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Monsoon Rainfall in the GEOS-1 Assimilation: Sensitivity to Input Data

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ABSTRACT

The Data Assimilation Office (DAO) at Goddard Space Flight Center is currently producing a multiyear gridded global atmospheric dataset using a fixed assimilation system designed to remove the variability due to algorithm changes. While the signal due to system changes has been eliminated, changes in the input data are another potential source of spurious climate signals. In this study, a set of sensitivity experiments are performed with the Goddard Earth Observing System Version 1 (GEOS-1) assimilation system to assess the impact of including temperature and moisture information from stations on the NCEP's (National Centers for Environmental Prediction) reject list.

The results from the sensitivity experiments for the northern summer of 1994 indicate that the impact of including the reject list reports is significant in the tropics. The most significant difference is found in the precipitation over the Indian summer monsoon region and the western Pacific. The precipitation without the reject list reports is unrealistically dry over the Indian monsoon region. The monthly precipitation pattern is substantially improved by including the reject list reports, which are mainly located on the Indian subcontinent. The sensitivity experiments further indicate that the difference is primarily a result of using the moisture information.

The temporal variations of the monsoon precipitation also indicate that the assimilation that includes the reject list stations has much enhanced intraseasonal low-frequency fluctuation with a period of about two weeks. However, a coherent variation in the rainfall increase and the number of moisture observations over the monsoon region suggests that the enhanced quasi-biweekly oscillation is not dynamically driven, but forced by the inconsistent injection of moisture data. Whereas the inclusion of the reject list reports appears to have a substantial positive impact on the mean rainfall over the Indian monsoon region for this time period, the forcing from inconsistent input data introduces spurious temporal variation in the intraseasonal time-scales.

This study suggests that the input data need to be carefully examined for consistency and that caution is needed when a new data type is introduced in the reanalysis.

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1 Introduction

Operational analyses produced by analysis/forecast systems have become an important tool for climate research. One of the most difficult problems often encountered in using the operational analysis field, however, is the spurious variations in the analysis data introduced by frequent changes and improvement of the NWP systems. Reanalysis, for this reason, has become an important subject with the hope that it will resolve this problem with the operational analyses. The primary objective of reanalysis is to minimize the variability due to algorithm changes and to isolate the climate signals by using a fixed assimilation system. Whereas the signals due to model changes can be successfully eliminated in the reanalyses, changes in the input data are another potential source of spurious climate signals even in the nonvarying analysis system. The changes in input data may result from, for example, increasing the number of observation stations, the introduction of new data types and changes to quality control procedures. The sensitivity of monsoon rainfall to the input data was discovered during the assimilation of the summer of 1994, during which the East Asian monsoon was abnormal (Park and Schubert 1997). The primary interest in this study is to evaluate the sensitivity of monsoon rainfall to the moisture and height reports from the NCEP's reject list stations largely distributed in the Indian subcontinent during the summer of 1994.

2 Multiyear GEOS-1 Reanalyses

The Data Assimilation Office (DAO) at the NASA's (National Aeronautics and Space Administration) Goddard Space Flight Center has recently produced a multi-year global dataset (Schubert et al. 1993) and a special dataset for the summer of 1994, employing a fixed assimilation system. The climatological features and temporal variations in various time-scales are documented and compared to those of the ECMWF (European Centre for Medium-Range Weather Forecasts) analyses in Schubert et al. (1995). The GEOS-1 Data Assimilation System (DAS) is briefly described in the Appendix.

Figure 1 shows the anomalies of the GEOS precipitation and the GOES (Geostationary Operational Environmental Satellite) precipitation index (GPI) averaged over the Indian monsoon region. The GPI is a method used to estimate rainfall amount in the global tropics from time scales of weeks to months. The method uses satellite infrared imagery to determine cloud-top temperature and computes rainfall based on the fractional coverage of cloud below a threshold temperature of 235 K. Detailed information on the method is described by Arkin and Meisner (1987). The anomalies are the departures from their respective seasonal cycles. These quantities clearly show the large fluctuation in the monsoon rainfall during the 1987-1988 ENSO (El Nino-Southern Oscillation) cycle from severe drought in 1987 to flood in 1988. The GEOS precipitation indicates somewhat drier conditions in the summer of 1987. Whereas the two quantities show a fair agreement for the first few years, substantial differences are found after the spring of 1989, particularly in the summers of 1989-90 and 1992-93: the GEOS rainfall indicates unrealistically wet conditions in 1989 and 1990, and dry conditions in 1992 and 1993.

Figure 2 shows the daily counts of the total number of rawinsonde reports accepted

