Comparison of Cloud Fields from AGCM, In Situ and Satellite Measurements

Robert D. Haskins[1], Tim P. Barnett[2], Mary Meyer Tyree[2], and Erich Roeckner[3]

Abstract

This paper focuses on the comparison of cloud amounts derived from an Atmospheric General Circulation Model (AGCM), Satellite-observed clouds, and Ground-based cloud observations. This is distinctly different from Earth Radiation Budget Experiment (ERBE)-type comparisons because it does not mix potential errors in the cloud amount with those in the radiation code embedded in the model. Long term cloud climatologies were used to compare global cloud amounts and regional seasonal cycles. The results obtained were surprising in many respects. The AGCM successfully reproduced the signatures of the warm pool and North Pacific seasonal cycle cloudiness but failed in the low stratus region off the coast of South America, a known problem for AGCMs. The data sets also reproduced the anomaly signature associated with El Niño in the warm pool region, but the model amounts were lower. Global results had a similar success rate, with the model generally producing lower total cloud amounts compared to the satellite and in situ measurements. Also, an attempt was made to compare cloud vertical distributions between the data sets. Because of the inherent differences in the measuring processes among the three data sets, the cloud height may need to be validated using the corresponding radiation fields.

Unfortunately there were also some large discrepancies between the two observed cloud data sets. We conclude that the character of the observed cloud data sets, while tremendously improved over the last decade, must be substantially enhanced before they will be useful in validating AGCMs by any but the crudest levels of comparison.

1 Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109
2 Scripps Institute of Oceanography, University of California, San Diego
3 Max Planck Institute for Meteorology, Hamburg, Germany

1. Introduction

The goal of this research is to compare the cloud distributions produced by an Atmospheric Global Circulation Model (AGCM) with measured (satellite and surface based) data to attempt to gain an understanding of the model strengths and weaknesses, as well as the degree of agreement between modern cloud data sets. The importance of clouds in the hydrological cycle and as an agent of global change is well known and will not be repeated here. Suffice it to say, the cloud parameterizations in AGCMs are the most sensitive element of these complex computer models (for example, Kiehl and Williamson, 1991 and Slingo and Slingo, 1991). Errors of only a few percent in the AGCM-produced cloud fields have the potential to seriously degrade the performance and believability of the models. The successful simulation of cloud cover and vertical cloud distribution is also important with respect to coupled ocean-atmosphere models. As described in several studies, errors in the simulated cloud fields can translate directly into errors in the simulated sea surface temperature (SST) field (for example, Latif *et al.* (1994) and Stockdale *et al.* (1994)). Thus, although the cloud errors do not necessarily have a large effect on the simulated climate in atmospheric models when run in a stand-alone integration with prescribed SSTS, cloud errors can easily cause serious problems in coupled integrations.

Many comparisons between output AGCM radiation fields (cloud forcing, outgoing long wave, etc.) and Earth Radiation Budget Experiment (ERBE) - type measurements have yielded varying results (Roeckner *et al.*, 1992; Peterson *et al.*, 1992; Cess *et al.*, 1990; Kiehl and Ramanathan, 1990). These comparisons test simultaneously two components of the AGCMs: the calculated cloud fields and the corresponding radiation calculation. There is much disagreement among the radiation codes themselves (see Luther *et al.*, 1988). This paper isolates first the comparison with clouds with subsequent research to compare the radiation fields.

Past studies of the cloud data have been rather bimodal. On the one hand, there have been intercomparisons of various cloud data sets (cf. Rossow and Schiffer, 1991; Mokhov and Schlesinger, 1993; Klein and Hartmann, 1993). At the same time, numerous studies have showed the critical importance of cloud parameterizations to AGCM performance (cf. Cess *et al.*, 1990; Wetherald and Manabe, 1986; Slingo, 1990) while other studies have shown selected features of the model that strongly affect cloud distributions (for example, resolution, Kiehl and Williamson, 1991). However, few studies have attempted to compare directly the abundance and distribution of clouds in models with those observed. As noted above, such an endeavor is clearly different from joint testing of cloud and radiative schemes in models (Peterson *et al.*, 1992; Randall and Tjemkes, 1990; and others).

Strictly comparing the cloud fields also has its uncertainties. Satellite retrieval of cloud amount can depend on the size of their observational viewing area as shown by Wielicki and Parker, 1992. These errors are also cloud-type dependent. Some of these errors can be traced to an algorithm-related effect of "beam filling" which is related to the size and distribution of the cloud-type. To further complicate these comparisons is the problem of changing cloud amount with changing AGCM spatial resolution. As Kiehl and Williamson have shown (1991), at least for the NCAR Community Climate Model (CCM), the cloud amount decreases as the horizontal resolution increases. For example, the CCM T42 (approximately 2.8° x 2.8°) total cloud fraction was found to be 0.36 that decreased to 0.26 for the T106 (approximately 1.00 x 1.OO) resolution. Furthermore, the different observational techniques, (satellite Vs ground observation) have inherent biases in the data sets. Because of these problems, the focus of this paper is the regional validation of clouds that allows the isolation of certain types of clouds (for example, cirrus Vs stratus). There are no correct or incorrect cloud data sets; all have their relative merits. By viewing three very differently derived data sets, it is hoped that when at least two agree, it is more than a coincidence, and that the underlying Physics will explain the agreement (or when they disagree).

The paper is organized as follows. Section 2 gives a brief description of the cloud data sets used in this research. Section 3 discusses three cloud climatologies during the 1979 FGGE year. This section begins with simple zonal mean comparisons, and quickly switches to regional comparisons. Section 4 compares regional seasonal cycles for the three long term cloud climatologies and shifts back to a seasonal global perspective. The satellite cloud climatology used in this section changes to the International Satellite Cloud Climatology Project (ISCCP) data because of its longer time scale. The regional vertical structure of the cloud field is discussed in section 5 using an EOF analysis and regional interannual variability in Sect on 6. Section 7 follows with the conclusions of this research.

2. Data Set Description

In this section we discuss the data sets used in this analysis. This paper focuses on one AGCM, one satellite data set, and one surface based data set. The data sets were chosen mainly based on the length of the data records in order to calculate seasonal cycles. However, Section 3 discusses the satellite-derived clouds produced by HIRS2. The reason for this is the near term potential for a consistent long term global data set using the TOVS Pathfinder data set (+15 years).

2.1 Atmospheric Model

The atmospheric general circulation model (AGCM) is the European Center Hamburg Model (ECHAM3) provided by the Max Planck Institute for Meteorology in Hamburg. The model data used in this study were obtained from a 10 year long T42 resolution run made using specified sea surface temperatures (SST), i.e., the Atmospheric Model Intercomparison Program (AMIP) runs (Gates, 1992). This version of the model had 19 levels in the vertical, prognostic cloud water content and other advanced physical parameterizations. A full description of the model may be found in Roeckner *et al.*, 1992. The following paragraphs summarize certain key features of the model physics that pertain to this study.

The ECHAM3 model deals with convective and stratiform clouds separately. It uses a comprehensive mass flux scheme for cumulus convection (Tiedtke, 1989). The cumulus convection scheme comprises the effect of deep, shallow and mid-level convection on the budget of heat, water vapor and momentum. Cumulus clouds are represented by a bulk model including the effect of entrainment and detainment on the updraft and downdraft convective mass fluxes. Mixing due to stratocumulus convection is parametrized as a vertical diffusion process (Tiedtke *et al.*, 1988) with eddy diffusion coefficients depending on the cloud water content, cloud fraction and relative humidity jump at cloud top.

The prediction of stratiform clouds is based upon the cloud water equation including sources and sinks due to condensation/evaporation and precipitation formation by coalescence of cloud droplets and sedimentation of ice crystals (Sundquist, 1978; Roeckner *et al.*, 1991). The key large-scale elements in the formation of the low clouds are specific humidity, saturation specific humidity, and a stability factor. Sub-grid scale condensation and cloud formation are taken into account by specifying appropriate thresholds of relative humidity depending on height and static stability.

2.2 The Satellite Data Sets

ISCCP-C2

The International Satellite Cloud Climatology Project (ISCCP) has been routinely collecting, reformatting, and calibrating visible and infrared images from a host of operational geostationary and polar-orbiting meteorological sounders since July 1983 (Schiffer and Rossow, 1985; Rossow *et al.* 1985). Atmospheric temperature, humidity, and column ozone abundance are obtained from the NOAA operational analysis as well as ice and snow data from NOAA and the U.S. Navy.

The determination of the cloud parameters is performed by the ISCCP Global Processing Center at the Goddard Institute for Space Science (GISS). The ISCCP cloud analysis procedure is based on three parts: cloud detection, radiative analysis, and statistical analysis. The processing starts with a normalized calibrated reduced resolution version of the original data at a nominal spacing of 3 hours and 30 km. The data is gathered for a period of one month to collect statistics on clear and cloudy scenes. This aids the threshold determination in two ways: only an estimate of clear radiances is needed (not clear Vs cloud) and time is used as a discriminator. Next measured radiances are compared to calculated clear and cloudy radiances using the NOAA atmospheric products and surface models as input. This step determines the radiative properties of the cloud such as cloud height and cloud optical thickness (at least as many as can be determined by the limited frequency coverage of the satellite measurements). The final step is the merging and projection of the pixel data onto 280 km equal area grid points (ISCCP-C1). This data is then averaged into monthly quantities (ISCCP-C2). The data used in this study is the ISCCP-C2.

HIRS2

The HIRS2/MSU data sets are derived from the measurements in 19 channels from the High Resolution Infrared Radiation Sounder (HIRS) instrument, and 4 channels from the Microwave Sounding Unit (MSU), which fly on NOAA's polar orbiting meteorological platform. Susskind and others (Susskind *et al.* 1984) have developed a set of up to 40 meteorological parameters from the multispectral HIRS2/MSU data. Among the derived parameters are day and night fields of: atmospheric temperature profiles (surface to 70 rob), surface temperature (land and ocean), vertical water vapor distribution, effective cloud amount, cloud top height, and cloud top temperature.

A consistently derived data set is currently available for December 1978 to November 1979 at spatial resolution of 125 x 125 km, with 250 km spacing between grid points on a daily basis. The Goddard program, in conjunction with Pathfinder, is planning to generate the full HIRS2/MSU derived data set starting with April 1987 to the present and returning to 1978.

The HIRS2/MSU data analysis scheme uses five infrared channels which sample different regions of the atmosphere to calculate cloud parameters. The important difference between the HIRS2/MSU cloud retrieval and other schemes is that HIRS2/MSU cloud products are produced such that the thermodynamic atmospheric state (temperature, water vapor, and clouds) in a column is retrieved consistent with the radiances as measured by the instruments, This approach eliminates the so called "beam filling" problem traditionally associated with thresholding methods.

2.3 The Surface based Data Set

Warren, Hahn, and London, (WHL)

The data sources for this collection of surface-based cloud observations were obtained from the SPOT archive of the Fleet Numerical Oceanography Center in Monterey, California and from the Comprehensive Ocean-Atmosphere Data Set (COADS) see Warren *et al.,* 1985,1986, 1988. Approximately 116 million reports from January 1971 through December 1981 were analyzed from the SPOT data and 43 million reports from the COADS set for the period 1952-1981.

