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Verification of FGGE assimilation of the tropical wind field: the effect of model and data bias

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ABSTRACT

We examine the tropical wind field analyses produced by a recent assimilation of the Final FGGE II-b dataset. Our aim is to estimate the effects, on the tropical wind analyses, of biases in the data and biases in the assimilation system. The assimilation system was similar to that used operationally at ECMWF in the first half of 1985. The period studied is the first Special Observing Period (SOP-I).

Important differences occur in the intensity of divergence at upper and lower levels in the western Pacific, as measured by cloud-track winds (SATOBs) and by rawinsondes (TEMPs). There appear to be important biases also in the SATOB estimates of the zonal flow at upper and lower levels in the eastern Pacific. There are substantial biases in the wind directions at some west African stations.

The 6-hour forecasts which provide the background fields for the analyses show important under-estimates of the mean intensity of the tropical divergence field, particularly in the equatorial western Pacific. The errors in the background field probably occur because of underestimation of the intensity of tropical convection in the diabatic initialisation and in the course of the forecast; the heavy spatial smoothing applied to the convective heating in the initialisation probably also plays a role.

Data was available in sufficient quantities that the analysis algorithm corrected the mean errors in the background field to a very large extent. As a result, any residual uncertainty in the mean analyses is within the uncertainty of the observations. The analysis algorithm has a rather poor response to divergent information even on large scales, so the analysed divergence field agrees best with the observational data showing the weakest divergence, both in the upper and lower troposphere. The mean analysed divergence field in the west Pacific agrees with the 850mb TEMP data but is weaker than the intensity suggested by the low-level SATOBs and the SHIPs. In the upper troposphere the analysed divergence is weaker than that suggested by the TEMPs, but agrees with that suggested by the (probably less reliable) SATOBs. Thus in this important area in the tropics the biases in the new analyses of the mean divergent wind field appear to be within the range of biases in the data, but the divergence is probably still under-estimated in the upper troposphere and near the surface.

1. INTRODUCTION

In the years since the FGGE experiment diagnostic work on the general circulation has shown an increased emphasis on studies of the fields produced by data assimilation methods. This new emphasis has occurred because the data coverage during the FGGE experiment enabled the production of global analyses of unprecedented quality. The lessons learned in that effort have been applied in routine operational global analysis and forecasting. The routine global analyses produced in this way have also proved useful in research work on the general circulation (Hoskins, 1987). The gridded analyses of both FGGE and operational data must be used with care, however, because they can be subject to both random and systematic errors. In this paper we examine the question of systematic error in a recent set of ECMWF analyses of the Final FGGE II-b observational dataset.

Analyses of the Main FGGE II-b observational dataset produced by data assimilation methods (Miyakoda, 1986) differ in important respects from analyses generated solely from conventional synoptic data (Rosen et al., 1985). The largest differences occur in the areas where space based data, or aircraft, were the main data sources.

There have also been important discrepancies between FGGE analyses produced by different data assimilation systems (Kung and Tanaka, 1983; Lambert, 1984; Lau, 1984; Lorenc and Swinbank, 1984; Rinne and Jarvenoja, 1984; Boer, 1986; Holopainen and Fortelius, 1986; Paegle et al., 1986). Some of these discrepancies are explainable in terms of the different FGGE II-b observational datasets used in the assimilations. Even when assimilation systems are presented with exactly the same observational datasets, important discrepancies are found between analyses because of differences in quality control procedures, or because of differences in the relative weights assigned to various observation types (Hollingsworth et al 1985).

All data assimilation methods use a forecast model to provide a background field for the analysis of synoptic and asynoptic data. Discrepancies between analyses therefore arise because of differences in the assimilating models, particularly in data-sparse areas. If the assimilating models have systematic errors in a data sparse area, these may produce systematic errors or biases in the analyses. Attempts have been made to quantify such effects (Lau, 1984;

Brankovic, 1986; Tiedtke et al., 1988), but no fully satisfactory methods have been developed so far. The discrepancies between different assimilations have resulted in repeated calls for improved methods of analysis verification.

The Final II-b observational dataset became available in 1985. It contains many additions and corrections compared to the Main FGGE II-b data set. The Final II-b data were analysed at ECMWF (Uppala, 1987) for the Special Observing Periods (SOPs) of FGGE; SOP-1 lasted from January 5 1979 to March 5 1979, while SOP-2 lasted from May 5 to July 5 1979.

Uppala (1987) gives an extensive discussion of the data and the assimilation results. He evaluated the quality of the new assimilations using a number of yard-sticks:- fit of the analyses to the observations; accuracy of the short-range forecasts when compared to observations; means and variances of analysis increments; intensity of the tropical divergent circulations; intensity of the mid-latitude jet streams; and the quality of the medium range forecasts based on the data. In all these respects the new assimilations are of better quality than the earlier ECMWF assimilations of the Main FGGE II-b dataset.

The main interest in this report is the question of bias in the analysis of the tropical wind field. We concentrate on this problem because of its great importance for atmospheric energetics. Much concern has been voiced about the influence of model bias on analysis accuracy. As demonstrated by Hollingsworth et al. (1986), biases in the observations can also have deleterious effects on the analysed fields. So we discuss the effect of both model bias and data bias on the tropical wind analyses produced in the recent assimilations of the Final FGGE II-b dataset during SOP-1 of the FGGE year. The results show clearly that observational bias is just as important as model bias.

Model and data bias is studied through a detailed examination of the differences between observations (OB) and the three fields used in the assimilation namely the first-guess (FG), analysis (AN), and initialised analysis (IN) fields. Analysis verification is discussed using the standard deviation of the observation minus analysis (OB-AN) differences as the main verification tool. Maps of the bias and standard deviation of the OB-AN differences, calculated for 5 degree boxes and for each observation type, prove a useful tool for discussing analysis accuracy and have proved useful in detecting both observational bias and model bias (Delsol, 1985). They are in regular use in monitoring the Global Observing System.

On the question of verifying the analyses, one must remember that an analysis scheme which fits the data exactly is by no means optimal. In such a case the analysis error is the same as the observation error (at observation points), and the analysis error is perfectly correlated with the observation error. As discussed by Hollingsworth (1987), an optimal analysis filters the observations; ideally it fits them only to within the observational error. Hollingsworth and Lonnberg (1988) show that a good estimate of analysis accuracy is provided by the spatial coherence of the fit of the analyses to the observations. We pursue a simpler line of investigation here, and limit ourselves to displaying the OB-AN standard deviations for the most important data types. The documentation of these statistics is an essential first step in resolving controversies about the relative accuracies of different analyses.

The calculations described here are almost trivial in terms of the cost of computation. However large amounts of data must be manipulated to make the calculations. The data manipulations were done in the course of the assimilation of the Final FGGE II-b data set. Because of the large data handling demands, and because certain essential quality flags had not been saved, it was not possible to make equivalent calculations for the Main FGGE II-b and III-b data sets. The data manipulations are now part of the ECMWF daily operational assimilations, and so extensive diagnosis of the accuracy of the TOGA datasets will be possible.

The paper is organised as follows. The FGGE observational and analysed datasets are described in section 2. Biases in the first-guess field relative to wind observations (OB-FG) are discussed in section 3; biases of the analyses relative to observations (OB-AN) are discussed in section 4; and biases in the initialised fields (OB-IN) are discussed in section 5. The analysed wind fields are verified against observations in section 6, using the standard deviation of the observation minus analysis (OB-AN) differences as the main verification tool. The results are summarised in section 7.

2. THE FGGE II-B AND III-B DATASETS

The analysed data discussed here are the results of assimilations of the final FGGE II-B data sets for SOP-1, (Uppala, 1987). We assess the accuracy of the assimilation by scrutiny of the differences between the observations and the assimilation fields. This is done in considerably more detail than has been possible hitherto.

a) The Final FGGE II-b Dataset

The differences between the Main and Final II-b datasets are described in Uppala (1987). The Final dataset contained additional data from the regional experiments conducted during FGGE, the Summer and Winter Monsoon Experiments (SMONEX and WMONEX) and the West African Monsoon Experiment (WAMEX). Additional ship data were included, as well as higher density satellite temperature retrievals (SATEM) and cloud track winds (SATOB), both resulting from the U.S. special effort to enhance the data set; some additional Arctic buoy data were also included. Numerous errors detected in the processing of the Main II-b data sets were corrected, such as incorrect station positions or elevations, or incorrect heights for cloud track winds.

b) The 1985/6 ECMWF FGGE III-b Data Assimilation System

The ECMWF assimilation system used to assimilate the Final II-b data in 1985/6 (Uppala, 1987) contained many developments from that used to assimilate the Main II-b data in 1980/81. The main changes to the mass and wind analysis algorithm are discussed in Shaw et al (1987). The main changes to the humidity analysis are discussed in Illari (1987), and Pasch and Illari (1985). The incorporation of diabatic effects in the initialisation, and the initialisation condition for the tides, are discussed in Wergen (1986). The assimilating model was a T63 spectral model (Girard and Jarraud 1983), with mean orography based on the US Navy data (Wallace et al 1983). The physical parameterisations are discussed in Tiedtke et al (1988).

c) Methodology; Patterns of Data Availability

We follow the approach of Delsol (1985) in condensing the statistics of the differences between the observations and the fields produced by the data assimilation system. Bias and standard deviation statistics of the differences are calculated for a network of 5x5 degree boxes over the globe. The calculations are done separately for each data type. In examining the results one must remember that each observing system delivers data with a characteristic spatial and temporal distribution.

Rawinsonde observations are most abundant at the main synoptic hours. Aircraft traffic on a given route is heaviest at certain times of the day. The production of cloud-track winds (SATOBs) depends on the availability of computer resources. As an example Fig 1(a,b,c,d) shows the biases in the observation minus first guess for SATOBs at or below 850mb, for the 6-hour time periods centred on 00,06,12,18 UTC during SOP-1. Cloud track winds were produced from all 5 geostationary satellites at 0000 and 1200 UTC; the only winds produced at 0600 UTC are from the Indian Ocean Satellite, while no winds are produced from the European or Japanese satellites at 1800 UTC.

All the results to be presented below are averaged over all analysis times during SOP-1. In interpreting maps of this kind one must have an indication of the volume of data used in each box. In plots such as Fig 1 the data volumes are indicated by the thickness (not the length) of the arrow; three categories are used: thick arrows for more than 50 reports in the period, medium arrows for 10-50 reports in the period, and thin arrows for less than 10 reports. The present calculations are limited to data actually used in the assimilation; rejected data are excluded from the results presented.

Because of limitations of space, we discuss results for TEMP, SATOB, AIREP, and SHIP data only. Compared to the data volumes from these observing systems, the data volumes from dropsondes and constant level balloons were small. The wind component observation error settings for these observing systems are described in Shaw et al. (1987), and are summarised in Table 1 for the 850 and 200 mb levels. The corresponding errors assigned to the first guess field fluctuate in time as a result of variations in data density, but are roughly of the same order of magnitude as the rawinsonde (TEMP) errors.