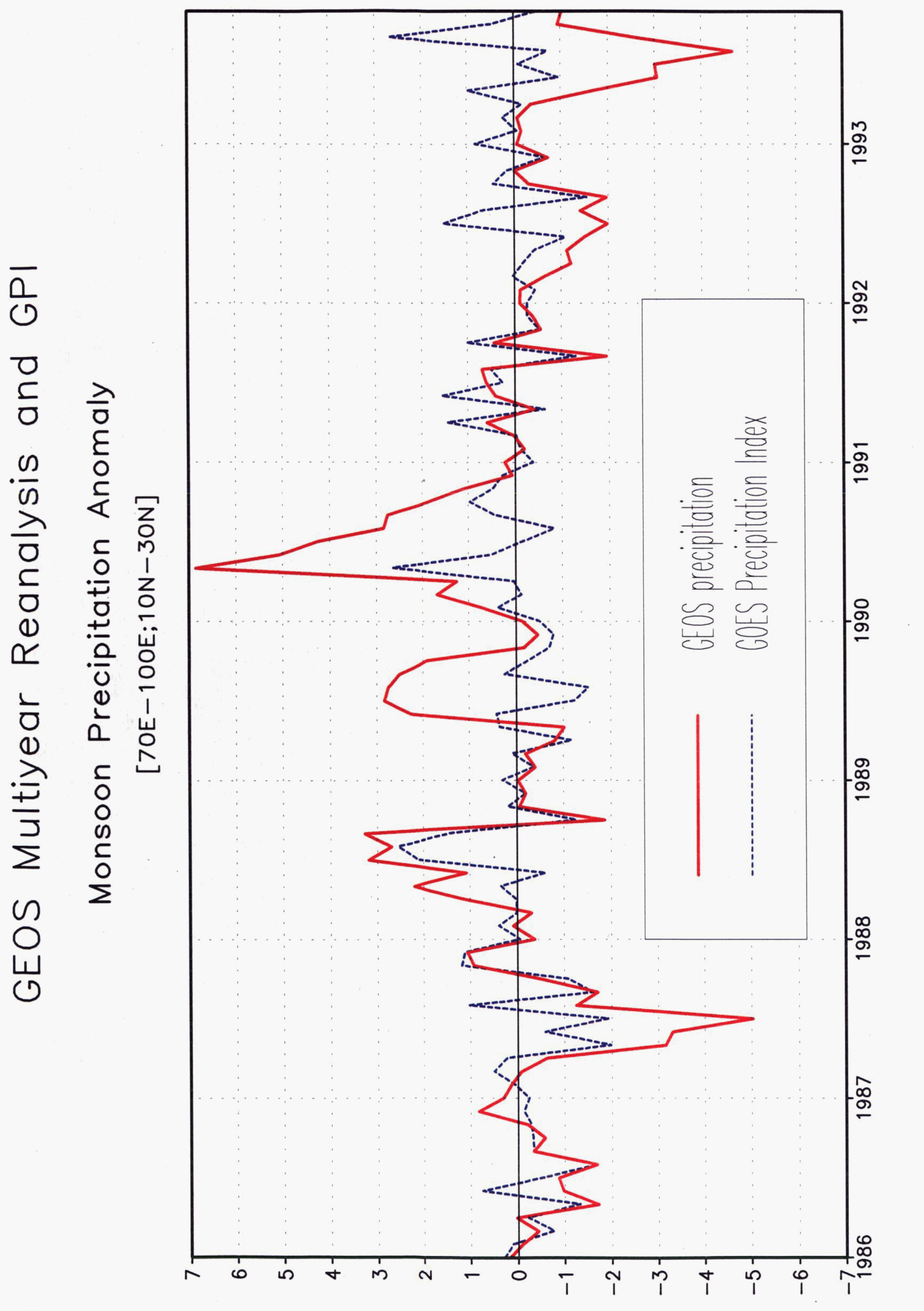

Figure 1: Temporal variations of the Indian monsoon precipitation anomalies from the GEOS assimilation and the GOES Precipitation Index (GPI).

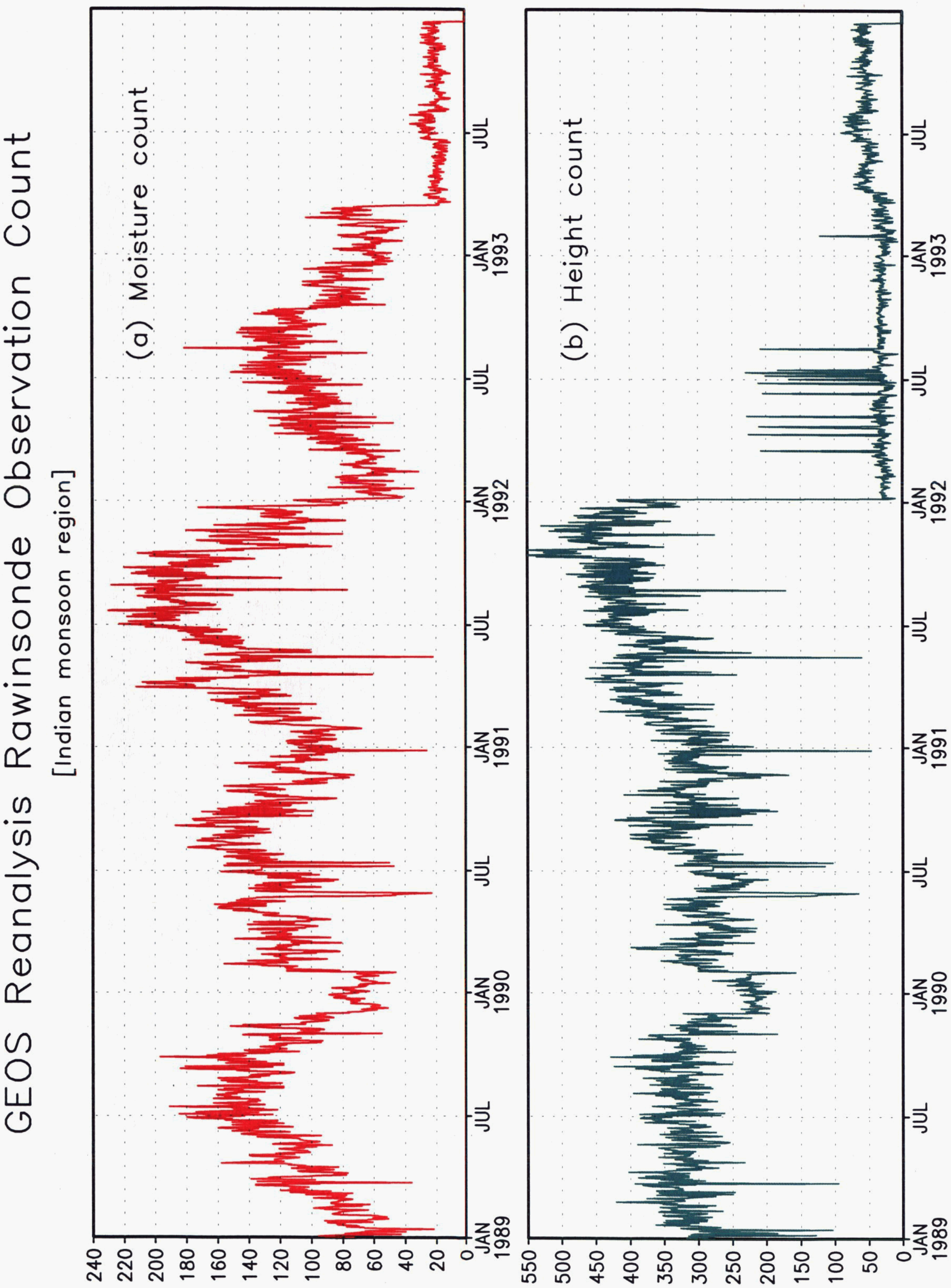

Figure 2: Temporal variations of the number of rawinsonde reports for (a) moisture and (b) height over the Indian monsoon region [70°E-100°E,10°N-30°N].

to assimilation over the Indian monsoon region for moisture and height. The moisture reports are slightly increased during the summer. The number of moisture reports is reduced almost in half in 1992, and nearly absent in 1993, while the number of height reports drastically drops down to near zero beginning January 1, 1992. These observation data counts suggest that the unrealistic rainfall variation in 1992-93 may be tied to a change to quality control (QC) procedure during that time, which is responsible for the significant reduction in input data.

