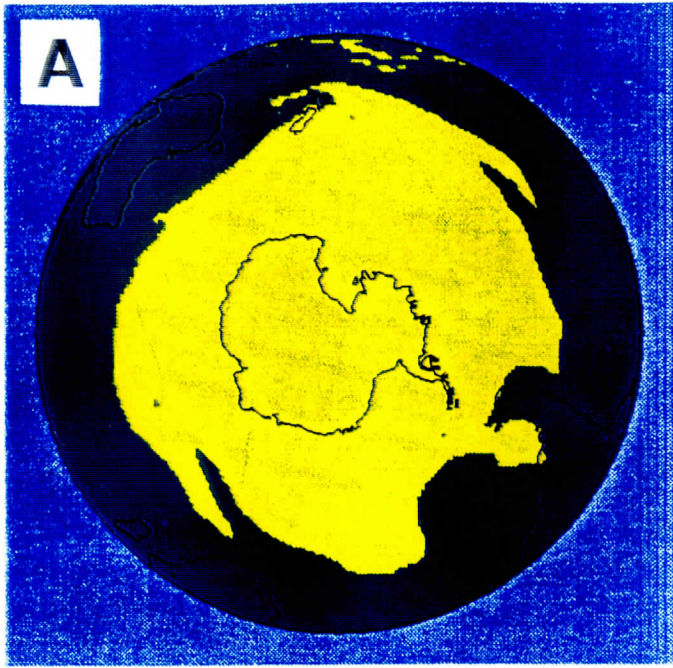


Fig. 1. The 370 K water vapor distribution from the hybrid model for (a) 50-h, (b) 30-h, (c) 100-h and (d) 120-h. Light green values represent concentrations of 2 ppm while dark green values are 4 ppm.

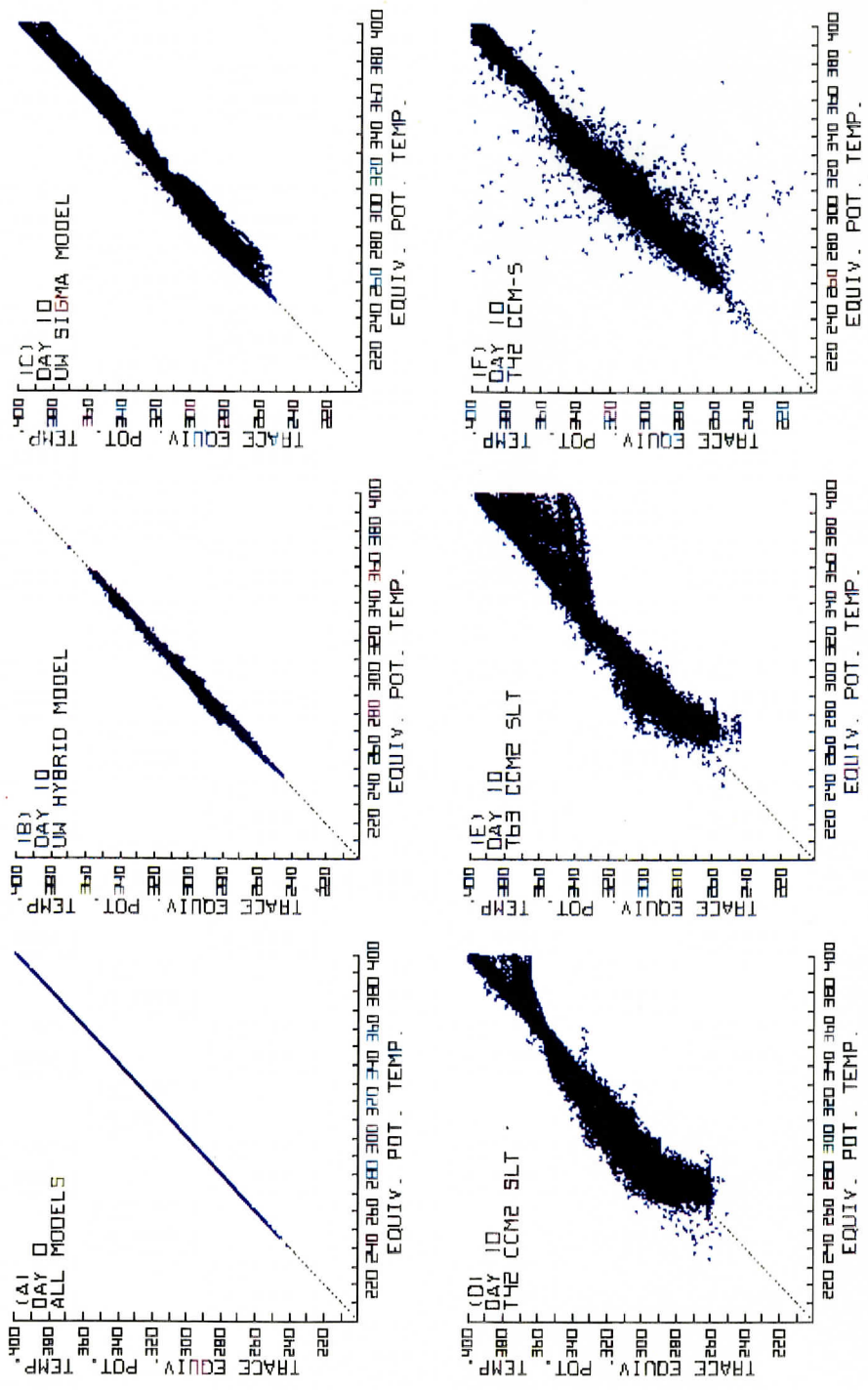


Fig. 2 Scatter plots of the distributions of EPT versus tEPT (a) initially for all sigma models, and at day 10 in the (b) UW hybrid model, (c) UW sigma model, (d) T42 CCM2, (e) T63 CCM2, and (f) T42 CCM-S.

Summary of Progress
Global Water Vapor Modeling
NOAA Grant #NA36GP0481
1 September 1993 - 28 February 1994

The primary emphasis in the UW hybrid (θ - σ) modeling effort has been on simulation and analysis of the atmospheric hydrologic cycle. During the past four months, global, hemispheric and regional simulations of atmospheric hydrologic processes (water vapor transport, condensation/precipitation, cloud generation and transport) and trace constituent transport have been conducted. Considerable attention has been given to the problem of atmospheric dispersion of water vapor, cloud and trace constituent transport within sigma models (UW grid point and CCM2 semi-Lagrangian) as compared to the relatively dispersion-free transport within the hybrid (θ - σ) model.