The analysis system updates (or increments) the background field (i.e. the short range forecast) by addition of an analysis increment. The analysis increment is calculated by multivariate interpolation to the model's coordinates of the differences between observations and the background field, i.e. by interpolation of the observation increments. The version of the analysis system used here assumes that all observation increments occur at standard pressure levels. If an observation does not occur at a standard pressure level, the first guess is interpolated to the observation pressure, the observation increment is calculated there, and it is then used as if it had occurred at the nearest standard pressure level. This simplification is removed in more recent versions of the system.

d) Data Calibrations

Experience with the Main II-b data set, and with operational data since 1979, indicated a number of long-standing problems with the Global Observing System (GOS). In the analysis of the Final II-b data set attempts were made to circumvent some of the more severe and well-known problems. These involved discarding some data and calibrating other data.

Collocation studies between upper tropospheric aircraft (AIREP), rawinsonde (TEMP), and cloud track wind (SATOB) reports (Pierrard, 1985; Kallberg and Delsol, 1987) indicated that the upper-level SATOB data near jets had marked bias towards low speeds. This was evident in the FGGE II-b data, and in operational data since FGGE. For this reason Northern Hemisphere upper-level SATOB data were used only equatorward of 20N. It was felt that enough AIREPS were available in the Final II-b dataset to define the main jets poleward of 20N.

In the southern hemisphere, aircraft data were sparser, and it was decided to calibrate the upper-level SATOB winds stronger than 20m/s (from METEOSAT, GOES-Indian Ocean, and HIMAWARI) with a speed dependent correction when they were used poleward of 20S. There was insufficient collocation data to determine such a correction for GOES-East and GOES-West, so their reports were used in the original form.

Between 20N and 20S NO corrections were applied to SATOB data.

Apart from these calibrations, the only other correction applied to the Final II-b wind data was a correction to the winds at two Southern Oceanic island stations. Earlier studies indicated directional biases at these stations, which justified a correction to the reported directions.

The geopotential data from a number of tropical radiosonde stations were discarded as unusable because of large random errors at these stations. The stations affected have a long history of unreliable height reports, extending over many years up to the present. In addition, wind data from two Latin-American rawinsondes were discarded, because of their poor performance during the test re-assimilation for December 1978.

e) The Tropical Wind Field During SOP-I

As background for the discussion, Figs 2a,b show the 200mb SOP-1 mean stream-function and divergence fields taken over all analyses during January 1979, from the ECMWF analyses of the main FGGE II-b observational dataset (Bengtsson et al 1982, Fig 2a), and the ECMWF analyses of the final FGGE II-b dataset (Uppala, 1987, Fig 2b); both plots are truncated at a total wave-number 20. The stream-function fields are quite similar between the two sets of analyses. The major differences occur in the tropical divergence fields.

Two features of the mean field will be the subject of particular study, the intensity of the tropical zonal flow at upper and lower levels, and the associated divergence field at upper and lower levels. Large differences in these features have been noted between different analyses of the Main FGGE II-b data set (Lau, 1984; Miyakoda, 1986). The only way to resolve such disagreements is by comparison with the observations (Arpe, 1985).

The divergence fields in the new ECMWF FGGE analyses are much more intense than in the old ECMWF analyses. For example, over Indonesia the peak divergence barely exceeded 2 10-6s-1 in the old analyses, and is about three times more intense in the new analyses. Changes of similar magnitude may be seen in the other major convective areas over the Indian Ocean, Africa and Latin America, and the South Pacific Convergence zone. The patterns for February are rather similar, and are not shown.

For comparison, Fig 2c shows the mean Outgoing Longwave Radiation (OLR) data (Gruber and Krueger, 1984) for the period Jan 1- March 1 1979. The OLR data reflects the important areas of upper level divergence over Africa, Latin America, the Indian Ocean just south of the Equator, with the major centre extending eastwards from Indonesia to the dateline, and lying mainly in the Southern Hemisphere. The convection in these areas is the main energy source for driving the atmospheric heat engine as a whole, and for driving the trade wind circulation in particular.

3. OBSERVATION MINUS FIRST-GUESS BIASES

Most operational assimilation systems using Statistical Analysis (also called Optimal Interpolation, O/I) assume that the assimilating model and the observational data are both unbiased. This assumption is not valid in general, and it is necessary to estimate the extent to which biases in the data and in the model affect the analyses produced by the assimilation. This can be done by comparison of the mean Observation minus First Guess (OB-FG) biases relative to different observing systems. If the OB-FG statistics show a common bias for all observation types, then we can be confident that the background field is biased; otherwise both background and data may be biased, and one has to use independent knowledge of the reliability of different observing systems.

3.1 Tropical Oceanic Wind Forecast Biases in the Lower Troposphere

The cloud track winds are a good starting point for the discussion, as they provide an extensive view of the Tropical regions. Fig 3a shows the mean OB-FG winds for all analysis times in SOP1 for SATOBs at or below 850mb. A number of important areas of forecast bias are documented in this plot. Evidence that the biases arise mainly from the model is provided by calculations for other observing systems.

a) Areas with Deficiencies in the Low-Level Background Field

The main tropical convection (and convergence) was centred over Indonesia, and extended east across the Pacific just south of the equator, and as far as the dateline, Fig 2a,b. The forecast for the low-level convergence field in the area is inadequate, as implied by the strong convergence in the low-level OB-FG winds (Fig 3a) just north of the equator between 140E and 180E, where the OB-FG winds are as large as 4m/s. The divergence field in the subtropical high of the North-East Pacific is also too weak in the forecasts, as is evident in Fig 3a along 17N between 120W and 140W. There is a marked diurnal variation in the magnitude of the forecast error for the convergence in the Western Pacific, with the errors being much larger at 0000 UTC than at 1200 UTC (Fig 1).

The interpretation of these biases as model biases rather than data biases is supported by independent wind data. Fig 3b shows OB-FG biases for SOP-1 for 850mb winds as reported by rawinsondes and pilot-balloon reports; we shall call both these data sources TEMP data, for short. The underforecast of convergence in the convection area in the maritime continent is clearly evident in these data over Southeast Asia and the Pacific Islands north of the Equator, between Asia and the dateline. Unfortunately the corresponding OB-FG data was not stored for SHIP reports.

Another area where the low-level wind field in the background appears to be defective is in the vicinity of Central America and the Caribbean where the 850mb TEMPS and SATOBs agree in indicating a westerly bias with magnitudes between 2 and 5 m/s.

b) Areas with Inconsistencies in the Low-Level Data

To the east of the dateline the SATOBS (Fig 3a) suggest that the forecast for the easterly component of the trade winds is too weak between 140W and 180W, and that there is an under-forecast of the low-level convergence along the ITCZ in the East Pacific (at about 5N between 140W and 180W, and at about 10N between 100W and 140W). In these longitudes (140W to 180W) the biases relative to TEMPs (Fig 3b) are small when compared with the biases relative to SATOBs, and the TEMP data give no suggestion of a consistent under-forecast of the low level easterlies. Since the in-situ TEMP measurements are probably more reliable the suggestion must be that the low level easterlies are over-estimated by the SATOBs between 140W and 180W.

Near the northeast coast of Brazil the on-shore and along-shore biases relative to SATOBS (Fig 3a) are almost orthogonal to the off-shore direction of the biases relative to TEMPS (Fig 3b). It had been intended not to use low-level cloud-winds over land, because of the risk of error due to orographic effects. Due to a programming error this was not done over Latin America at 1800UTC, nor in a few cases over Africa. Since the data in these locations only enters the calculation once per day, it does not represent even a crude daily average, and so should be ignored.

In the tropical Atlantic north of the equator the 850mb wind biases relative to TEMPS are quite small, while the biases relative to the SATOBs are rather larger (up to 3m/s) and are mainly northerly. In the tropical Atlantic south of the equator, the forecast southerly component of the trade winds is weak by

2-3m/s compared to SATOBs (Fig 3a), with a clear suggestion that the associated convergence just south of the equator is too weak. However the bias relative to the St Helena TEMP (Fig 3b) is westerly at about 2m/s and is orthogonal to the SATOB bias. Conflicts of this kind between different data sources will occur frequently in our discussion.

c) Areas with Satisfactory Low-Level Model and Data Performance

Over Africa the forecast biases relative to TEMPs are fairly small and randomly distributed, except in east Africa, where the bias is westerly with magnitudes of about 3m/s.

In the tropical Indian Ocean the forecast winds were rather unbiased, as implied by the fact that the forecast biases are generally weak relative to the SATOBs (Fig 3a). The only exception is in the area just to the west of Australia, where the biases reach 3m/s. This general result for the Indian Ocean must be treated with caution, since SATOBS are the predominant data source in the area. However the biases relative to the available TEMP data (Fig 3a) are also very small. Taken together, these results suggest that the 6-hour forecasts perform better in the Indian Ocean basin than in the other two basins, or alternatively, that the laboratories that produced the low-level winds for the Pacific and Indian Oceans had different levels of skill.

3.2 Upper-Tropospheric Tropical Wind Forecast Biases

The OB-FG results for the low-level wind suggest that the forecast substantially under-estimates the low-level convergence in the main convective area in the equatorial western Pacific. We now consider the upper level tropical wind field to see if the upper-level forecasts and observations are consistent with such a view.

a) Areas with Deficiencies in the Upper-Level Background Field

Fig 4 shows OB-FG winds for SATOB in the 200-300mb layer (Fig 4a) for TEMPS at 200mb (Fig 4b), and for aircraft reports in the 200-300mb layer (Fig 4c). In the vicinity of the main convection area in the equatorial western Pacific, the upper-level SATOBS (Fig 4a) indicate a notable under-forecast of the convectively driven outflow. The main convective area was south of the equator; the OB-FG biases relative to the SATOBS have a marked southerly component between the equator and 20N and between 140E and 180E. The forecast underestimates the southerly component of the wind by about 4m/s.

The 200mb TEMP data between the Equator and 10N, and between 120E and 180E (Fig 4b) show very convincing evidence for the same conclusion, both in the direction and magnitude (about 5m/s) of the forecast wind error. Between the Equator and 5N these Western Pacific stations show a south-easterly bias, while between 5N and 10N the bias is almost entirely southerly. The suggestion from the SATOB data that there is a marked under-forecast of the upper tropospheric divergent wind field of order 4m/s in the equatorial west Pacific finds strong support from the TEMP data. They suggest that the error in the background field exceeds 5m/s. These findings are consistent with our findings from the low-level data. This consistent set of results is the clearest indication we have of an unambiguous deficiency in the background field. There are insufficient AIREP data in the area to provide much further information.

Since Fig 4b represents a mean forecast error, there must be a substantial error in the model's diabatic forcing. The turning of the wind with latitude is reminiscent of the very simple response to thermal forcing discussed by Gill (1980).

The SATOB data (Fig 4a) show a marked underforecast in the intensity of the divergence over Africa, where the bias in the forecast winds relative to the SATOB wind speeds exceeds 5m/s. This is supported by some of the upper level TEMP data (Fig 4b) in Central Africa, though the TEMP data at 850mb (Fig 3b) give little indication of such a forecast error. The vertical scale of the error is apparently not deep enough to encompass the whole troposphere. The biases relative to TEMPs over West Africa are very noisy, and may suggest biases in the wind-finding equipment.

b) Areas with Inconsistencies in the Upper-Level Data

In the western hemisphere north of the equator, the most marked feature on Fig 4a is the marked easterly bias in the OB-FG differences for the SATOBS. The SATOBs were not used poleward of 20N, and no corrections were applied to SATOB data between 20N and 20S. The upper tropospheric winds are mainly westerly between the equator and 20N in the western hemisphere between 180W and 0W, (Fig 2). The mainly easterly component in the OB-FG biases for the SATOBS, Fig 4a indicate that the forecast westerlies were stronger than the SATOB reports by 5-7 m/s.

