# Jet Stream Winds: Comparisons of Aircraft Observations with Analyses

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ABSTRACT

Wind measurements have been obtained from commercial aircraft crossing the 1992 winter subtropical jet streams over southwest and east Asia. Comparisons of these data with new, high-resolution analyses from four of the major operational centers show that the peak analyzed winds are still too weak by about 10%. In addition, about 17% of the cases show larger errors in which the analyses substantially miss the location or magnitude of individual jet streaks. Both the aircraft data and the highest-resolution analysis (European Centre for Medium-Range Weather Forecasts, equivalent equatorial quarter-wave grid spacing of 47 km) show evidence of orographically generated gravity waves but differ in their vertical damping.

## 1. Introduction

Global analyses and forecasts of peak winds at the core of jet streams are systematically too weak as determined by comparisons with independent aircraft data (Tenenbaum 1991) and radiosondes (Lyne 1991). This result represents a reversal of problems seen at the upper portions and above jets in earlier general circulation models (Kasahara et al. 1973; Stone et al. 1977; Pitcher et al. 1983; Arpe and Klinker 1986) when compared against analyses. In this paper we report on a new series of measurements using information from commercial aircraft flight data recorders over a wider geographical area containing strong, nearly zonal, jets. Comparisons are made between the peak measured jet stream winds and four major global analyses at equivalent grid spacings of 47–206 km. The analyzed peak jet stream winds are still too weak by about 10%. This value represents a decrease from a 1989 study where the coarser grid resolutions and simpler physical parameterizations then in use produced winds that averaged 15% too weak and had a much larger range of deficits (11%–17%) over southwest Asia (Tenenbaum 1991).

The causes and effects of these errors are significant for several reasons. If the problem is due to sparse or inaccurate observational data, the next generation of possible and planned satellite instruments [Atmospheric Infrared Sounder, NASA (1993a); Laser Atmospheric Wind Sounder, Baker et al. (1995)] may help, but their input will not be available until the turn of the century. If the problem is intrinsic to the resolution of finite grid general circulation models, recent results indicate that increases in horizontal resolution produce decreasing medium-range forecast improvements [A. Hollingsworth, European Centre for Medium-Range Weather Forecasts (ECMWF), 1994, personal communication]. The practical result is that ensemble forecasts rather than further increases in horizontal resolution are the major priority for global-scale models in the near future (McPherson 1994).

At present, no single cause seems to explain the discrepancy in both data sparse and data dense regions. Complicating the problem, especially in data-sparse areas, is the major dependence of the analysis on the first-guess forecast. The independent aircraft data reported here can provide quantitative estimates of errors in the newest analysis systems. But until much larger amounts of data are available, we may not be able to provide definitive explanations.

Tenenbaum (1991) gives a further history of the use of automated aircraft wind reports beyond those manually transmitted in real time via voice radio (AIREPs). Automated transmissions have increased rapidly over the past few years, especially over North America, and their use has produced major benefits for aviation operations (Benjamin et al. 1991, 1993; Bleck and Benjamin 1993). But over the rest of the globe, inaccuracies in the analyzed jets can lead to forecast errors (Lyne 1991; Tenenbaum 1992), biases in fundamental transports such as the Hadley circulation and stratospheric–tropospheric exchange (Albritton et al. 1993), and difficulties for climate-oriented analyses (Schubert et al. 1993).

Section 2 describes the techniques used in this experiment and changes from the 1989 version (Tenenbaum 1991). Section 3 presents our results over the winter ensemble, and section 4 presents some individual cases. In section 5 we show observations of gravity

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TABLE 1. Nominal horizontal resolution of the data as received, and vertical resolution of the underlying forecast model. Note that for spectral data the nominal resolution listed is the equatorial quarter-wavelength of the highest wavenumber. Disagreements exist as to whether four points are sufficient to ''resolve'' a wave. The vertical resolution is the nominal value between 200 and 300 mb. The final columns give the horizontal resolutions and number of levels for the three centers used in the 1989 experiment (Tenenbaum 1991).

| | | Current model | | | | Previous model | |
|---|---|---|---|---|---|---|---|
| Center | Data type | Data format | Horiz. resol. (km) | Levels | Vert. resol. (km) | Horiz. resol. (km) | Levels |
| ECMWF | Spect. | T213 | 47 | 31 | 0.8 | 94 | 19 |
| JMA | Grid | 1.875° × 1.875° | 206 | 21 | 1.6 | — | — |
| NCEP (NMC) | Spect. | T126 | 79 | 18 | 1.3 | 164* | 18 |
| UKMO | Grid | 0.8333° × 1.25° | 92 × 138 | 20 | 1.3 | 208 | 15 |

* The previous NCEP value has been restated to be consistent with the equatorial quarter-wave calculation.

waves both in the aircraft data and in the highest-resolution general circulation model. Finally, section 6 contains a discussion of our results and summarizes our conclusions.

## 2. Techniques and changes

The automated recording systems on modern wide-body aircraft record a wealth of data that are meteorologically useful (Julian and Steinberg 1975). Tenenbaum (1991) describes the capabilities and limitations of these observations. For this experiment, the major changes were to expand the number of cooperating carriers (adding Lufthansa German Airlines and Japan Airlines to British Airways), operational centers {adding the Japan Meteorological Agency (JMA) to the ECMWF, the U.S. National Centers for Environmental Prediction [NCEP, formerly known as the National Meteorological Center; see McPherson (1994)], and the United Kingdom Meteorological Office (UKMO)}, and geographical regions (adding east Asia to southwest Asia). The latter change addressed the possibility that the previous findings over southwest Asia dealt with an area that was unusually limited in the quality and quantity of available data.

