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COMPARATIVE ANALYSIS OF OPERATIONAL FORECASTS VS ACTUAL WEATHER CONDITIONS IN AIRLINE FLIGHT PLANNING

SUMMARY

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Project Manager, Robert Steinberg, Aircraft Propulsion Division, NASA Lewis Research Center, Cleveland, Ohio 44135

16. Abstract

A study was conducted on the impact of more timely and accurate weather data on airline flight planning with the emphasis on fuel savings. This summary report discusses the results of each of the four major tasks of the study. Task I compared airline flight plans based on operational forecasts to plans based on the verifying analyses and found that average fuel savings of 1.2 to 2.5 percent were possible with improved forecasts. Task II consisted of similar comparisons but used a model developed for the FAA by SRI International that simulated the impact of ATC diversions on the flight plans. While parts of Task II confirmed the Task I findings, inconsistency with other data and the known impact of ATC suggested that other Task II findings were the result of errors in the model. Task III compared segment weather data from operational flight plans with the weather actually observed by the aircraft and found the average error could result in fuel burn penalties (or savings) of up to 3.6 percent for the average B747 flight. In Task IV an in-depth analysis of the weather forecast for the 33 days included in the study found that significant errors existed on 15 days. Wind speeds in the area of maximum winds were underestimated by 20 to 50 kts., a finding confirmed in the other three tasks.

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TABLE OF CONTENTS

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1. INTRODUCTION

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PRC Speas, assisted by David R. Bornemann Associates, Inc., has conducted analyses of flight plan data for the National Aeronautics and Space Administration-Lewis Research Center under Contract #NAS3-22748.

The objective of these analyses was to assess the potential improvement in fuel savings which may be possible from improved meteorological data. Flight plans calculated from prescribed input parameters and meteorological data sets were used as quantitative indicators of differences in fuel burn and other relevant parameters. Flight plan data were provided through the cooperation of two airlines which will be referred to as "BLUE Airlines" and "RED Airlines" throughout this report in order to maintain anonymity.

The work program under this contract was divided into four tasks, each of which involved various comparisons of flight plans, flight tracking, or wind and temperature data developed from weather forecasts or actual analyses under different sets of conditions. The final report consists of four volumes, each presenting the findings for one of the tasks, and this volume which summarizes the entire study and its findings.

2. SUMMARY OF RESULTS

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2.1 OVERVIEW

The results of this study have shown that the potential fuel savings from using more timely and accurate weather data in flight planning and route selection are conservatively estimated to be between 1.2 and 2.5 percent. This occurs when comparing a flight plan based on the operational Suitland forecast and on a route compatible with the North Atlantic tracks with one based on the actual weather (verifying analysis) using the minimum fuel track routing. Further results from actual flights show that savings may be greater.

In order to verify the accuracy of the Suitland forecast, flight plans developed on it were compared with actual data observed by the aircraft (and averaged over 10 degree segments). The results showed that the average difference between the forecast and observed wind speed was 9 kts. without considering direction, and the average difference in the component of the forecast wind parallel to the direction of the observed wind was 13 kts. - both indicating that the Suitland forecast under-estimates the wind speeds. The Root Mean Square (RMS) vector error was 30.1 kts. The average absolute difference in direction between the forecast and observed wind was 26 degrees and the temperature difference was 3°C. These results indicate that the forecast model as well as the verifying analysis used to develop comparison flight plans was a limiting factor and that the average potential fuel savings or penalty are up to 3.6 percent depending on the direction of flight. These potential savings are entirely attributable to improved forecast accuracy since the routes were the same.

Data are also developed which show that the track selection methodology of many airlines operating on the North Atlantic may not be optimum and that the interpolation process (or lack of it) in developing proper wind and temperature fields is an important source of error.

Additional data show that the most fuel efficient routes between South America and Europe do not include the fixed ATC track.

An in-depth analysis of differences between the forecast and verifying analysis during the 33 day test period was conducted. Fifteen of the 33 days showed significant errors in the operational forecast. On these days forecast wind speeds in the area of maximum winds were in error by at least 20 to 25 kts. and sometimes by more than 50 kts. All of these days were in the summer or fall and one might expect errors of larger magnitude during the winter.

2.2 OBJECTIVES AND METHODOLOGY

This study consisted of four data analysis tasks.

- Task I compared fuel burn, flight time, air miles and ground miles on flight plans that were based on the U.S. National Weather Service (NWS) forecasts with corresponding plans based on the NWS verifying analyses valid at the time of the forecasts to determine the fuel savings that were possible through improved weather forecasts. The comparisons involved flight plans that were produced on the RED and BLUE Airlines flight planning systems.