Six different types of clouds were summarized as well as fog and clear sky. Frequencies and amounts of the low cloud types (Cu, St, and Cb) and mid cloud types (As and Ns) were also computed. The global observations were averaged into 5° x 5° bins except for the FGGE year (December 1978-November 1979) which were 2.5° x 2.5° in resolution. Separate land and ocean data sets are provided.

3.1979 FGGE Year

This section looks at three cloud products that are coincident in time, namely the 1979 FGGE year. Zonal averages are presented in Section 3.1 and regional comparisons presented in Section 3.2

3.1 Simple Zonal Means - Gross Features

As shown in figures 1 and 2, the shapes of the zonal cloud cover curves for the data sets over the oceans and over land are similar, with local maxima associated with the Intertropical Convergence Zone (ITCZ), mid latitude frontal zones, and local minimum in the subsidence regions near ±30°. There is a more pronounced zonal amplitude associated the land as expected. In both cases, the clouds determined from HIRS show a remarkably constant offset from the WHL data with the ratio of HIRS to surface based approximately .75. This result is similar to that obtained by Chahine and Haskins, 1982 using VTPR data, the precursor atmospheric sounder to HIRS.

The reason the magnitude of the HIRS2/MSU effective cloud fraction is lower than that for other cloud climatologies could be due to several factors, For instance, the HIRS2/MSU effective cloud fraction is defined as the product of the cloud amount and the cloud emissivit y, which is generally less than 1.0 (the cloud emissivity is much less than one for cirrus clouds). Another complication is the effect of cloud opacity. There can be an ambiguity in interpreting the outgoing radiation as measured by the satellite. An optically thinner cloud at higher (colder) elevation (cloud height higher, cloud amount smaller) can reduce the emerging radiance as much as an optically thicker cloud at a lower level (cloud height lower, cloud amount larger). The retrieval methodology for HIRS2 attempts to resolve this ambiguity by using multiple measurements sensitive to different heights. The model results show a much more pronounced variation oscillating between the surface based data and the HIRS results. This may be indicative of the effects of cloud opacity in the model.

3.2 Regional Comparisons

We have focused on three regions that are both climatologically interesting and important testing areas for the AGCM. The first region is the Indo-Pacific warm pool (WP region) defined here as lying between 10N-1OS and 90 E-150E. The second region is a prime weather generator for North America and is in the central North Pacific (NP region) between 45-60N and 150W-180. The final regional focus is in the heavy stratus region off the west coast of South America (SA region) located in the area 10-30S and 75W-90W. Seasonal averages of the total cloud amount for 1979 are shown for the three regions in Figure 3. Recall that the HIRS retrieves an 'effective cloud fraction', i.e., the cloud amount scaled by the cloud emissivity. Hence, the HIRS data has been scaled by a factor of (1 /.75) consistent with the zonal means discussed in the previous section.

3.2.1 Warm Pool Region

The seasonal minimum for 1979 is reproduced by all three data sets but with some key differences. The AGCM seems to overestimate the clouds in the winter months compared to either observational set. The HIRS data duplicates the WHL signature but, even with the scaling factor applied, seriously underestimates the cloud amount. This is most likely due to the fact that the emissivity of the cirrus clouds is much lower than the assumed .75 scaling factor. This also may be due in part to a known problem with cloud contamination in the MSU microwave channels, which is used in conjunction with the infrared channels for cloud clearing.

3.2.2 North Pacific Region

The seasonal maximum is consistent for both the WHL and the AGCM, although lower amounts were attributable to ECHAM3 by roughly 15%. The HIRS data scales well with the WHL in the Winter and Spring months, but fail to reproduce the Summer maximum. The WHL data show an increase in all cloud types (High, Middle and Low) in the summer and it is quite possible that the satellite cannot 'see' the increase in the middle and low cloud decks.

3.2.3 South American Region

Remote sensing of low clouds, common in the region, is notoriously difficult, as will be seen later in the ISCCP data. However, the scaled HIRS data does a fairly good job of replicating the WHL data for all the months in the coastal stratus test region. The uniform cloud decks must exhibit a fairly constant cloud opacity / cloud emissivity in this region. The model data underestimate the fairly constant cloud in the Southern Hemisphere summer and fall months. The model clearly fails to reproduce the period of seasonal increase for Southern winter and spring.

4.0 Seasonal Cycle

4.1 Regional Results: Total Cloud Amount

The above results, while informative, are based on but one year's data. In an attempt to overcome these shortcomings, we have concentrated on two longer data sets (Warren et *al.*, 1985,1986,1988 and ISCCP) that represent the most *modern* satellite-derived cloud product and the most comprehensive directly observed cloud product. The nature of the seasonal cycle for both the observed data and model is considered in each of the regions described in 3.2.

4.1.1 Warm Pool Region

The period over which the seasonal cycle was computed varied markedly between data, as noted in Section 2. Nevertheless, there are some striking similarities among the three estimates over the WP region. Most notable is the springtime minimum observed during the April-May period (Fig. 4) as seen in Section 3.2. Investigation of the model physics showed this feature coincided with a minimum in the near surface wind field convergence and a maximum in the annual cycle of static stability. The magnitude and asymmetric character of the annual cycle is also quite similar among the three data sets, even to the small secondary peak in the June-July time frame. The magnitude of this peak is small in the model, only about 2%, but present at that level in the observed data sets. The wintertime maximum is also well reproduced in all data, with especially good agreement between the ISCCP and ECHAM3.

The annual mean for the observations and model, averaged over the year, differ little. The WHL set has a mean of approximately 65%, the ISCCP is close to 69%, and the model is also approximately 68%. The main disagreement between model and observation occurs in the magnitude of the seasonal cycle. Both the observational sets show a range of 8%, while the model shows more magnitude (14%), suggesting an exaggerated seasonal cycle in the large scale convection.

In summary, we were somewhat surprised to see that the model reproduced virtually the same seasonal cycle in total cloud cover as that obtained from the two different observation sets.

4.1.2 North Pacific Region

The model data agreement for the NI' region (Fig. 5) might best be described as moderate. All curves show a maximum in the June-July time frame. The WHL and model data suggest a minimum in October-November, but this minimum appears in December in the ISCCP data.

The major difference is in the annual mean of the total cloud amount. The observations have values of approximately 84-8770, while the model is close to 72%. The model also underestimates the maximum values of the seasonal cycle (77% vs. 93% for both observed sets), a result largely accounted for by the bias just noted. However, the range or magnitude of the seasonal cycle, after removal of the mean, is about the same for all three data sets (12%).

In summary, the performance of the model in the North Pacific region is comparable with that of the observation sets in the sense that the model-data differences are of the same order of magnitude as the differences between the observational sets themselves. The main exception to the generally good agreement is found in the annual mean cloud amount, which is lower in the model.

4.1.3 South American Region

All three climatologies show marked disagreements in this region. The ability of the model to reproduce the seasonal cycle of total cloud cover in the SA region is poor (Fig. 6). The observations show the maximum cloudiness to occur in July-September (WHL) or September-November (ISCCP), a substantial disagreement in and of itself. However, the model favors a very weak bimodal maximum cloudiness (March and June), which is supported by neither of the data sets. Note also that the annual mean for both data sets is of order 70-75%, while the model obtains a value of only 32%. The ISCCP also fails to pick up the cloud maximum present in the WHL data in the Southern Hemisphere winter and spring. The model failure in reproducing the correct cloud amount in the stratus regions has a significant impact on the behavior of a coupled ocean-atmosphere model in which the ECHAM3 model served as the atmosphere component. As described by Latif (1994), cloud cover error can lead to SST errors of a few degrees in the Southeast Pacific and Atlantic Oceans.

In summary, the model fails to reproduce the seasonal cycle of cloudiness in the region off South America. We shall see that this result is due to the inability of the model to produce enough stratus or low level clouds (cf. Section 5).

4.2. Global View: Total Cloud Amount

The comparison of the total cloud amounts is now expanded to a fully global perspective and so offers another view of the agreement, or lack thereof, among the three data sets. In the following discussion we limit ourselves to the northern winter (DJF) and summer (JJA) conditions.

4.2.1 Northern Winter

The total cloud amount, in percentage, averaged over December, January and February is shown in Figure 7. We chose to show total cloud amounts rather than differences between various products because it is not clear that observed product is *correct* (and the differences between them are substantial).
A regional comparison of the three panels leads to the following conclusions:

i) The observations show the North Pacific to be covered with approximately 70-80% clouds, while the model underestimates this value by order 10-20%, just as noted above.

ii) The tropical ridge near 20N in the Pacific, indicated by a minimum in cloud cover, is a clear feature in all three data sets, as is the equatorial Pacific cold tongue region between 120-150W. The model values are slightly smaller than observed and slightly shifted in longitude to the East.

iii) The minima in cloud coverage immediately west of Australia, west of North Africa, off Mexico/Central America, and on both sides of India is all obvious in both the observations and model cloud fields. Again the model values are somewhat smaller than the observations, but the spatial pattern agreement is impressive given the small scale of the features.

iv) The cloud cover over the Indonesian Low region is perhaps a little stronger in the ISCCP than is found in the model data. However, this important climatological feature is almost totally missing from the WHL data. In this case Figure 7 shows the difference between observational sets is as large as, or larger than, the difference between model and observed data.

v) The large regions of low total cloud amount in the observations located off the west coasts of South Africa and Chile are not found in the model. It will be shown below that these differences arise from the model underestimation of the low level clouds, a problem common to most AGCMs.

vi) The total cloud amount n the high southern latitudes is somewhat lower in the model, just as it is in similar latitudes of the northern hemisphere. Note, however, that the differences in this region between WHL and ISCCP are as large as the apparent model value relative to either observed data set.

vii) The differences between the observed sets and the model are of the same size in the North Atlantic region, so we really can draw no conclusions from these disparate results. Again the WHL fails to resolve the large cloud feature associated with the Gulf Stream off the North Eastern US.

In summary, the model reproduces the spatial structure of the wintertime average total cloud field with reasonable, in some cases surprising, accuracy. The main problem with the model seems to be a consistent underestimation of the magnitude of the cloud cover compared to the observed data sets.

4.2.2 Northern Summer

The comparison of total cloud cover averaged over June, July and August (Fig. 8) holds many of the same features and conclusions seen for the winter, and a detailed recitation will not be offered. Instead we note the most salient features:

i) The large discrepancies in the low stratus region off both Central America, South America and North Africa are now clearly apparent. However, the decreasing equatorial cloud feature about 60° off the west coast of South America is reproduced by the model.

ii) The monsoon cloudiness is now readily apparent and there is good agreement between the three data sets data sets.

iii) The agreement between all data sets in the North Pacific is reasonable. The North Atlantic is also an area of agreement in spatial pattern, if not magnitude.

iv) The high latitudes of the Southern Hemisphere are now a region where the data sets more or less agree amongst themselves and with the model.

This may be somewhat misleading because the ISCCP data, along with other satellite climatologies, have trouble distinguishing between ice and clouds in the visible and the scarcity of ground based observations in the WHL can lead to a less representative data set.

In summary, we conclude that on the whole the model data agreement is about the same during the summer as during the winter. The major exception to this statement is the large cloud minimums found in the model but not the observations off the west coasts of the major continents, Europe excepted.