The operational analyses considered in this study were obtained at the highest horizontal resolution used internally by each center (see Table 1) on the standard pressure levels. These are not the resolutions at which the centers interchange their analyses and forecasts for World Meteorological Organization comparisons or deliver their forecasts to users. The purpose in retaining the high resolutions was to avoid smoothing the sharp shears associated with the poleward flank of the subtropical jet (see section 4).

Analyses were interpolated in space and time to the aircraft location and observation time. Except over the former Soviet Union, long-haul Boeing 747 aircraft almost always cruise at pressure altitudes nominally equivalent to 31 000, 33 000, 35 000, or 37 000 ft (9449–11 278 m). Checks were made that the linear vertical interpolations did not introduce any significant errors. Because of the nature of airline schedules over southwest Asia, and unlike the Atlantic region, most crossings of subtropical jets are quite near 0000 UTC for both eastbound and westbound aircraft.

Comparisons were made of the peak wind encountered by the aircraft as it crossed the jet with the peak wind seen in the analysis along the aircraft's trajectory. This approach avoided confusing small positional errors of the analyzed jet with errors in the peak strength. For some east Asian flights, an aircraft approaches the jet at a relatively small angle and descends into Tokyo before reaching the jet core. Comparisons with meridional flight paths indicated that these near-zonal flight paths did not bias the results.

Data were collected weekly from British Airways, Japan Airlines, and Lufthansa German Airlines flights crossing jet streams near 0000 UTC on Thursdays from 9 January 1992 through 26 March 1992. The limitation to once per week was due to the costs of acquiring and processing the flight recorder tapes; the choice of Thursday was due to the availability of some twice per week trans-Pacific flights.

The results presented here come primarily from about five British Airways and Japan Air Lines flights per week that passed close to the southwest Asian and east Asian subtropical jet streaks near 0000 UTC on Thursdays. Of these, data from the 36 flights that had clean recordings were used in the ensemble and case study results of sections 3 and 4.

## 3. Ensemble results

Figure 1 illustrates a typical flight path and depicts observed and analyzed (ECMWF) wind speeds for southwest Asia. The figure presents the analyzed and observed wind speeds as a color map; for the subtropical jet, wind directions rarely depart more than 20° from westerly. The agreement is reasonable but shows two features that recur: the aircraft observes a sharper shear on the poleward flank and shows a finer structure in and near the jet core. Figure 2 gives the ensemble results of aircraft minus UKMO-analyzed winds for the entire 1992 winter for both east Asia and southwest