The CQCHT (Complex Quality Control of Heights and Temperatures) is run operationally at NCEP on the radiosonde observations reported over the GTS. Gandin (1988) describes the complex quality control of rawinsonde height and temperature. The radiosonde observations, however, undergo further processing, including the addition of quality marks by a "deleter" code. Radiosonde stations that consistently report observations of bad quality are put on the "reject list"; a separate reject list is maintained for heights/temperatures and winds. Any radiosonde observations from a station on the reject list are marked with a flag of "R", and not used in the NCEP analysis, even if these data are otherwise considered "good". Good data could be that arriving with an acceptable quality mark from the producer or height and temperature data that pass or are corrected by the CQCHT.

The DAO receives the observations in Office Note 29 format either directly from NCEP or through the data archive at NCAR. These observations are "preprocessed" by the DAO to reformat them into REPACK files and to check them before they are ingested into the GEOS DAS. The DAO observational data preprocessing system includes a gross limit check on the observations, and a hydrostatic check on the radiosonde heights and temperatures. It also eliminates data that are missing coordinates or time stamps, removes duplicate reports and converts the quality marks provided on the NCEP supplied observations to DAO quality marks.

During the processing of the GEOS-1 multiyear reanalyses, the influx of the input data was significantly altered by the quality control: at the beginning the REPACK program used at the DAO did not screen for "P" quality marks in the NCEP data, which indicates that the datum was purged by the SDM (Senior Duty Meteorologist at NCEP), or was rejected because it was on the NCEP's reject list, so these data were allowed into the reanalysis. The REPACK program started rejecting observations with the "P" quality mark beginning January 1, 1992. Then, on June 10, 1992, NCEP introduced a new quality mark table (see NCEP Office Note 29) that separated the SDM purged observations ("P") and the reject list observations ("R"), and the REPACK program began to reject observations with either of these marks. Thus, data marked with "P" or "R" are not used in the GEOS-1 reanalysis beginning January 1, 1992. The global distribution of rawinsonde stations and reject list stations for July 1994 are shown in Figure 3. These changes in the NCEP's QC consequently exert a significant impact on the GEOS assimilation. Currently, DAO is developing an independent quality control system, based on the NCEP system, which will be implemented in the GEOS data assimilation system (Dee and Alice 1996), and in an on-line monitoring system (da Silva et al. 1996).

While a dry bias in the GEOS-1 GCM particularly in the convective regions of tropics has been documented by Molod et al. (1996) and Schubert et al. (1995), the reasons for the unrealistically wet conditions in the summers of 1989 and 1990 are unclear. There is no obvious difference in the number of rawinsonde reports in 1989 and 1990. The unrealistically wet conditions may be related to a different problem. One potential source of the spurious variation may be related to a series of changes in NCEP's QC procedure around this time period: The CHQC (Comprehen-

Figure 3: Locations of rawinsonde stations (plus sign) for height and temperature and reject list stations (triangle) for July 1994.

sive Hydrostatic QC) developed by Collins and Gandin (1990) was first implemented on December 14, 1988 for mandatory levels only, replacing HYDSTCHK (hydrostatic QC for rawinsonde heights and temperatures). A series of minor changes were made until CQCHHTM (Complex QC of rawinsonde heights and temperatures) was implemented on November 15, 1991 (see Collins, 1991). The quality of input data used at DAO are questionable since almost all the moisture and height data, even with "R" quality mark, are allowed in the reanalyses prior to January 1, 1992.

3 Sensitivity Experiments

We have performed a series of experiments to evaluate the sensitivity of the analysis to the input data changes for the summer of 1994. In experiment A, the rawinsonde data purged by the SDM or on the reject list are not used in the assimilation, while the reports from the reject list stations are used in experiment B. In experiment C, only the moisture information from the reject list stations is used, while only the height information from the reject list stations is used in experiment D. The information from the reject list stations used in these experiments are summarized in Table 1.

Table 1: Sensitivity experiments:June-July 1994

	Experiment			
Rawinsonde	A	B	C	D
Height	No	Yes	No	Yes
Moisture	No	Yes	Yes	No
Wind	No	Yes	No	No

4 Results

4.1 Mean precipitation

Figure 4 shows the difference between the assimilated precipitation with and without using the rawinsonde reports from the reject list stations for June and July 1994. It is found that the precipitation is substantially increased over the Indian subcontinent region by using the rawinsonde reports from the reject list stations. The maximum difference of the monthly mean rainfall exceeds 10 mm/day near the northern tip of the Bay of Bengal. Increased precipitation is also found over the western Pacific and northwestern South America, where the observations are sparse. The precipitation increase over these regions suggests that the reject list station reports have a significant impact on the assimilated rainfall over the data sparse regions, while the impact appears to be insignificant over East Asia where the rawinsonde observation stations are dense.

Figure 5 indicates that the assimilated rainfall without using the reject list reports is drier over the Indian monsoon region compared to the anomaly patterns represented by the GPI and NOAA (National Oceanic and Atmospheric Administration) OLR (outgoing longwave radiation). The rainfall anomaly pattern becomes more realistic by using the reject list reports in the assimilation (Fig. 5b).

Figure 6 shows the sensitivity of the assimilated precipitation to the moisture and height information separately. As shown in Fig. 6(a), the precipitation difference is mainly due to the additional moisture reports, while the impact from the height information is much weaker over the Indian monsoon region. The impact of wind appears to be much less important compared to the height and moisture impacts.

