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Stratospheric tides and data assimilation

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Abstract. In the upper stratosphere the atmosphere exhibits significant diurnal and semidiurnal tidal variations with typical amplitude of about 2 K in midlatitudes. In this paper we examine how well the tidal variations in temperature are represented by the GEOS-2 data assimilation system. It is shown that the GEOS-2 atmospheric model is quite successful at simulating the tidal variations. However, the assimilation of satellite temperature soundings significantly damps the simulated tides. The reason is that the tides are not well represented by the satellite retrievals used by the assimilation system (which have a typical tidal amplitude of about 1 K). As a result of this study, we suggest improvements that should be made to the treatment of satellite sounding data by the assimilation system.

1. Introduction

The aim of an atmospheric data assimilation system is to combine information from a variety of sources to capture the essential features of the evolving state of the atmosphere. However, diagnostics from the GEOS-2 (Goddard Earth Observing System, version 2) data assimilation system suggest that the system is not currently representing the tidal variations well; the aim of this study is to explore the reasons for those shortcomings.

Much of the emphasis of atmospheric data assimilation has been on the production of initial data for operational weather forecasting. In recent years there has been more interest on the assimilation of stratospheric observations, as well as tropospheric data. Firstly, improved specification of the stratosphere has contributed to improvements in the quality of operational forecasts [e.g., *Simmons*, 1994]. Secondly, assimilated data have been used for studies of the stratospheric circulation [e.g., *O'Neill et al.*, 1994]. The Upper Atmosphere Research Satellite (UARS) program gave a particular impetus to stratospheric data assimilation, with the development of the U. K. Meteorological Office (UKMO) stratospheric system [*Swinbank and O'Neill*, 1994]. Analyses produced by the UKMO system and made available to the UARS science team have proved invaluable in the interpretation of UARS measurements. Data assimilation systems for the stratosphere have also been developed at the NASA Goddard Space Flight Center. An early version was the stratospheric analysis (STRATAN) system described by *Rood et al.* [1990]. The latest version is the GEOS-2 data assimilation system (DAS), used for this study [*Data Assimilation Office (DAO)*, 1996]. Assimilated data sets produced by the GEOS-2 system are generally of high quality, although there remain some shortcomings in the results in the upper stratosphere. Diagnostics from the assimilation system show that large analysis increments were being calculated by the GEOS-2 DAS, revealing that the system is not dealing properly with the strong tidal variations near the stratopause.

Atmospheric tides have been studied by a number of different investigators; the definitive modern study of atmospheric tides was made by *Chapman and Lindzen* [1970]. Atmospheric tides are global scale daily oscillations which are primarily forced by diurnally varying absorption of solar radiation by trace gases, notably water vapor in the troposphere and ozone in the stratosphere. These diurnally varying forcings excite various atmospheric waves which may be trapped or propagate vertically. To a good approximation, the migrating tidal oscillations can be modeled by determining the atmospheric response to radiative forcing, using Laplace's tidal equations for an atmosphere that is basically at rest. In the upper stratosphere the diurnal variations are largely (especially in midlatitudes) due to ozone heating, which excites a trapped mode. In addition, there are vertically propagating modes, which predominate in the tropics.

Tidal oscillations have been modeled by global scale wave models which take into account variations in the background wind, and other factors that modify the propagation of the waves [e.g., *Forbes*, 1982, *Hagan et al*, 1995]. Such models are now successful at simulating many aspects of the observed tidal fluctuations in the middle and upper atmosphere. General circulation models of the lower and middle atmosphere should also be capable of simulating the diurnal tidal oscillations, provided that they include a good representation of all the relevant physical processes. *McLandress* [1997] showed that the Canadian middle atmosphere model (CMAM) produces

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generally realistic simulations of the tidal variations of the wind field in the middle atmosphere.

Several investigators have used measurements from satellites and lidar to assess the diurnal temperature variations associated with the atmospheric tides. *Hitchman and Leovy* [1985] used Limb Infrared Monitor of the Stratosphere (LIMS) (noon minus midnight) temperature differences to estimate the amplitude of the diurnal tide. *Brownscombe et al.* [1985] evaluated tidal variations in radiances measured by Stratospheric Sounding Units (SSUs) on NOAA polar orbiter satellites and compared them with model calculations; again, only a restricted sampling of diurnal variations was possible. *Nash and Forrester* [1986] compared the tidal variations in SSU radiances measured by satellites in different orbits. *Dudhia et al.* [1993] and *Wu et al.* [1998] used measurements from the Improved Stratospheric and Mesospheric Sounder (ISAMS) and the Microwave Limb Sounder (MLS) instruments onboard UARS to study the diurnal tide; since UARS is not in a Sun-synchronous orbit, it was possible to sample different local times and hence calculate the phase as well as the amplitude. *Keckhut et al.* [1996] used lidar measurements to estimate tidal variations over two sites in France.

Tidal variations are also evident in atmospheric analyses. For example, *Trenberth* [1997] showed the importance of taking into account tidal variations when calculating atmospheric budgets in the troposphere. *Bowman et al.* [1998] have pointed out apparent stationary anomalies in daily stratospheric analysis data sets, which can partly be attributed to tidal variations in stratospheric geopotential height fields.

Because these tidal modes are an important component of the atmospheric circulation in the stratosphere, the data assimilation system should be capable of representing them. In subsequent sections of this paper we first verify that the GEOS-2 model produces reasonably realistic simulations of tides in the stratosphere. Then, we demonstrate that when satellite data are assimilated into the model, the tidal signals are significantly damped. By investigating the reasons for the conflict between the data being assimilated and the model, we highlight some shortcomings in the satellite soundings and in the current configuration of the assimilation system, which will be targeted for future improvement.

2. GEOS-2 GCM and DAS

The primary goal of the Data Assimilation Office (DAO) at Goddard Space Flight Center is to produce the best possible assimilated data sets from meteorological observations. This makes the mission of the DAO unique, since the main goal of other centers is to produce the best possible weather forecasts, using the assimilated data as initial conditions. The DAO products are used by a range of customers, but a particular emphasis is to produce data to support various NASA programs, many of which require high-quality meteorological fields in the stratosphere. Thus there is a strong emphasis on optimizing the assimilation of stratospheric data.

The first DAO assimilation system was designated GEOS-1 [*Pfaendtner et al.*, 1995]. The GEOS-1 system used an optimal interpolation (OI) analysis scheme, in combination with a comprehensive GCM [*Molod et al.*, 1996] to produce six-hourly assimilated data. The standard version of the GEOS-1 system focused on the analysis of tropospheric data. It was successfully used to produce a reanalysis of meteorological data for the period 1979-1994 [see *Schubert et al.,* 1993]. Stratospheric versions of the system were also developed and have been used to assimilate observations in conjunction with the UARS project [*Reber*, 1993] and various stratospheric measurement campaigns, such as the Airborne Southern Hemisphere Ozone Experiment / Measurements for Assessing the Effects of Stratospheric Aircraft (ASHOE/MAESA) [*Tuck et al.*, 1997].

The GEOS-1 system has recently been replaced by GEOS-2. The main change was the replacement of the OI analysis scheme by the PSAS (physical-space statistical analysis system) algorithm [*Cohn et al.*, 1998]. This new analysis algorithm allows more optimal use of observational data. The OI scheme was limited to a local analysis of selected observations, which tended to produce spurious noise in the analyses. The PSAS scheme produces a global analysis of all available data, leading to a more consistent product. In this way it is similar to the spectral statistical interpolation scheme of *Parrish and Derber* [1992] and the three-dimensional variational scheme of *Courtier et al.* [1998]. In addition to removing the adverse consequences of data selection, the GEOS-2 system allows easier incorporation of new types of observation and more flexibility in error covariance modeling.