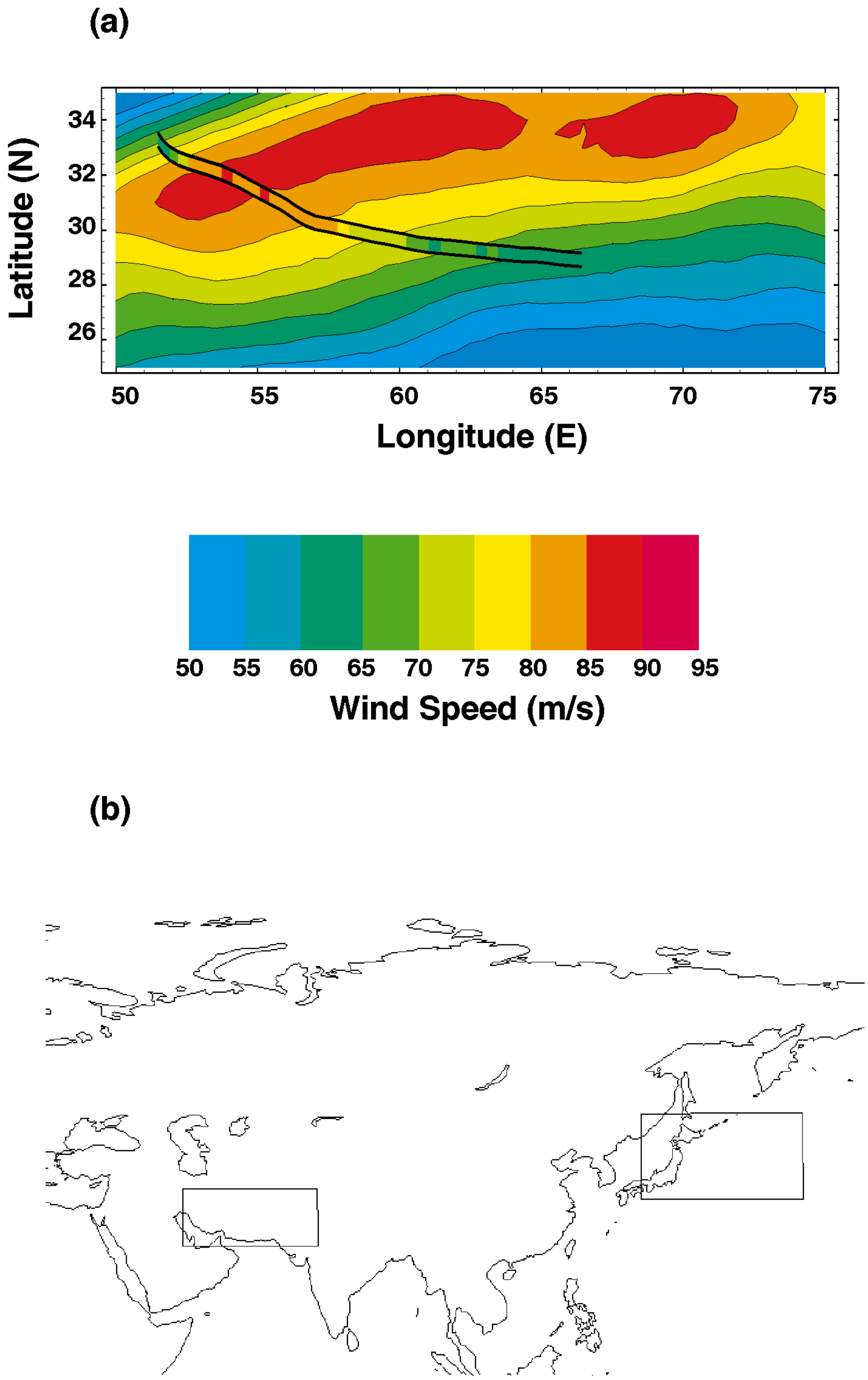



FIG. 1. Wind speeds interpolated to the level of a flight at 37 000 ft (approximately 217 mb) over south Asia at 0000 UTC 27 February 1992. Contour map is from ECMWF analysis. Flight track depicts data from a British Airways flight data recorder.

Asia. For both regions, there is clear evidence of the analyses being biased toward weaker wind speeds. As illustrated by the presentation versus flight level (labeled in hundreds of feet), there is no obvious variation with height. An analogous plot versus aircraft wind speed (not shown) shows a weak dependence of the error on wind speed consistent with a constant percentage rather than absolute wind error.

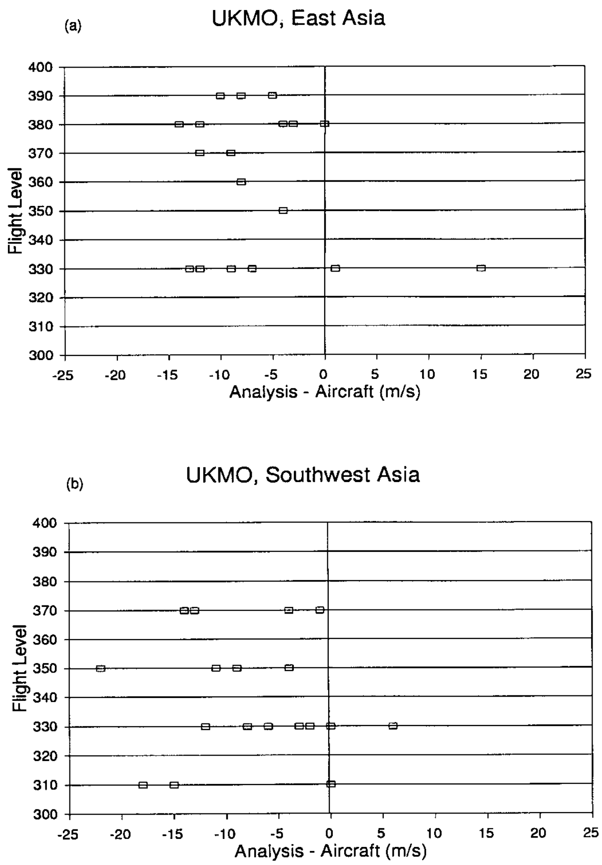



FIG. 2. Ensembles of peak jet stream wind in the UKMO analysis minus the peak wind encountered by the aircraft versus standard flight level (in hundreds of feet). Ensembles are for east Asia and southwest Asia for data taken at 0000 UTC on Thursdays from 9 January 1992 to 26 March 1992. Analyses have been interpolated vertically and horizontally to aircraft position.

Table 2 summarizes the available results for all four major operational centers (ECMWF, JMA, NCEP, UKMO). The overall weighted-average deficit of analyzed wind speeds is about 10%, with much less scatter than the corresponding results from the 1989 comparison derived from lower-resolution models (Tenenbaum 1991), which had biases of −11%, −17%, and −17% for ECMWF, NCEP, and the UKMO, respectively. (JMA did not participate at that time.)

Probably the key conclusion is that for a given operational center and for the average of all four centers both southwest and east Asia have weak analyses, although there is less bias in the more data-dense east Asian region. There is also some indication of a dependence on some combination of vertical resolution and equivalent grid spacing, with ECMWF (nominal equatorial quarter-wave resolution of 47 km, T213 spectral truncation) having the least error. It should be noted that ECMWF also has the latest cutoff time with data for the 1200 UTC analysis accepted until about 2000 UTC, though aircraft data normally arrive promptly.

## 4. Case studies

As discussed in Lyne (1991), the ensemble bias is partially reduced in operational use at the UKMO by a simple multiplicative factor for wind speed in transmitted wind forecasts (1.06 in 1992 and 1.04 currently). These numbers, derived from comparisons of models with radiosondes, are applied to all winds—not just strong jets—and are intended to decrease the errors in total integrated headwinds over long-haul flights, not just in the peak wind speed. NCEP is currently planning to introduce such a correction (J. Alpert 1995, personal communication).