A hemispheric version of the UW hybrid θ - σ model has been developed and studied for utilization during the ASHOE field program. A preliminary experiment has been conducted to investigate water vapor exchange between Southern Hemisphere polar and subtropical latitudes. A focus of this effort has been to understand the extent to which dehydrated air within the Antarctic vortex reaches subtropical latitudes during baroclinic wave amplification.

**Summary of Progress
NOAA Office of Programs
(Grant #NA36GP0481)
Global Water Vapor
September 1993 - January 1994**

The NOAA Office of Global Change grant to the UW-Madison began September 1, 1993. Plans for the first year are to investigate improvements to the water vapor retrieval algorithm from high spectral resolution radiance measurements by the High resolution Interferometer Sounder (HIS) and produce analyses of upper level water vapor distribution. The HIS has flown in several field programs the past few years, including FIRE I & II, SPECTRE, STORM-FEST AND CAMEX. Data sets exist for each of these programs, with a good diversity of water vapor environments, although all experiments were conducted in the mid-latitudes. Work began in November on this Global Water Vapor grant; a brief summary of progress is provided below

Summary of Work Provided under Global Change Grant

An intensive effort has been underway to improve vertical water vapor profile retrievals from high spectral resolution water vapor radiance spectra observed with the HIS. There are currently two major factors limiting the water vapor sounding performance; (1) spectroscopy uncertainties, and (2) algorithm non-linearity.

1. Spectroscopic Uncertainties

By spectroscopic uncertainties we are referring to errors in the basic absorption line parameter and continuum approximations used to calculate the spectrum of atmospheric transmittance as a function of water vapor concentration. Errors in the transmittance computation model cause errors in the retrieved water vapor profile from spectral radiance observations. Considerable effort has been devoted to understanding and alleviating spectroscopic errors through numerous comparisons of water vapor radiance spectra observed with the HIS, with calculations performed on the basis of coincident radiosonde and RAMAN LIDAR water vapor profiles. The result of these comparisons has led to the formulation of an improved continuum model and a tabulation of line absorption coefficient correction factors which minimize the discrepancy between observed and calculated water vapor radiance.

2. Algorithm Non-Linearity

The inverse solution of the radiative transfer equation for the water vapor profile is highly non-linear in that the kernel of the equation (i.e., the mixing ratio weighting function) is a strong function of the unknown water vapor mixing ratio profile. An iterative matrix inverse retrieval algorithm is under development to account for this non-linearity. The algorithm utilizes an initial profile obtained by the inversion of a linearized form of the radiative transfer equation. The full non-linear retrieval usually takes about six iterations to converge to a solution to the radiance measurements. The non-linear algorithm is to be implemented for the run-time processing of HIS data to be achieved during the ASHOE.

3. Example Result

Figure 1 below shows a comparison between a radiosonde atmospheric temperature profile, and radiosonde and RAMAN LIDAR water vapor dewpoint profiles, with a temperature and dewpoint sounding retrieved from the HIS radiance spectrum observed over Wallops Island, VA at the time of the radiosonde launch and the RAMAN LIDAR observations. The apparent accuracy of the HIS water vapor sounding is noteworthy. In the upper troposphere, the HIS compares more favorably with the RAMAN LIDAR than with the radiosonde water vapor measurements. This result is positive in that radiosonde observations of water vapor at low pressure altitudes are notoriously poor quality.

4. ASHOE Preparations

Considerable effort under this grant has been devoted to preparations for routine HIS data processing during the ASHOE. Algorithms for the retrieval of: (a) temperature profiles, (b) water vapor profiles, (c) ozone profiles, (d) upward and downward longwave radiation flux profiles, (e) cooling rate profiles, (f) surface skin temperature, and (g) cloud top height and emissivity have been developed. These algorithms are currently undergoing tests using pre-ASHOE data. Plans are to operate these algorithms at ASHOE in a routine, near real time fashion in order to provide quick look atmospheric profile data for the scientific analysis to be performed in the field.

The UW-CIMSS proposal discussed participation in a field program in the second year of the grant. Shortly after the NOAA award, it became evident that the HIS instrument should participate in the Airborne Southern Hemisphere Ozone Mission (ASHOE), which runs from March to November, 1994. Since this field program is actually occurring in year 1 of the NOAA grant, the initial objectives of the program were adjusted, with the consent of the NOAA Program Manager, to include preparation for ASHOE.

In January the UW-CIMSS aircraft HIS instrument was prepared at Madison for checkout flights at NASA Ames Research Center, prior to shipment to Christchurch, New Zealand. The instrument alignment and calibration were verified, the detector cooler enclosure (liquid helium dewar) was refurbished, the interferometer scanning mechanism was cleaned and adjusted, and the power supply and cables were replaced. Also, instrument calibration software was improved through code optimization, and the software was made more automated to speed data delivery for post-flight analysis.

The HIS was shipped to NASA Ames in January, 1994 and participated in two checkout and one science flight in January and February. The instrument was tested for a new aircraft interface, and weight and balance measurements were updated. Instrument performance was excellent and the HIS was accepted for ASHOE.

**Summary of Progress
Global Water Vapor Modeling
NOAA Grant #NA36GP0481
1 March 1994 - 31 August 1994**

The UW hybrid (θ - σ) modeling group provided 0 to 84 hour hemispheric forecasts of atmospheric structure and processes on isentropic surfaces in support of the ER-2 flights for operational activities in Christchurch, New Zealand during the four IOPs of the 1994 ASHOE/MAESA. Onsite predictions of the tropospheric/stratospheric distributions of winds, temperature, water vapor, potential vorticity and corresponding transport processes were provided daily. The temporal evolution of atmospheric structure was displayed using the University of Wisconsin Vis 5d visualization software.

Several periods of strong baroclinic wave amplification during the four IOPs of ASHOE/MAESA were selected for further study. Preliminary research has been initiated for these periods to investigate the Southern Hemisphere hydrologic cycle and to assess the impact of baroclinic wave amplification on the meridional exchange of water vapor. Research continues to investigate the relative capabilities of numerical models based on different numerical schemes and coordinate systems to accurately transport atmospheric properties with emphasis on water vapor. This research continues to demonstrate decided advantages for numerical simulation of hydrologic processes and trace constituent transport within isentropic coordinates.

**Annual Report for NOAA Grant NA36GP0481
Covering the period 9/1/94-9/30/95**

This annual report summarizes the UW-Madison participation in the ASHOE/MAESA (Airborne Southern Hemisphere Ozone Experiment / Measurements for Assessing the Effects of Stratospheric Aircraft) field program, supported by NOAA Grant NA36GP0481. There were two separate activities supported by this grant; one activity supports the participation of the High resolution Interferometer Sounder (HIS) aboard the ER-2 aircraft in the data gathering campaign, and the other activity supports onsite forecasts of isentropic atmospheric structure and circulation in support of the ER-2 flights and modeling the global hydrologic cycle.