At the heart of the assimilation system is the GEOS-2 GCM (A. Molod et al, manuscript in preparation, 1999), which includes many improvements over the GEOS-1 model. It is a 70-level, sigma-coordinate, gridpoint model, with a horizontal resolution of 2° latitude by 2.5° longitude. In the stratosphere the vertical resolution varies from about 1.0 km near the tropopause to 1.6 km near the stratopause, and the top of the model is at 0.01 hPa (approximate altitude 80 km). A novel attribute of the GEOS-2 GCM is that it uses a rotated latitude-longitude grid, with computational poles on the equator, in order to minimize numerical problems prone to occur when modeling cross-polar flow with gridpoint models.

The GEOS-2 DAS uses a 6-hour analysis-forecast cycle. Starting 3 hours before each synoptic time, a forecast is run to produce background fields for the analysis. Next, the analysis is carried out using the PSAS algorithm to combine observations taken in a 6-hour time window with the model forecast, in a statistically optimum way. Finally, a second 6-hour integration of the model is carried out, with additional forcing terms to bring the model fields towards the PSAS analysis; this procedure is known as the incremental analysis update (IAU), [*Bloom et al.*, 1996].

In the stratosphere the most important observations are satellite temperature soundings, derived from radiances measured by the TOVS (TIROS Operational Vertical Sounder) instruments on the NOAA polar orbiter satellites. The temperature retrievals currently used by GEOS-2 DAS are produced by the National Environmental Satellite Data Information Service (NESDIS). (Since the GEOS-2 DAS currently analyzes geopotential height rather than temperature, the satellite soundings are converted to heights by integration of the layer-mean temperatures). Radiosonde soundings of temperature, wind, and humidity are used where available, generally up to the midstratosphere. A wide range of other observation types is used in the troposphere.

The assimilation output data will be a combination of information from the observations near a particular synoptic hour and the corresponding model forecast. The forecast organizes and summarizes information from previous observations, using physical relationships built into the GCM. Some aspects of the atmospheric state will be well captured by the observing system, and the assimilation data should provide a faithful representation of those observations. However, other aspects of the atmospheric state may not be observed very well, if at all. In the latter case, the assimilation system depends upon the GCM to provide realistic output fields that are consistent with the observations. In practice, it has been found that data assimilation systems can produce reasonable estimates of aspects of the atmospheric circulation that are not well observed, such as the mean meridional circulation [e.g., *Coy and Swinbank*, 1997], although they are liable to be affected by biases in the GCM.

3. Tides in the GCM

To understand the tidal signals in the assimilation output, one first needs to assess how well the model, on its own, simulates the atmospheric tide. The output of the free-running GCM, as well as the DAS, is available every six hours. We have used six-hourly data for a full month to analyze the tidal variations (although similar results can be obtained using shorter sequences of data). Figure 1 shows the monthly mean temperatures at 1 hPa for a particular January from an integration of the GCM, calculated for each of the four synoptic times (0000, 0600, 1200 and 1800 UTC), with the zonal mean subtracted. The Northern Hemisphere is dominated by strong stationary anomalies associated with planetary waves, but in the Southern Hemisphere and tropics, there are clear tidal anomalies that move westward by approximately 90° every six hours.

One can eliminate the stationary waves, and highlight the migrating tides, by averaging fields together using a Sun-synchronous coordinate system (by shifting the longitudes by 90° every six hours). Figure 2 shows the migrating temperature variations at 1, 10, and 100 hPa. The coordinate system corresponds to true longitude at 0000 UTC but can be thought of as representing local solar time (LT); the Greenwich meridian, as plotted, is equivalent to 0000 LT, 90°E is equivalent to 0600 LT, 180°E is equivalent to 1200 LT and 90°W is equivalent to 1800 LT. Since a stationary zonal wave number 4 (or any multiple of 4) would appear as a migrating mode in this analysis, only wave numbers 1-3 have been included. This analysis procedure is very robust, so for example, trends or oscillations in zonal-mean temperatures over the month have very little impact on the diagnosed tidal amplitudes.

At 1 hPa the midlatitude variations are dominated by wave 1 (the diurnal tide), which has an amplitude of around 2-3 K. The temperatures are warmer in the afternoon hemisphere, with the maximum typically at about 1600 LT, and colder in the morning, with a minimum at about 0600 LT. The amplitude is stronger in the Southern Hemisphere than in the Northern Hemisphere; similar calculations for NH summer confirm that the summer hemisphere shows stronger variations than the winter hemisphere. In the tropics the semidiurnal tides become more important and of similar magnitude to the diurnal variations. Lower in the stratosphere (at 100 and 10 hPa), the tidal variations are clearly much weaker than at 1 hPa, although the tidal variations show somewhat similar patterns.

Figure 3 shows the amplitude of the diurnal tide as a function of latitude and pressure. The behavior of the simulated diurnal tide is very similar to the observed behavior [e.g., *Andrews et al.*, section 4.3, 1987]. In midlatitudes the diurnal tide is trapped in the vertical, close to the region where it is forced by the ozone heating. However, in the tropics the amplitude increases strongly with altitude at the upper levels, as it propagates into the mesosphere.

The tidal amplitudes are similar to the results found by *Keckhut et al.* [1996]. They used lidar measurements from two sites in France (both at latitudes close to 44°N) to estimate the local amplitude of diurnal and semidiurnal temperature variations. They found diurnal amplitudes of around 2 K at the stratopause, with weaker variations at lower altitudes. However, one should remember that the local tidal variations are not necessarily the same as the amplitude of the migrating tides, since there may be local effects that would modify the global tidal modes. This is probably more of an issue in the tropics, where there tend to be strong variations in convection over some regions, such as the continents, and weak diurnal variations over other regions, such as the oceans [e.g., *Hsu and Hoskins*, 1989].

A more satisfactory comparison is with MLS temperature data, since they give a global rather than a local picture of the tidal variations. Figure 4 shows cross sections of the amplitude of the diurnal tide calculated for a 70-day period spanning January 1992, analyzed in a similar way as by *Wu et al.* [1998]. This period of 70 days corresponds to two UARS yaw periods. (Approximately every 36 days UARS executes a yaw maneuver to keep most instruments on the shaded side of the spacecraft, as its orbit precesses). The MLS observations are essentially only available at two local times for each observed latitude on any given day, one on the ascending and one on the descending parts of the orbit; as the orbit precesses, different local times are sampled. From the ascending minus descending differences at each latitude and each day, the diurnal and semidiurnal tidal variations may be calculated. However, slow temperature variations due to other factors might be misinterpreted as tidal variations, so the estimates of MLS tides are probably less robust than the GCM estimates. Ideally, we would have sampled the GCM output in exactly the same way as MLS samples the atmosphere in order to compare the results, but this was impossible since the GCM output is only kept every six hours.

In the first yaw period, MLS was viewing the Northern Hemisphere, while in the second period, it was viewing the Southern Hemisphere. Outside the tropics the results are based on one half of the 70-day period, while the tropical amplitudes are based on both yaw periods. The general nature of the tidal variations is similar to the model results. The MLS results show tidal amplitudes of about 2.5 K in the Southern Hemisphere, close to the stratopause (note that the MLS data have been smoothed in both the vertical and the horizontal to reduce noise in the original data, so the tidal variations appear less shallow than in the GCM data). The diurnal variation in the Northern Hemisphere is weaker than in the model. It is possible that slowly varying planetary waves have been misinterpreted by the MLS tidal analysis procedure, leading to changes in the diagnosed amplitudes; the Northern Hemisphere results are more susceptible to that problem than the Southern Hemisphere, because the planetary waves are much stronger in the winter hemisphere. In the tropics, there is a local minimum near the stratopause, with amplitudes increasing into the mesosphere.