5.0 Vertical Structure of Cloud Field

5.1 A "standardanalysis"

An attempt was made to compare the vertical structure of cloud amounts between the model and the observations in the three regions described above. We again concentrate on the seasonal cycle in the three key regions described above. In this comparison, the seasonal cycle of high (HI), mid-level (MID) and low (LO) cloud was obtained from each of the observed sets according to the various conventions /definitions that accompany them (see Section 2 and original references). The empirical orthogonal functions (EOFs) were used to characterize the vertical variance of these observed cloud height profiles (i.e., there were 3 levels and 12 monthly time values). The seasonal cycle for the model's monthly cloud amounts at all 19 levels were also computed and subjected to EOF analyses.

The leading EOFs, which generally captured 65-75% of the variance for each data set, are shown in Fig. 9. The EOFs were normalized to include the variance of each data set. The ISCCP data show a bimodal primary EOF in all three study regions, As shown by the ISCCP data, when high clouds are in abundance in any of the regions, low clouds exist in minimum amounts and vice versa.[1] The AGCM and WHL, on the other hand, suggest coherent vertical cloud variations in the WP with the HI and MID clouds being most numerous. Over the NI' the AGCM shows the coexistence of the HI and LO clouds at the expense of the MID clouds (and vice versa). This is clearly different from WHL that shows coherent cloud variations in the vertical or ISCCP that showed a bimodal distribution. Thus

[1] The leading EOF of the anomalous vertical cloud amounts were highly similar to those shown in Fig. 5.1. for all the data sets studied.

in this region all three products differ in the vertical structure of their seasonal cycles. Off South America, all three data sets show higher concentrations of HI and MID clouds go with smaller concentrations of LO clouds and vice versa.

On the basis of on the above disparate results, what can we say about the model performance? The data sets themselves differ fairly dramatically. One reason for this may be as follows: The satellite will not 'see' low clouds in the presence of high/mid level clouds since it cannot see through the intervening cloud mass. Similarly, it will see low clouds only if no high/mid level clouds are present. This is precisely one interpretation that can be drawn from EOF1 of the ISCCP data. The same problem exists to some extent with the surface based observations of the WHL data, only in reverse. For this data set the problem may not be as severe except in heavy stratus regions (for example, South America) where a solid lower cloud deck would preclude an observer from seeing also HI/MID clouds (if they were present). Thus one could conclude that the vertical distribution of cloud from the observed data sets, especially ISCCP, are merely an observational artifact... indeed, a necessary result of the observation techniques.

In summary, the available cloud data sets we have used do not allow us to answer the critical question: How well did the model simulate the vertical distribution of cloud associated with the seasonal cycle? This is a deplorable state of affairs that needs to be remedied before critical questions of AGCM cloud parameterization can be much advanced.

5.2 A "nonstandard analysis"

Another attempt to compare the seasonal cycle of the vertical distribution of clouds in the model/observations was made as follows: The ISCCP product should always 'see' the HI cloud and so we assume its estimates of that quantity should not be significantly contaminated by MID/LO clouds. Similarly, the WHL estimates of LO clouds ought to be largely unbiased by observational technique. Thus, we formed a composite seasonal cycle of cloud variations by using the ISCCP for the HI data and WHL for the LO. No attempt was made to estimate MID, for we feel such estimates are likely biased in either observed data set.

Comparison of the seasonal cycle of vertical cloud distribution for the SA and WP region (Fig. 10-11) demonstrates the principal model/observation agreements and disagreements and lead to the following conclusions:

(1) In the WP the HI cloud seasonal cycle for ISCCP and ECHAM3 are similar in shape and range. The model does underestimate the annual average by 5-7%, approximately the same magnitude as the amplitude of the seasonal cycle. However, the LO cloud is lower; 3-4% versus 40-45% from WHL.

(2) The distribution of model HI/LO cloud in SA is very low; 47-73% observed for LO level vs. 3-5% for the model, This feature in ECHAM3 has been noted by Latif et *al.,* 1994 and Stockdale *et al.,* 1994 as previously mentioned. This explained why, in coupled simulations using ECHAM3, the ocean model tended to produce sea surface temperatures that were too warm in this region (excessive shortwave radiation input to the ocean).

The reason for the lack of low clouds in the model is not entirely clear, Inspection of the vertical profiles of temperature in, say, the SA region shows no low level inversion as one might expect (from observations) to exist in stratus regions. This, in turn, may be due to the coarse vertical resolution in the boundary layer. There does appear to be enough moisture in the lower layers for cloud formation. However, without an adequate definition of the near-surface boundary layer, the subsidence associated with the Southeast Pacific High which is (correctly) located near the SA region appears to penetrate all the way to the surface and so prevent stratus formation. Another key factor, associated with the lack of an inversion layer, is the fact that the static stability is low over the SA region. Early work by Klein and Hartmann (1993) found this situation was not conducive to the existence of low level clouds. The other key regions show somewhat the same situations noted above, although not to the degree seen off South America.

The above results, taken together with those cited previously, suggest the ECHAM3 does a creditable job of reproducing the seasonal cycle and amount of high cloud. It does need improvement in its representation of low (stratus) cloud. This latter defect is common to most atmospheric AGCMs.

6.0 Interannual Variability

It is interesting to ask if the observed and model cloud data tend to exhibit the same type of interannual variability, in spite of the tremendous dichotomies that attend each data set (methodology, time span, etc.) A preliminary answer was obtained by investigating the variability in total cloud amount over the warm pool region. This is the region where the three cloud data sets agreed most favorably.

It is also the same region known to experience large interannual variations in cloud cover associated with El Niños. During large warm events the center of convective activity moves eastward out of the warm pool (as we have defined it here) and tends to locate near the dateline. During cold events the convection center is close to Asia, maybe weaker, and centered more nearly over our warm pool region.

In order to see how well the climatologies reproduce this anomalous shift, we studied the full time series of total cloud anomaly for each data set (Fig. 12-13). A light smoothing has been applied to suppress high frequency noise. The times of occurrence of maximum/minimum SST in region NINO3 (90-150W, 5N-5S, a traditional El Niño index) are shown to help label the major warm/cold events defined here as exceeding ± 1° C.

One note of caution in the observational data sets is warranted here. As noted by Klein and Hartmann 1993b, The ISCCP data suffer from calibration problems causing a spurious decrease in cloud amount over the eight year time period on the order of a few percent. The ISCCP data used in the warm pool study also show a 4% decrease in the time frame consistent with the results for Klein and Hartmann cirrus cloud amount. The signal we are searching for was as large or larger than this anomalous behavior. Furthermore, the nature of the calibration error made it difficult to correctly subtract out this effect. There is also a trend in the WHL data of approximately a 3 % increase in the 30 year data set in the warm pool region (and elsewhere) accompanied by a larger decrease in the standard deviation.

Inspection of Figs. 12-13 leads to the following conclusions:

i) All data sets suggest a minimum of cloudiness near the height of warm events. The major exception to this statement occurs in the very beginning of the ISCCP data where the large 1982-83 event is absent in the observed data. The coincidence of cold events with cloud maxima is apparent but the relation is far less robust than for warm events.

ii) The difference in total cloud amount between warm-cold events is order 10-20% with ECHAM3 showing about a factor of two greater sensitivity than the data sets. These large values will have a substantial impact on the heat balance of the warm pool (Schneider *et* al., 1994) and interact strongly with the El Niño signal itself, For example, suppose a strong warm event is in progress so the anomalous change in shortwave will act to heat up the warm pool region, which is normally colder than normal during an El Niño event. A comparable decrease in short wave radiation due to the increased clouds is simultaneously found in the central equatorial Pacific (Barnett *et* al., 1991). This latter region is typically warmer than normal during an El Niño event so the clouds will try to cool it. Thus, the cloud field reacts as a negative feedback process that tries to restore the warm pool to the western Pacific while damping the SST warming in the central Pacific through a reduced shortwave radiation. In essence, the reaction of the cloud field is such as to help terminate warm events. The same argument works more or less in reverse for cold events.

7. Summary and Conclusions

The comparison of model output, surface based, and satellite data is at best a difficult task. Differences in basic assumptions, parameterizations, and even the quantities being compared make the job unwieldy. Our tack on this problem was to attempt to isolate, as much as possible, the model physics and compare the cloud fields generated with observations. Because the cloud model physics also differs on a global scale, regional analyses were performed.

There are a few important conclusions to be drawn from this research:

(l). All data sets replicated the signature of the seasonal cycle and the El Niño cloud anomaly in the warm pool. This result is somewhat striking, given the alleged difficulty of modeling moist tropical convective processes in models. This may be more indicative of reproducing the variations in the large-scale dynamics relatively well.

(2). The GCM has drastically fewer low clouds in the coastal stratus than both of the observational data sets. This is suggestive of an inadequate boundary layer parameterization in the GCM. This may also be the cause of the lack of GCM cloudiness in the North Atlantic, North Pacific, and the ocean surrounding Antarctica.

(3). Cloud vertical structure comparisons were somewhat discouraging. Because of the inherent differences among the three types of data sets, it may only be possible to unravel the cloud height distribution in a model by studying the corresponding radiation field.

(4). Current observational cloud data sets can act as crude measures for model validation. However, the observations have significant problems that seriously hamper their usefulness. Given the critical nature that clouds are supposed to play in the global climate, this state of affairs is wholly unsatisfactory.

Acknowledgments

We would like to thank W. Collins and M. Latif at S10 for their incisive comments, One of us (rdh) would like to thank Stephanie Granger at JPL for her help with the HIRS data and Ralph Kahn at JPL, Also, the comments of the anonymous reviewers were very valuable. Part of the research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration,

References

Barnett, T. P., E. Kirk, M. Latif, and E. Roeckner, 1991: On ENSO physics, *J. Climate*, 4,487-515.

Cess, R. D., G.L. Potter, J.P. Blanchet, G.J. Boer, A.D. Del Genie, M. Dquè , VG. Dymnikov, V. Galin, W.L. Gates, S.J. Ghan, J.T. Kiehl, A.A. Lacis, H.Le Treut, Z.-X. Li, X,-Z. Liang, B.J. McAvaney, V.P. Meleshko, J.F.B. Mitchell, J.-J. Morcrette, D.A. Randall, L. Rikus, E. Roeckner, J.F. Royer, U. Schlese, D.A. Sheinin, A. Slingo, A.P. Sokolov, K.E. Taylor, W.M. Washington, R.T. Wetherald, 1. Yagai, and M.-H. Zhang, 1990: Intercomparison and Interpretation of Climate Feedback Processes in 19 Atmospheric General Circulation Models. *J. Geophys. Res.*, 95, 16,601-615.

Chahine, M. T., and Haskins, R. D., 1982: Infrared Remote Sensing of the Vertical and Horizontal Distribution of Clouds, Cloud Dynamics, E.M. Agee and A Tsai (eds.), 57-71.

Gates, W. L., 1992: AMIP: The Atmospheric model intercomparison project, *Bull. Am. Met. Soc.*, 73(12), 1962-1970.

Kiehl, J. T., and V. Ramanathan, 1990: Comparison of cloud forcing derived from the Earth Radiation Budget Experiment with that simulated by the NCAR Community Climate Model. *J. Geophys. Res.*, 95, D8, 11,679-11,698.