In Figure 7, the latitude-pressure sections over the Indian monsoon region (70°E-100°E) reveal that both height and moisture fields are substantially modified by the rawinsonde reports from the reject list stations. It is interesting to note that in Fig. 7(a) the height fields increase in the upper troposphere and decrease in the lower troposphere due to moisture information from the reject list stations. Fig. 7(b) shows that the low level moisture is enhanced over the Indian subcontinent region with maximum at around the 800 mb level between 10N and 25°N. This is consistent with systematic dry bias in the GEOS-1 GCM, which is most pronounced over the Indian Ocean and the western Pacific region. The influence of the moisture increase also extends over the Indian Ocean south of the Equator. The enhanced convection associated with the moisture changes is likely responsible for the dynamically driven height changes over the Indian monsoon region. The height changes due to moisture data are comparable to the height changes due to height data (Fig. 7c). The moisture changes due to height information in Fig. 7(d) indicate that the moisture changes are induced by the circulation changes associated with the enhanced upper level divergence and low level convergence. The moisture increase south of the high mountains suggests that a part of the moisture increase around 30°N in Fig. 7(b) may also be dynamically driven.

4.2 Temporal variation

The assimilated precipitation with and without using the reject list stations (Figure 8) shows a substantial difference in low frequency variation: the rainfall variation without using the reject list reports (Fig. 8b) is much weaker than that with using the reject list reports (Fig. 8a) during the monsoon period except for the variation associated with diurnal cycle. The difference (Fig. 8c) indicates that the reports from the reject list stations introduce substantially stronger rainfall variations with a period of about two weeks.

The five-day running means of the rainfall, moisture, and the number of reports from the reject list stations are compared in Figure 9 in order to examine whether the low frequency fluctuation is generated by the internal dynamics or forced by the low level moisture fluctuation associated with the observations from the reject list stations. Fig. 9(a) shows the temporal variation of the Indian monsoon precipitation difference due to the reports from the reject list stations. The temporal variation is similar to the variation of the vertically integrated moisture difference in Figure 9(b). The number of moisture reports from the reject list stations over the Indian monsoon region in Figure 9(c) clearly show a low frequency variation similar to that of the precipitation difference and the moisture variations, except for the period between

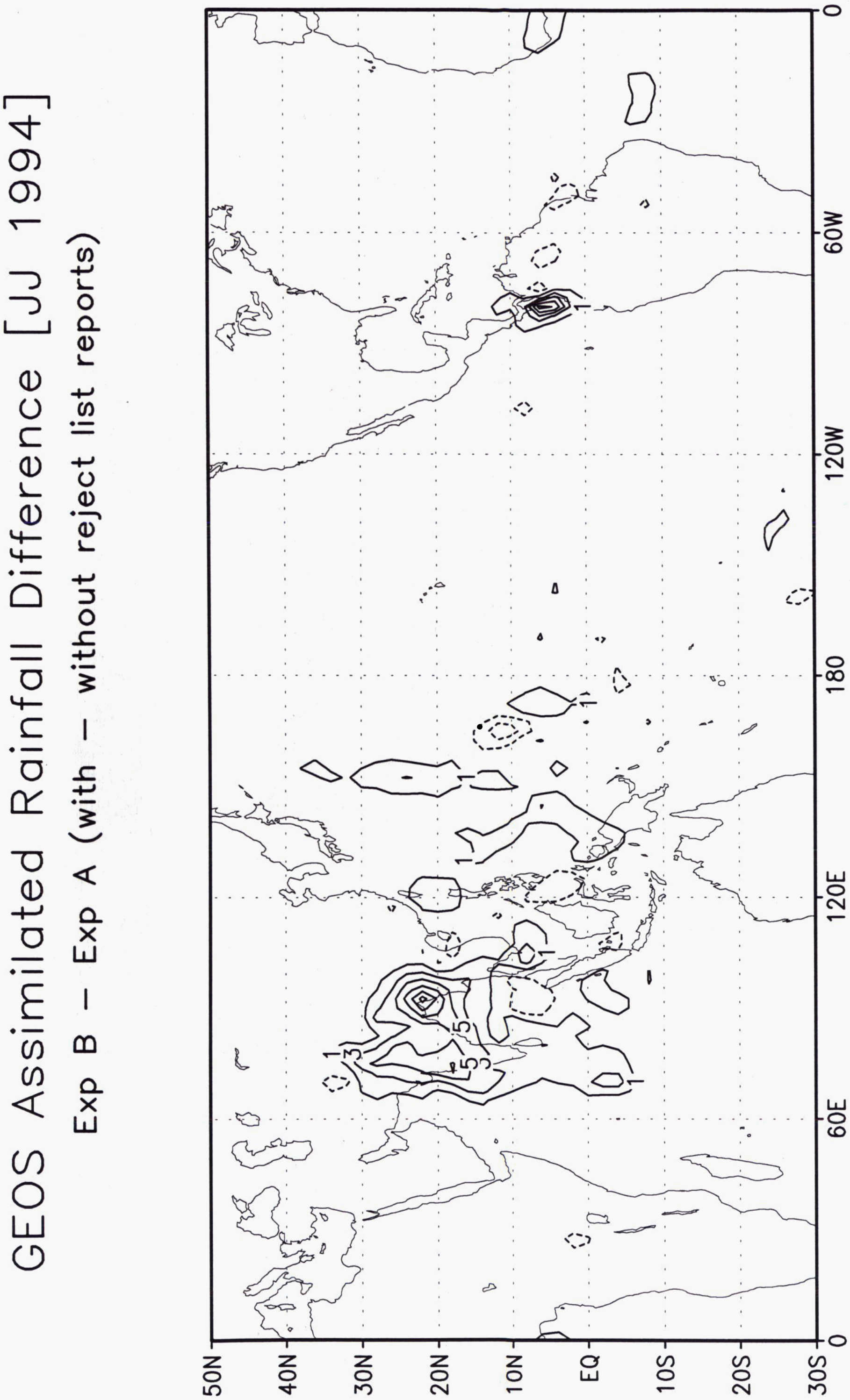

Figure 4: Difference between precipitations assimilated with (EXP B) and without (EXP A) using the reject list reports for June/July 1994. Contour interval is 2 mm/day.