Bearing in mind the limitations of the comparisons with MLS and lidar data, we can conclude that the GEOS-2 GCM appears to produce realistic simulations of the temperature variations associated with the atmospheric tides.

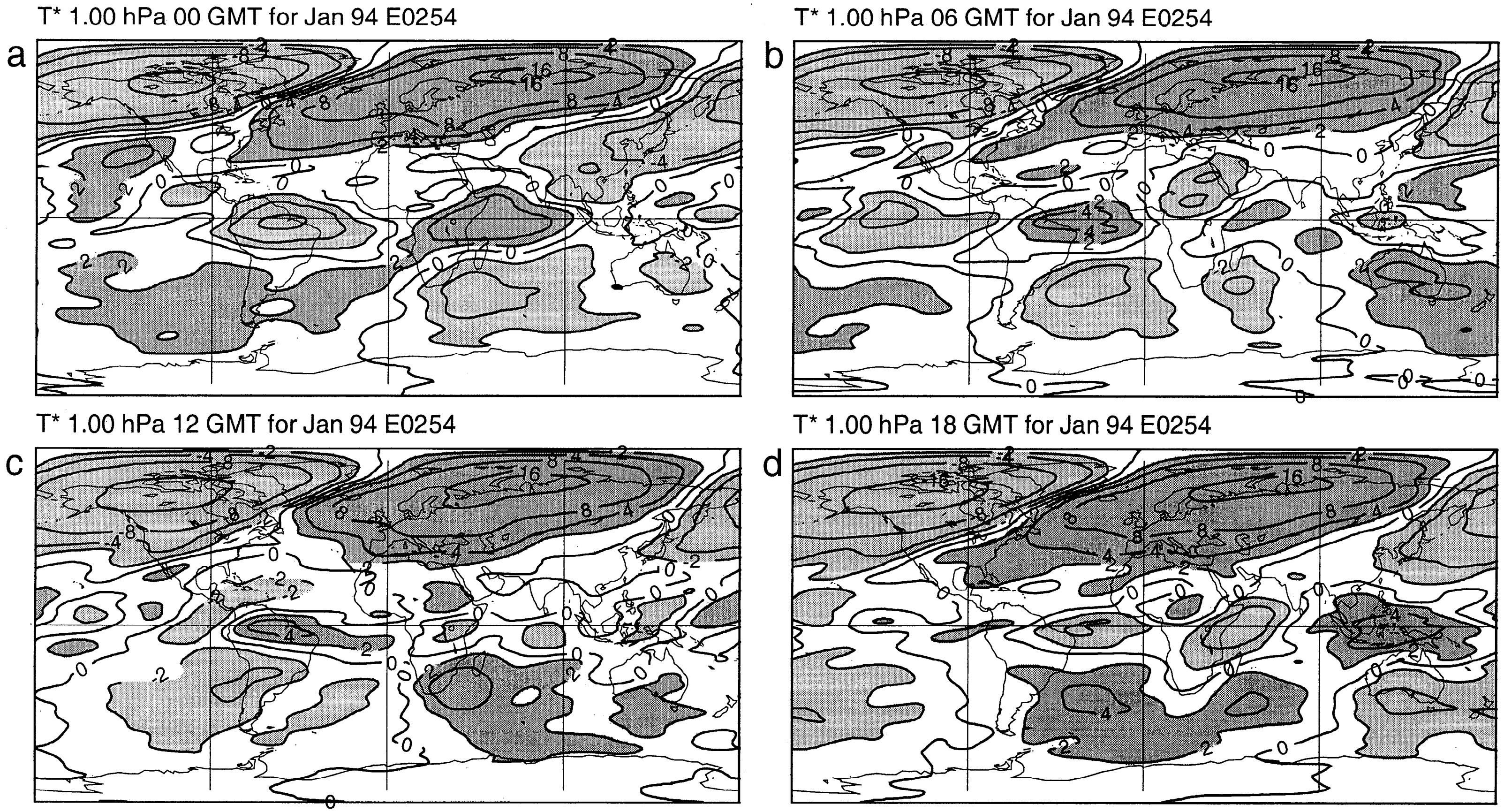

Figure 1. Temperature anomaly from zonal-mean values at 1 hPa, calculated from GEOS-2 GCM data, averaged over "January 1994" in model time. The anomalies are plotted for the four synoptic times: (a) 0000 UTC, (b) 0600 UTC, (c) 1200 UTC and (d) 1800 UTC. Contours are drawn at 0, and ± 2, 4, 8, 16 K. Anomalies of magnitude greater than 2 K are shaded; light shading indicates cold anomalies and dark shading warm anomalies.