Kiehl, J. T., and D.L. Williamson, 1991: Dependence of Cloud Amount on Horizontal Resolution in the NCAR Community Climate Model., *J. Geophys. Res.*, 96, D6, 10,955.

Klein, S.A. and D.L. Hartmann, 1993a: The seasonal cycle of low stratiform clouds, *J. of Clim.*, 6, 1587-1606.

Klein, S.A. and D.L. Hartmann, 1993b: Spurious Changes in the ISCCP Dataset, *GRL, 20,6,455-458.*

Latif, M., T. Stockdale, O. Wolff, G. Burgers, E. Maier-Reimer, M.M. Junge, K. Arpe, and L. Bengtsson, 1994: Climatology and variability in the ECHO coupled GCM. Tellus. In Press.

Luther, F. M.,Ellingson,R.G., Forquart, Y., Fels, S.,Scott, N. A., Wiscombe, W., 1988: Intercomparison of Radiation Codes in Climate Models (ICRCCM): Longwave Clear-Sky Results - A Workshop Summary. *Bull. Am. Met. Soc.*, 69,1.

Mokhov, 1.1. and M.E. Schlesinger, 1993: Analysis of global cloudiness, 1. Comparison of Meteor, Nimbus 7, and International Satellite Cloud Climatology Project (ISCCP) Satellite Data, *J. Geophys. Res.*, **98(D7)**, 12,849-12,868.

Peterson, T. C, T. P. Barnett, E. Roeckner, and T, H, Vender Haar, 1992: An analysis of the relationship between cloud anomalies and sea surface temperature anomalies in a global circulation model. *J. Geophys. Res.-Atmospheres*, **97(D18)**, 20,497-20,506.

Randall, D. A., J.A. Coakley Jr., C.W. Fairall, R.A. Kropfli, and D.H. Lenschow, 1984: Outlook for research on subtropical marine stratiform clouds, *Bull. Amer. Meteor. Soc ,65, 1290-1301.*

Randall, D.A. and Tjemkes, 1991: Clouds, the Earth's radiation budget, and the hydrologic cycle. *Palaeogeogr. Palaeoclimatol. Palaeoecol. (Global Planet. Change Sect, ,90, 3-9.*

Roeckner, E., K. Arpe, L. Bengtsson, S. Brinkop, L. Dumenil, M. Esch,E. Kirk, F. Lunkeit, M. Ponater, B. Rockel, R, Sausen, U. Schlese, S. Schubertand M. Windelband, 1992: Simulation of the present-day climate with the ECHAM model: Impact of model physics and resolution, *Max Planck Institutfur Meteorologic,* Rep. No. 93.

Roeckner, E., M. Rieland, and E. Keup, 1991: Modeling of cloud and radiation in the ECHAM model. ECMWF/WCRP *Workshop on Clouds, Radiative Transfer and the Hydrological Cycle, 2-15 Nov., 1990,* ECMWF, Reading, UK.

Rossow, W. B., Mosher, F., Kinsella, E., Arking, A., Desbois, E., Harrison, E., Minnis, P., Ruprecht, E., Seze, G.,Simmer, C., and Smith, E., 1985: ISCCP cloud algorithm intercomparison., *J. Climate Appl. Meteor.* , 24 877

Schiffer, R. A., and W.B. Rossow, 1983: The International Satellite Cloud Climatology Project (ISCCP) - The first project of the World Climate Research Program, *Bull. Amer. Meteor. Sot.* , 64779-784,

Schneider, N., T. I'. Barnett, and M. Latif, 1994: Origin of the west Pacific warm pool, in preparation.

Slingo, A., 1990: Sensitivity of the Earth's radiation budget to changes in low clouds. *Nature,* 343, 6253, 49-51.

Slingo, A. and J.M. Slingo, 1991: Response of the National Center for Atmospheric Research Community Climate Model to Improvements in the Representation of Clouds. *Geophys. Res.-Atmospheres,* **96(D8),** *15,341*-15,357.

Smith, W. L., Woolf, H.M.,Hayden, C. M., Wark, D. Q., and McMillin, L.M.,1979: The TIROS-N Operational Vertical Sounder, *Bull. Amer. Meteor. Sot., 60,* 1177.

Stockdale, T., M. Latif, G. Burgers, and J. - 0. Wolfl, 1994: Some sensitivities of a Coupled Ocean-Atmosphere GCM, submitted to Tellus.

Sundquist, H., 1978: A parameterization scheme for non-convective condensation including prediction of cloud water content, *Quart. J.Roy. Meteor. Sot.,* 104, 677-690.

Susskind, J., Rosenfield, J., Reuter, D., Chahine, M. T., 1984: Remote sensing of weather and climate parameters from HIRS2/MSU on TIROS-N, *J. Geophys. Res.* 894677-4697.

Tiedtke, M., 1989: A comprehensive mass flux scheme for cumulus parameterization in large-scale models. *Mon. Wea. Rev.*, 117,1779-180.

Tiedtke, M., W.A. Heckley, and J. Slingo, 1988: Tropical forecasting at ECMWF: On the influence of physical parameterization on the mean structure of forecasts and analyses. *Quart. J. Roy. Meteor. Sot.*, 114, 639-664.

Warren, S., J. Hahn, and J. London, 1985: Simultaneous occurrence of different cloud types, *J. Climate Appl. Meteor.*, 24 658.

Warren, S. G., C.J. Hahn, J. London, R.M. Chervin, 1988: Global distribution of total cloud cover and cloud type amounts over ocean. *NCAR Tech. Nofe NCAR/TN-317+STR*, National Center for Atmospheric Research, Boulder, CO, 42 pp. plus 170 maps.

Warren, S. G., C.J. Hahn, J. London, R.M. Chervin, and R.L. Jenne, 1986: Global distribution of total cloud cover and cloud type amounts over land. *NCAR Tech. Note NCAR/TN-273+STR*, National Center for Atmospheric Research, Boulder, CO, 29 pp. plus 200 maps.

Wetherald, R. T., and Manabe, S., 1986: An investigation of cloud cover change in response to thermal forcing. *Clim. Change*, 8, 5-23.

Wielicki, B. A., and Parker, L., 1992: On the Determination of Cloud Cover From Satellite Sensors: The Effect of Sensor Spatial Resolution. *J. Geophys. Res.* 97(**D12**), 12799-12823

Figure Captions

Figure 1: January and July 1979 (FGGE) ocean-only zonal means for Warren, Hahn, and London (WHL) surface based data (dotted line), HIRS2/MSU (dashed line), and AGCM (ECHAM3) data (solid line). Note the close correlation in shapes between the WHL and HIRS data.

Figure 2: Same as Figure 1 except for land-only. Again note the close correlation between the WHL and HIRS data even over land.

Figure 3: Regional 1979 time series for Warren, Hahn, and London (WHL) surface based data (dotted line), HIRS2 (dashed line), and AGCM (ECHAM3) data (solid line). The upper frame is the warm pool region (WP), middle frame the North Pacific (NP), and lower frame is the region off the western coast of South America (SA). Note the good agreement in the WP region and poor agreement in the SA region.

Figure 4: Warm pool region seasonal cycle total cloudiness for Warren, Hahn, and London (WHL) surface based data (dotted line), AGCM (ECHAM3) data (solid line), and ISCCP (solid line). Note the agreement in minimum and maximum for the three climatologies.

Figure 5: Same as Figure 4 except for the North Pacific Region. Note the agreement in summer cloudiness maximum but the 20 - 25% underestimate in total cloud fraction by the model.

Figure 6: Same as Figure 4 except for the Coastal South America Region. Note the general disparity in all three cloud climatologies.

Figure 7: Global total Northern Winter cloudiness for Warren, Hahn, and London (WHL) surface based data, AGCM (ECHAM3), and ISCCP.

Figure 8: Global total Northern Summer cloudiness for Warren, Hahn, and London (WHL), AGCM (ECHAM3), and ISCCP.

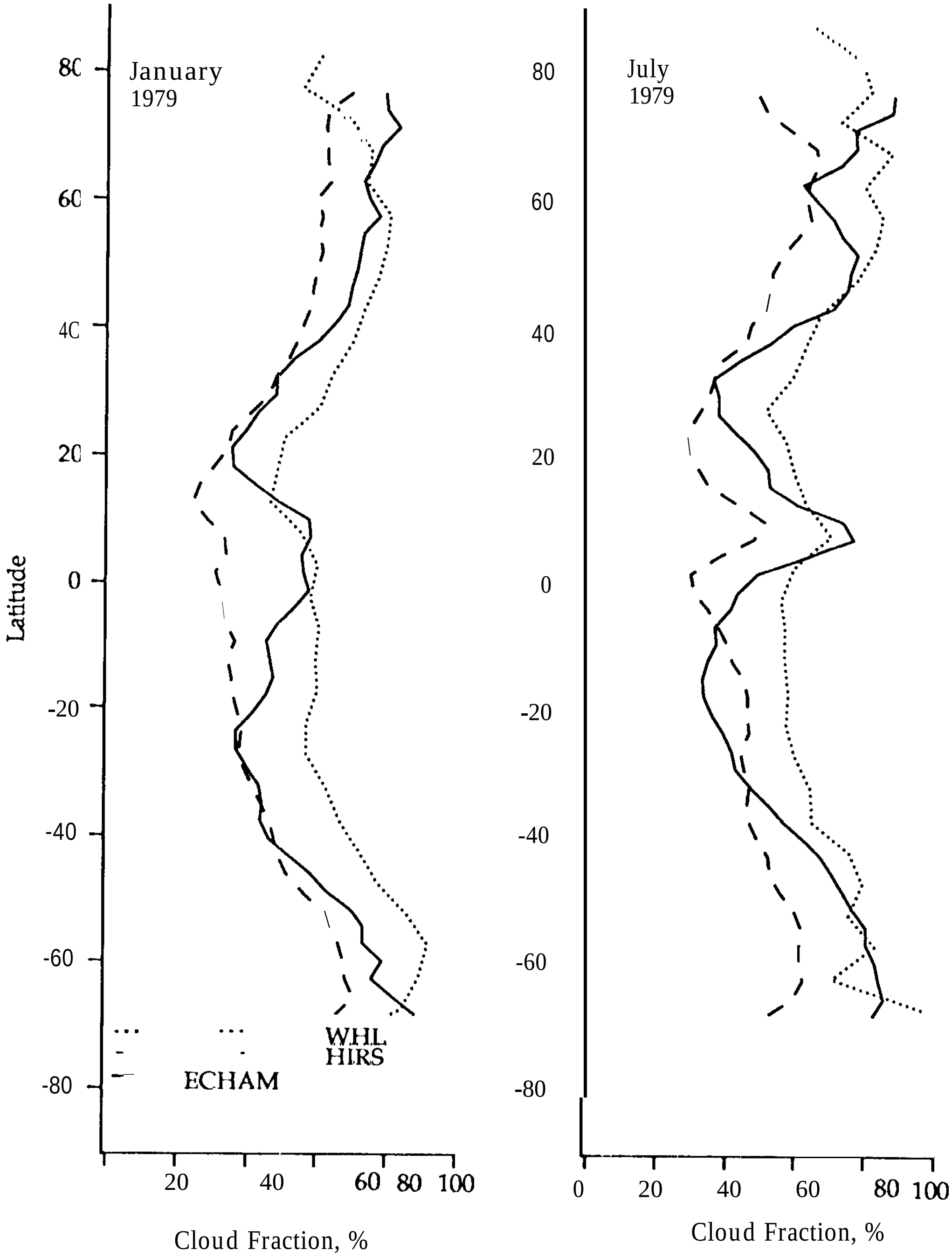
Figure 9: Vertical seasonal cycle cloud structure for Warren, Hahn, and London (WHL), AGCM (ECHAM3), and ISCCP as deduced by an EOF analysis.