- Task II consisted of similar comparisons to those in Task I but was based on flight plans and flight tracking data that were produced by a different system developed at SRI International for the Federal Aviation Administration. The flight tracking data simulated actual flight operations and accounted for flight plan deviations such as those required by air traffic constraints.

- Task III compared segment winds and temperatures from flight plans based on NWS forecasts to the actual winds and temperatures observed by aircraft that operated those flights.

- Task IV used flight plan segment wind and temperature differences from Task I as indicators of forecast errors which were then analyzed further to determine their probable cause, extent and significance.

Even though the data sources and methodology differed in each Task, all four tasks resulted in conclusions that clearly suggested there is potential for further fuel savings through more accurate weather forecasts and flight plans.

2.3 KEY FINDINGS

Some key findings from the various tasks are summarized below:

- Task I comparisons between B747 flight plans on operational routes (which were probably not minimum fuel tracks) based on the NWS forecast and plans on the same routes based on the verifying analysis showed that fuel savings per flight on eastbound North Atlantic routes would average 462 kg (151 gal.) if the forecasts and verifying analyses were identical, or in other words, if the forecasts were perfectly accurate. Savings for westbound flights were negligible. Differences in fuel burn between the plans on the forecast and the plans on the verifying analysis were always positive eastbound and negative westbound, suggesting that wind speeds are always underestimated in the forecast.

- Further Task I analyses showed that if operational constraints on the use of minimum time tracks and optimum flight levels were not imposed by the ATC system the potential savings per flight increases to 1048 kg (345 gal.) or 1879 kg (618 gal.) depending on the direction of flight.

- Based on analyses of tracks selected in 144 cases it was determined that airlines whose track selection methodology is based on minimum time rather than minimum fuel, and airlines that select a preliminary minimum time track at a constant flight level before optimizing the flight level, do not select the optimum fuel NAT track 45 to 50 percent of the time.

- Comparisons of track selections between Amsterdam and Caracas on a single fixed route that had been used by one airline and on eight other routes laid out by NASA showed that the original route was optimum only six times out of 60 cases. The average fuel burn penalty for being on this route was 1,054 kg (347 gal.) per flight.

- Task II comparisons of flight plans based on the NWS forecast with corresponding plans based on the verifying analysis but using the SRI model, resulted in the comparable finding that fuel savings of 364 kg (122 gal.) were possible for eastbound B747s on existing operational North Atlantic routes if the forecasts were equal to the verifying analysis.

- Task II comparisons involving flight tracking data found that actual fuel burn and flight times were always higher than planned, in either direction, and even when the same weather data set was used. This suggests that either there is an error in the flight tracking algorithm or that a penalty is incurred due to traffic congestion and resolution of ATC system conflicts in addition to the penalty incurred from inaccurate weather forecasts. Since the flight tracking model output resulted in more diversions than is known to be the case, it was concluded that there is an error in the flight tracking algorithm.

- Based on analysis of 2,430 flight segments when the flight plan winds and temperatures based upon the NWS forecast were compared in Task III to actual data observed by the aircraft, the average difference between the forecast and observed wind speed was 9 kts., the direction difference averaged 26 degrees and the average temperature difference was 3°C. The average difference in the component of the forecast wind parallel to the direction of the observed wind was 13 kts. In the worst case (when the wind is always from the direction with maximum impact on the direction of flight) this 13 kt. error results in fuel burn and time penalties of up to 15 minutes and 2,835 kg (932 gal.) of fuel for the average B747 flight. These flight segments were from operational routes which were not minimum fuel tracks and may not have been in the area of maximum wind and thus actual errors may be larger.

- Although BLUE and RED Airlines data agreed that the absolute value of the average temperature errors was 3°C, BLUE found the temperatures warmer than forecast while RED found them colder than forecast. Similarly, BLUE found the wind direction forecast error toward decreasing azimuthal directions while RED found errors toward increasing azimuth eastbound and decreasing westbound, indicating that weather data interpolation errors probably exist in one or both flight planning systems.

- The Task IV analysis showed that significant forecast errors existed on 15 of the 33 days included in the study. In particular:

  - Wind speeds were underestimated by at least 20 to 25 kts. and sometimes up to 50 kts. in the area of maximum wind on 14 days. Speeds were underestimated on most other days, as well, but to a lesser extent.

  - There is a tendency to repeat the same forecast errors from prog to prog even though the intervening analysis showed clearly that the errors had occurred.

  - The Task IV analysis also showed that some perceived forecast errors may be the result of inadequacies in the weather data interpolation techniques used in the airline computer flight planning systems.

In Tasks I and III findings were presented separately for data based on the BLUE and RED flight planning systems which had different sample sizes. The figures given above represent weighted averages of the results from both data sources.