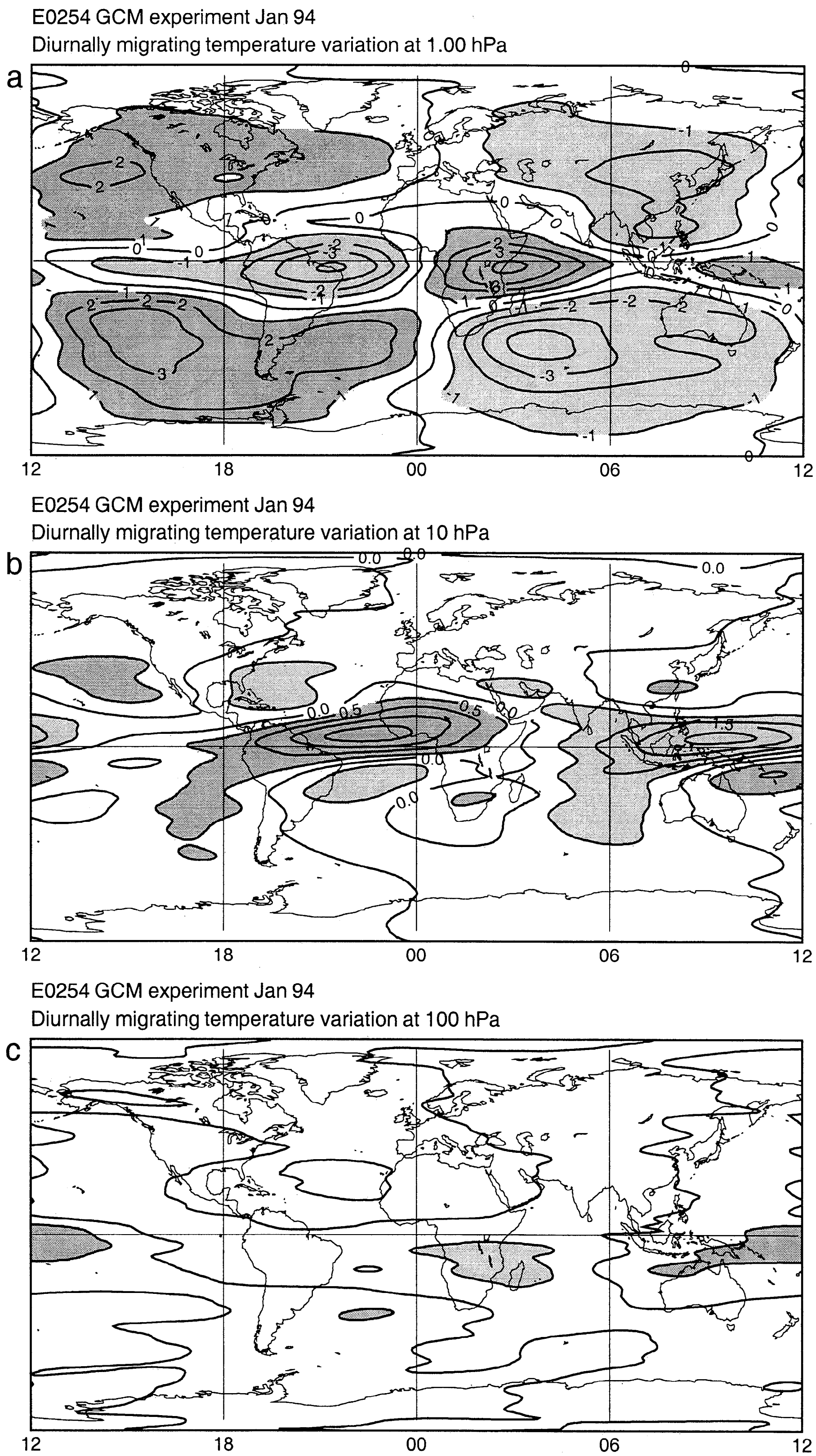

Figure 2. Maps of the migrating component of diurnal temperature variations at (a) 1 hPa, (b) 10 hPa, and (c) 100 hPa. The data are plotted using a Sun-synchronous coordinate system, such that 0000 LT corresponds to 0°E, 0600 LT to 90°E, 1200 LT to 180°E and 1800 LT to 90°W. (The longitudes indicate where migrating tidal variations would be at 0000 UTC; equivalent local times are indicated along the bottom edge of the maps). The contour intervals are 1.0, 0.5, and 0.2 K at 1, 10, and 100 hPa, respectively. Light shading indicates cold anomalies and dark shading warm anomalies.

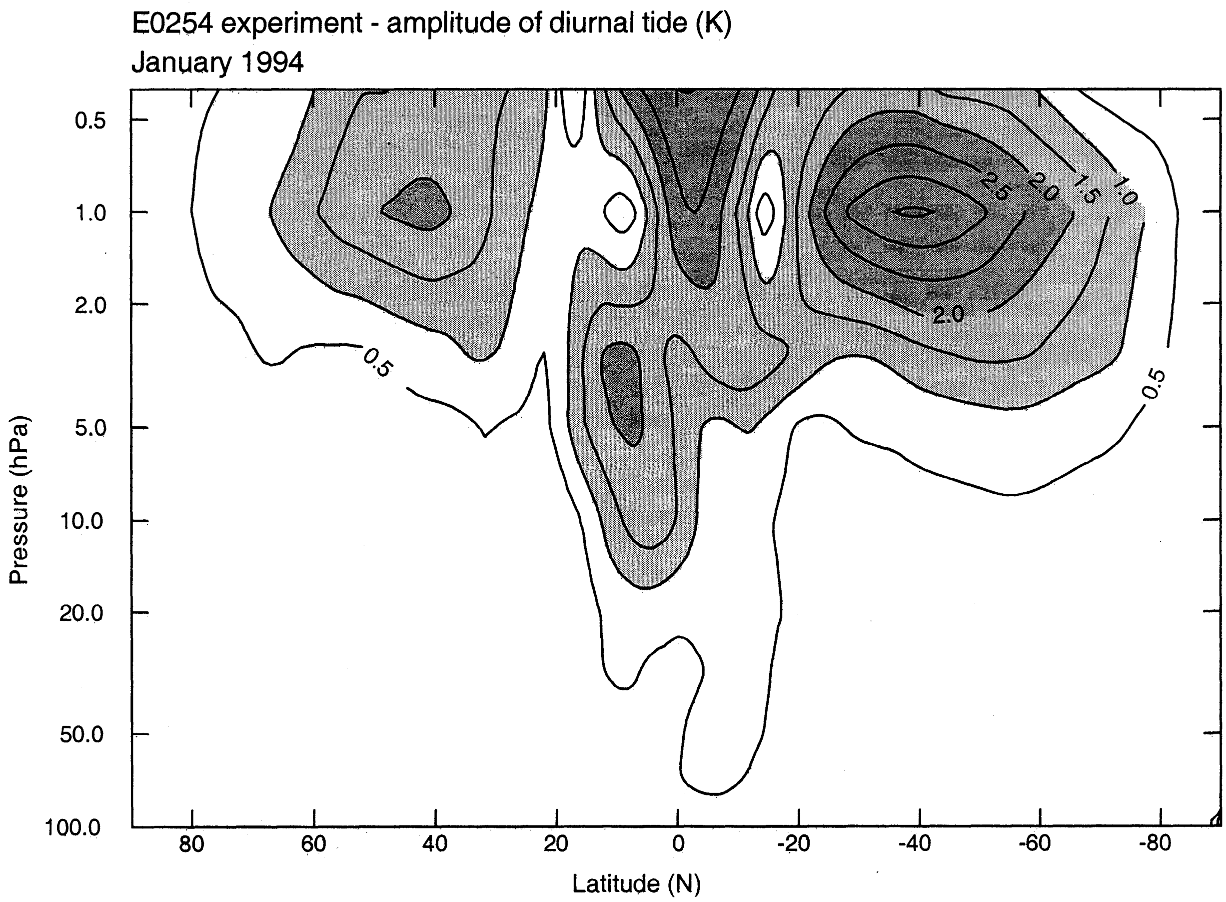

Figure 3. Cross section of the amplitude of the diurnal tidal variations in temperature, as simulated by the GEOS-2 GCM, for "January 1994". Light shading indicates amplitudes greater than 0.5 K and dark shading more than 2.0 K.

4. Tides in the Assimilation

Output from the GEOS-2 assimilation has been processed in exactly the same way as the GCM output, to analyze the tidal variations. Figure 5 shows the migrating tidal temperature variations at 1 hPa calculated from a GEOS-2 assimilation experiment for January 1992. The assimilation results show generally similar but slightly weaker tidal variations to those produced by the free-running GCM (compare Figure 2). The peak amplitude of diurnal variation in the assimilation was 2.5 K in the southern hemisphere (3.5 K in the GCM) and 2.1 K in the northern hemisphere (2.2 K in the GCM). Although only one month of each data set is shown, the differences are representative of other cases.

Figure 6 shows the IAU increments at 1 hPa, averaged over the month of January 1992, for the four synoptic times. Comparing these maps with Figure 1, it is clear that the analysis increments are acting to damp the tidal signals rather strongly. (Recall that the Northern Hemisphere tidal variations are masked by planetary waves in Figure 1.) The IAU increments are much larger than one would expect if the assimilation system were merely correcting relatively minor model errors. The assimilation system is acting in such a way as to damp out the tides, even though we believe (from the evidence in section 3) that the model produces a good simulation of the tides. Thus, the assimilated data contain tidal signals which are a compromise between relatively strong variations in the free-running GCM and weaker variations forced through the assimilated observations.

It should be remarked that the 6-hour timescale of the assimilation procedure means that high frequencies will be filtered out, as discussed by *Bloom et al.* [1996]. The IAU will damp the amplitude of increments associated with semidiurnal tides by about one third, but the increments associated with the diurnal tides will only be damped by about 10%. Thus this effect can (to a first approximation) be neglected when considering the diurnal tides, but the semidiurnal tides in the assimilation data will tend to be closer to the free-running GCM than one would otherwise have anticipated.

5. Tides in Satellite Sounding Data

There are several possible reasons why the assimilation of satellite temperature soundings might damp out the tidal variations in the model: for example, the tides may not be captured by the satellite data, or the DAS may not be correctly assimilating the tidal signal in the data.