1. HIS field program participation during ASHOE/MAESA

ASHOE/MAESA was sponsored by NASA, NOAA, NSF and others to address questions about the causes of the year round mid latitude ozone loss observed in the Southern Hemisphere (S.H.) in the last 15 years. A major goal of these programs was to gain an understanding of the composition of the lower stratosphere and its consequent effects on the radiative balance of the atmosphere. To support this and other requirements, flights of the NASA ER-2 high altitude aircraft were conducted to provide observations from which to diagnose the chemistry, physics and motion of the air in the lower stratosphere and troposphere. Measurements were made at four separate time periods; March, June, August and October to capture the seasonal cycle of S.H. circulation.

The UW-Madison HIS instrument participated in all four phases of the dynamics and radiation field campaign aboard the ER-2 aircraft; the first three phases were during the period covered in this report. Table 1 summarizes the data gathering flights made from Christchurch, New Zealand (NZCH), primarily flying south into the polar vortex.

Summary of UW HIS Experiment Data Collection Flights during ASHOE/MAESA

<u>Date</u>	<u>Launch - Return time</u>	<u>Flight Location</u>	<u>Mission</u>
04/13/94	1930 - 0330 UTC	NZCH - 68S	Antarctic vortex
04/15/94	0052 - 0350 UTC	NZCH - 38S	Volcano overflight
06/05/94	2000 - 0200 UTC	NZCH - 68S	Antarctic vortex
06/08/94	2000 - 2100 UTC	NZCH - 45S	Test flight
08/08/94	2200 - 0620 UTC	NZCH - 69S	Antarctic vortex
08/10/94	2100 - 0430 UTC	NZCH - 67S	Antarctic vortex
10/03/94	2130 - 0530 UTC	NZCH - 68S	Antarctic vortex
10/05/94	2100 - 0445 UTC	NZCH - 65S	Antarctic vortex

This grant provided support for the deployment of the HIS science and technical support team to Ames Research Center for pre-experiment instrument checkout and to Christchurch, New Zealand on four separate occasions for the measurement campaign. Partial support to CIMSS for deployment in the field phase of ASHOE/MAESA was also provide by NASA.

From the HIS measurements taken during the ASHOE/MAESA field campaign, software developed under year 1 funding was applied to the HIS radiance spectra to calculate temperature, moisture and ozone structure in the upper troposphere and lower stratosphere. The vertical profiles below the ER - 2 are computed from the HIS radiance observations using a retrieval method which is totally independent of contemporary meteorological data and as such the results are totally independent of the numerical model analyses which are to be validated. HIS temperature and water vapor profile data were used to validate the thermodynamic characteristics of global data assimilation / forecast models that provide the global circulation patterns used to analyze the transport of the constituents associated with the Ozone depletion process. HIS temperature and moisture retrievals were also used to calculate atmospheric cooling rates, which were compared to cooling rates calculated using input from global forecast models. As the time period for this report covers the field phase of ASHOE/MAESA, results of the data analysis efforts will be provided in the final report.

2. Isentropic model forecast support during ASHOE/MAESA

As part of the 1994 Airborne Southern Hemisphere Ozone Experiment /Measurement for Assessing the Effect of Stratospheric Aircraft (ASHOE/MAESA) program under the direction of Dr. Adrian Tuck of the NOAA Aeronomy Lab, the UW θ - σ modeling group under Professor Donald Johnson's direction was deployed to provide onsite forecasts of isentropic atmospheric structure and circulation in support of ER-2 flights carried out from Christchurch, New Zealand during the four Intense Observation Periods (IOPs). Daily 0 to 84 hour forecasts of tropospheric/stratospheric winds, temperature, water vapor, potential vorticity and corresponding transport processes were provided to determine the most beneficial flight path for each mission.

Several events during the IOPs were selected for scientific study. Emphasis was placed on investigating the Southern Hemisphere hydrologic cycle and the role of amplifying baroclinic waves on the meridional transport of water vapor, ozone and other trace constituents. Comparisons were made with corresponding forecasts from the nominally identical UW sigma coordinate model in order to investigate the impact of the vertical coordinate on simulation of atmospheric circulation and hydrologic processes.

An experiment was initiated to examine the relative capabilities of isentropic and sigma coordinate models to conserve joint distributions of potential vorticity (PV) and trace constituent transport for an ASHOE IOP using simulations from the UW θ - σ and σ coordinate models and the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM2). An initial proxy distribution of ozone (O_3) was specified analytically as a function of the initial PV on each model level. The capability of a model to retain a correlation of unity through the integration is a measure of its predictability of transport processes within the atmospheric continuum. At and above 370 K, the UW θ - σ model correlations remained above 0.99 throughout the 10-day simulation while correlations in the UW σ model simulation decreased to 0.50 by day 10 in the lower stratosphere. The corresponding correlations in simulations from CCM2, a state of the art climate model, decreased to near 0.95 in the low stratosphere at day 10. The correlations in the upper troposphere were further reduced in CCM2 compared to the UW θ - σ model with some decreasing to 0.6. These results, presented in Zapotocny et al. (1996a), document the superior conservation characteristics in the upper troposphere and lower stratosphere of models based on isentropic coordinates.

**Annual Report for NOAA Grant NA36GP0481
Covering the period 10/1/95-2/29/96**

This annual report summarizes the UW-Madison participation in the ASHOE/MAESA (Airborne Southern Hemisphere Ozone Experiment / Measurements for Assessing the Effects of Stratospheric Aircraft) field program, supported by NOAA Grant NA36GP0481. There were two separate activities supported by this grant; one activity supports the participation of the High resolution Interferometer Sounder (HIS) aboard the ER-2 aircraft in the data gathering campaign, and the other activity supports onsite forecasts of isentropic atmospheric structure and circulation in support of the ER-2 flights and modeling the global hydrologic cycle.

1. HIS field program participation during ASHOE/MAESA

The UW-Madison HIS instrument participated in all four phases of the dynamics and radiation field campaign aboard the ER-2 aircraft, the fourth and final phase occurred during the period covered in this report. The October HIS flights were included in order to characterize the polar vortex during the period of maximum ozone depletion. Table 1 summarizes the data gathering flights made from Christchurch, New Zealand (NZCH), primarily flying south into the polar vortex.

