STRATOSPHERIC DATA ASSIMILATION FOR THE UARS PROJECT

R Swinbank
UK Meteorological Office,
Bracknell, England

Summary: A stratosphere-troposphere data assimilation system has been developed at the UK Met Office, based on the "Analysis Correction" scheme used for operational analyses. This system is currently being used to supply near real time analyses of meteorological fields from the troposphere and stratosphere to the Upper Atmosphere Research Satellite (UARS) Science Team. These analyses are primarily based on temperature soundings from NOAA polar orbiter satellites and radiosonde data.

As part of the UARS science programme, the analyses have been compared with equivalent products from NMC, as well as observations from UARS instruments. Some of those intercomparisons are presented in this paper.

The system has been extended to assimilate data from UARS instruments in addition to the other observation types. In particular, temperature soundings from the Improved Stratosphere and Mesosphere Sounder (ISAMS) have been assimilated. Future experiments will also include observations of winds and long-lived chemical species.

The analyses are being used for a variety of investigations of stratospheric dynamics. In one case, the analysed winds have been used to study the evolution of stratospheric winds over the equator. The winds show clear signals from both quasi-biennial and semi-annual oscillations. The results are consistent with previous investigations of those phenomena, and also agree well with observations from tropical radiosonde stations.

1. INTRODUCTION

The Upper Atmosphere Research Satellite (UARS) was launched on 12th September 1991. Its aim is to make a systematic investigation of the stratosphere and mesosphere by taking a range of meteorological and chemical measurements. To that end, UARS carries a wide range of instruments to measure temperature, winds, composition and energy input of the atmosphere.

The aim of this paper is to present results from the stratosphere-troposphere data assimilation system which has been developed at the UK Meteorological Office for the UARS project. The data assimilation system is a development of the system used at the Met Office for operational weather forecasting (Lorenc et al 1991). A short description is given in this paper, but it has been described in more detail by Swinbank and O'Neill (1993a).

The system is currently being used on a regular basis to assimilate a variety of meteorological data, primarily operational satellite temperature soundings and radiosonde ascents, into a global atmospheric general circulation model. The resulting analyses are supplied daily to the UARS science team as correlative data to help validate UARS measurements and for diagnostic studies. Some results from these analyses are presented in this paper. An outline of the data assimilation system is presented in section 2. As part of the UARS science programme, the correlative analyses have been validated against observations and independent analyses. Some of these intercomparisons are presented in section 3.

On an experimental basis, observations from selected UARS instruments are now being assimilated in addition to the operational observations. In section 4, we present some results from assimilation experiments which included temperature profiles from the Improved Stratosphere and Mesosphere Sounder (ISAMS). It is planned that the system will be extended so that it also incorporates observations of winds and long-lived chemical species from UARS instruments.

The analyses are currently being used for a variety of different investigations of the stratospheric circulation, which will be published in due course. One particular study is a survey of the evolution of stratospheric winds over the equator. Selected results from this study are given in section 5.

2. THE ASSIMILATION SYSTEM

2.1 Overview

Figure 1 illustrates the main data flows in the assimilation system. Observations are first extracted from Met Office data banks, or, in the case of UARS data, from the UARS Central Data Handling Facility (CDHF). The data are then passed to an observation processing stage, the main component of which is quality control. In the quality control stage, the observations are checked against forecast data, using the Bayesian approach developed by Lorenc and Hammon (1988). For the purposes of observation processing only, the observations are grouped into six-hourly batches, so each observation is checked against the model field from the nearest forecast time.

Next, the observations are assimilated into a numerical model of the atmosphere, as illustrated by Figure 2. The central arrow represents the integration of the numerical model. The model is run for twenty-four hours in data assimilation mode, in which the model fields are adjusted towards observed values. The observations are inserted asynoptically, with maximum weight being given to the data at the observation times. At the end of the assimilation period the model writes out a set of analysed fields interpolated to a set of 22 UARS standard pressure levels (equally spaced in log pressure, with six levels per factor of 10 in pressure, from 1000 HPa to 0.32 HPa). Immediately after the data assimilation, the model is run for twenty-four hours in forecast mode to produce background fields which are used for observation quality control. During both assimilation and forecast stages model fields are written out every six hours for use by the observation processing (denoted 'A' for analysis or 'B' for background in Fig 2)

After the assimilation stage, a second phase of the observation processing is run, in which an "Observation Processing Dataset" (or OPD) is compiled. The OPD is a major resource for validation of both the observations and the assimilation process. For each observation, the OPD stores the observed value, its difference from the analysis value (co-located with the observation),

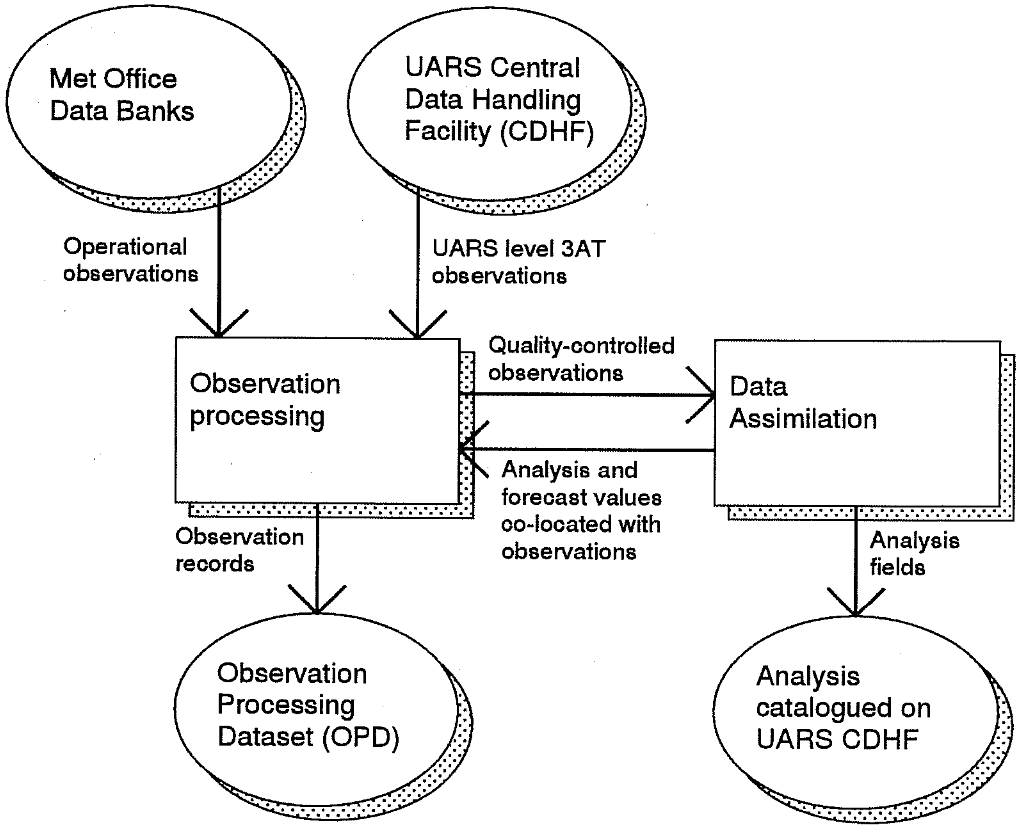


Fig. 1 Block diagram illustrating the organisation of the Stratosphere-Troposphere data assimilation system