In this section we will consider the first issue. One important point is that, typically, only one of the two operational NOAA polar orbiter satellites carries an SSU as part of the TOVS instrument package. In order to retrieve temperature

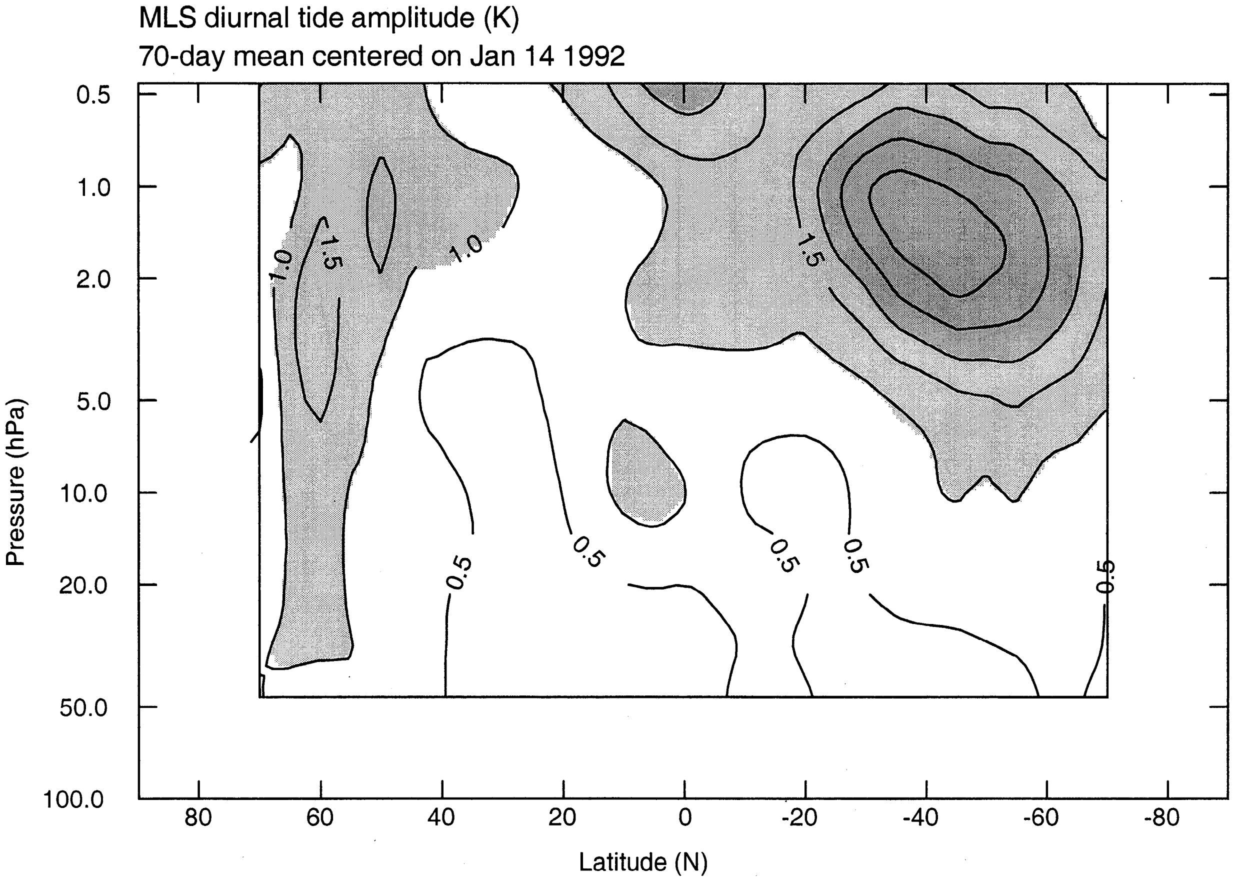

Figure 4. As Figure 3 but for Microwave Limb Sounder (MLS) temperature measurements (version-4 retrievals) and for a period spanning January 1992. The data have been smoothed in both the horizontal and the vertical.

profiles from the second satellite, measured SSU radiances from the first satellite are remapped onto the measurement locations of the second satellite. It is clear that the stratospheric temperature soundings from the second satellite will not contain the correct tidal information. At present, the GEOS-2 data assimilation system uses stratospheric data from both satellites, even though it would clearly be preferable to omit the uppermost levels of the temperature profiles from the second (non-SSU) satellite.

It is still necessary to assess the temperature profiles from the satellite which does carry the SSU instrument. Since NOAA polar orbiter satellites are in Sun-synchronous orbits,

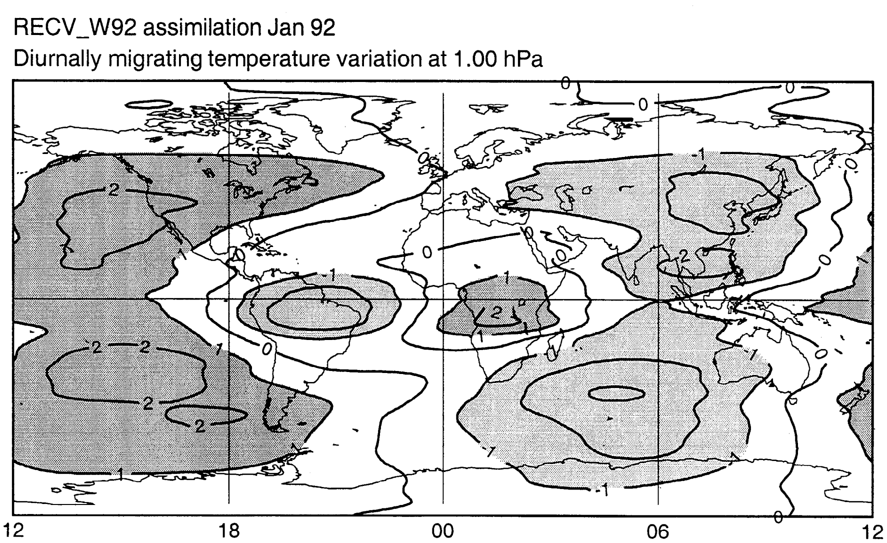

Figure 5. As Figure 2a but calculated from the assimilation experiment for January 1992.