Summary of UW HIS Experiment Data Collection Flights during ASHOE/MAESA

<u>Date</u>	<u>Launch - Return time</u>	<u>Flight Location</u>	<u>Mission</u>
04/13/94	1930 - 0330 UTC	NZCH - 68S	Antarctic vortex
04/15/94	0052 - 0350 UTC	NZCH - 38S	Volcano overflight
06/05/94	2000 - 0200 UTC	NZCH - 68S	Antarctic vortex
06/08/94	2000 - 2100 UTC	NZCH - 45S	Test flight
08/08/94	2200 - 0620 UTC	NZCH - 69S	Antarctic vortex
08/10/94	2100 - 0430 UTC	NZCH - 67S	Antarctic vortex
10/03/94	2130 - 0530 UTC	NZCH - 68S	Antarctic vortex
10/05/94	2100 - 0445 UTC	NZCH - 65S	Antarctic vortex

HIS measurements taken during the final phase of ASHOE/MAESA used software developed under year 1 funding, applying the HIS radiance spectra to calculate temperature, moisture and ozone structure in the upper troposphere and lower stratosphere. HIS temperature and water vapor profile data were then used to validate the thermodynamic characteristics of data assimilation models that provide the global circulation patterns used to analyze the transport of the constituents associated with the Ozone depletion process. HIS temperature and moisture retrievals were also used to calculate atmospheric cooling rates, which were compared to cooling rates calculated using input from global forecast models. Results of the ASHOE/MAESA data analysis are provided in the final report.

2. Isentropic model forecast support during ASHOE/MAESA

Research over this five month period investigated the global hydrologic cycle with emphasis on the Southern Hemisphere circulation. The focus was to understand the underlying reasons for the relatively limited progress being made in the prediction of the atmosphere's hydrologic processes, cloudiness and energy exchange. The consensus of modelers utilizing σ coordinates is that with improved parameterization and increased resolution, the predictability of both weather and climate will improve. However, attempts to improve simulations through improving parameterizations have had limited success and the results from climate models with resolutions greater than T42 (or T63) do not demonstrate the expected improvements.

As a continuation of this effort, a second experiment examined the conservation capability of models to appropriately conserve properties. In a series of simulations, this experiment which is extremely pertinent to the hydrologic cycle compared the UW θ - σ and σ models, and the NCAR CCM2 abilities to conserve equivalent potential temperature (θ_e) during 10 day integrations under both dry and reversible moist adiabatic processes. Non-conservation of θ_e constitutes an error that seriously degrades a model's ability to simulate the full range of the atmosphere's hydrologic processes. The initial θ_e distribution from ASHOE IOP data was inserted as a trace constituent in each model. The models were then integrated to 10 days and conservation examined. The correlations remain higher in the UW θ - σ model than in the other two models. The results of these numerical experiments documented inherent advantages of modeling hydrologic processes in isentropic coordinates and demonstrated the potential for advancing the understanding and modeling of the hydrologic cycle, energy exchange and regional climate. Results from this experiment are presented in Zapotocny et al. (1996b).

Attachment 2: Summary of HIS data delivered to ASHOE/MAESA Science Team

Following is the data that was submitted to ASHOE/MAESA archive, in "HP" and "EM" data types. At the bottom is a directory listing of the files and the flight dates they cover.

EM FILES:

10-wavenumber average of cloud emissivity (percent)

NX(1) is the number of altitudes in subsequent data records
aircraft latitude (degrees north)
aircraft longitude (degrees east)
aircraft altitude (m)

The EM files contain a 40 bin summary of the High Resolution Interferometer (HIS) derived infrared cloud emissivity spectra averaged within 10 wavenumber bins between 800 and 1200 cm^{-1} (8.3 - 12.5 μm). Cloud top heights, derived from the Cloud Lidar System (CLS) on the ER-2, are used with HIS spectra radiance measurements to calculate the cloud emissivity spectra. The CLS heights are also contained in this file. The infrared cloud emissivity data contained in this archive are restricted to single level cloud, as determined by the CLS. A statistical filter of full resolution (i.e., 0.5 cm^{-1}) emissivity values is used to detect and exclude erroneous emissivity spectra.

HP FILES:

Retrieved Temperature (K)
Water Vapor Mixing Ratio (g/kg)
Ozone Mixing Ratio (ppMV)
Cooling Rate (K/day)
Potential Temperature (K)

NX(1) is the number of altitudes in subsequent data records
Station Latitude (deg)
Station Longitude (deg)
Aircraft Pressure (mb)
Skin Temperature (K)

HIS temperature and water vapor profiles (Aircraft Level -1000 mb) with skin-temp are retrieved from non-edited spectra. In general, temperatures are believed to be of good quality except below the cloud level (set to missing when detected). Water vapor mixing ratio profiles are valid from the tropopause down to cloud level. Retrievals of water vapor in the stratosphere are not considered to be reliable because of the very weak stratospheric water vapor emission signal. Ozone profiles are not yet considered to be reliable, particularly in the troposphere. The ozone retrieval technique is under development.

File Summary:

11-18-96	11:03p	5533	0	em960415.ea1
12-17-96	4:26p	250371	0	em960416.ea1
11-18-96	11:04p	217505	0	em960420.ea1
11-18-96	11:04p	324904	0	em960421.ea1
11-18-96	11:04p	283329	0	em960423.ea1

11-18-96	11:04p	56303	0	em960426.eal
11-18-96	11:05p	247227	0	em960427.eal
11-18-96	11:05p	178933	0	em960502.eal
11-18-96	11:05p	1917	0	em960503.eal
11-18-96	11:05p	2517	0	em960504.eal
11-18-96	11:05p	410450	0	em960507.eal
11-18-96	11:23p	538580	0	hp960402.eal
11-18-96	11:23p	413351	0	hp960403.eal
11-18-96	11:23p	952295	0	hp960408.eal
11-18-96	11:23p	1038841	0	hp960413.eal
11-18-96	11:23p	1381608	0	hp960415.eal
11-18-96	11:23p	652307	0	hp960416.eal
11-18-96	11:23p	393484	0	hp960420.eal
11-18-96	11:23p	134776	0	hp960421.eal
11-18-96	11:23p	420589	0	hp960423.eal
11-18-96	11:23p	696308	0	hp960426.eal
11-18-96	11:23p	426567	0	hp960502.eal
11-18-96	11:23p	2058094	0	hp960503.eal
11-18-96	11:23p	1137178	0	hp960504.eal
11-18-96	11:23p	615818	0	hp960507.eal
11-18-96	11:23p	1268451	0	hp960508.eal
11-04-97	1:07p	4562	0	doc
11-18-96	11:03p	14311	0	em960413.eal

HIS Regression and Physical Retrieval Production

1.) **Calculate to skin temperature** file using CTGSKN. Obtain RAOB file from Hal Woolf.