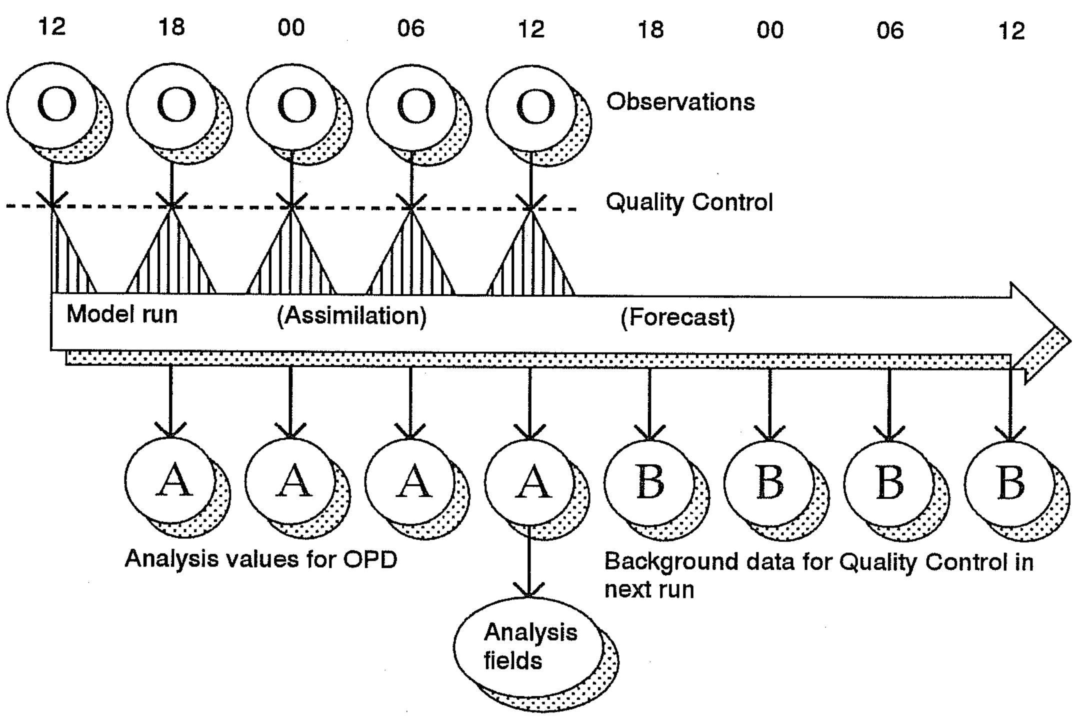


Fig. 2 The assimillation process in terms of the simulated model time. For the first 24 hours the observations (O) are assimilated into the numerical model, and analysis fields are output every 6 hours. The model integration is continued in forecast mode, producing background data (B) for observation quality control

and also its difference from the background value. These differences may be used for routine monitoring and subsequent statistical analysis, giving valuable information to users about the quality of the analyses.

The main type of observations used in the stratosphere are temperature soundings from the polar orbiter satellites operated by the National Oceanographic and Atmospheric Administration (NOAA). These soundings are layer-mean temperatures produced by the National Environmental Satellite Data and Information Service (NESDIS) from the original radiance measurements. Two sources of satellite data are used: first "SATEM" reports, which comprise satellite soundings at approximately 500 km horizontal resolution and levels up to 1 HPa; and second, higher resolution soundings, originally supplied at 250 km resolution up to 1 HPa, and from late 1991 at 120 km resolution up to 0.4 HPa . The latter data could not be included in all the assimilations owing to problems with the new data formats. Another important set of data are radiosonde soundings of temperatures and winds; these are occasionally available up to about 10 HPa, though more typically up to around 50 HPa. Additional observation types include aircraft winds and temperatures, satellite cloud-track winds and surface observations of pressure.

2.2 Numerical Model

The numerical model used by the stratospheric assimilation system is the Met Office's "Unified Model" (UM) (Cullen, 1993). It was designed for a variety of applications, including operational weather forecasting and climate simulations. For our application, a stratosphere-troposphere configuration of the model is used. The model uses a regular latitude-longitude (Arakawa B) grid with a north-south resolution of 2.5° and an east-west resolution of 3.75°. This grid is the same as the one used for climate simulations, but three times coarser than that used for operational forecasting. A dynamics advection time-step of 20 minutes is currently used, with three adjustment steps per advection step; the advection step is the time-step used by the physical parametrizations. A hybrid vertical coordinate system is used: the levels are terrain-following near the ground, but gradually become constant pressure surfaces higher up. There are 42 levels, with a vertical resolution in the stratosphere of approximately 1.6 km (10 levels per factor of 10 in pressure); the top level of the model is at 0.28 HPa.

In this configuration, it was found necessary to amend the original radiation scheme (Ingram, 1992), following the approach described by Morcrette et al. (1986). This gave smoother and more accurate long-wave heating rates. Amendments to represent the effects of Doppler line broadening have also been included. The gravity-wave drag scheme (Palmer et al., 1986), which was also developed for tropospheric models, introduced too much noise in the stratosphere. As a temporary expedient, it was retained in the troposphere and lower stratosphere, but replaced by simple Rayleigh friction at higher altitudes, whose effect is negligible in the stratosphere and increases with altitude in the mesosphere (see Fisher, 1987).

2.3 Assimilation Scheme

The UARS data assimilation system is based on the Met Office operational assimilation scheme, known as the "Analysis Correction" (or AC) scheme, which has been described by Lorenc et al (1991). The AC scheme is a modified version of the successive correction method of data assimilation. It incorporates repeated asynoptic insertion of data, in which the model is gradually adjusted to new observational data so that a measure of dynamical balance is retained. Since the original implementation, it has been adapted for use in conjunction with the Unified Model (Bell et al, 1991).

As previously noted, the model configuration used for the stratosphere-troposphere assimilation system uses a longer time-step and a coarser horizontal grid than is used for operational weather forecasting. It is designed to produce optimum analyses in the stratosphere, whereas the operational system is primarily designed for the troposphere. In view of these differences, the assimilation parameters used for the stratospheric assimilation are amended from those used by the operational system. In particular, a longer horizontal correlation scale is used in the UARS system, and geostrophic wind increments are used to balance temperature increments in the stratosphere (rather than being reduced to zero at upper levels). Further details are given in Swinbank and O'Neill (1993a).

The temperature sounders on board the NOAA polar orbiters have rather low vertical resolution, so retrieved temperatures are reported as layer-mean values, which are directly related to layer thicknesses. However, many other assimilation schemes, including an earlier version of the AC scheme, treat such temperatures as point values, in a similar manner to temperature profiles from radiosondes. Such an approach is inconsistent with the data and leads to problems when attempting to assimilate satellite and radiosonde data together. By contrast we treat the measurements correctly as layer thicknesses. The model temperature fields are adjusted so that the geopotential difference (thickness) between a pair of pressure levels in the model is consistent with the reported satellite layer-mean temperatures. This allows the analysis to incorporate information on finer vertical scales from radiosondes and yet remain consistent with the satellite data. This interpolation method is detailed by Swinbank and O'Neill (1993a)

3. TEMPERATURE INTERCOMPARISONS

In order to validate the analyses, several intercomparisons have been made with equivalent analyses from the US National Meteorological Center (NMC) and ECMWF, with particular reference to the quality of the temperature analyses in winter in both hemispheres. Comparisons have also been made with satellite and radiosonde observations, using the OPD facility described earlier. In addition, as part of the UARS validation exercise, comparisons have also been made with some data from UARS instruments. In this section, some representative comparisons are presented; further comparisons are presented by Swinbank and O'Neill (1993a), and in UARS validation reports to be published by NASA.

To illustrate how the Met Office analyses compare with NMC data, we present a representative example from 25 January 1993. Figure 3 shows the zonally-averaged temperatures from our analyses (denoted UKMO), together with the differences between the UKMO and NMC temperatures (UKMO-NMC). Note that no bias corrections have been added to either dataset for this comparison. In the troposphere and lower stratosphere the temperature differences are generally small (typically less than 1 K).