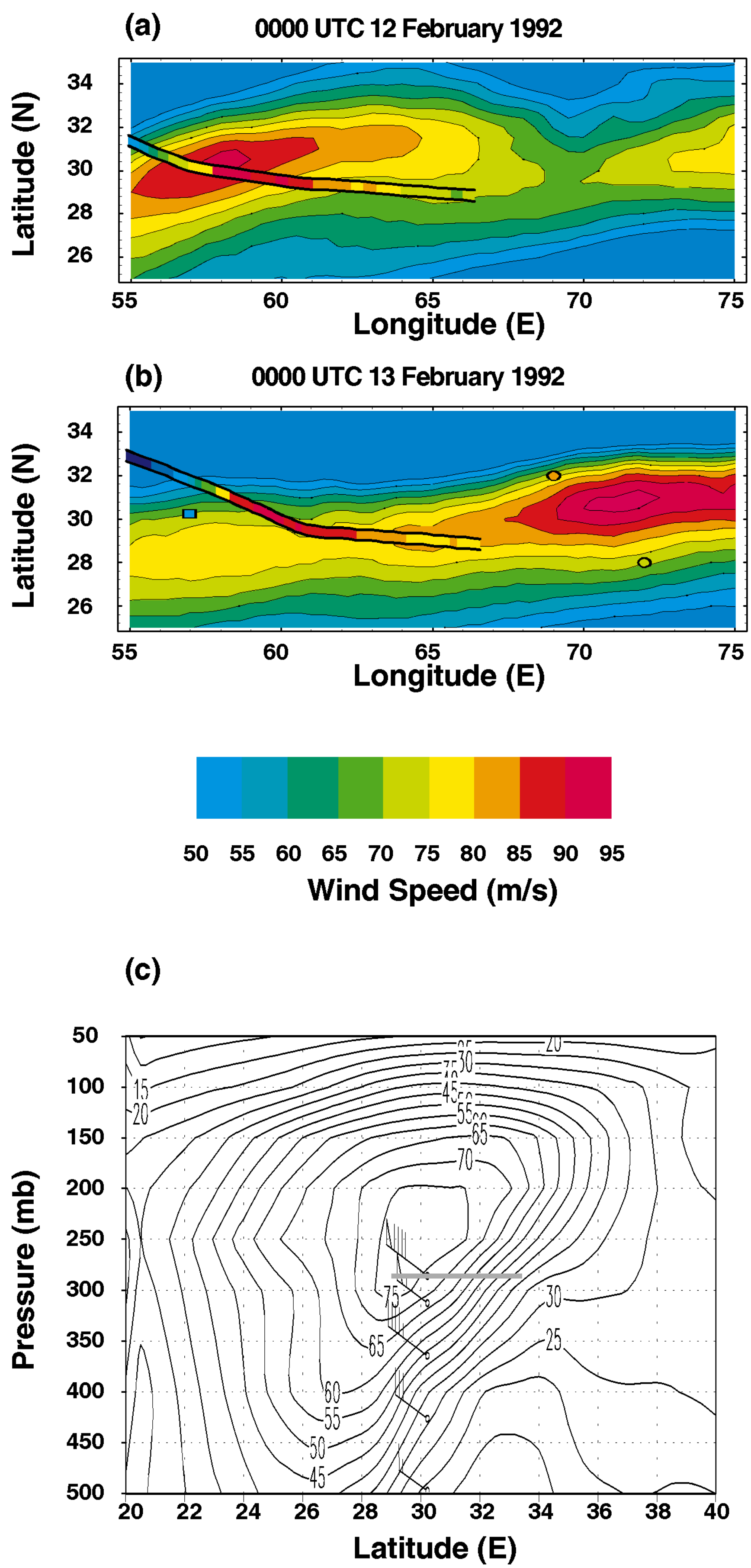
If one applies mean UKMO corrections from Table 2 to the data in Fig. 2, there are still 4 (out of 18) outliers greater than two standard deviations. In this section we examine some of those cases and also examine the detailed shape of the jet stream as determined by the aircraft traverses and contrast it with the shape displayed in the analyses.

The forecast and analysis for 0000 UTC 13 February 1992 over southwest Asia was a major problem for three of the four participating operational centers (all but NCEP). Using the analysis from ECMWF (Fig. 3), we can see that a jet streak at 300 mb tracked through the region of interest. Examination of earlier and later ECMWF analyses for 0000 UTC on 11 and 14 February 1992 (not shown) indicated a consistent time-dependent behavior with similar (though weaker peak speeds) for the other centers.

The only nearby conventional observations (one radiosonde and two AIREPS) available on 13 February are plotted on the figure and were consistent with the presence of a streak at 70°E and gave no indication of the streak at 60°E. The radiosonde at 30°N, 57°E illustrates a common problem in this region: weak winds at the top levels of radiosonde ascents (see Radford 1987 and Fig. 4 in Tenenbaum 1991). In the absence of other nearby data, the analysis draws toward such weak winds. However, it is clear from the aircraft flight data recorder winds in Fig. 3 that the analysis either tracked the streak too rapidly eastward or significantly underestimated its longitudinal extent. (Substantial checks established that the aircraft data came from the correct date and other AIREPS going into the UKMO first

TABLE 2. Ensemble averages of peak analyzed wind minus peak wind encountered by aircraft as a percent of the aircraft wind. Ensemble is overall available data taken at 0000 UTC on Thursdays from 9 January 1992 to 26 March 1992. Analyses have been interpolated vertically and horizontally to aircraft position. NCEP data for east Asia were not readily available.