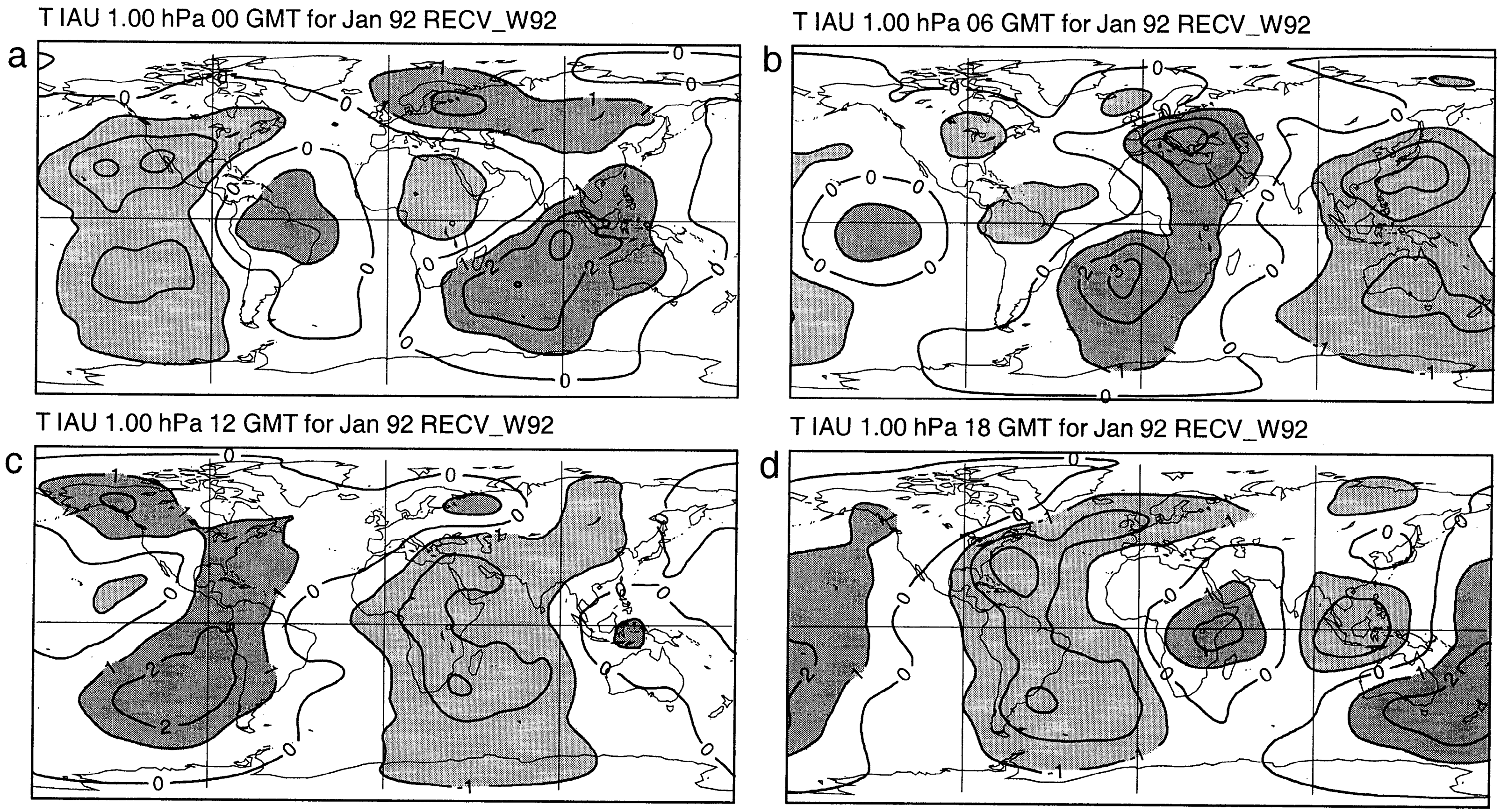

Figure 6. Maps of the incremental analysis update (IAU) temperature increments used to force the GEOS-2 assimilation model, averaged over January 1992. The plotted values are the integrated value of the forcing over six-hour periods centered on each synoptic hour: a) 0 UTC, b) 6 UTC, c) 12 UTC and d) 18 UTC. The contour intervals are 1 K per 6-hour period. Light shading indicates negative increments and dark shading positive increments.

they will always sample the same phase of the migrating tides at the same part of the orbit. The path of the subsatellite point is a great circle in the Sun-synchronous coordinate system that was defined in section 3. During January 1992 the NOAA-11 satellite carried an SSU while NOAA-12 did not. We have taken all the available NESDIS satellite profiles for NOAA-11 for the month, and binned them according to their latitude and local time. The bin size is 2° latitude and 10 min. in time (equivalent to 2.5° longitude in the Sun-synchronous coordinate system). The mean temperature was calculated for each bin, provided there were at least five soundings. The zonal mean temperature (from the assimilation data) was subtracted at each latitude to allow comparison with the assimilation and GCM data.

Plate 1 shows the binned temperature anomalies in the Sun-synchronous coordinate system for the 1-2 hPa layer. In Southern Hemisphere midlatitudes the soundings sample warm anomalies in the ascending part of the orbit (across the Pacific Ocean, as plotted) and cold anomalies in the descending part of the orbit. In the tropics the satellite samples warm anomalies near both ascending and descending nodes. In the Northern Hemisphere the tidal signals are largely masked by strong planetary waves, leading to "noisy" binned data.

These results are qualitatively consistent with the tidal variations shown in Figure 2. To carry out a more quantitative comparison, the tidal variations in the GCM and assimilation were recalculated in terms of layer-mean temperatures (for the same layers as the NESDIS temperature soundings). The fields of tidal variations were then sampled along the great circle defined by the path of the subsatellite point. The resulting temperature anomalies along the satellite orbit were then plotted as a function of latitude, as shown in Figure 7. (At each latitude spanned by the satellite orbit, there are two values, showing the tidal anomalies at two different local times). The binned temperature anomalies from the NESDIS retrievals, as shown in Plate 1, are plotted for comparison.

Figure 7 clearly shows that the tidal variations in the NESDIS satellite soundings are much weaker than in either the free-running GCM or the assimilation data. The amplitude of the variations in the assimilation output are weaker than in the GCM; assimilating the satellite data reduces the tidal temperature variations, in conflict with the model's radiative forcing. Since the tidal variations generally have quite shallow vertical scales (see, for example, Figure 3), they are not properly resolved by the SSU instruments, which have poor vertical resolution (or, equivalently, deep weighting functions). So it is hardly surprising that the tidal signals in the temperature soundings are too weak.

The NOAA-12 data have been examined in a similar way, although they are not plotted here. In midlatitudes there is a very weak tidal signal, which comes from the remapped NOAA-11 SSU data; this will damp the tides in the assimilated data even more than the NOAA-11 soundings. In the tropics there is a large discrepancy (typically 3 K) between the temperature anomalies from the soundings and the anomalies in the assimilation and GCM data, because the two satellites should sample opposite phases of the semidiurnal tide. Thus the NOAA-12 data damp the tides in the assimilation even more strongly than the NOAA-11 data.

Returning to the NOAA-11 data, one can hypothesize that, if the first guess profiles used by the retrieval system already included tidal variations, the resultant retrievals should be improved. In order to test this hypothesis, we have repeated the comparison using temperature soundings from the DAOTOVS retrieval system (J. Joiner and L. Rokke, Variational cloud-clearing with TOVS data, submitted to *Quarterly Journal of the Royal Meteorological Society*, 1998). The DAOTOVS system is an interactive retrieval system that is being developed to improve the treatment of satellite retrievals by the DAO assimilation system. The retrieval of satellite data can be optimized by combining the measured radiances with the best available estimate temperature profiles at the observation locations, taken from short forecasts with the GCM. Provided that the forecast is of good quality, this is a much better approach than using climatological first-guess profiles. The retrieval system adjusts the first guess profiles in such a way as to make them consistent with the TOVS radiances. Once the DAOTOVS system is integrated into the DAS, the soundings will be assimilated into the model in place of the NESDIS soundings. At the time of writing, the system has not fully been implemented, but experimental DAOTOVS temperature retrievals are available.

Figure 8 shows a comparison between the binned DAOTOVS retrievals and the sampled assimilation and GCM fields. The first guesses used to derive these retrievals are from short forecasts made in the course of running the January 1992 assimilation experiment. It is clear that the tidal signals in the DAOTOVS retrievals are very similar to those in the assimilation data, confirming that the observed radiances are not inconsistent with the tidal variations in the assimilation. (If the actual atmospheric tides were very different from the tides in the first guess profiles, one would expect to see a significantly different amplitude in the retrieved data).

Although the DAOTOVS system has not yet been implemented, these results indicate that the new soundings would lead to more realistic tides in the assimilation data.

6. Discussion and Conclusions

We have demonstrated that the free-running GEOS-2 GCM produces a good simulation of the atmospheric tides in the upper stratosphere, which compares well with independent observations. However, the assimilation of satellite data acts to damp the tidal variations. One important reason for that is that stratospheric temperatures from the operational NOAA polar orbiter which does not carry an SSU is used in the assimilation system. This problem can simply be addressed by not using such data in the assimilation system. However, we have also demonstrated that the tidal variations are too weak in the temperature soundings from the satellite which does carry an SSU. The optimal use of those data requires more careful treatment of satellite soundings by the data assimilation system. In particular, we would like to reduce the effect of spurious tidal information in the satellite soundings, while still fitting nontidal components of the measurements.