The most significant differences between the analyses are in the upper stratosphere. Moreover, there seems to be a coherent vertical structure in the difference field: UKMO zonal-mean temperatures are generally about 5 K warmer than NMC's near the stratopause (about 1-2 HPa), and are colder above and below. This difference is consistent with, though smaller than, the estimated bias in the NMC analyses near the stratopause (Finger et al., 1992). Part of the documented bias in the NMC analyses is probably attributable to systematic errors in the NESDIS temperature profiles that are used by both analysis systems; this would not be manifest in any calculation of UKMO-NMC differences. A possible reason for the differences between UKMO and NMC is that the NMC analysis scheme uses the NOAA soundings as point temperatures rather than layer-mean temperatures, while the UKMO scheme treats the temperature data more correctly (see section 2.3).

There are some other significant differences in the stratosphere near the North Pole. There was a strong winds near the pole at this time and the differences can probably be accounted for by numerical errors in the Met Office model. On other occasions the differences near the North Pole were similar to those found at other latitudes.

Comparison of synoptic maps show that, in the lower stratosphere, the agreement with NMC is very good, reflecting the comparatively rich observational coverage. The agreement with ECMWF analyses is also very good at this level. In mid-stratosphere, the large-scale features of the temperature maps are still in good agreement, but the UKMO analyses have more small-scale features than the NMC data. Near the stratopause the differences are of the same character but of larger magnitude. At this level the satellite temperature soundings are less accurate, as is the model because of proximity to its upper boundary.

Important information on the quality of the UKMO analyses is provided by the Observation Processing Dataset of error statistics (Section 2.1). They measure differences from observations of the model forecast and the final analysis. Figures 4 (a) and (b) show globally averaged values for temperature of observation minus analysis, O-A, and observation minus background, O-B. The figures summarise statistics for all satellite temperature soundings averaged over August 1992 (apart from two days when the data were not available). The central graph shows the global mean O-A (or O-B) values, divided into pressure layers, and the dashed lines show the mean plus or

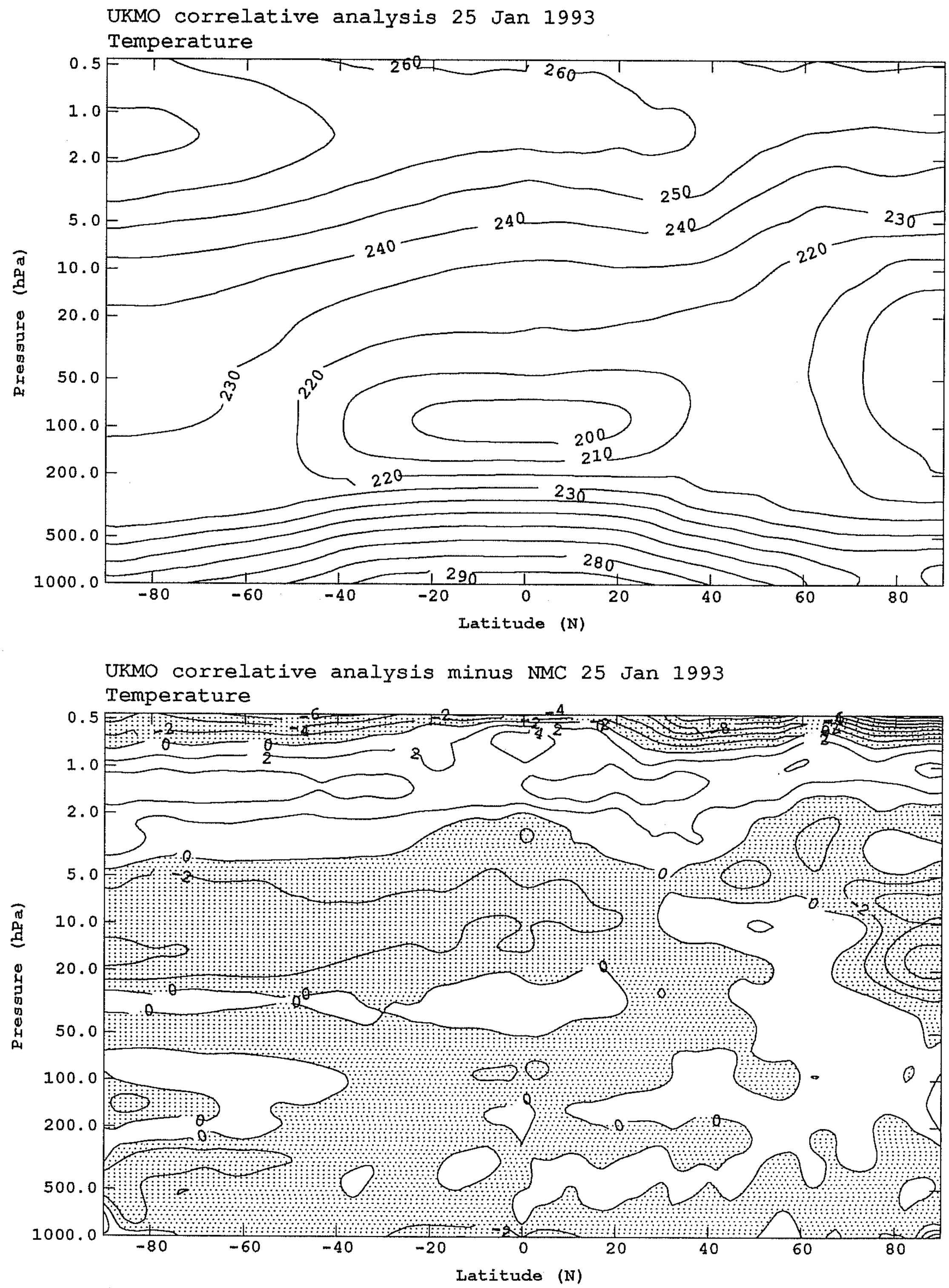
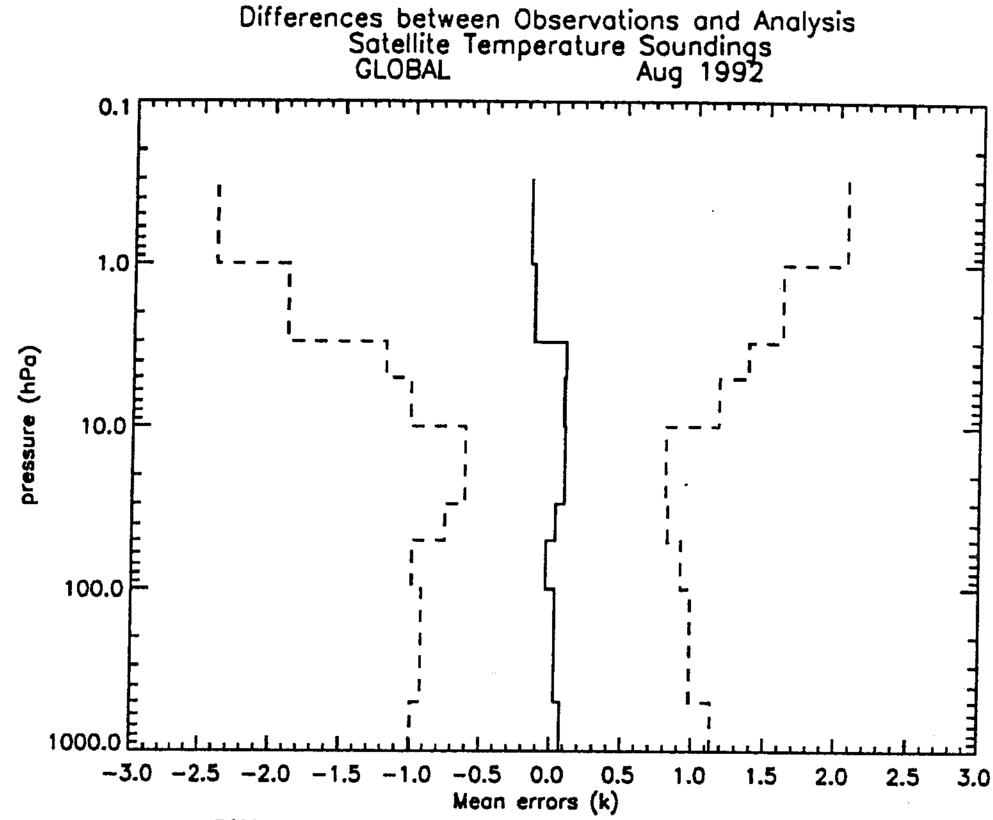


Fig. 3 Zonal-mean cross-sections of temperature for 25 January 1993. Top: UK Met Office correlative analysis (contour interval: 5K) Bottom: difference UKMO analysis minus NMC (contour interval: 2K).