Aircraft reports in the Central Pacific between 180W and 130W, and between the equator and 20N (Fig 4c) suggest that the forecast westerlies were weaker than the AIREPS by 3-5m/s. A similar result is found for AIREPS in the same band of latitude from 80W over Latin America to 0W over Africa. In the same latitude band, the TEMP reports (Fig 4b) in the Pacific east of the dateline indicate that the forecast westerlies were too slow in the mean, as indeed do the TEMPS in the Latin American sector, and over the Atlantic.

Even if these diverse observations are not necessarily coincident in time, the weight of the evidence nevertheless suggests that the SATOB westerly winds, particularly in the eastern Pacific, were probably too weak by 5 to 7m/s. The OB-FG biases contain both data and forecast biases. If we can assume that the TEMP and AIREP data are unbiased, then several conclusions follow: the forecast westerlies in the east Pacific are too slow by a few meters per second, the SATOBs have a speed bias somewhat larger than is indicated by the OB-FG results in Fig 4a, and the forecast westerlies are probably too slow because the SATOB data were used at an earlier analysis time. Before one can rely on these conclusions however, one must consider the extent to which the SATOB data affect the analyses, and the initialised analyses.

In the southern hemisphere, between the equator and 20S in the sector 160W-100W, the mean upper tropospheric winds were also westerly during SOP1, and of approximately the same strength as the westerlies just north of the equator. In this area the forecast westerlies were slightly stonger than the SATOB winds (Fig 4a), and slightly stronger than the TEMP reports in Polynesia, (Fig 4b). This could happen if the correction applied to the SATOBs poleward of 20S had been slightly too large. Corrections were not applied to the GOES-W data in this band of longitude, but were applied to the Himawara data upstream.

The largest biases relative to upper level TEMP data occur over west Africa. As discussed in the next section, this is probably due to noise in the data.

c) Areas with Both Background and Data Deficiencies

Over Latin America, the upper-level subtropical high associated with the intense convection over the Amazon Basin is centred at about 18S,70W, with the mid-Atlantic upper level trough located at 20S and 30W. The upper level divergence maxima over Latin America are also centred at about 15S near the centre of the high. The OB-FG winds for the SATOBS (Fig 4a) over Latin America between the equator and 20S are from the north-east at about 5m/s. The OB-FG winds for the AIREPS (Fig 4c) are generally from the west and of about the same magnitude, while the TEMP biases (Fig 4a) in north-east Brazil show a generally southerly bias, and are of somewhat larger magnitude. Recognising again that the diverse observations are not coincident in time, one nevertheless concludes that, in the mean, the forecast lies somewhere between the diverse, and partly conflicting data sources. Over Latin America, the mean winds are low, of order 10m/s. Biases of order 5 m/s between forecasts and observations are indicative of a rather high level of observational error at these low wind speeds. The most reliable observing system, the TEMPS, suggest very clearly that the upper level convective outflow is much too weak from the main convective area.

Biases over the Indian Ocean (relative to SATOBs, Fig 4a) appear to be smaller and less coherent than over the Western Pacific. The SATOBs appear to suggest a mild underforecast of the upper level divergence over the Indian Ocean. The OB-FG biases relative to AIREPS (Fig 4c) over Malaysia, Sumatra and the southern Bay of Bengal are consistent with this view. TEMP data (Fig 4b) were only available in quantity over India and South East Asia. The OB-FG statistics for the Indian TEMPS are mainly northerly, and conflict with both the AIREPS and SATOBs. To the west of Sumatra, the available TEMP data suggest a localised error in the forecast of divergence. The scale of this feature is about 10-20 degrees. Given this rather short scale, the divergent pattern in the OB-FG TEMP biases may alternatively be due to biases in the observations.

3.3 Summary and Discussion

The biases documented in the OB-FG tropical wind results may be categorised as model biases, data biases, and biases which cannot be attributed unambiguously to either model or data.

The most important weakness in the background field for the analysis is the under-estimation of the intensity of the tropical divergent wind-field. This bias affects the main convection areas over Africa and Latin America, perhaps also over the Indian Ocean south of the equator. It is most severe over the Tropical Western Pacific, where the low-level wind feeding the main convection centres could be under-estimated by as much as 5m/s in places.

The most reliably determined observational bias is the under-estimation of the upper-level westerly flow in the western hemisphere between the Equator and 20N. This is associated with the under-estimation of westerlies further north which led to the decision to discard the upper-level SATOBS north of 20N. There are many randomly distributed biases in the TEMP wind data, some of quite large magnitude. Some of these must be observational errors. Biases such as this can frequently be corrected at the observing station, once the station operator knows about the problem.

Before one can discuss the extent to which the biases in the analysed fields are due to the forecast model, it is necessary to consider the performance of the analysis algorithm, and of the initialisation scheme, as discussed in the next two sections.

4. OBSERVATION MINUS ANALYSIS BIASES

The discussion of the last section has established the main characteristics of the model biases, and of some of the more important data biases. In this section we document the extent to which the biases in the background field are corrected by the analysis algorithm. The section begins with a general review of the properties of the O/I analysis filter, which suggests that if instrument biases are randomly distributed the analysis algorithm will filter them, and so limit their effect on the analysed fields. We then go on to discuss the bias in the analysed fields.

For ease of comparison, the plots of the observation minus analysis (OB-AN) biases follow the same sequence as the plots of the OB-FG biases, so that Figs 5 and 6 show results for the OB-AN biases, with a layout similar to Figs 3 and 4.

4.1 Data Biases, Model Biases, and Analysis Constraints

One might expect that the OB-AN biases should be identically zero at locations where data is regularly available. In the O/I system there are several reasons why this need not be so. The O/I analysis algorithm assumes that both the data and the model are unbiased. It will therefore tend to produce an analysis at the observation point which lies between the first-guess and the observation, but it will seldom draw exactly for the observation. Any bias in the model or in the data will therefore bias the analysis.

The general result that the OB-AN biases will not be zero, if the model or data is biased, does not indicate how large the OB-AN bias is likely to be. The magnitude of the OB-AN biases relative to the OB-FG biases is controlled in part by the filtering properties of the analysis algorithm (Hollingsworth, 1987). The main filters in the ECMWF analysis algorithm (Lorenc, 1981; Shaw et al., 1987) are the requirements that the mass and thickness be in hydrostatic balance, that there be a strong geostrophic coupling between mass and wind in the extra-tropics, and that the (continuous) wind increment calculated within an analysis volume should be non-divergent.

The filter properties of the O/I analysis algorithm are a powerful tool to identify observational bias in areas where regularly available data has uncorrelated errors and randomly distributed biases. The O/I analysis algorithm acknowledges the presence of observational error, and seeks a reasonable compromise between noisy data sources and the first-guess. If the model is rather unbiased relative to the observations and if there are randomly distributed biases in the observations, the compromise will, on average, tend to reject the effect of biases at individual stations. The OB-AN biases will therefore indicate the observational biases.

Model bias tends to be spatially correlated; it also tends to be both non-divergent and approximately geostrophic in mid-latitudes. As a result model bias in mid-latitudes is readily corrected by the O/I analysis algorithm. In tropical and equatorial regions however, the model bias has a strong contribution from the divergent wind.

The constraint of non-divergence on the analysis increments is imposed locally in the analysis calculation for each analysis volume. The data selected for an analysis volume changes from one analysis volume to the next, so the constraint of non-divergence is not enforced on scales larger than about 1000km (Lorenc, 1981). This gives the analysis algorithm a limited capability to analyse divergent wind information on larger scales (Lorenc, 1981). The ECMWF analysis bases its calculations on the differences between the observations and the background field, sometimes called observation increments. For divergent wind information on large scales, and for observation spacing of about 500km, Daley (1985) suggests that only about 50% of the divergent wind information in the observation increments is communicated to the analysed field. For shorter scales the response is much poorer than 50%. Bias in the background field will therefore be more difficult to correct in tropical regions than in mid-latitudes.

The O/I formalism can be extended to account explicitly for biased data. This has not been tested in operational practice. A simpler approach is to correct the data if the respective biases are known and are stable. Some winds were corrected in the analysis of the Final FGGE II-b dataset discussed here, based on experience with the assimilation of the main FGGE dataset. One could also extend the O/I formalism to account for model bias. Experience at a number of institutes, and indeed results to be presented below, demonstrates that many model biases are rapidly re-established when a model integration begins from rather unbiased data. If one's main goal is weather prediction, it is preferable to use finite manpower resources to improve the model than to develop elaborate bias correction schemes for the analysis, when the effect of the correction may be lost very rapidly in the forecast.

With these general considerations in mind, we now consider some of the main features of the OB-AN biases.

4.2 Data Inconsistencies and the Analysis of Low-Level Divergence

The OB-AN biases relative to low-level SATOBS, Fig 5a, are typically of the order of 2m/s or less over most of the tropics. The divergent patterns noted in the OB-FG biases (Fig 3a) are still well marked on smaller scales in the OB-AN biases, despite the smaller amplitudes. This is most marked in the West Pacific, but is also clearly discernible in the East Pacific and in the Atlantic and Indian Oceans. Patterns of divergence are well marked also in the divergence centres of the sub-tropical highs. In the SHIP OB-AN data (Fig 5c) one also finds similar well marked patterns of convergence/divergence both in the convergence zones, and in the divergence centres of the sub-tropical highs.

The corresponding OB-AN results for the TEMPs, Fig 5b, show no indication of a markedly convergent pattern in the equatorial western Pacific; the pattern of OB-AN biases for the TEMPs is rather random there. This indicates a conflict between an estimate of convergence derived purely from the TEMP data, and one derived purely from the SATOB data. In this case the analysis algorithm has given more weight to the TEMP data, which shows the weaker divergence field.

Fig 5c shows the OB-AN statistics for the SHIP wind data at 1000mb. (Unfortunately, the corresponding OB-FG and OB-IN statistics for SHIPs are not available). The SHIP results at 1000mb are broadly consistent with the SATOB results at 850mb in showing a marked convergence pattern in the western equatorial Pacific, in agreement with the SATOB data.

Much of the difference between the TEMP results and the SATOB and SHIP results could simply be sampling error, due to the different distributions of the observations in time. Moreover there is no reason to expect a simple relation between errors in the forecast convergence at 1000mb and at 850mb. Nevertheless it is hard to resist the conclusion that in the face of data showing different intensities of convergence, the analysis algorithm has drawn most closely to the data showing the weakest intensity of the convergence. In view of the results of Daley (1985) on the weak response of the analysis algorithm to divergent information, it is likely that the response to the weak divergent information in the TEMPs would not have occurred without the presence of the stonger divergent information in the other data sources.

Besides the equatorial west Pacific, there are other areas of the tropics where the OB-AN results appear to suggest biases between the three low-level observing systems, including the eastern Pacific and the Atlantic. In the equatorial Atlantic just north of the equator, both the 1000mb SHIP data and the 850mb SATOB OB-AN results show a marked pattern of convergence, which is not found in the 850mb TEMP data. In support of the SHIP data it is worth noting that Cardone et al. (1988) found, in comparisons of SHIP and in-situ data with operational ECMWF analyses in the tropical Atlantic in 1982-1984, that the analyses underestimated the low-level convergence.