Figure 10: High and low seasonal cycle cloud amounts for the warm pool region. This “non-standard” analysis attempted to overcome differences in observational geometries by using ISCCP for high cloud amount and WHL for low cloud amount.

Figure 11: Same as Figure 11 except for the South America Region.

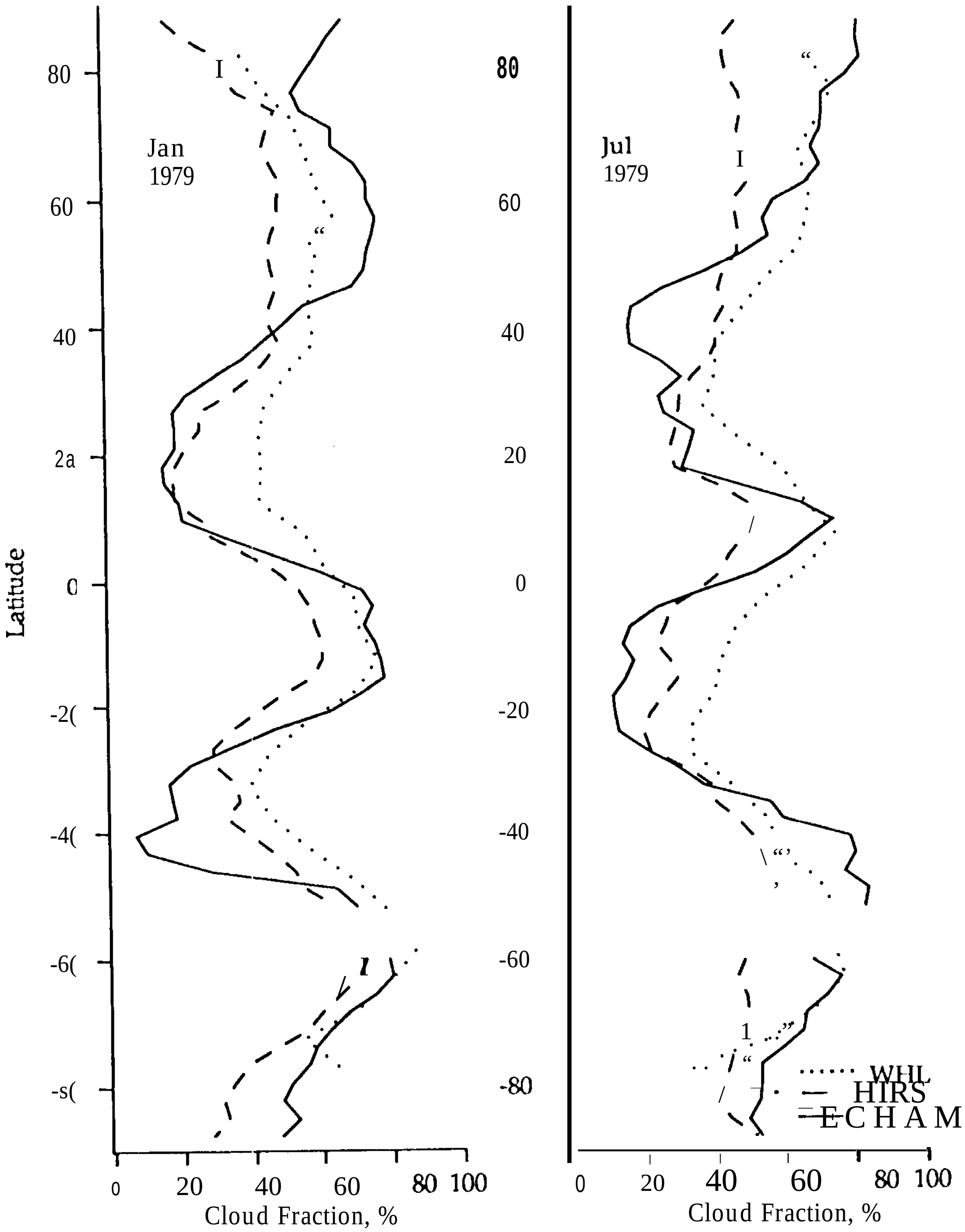
Figure 12: Warren, Hahn, and London (WHL) total cloud anomaly for the warm pool region. The times of occurrence of maximum/minimum SST in region NIN03 (90-150W, 5N-5S) are shown to help label the major warm/cold events defined here as exceeding ± 1° C and are labeled with a W or C.

Figure 13: Same as Figure 12 except showing AGCM (ECHAM3) and ISCCP total cloud anomaly for the warm pool region.



January
1979
July
1979
80
60
40
20
0
-20
-40
-60
-80
Latitude
WHL
HIRS
ECHAM
0
20
40
60
80
100
Cloud Fraction, %
Cloud Fraction, %

Figure 1



Jan
1979
Jul
1979
Latitude
80
60
40
20
0
-20
-40
-60
-80
0 20 40 60 80 100
Cloud Fraction, %
WHL
HIRS
ECHAM

Figure 2

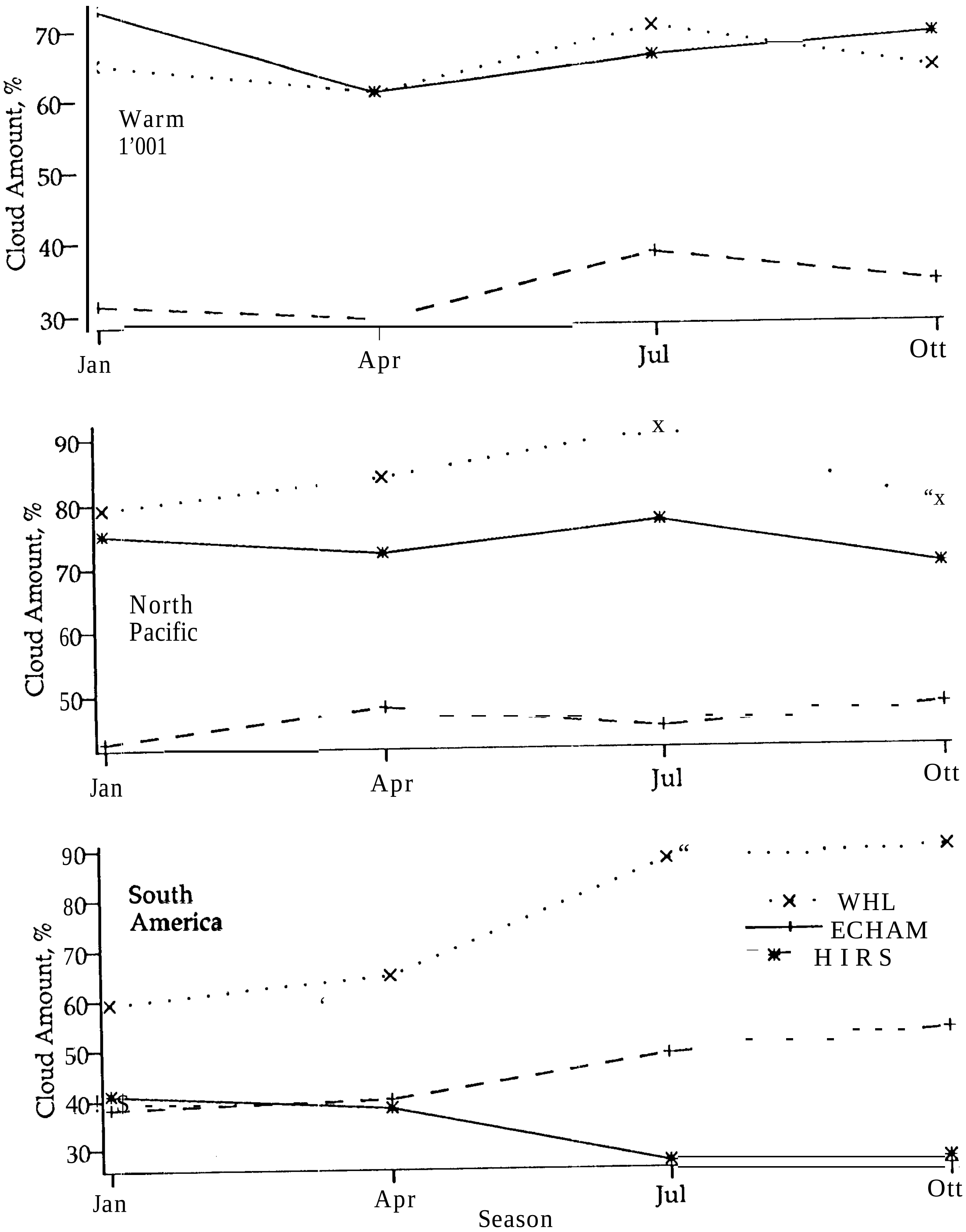

Cloud Amount, %
70
60
50
40
30
Warm
1'001
Jan
Apr
Jul
Ott
Cloud Amount, %
90
80
70
60
50
North
Pacific
Jan
Apr
Jul
Ott
Cloud Amount, %
90
80
70
60
50
40
30
South
America
WHL
ECHAM
H I R S
Jan
Apr
Jul
Ott
Season