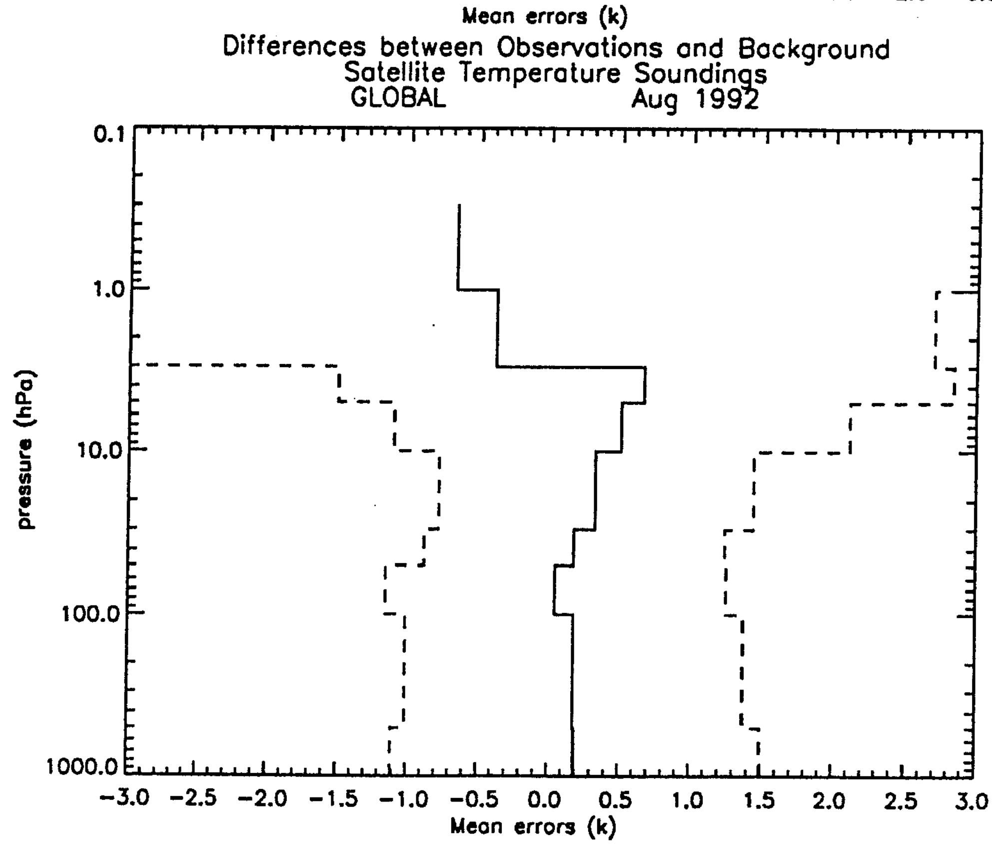


Fig.4 Statistics showing the fit of the analysis (top) and background (bottom) fields to the observations, as calculated from the OPD. In each case the full line shows the mean difference between the observed values and co-located values from the analysis (O-A) or background (O-B) fields. The dashed lines show the mean values, plus or minus one standard deviation, as calculated from the statistical distributions of O-A or O-B for each layer. The statistics are averaged over the globe for August 1992.

minus the standard deviations. The O-A graphs show that the analyses fit the observations with a small bias of magnitude less than 0.2K. The standard deviation varies from around 1 K below 10 HPa to around 2 K above 1 HPa. The statistics therefore show that the analyses fit the observations to within the expected observation accuracy, with only a small bias.

The O-B graphs indicate that the forecast fields have a bias of up to 1K in the upper stratosphere, which is corrected by the assimilation. This geographically varying bias indicates systematic errors in the numerical model. Further examination has indicated that it results from shortcomings in the parametrizations of gravity-wave drag and radiation. The OPD statistics are being used to guide improvements to the model, which will in turn improve the analyses.

As part of the UARS data validation, the analyses have been compared with observations from various UARS instruments. Figure 5 (Dudhia, pers. comm.) summarises the comparison between temperatures measured by the Improved Stratosphere and Mesosphere Sounder (ISAMS) and the UKMO analyses (for 121 days between 7th December 1991 and 29th July 1992). (Note that the ISAMS temperatures shown here are derived using the version 8 retrieval algorithm; they should be improved further in subsequent verions). Figure 5(a) shows the mean temperature difference (ISAMS minus UKMO). In the lower stratosphere, ISAMS gives temperatures that are up to about 2K warmer in the tropics and colder by a similar at high latitudes (these differences may stem from aerosol produced by the eruption of Mount Pinatubo in June 1991, which probably affects both NOAA and ISAMS soundings to some degree). In the mid-stratosphere the ISAMS data are slightly warmer than UKMO at all latitudes; in the upper stratosphere there is little overall bias. Near the stratopause (towards the top of the UKMO analysis domain and at the top of the NOAA soundings), the systematic differences become quite large. The standard deviation of the differences (Fig 5b) increases almost uniformly with height, consistent with the OPD results. Similar comparisons have also been made between NMC data and ISAMS (not shown). After adding in a correction for the estimated bias in NMC data, the NMC comparison is very similar to the UKMO comparison. This indicates that a large part of the UKMO minus ISAMS differences probably stem from differences between NOAA observations and ISAMS soundings; these may be reduced by future improvements to the ISAMS retrieval calculations.

4. ASSIMILATION OF ISAMS DATA

The stratosphere-troposphere data assimilation system has been extended to incorporate temperature soundings from UARS instruments. In the future, it will also be used to assimilate wind and chemical data measured by UARS.

ISAMS measures temperature and the concentrations of a variety of important chemical constituents. In common with most of the other UARS instruments ISAMS is a limb sounder. This approach gives the ISAMS observations a much better vertical resolution than is possible from nadir sounders, such as those on the NOAA polar orbiters. As a further consequence of the