On balance, these results suggest that there is a conflict between the 850mb mb wind data from SATOBs and TEMPs at low levels, but that the SHIP data identify a real problem in the analyses. The 850mb results support the view that in areas where a mix of data occurs, the OB-AN results contain a strong component from the observational biases. This will prove to be true also at upper levels. It should be clear that we do not claim that our present results imply that the low level analysis of the mean divergence field is free of bias in areas where a mix of data is available. We do suggest however that the level of bias in the mean analysed divergence is within the range of biases in the observations.

A final comment concerns the fact that the analysed field reflects the low-level SATOB data in the tropical Pacific east of the date-line, so that the analysed field have stronger easterlies than the background fields, when SATOB data is available. Despite this, there is little bias in the analysed fields relative to TEMP data, when it is available. This is possible if the two data types do not always occur at the same times. This result also indicates that if different data types are not always available at the same time, then the OB-AN statistics will underestimate any differences in bias between the two data types.

4.3 Biases in the Analysis of Upper-Level Winds

The OB-AN tropical upper-level wind biases relative to SATOBS (Fig 6a), TEMPS (Fig 6b), AIREPS (Fig 6c) show much smaller wind speeds than the OB-FG results. The patterns of the OB-AN biases are also much less organised than the corresponding OB-FG biases (Figs 4). Relative to SATOBS (Fig 4a), the OB-FG biases in the zone 20N to 20S are frequently between between 5 and 10m/s, while the corresponding OB-AN biases (Fig 6a) seldom exceed 2 to 4 m/s.

Patterns of upper level divergence are apparent in the OB-AN biases relative to TEMPs (Fig 6b) over the equatorial western Pacific, but they are much weaker than the divergence patterns in the OB-FG biases, indicating that the analysis algorithm has responded to the divergence information. The analysed upper-level mean divergence field in the equatorial western Pacific reflects the weaker mean divergence in the local SATOB data rather than the stronger mean divergence field in the local TEMP data. Analogous behaviour has already been noted in the analysis of the low-level divergence field, but there the TEMP data had the weaker divergent signal. In all likelihood one would not see the agreement between the analysis and the (weak) divergence in the SATOBs, without the presence of the strong divergence in the TEMPs (Daley 1985).

In northern South America the analysis (Fig 6b) reflects the TEMP data (Fig 4b), which show a strong southerly divergent outflow across the equator from the convective area over Latin America. As a result the OB-AN biases relative to TEMPS are small and randomly distributed, which indicates a good performance by the analysis algorithm in this area.

The OB-AN upper level wind biases are smaller than OB-FG biases even for apparently conflicting data sources such as SATOBS on the one hand and AIREPS and TEMPS on the other in the latitude band Equator-20N in the western hemisphere. This is possible because the SATOB, AIREP and TEMP data are not available at the same times. There have seen cases in operational work (J Pailleux, pers comm, 1985) where at one synoptic hour the AIREPS are the only upper-air data in the Eastern Pacific between Hawaii and North America, while at the previous and succeeding synoptic hours the SATOBS are the only upper-air data in the same area. The bias in the SATOB data in such a situation can lead to cyclic changes in the strength of the upper-level zonal wind in the area, because the aircraft scedules and the schedule of SATOB production are regular on a daily basis. Similar effects may occur in the FGGE analyses, but we have not documented them.

Finally we note that the largest OB-AN biases for TEMPs at 200mb occur over West Africa, where they can be as large as 5m/s. This is probably due to biases in the TEMP data, resulting in reports showing unrealistically high levels of small-scale activity. The analysis algorithm filters out this information, and prevents it affecting the analysed fields unduly. As a result the OB-AN statistics have a strong component from the observational biases.

4.4 Discussion

The results so far show that there are important biases in the short-range forecasts of the divergent wind field in the Tropics particularly in the west Pacific. There may also be biases in the strength of the trade winds in the eastern Pacific, but the evidence form different data types is conflicting. We are confident that the SATOBs underestimate the strength of the upper-level westerlies in the east Pacific.

The analysis algorithm draws to the observations in such a way that the OB-AN biases are a good deal smaller than the OB-FG biases. Where a mix of data is available the OB-AN biases reflect the biases in the data. In such areas the bias in the analysis is well within the range of biases in the data. For the divergent component of the mean flow in the tropical west Pacific, where a mix of data is available at both upper and lower levels, the analysis algorithm responds best to the data system showing the weakest divergence - TEMPs at low levels and SATOBs at upper levels. It is likely that this level of agreement between observation and analysis would not have happened without the presence of data showing a stronger divergent signal, because of the filtering constraints used in the algorithm.

The aircraft data is drawn-to very closely in all areas. In some areas apparently contradictory AIREP and SATEM data can be drawn-to in the mean. Such an effect can occur if the different observation types are available at different times of day. Studies of diurnal variations which use the FGGE III-b data must be aware that artefacts might be generated in the data through such a mechanism.

The TEMP-AN upper-level wind biases show a good deal of random small-scale structure. In many areas this is thought to reflect biases in the wind-finding equipment at individual stations.

5. OBSERVATION MINUS INITIALISED-ANALYSIS BIASES

The assimilation of the Main FGGE II-b dataset used an adiabatic initialisation procedure (Temperton and Williamson, 1981; Williamson and Temperton, 1981), following Machenhauer (1977). This had a deleterious effect on the intensity of the tropical divergent circulations (Hollingsworth and Cats, 1981; Bengtsson et al., 1982). The diabatic initialisation procedure used for the present assimilation is described in detail by Wergen (1987). In the diabatic initialisation procedure a smoothed estimate of the diabatic forcing is introduced in the initialisation procedure in order to preserve more of the tropical divergence field than is possible with an adiabatic initialisation.

Wergen (1987) also ensured that the initialisation condition on the tidal components of the flow should recognise the propagating character of the tides. Hsu and Hoskins (1988) discuss the representation of tides in ECMWF operational assimilations after this idea was implemented in operations in early 1986. Their results should be relevant to the FGGE re-assimilations discussed here.

To facilitate comparison with the earlier results, the OB-IN results are presented in the same order as the earlier sets of plots for OB-FG and OB-AN biases.

5.1 Biases in the Initialised Winds

Fig 7a-b shows the OB-IN wind biases at 850 mb for SATOBs and TEMPs. Comparison of these results with the corresponding results for OB-FG and OB-AN biases shows immediately that the effect of the initialisation is to reject some of the large scale divergent wind information, and even rotational wind information, which was introduced by the observations during the analysis step. This is seen most clearly in the the SATOB-IN biases in the Central and Western Pacific, where the main features of the OB-IN SATOB biases are very similar the OB-FG biases, in pattern if not intensity.

A similar result is found in the upper troposphere. Fig 8a-c shows the OB-IN wind biases in the upper troposphere for SATOBs, TEMPs and AIREPs. Some of the main changes introduced by the analysis step are partly undone by the initialisation step. This is particularly marked in the OB-IN biases for

TEMPs in the tropical Western Pacific and SATOBs in Central Africa, showing that the upper level divergence field in the initialised analysis is closer to the first-guess field than it is to the analysed field (cf Hollingsworth et al., 1985 where a similar result is found in mid-latitudes).

5.2 Effect of Model Bias in the Initialisation

The OB-IN biases, reflecting an under-estimation by the initialised analysis of the convectively driven mean flow in the Western Pacific, lie roughly half-way between the OB-FG biases, and the much smaller OB-AN biases. Such an effect almost certainly arises because the diabatic terms used in the initialisation are unable to provide enough forcing to support the divergent flow field produced by the analysis algorithm.

The diabatic forcing used in the initialisation is smoothed in such a way that the retained components can force gravity waves with periods longer than eleven hours. This amounts to a very heavy spatial filter, as documented in Wergen (1987). Given that the OB-FG biases are still larger than the OB-IN biases, one may conclude that the convective forcing is under-estimated both in the forecast and in the initialisation, and that the smoothing used in the initialisation may be too heavy.

5.3 Rejection of SATOB Rotational Wind Information

Implicit data rejection in the initialisation step is also apparent in the SATOB-IN biases in the Pacific north of the Equator and east of the date-line. In this region it seems that some of the rotational wind information derived from the SATOB data in the analysis procedure has been rejected in the initialisation procedure. This might appear a surprising result, since one expects the initialisation to retain rotational wind information at least on synoptic scales. However on larger scales the initialisation tends to give more weight to the mass field.

The correlation model for the forecast error used in the analysis algorithm includes terms representing large scale forecast errors in height and wind (Hollingsworth and Lonnberg, 1986; Lonnberg and Hollingsworth, 1986). These terms in the correlation model correspond to errors in the mean wind, or mean height, over the analysis volume. By design, the analysis algorithm does not impose any relation between the large scale mass and wind terms in the correlation model, so the analysis algorithm imposes no relation between the mass and wind changes on the largest scales. The assimilation system therefore relies on the initialisation algorithm to achieve a reasonable dynamical balance on the largest scales. The fact that part of the SATOB information is rejected both at upper and lower levels implies that it is inconsistent to some extent with other wind and mass data (e.g. SATEM data).

This partial rejection of the SATOB information is reassuring, since the TEMP and AIREP data suggest that the SATOB data is less accurate than other wind data in the tropics. This rejection also provides support for the decisions not to use the SATOB poleward of 20N, and to calibrate some of it poleward of 20S. Kallberg and Delsol (1987) have shown that the upper-level SATOB data have important errors in mid-latitudes when the winds are strong.

6. THE STANDARD DEVIATION OF THE OB-AN DEPARTURES

Uppala (1987) presented area-averaged verification statistics on the fit of the analyses to the observations. In this section we present a more detailed account of the standard deviation of the OB-AN departures. The main purpose is to demonstrate that the summary statistics do not conceal an undue amount of regional variation. It follows that the analysis quality is rather uniform in those areas for which data is available.

6.1 Verifications of the Analysis of Low-Level Winds

Fig 9a-c shows the standard deviation of the low-level OB-AN differences, calculated for the same 5 degree boxes used in the bias calculations, for SATOB and TEMP data at 850mb, and for and SHIP data at 1000mb. The data volumes available in each box are indicated by the size of the figure in box. Three sizes of digit are used: the tallest difits for more than 50 reports in a box in the period, medium digits for 10-50 reports in the period, and short digits for less than 10 reports. The present calculations are limited to data actually used in the assimilation; rejected data are excluded from the results presented. Within each box the verification statistics are rounded to the nearest whole m/s. At the right of the figures are shown rms verifications for the four 10 degree wide latitude bands between 20N and 20S.

Fig 9a, for the SATOBs, shows a remarkably uniform standard deviation of about 3m/s. For most boxes, the standard deviation lies between 2 and 4 m/s. Such a pattern would be expected if the SATOBS were the only data available, or if there were no conflicts between the SATOBs and other data. In fact the SATOBs are the most abundant low-level data. The very smooth results in Fig 9a suggest that their effect on the analysis may well dominate the effect of other data types. Typical values of the fit are 3 to 3.5m/s for zonal average statistics.