| Region/Center | ECMWF | JMA | NCEP | UKMO | Average |
|---|---|---|---|---|---|
| Southwest Asia | −9.0% | −13.5% | −9.0% | −12.1% | −10.9% |
| East Asia | −7.2% | −7.8% | * | −8.8% | −7.9% |
| Average | −8.1% | −10.7% | −9.0% | −10.4% | |
| Weighted average | | | | | −9.6% |


(a)
0000 UTC 12 February 1992
Latitude (N)
34
32
30
28
26
55
60
65
70
75
Longitude (E)
(b)
0000 UTC 13 February 1992
Latitude (N)
34
32
30
28
26
55
60
65
70
75
Longitude (E)
50 55 60 65 70 75 80 85 90 95
Wind Speed (m/s)
(c)
Pressure (mb)
50
100
150
200
250
300
350
400
450
500
20 22 24 26 28 30 32 34 36 38 40
Latitude (E)
15
20
30
45
55
65
70
75
65
60
55
50
45
30
25

guess, and analysis on that date indicated that there were indeed serious problems as illustrated in Table 3.)

A separate type of problem is illustrated in Fig. 4. Here, we have an analysis over east Asia and a plot of data from an aircraft departing Tokyo for New York. The region shown is just east of Japan and downstream of the dense radiosonde network (50 stations) of China, Manchuria, and Korea. Data from Japanese radiosondes and available aircraft are also indicated. The analysis is reasonably consistent with the observations and shows the normal merging of the polar and subtropical jets. But even with this amount of upstream data and ECMWF's T213 resolution, the aircraft data indicate a clear minima between the two jets that the first guess cannot produce.

A third result illustrated by individual cases involves the representation of horizontal and vertical shears, primarily on the poleward flanks of the jet. Data assimilation procedures (Daley 1991) must balance two conflicting goals: representing the smallest-scale features appropriate to the model resolution, while smoothing observational data that deal with phenomena that occur on even smaller scales.

A sampling of the strong horizontal shears recorded by the aircraft throughout the ensemble of section 4 shows significant discrepancies. When the southwest Asian jets are strong ($>70$ m s$^{-1}$, about one-third of the ensemble), aircraft observe shears two to three as large as those shown by the analyses.[1] For two cases over southwest Asia, very strong jets were detected by aircraft making an approximately perpendicular crossing. Table 4 presents data for the 0000 UTC 13 February and 27 February 1992 cases. They show shears that bring the advective timescale close to the Coriolis timescale (Daley 1991, 187–188) and could excite (or require additional filtering against) inertia–gravity waves.

## 5. Orographically induced gravity waves

The effects of orographic gravity waves in general circulation models were the subject of intense work during the mid-1980s, when parameterizations were added to the models (Boer et al. 1984; Palmer et al. 1986; Helfand et al. 1986). Each of the approaches taken had some tunable parameters, but there was a general sense that inclusion of the waves had a positive effect. While gravity waves can exist without orographic gravity wave parameterizations, the aircraft data provides a very useful observational check. Explicit comparisons can be made in regions with and without substantial variations in orography.

In the course of making the comparisons described in sections 3 and 4, the analyzed jets were studied using improved versions of the three-dimensional graphics rendering shown in Fig. 4 of Tenenbaum (1991). Close examination of the ECMWF analyses near where the flight paths crossed the subtropical jet over southwest Asia showed evidence of gravity waves in both the first-guess forecast and the resulting analyses. Figure 5a shows a three-dimensional view of the 0000 UTC 27 February 1992 case. Note particularly the lobe extending downward from the jet core above southern Iran. Figure 5b shows the rather unusual perspective of the 55 m s$^{-1}$ isosurface as *viewed from below.* Note the clear evidence of a series of slightly curved wavefronts (bright ridges) on the bottom of the analyzed isosurface. The lower-resolution analyses of the JMA, NCEP, and the UKMO do not show such waves.

Further details of the analyzed waves are illustrated in Figs. 6a and 6b, which show vertical slices through the ECMWF analysis of the jet at 29°N for 0000 UTC 16 January and 27 February 1992. Waves of moderate amplitude (several meters per second) are present at the lower levels of the figure (500 and 400 mb) and decrease with height. Similar plots of 6- and 12-h forecasts (not shown) show the same undulations. Examination of the underlying topography of southern Iran shows an almost washboardlike pattern of mountains,

[1] The flight paths for this experiment in east Asia are too closely parallel to the jet axis to give a clean signal for the shear.

TABLE 3. Details of the peak wind analysis history in the vicinity of 30°N, 60°E for the 0000 UTC 13 February 1992 case. Three of the four operational centers had particular difficulties with this case. The UKMO processing can be summarized as follows below.

| Source | Wind speed |
|---|---|
| 12 February 1992 | |
| first guess | 120 kt (62 m s$^{-1}$) |
| Lufthansa report | 180 kt (93 m s$^{-1}$) |
| resulting analysis | 130 kt (67 m s$^{-1}$) |
| 13 February 1992 | |
| winds encountered by BA aircraft (Fig. 3b) | 185 kt (95 m s$^{-1}$) |

FIG. 3. Time sequence of 300-mb wind speeds over southwest Asia at 0000 UTC (a) 12 February 1992 and (b) 13 February 1992. Contour maps are from analyses of the ECMWF. Flight tracks depict data from British Airways flight data recorders. Note that the core of the analyzed jet streak has advected eastward in contradiction to the aircraft data on 13 February 1992. The limited conventional data near 300 mb—two AIREPs (ovals) and one radiosonde (rectangle)—are superimposed for 13 February. (c) Vertical cross section for 0000 UTC 13 February 1992 of the wind speed analysis and vertical profile of the radiosonde report at 57°E (all available levels above 500 mb; highest is near 310 mb). The shaded bar and report near 290 mb indicate the location and peak wind speed from the independent (slightly downstream) aircraft data. Wind direction is indicated as for a horizontal plot. See left rectangle in Fig. 1b for approximate geographical location.