Input file contains :

- RAOB input file (format of RAOB files is explained at the end of the document)
- RAOB output file containing skin temps
- record bounds (first and last) to be processed
- Threshold surface skin temperature defining clear or cloudy view (typically set to approx. 250K). Anything below the threshold value will be deleted from average RAOB profile. **BE CONSISTENT WITH THIS THRESHOLD VALUE, SINCE IT IS USED IN LATER STEPS.**

example :

```
succ95ax
succ95ax.sk4
1 3070
240.
```

2.) **Determine cloudy and clear retrievals** using CLDRAOBNP. For lowest 10 pressure levels, program will assume cloudy view when relative humidity is above 95%; above this, 80% relative humidity will define a cloudy view. Program works top-down (starting at 50mb). Isothermal profile is set below cloud level, with surface skin temperature reset to cloud top temperature for these cases. This file is known as the TIGR data set in various programs to follow.

Input file contains :

- RAOB/skin temp file
- Record bounds to process
- RAOB output file (TIGR) modified w/ cloud top temps for cloudy views
- Cloud check temperature value (same as in step 1)

example :

```
succ95ax.sk4
1 3070
succ95ax.sk4.cld
240.
```

3.) **Create an average RAOB profile** from the complete set of RAOB profiles using RAOBAVG.

Input file contains :

- RAOB input file (TIGR) (from step 2)
- RAOB average profile output file (one record)
- Record bounds to process (number of clear records; different than step 1 and 2)
- Cloud check temperature value (same as in step 1)

example :

```
succ95ax.sk4.cld
succ95ax.sk4.cld.avg
1 2230
240.
```

4.) **Calculate synthetic HIS spectra** from RAOB file profiles using HISSPE. Gamma correction is applied to calculation of spectra. Must be done separately for each band/channel (separate input file for each band/channel).

Input file(s) contain :

- RAOB input file (TIGR) (from step 2)
- Tag for old or new data format
- Record bounds to process
- Band number to process (NOT channel number)

- Constituent types
- Output file containing synthetic HIS spectra for selected band
- Output format (radiance or brightness temperatures)
- Gamma correction input flag (non-zero to use a gamma correction)
- Gamma correction input file (if used)
- Transmittance output flag (non-zero to output transmittances)
- Transmittance output file (if desired)
- Cloud check temperature value (same as in step 1)
- Aircraft flight level (50mb most cases)

example :

```

succ95ax.sk4.cld
new
1 2230
2
all
suc95bt2.sk4.cld
tbb
1
gammchn3.95.bgm.hgt.np.opq.nl
0
240.
50.

```

5.) **Calculate eigenvectors** using EIGBRTC2 (channel 2) and EIGBRTC3 (channel 3).

Input file(s) contain :

- Spectral coverage range (band/channel dependent)
- Synthetic HIS spectra input file (from step 4)
- record bounds to process
- Eigenvector output file
- Channel selection output flag (non-zero to output channel flag file)
- Channel selection output file (if desired)
- Cloud check temperature value (same as in step 1)

example :

```

1125. 1600.
suc95bt2.sk4.cld
1 2230
brteigv2.suc95
1
chnself2.204
240.

```

6.) **Compute regression retrieval coefficients** using TQEIGBTREGCDNEW.

Input file contains :

- RAOB input file (TIGR) (from step 2)
- Mean RAOB profile input file (from step 3)
- Synthetic HIS spectra input file, any band (from step 4)
- Record bounds
- Channel position in synthetic HIS spectra file name
- Band processing flags (non-zero to process)
- Band 1 spectral range (if desired)
- Band 2 spectral range (if desired)
- Band 3 spectral range (if desired)
- Diagnostics flag (non-zero to print)

- Eigenvector input file, any band (from step 5)
- Noise radiance input file (changes from flight to flight)
- Channel flag input flag (non-zero to input channel flag file)
- Channel flag input file (from step 5, if output)
- Cloud check temperature value (same as in step 1)
- Regression coefficient output file

example :

```

succ95ax.sk4.cld
succ95ax.sk4.cld.avg
suc95bt3.sk4.cld
1 2230
8
1 1 0
670. 950.
1125. 1600.
0
brteigv3.suc95
hotnois3.413
1
chnselt3.204
240.
eigbtcof.suc95.sk4.cld

```

NOTE : Steps 1 - 6 are "generic" for each experiment, and only need to be done once. They are known as the "Regression Set-up" steps. After creating regression coefficient files in step 6, the following steps must be done separately for each flight during the experiment in order to compute the actual regression and physical retrievals.

7.) **Calculate regression retrievals using TQEIGBTRETCDNEW.**

Input file contains :

- Mean RAOB input file (from step 3)
- HIS observed spectra (brightness temperatures)
- Record bounds
- Channel position in observed spectra file name
- Band processing flags (non-zero to process; be consistent with step 6)
- Band 1 spectral range (if desired)
- Band 2 spectral range (if desired)
- Band 3 spectral range (if desired)
- Diagnostic message flag (non-zero if desired)
- Eigenvectors input file (from step 5)
- Regression coefficients input file (from step 6)
- Noise radiance input file
- Channel selection input flag (non-zero to input channel flag file)
- Channel selection input file (from step 5, if output)
- Cloud check temperature value (same as in step 1)
- Aircraft height output units (non-zero for meters, otherwise feet)
- Regression retrievals output file
- ASCII file dump flag (non-zero to output)
- ASCII file dump output file (if desired)

example :

```

succ95ax.sk4.cld.avg
ha13btc3
1 551

```

```

8
1 1 0
670. 950.
1125. 1600.
0
brteigv3.suc95
eigbtcof.suc95.sk4.cld
hotnois3.413
1
chnselt3.204
240.
1
regrtv.a13
0

```

8.) **Calculate physical retrievals using TQNEWT5.**

Input file contains :