The zonal averages of the fit of the analyses to the 850mb wind data from TEMPs (Fig 9b) show somewhat larger values than for SATOBs, by about 0.5 m/s. Detailed inspection of the verifications shows that there are a few boxes where the standard deviation is large and the volume of data is small. For most boxes the standard deviation lies between 3 and 5 m/s. For many boxes over the oceans the data volume is low, because observations were not available on a regular basis throughout the period. Presumably this feature contributes to the rather large standard deviations.

In areas where SHIP data was plentiful, the fit to the 1000mb ship winds is not as close as it is for SATOBs, being about 4m/s. In areas where the SHIP data is scarce, and sample sizes small, the fit is not as close as it is in the more data-rich areas.

6.2 Verifications of the Analysis of Upper-Level Winds

The verification results in the upper troposphere (Fig 10 a-c) are not quite as featureless as the results in the lower troposphere. In the equatorial west Pacific, the standard deviation of the analysis fit to the TEMP data (3-4 m/s) is rather tighter than the fit to SATOB data (4-6m/s), even though the analyses show a larger bias relative to the TEMP data than to the SATOB data (Fig 6 a,b). In the eastern Pacific north of the equator, the standard deviation of the analyses fit to the SATOB and AIREP data is about the same (6-7m/s), and is somewhat larger than the equivalent results for TEMP data (3-5m/s). A similar result is found over the tropical Atlantic, and indeed over the Indian Ocean.

Over Latin America the standard deviation of the fit to TEMPs (4-6m/s) is noticeably tighter than the fit to SATOBs (4-7m/s), which in turn is tighter than the fit to AIREPs (2-10m/s). Over Africa on the other hand, where the TEMP data is noisy, the smallest standard deviations are found for the SATOBs (4-6m/s).

There are a few places where the quality control algorithms failed to reject obviously bad data. Some bad TEMP data was accepted in one box over west Africa, and some bad AIREP data was accepted in a few boxes near the equator in the east and west Pacific, in the Atlantic, and in the Indian Ocean.

It is clear that the SATOBs are the dominant data source in the upper troposphere in the Tropics. This makes it all the more important that the SATOB wind retrieval methods be improved so as to provide good quality tropical winds for operational use, and for TOGA research.

7. INFLUENCE OF MODEL BIAS AND DATA BIAS ON THE ASSIMILATION

This study of the wind biases between the observations and the three fields (FG, AN, IN) which occur in the assimilation has shown a number of important results on the way model bias and data bias affect the assimilation.

Data bias affects the assimilation most clearly if it occurs in widely distributed reports such as those from a space based observing platform. The most pervasive data biases such as those in this study were in the SATOB data, where we found an over-estimate of low-level convergence, and an underestimate of upper level convergence in the western Pacific, together with an underestimate of the upper-level westerlies in the oceanic trough in the east Pacific north of the equator. Data bias will also have a clear effect on the assimilation if it occurs at an isolated ground-based station (Hollingsworth et al. 1986). If data bias is randomly distributed among observations which are not too far apart (e.g. TEMPs) then the assimilation system has a capability to filter out much, but probably not all, of the data bias. Examples of this effect were found in west Africa, where the wind directions at some stations were seriously in error.

Model bias affects the assimilation in a pervasive manner, through the consistent biases it introduces in the first-guess field. The effect is most important in data-sparse regions. The most important biases in the assimilating model occur in the tropical troposphere and arise from an under-estimate of the convective heating which drives the tropical circulation. The under-estimate of the convection in the model may also contribute to the reduction of the intensity of the tropical circulation which occurs in the initialisation procedure. The implicit spatial filter applied to the diabatic forcing used in the initialisation may also contribute to the damping of the tropical circulations in the assimilation. Roughly speaking, about half the error in the large-scale divergence in the background field in the tropics is introduced in the initialisation, and the remainder is introduced in the course of the 6-hour forecast.

Data was available in sufficient quantities that the analysis algorithm corrected the mean errors in the background field to a very large extent. As a result, any residual uncertainty in the mean analyses is within the uncertainty of the observations. The analysis algorithm has a rather poor response to divergent information even on large scales, so the analysed divergence field agrees best with the observational data showing the weakest divergence, both in the upper and lower troposphere. The mean analysed divergence field in the west Pacific agrees with the 850mb TEMP data but is weaker than the intensity suggested by the low-level SATOBs and the SHIPs. In the upper troposphere the analysed divergence is weaker than that suggested by the TEMPs, but agrees with that suggested by the (probably less reliable) SATOBs. Thus in this important area in the tropics the biases in the new analyses of the mean divergent wind field appear to be within the range of biases in the data, but the divergence is probably still under-estimated in the upper troposphere and near the surface.

Changes to the operational ECMWF system in early 1988 relaxed the constraint of local non-divergence in the analysis algorithm (P Unden, pers comm, 1988) and reduced the filtering on the diabatic tendencies used in the initialisation (K Puri and W Heckley, pers comm, 1988). Pre-operational tests indicate distinct improvements in the analysed fields in the tropics. A variety of ways of improving the SATOB data are also under development by the SATOB producers. These developments should lead to improvements in operational analyses of the tropical wind field for TOGA.

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LEVEL	1000 MB	850 MB	200 MB
SHIP	3.6		
TEMP		2.5	3.0
AIREP		3.5	5.0
SATOB		2.5	5.0

Table 1: Wind component observation errors assigned to the data types discussed in this paper (m/s).

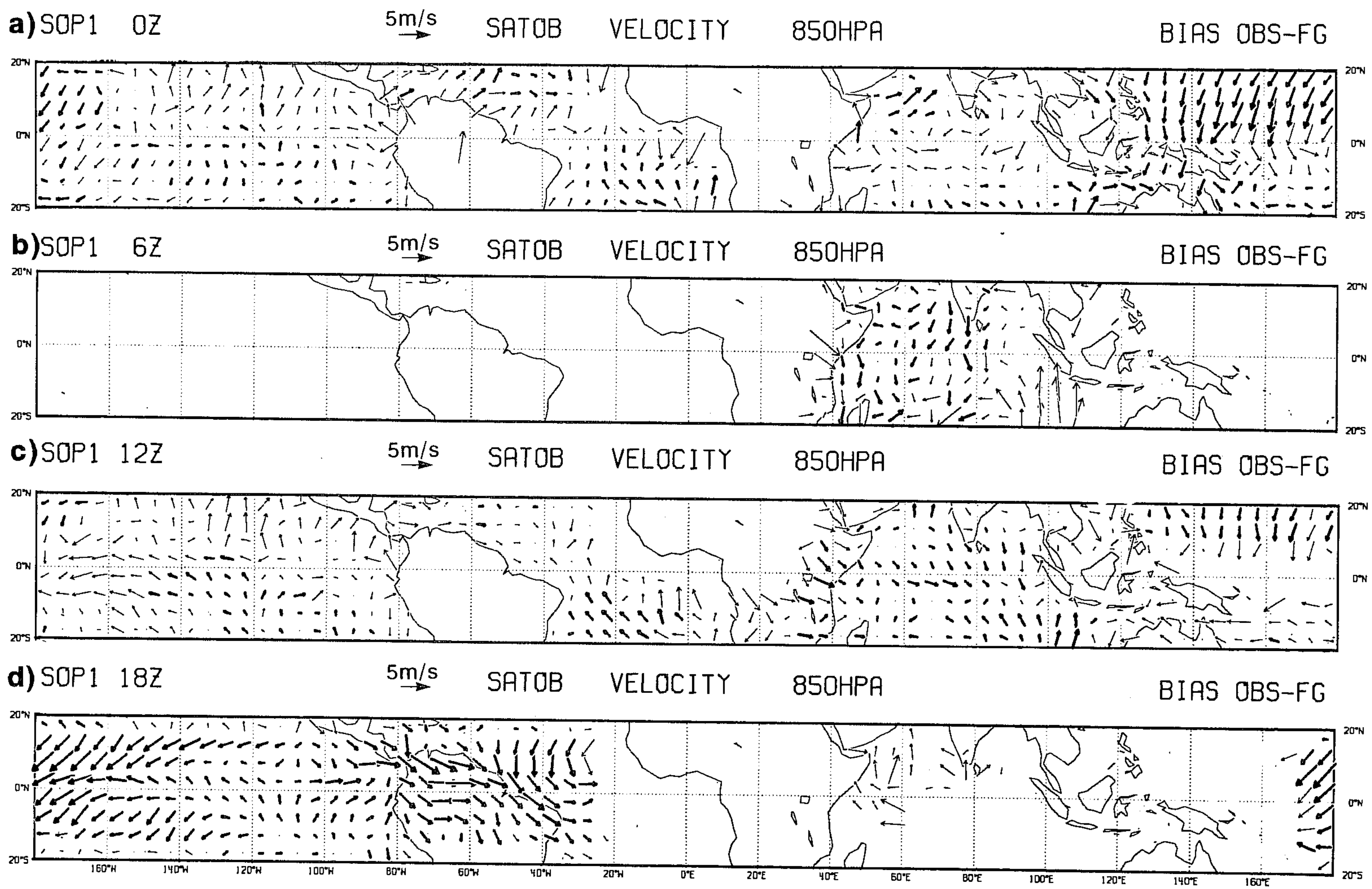

Fig 1 (a,b,c,d) Biases in the observation minus first guess for cloud track winds below 850mb, for the 6-hour time periods centred on 00,06,12,18 UTC during SOP-1. The data volumes are indicated by the thickness (not the length) of the arrow; three categories are used: thick arrows for more than 50 reports in the period, medium arrows for 10-50 reports in the period, and thin arrows for less than 10 reports. The velocity scale is given by the 5m/s arrow.