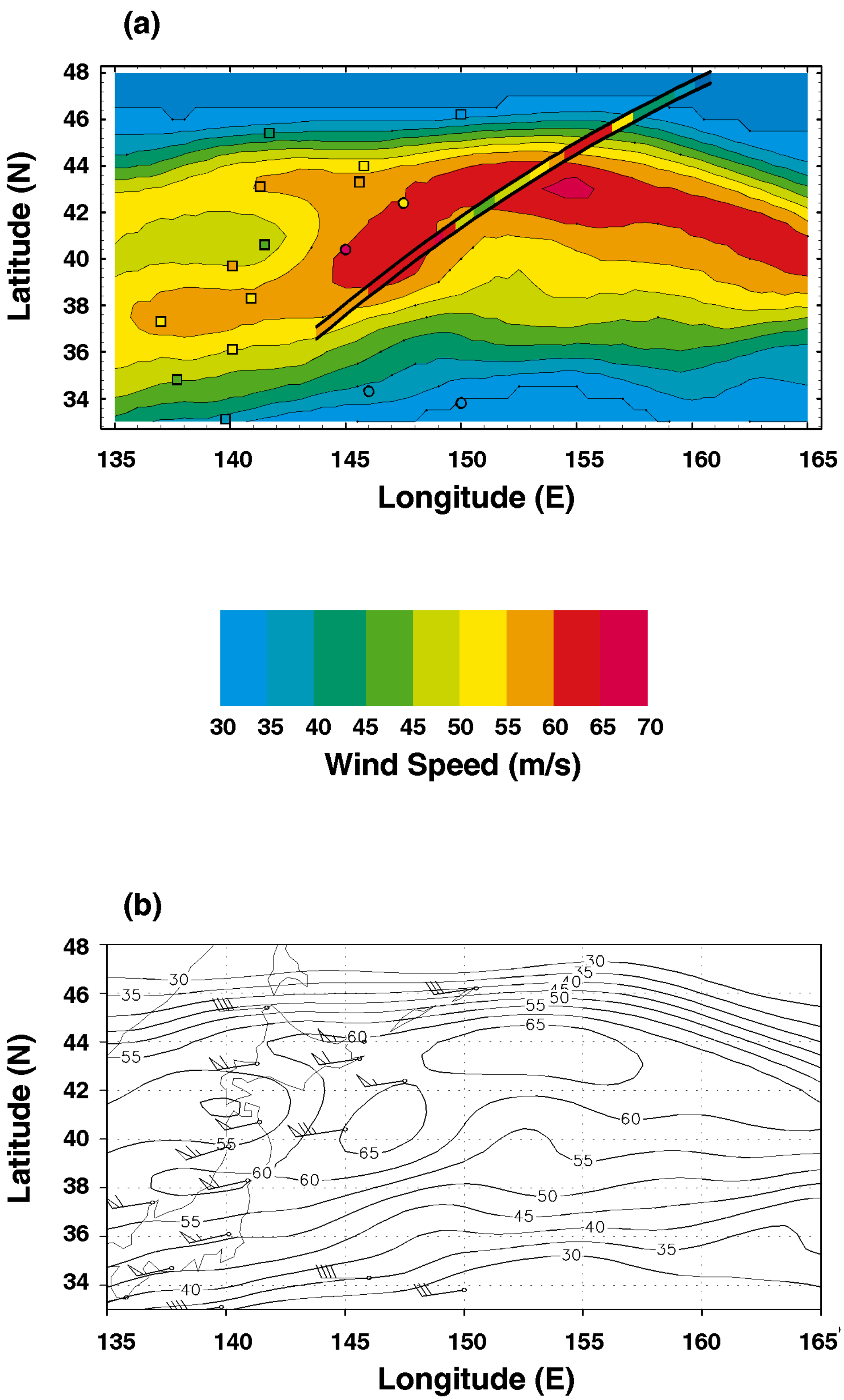



FIG. 4. ECMWF wind speed analysis just east of Japan at 250 mb for 0000 UTC 26 March 1992. (a) Analysis plus color-coded wind speeds from flight data recorders and conventional data near 250 mb including radiosondes (rectangle) and AIREPs (ovals). (b) Analysis plus barbs indicating wind speed and direction for the conventional data. Note the separation of the polar and subtropical jet streaks at the left and their merger at the center. The aircraft data indicates that the actual streaks remained separated. See also the map in Fig. 1 for depiction of exact geographical location. Small differences in contour locations indicate variability due to differing contouring routines. Small differences in wind speeds of conventional data reflect the different plotting conventions of color-coded contour maps and station models (bin boundary or midpoint at the 5 m $s^{-1}$ interval). Units are m $s^{-1}$.

TABLE 4. Peak values of strong shears ($< -30 \times 10^{-5}$ s$^{-1}$) on the poleward flank of two strong (>70 m s$^{-1}$) subtropical jets as measured by the aircraft and as seen in the ECMWF analysis. The ECMWF analysis is taken from a full-resolution (T213) dataset.

| | Peak shear ($10^{-5}$ s$^{-1}$) | | |
|---|---|---|---|
| Date (1992) | Aircraft | ECMWF analysis | Ratio |
| 13 February | −56 | −24 | 2.3 |
| 27 February | −41 | −12 | 3.4 |

with wavelengths close to the 280 km of Figs. 5b, 6a, and 6b.