- Flag for spectra files (A - PLOVR format)
- Regression retrieval input file (from step 7)
- Record bounds
- Total number of records in regression retrieval file
- Observed HIS spectra file (any band)
- Channel position in observed spectra file name
- Atmosphere type (trace gas profile)
- Bias spectra input file flag (non-zero to use)
- Bias spectra input file name (if desired, any band)
- Bias spectra record number (if desired)
- Noise radiance input file flag (non-zero to use)
- Noise radiance input file (if desired)
- Band processing flags (non-zero to process; be consistent with step 6)
- Band 1 spectral range (if desired)
- Band 2 spectral range (if desired)
- Band 3 spectral range (if desired)
- Diagnostic message flag (non-zero if desired)
- Physical retrieval output file name
- ASCII file dump flag (non-zero to output)
- ASCII file dump output file (if desired)
- Tb(obs)-Tb(ret) spectra difference output file name
- Sequential retrieval output flag (non-zero for sequential)
- Number of iterations for retrieval calculation (6 is standard)
- Type of retrieval flag (0=Tdry/Twet RTV, 1=DB/DQ RTV, 2=Alpha RTV)
- Another retrieval flag (0=mini-inf RTV, 1=M.L.H. RTV)
- Gamma value or T/Q covariance inverse file name (dependent upon previous)
- Gamma correction flag (non-zero to use)
- Gamma correction input file (if desired, from step 4)
- Channel covariance inverse matrix flag (non-zero to use)
- Channel covariance inverse matrix input file (if desired)
- Total channel number value (if desired)
- Channel selection flag (non-zero to use)
- Channel selection input file (from step 5, as used in step 7)
- Eigenvector correction option flag (non-zero to use)
- Observation brightness temperature eigenvector input file
- Aircraft height output units (non-zero for meters, otherwise feet)

- Dry factor (0.9 typical value)

example :

A
regrtv.a13
1 551
551
ha13btc3
8
3
0
1
hotnois3.413
1 1 0
670. 950.
1125. 1600.
0
tqnewt5.a13
0
dtbchnc3.a13
0
6
2
0
1. 5.
1
gammchn3.95.bgm.hgt.np.opq.nl
0
1
chnselt3.204
0
1
0.9

HIS RAOB and retrieval file format :

Files are binary format, 90 words/record, 4 bytes/word, 32 bit words.

Words 1 - 40 : Temperature (degrees K) from 50mb-1000mb
Words 41 - 90 : Mixing ratio (g/kg) from 50mb-1000mb
Word 81 : Original surface pressure (mb)
Word 82 : Original surface temperature (degree K)
Word 83 : Original surface mixing ratio (g/kg)
Word 84 : Station Elevation (meters)
Word 85 : Station latitude (degree, +N)
Word 86 : Station longitude (degree, +E)
Word 87 : Aircraft pressure (mb)
Word 88 : Julian date (YYDDD format)
Word 89 : Time (HHMMSS format)
Word 90 : Surface skin temperature
Pressure levels : 50, 60, 70, 75, 80, 85, 90, 100, 125, 150, 175,
200, 250, 300, 350, 400, 450, 500, 550, 600, 620,
640, 660, 680, 700, 720, 740, 760, 780, 800, 820,
840, 860, 880, 900, 920, 940, 960, 980, 1000

HIS - Validation of NWP Model Performance During ASHOE

W.L. Smith, H.E. Revercomb, H. L. Huang, X. L. Ma, H. B. Howell, H.M. Woolf, R. G. Dedecker, R. Herbsleb, F. Best, and R.O. Knuteson

**Cooperative Institute for Meteorological Satellite Studies
University of Wisconsin - Madison
Madison Wisconsin**

Introduction

The High resolution Interferometer Sounder (HIS) is a fourier transform spectrometer which samples the the upwelling radiance spectrum (3.7 - 18 μ m) with high spectral resolution ($\lambda/d\lambda=2000$). The radiometric data is used to provide vertical profiles of temperature, tropospheric water vapor, and stratospheric ozone beneath the aircraft with a horizontal resolution of 2 Km. The vertical resolution of the profiles is 1 to 2 Km, depending upon atmospheric level. The radiative effects of tropospheric and stratospheric water vapor and other radiatively active constituents (e.g., CH₄, N₂O, CO, and the CFC's) as well as aerosols and clouds are observed. Techniques are available to derive the radiative properties of cirrus clouds, including the optical depth spectrum and effective microphysical properties, such as the particle size and ice water path, responsible for the cloud absorption observed from the ER - 2. During the ASHOE / MESA campaign the HIS temperature and water vapor profile data are being used to validate the thermodynamic characteristics of data assimilation models that provide the global circulation patterns used to analyze the transport of the constituents associated with the Ozone depletion process.

The vertical profiles below the ER - 2 are computed from the HIS radiance observations using a retrieval method which is totally independent of contemporary meteorological data and as such the results are totally independent of the numerical model analyses which are to be validated. The retrieval process is a two step procedure. In the first step a close estimate of the temperature and water vapor profiles are achieved using regression relations between coefficients of radiance eigenvectors and temperature and water vapor mixing ratio values derived from a diverse sample of Southern Hemisphere radiosonde observations taken over the entire year of 1993. One novel feature of this regression estimate is that the radiance eigenvectors used to achieve the regression relations are derived from the spectral radiance observations for the particular flight being analyzed. The coefficients are achieved by fitting these to synthetic spectra calculated from the climatological set of temperature and moisture profiles. This process tends to filter the climatological data set for the meteorological conditions actually observed during the flight in question. Given a good regression estimate of the temperature and moisture profile, a final estimate is achieved using a full non-linear physical inverse solution of the radiative transfer equation using one dimensional variational analysis principles.

Comparison of HIS, TOVS, and Operational Thermodynamic Analyses

The main source of data for numerical analyses of the thermodynamic characteristics of the Southern Hemisphere oceans is from the TIROS Operational Vertical Sounder (TOVS) which is aboard the operational NOAA satellites. For the ASHOE observation region (45° S to 70° S, and 175° E to 175° W), there are New Zealand and Antarctic radiosondes available to influence at the northern and southern edges of the analyses along the ER - 2 flight path. Since the TOVS is a low vertical resolution sounding system which provides mean temperature and relative humidity of relatively thick layers, the analyses resulting from a good dynamical model data assimilation system should be an enhancement of the vertical resolution of this input data. In any event, it of interest to compare numerical model analyses with static analyses of TOVS only data both to be validated against static analyses of the relatively high vertical resolution ER -2 HIS profiles, regarded here as the measure of "truth" along the ER - 2 flight track.

As part of the ASHOE data analysis program the HIS, TOVS, and dynamical model analysis comparisons are being made for temperature, and water vapor (as well as the infrared cooling rate derived from these profiles). The results from five different data assimilation models are being compared in an effort to understand the dependence of the results on the different characteristics of each model and on the manner in which they assimilate the satellite sounding data. The five different model results are from the: (1) Australian Bureau of Meteorology, (2) British Meteorological Office, (3) European Centre for Medium range Weather Forecasting, (4) NASA Goddard Space Flight Center, and (5) NOAA's National Meteorological Center. Because of the limited space available here, only temperature results from the Australian and ECMWF models are shown here. During the oral presentation, results from all five models are intercompared. It important to note that for the five models considered, the temperature analyses from the Australian model compared most closely with the static analyses of the HIS temperature profile retrievals.