Figure 3

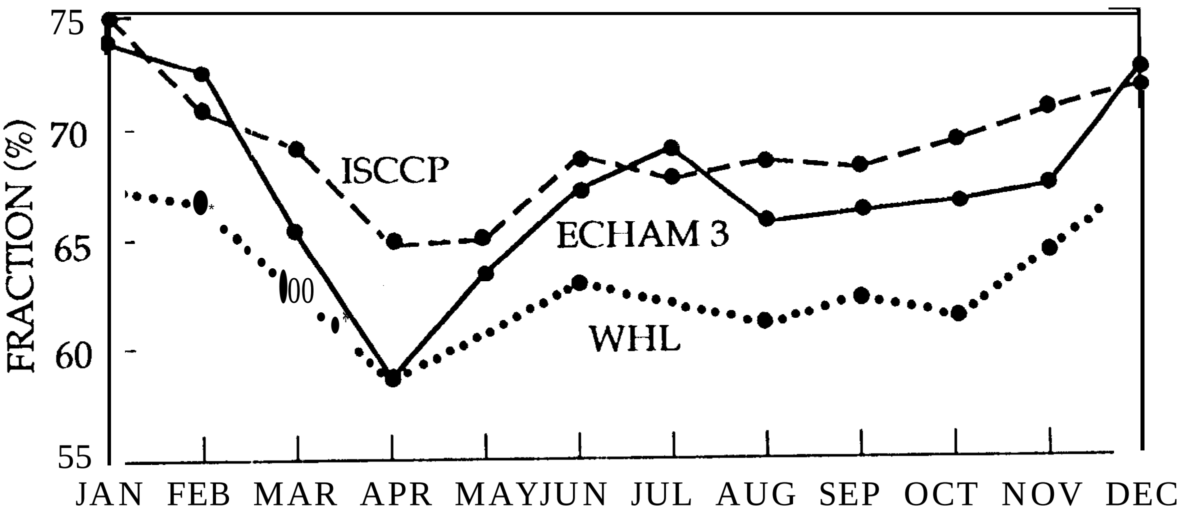
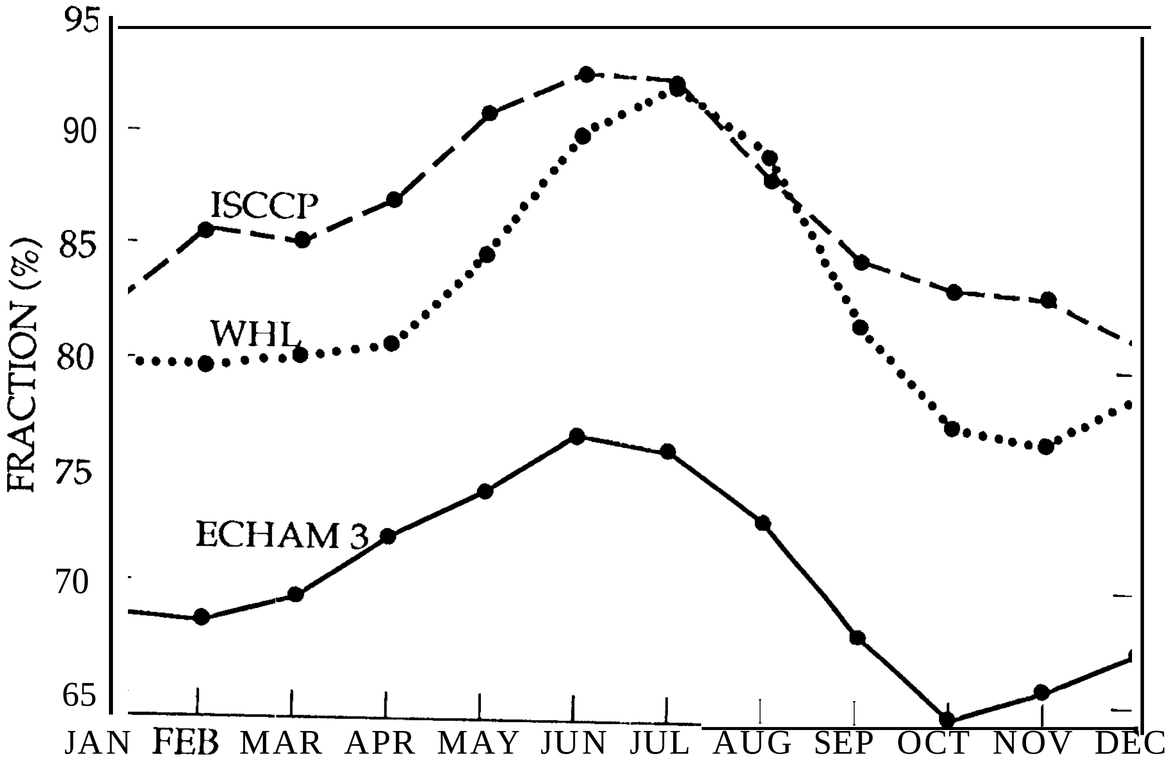

75
70
65
60
55
FRACTION (%)
ISCCP
ECHAM 3
WHL
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

Fig. 4



95
90
85
80
75
70
65
FRACTION (%)
ISCCP
WHL
ECHAM 3
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

Fig. 5

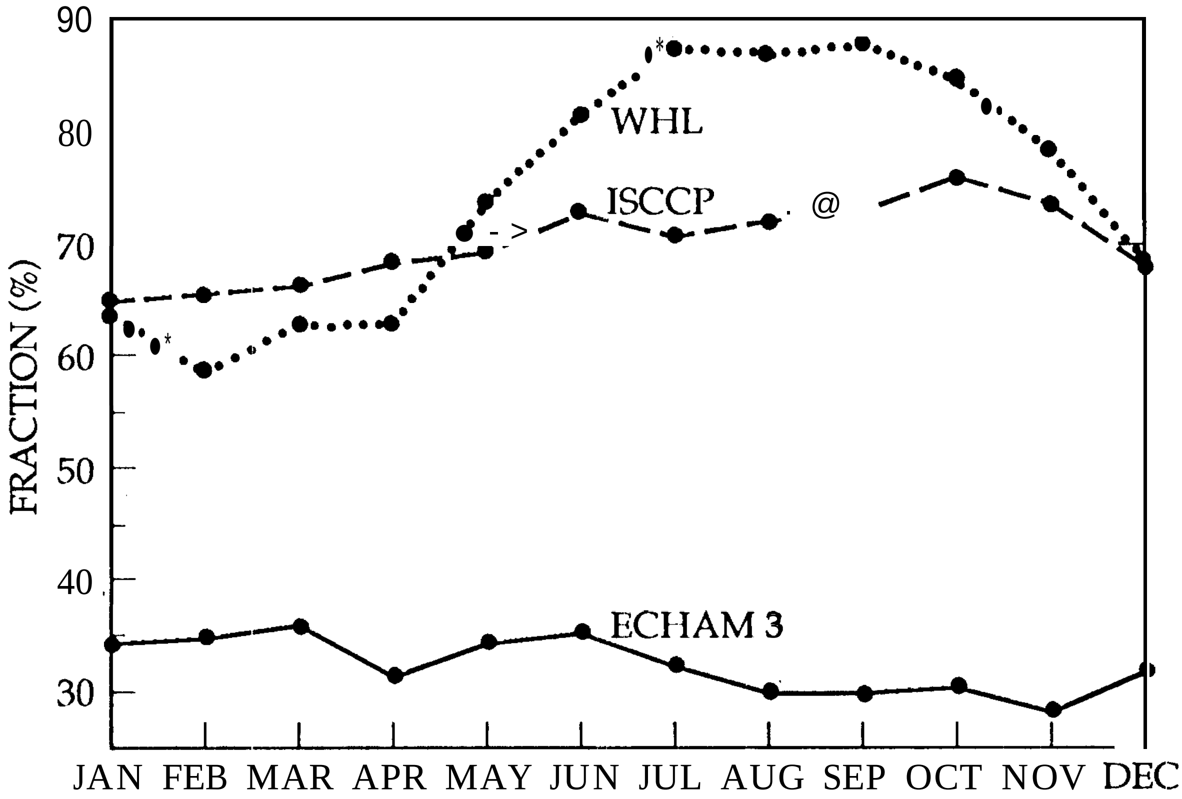

90
80
70
60
50
40
30
FRACTION (%)
WHL
ISCCP
ECHAM 3
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