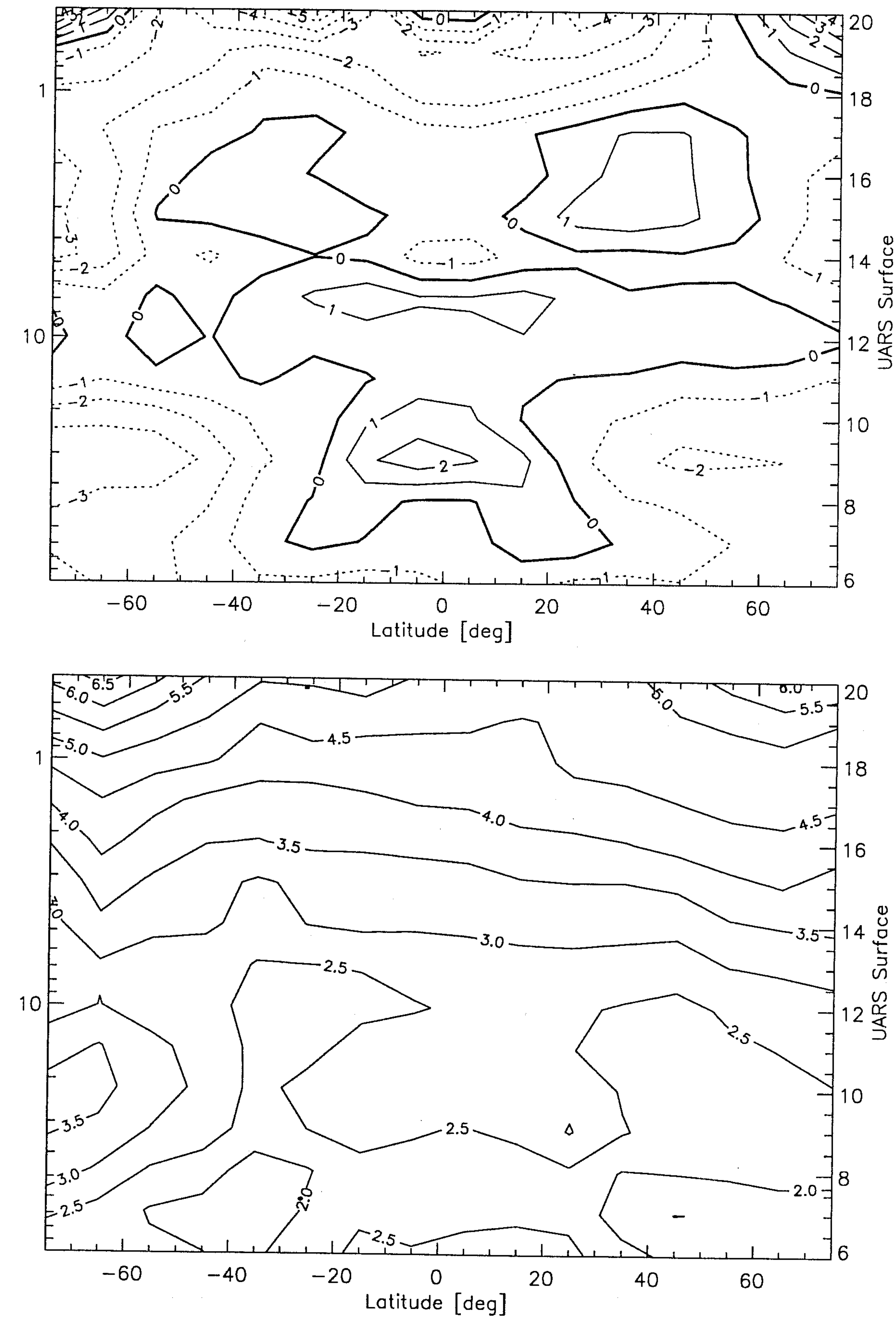


Fig. 5 Mean bias (top) and standard deviation (bottom) between ISAMS temperatures and UKMO data. A positive bias indicates that ISAMS is warmer than UKMO.

limb-sounding geometry, the horizontal resolution of the soundings is much poorer; however the footprint (of roughly 300 km) is comparable with the horizontal resolution of the numerical model, so no modifications were made to the assimilation scheme on account of this difference.

The orbit of the UARS spacecraft has an inclination of approximately 57° to the equator, and at any one time ISAMS scans the atmosphere to one side of the spacecraft orbit. This leads to a latitude coverage from approximately 80° in one hemisphere to 34° in the other hemisphere. For some orbits ISAMS viewed from each side of the spacecraft in turn, giving coverage from 80°N to 80°S.

The ISAMS observations were processed at the CDHF to a standard UARS "level 3AT" format. These data consist of soundings at the standard UARS pressure levels approximately every minute along the spacecraft viewing track. The data assimilation system was designed to use this format, since it is common to most of the UARS instruments. In addition to the observation values, the level 3AT files also include an estimate of the observation errors. These errors are used for the observation quality control, and to derive the weights used within the data assimilation scheme. The vertical interpolation used for UARS temperature soundings is consistent with the approach used for NOAA data, which was described in section 2.3. Because of their superior vertical resolution, the interpolation method used for UARS profiles is very similar to that used for radiosonde soundings.

At the time of writing, two experiments have been run in which temperature soundings from ISAMS were included in the assimilation, in addition to the data available operationally. The first experiment was run from 1st to 18th January 1992. In parallel to the last four days, a control experiment was run in which no ISAMS data were used. Figure 6 compares the two analyses at 1hPa at 12GMT on 18th January. Close to Japan, the ISAMS assimilation run has a significantly sharper gradient in the temperature field. Figure 7 shows temperature cross-sections through this region from the two experiments, together with a plot of the temperature differences. The ISAMS data make a very significant difference to the vertical temperature structure, sharpening the gradients in the upper stratosphere (around 2 hPa). This clearly shows that the superior vertical resolution of the ISAMS data is having a positive effect on the analyses.

Figure 8(a) and (b) illustrate the fit of the analysis to both the NOAA and the ISAMS observations, for 10th January 1992. (The format of the graphs is similar to the OPD plots presented in section 3, but these statistics are calculated on model levels during the assimilation run.). Clearly, the analyses are fitting the NOAA soundings much better than the ISAMS data. The main reason is that the ISAMS soundings are swamped by the much more numerous NOAA soundings. The assimilation scheme treats each observation as though they are independent. However the NOAA soundings are certainly not independent data, and so are given too much weight by the data assimilation scheme. After some preliminary experimentation, it was decided to increase the weight of the ISAMS data by an empirical factor of 4 to compensate for this effect. A second