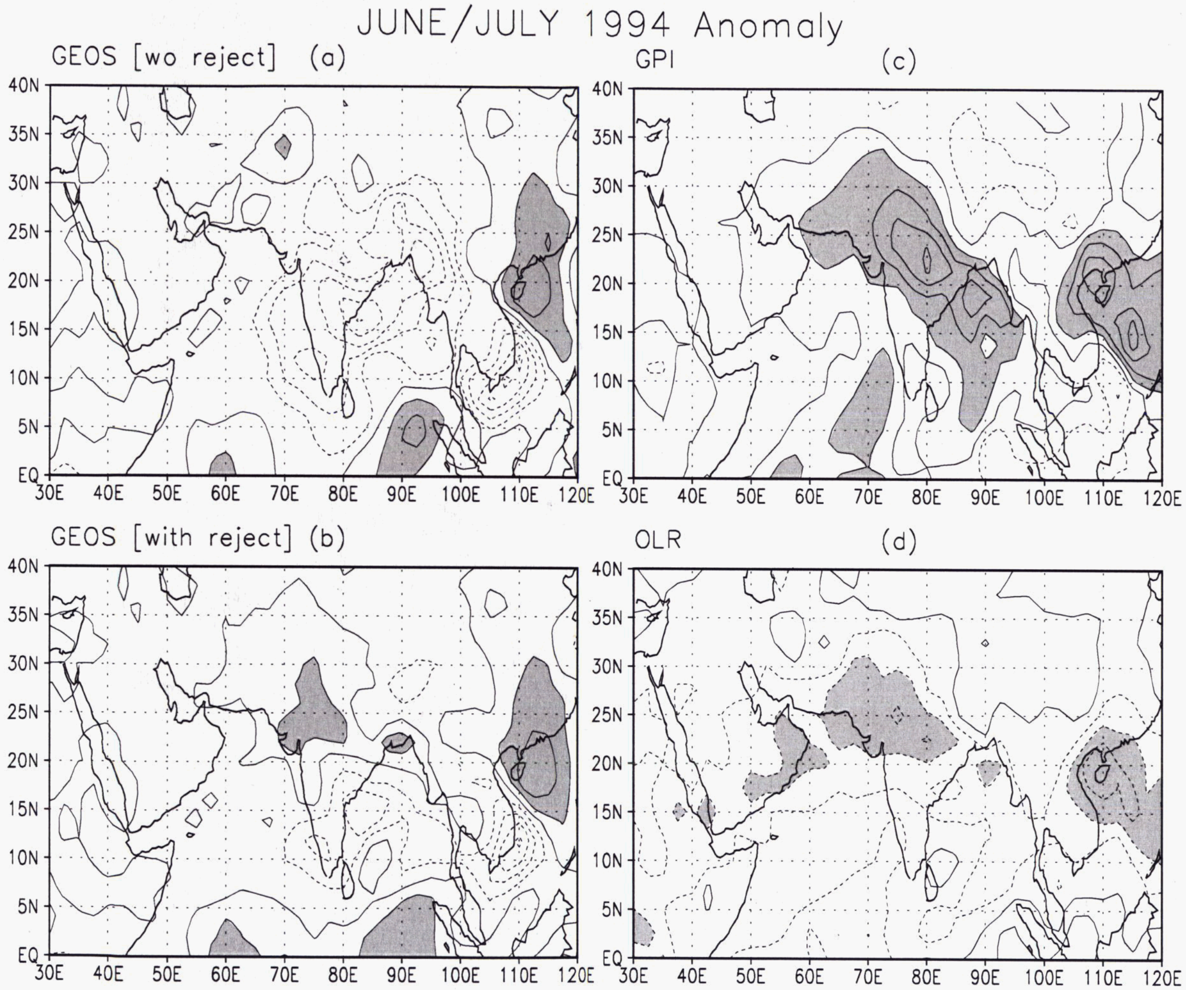

Figure 5: The June/July 1994 anomaly patterns for (a) the GEOS rainfall assimilated without reject list reports, (b) the GEOS rainfall assimilated with reject list reports, (c) GPI, and (d) NOAA OLR. Dotted lines represent negative values. Contour intervals are 2.0 mm/day in (a)-(c) and 10 W/m^2 in (d). Shading represents the values greater than 2 mm/day in (a)-(c) and the values less than -20 W/m^2 in (d).