3. BACKGROUND

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The work conducted in this study was in support of the NASA Commercial Aircraft Fuel Savings Program which was developed to investigate the potential fuel savings which could be provided by an improved meteorological data base. Other portions of the program have investigated the impact of various factors, such as data collection procedures, on the quality and timing of the meteorological forecasts.

The Commercial Aircraft Fuel Savings Program was conceived by NASA in 1978 partly to take advantage of numerous additional data that were then being collected as a result of a major international global experiment that was being conducted at that time. Prior to that time, sufficient data were never available on a global scale to study systematically the potential improvement that could result were significant quantities of additional data added to the analysis and forecast process.

During this global experiment in 1979 a number of DC10 and B747 aircraft were equipped with Aircraft Integrated Data Systems (AIDS). AIDS is an onboard data processing and storage system which is used by airlines to monitor aircraft and engine performance data. For this experiment AIDS was used to collect data on position, altitude, temperature, wind velocity and time. The data were stored on magnetic tape for ground processing.

Since U.S. and foreign carriers cooperated in the experiment, AIDS flights operated throughout the world, although the largest concentration of additional data were collected in the North Atlantic area.

On certain days during 1979 NASA collected AIDS data and corresponding airline flight plans for the subsequent analyses conducted in this project. AIDS data were provided to the U.S. National Weather Service which reran its numerical analysis model for those days to provide a new analysis output which had been enhanced by the additional AIDS data. NASA also retained on magnetic tape (and in hard copy) copies of the original operational forecasts issued on those days to airlines for flight planning.

The plan was to use the airline flight plans as a sensitive indicator of the differences between various meteorological data sets, measuring fuel burn and flight time or winds and temperatures. Comparisons could be made, for example, between the original operational forecast and the AIDS enhanced analysis valid at the time of the forecast or between flight plans based on the forecast and the raw AIDS data. It was expected that the study would show that enhancing the analysis with the AIDS data would result in improved forecasts and, in turn, more accurate flight plans and fuel savings.

Much of the data used in this study were developed later by NASA through the cooperation of the RED and BLUE Airlines. NASA provided these airlines with magnetic tape copies of the original NWS operational forecasts and analyses reruns, in effect, simulating a real time transmission of the current Aviation Digital Data. The airlines were also supplied with flight plan inputs, prepared by NASA, and designed to control variables such as routings and aircraft weights so as to eliminate unwanted effects of these variables that are not solely the result of the weather data.

The flight plans calculated on these data by the RED and BLUE Airlines, using raw AIDS data for positional and altitude information, the original operational flight plans used on those days in 1979 for the AIDS flights, and flight plans produced by the SRI International flight planning and flight tracking simulation model were all retained on magnetic tape and provided as input to the analyses conducted in this project.

4. DISCUSSION OF TASK I RESULTS

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Task I involved various comparisons of groups of flight plans that were based on the operational NWS forecast (the Nine Level Primitive Equation Model) and plans that were based on the NWS verifying analysis (the Flattery Analysis Model) valid at the time of the forecast. All of the flight plans used in the comparisons were produced by the RED or BLUE Airlines flight planning systems based upon inputs prepared by NASA. These inputs exercised optional control over such parameters as routing, flight level, cruise speed and payload so that the affect of these variables could be isolated or eliminated and differences between the flight plan groups could be attributed properly to differences in the weather data. Ten to 20 of the routes were selected to correspond to actual flights that were operated on that day by aircraft equipped with an Aircraft Integrated Data System (AIDS). (AIDS provided for collection and storage of actual weather observation data on magnetic tape for subsequent processing.) The remaining flight plans were computer generated and did not necessarily represent any flights actually flown.

Weather and flight plan data sets from 31 days in August through November and two from January, were used in the Task I analysis. In order to randomize the data set selection, data from all Mondays and Fridays during this period were used.

Four categories of flight plan types were considered in Task I. These were:

(1) Flight plans based on operational forecasts on routes that were flown by AIDS equipped aircraft;

(2) Flight plans based on operational forecasts on minimum time/minimum fuel routes;

(3) Flight plans based on the verifying analysis valid at the times of the forecasts in (1) and (2) and on the same routes used in (1);

(4) Flight plans based on the verifying analysis valid at the times of the forecasts in (1) and (2) but on the minimum time/minimum fuel track determined from the verifying analysis.

Differences in fuel burn, flight time, air miles, ground miles and the ratio of air miles to ground miles for B747 aircraft were determined for the following five comparisons between the above groups:

Case 1 - Group 1 minus Group 3

Case 2 - Group 2 minus Group 4

Case 3 - Group 1 minus Group 2

Case 4 - Group 3 minus Group 4

Case 5 - Group 1 minus Group 4

In addition to the above comparisons, an analysis was conducted of track selections by the RED and BLUE Airlines flight planning systems from the available North Atlantic Organized Tracks between New York and Amsterdam.