Using experimental satellite retrievals from the DAOTOVS system, we have confirmed that better first-guess profiles, containing realistic tidal information from the model, lead to better retrievals. Thus we anticipate that the tidal amplitudes in the assimilated data will be better, and closer to the GCM results, once the DAOTOVS system is fully implemented.

The use of satellite retrievals, and other observations, by a statistical analysis scheme such as PSAS is fundamentally dependent on the specification of the observation and first-guess error covariances. At present, the vertical observation error

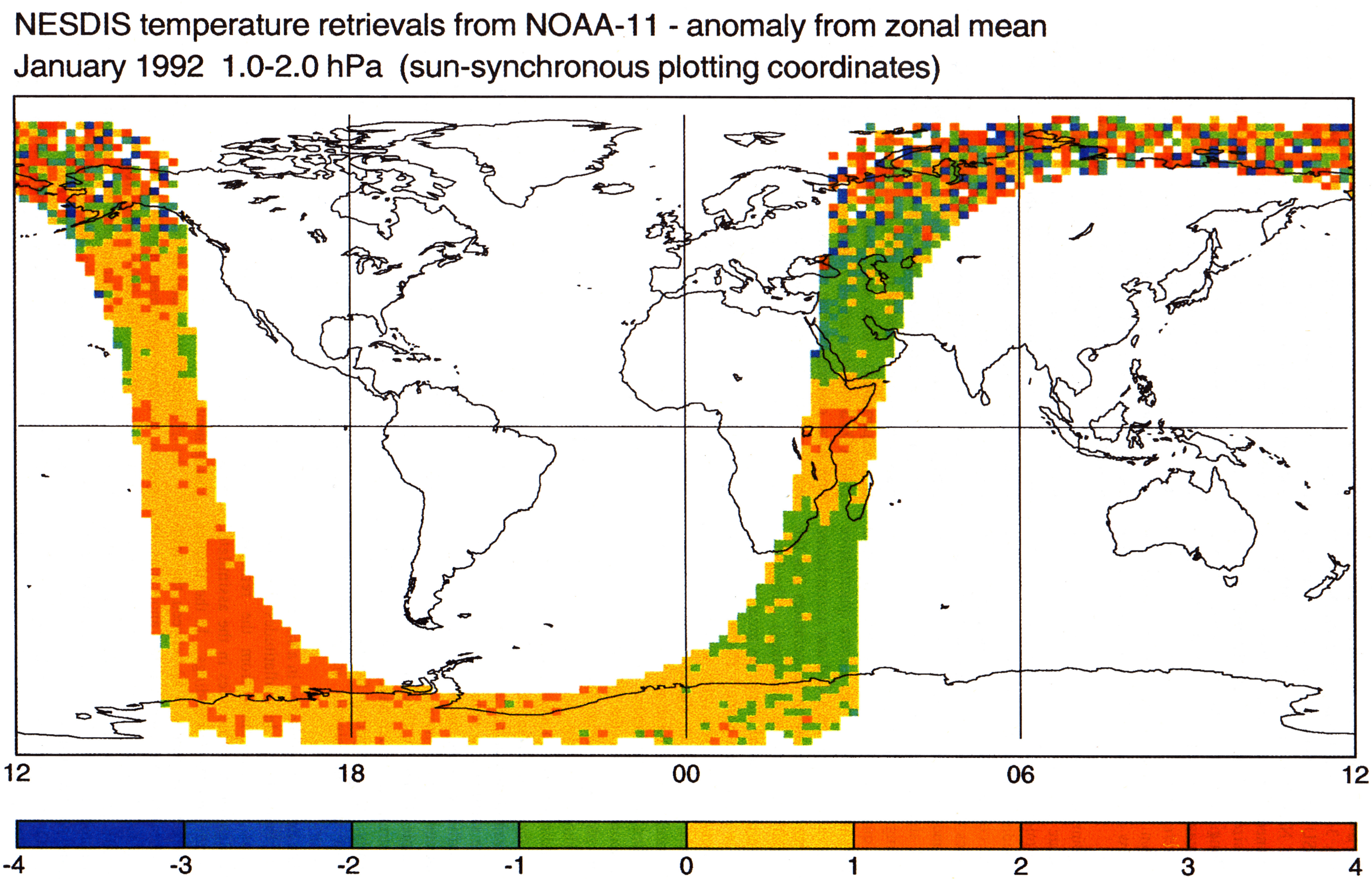

Plate 1. Temperature anomalies for the 1-2 hPa layer, derived from NESDIS soundings for January 1992. The data have been binned on a 2° x 2.5° latitude-longitude grid, in the Sun-synchronous coordinate system. The anomalies were calculated by subtracting the zonal-mean temperatures from the assimilation data. Anomalies between -4 K and +4 K are colored, larger anomalies or missing data are left white.