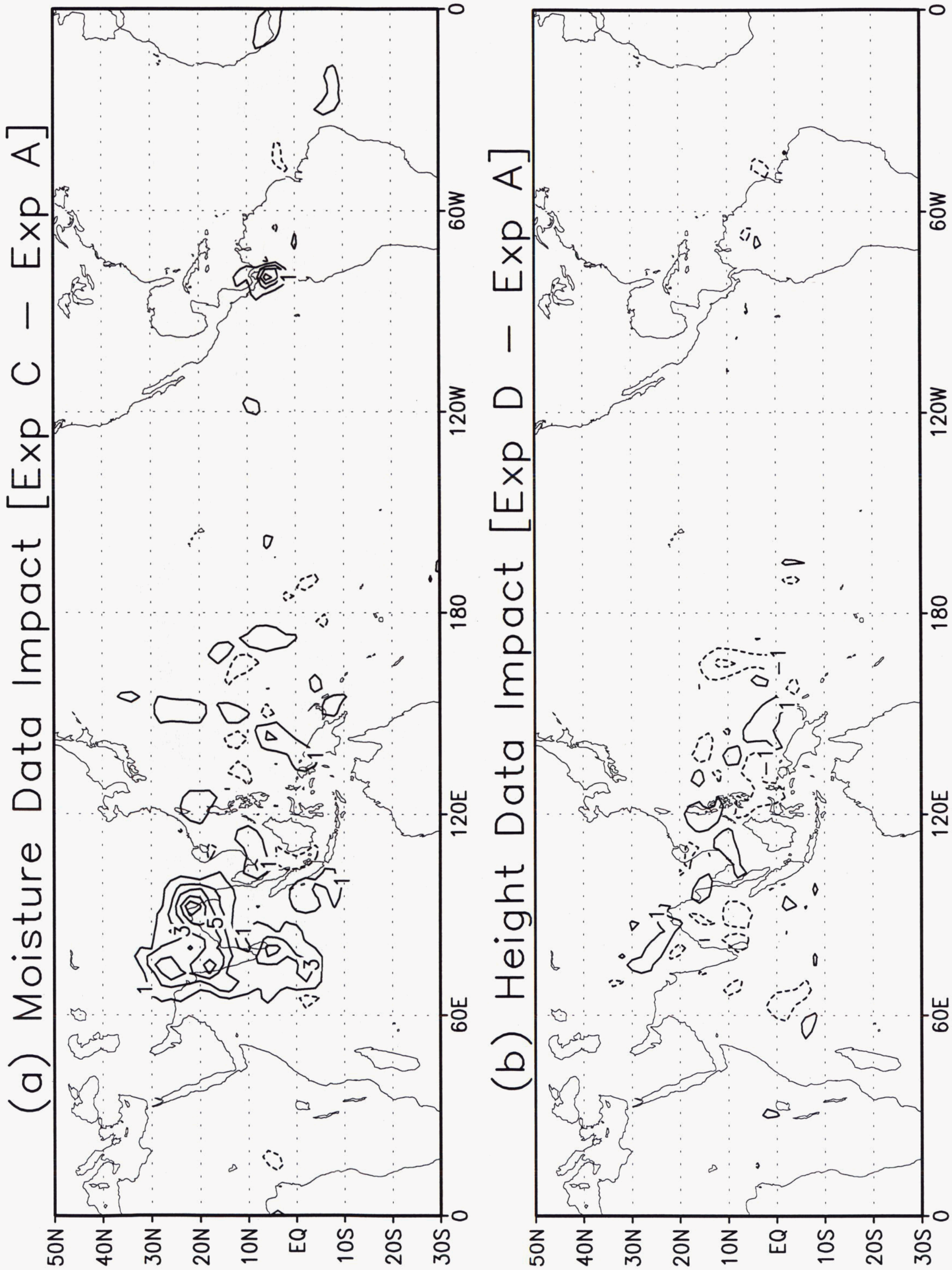

Figure 6: Difference between precipitations assimilated with and without (a) the moisture data and (b) height data from the reject list stations for June/July 1994. Contour interval is 2 mm/day.

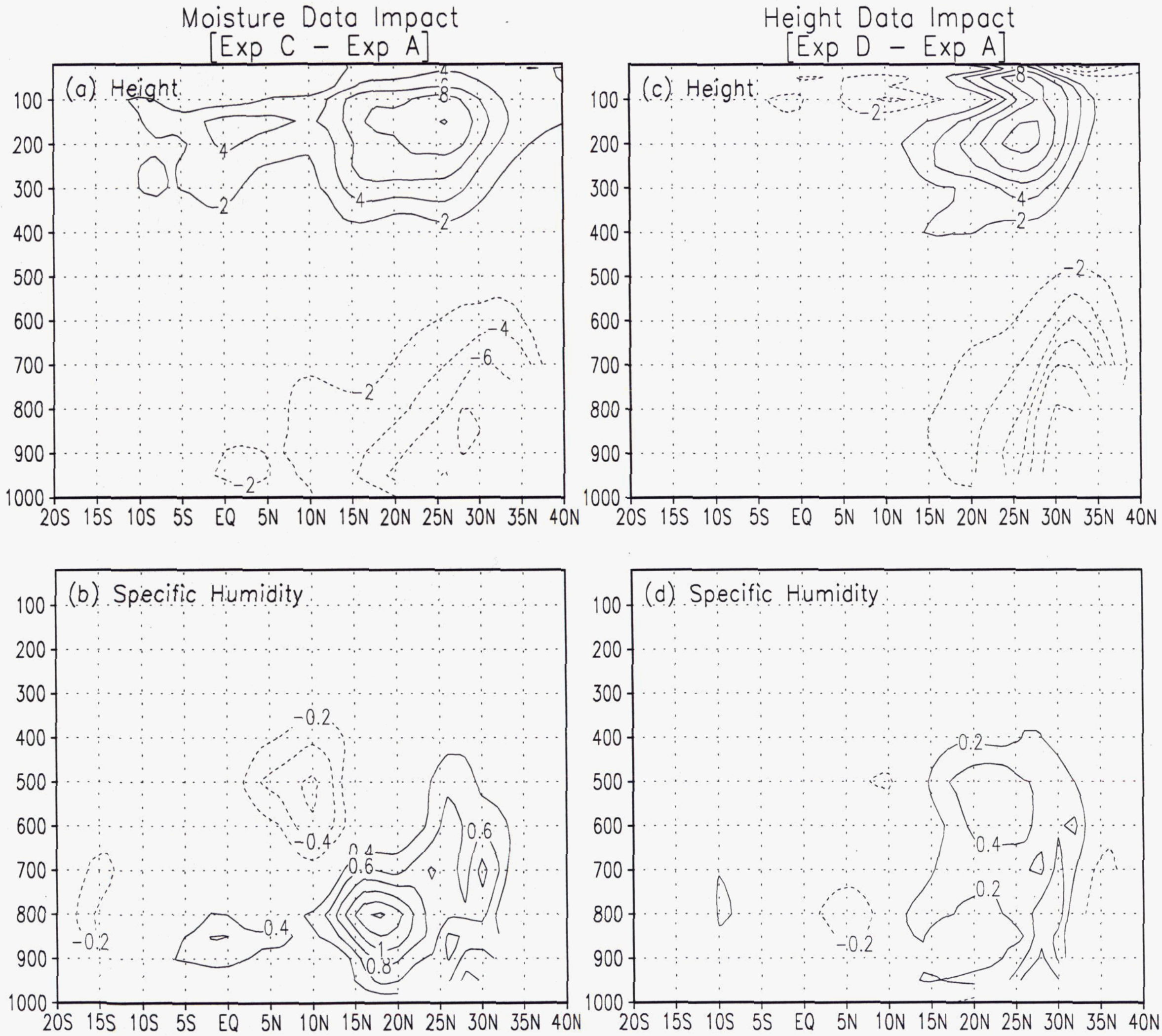

Figure 7: Latitude-pressure section over the Indian monsoon region [70°E-100°E] of (a) height and (b) moisture difference due to moisture data and (c) height and (d) moisture due to height data from the reject list stations for June/July 1994. Contour intervals are 2 meter for height and 0.2 g/kg for specific humidity.