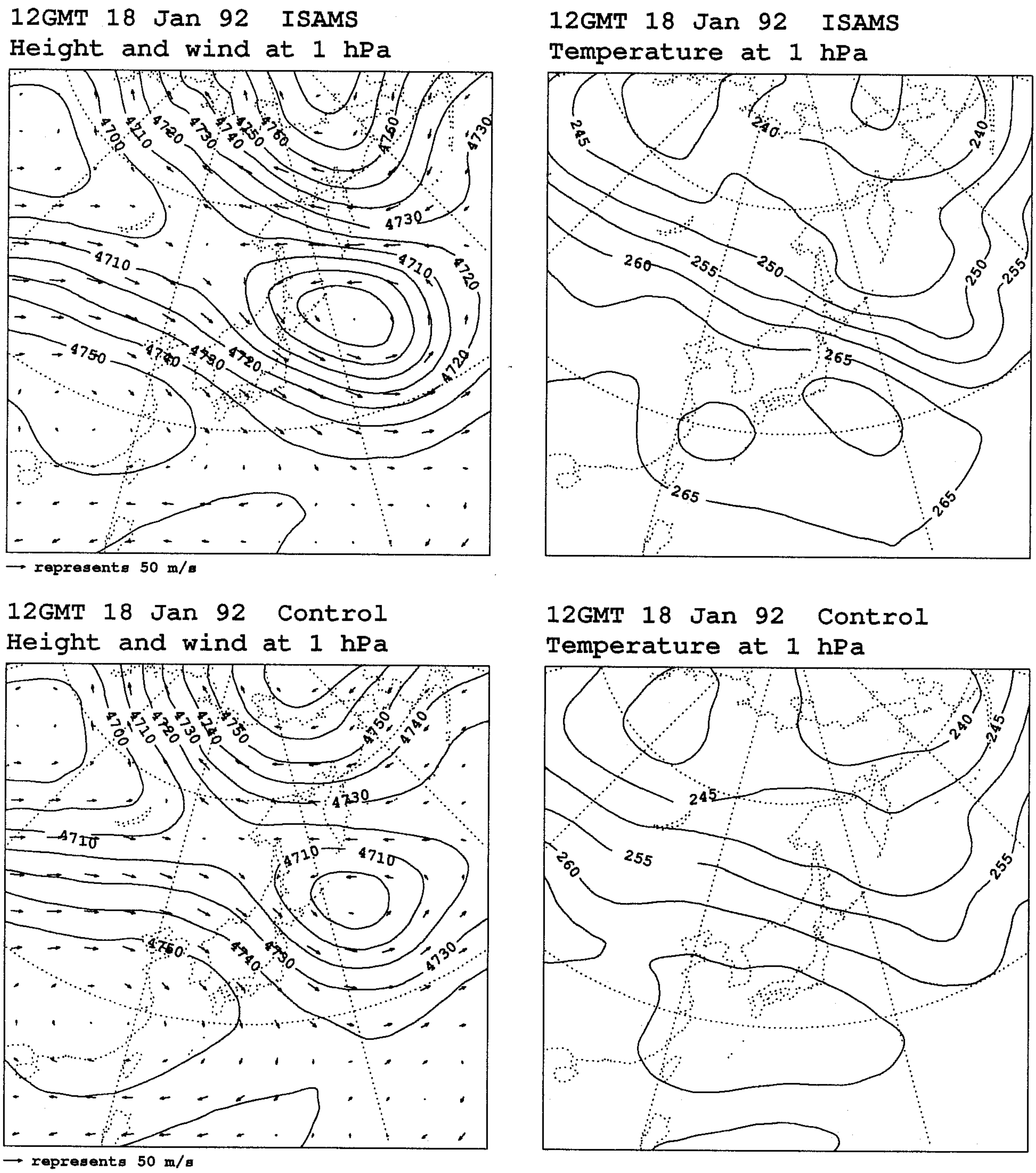


Fig. 6 Comparison of analyses near Japan at 1 hPa on 12 GMT 18th January 1992. The upper panels show results from an assimilation experiment which included ISAMS temperature soundings. Results from a parallel experiment without ISAMS data are shown in the lower panels.

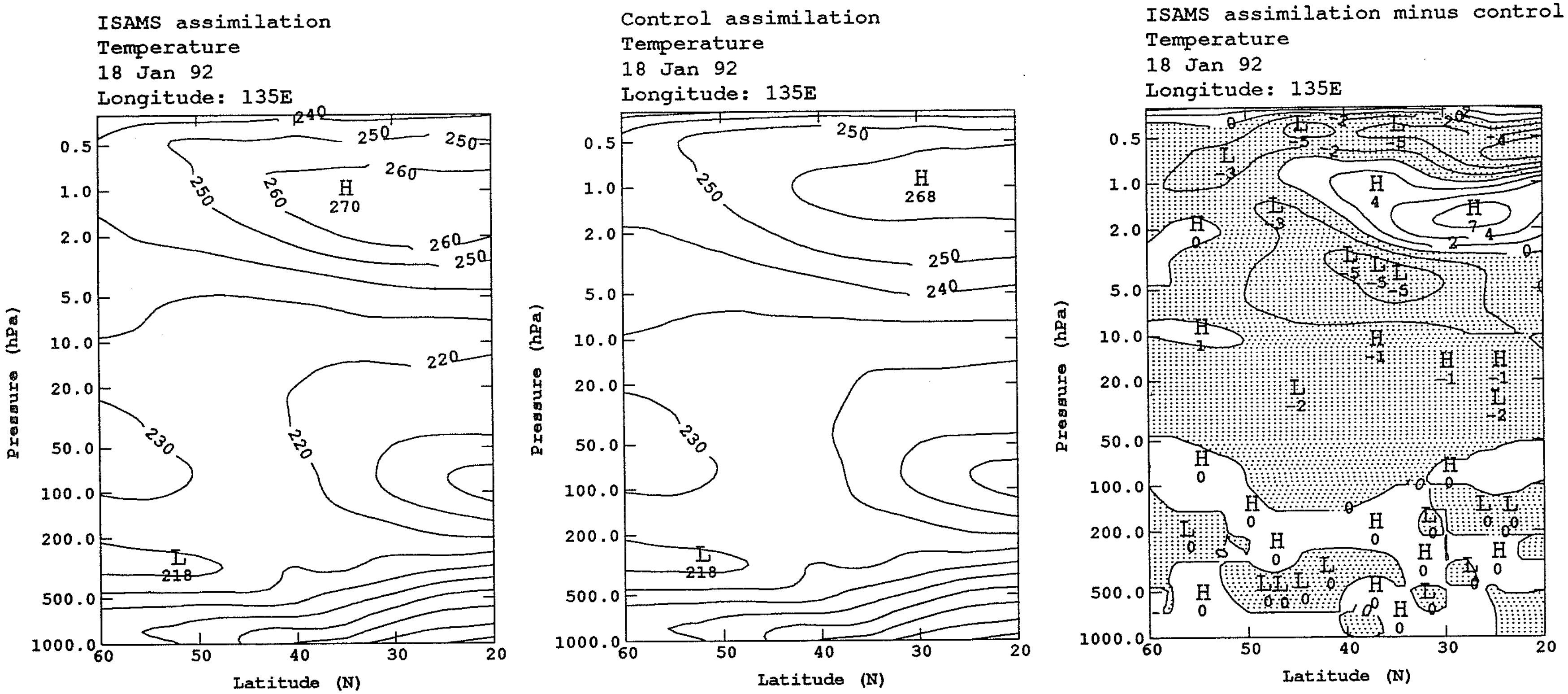


Fig. 7 Comparison of temperature cross-sections from the two analyses shown in Fig. 6. The cross-sections are taken along a north-south line through the centre of the map area in Fig. 6.