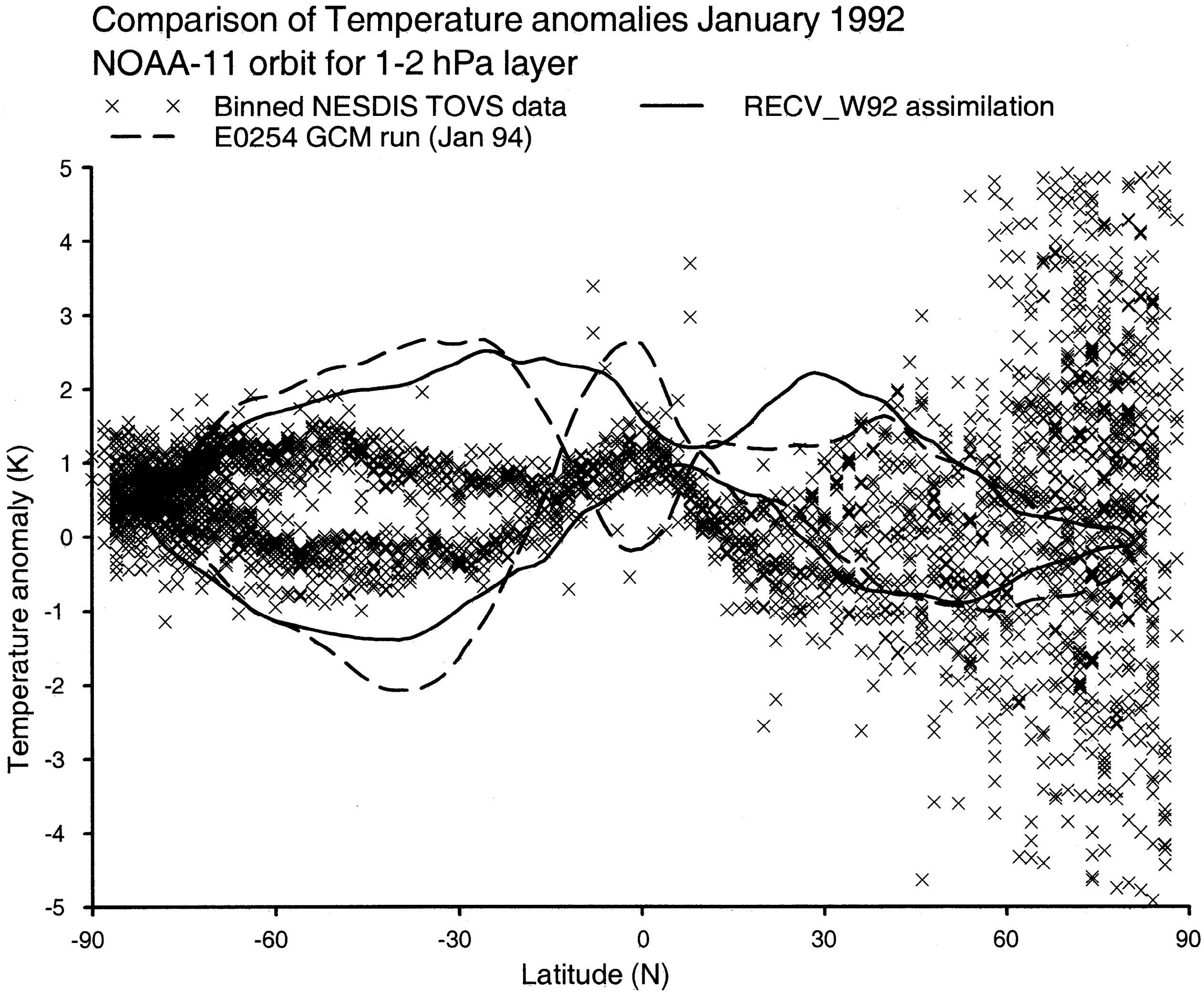

Figure 7. Temperature anomalies for the 1-2 hPa layer along the orbit track of NOAA-11 during January 1992 plotted as a function of latitude. The "January 1994" GCM simulation and the January 1992 assimilation results are compared with the binned NESDIS data (as shown in Plate 1).

correlations used for the TOVS temperature soundings are currently rather shallow. By using more appropriate covariances, it should be possible to improve the treatment of satellite data by the GEOS-2 data assimilation system. Rather than revising the error covariances used for the NESDIS retrievals, we propose to revise the covariances in conjunction with the implementation of DAOTOVS. (The statistical characteristics of the two sets of retrievals are significantly different, primarily because the DAOTOVS retrieval system uses a forecast first-guess). It is planned to derive suitable covariances using a similar approach to that described by *Dee and da Silva* [1999] and *Dee et al.* [1999]. They described a statistical method whereby observation minus forecast differences can be used (with certain assumptions) to derive radiosonde observation and forecast error covariances.

Another issue that affects the assimilation of tidal information is the treatment of asynoptic satellite data as if it were synoptic data. In the GEOS-2 DAS, all data within a 6-hour time window are treated as if they are valid at a single synoptic time, so satellite data may be assimilated at a time up to three hours too early or too late. Now that greater use is being made of satellite and other asynoptic data types, and model resolutions are being improved, the mistreatment of asynoptic data is becoming more of an issue, in both the troposphere and the stratosphere. Experiments with the DAO assimilation system, focusing on the analysis of surface observations, have indicated that errors due to use of a 6-hour time window were not negligible. There are also early indications from the ECMWF 4D-Var system that the use of data at the correct time is beneficial [e.g., *Isaksen*, 1998]. Recent experience with the GEOS-2 assimilation system has shown that use of a 6-hour time window is leading to biases and misweighting of data in the upper stratosphere as a result of tidal variations. Although the issue has not been addressed in this paper, it is the subject of ongoing investigations. For the present, we point out that the errors in the treatment of the tides due to the 6-hour time window are manifest as wave-4 (or higher wave number) features. In this paper we have filtered out those scales to avoid aliasing errors (as discussed in section 3), so the results presented here are not sensitive to that problem.

This study has highlighted several areas which will be the subject of future work at the DAO. As already mentioned, work

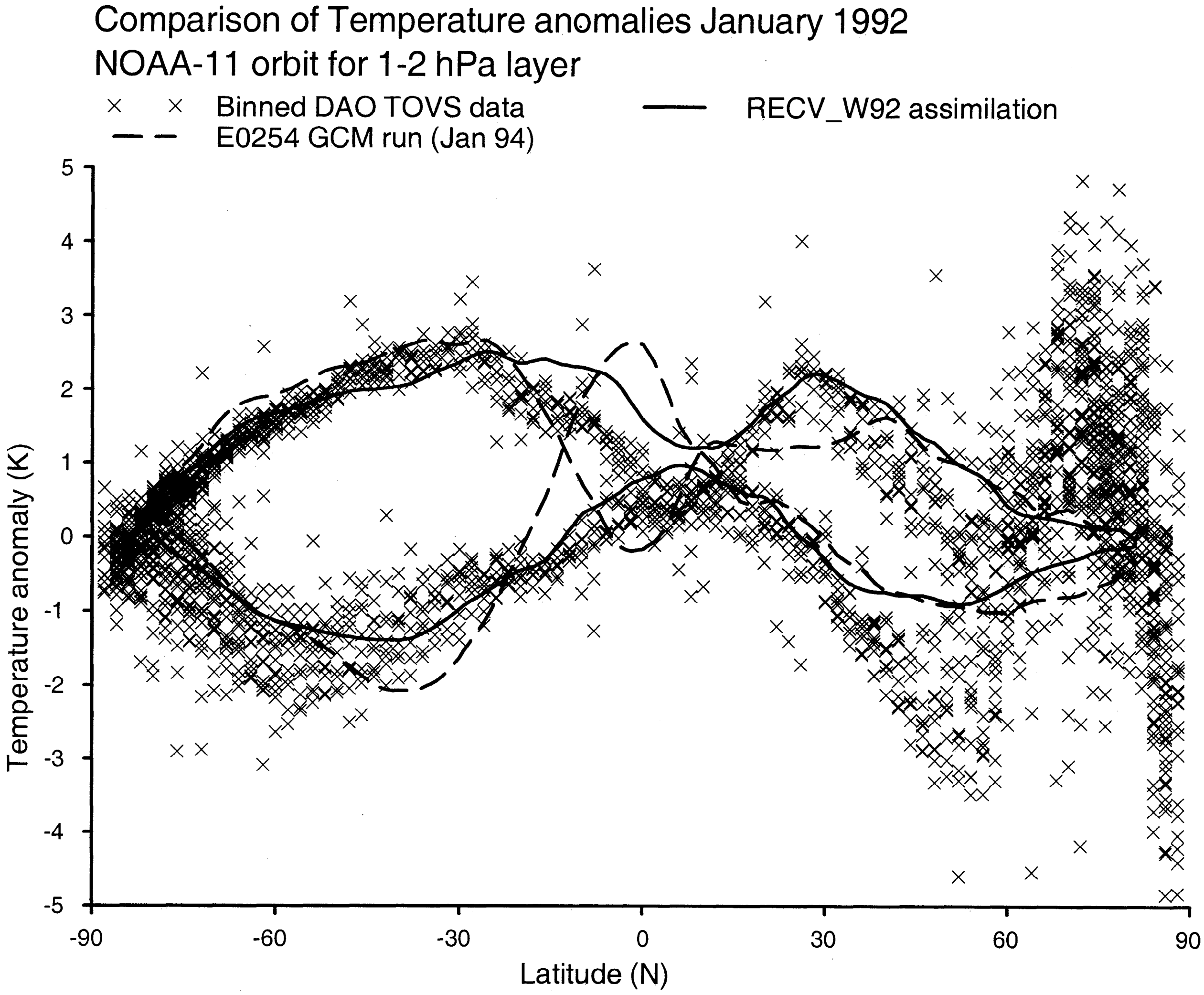

Figure 8. As Figure 7 but comparison of the GCM and assimilation data with binned DAOTOVS data.

is in progress to implement the DAO TOVS retrieval system. In addition to a reassessment of the vertical observation error correlations used for TOVS data, a more general effort will be made to improve the formulations of the error covariances, building on the work of *Cohn* [1993] and *Riishojgaard* [1998]. Thirdly, better approaches to the assimilation of asynoptic data will be developed, so that the data assimilation system will make more optimal use of satellite observations.

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