Figures 6c and 6d show the aircraft traverses corresponding to the analyses of Figs. 6a and 6b. (The major airway over India is almost a straight east–west line at 29°N in this area.) While the locations of the wave peaks are not identical to those shown in the analyses, there is clear observational evidence of waves with amplitude and wavelength similar to those in the ECMWF analysis. Note that unlike the amplitudes seen in the analyses, the amplitude observed by the aircraft is still significant at 300 and 217 mb (approximate flight levels of 31 000 and 37 000 ft, respectively). Examination of ECMWF jet analyses and aircraft observations elsewhere shows smooth lower ''surfaces'' of jets over oceans. Only just east of the Tibetan plateau (35°N, 45°E) are there other waves in both the analyses and aircraft data.

## 6. Discussion

Our primary conclusion is that the four major operational centers have analyzed subtropical jet streaks that average about 10% too weak. While this value represents an improvement from the previous experiment whose deficit averaged 15%, the weak jets persist in spite of the increased model resolutions and various other improvements. Although there is some geographical dependence, the weak jet streaks appear in both data-dense and data-sparse regions, implying that the problem is not dominantly due to the observational data. There is a slightly stronger indication of a resolution dependence, with the highest-resolution ECMWF results (nominal equatorial quarter-wave resolution of 47 km) showing the least error.

Two further steps are possible concerning resolution effects. First, both JMA and the UKMO have higher-resolution regional models in areas including strong subtropical jet streaks. These need to be compared with the corresponding global results. Second, additional aircraft data at high resolution (~25 km) should be obtained over the western Atlantic and Pacific Oceans. One problem is that the resulting comparisons may still be dominated by the ''picket fence'' pattern of the existing aircraft reports (oceanic flights report wind and temperature data every 10° of longitude).

Beyond the biases in the overall results, individual cases present a real challenge for all global models. Their relevance is both for the effect on aviation users of upper-air forecasts and analyses [unscheduled diversions, Tenenbaum (1992)] and for the light that they may shed on the underlying problems in current models. The 0000 UTC 13 February 1992 cases stumped three of the four operational centers and, at least for some centers, illustrated the ''stiffness'' of current analysis systems with respect to utilizing very strong wind reports. In addition, the horizontal shears of very strong southwest Asian jets (about one-third of the ensemble) seem too weak by a factor of 3. In extreme cases, such gradients pose the problem of ascribing mesoscale-type gradients to objects that we want correctly depicted by a global model.

(a)

(b)

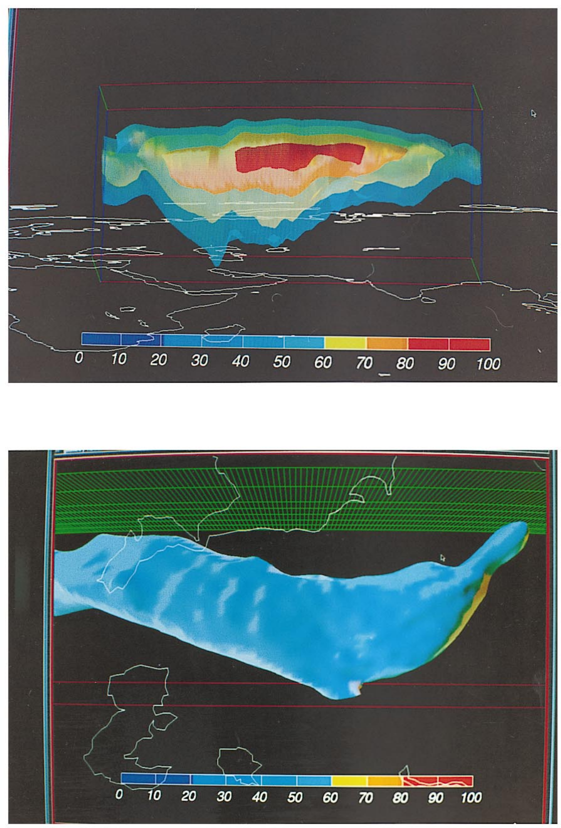



FIG. 5. (a) Partially transparent three-dimensional rendering of portions of the ECMWF analysis of the subtropical jet over southwest Asia for 0000 UTC 27 February 1992. Isosurfaces of 85, 75, 65, and 55 m s$^{-1}$ indicated by red, orange, green, and blue surfaces, respectively. Latitude (20°–40°N) and longitude (30°–90°E) bounds indicated by quasi-horizontal rectangles; pressure bounds extend from 500 mb at the bottom to 50 mb at the top. Note the downward lobe with undulating lower isosurfaces over southern Iran. (b) View *looking up through the earth's surface* at the bottom of the 55 m s$^{-1}$ isosurface of the subtropical jet over southwest Asia. Persian Gulf and south are at top, Caspian Sea and north are at the bottom, and east and west are normal. Data are from an ECMWF analysis for 0000 UTC 27 February 1992 (same case as Fig. 1). Note the slightly curved (bright) ridges and valleys whose wavelength, about 280 km, is consistent with the ridgelike orography of southern Iran.