An analysis of track selections from a group of fixed tracks between Amsterdam and Caracas was also conducted.

The principal findings for each case are summarized in the following subsections. The detailed findings are presented in Volume I of the final report by direction of flight, region of the world, and data source (RED or BLUE flight planning system), and include the standard deviation, variance, 90 percent confidence limits and mean value for each group of comparisons. Since the sample sizes vary widely the findings for some regions are less significant statistically and may be misleading. Therefore, only the fuel burn results for the North Atlantic and for the total will be presented here. In some of the comparisons all, or nearly all, of the plans are for North Atlantic flights.

4.1 CASE 1

The first case compared recreated AIDS flights on the forecast weather to recreated AIDS flights on the verifying analysis. Since all other flight plan parameters (route, flight level, etc.) were held constant, differences between the flight plans reflected differences between the weather data sets and, in this case, the potential fuel savings that would result if the forecast and analysis were equal, or in other words, if the forecast were perfectly accurate.

The number of flight plan comparisons in the sample and the average differences (forecast plan value minus actual plan value) in fuel burn were:

BLUE System Flight Plans	Sample Size	Burn Difference
All eastbound flights	222	369 kg
North Atlantic eastbound flights	109	569 kg
All westbound flights	305	-140 kg
North Atlantic westbound flights	143	-295 kg

RED System Flight Plans	Sample Size	Burn Difference
All eastbound flights	95	384 kg
All westbound flights	147	-371 kg

The positive differences eastbound, and negative differences westbound indicated that wind speeds are generally underestimated in the NWS forecast model.

4.2 CASE 2

Case 2 compared minimum time tracks on the forecast to minimum time tracks on the verifying analysis and, as such, was quite similar to Case 1 except for the use of different routes. The objective was to determine the potential fuel savings that would result if the forecast were perfect and if carriers could use random tracks.

The number of flight plan comparisons in the sample and the average differences in fuel burn in this case were:

BLUE System Flight Plans	Sample Size	Burn Difference
All eastbound	229	739 kg
North Atlantic eastbound	199	815 kg
All westbound	231	-409 kg
North Atlantic westbound	202	-322 kg

RED System Flight Plans	Sample Size	Burn Difference
All eastbound	29	475 kg
All westbound	29	-324 kg

4.3 CASE 3

Case 3 compared flight plans on routes actually flown by AIDS flights on the forecast weather to the corresponding minimum time track on the forecast weather. The objective was to show the potential fuel savings that could result if carriers were free to fly the minimum time track.

Based on the raw data the sample sizes and the average differences or savings in fuel burn were:

BLUE System Flight Plans	Sample Size	Burn Difference
Eastbound North Atlantic	36	511 kg
Westbound North Atlantic	49	1978 kg

RED System Flight Plans	Sample Size	Burn Difference
Eastbound North Atlantic	7	1842 kg
Westbound North Atlantic	10	1760 kg

Since this case compared recreated AIDS flights to minimum time tracks, the BLUE data were distorted due to the use of direct routings from origin to oceanic entry point and due to flight level differences (See Section 8.2 for further discussion). Estimates of the effect of these routing and flight level differences were computed and the estimated BLUE differences after these adjustments were applied were:

	Burn Difference
Eastbound	1061 kg
Westbound	1397 kg

4.4 CASE 4

Case 4 was identical to Case 3 except that both the AIDS flights and minimum time tracks were based on the verifying analysis.

Fuel burn differences using the raw data were:

BLUE System Flight Plans	Sample Size	Burn Difference
Eastbound North Atlantic	35	666 kg
Westbound North Atlantic	48	2096 kg

RED System Flight Plans	Sample Size	Burn Difference
Eastbound North Atlantic	7	1931 kg
Westbound North Atlantic	10	1937 kg

After applying an adjustment for the routing and flight level differences, the BLUE savings were:

	Burn Difference
Eastbound	1216 kg
Westbound	1515 kg

4.5 CASE 5

Case 5 combined the conditions of Cases 3 and 4 and compared AIDS flights on the forecast weather to minimum time track flights on the verifying analysis. The objective was to show the combined savings from improved forecasts and from eliminating ATC restrictions on the use of the minimum time track.

Again, based on the raw data alone, the potential savings were:

BLUE System Flight Plans	Sample Size	Burn Difference
Eastbound North Atlantic	36	1311 kg
Westbound North Atlantic	49	1594 kg

RED System Flight Plans	Sample Size	Burn Difference
Eastbound North Atlantic	6	1989 kg
Westbound North Atlantic	10	1220 kg

Applying the adjustment to the BLUE data results in savings of:

	Burn Difference
Eastbound	1861 kg
Westbound	1013 kg

4.6 NORTH ATLANTIC TRACK SELECTION

Analysis of flight plans run on each of the North Atlantic Organized Tracks at each available flight level on each of 30 days in both directions tested three hypotheses, each of which is followed by some airlines and is incorporated in their track selection algorithms.