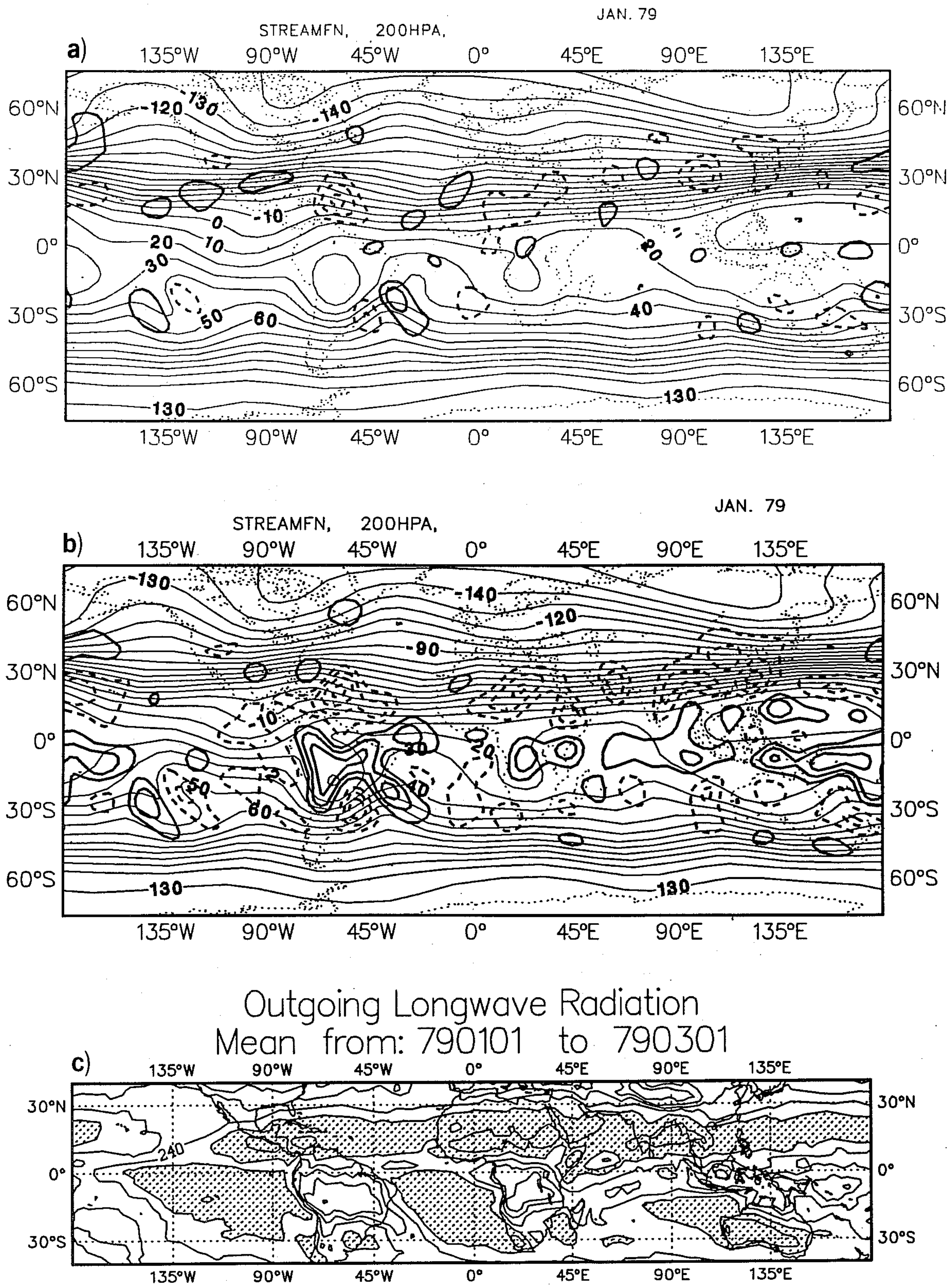

Fig 2 (a) Monthly mean stream-function (thin lines) and divergence fields (thick lines) for January 1979, as analysed in the ECMWF analyses of the Main FGGE II-b observational dataset (Bengtsson et al ,1982). The contour interval for stream-function is 10**7 m2/s, so that a gradient of 1 contour in 10 degrees latitude corresponds to 10m/s; the contour interval for divergence is 2. 10**-6 s-1 starting at +/- 2.10-6 s-1, with negative isolines dashed. (b) The ECMWF analyses of the Final FGGE II-b observational dataset (Uppala, 1987). (c) Mean outgoing long-wave radiation expressed as an equivalent radiative temperature for the period Jan 1- March 1 1979. The contour interval is 20K and the regions with temperatures above 260K are shaded.

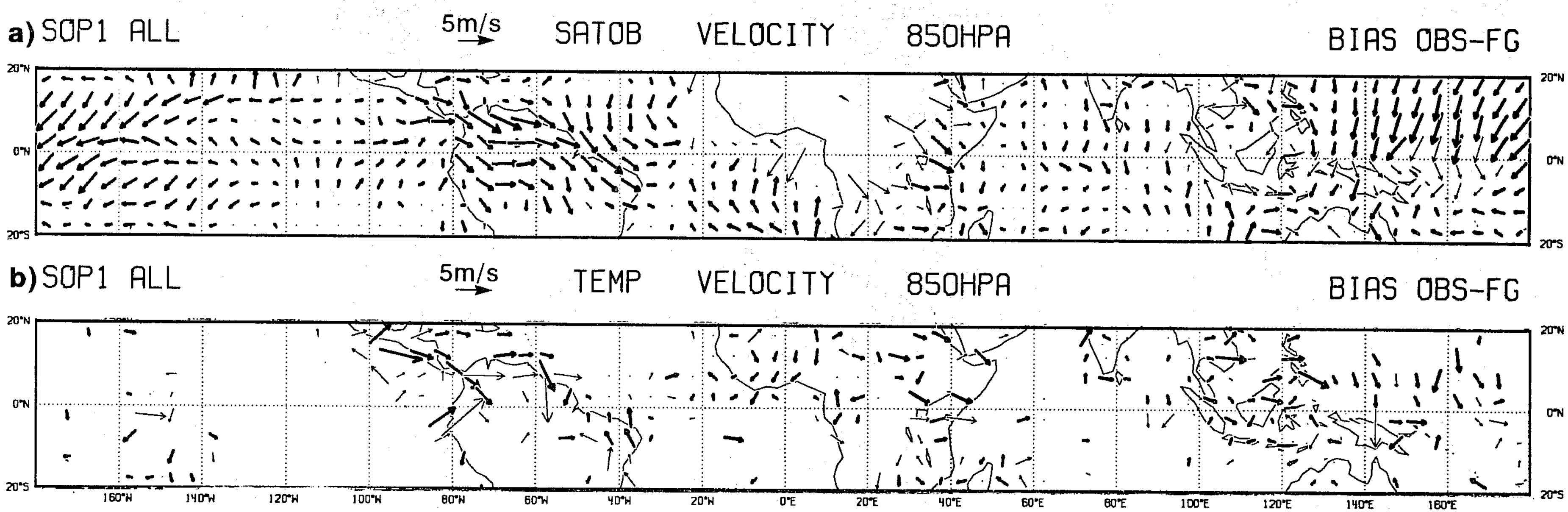

Fig 3 (a) The mean OB-FG (Observation minus First guess) winds for all analysis times in SOP1 for cloud-track winds below 850mb; (b) The OB-FG biases for SOP-1 for 850mb winds as reported by rawinsondes and pilot-balloon reports. The velocity scale is given by the 5m/s arrow.

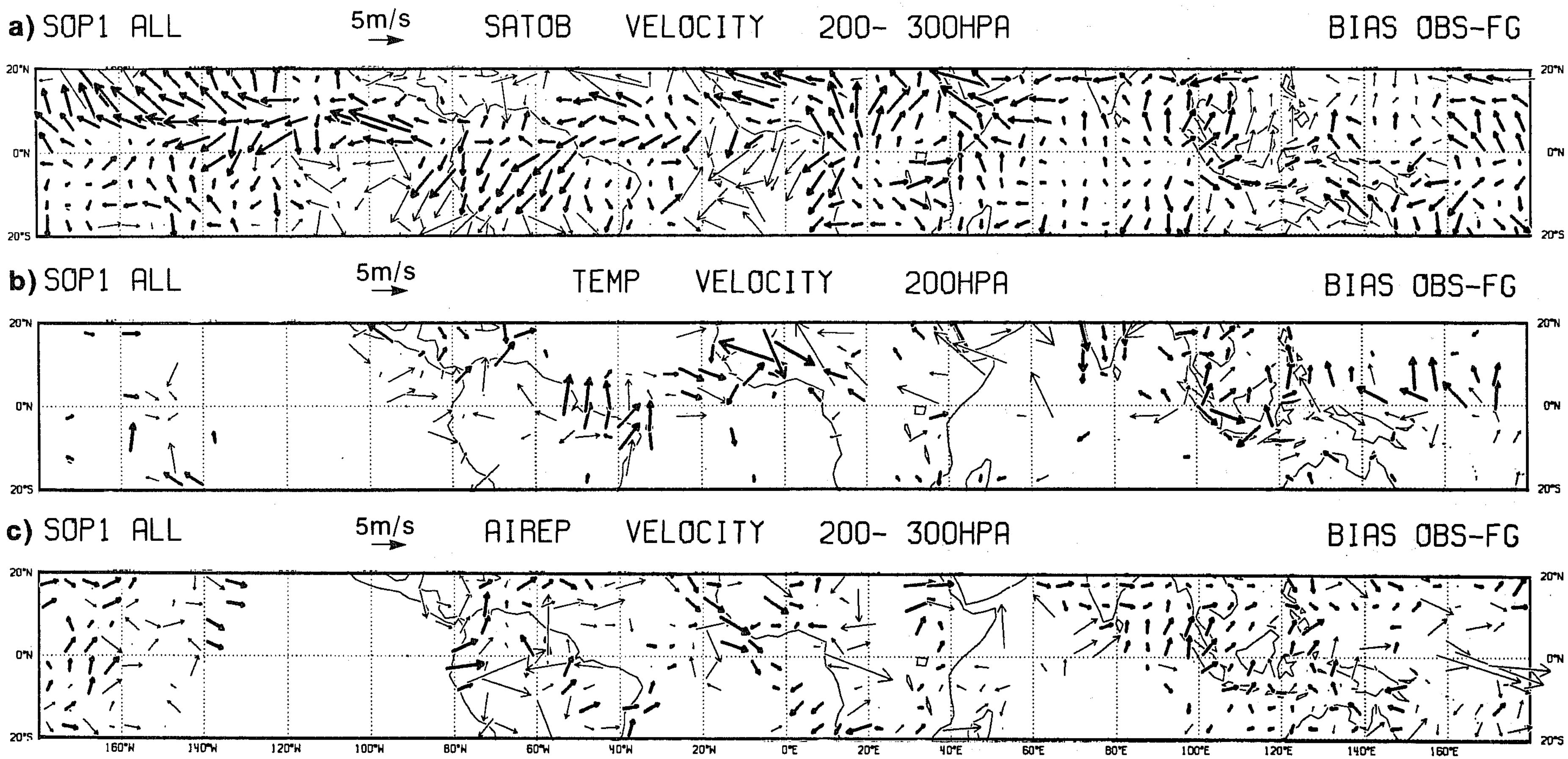

Fig 4 (a) The OB-FG biases for SATOBS for SOP-1 in the 200-300mb layer; (b) The OB-FG biases for TEMPS for SOP-1 at 200 mb; (c) The OB-FG biases for AIREPS for SOP-1 in the 200-300mb layer. The velocity scale is given by the 5m/s arrow.