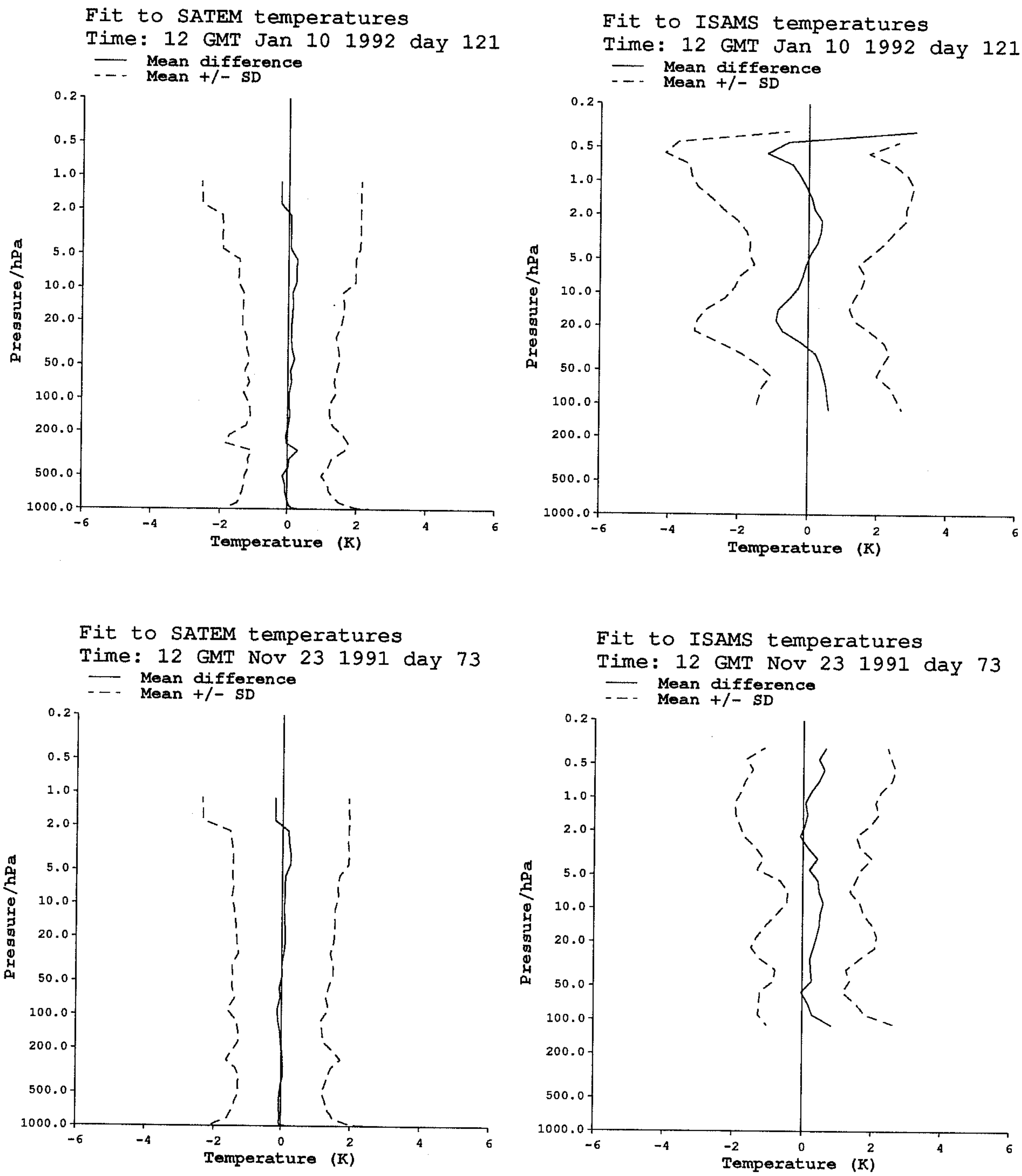


Fig. 8 Graphs showing the fit of the analyses for (top) 12 GMT 10th January 1992 and (bottom) 12 GMT 23rd November 1991 to satellite temperature soundings. In each case the data assimilation scheme used both NOAA and ISAMS temperature soundings. The format of the graphs is similar to those in Fig 4, but these statistics are calculated for model levels.

experiment was run for the period 18th to 28th November 1991, using the revised weighting. Figure 8(c) and (d) illustrate the fit to the observations for 23rd November. The fit to the ISAMS soundings is much more in keeping with their expected accuracy, and the fit to the NOAA soundings is virtually unchanged.

5. EQUATORIAL WINDS

The analyses produced by the stratosphere-troposphere data assimilation system are being used for a variety of diagnostic studies of the middle atmosphere. In one study (Swinbank and O'Neill, 1993b) they have been used to examine the evolution of equatorial winds in the stratosphere; the main findings are summarised in this section.

The daily analyses have been combined to make monthly-mean datasets for each of the complete months from November 1991 to September 1993 inclusive. Figure 9 shows the evolution of the zonal-mean westerly winds at the equator as a function of pressure, as calculated from these datasets. In the middle to lower stratosphere, Fig 9 clearly shows almost a complete cycle of the quasi-biennial oscillation (QBO, see Naujokat, 1986). There are zonal-mean easterlies from the start of the period until about September 1992 in the mid stratosphere. The easterlies are then replaced by a downward propagating regime of westerly winds. Towards the end of the period, the westerlies are in turn replaced by easterlies in a similar manner. The oscillation is strongest between approximately 50 hPa and 10 hPa. The peak value of the mean easterly wind is about 25 ms^{-1}, the peak westerly is about 13 ms^{-1}.

The time-series of zonal wind data has been compared with monthly-mean radiosonde data for stations close to equator. Figure 10 shows comparisons for two representative stations, Singapore and Trinidad. Observed winds at 50 and 30 hPa are compared with analysed winds at 46.4 and 31.6 hPa respectively, interpolated to the station locations. The Singapore time series in particular show clear quasi-biennial variations. The transition from easterlies to westerlies occurs about half way through the period. There is a very strong vertical wind shear around transition time, with about 4 months differences between onset of Westerlies between 50 hPa and 30hPa. The analyses show a weaker vertical wind shear partly, but not entirely, because analysis levels are closer together. The Trinidad data show similar quasi-biennial variation, consistent with the QBO varying little with longitude. A significant annual cycle is also seen, demonstrating that the station is on the edge of the equatorial QBO regime, being some distance away from the equator.

Above about 10 hPa the QBO signal dies rapidly to be replaced by a pronounced semi-annual oscillation (SAO) in the wind. Consistent with previous findings (e.g. Hirota, 1978), Fig 9 indicates that there is at least a local maximum near the stratopause. The maximum easterly winds occur near the solstices in January and July, whereas the peak westerlies are near the equinoxes in April and October. The results also indicate that the peak in the easterlies is somewhat higher than the peak in the westerlies, with the exception of the lower westerlies at the start of the period

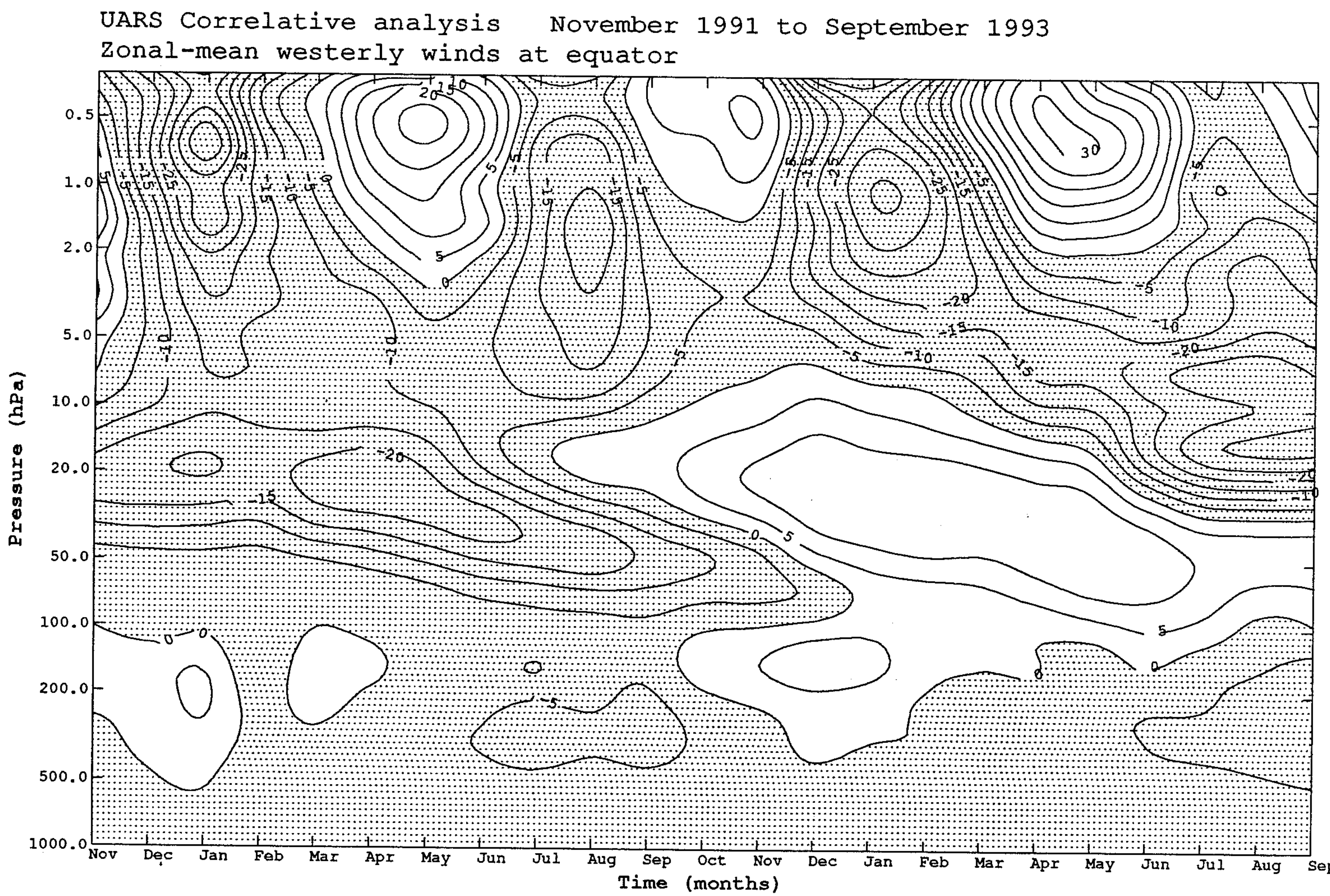


Fig. 9 The evolution of zonal-mean westerly winds over the equator, as shown by monthly-mean fields from the UARS correlative analyses.