1) On 40 out of 84 "days" (30 eastbound and 30 westbound for BLUE, and 16 eastbound and 8 westbound for RED) the minimum time track was not coincident with the minimum fuel track. Thus, airlines whose track selection is based on time rather than fuel are on the wrong track 45 percent of the time.

2) In 28 out of 60 cases the minimum time track selected at FL330 or FL350 was not the minimum fuel track at optimum altitude. This indicates that airlines that select a preliminary minimum time track at a constant flight level and then optimize for fuel in the flight plan are on the wrong track 47 percent of the time and incur an average fuel burn penalty of 248 kg each time they are on the wrong track. (This is based on comparisons of flight plans using the NWS models operational in 1979. Data from other tasks in this study indicate that the penalty would be larger if actual data were compared.)

3) In 19 out of 60 cases the minimum fuel track on the verifying analysis was not the same track as the minimum fuel track on the forecast. This is contrary to the beliefs of many carriers who feel that the weather changes so slowly that the best track does not change between the forecast and the verifying analysis even though the time and fuel burn on that track might change.

4.7 AMSTERDAM-CARACAS TRACKS

One airline, and possibly more, had been using a single fixed route between Europe and the Caribbean. NASA laid out eight additional routes and ran flight plans on each one, in each direction for 30 days.

The original fixed route proved to be the best one only six times out of the 60 cases. The average fuel burn penalty for being on this route was 1054 kg per flight.

5. DISCUSSION OF TASK II RESULTS

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In Task II comparisons were conducted between various categories of flight plans and flight tracking data that were produced by a simulation system developed at SRI International for the Federal Aviation Administration. Based upon a given set of weather data the system produced flight plans and flight tracking data. Flight tracking data simulate the actual flight tracks of all aircraft operating on a given weather data set and provide such features as the rerouting of some flights as necessary to resolve ATC conflicts. The weather data used were the same NWS forecasts and verifying analyses used in Task I but covered fewer days.

Four categories of data were analyzed. These were:

(1) Flight plans based on an operational forecast;

(2) Flight tracking based on the flight plans in (1) but using the weather from the verifying analysis valid at the time of the forecast;

(3) Flight plans based on the actual weather valid at the time of the forecast used in (1);

(4) Flight tracking based on the flight plans in (3) and using the actual weather from the verifying analysis.

As in Task I comparisons were made of differences in fuel burn, flight time, air miles, ground miles and the ratio of air miles to ground miles between the following flight plan and flight tracking categories:

Case 1 - Group 1 and Group 2

Case 2 - Group 1 and Group 3

Case 3 - Group 2 and Group 4

Case 4 - Group 3 and Group 4

Case 5 - Groups 1 and 3 with the actual airline flight plans from Task I

Comparisons were made for entire flights and for flight segments and were presented by direction of flight, region and by aircraft type groups such as B747s, DC10/L1011s, or B707/DC8s. The detailed findings are presented in Volume II of the final report.

The results of the comparisons for B747 aircraft for each of the five cases are summarized in the following subsections. Findings for other aircraft type groups were comparable but only the B747 data are presented here for consistency in comparisons to the Task I findings which were exclusively for B747s.

5.1 CASE 1

The first set of comparison data were developed by subtracting the flight tracking values on the verifying analysis from the flight plan values developed on the forecast weather. The conditions in this case were similar to those in Case 1 of Task I in that the comparison measured potential fuel savings that could result if the weather forecast were equal to the verifying analysis. Only the model, or source of the flight plans, was different and the actual effect of ATC diversions was included.

The numbers of B747 flight plan comparisons in the sample and the average differences in fuel burn were:

	Sample Size	Burn Difference
Eastbound North Atlantic	167	-775 kg
Eastbound Polar	36	-810 kg
Westbound North Atlantic	235	-1278 kg
Westbound Polar	39	-451 kg

The negative values eastbound are contrary to the Task I findings and would imply that wind speeds are always overforecast, or that the flight tracking fuel burn is always higher because of ATC diversions.

For westbound flights these findings are consistent with the Task I results but they are contrary to the eastbound results and imply that aircraft always burn more than flight plan regardless of whether they are flying against or with a wind forecast error. One must conclude that the differences are not entirely weather related and must be greatly influenced by the conflict resolution algorithm of the flight tracking model.