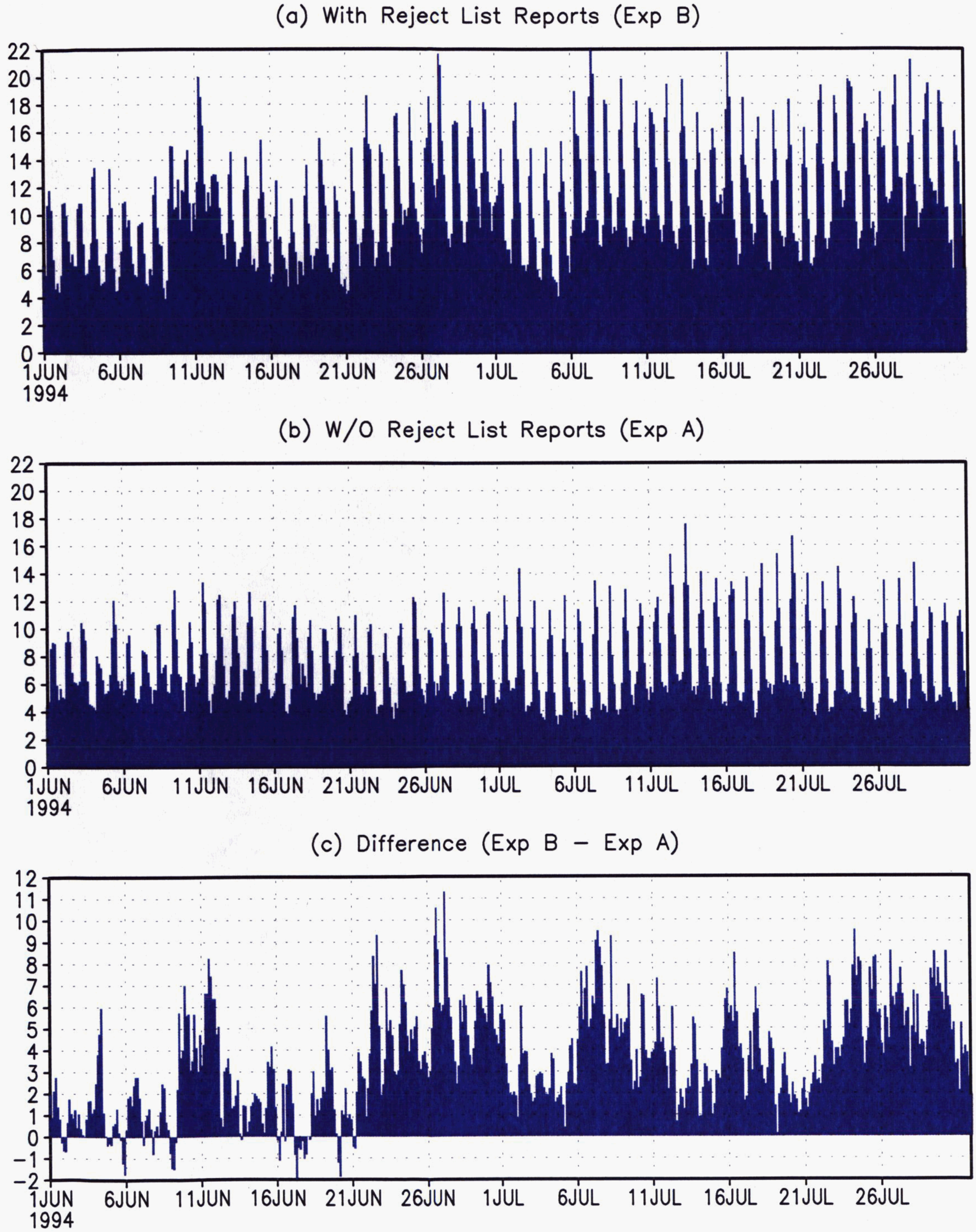

Figure 8: GEOS precipitation over the Indian monsoon region (a) with and (b) without using the reject list reports, and (c) their difference. Units are in mm/day.

June 15 and June 21. These highly correlated variations suggest that at least part of the monsoon rainfall fluctuation is an artifact of the moisture changes associated with uneven forcing from the observations ingested during the assimilation.

5 Summary

The Data Assimilation Office at the NASA's Goddard Space Flight Center has recently produced a multi-year global data, employing a fixed assimilation system. The rainfall shows during some years unrealistic anomalies over the Indian monsoon region. The unrealistically dry monsoon rainfall in the summers of 1992 and 1993 appears to be related to a dry bias in the GEOS GCM and a change in quality control which is responsible for substantial reduction in rawinsode reports since January 1, 1992. The reasons for the unrealistically wet conditions in the summers of 1989 and 1990 are still unclear.

A set of sensitivity experiments were performed with the GEOS assimilation system to assess the impact of including height and moisture information from stations on the NCEP reject list. The results from experiments for the northern summer of 1994 with and without the reject list reports indicate that the data impact on the assimilated rainfall is significant in the tropics: The precipitation without the reject list reports shows unrealistically dry conditions over the Indian monsoon region. The monsoon precipitation is substantially improved by including the reject list reports, which are mainly located in the Indian subcontinent. The sensitivity experiments indicate that the moisture information from the reject list stations has a significant positive impact on the monsoon precipitation, while the temperature information has a much less impact, although not absent.

The low-frequency intraseasonal variations of the monsoon precipitation is enhanced in the experiment that includes the reject list reports. It is found that the enhanced quasi-biweekly oscillation in the monsoon precipitation is not dynamically driven, but could be modulated by the observation data. Whereas the inclusion of the reject list reports has a substantial positive impact on the mean monsoon rainfall, the forcing from the inconsistent data introduces spurious temporal variation in the intraseasonal time-scales.

This study suggests that the input data need to be carefully examined for consistency and that caution is needed when a new data type is introduced in the reanalysis. It is important, especially for climate data assimilation, to have an unbiased model to minimize the sensitivity to the variations in input data.