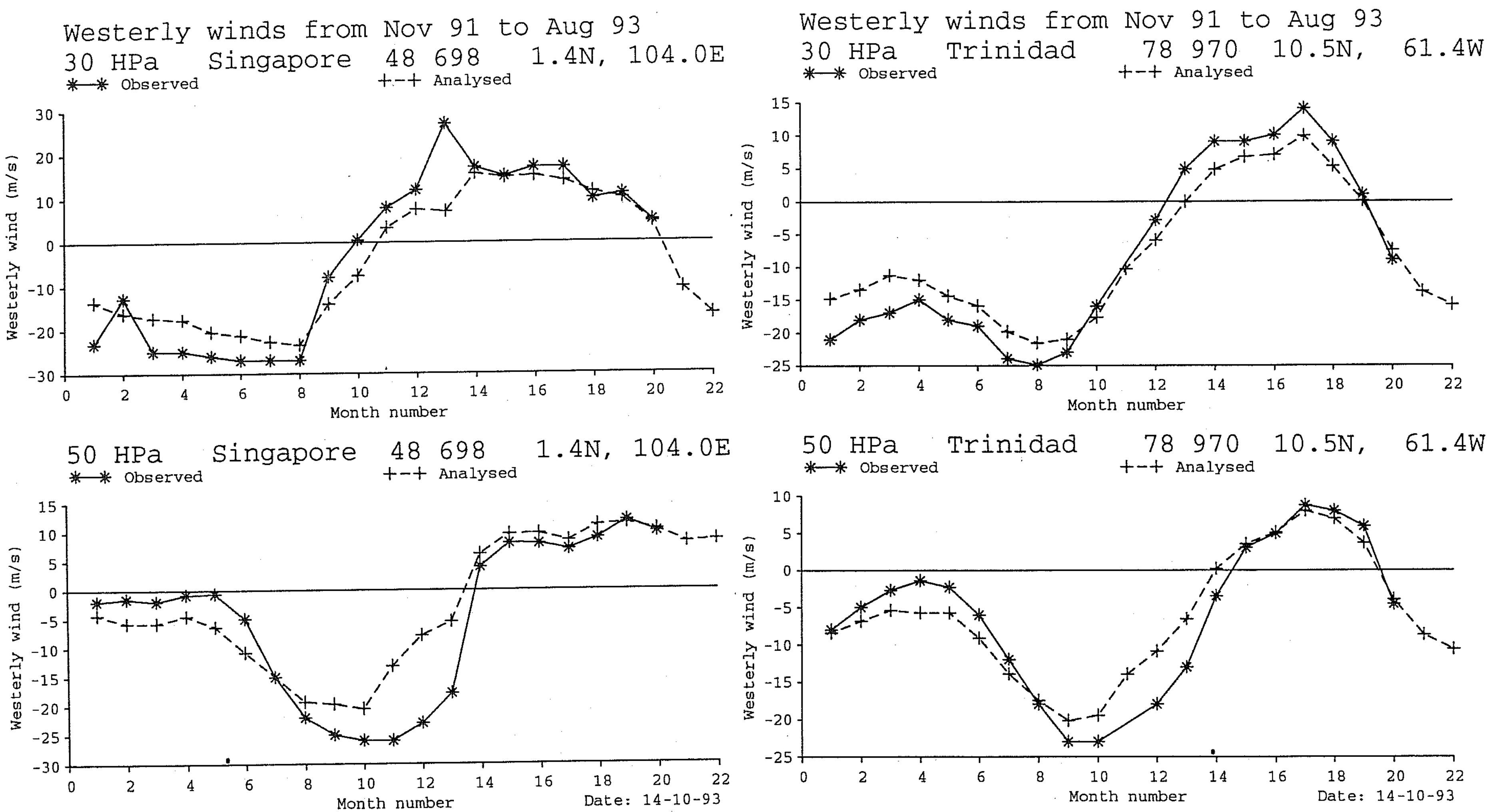


Fig. 10 Monthly-mean winds observed at Singapore (left) and Trinidad (right). Observed winds at 30 hPa (top) are compared with analysed values at 31.6 hPa, and the 50 hPa observations (bottom) are compared with 46.4 hPa.

(though it is possible that these result from teething problems at the start of the assimilation sequence).

Examination of the OPD has shown that few wind data are being assimilated in the tropical stratosphere. In the mid-stratosphere, these wind observations may be sufficient to define the given the quasi-biennial variation in the westerly winds. However the semi-annual variations in the wind which are evident near the stratospause must be entirely generated from the NOAA temperature sounding data. The numerical model used in the assimilation system generates wind fields that are consistent with the observations. However, that is not to imply that the model would generate realistic quasi-biennial and semi-annual oscillations without any observations to keep it on the right track; in fact it is notoriously difficult to simulate the QBO in a model integration.

6. CONCLUSIONS

The UK Met Office has been successfully operating a data assimilation system for the troposphere and stratosphere since October 1991. Global analyses of three-dimensional winds, temperatures and geopotential heights have been constructed daily. The data are held on a 2.5° latitude by 3.75° longitude global grid at 22 pressure levels from 1000 HPa to 0.32 HPa. They have been supplied to the UARS science team via the UARS Central Data Handling Facility. It is planned that they will also eventually be available to users in the UK via the Geophysical Data Facility (GDF) at the Rutherford Appleton Laboratory, and to other users via the Distributed Active Archive Center (DAAC) at Goddard Space Flight Center.

Error statistics have been compiled which have been used to validate the final analyses against the original observations. Typically, globally averaged biases in analysed temperatures were less than 0.2K at all levels; standard deviations ranged from 1K in the troposphere and lower stratosphere to 2K in the lower mesosphere. The OPD statistics showed that systematic errors in the forecast model were small, except near the upper boundary, where they were attributed to shortcomings in the physical parametrization schemes.

The assimilation system has recently been extended to process some of the UARS observations in addition to the operational data. Assimilation experiments show a positive impact from ISAMS temperature soundings, particularly in the upper stratosphere, although improved results are obtained when the ISAMS data were given extra weight. Later experiments will incorporate stratospheric winds measured by the High Resolution Doppler Imager (HRDI); these data will allow the study of the impact of wind observations on dynamical diagnostics. Observations of long-lived chemical species from various UARS instruments will also be assimilated; the model tracer advection scheme will be used to carry this constituent data forward in time.

The analyses constructed by the UK Met Office using the assimilation technique are being used by several research groups to interpret the unprecedented data that is being obtained from the UARS.

The combined datasets will greatly enhance our understanding of the middle atmosphere, enabling us to address pressing questions about ozone depletion and climate change.

Acknowledgements

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