5.2 CASE 2 FINDINGS

In the second case flight plans on the forecast weather were compared to flight plans on the verifying analysis. Except for the use of a different flight planning model as the data source and except for the fact that new NAT tracks were selected on the verifying analysis, and thus routings could be different, this analysis was also similar to Case 1 of Task I.

The numbers of B747 flights compared and the average fuel burn differences for Case 2 were:

	Sample Size	Burn Difference
Eastbound North Atlantic	159	374 kg
Eastbound Polar	33	318 kg
Westbound North Atlantic	154	-237 kg
Westbound Polar	24	-420 kg

The positive differences eastbound and negative differences westbound were consistent with and confirmed the Task conclusion that wind speeds were normally underestimated, and indicate that negative data sets in Task II Case 1 were probably the result of the flight tracking algorithm.

5.3 CASE 3 FINDINGS

Case 3 comparisons were developed by subtracting the times, burns and other parameters on the flight tracking data from Group 4, based on the verifying analysis, from the corresponding Group 2 flight tracking data which were also based on the verifying analysis but used flight plan inputs based on the forecast.

Since the same weather data were used in each case this comparison was a measure of the potential fuel savings (or penalty) that could result from improvements in the flight plan or track inputs to the flight tracking simulator.

The findings for B747 comparisons in Case 3 were:

	Sample Size	Burn Difference
Eastbound North Atlantic	159	273 kg
Eastbound Polar	33	96 kg
Westbound North Atlantic	154	243 kg
Westbound Polar	24	-79 kg

Positive values, both eastbound and westbound, suggest that either fuel burn penalty from the ATC system is less when an improved forecast is used in flight planning or that errors were introduced by the flight tracking algorithm.

5.4 CASE 4 FINDINGS

Case 4 compared data from flight plans based on the verifying analysis to flight tracking data developed from the same verifying analysis.

Since the same weather was used, differences found between these two groups of plans were unrelated to weather but represented a measurement of the potential effect of improved NAT track selection and the conflict resolution simulations of the flight tracking model.

The findings for the B747 comparisons in Case 4 were:

	Sample Size	Burn Difference
Eastbound North Atlantic	160	-927 kg
Eastbound Polar	33	-1034 kg
Westbound North Atlantic	154	-599 kg
Westbound Polar	24	-76 kg

The negative differences in both directions suggest that actual flight times, fuel burns and air miles are always greater than planned even when the plans were based on the verifying analysis, and that these penalties are the result of conflict resolution and traffic congestion in the ATC system or in the flight tracking algorithm.

5.5 CASE 5 FINDINGS

The objective of the final comparison in Task II was to determine the flight parameter differences between the flight plans developed by the SRI model for this task and the corresponding actual airline flight plans from Task III. However, since takeoff weights, flight levels and routings were quite different, average burn differences of more than 10,000 kg per flight were found. Since these variables could not be controlled, it would be difficult to attribute the differences to any particular cause and these data were judged to be of relatively little value.

6. DISCUSSION OF TASK III RESULTS

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The Task III analysis compared actual wind and temperature observations taken by AIDS equipped aircraft during eight months of 1979 with data from the flight plans used by those flights. The flight plans were based upon the NWS forecasts valid near the time the flights operated and were computed on the RED or BLUE Airlines flight planning systems. Flight plans for flights of the other airlines that use the BLUE Airlines system were also included in this analysis.

The objective of the Task III analysis was to determine differences that existed between the forecast winds and temperatures and those actually observed by the aircraft. In Task I, differences were determined (measured by fuel burn, flight time and air miles) between the forecast and the actual as represented by the NWS forecast and analysis models, after the data were subjected to the editing, smoothing, and other adjustments inherent in the model.

Computer programs were developed to extract the wind and temperature data from the flight plans and AIDS tapes, reduce them to comparable flight segments, and produce statistics on the differences between the forecast and actual winds and temperatures. While the flight plan winds and temperatures were normally already available as averages of ten degree longitude segments, the AIDS observations were typically spaced at 200 km intervals and averages for 10 degree segments had to be developed.

A cubic spline function was used to represent the AIDS flight's wind direction, speed, temperature and latitude as a continuous function of longitude along the flight path. The discrete values of these parameters were then determined for each five degree meridional crossing - i.e., 50W, 45W, 40W, 35W, etc. Average values for the ten degree segment were then determined weighting the midpoint twice the weight of each endpoint.

Segment data were checked for matches of month, day, flight number, origin, destination and flight level. Segments for which the AIDS flight did not match the operational flight plan were discarded.