Figures 1 and 2 show the results in terms of temperature profile cross-sections (500 - 50 mb) along the flight track of the ER -2 for two different flight days, August 8/9. and August 10/11, during the 1994 ASHOE. It should be noted that the HIS results near the top and bottom of these panels (ie., 50 mb and 500 mb) should be viewed with caution because the profiles are extrapolated above the actual flight level (nominally about 60 mb) to 50 mb isothermally and the pattern near 500 mb may be influenced by the existance of cloud which causes the retrieval to tend towards an isothermal state below cloud level, the degree to which depends upon the fraction and opacity of the cloud within the instruments 2 Km field of view. (Retrievals for radiances effected by cloud above the 500 mb level were excluded from the cross-section analyses shown here.) As can be seen there are significant variations in the thermal state between the two different measurement days. In general the dynamical model analyses compare more favorably with the HIS observation than does the static TOVS analysis suggesting that the data assimilation procedure is producing the desired effect of enhancing the low vertical resolution satellite data input. The only negative characteristic of the model comparisons shown here is that the finer scale features of the lower stratospheric temperature seem to be missed by the dynamical model analyses. This is particularly evident on the Poleward side of the Southern Polar Vortex near the southern most portion of each flight track pattern. It remains to be shown whether this is merely a consequence of the vertical and horizontal resolution of the analyses and / or due to inadequate physics for describing the vertical motions associated with the vortex. It is important to re-

emphasize that the comparisons shown here are the closest of the five models considered and as such may give a misleadingly optimistic impression of the accuracy of global analyses for this region.

Atmospheric Cooling Rate Calculations for the Airborne Southern Hemisphere Ozone Experiment (ASHOE) using MODTRAN3

S.C. Lee, R.O. Knuteson, H.E. Revercomb, and W.L. Smith

University of Wisconsin-Madison CIMSS
1225 W. Dayton St., Madison, WI 53706

I. Introduction

One of the objectives of the Airborne Southern Hemisphere Ozone Experiment (ASHOE) was to examine the causes of ozone loss in the Southern Hemisphere lower stratosphere, and to investigate how the loss is related to polar, mid-latitude, and tropical processes, including radiative transfer. Cooling rates were calculated for ASHOE in order to: (1) understand how the ozone depleted air is transported to populated regions outside the polar vortex, (2) relate vertical motions and transport of air around the South Pole to atmospheric cooling rates, and (3) validate cooling rates in dynamical models for the polar vortex using observed data and more accurate radiative transfer models.

II. Experimental Method

This analysis follows that of Clough et al. (1992). Consider monochromatic thermal radiation for clear sky at a given level, with μ = zenith direction cosine, and ϕ = azimuthal angle. The flux expressions may be written thus:

Upwelling flux

$$F_v^+ = \int_0^{2\pi} \int_0^1 I_v(\mu) \mu d\mu d\phi$$

Downwelling flux

$$F_v^- = \int_0^{2\pi} \int_{-1}^0 I_v(\mu) \mu d\mu d\phi$$

Azimuthally integrated flux

$$F_v^\pm = \pm 2\pi \int_0^{\pm 1} I_v(\mu) \mu d\mu$$

Three-point Gaussian quadrature was performed at the angles: 77.74°, 53.80°, and 24.29°. This yields a net flux:

$$F_v = F_v^+ - F_v^-$$

Strictly speaking, the monochromatic cooling rate is the divergence of the net flux. However, one may also express it in terms of the temperature change in a layer:

$$\left. \frac{\partial T}{\partial t} \right|_{p_j, j-1} = \frac{g}{C_p} \frac{F_{v,j} - F_{v,j-1}}{P_j - P_{j-1}}$$

III. Results

Cooling rate comparisons between models

In order to validate the cooling rates derived using MODTRAN3, a comparison was made to published results of Clough et al (1992). The models compared here are characterized as follows. FASCODE, a line-by-line transmittance model using HITRAN database (Clough, et al, 1986, Rothman, et al, 1992), has very high spectral resolution, but is computationally demanding. Phillips Laboratory's MODTRAN version 3 has lower spectral resolution at 2 cm⁻¹ (Wang, et al, 1996), but is computationally fast. Calculated cooling rates between the models agree very well from 750 mb up to 150 mb. (Fig. 1).

Sensitivity study to upper level water vapor

To assess the importance of upper tropospheric water vapor to the atmospheric cooling rates, a sensitivity study was performed using MODTRAN3. Removing the water vapor above 300 mb affects cooling rates, not only in that region, but also in the middle troposphere (Fig. 2). Results indicate that smaller water vapor amounts cause lower cooling rates.

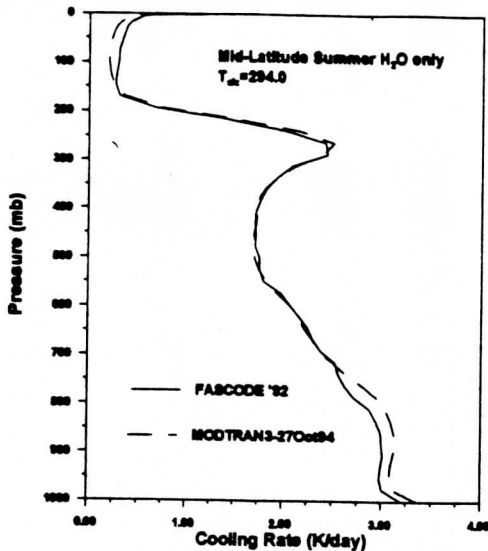


Figure 1. Cooling rate comparison

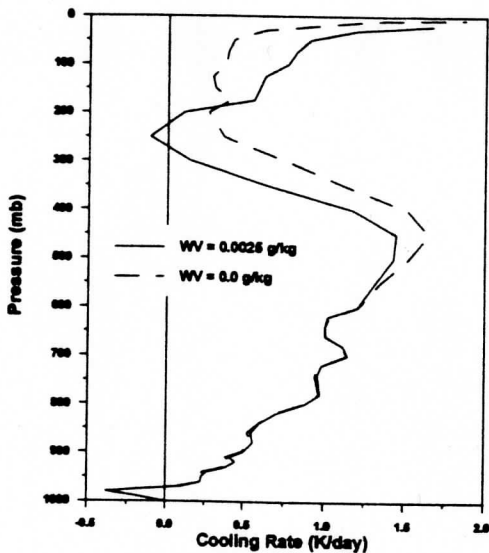


Figure 2. Comparison of cooling rates calculated with different upper atmospheric water vapor profiles

Polar region cooling rates

Retrieved temperature and water vapor from University of Wisconsin High-resolution Interferometer Sounder (HIS) (Smith et al, 1987) observations during ASHOE flights into the south polar vortex from New Zealand on 4 October 1994 were used to calculate cooling rates, which were

compared to cooling rates calculated using water vapor and temperature input from four global forecast models (Fig. 3). Overall, the forecast models tend to underestimate the stratospheric water vapor concentrations in polar regions, which leads to an underestimate of the cooling rate. Figure 4 shows layer mean cooling rates from water vapor, carbon dioxide, and ozone. Water vapor contributions dominate not only in the troposphere, but also in the stratosphere. Figure 5 shows the spectral cooling rate, with contributions from the seven primary infrared optically active gases.