Fig. 6

TOTAL WINTER CLOUDINESS

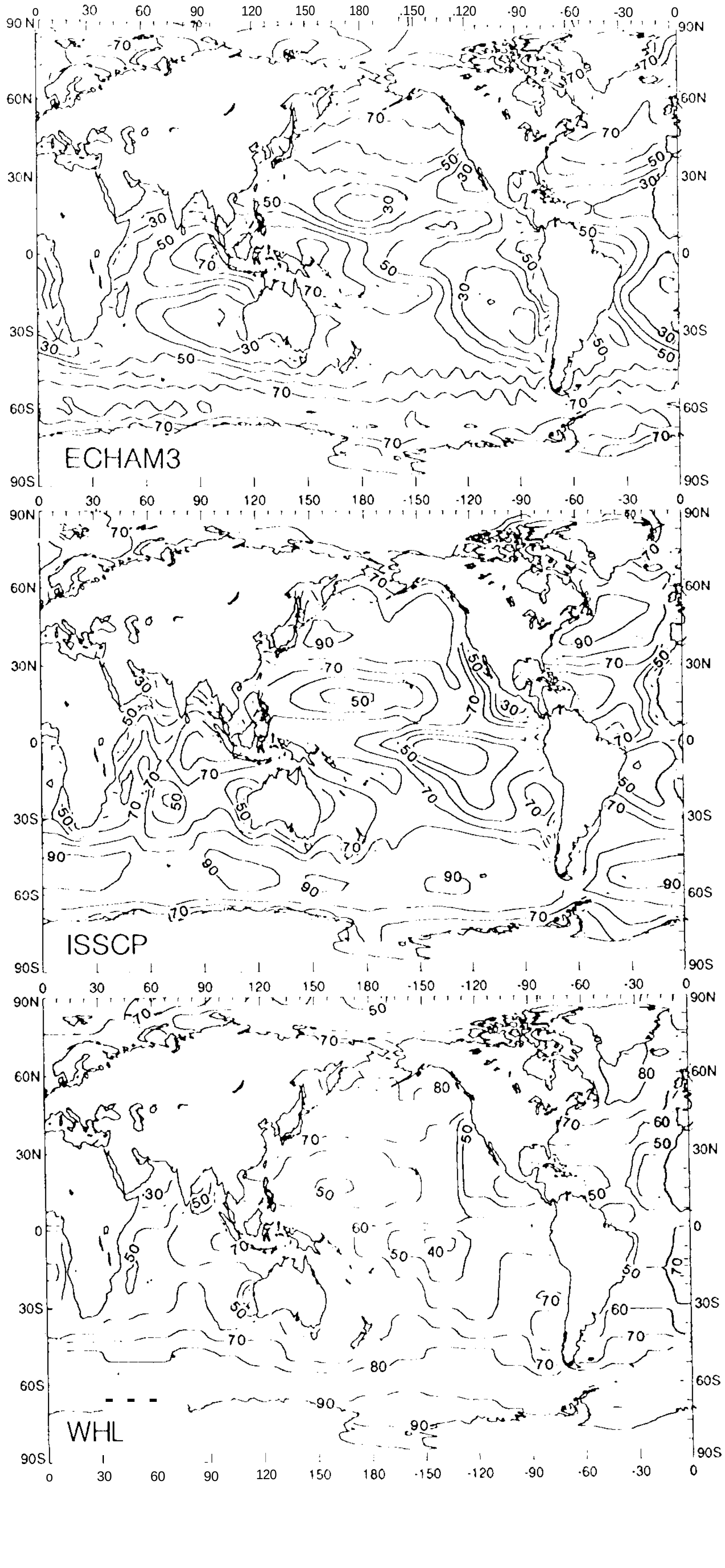


Fig 7

TOTAL SUMMER CLOUDINESS

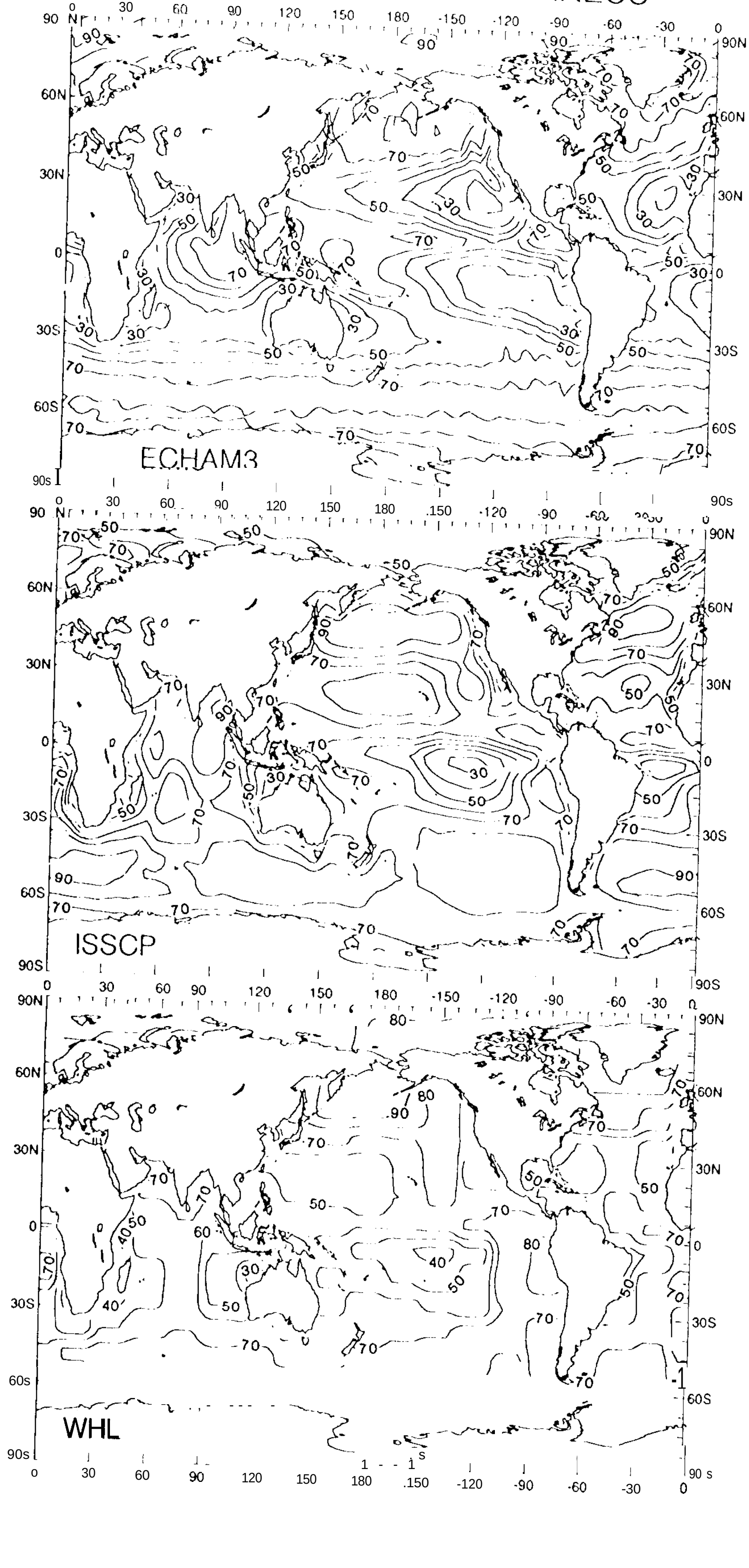
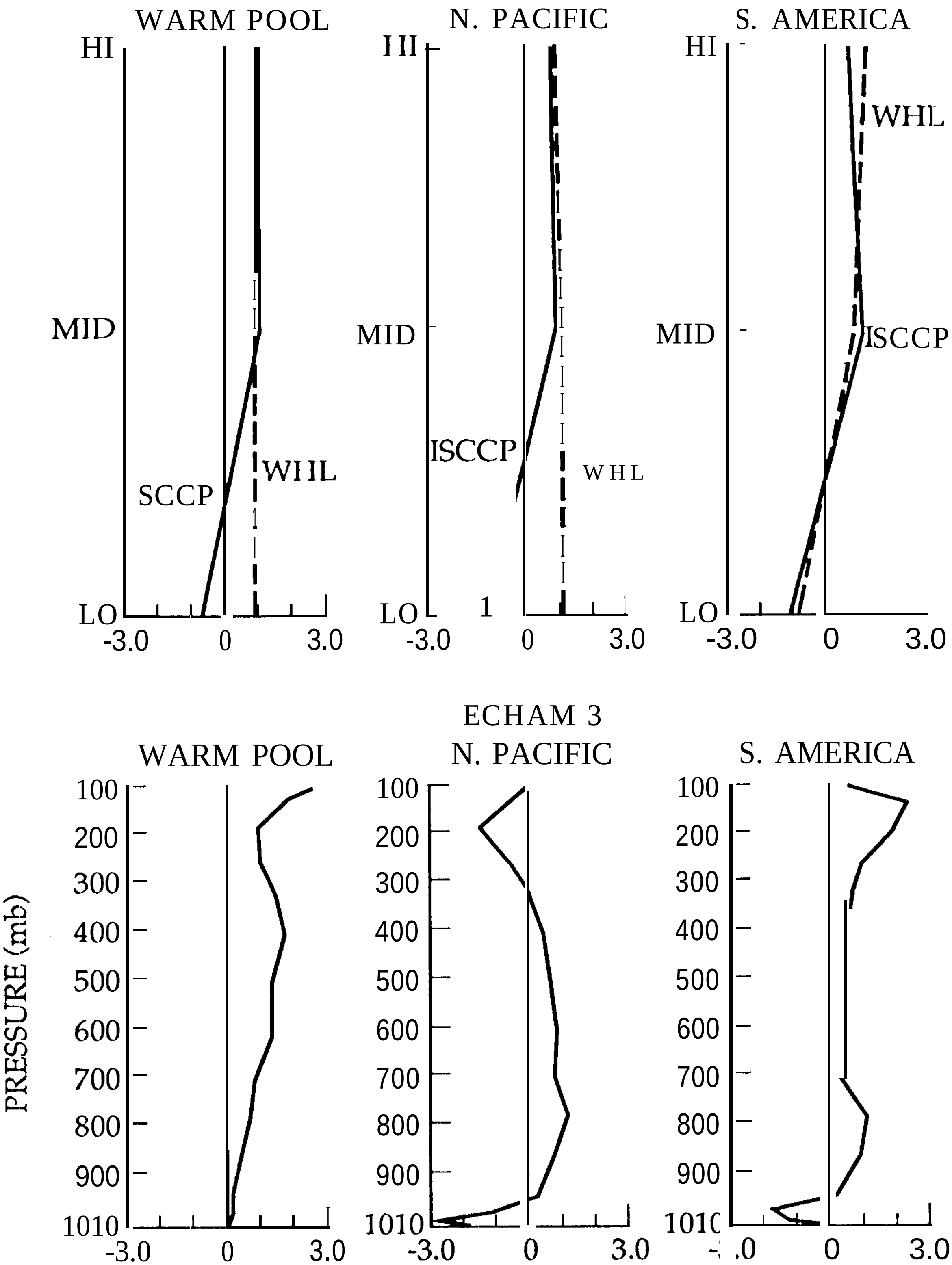
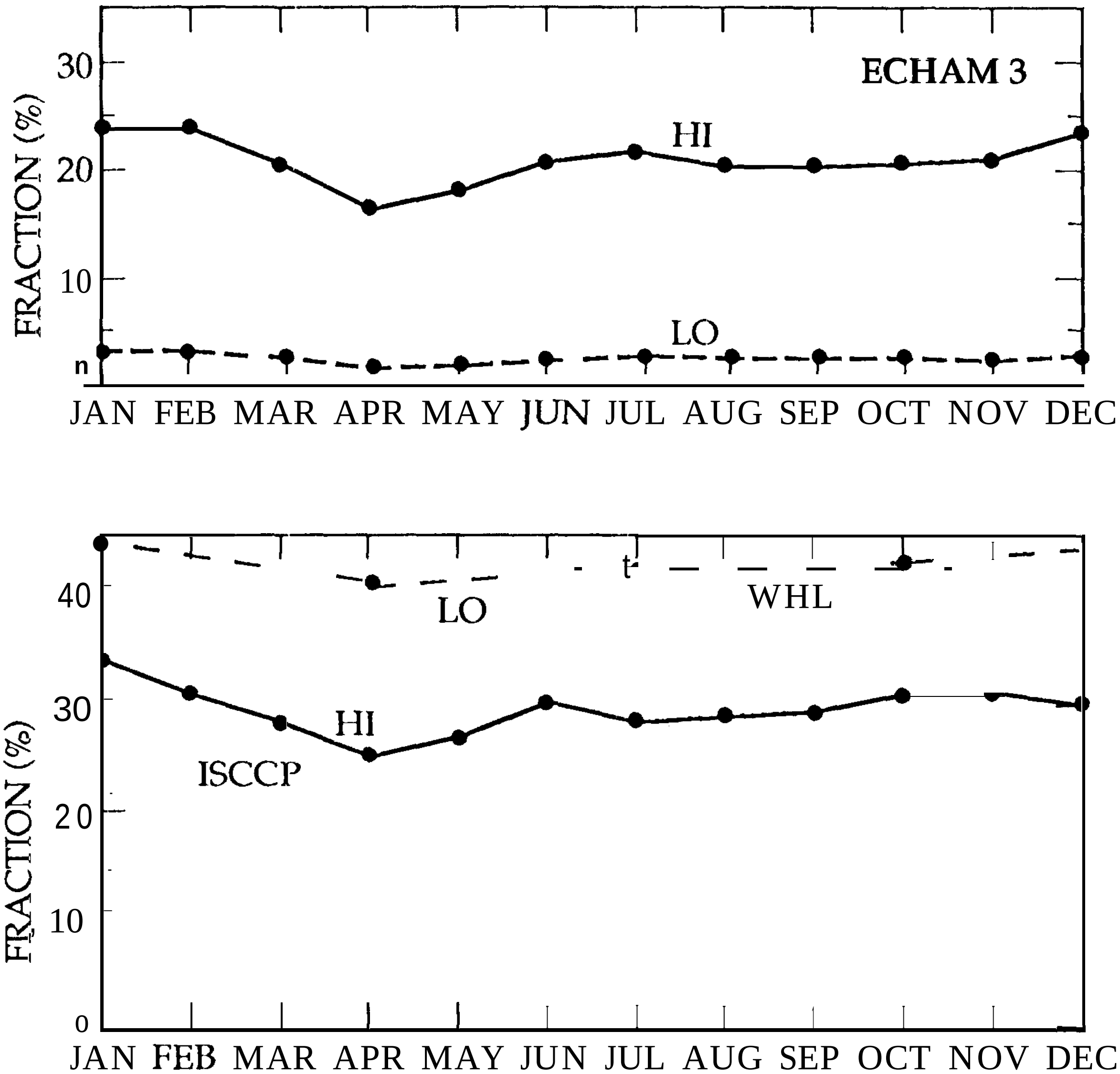


Fig 8



WARM POOL
N. PACIFIC
S. AMERICA
HI
MID
LO
WHL
SCCP
ISCCP
-3.0
0
3.0
ECHAM 3
PRESSURE (mb)
100
200
300
400
500
600
700
800
900
1010

Fig. 9



ECHAM 3
HI
LO
FRACTION (%)
30
20
10
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
LO
WHL
HI
ISCCP
FRACTION (%)
40
30
20
10
0
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