6.1 MAGNITUDE OF FORECAST DIFFERENCES

Matching data from AIDS flights and flight plans were found for 2,430 segments distributed regionally as follows:

	BLUE Airlines	RED Airlines
Eastbound North Atlantic	394	358
Westbound North Atlantic	696	736
Eastbound Polar	4	79
Westbound Polar	13	109
Eastbound Mid-Atlantic	9	
Westbound Mid-Atlantic	32	

Differences between the flight plans and AIDS data per flight segment, and thus between the forecast and the observed, are summarized below:

	BLUE Airlines	RED Airlines
Average Algebraic Difference		
Wind Direction	-5 deg	+1 deg
Wind Speed	-9 kts	-5 kts
Temperature	+2°C	+1°C
Average of Absolute Values of Differences		
Wind Direction	29 deg	20 deg
Wind Speed	14 kts	13 kts
Temperature	3°C	3°C
Average Difference in Component of Forecast Wind Parallel to Observed Wind	16 kts	8 kts
RMS Vector Error	33 kts	24 kts

Using data from Task I on average North Atlantic flight times and fuel burns, it was determined that in the worst case (when the wind is always from the direction with maximum impact on the direction of flight) this error results in fuel burn and time penalties of up to 15 minutes and 2,835 kg of fuel for a B747 flight. This fuel burn penalty, or potential savings if the forecast were perfect, amounts to 3.6 percent of the fuel burn for the flight.

Since the criteria for matching AIDS flights and flight plans resulted in some 70 to 80 percent of segments being rejected, a supplemental analysis was conducted with relaxed criteria to expand the size of the sample. In this second run segments with flight level differences of plus or minus 2,000 feet between the flight plan and AIDS data were not rejected. This resulted in a sample of 1,788 BLUE Airlines segments and 1,282 RED Airlines segments for a total of 3,070 segments. Even though the sample increased by 72 percent the average forecast error only changed by 1.08 degrees on wind direction, 0.1 kts on speed, and 0.34°C on temperature, leading to the conclusion that the original sample was large enough to be representative of the real world even though many data had to be rejected.

6.2 SIGN OF FORECAST DIFFERENCES

Since the average algebraic differences between the forecast values and the observed values were determined by subtracting the observed value from the forecast value, the algebraic sign of the differences provided further data on the forecast errors.

For the North Atlantic region the means of the algebraic differences between the operational flight plan and the AIDS data were:

	Temperature (°C)	Wind Direction (deg)	Speed (kts)
BLUE Airline			
Eastbound	-2.28	-5.35	-8.27
Westbound	-2.53	-4.17	-8.97
RED Airline			
Eastbound	+1.97	+1.94	-6.39
Westbound	+1.69	-2.04	-4.24

For both airlines the average wind speed differences were always negative, meaning the AIDS winds were stronger and implying that wind speeds were underestimated which confirms the findings of the other tasks in this study.

Negative temperature differences mean temperatures were warmer than forecast and the findings on temperature were somewhat incongruous. Even though both airlines' data agreed that the temperature forecasts were in error by approximately 3°C, the BLUE Airlines data showed the temperatures warmer than forecast while the RED data implied temperatures were colder than forecast (positive differences). Regarding wind direction, negative differences mean the forecast wind is from a lower azimuthal direction than the actual wind, or in other words, considering that the average wind direction should be from 270 degrees, negative differences suggest actual winds more northwesterly than forecast and positive differences suggest actual winds more southwesterly than forecast. On wind direction, the BLUE Airlines differences were always negative while the RED Airlines differences (for the larger North Atlantic sample) were positive eastbound and negative westbound. No information available to PRC Speas suggests an explanation for these latter two incongruous findings and it is suspected that they are the result of features peculiar to the weather data interpolation techniques in use by the RED or BLUE Airlines or both.

7. DISCUSSION OF TASK IV RESULTS

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7.1 OBJECTIVE AND ANALYSIS METHODOLOGY

In the Task IV analysis, differences between flight plan winds and temperatures based on the forecast and on the verifying analysis from Task I were used as indicators of dates and geographic areas for which significant forecast errors may have occurred. The objective of Task IV was to review available forecasts and verifying analyses valid at the forecast time so as to explain forecast errors which occurred and to discuss their significance.

Flight plan segments with wind direction differences greater than 30 degrees, speed differences greater than 20 kts., or temperature differences greater than 5°C, between the plan on the forecast and the plan on the analysis, were designated as segments with forecast errors. More stringent criteria were tried at first but it resulted in some 19,000 forecast error segments which were considered to be too numerous to be analyzed with meaningful results.

Many of these "error segments" were widely scattered or isolated geographically and of little significance. Others were clustered and consistent with other adjacent error segments. Since the objective of Task IV was to comment on significant forecast errors, the isolated error segments were ignored, while those that appeared in patterns of synoptic scale or large areal extent were identified for further analysis.