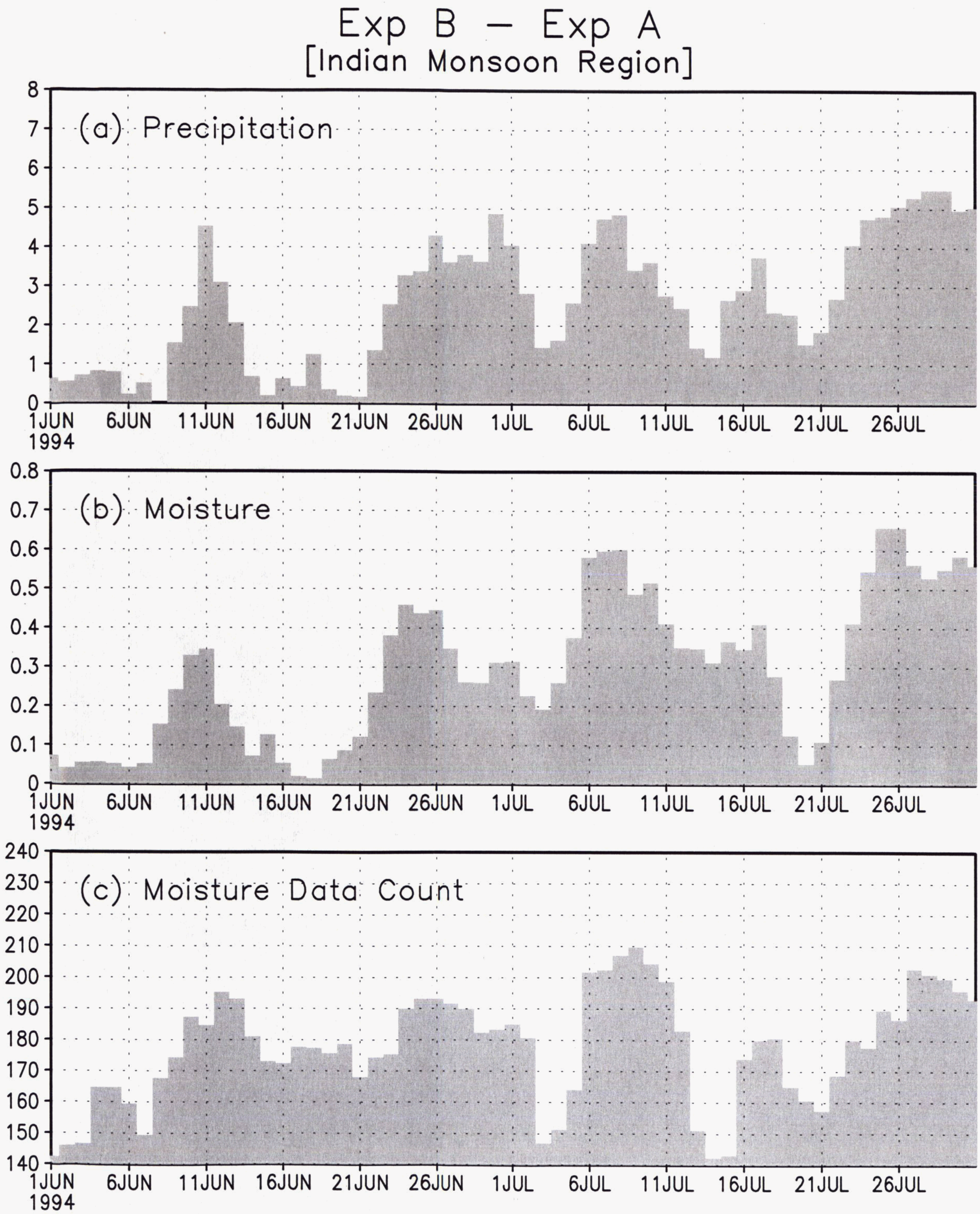

Figure 9: Temporal variations of the difference between (a) precipitations and (b) moistures assimilated with and without the reports from the reject list stations (with-without), and (c) the number of moisture observations from the reject list stations over the Indian monsoon region (10°N-30°N;70°E-100°E) represented by five-day running mean.

Appendix: GEOS-1 Data Assimilation System

The main components of the GEOS-1 data assimilation system (DAS) are the GEOS-1 atmospheric general circulation model (Takacs et al. 1994; Suarez and Takacs 1995) and a 3-dimensional, multivariate optimal interpolation (OI) scheme (Pfaendtner et al. 1995). The GEOS-1 (version 1) DAS is summarized below.

The OI analysis scheme is carried out at a horizontal resolution of 2° latitude by 2.5° longitude at 14 upper-air pressure levels and at sea level. The analysis increments are computed every 6 hours using observations from a +/- 3 hour data window centered on the analysis times. For the global sea level pressure and near surface wind analysis over the oceans, data from surface land synoptic reports (sea level pressure only), ships and buoys are used. The upper-air analyses of height, wind and moisture incorporate the data from rawinsondes, dropwindsondes, aircraft winds, cloud tracked winds, and thicknesses from the historical TOVS soundings produced by NOAA NESDIS. The assimilation system does not include an initialization scheme and relies on the damping properties of a Matsuno time differencing scheme to control initial imbalances generated by the insertion of observations. However, the initial imbalances and spinup have been greatly reduced over earlier versions by the introduction of an incremental analysis update (IAU) procedure (Bloom et al., 1991).

The GEOS-1 GCM uses the potential enstrophy and energy-conserving horizontal differencing scheme on a C-grid developed by Sadourny (1975). The model's vertical finite differencing scheme is that of Arakawa and Suarez (1983). The dynamics routines are organized into a plug-compatible module developed by Suarez and Takacs (1995). The infrared and solar radiation parameterizations follow closely those described by Harshvardhan et al. (1987). The penetrative convection originating in the boundary layer is parameterized using the Relaxed Arakawa-Schubert (RAS) scheme (Moorthi and Suarez, 1992), which is a simple and efficient implementation of the Arakawa-Schubert (1974) scheme. The planetary boundary layer (PBL) is explicitly resolved in a 2 to 4 layer region. Wind, temperature and humidity profiles in an "extended" surface layer, and the turbulent fluxes of heat, moisture, and momentum at the surface are obtained from Monin-Obukov similarity theory. Turbulent fluxes above the "extended" surfaced layer are computed using the second order closure model of Helfand and Labraga (1988).

The GEOS-1 GCM is run without a land surface model. For the assimilation described here, the soil moisture is computed off-line based on a simple bucket model using climatological surface air temperature and precipitation (Schemm et al., 1992). The snow line and surface albedo are prescribed and vary with the season. The sea surface temperature is updated according to the observed monthly mean values provided by the Climate Predictions Center at NCEP and the Center for Ocean-Land-Atmosphere Studies (COLAS).

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