Fig. 10

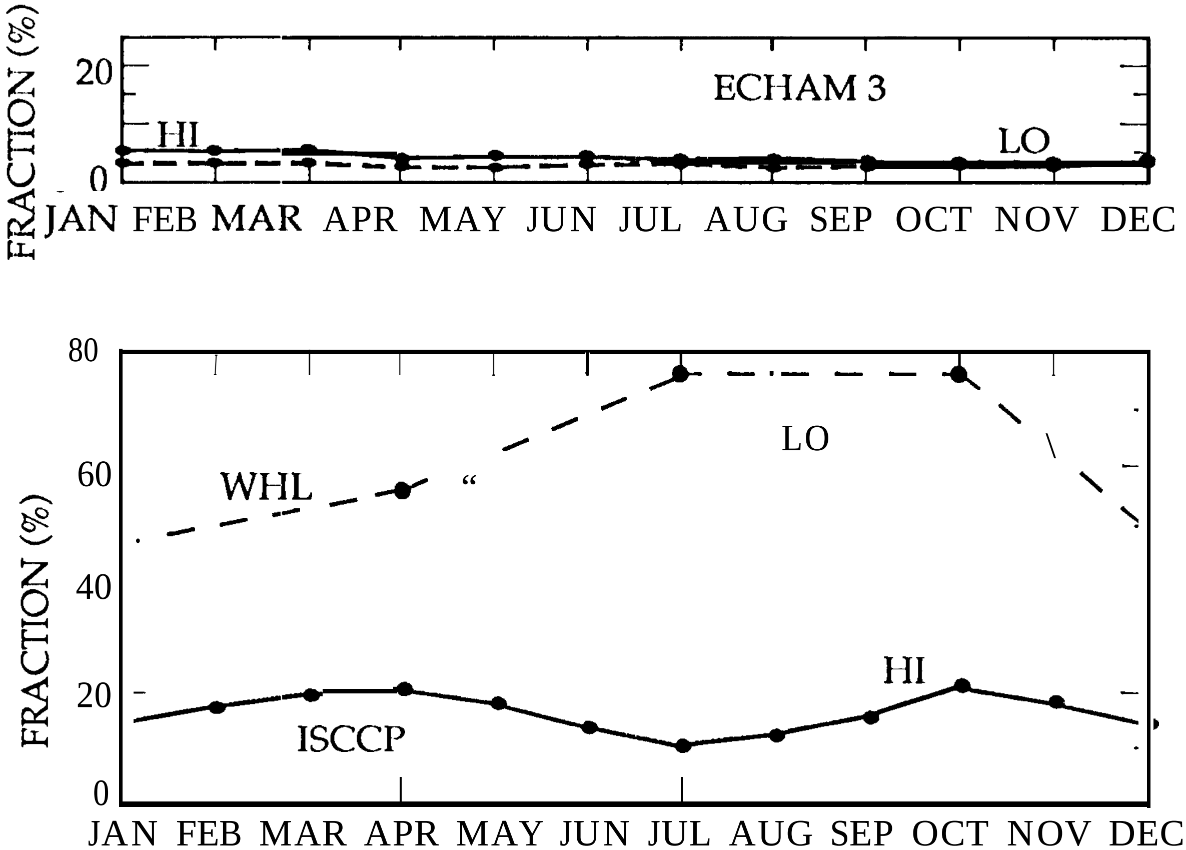

FRACTION (%)
20
0
HI
ECHAM 3
LO
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
80
60
40
20
0
FRACTION (%)
WHL
LO
HI
ISCCP
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

Fig. 11

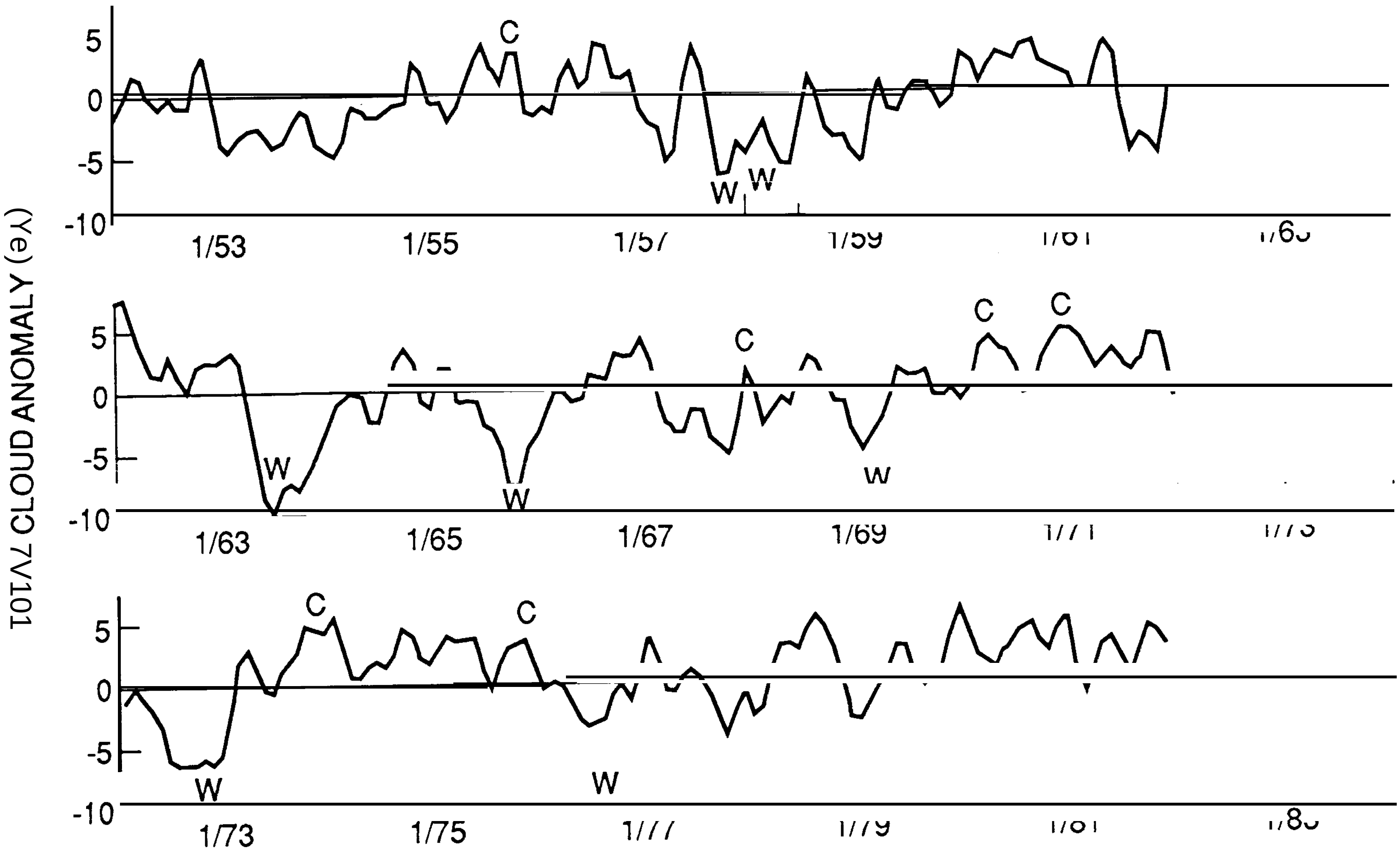

TOTAL CLOUD ANOMALY (eA)
5
0
-5
-10
C
W
W
1/53
1/55
1/57
1/59
1/61
1/63
1/65
1/67
1/69
1/71
1/73
1/75
1/77
1/79
1/81
1/83

Fig 12

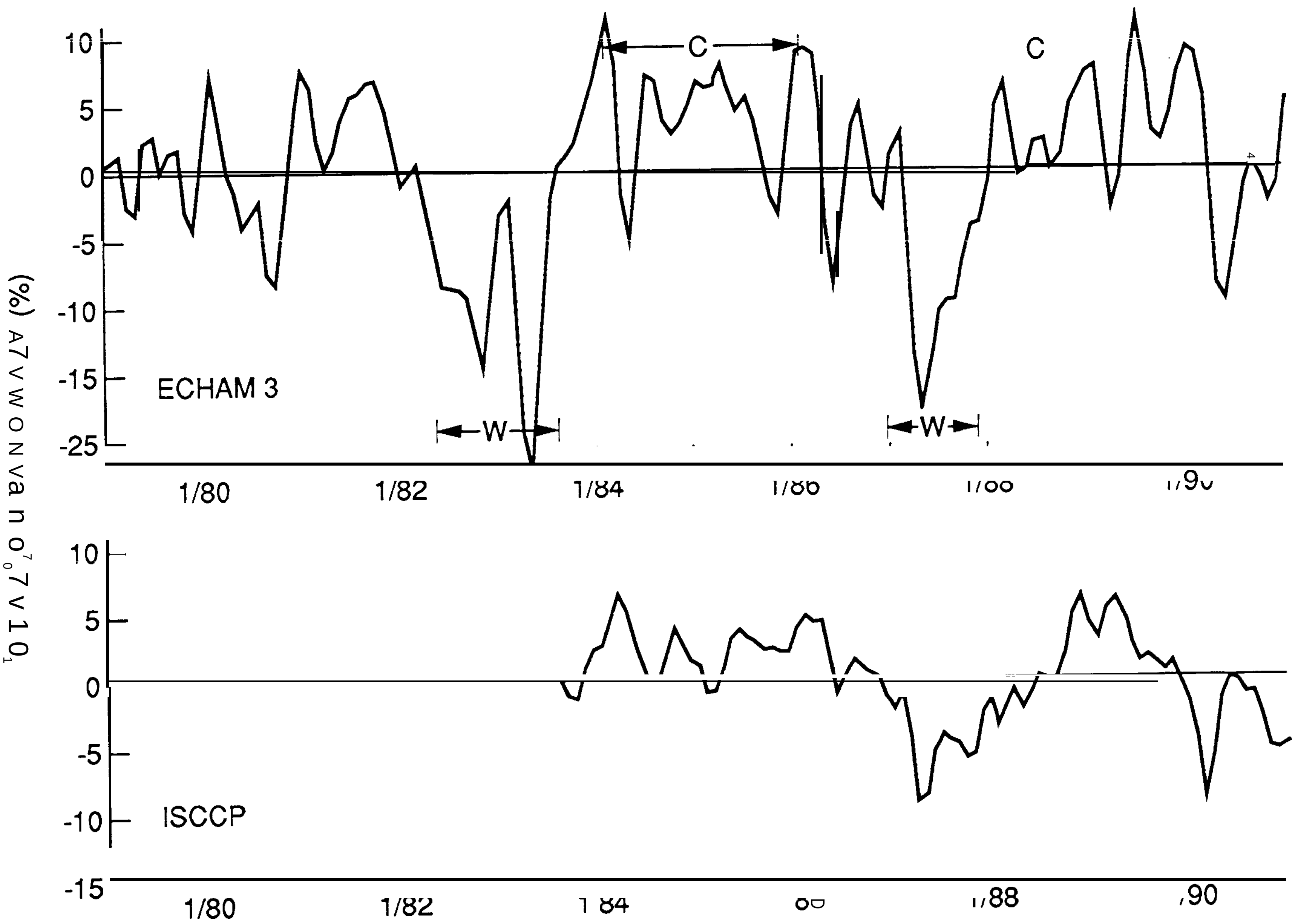


Fig. 13