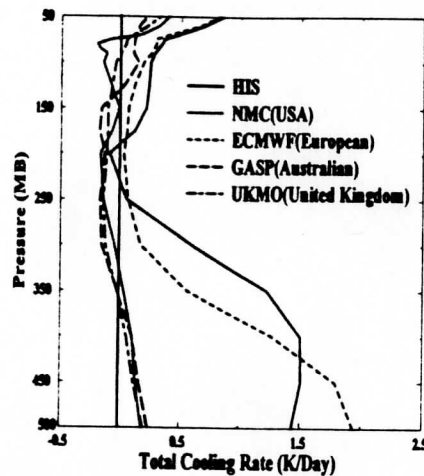


Figure 3. Cooling rate comparison for ASHOE - October 4 1994 68S

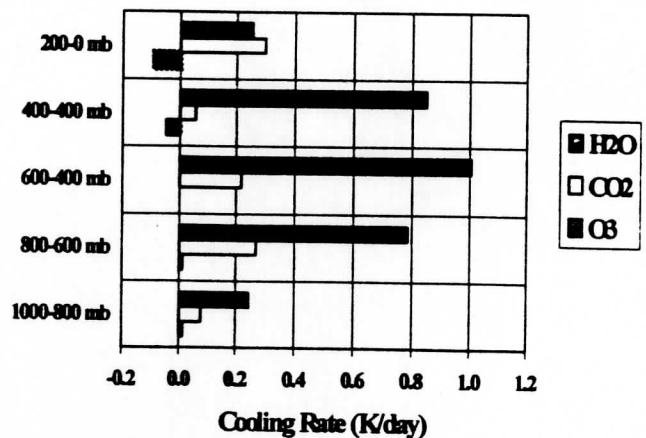


Figure 4. Layer mean cooling rates for H₂O, CO₂, and O₃

IV. Summary

If calculation models have little or no water vapor above 200 mb, then the model will produce an error in the cooling rate of about 0.2 K. In the upper troposphere and stratosphere, the cooling rate is not dominated by carbon dioxide alone, but also strongly by water vapor (between 400 cm^{-1} and 660 cm^{-1}). Results of case studies show that a drier atmosphere leads to a lower cooling rate in the upper troposphere.

V. References

Clough, S.A., Proc. of the 6th Conf. on Atmospheric Radiation, Williamsburg, VA, 1986.

Clough, S.A., M.J. Iacono, and J.-L. Moncet, Line-by-line calculation of atmospheric fluxes and cooling rates: Application to water vapor, *J. Geophys. Res.*, 97, 15,761-15785, 1992.
Rothman, L.S., et al, HITRAN molecular database: Edition '92, *J. Quant. Spectrosc. Radiat. Transfer*, 48, 469-508, 1992.
Smith, W.L., et al, 21st International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, 1987.
Wang, J., G.P. Anderson, H.E. Revercomb, R.O. Knuteson, Validation of FASCOD3 and MODTRAN3: Comparison of Model Calculations with Ground-Based and airborne Interferometer Observations Under Clear-Sky Conditions, in press, *Applied Optics*, 1996.

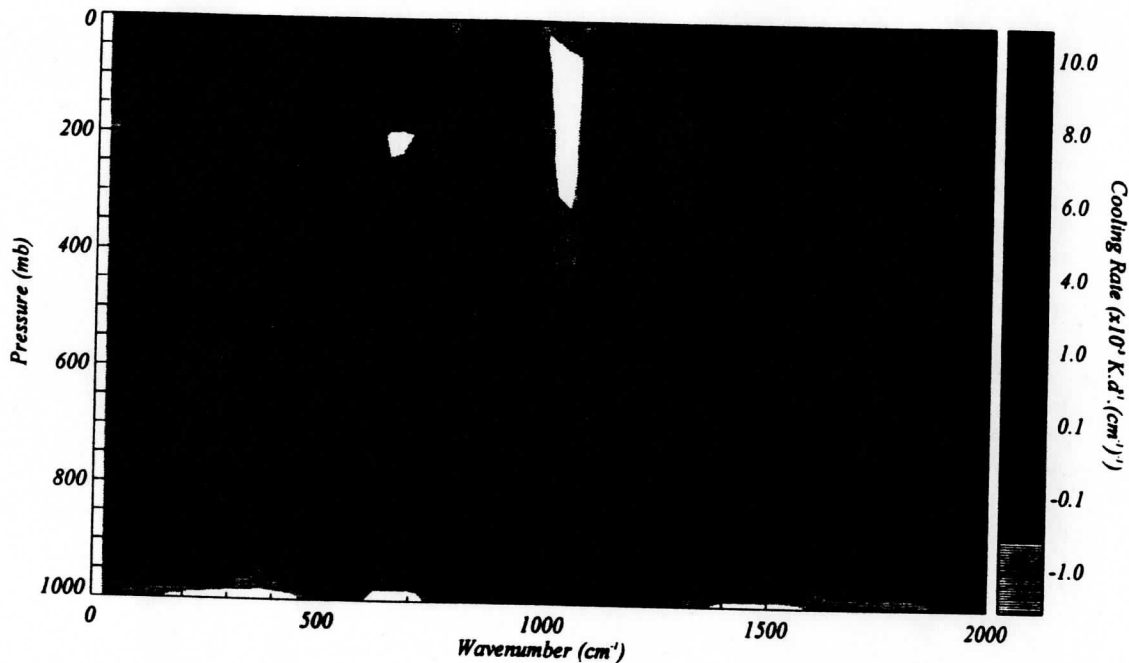


Figure 5. Spectral cooling rate profile as a linear function of pressure