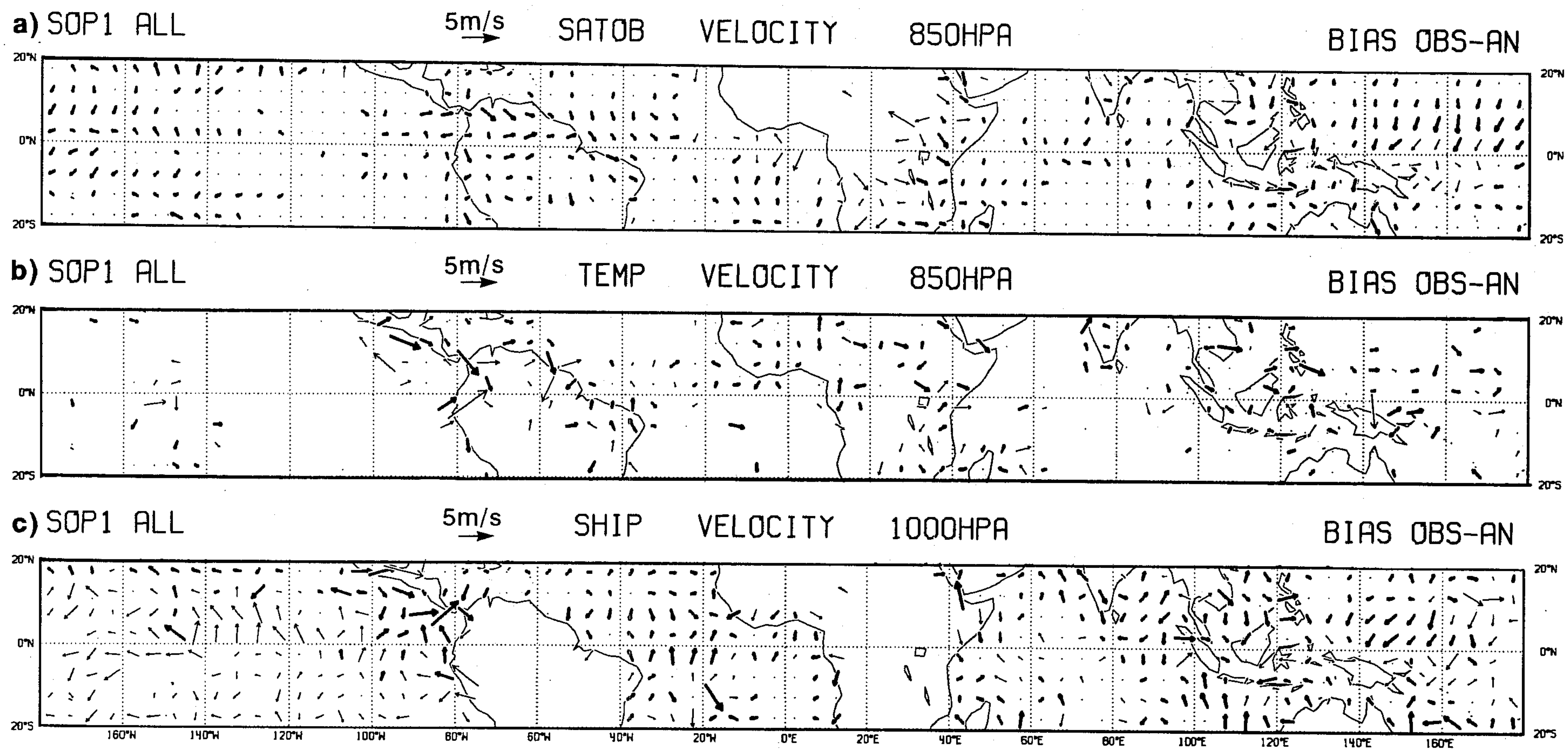

Fig 5 (a) The mean OB-AN (Observation minus Analysis) winds for all analysis times in SOP1 for cloud-track winds below 850mb; (b) The OB-AN biases for SOP-1 for 850mb winds as reported by rawinsondes and pilot-balloon reports; (c) The OB-AN biases for SOP-1 for ship winds at 10m. The velocity scale is given by the 5m/s arrow.

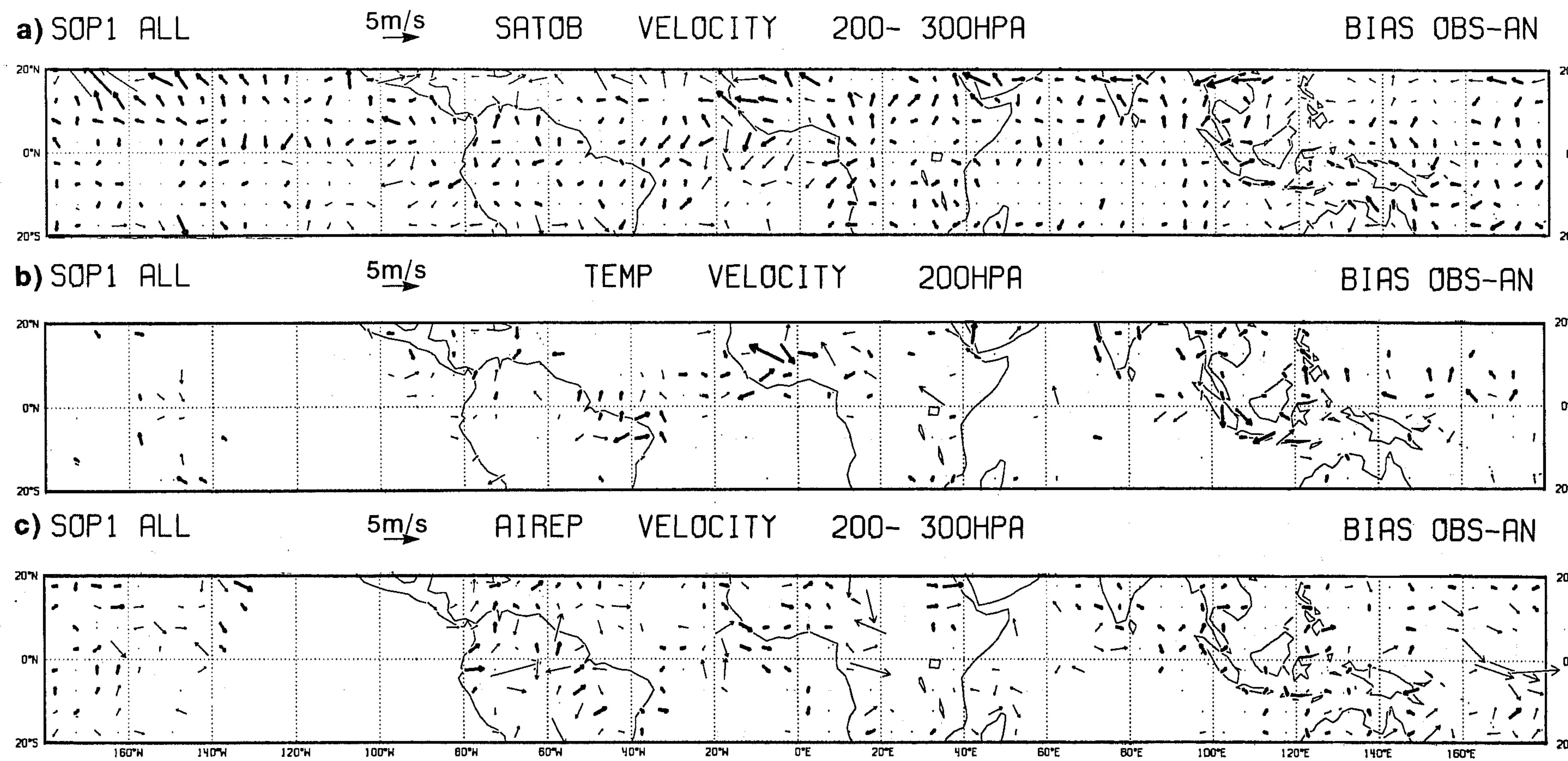

Fig 6 (a) The OB-AN biases for SATOBS for SOP-1 in the 200-300mb layer; (b) The OB-AN biases for TEMPS for SOP-1 at 200 mb; (c) The OB-AN biases for AIREPS for SOP-1 in the 200-300mb layer. The velocity scale is given by the 5m/s arrow.

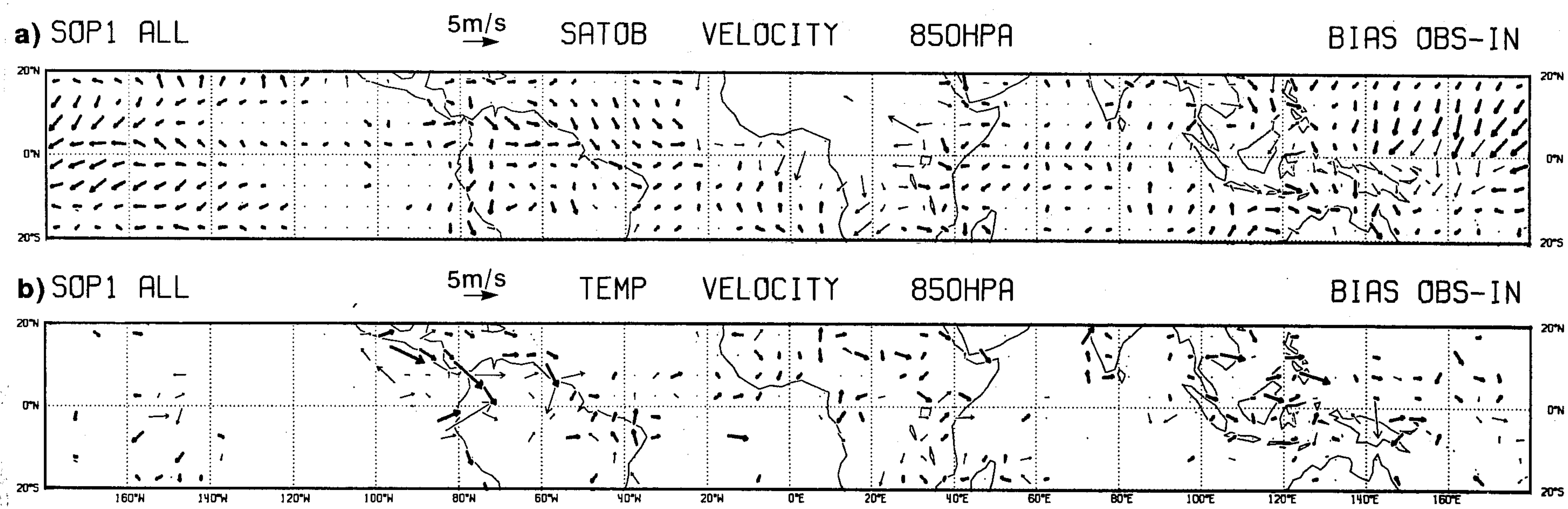

Fig 7 (a) The mean OB-IN (Observation minus Initialised Analysis) winds for all analysis times in SOP1 for cloud-track winds below 850mb; (b) The OB-IN biases for SOP-1 for 850mb winds as reported by rawinsondes and pilot-balloon reports. The velocity scale is given by the 5m/s arrow.