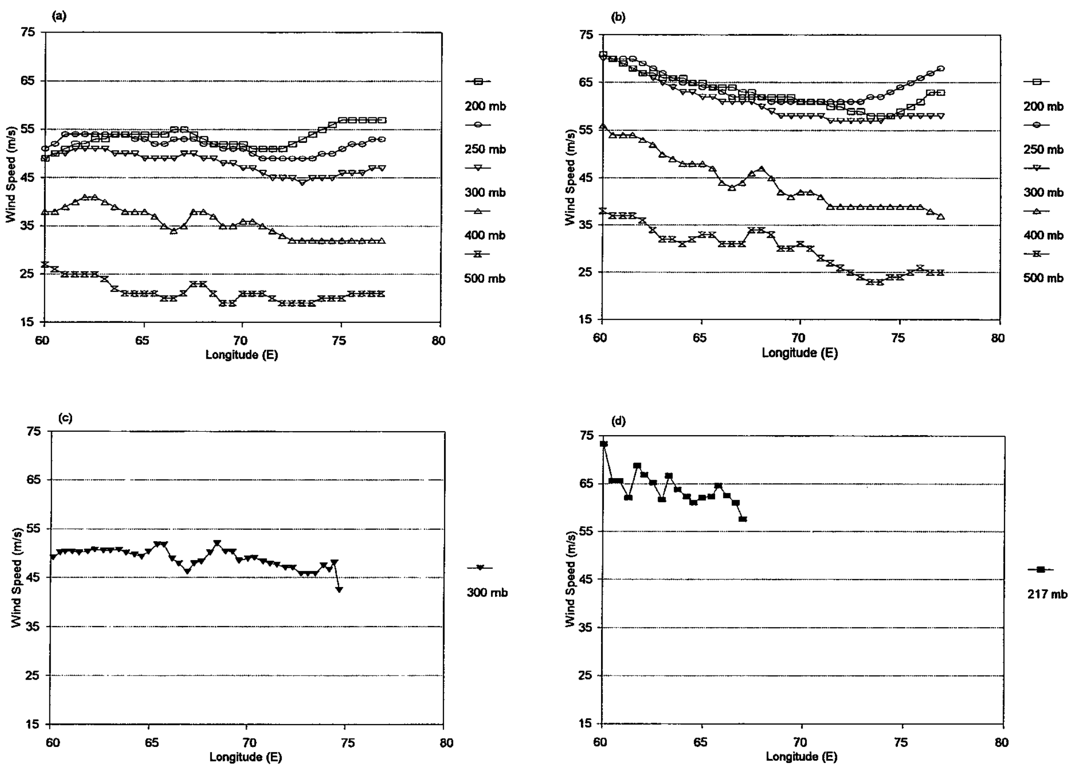



FIG. 6. Wind speed on vertical slices through the subtropical jet stream over southwest Asia at 29°N. ECMWF analyses for (a) 0000 UTC 16 January 1992 and (b) 0000 UTC 27 February 1992. Data is displayed at levels from 200 to 500 mb. Aircraft data at (c) 300 mb for 0000 UTC 16 January 1992 and (d) 217 mb for 0000 UTC 27 February 1992 corresponding to the analyses in (a) and (b).

The orographic gravity waves seen in the highest-resolution analysis (ECMWF) and the aircraft data are consistent with multiple studies of this phenomenon. While their parameterizations have been extensively discussed, our results indicate that the model's underlying first guesses are approaching the horizontal resolutions where gravity waves can be explicitly seen and are not necessarily artifacts of the limited horizontal resolutions (G. Kelly, ECMWF, and E. Kalnay, NCEP, 1995, personal communications). While three of the models fail to show direct evidence of gravity waves, the ECMWF model does but displays vertical damping of the waves inconsistent with the aircraft data. Further study is needed using multiple aircraft at different heights. The three-dimensional images of the jet streaks provide an effective way of examining the wave structure and locations.

Finally, we are left with the key question of what causes the problem of weak analyzed jet streams. If the inaccuracy is a consequence of limited resolutions, it may be difficult to correct. The initial results of the T213 ECMWF model (nominal 47-km equatorial quarter-wave resolution) raise the question of whether further increases in horizontal resolution are the optimal use of additional computing resources in a global model. The role of vertical resolution also needs investigation. A third possibility is that the tuning of the orographic gravity wave parameterizations in models that still use them excessively slows the jets.

The consequences of the negative bias in analyzed winds appear in several areas. Many of the studies of transports depend on accurate knowledge of the Hadley circulation. If analyses of the subtropical jets are wrong, the accuracy of such transports are called into question. Similarly, the work on global angular momentum budgets at seasonal timescales (Rosen and Salstein 1983; Rosen et al. 1990) and stratosphere–troposphere exchange (Hoerling et al. 1993) is dependent on correctly analyzed winds. Aviation users of upper-air forecasts have been helped by the simple step of a multiplicative bias correction. But, in a number of more sophisticated uses of the upper-air results, such an approach is not feasible.

Two directions for further work are clear. First, the resolution dependence of biases should be checked in existing higher-resolution regional models. Second, the flight data recorder observations represent a wealth of useful information even though they are not available in real time. A subsequent experiment (the Global Aircraft Data Experiment starting in 1995) will obtain and archive this data on a routine daily basis as part of the National Aeronautics and Space Administration's (NASA) Atmospheric Effects of Subsonic Aircraft and Mission to Planet Earth programs (NASA 1993b). Finally, a portion of the data can and should be incorporated in real time onto the Global Telecommunications Network by overcoming some of the financial and technical problems that have already been solved for North America by the ACARS program (Benjamin et al. 1993).

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