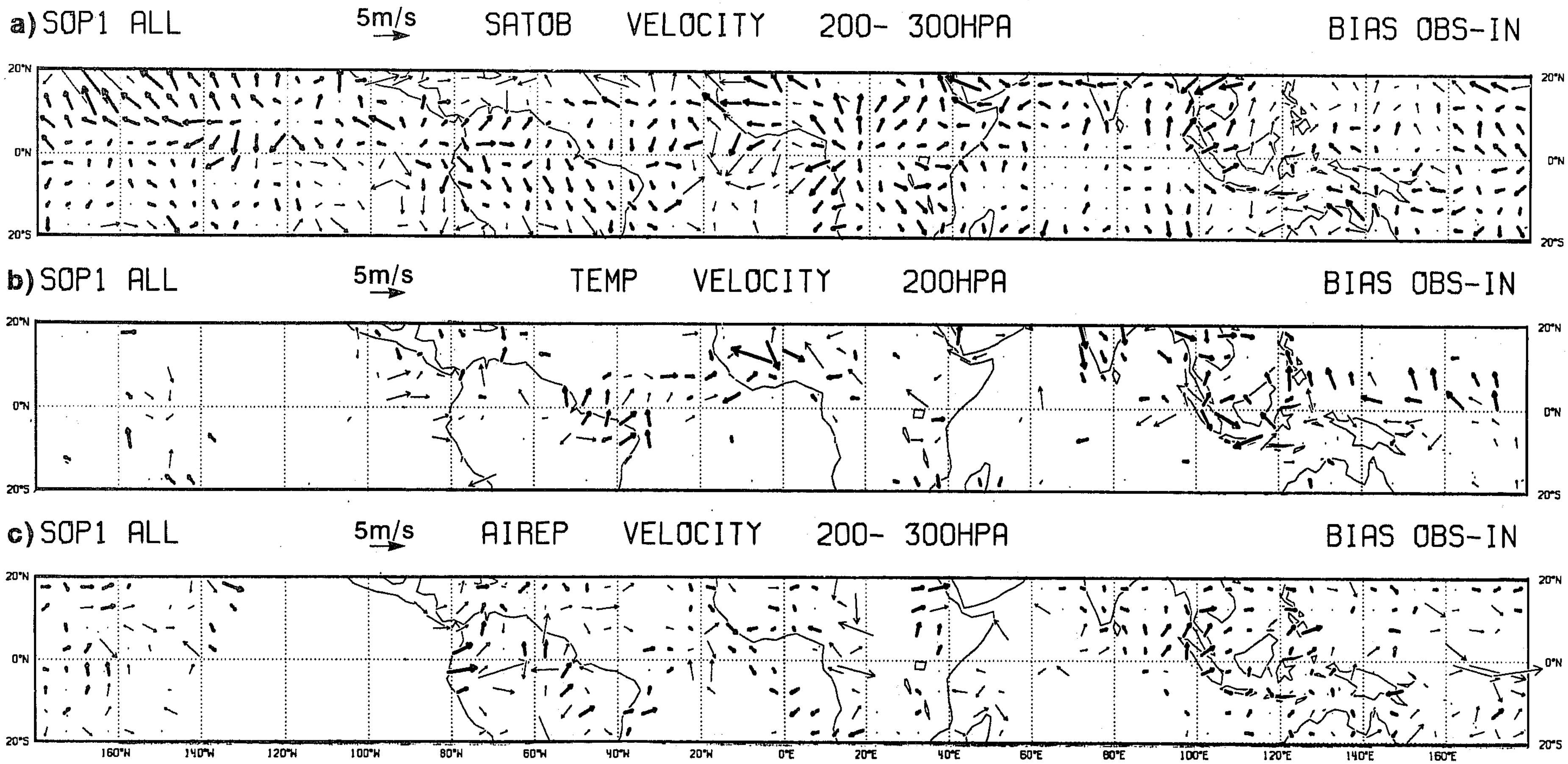

Fig 8 (a) The OB-IN biases for SATOBS for SOP-1 in the 200-300mb layer; (b) The OB-IN biases for TEMPS for SOP-1 at 200 mb; (c) The OB-IN biases for AIREPS for SOP-1 in the 200-300mb layer. The velocity scale is given by the 5m/s arrow.

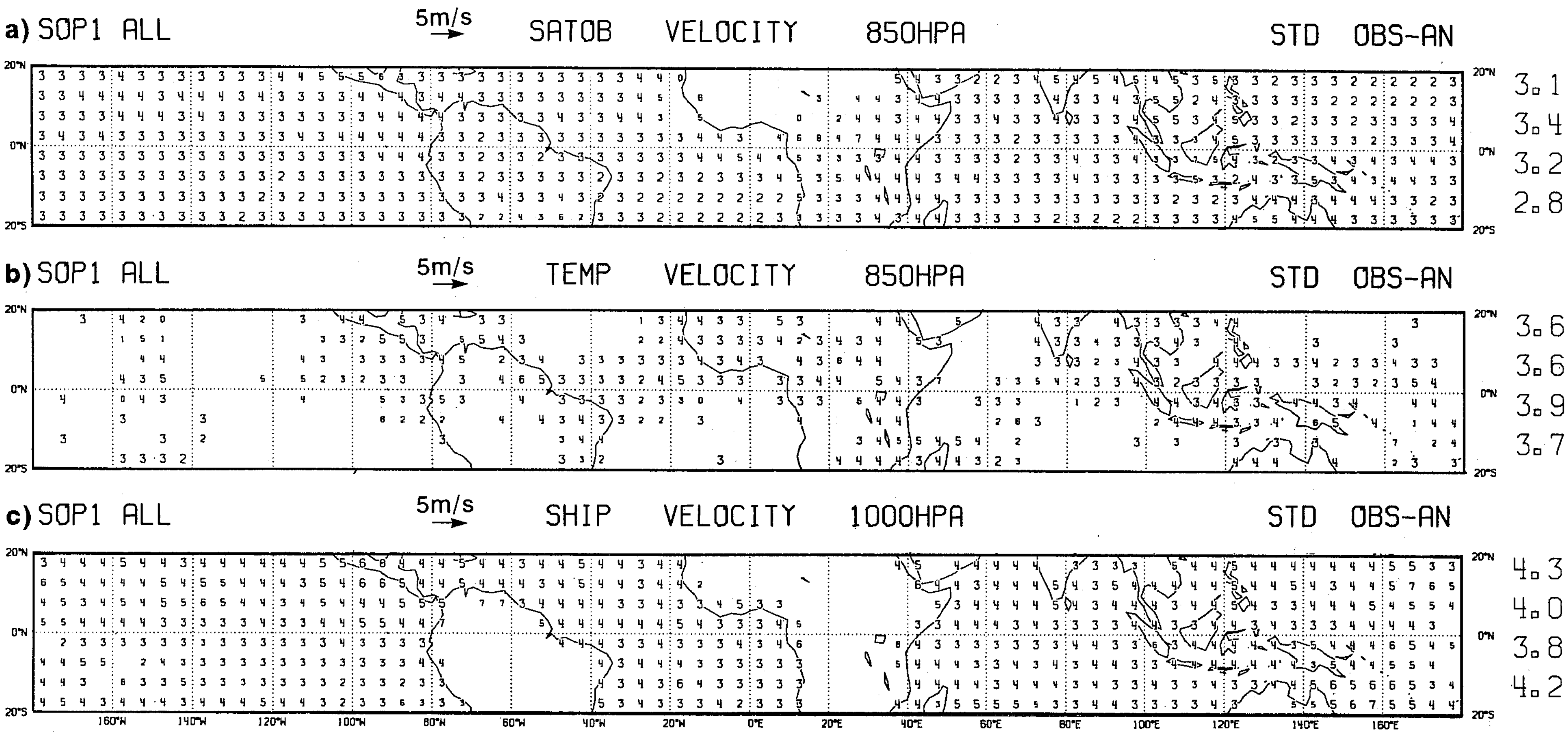

Fig 9 (a) The standard deviation of the OB-AN winds for all analysis times in SOP1 for cloud-track winds below 850mb, calculated by 5 degree boxes. The corresponding calculations for 10-degree latitude zones are shown on the right. (b) The OB-AN standard deviations for SOP-1 for 850mb winds as reported by rawinsondes and pilot-balloon reports. The corresponding calculations for 10-degree latitude zones are shown on the right. (c) The OB-AN standard deviations for SOP-1 for ship winds at 10m. The corresponding calculations for 10-degree latitude zones are shown on the right.

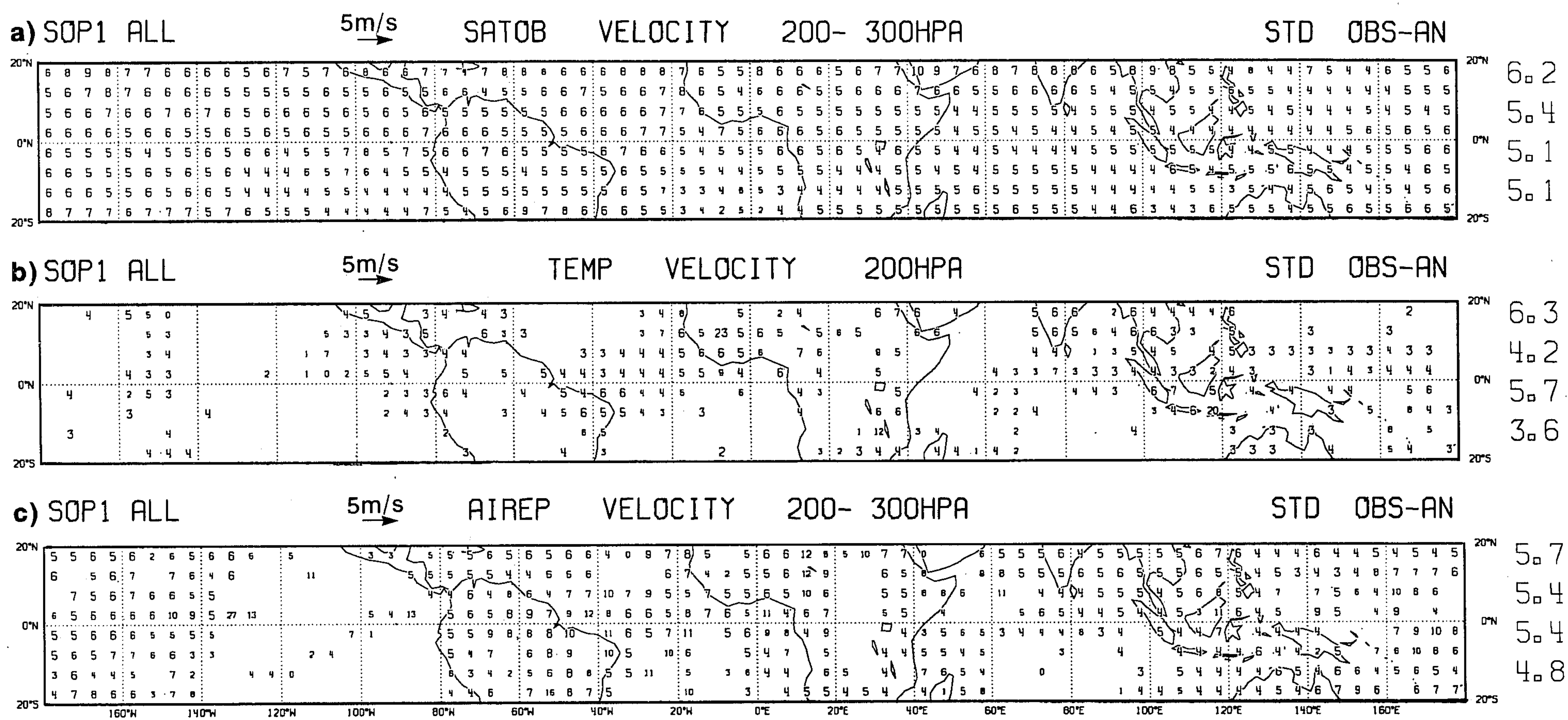

Fig 10 (a) The OB-AN standard deviations for SATOBS for SOP-1 in the 200-300mb layer The corresponding calculations for 10-degree latitude zones are shown on the right. (b) The OB-AN standard deviations for TEMPS for SOP-1 at 200 mb The corresponding calculations for 10-degree latitude zones are shown on the right. (c) The OB-AN standard deviations for AIREPS for SOP-1 in the 200-300mb layer. The corresponding calculations for 10-degree latitude zones are shown on the right.