7.2 IDENTIFICATION OF FORECAST ERRORS

For those dates and geographic regions so identified, other data provided by NASA were reviewed. These normally consisted of the National Meteorological Center (NMC) 250 mb. forecasts and analyses valid at 0000Z on the day under review and 0000Z on the following day. 250 mb. level analyses prepared by Delta Airlines were also used for some days.

The RED and BLUE Airlines data from Task I initially identified forecast errors on 31 of the 33 days included in the study. In Volume IV of the final report a summary is presented for each day which gives the number of RED and BLUE Airlines flights, the number of error segments, the areas in which forecast errors occurred and a discussion of the extent and significance of the errors.

Further review of the data revealed an inconsistency in the RED and BLUE Airlines data from Task I.

A substantially higher number of error segments were found by RED Airlines even though it operated fewer flights. For the BLUE Airline there were 853 flights and 908 error segments for an average of 1.06 per flight. For the RED Airline 262 flights encountered 858 error segments for an average of 3.2 per flight. If the Mid East segments are excluded the BLUE Airlines error segments are reduced to 528 for 651 flights, or an average of 0.8 per flight.

Since both airlines used the same weather data, it is obvious that there are differences in their interpolation algorithms since only one detected apparent "forecast errors" when both operated flights through the same area.

Further investigation showed that the RED Airlines winds were often completely incompatible with either the forecast or the verifying analysis. Wind direction errors of up to 180 degrees occurred on days, and in geographic areas, on which the BLUE Airlines data showed few or zero errors.

It was decided that some error in the data interpolation or flight planning algorithm in the RED system was causing an apparently erroneous identification of error segments.

When the BLUE data alone were considered, 10 of the 33 days were found to have forecast errors of significant magnitude and areal extent. For three additional days, the BLUE Airlines error segments indicated relatively minor forecast errors but, upon visual inspection of the forecast and analysis charts, it was determined that significant errors existed but were not detected by the BLUE Airline flights which were not routed near the forecast error area.

Even though most of the forecast errors indicated by the RED flight plans were discarded because they were not consistent with the other data, on two days the errors indicated by RED Airlines were confirmed by visual inspection of the charts and were judged to be significant.

Thus, between the RED and BLUE data, 15 of the 33 days were found to have significant forecast errors.

7.3 FINDINGS

7.3.1 Forecast Errors

Data for the 15 days identified two types of repetitive and significant errors. These were underestimated wind speeds, and repetition of forecast errors.

Underestimated Wind Speeds

A persistent error found throughout the analysis was the underestimation of wind speeds. In 14 of the forecast error situation the forecast maximum winds were at least 20 to 25 kts. and sometimes more than 50 kts. lighter than actual. Wind speeds further away from the core were proportionately in error out to the 70 kt. or 50 kt. level where the errors become insignificant. Since the actual value of the maximum wind speed and the lateral extent of the "significant" or stronger winds varied from day to day it is not possible in summary to quantify this finding further.

Wind speed forecast errors were also found on five additional days but these were judged to be less significant errors because of their lesser magnitude and extent.

Repetition of Forecast Errors

In the analysis it was noted that apparent forecast errors were not corrected on subsequent forecasts. Review of the forecasts issued 12 or 24 hours later showed that errors such as the wind speed errors noted above were carried from prog to prog even though the intervening analysis showed many actual observations of data that were in disagreement with the forecast. A forecast, for example, that showed a maximum wind isotach of 90 kts. would be followed by another with a 90 kt. maximum isotach value even though winds of 125 to 135 kts. were observed at the valid time of the prog. Sometimes, the same situation would have occurred 24 hours earlier and 24 hours later, as well, with the forecasts giving no indication of the existence of the stronger winds.

This repetition of the forecast errors was confirmed on five days of the 33 reviewed. There were indications that forecast errors were repeated on many of the other days but it was not possible to confirm this since data were only retained for the days involved in the study, and thus, data for the adjacent forecast periods were not always available.

Location of Synoptic Features

Even though there were frequent errors in wind speed forecasts, as noted above, the forecasts of the location, movement, development and intensity of synoptic scale features were usually quite accurate. On five days the forecasts were judged to have significant errors of this nature. Typically, these consisted of such errors as underestimating the extent of deepening of a trough which resulted in an extensive area of wind direction errors. On three additional days, less significant errors of this type were noted.

7.3.2 Other Errors

Analysis of the error segments and visual inspection of the corresponding forecast and analysis charts found several other errors which may have been perceived as forecast errors but are likely the result of some procedure or feature of the airline flight planning systems. These are discussed below.

Time Interpolation and Choice of Prog

It was apparent from the analysis that time interpolation between weather progs, or the choice of prog on which the flight plan is based, caused some of the wind differences between the forecast and analysis, especially in rapidly changing situations. On several days, review of the 0000Z forecast and analysis, and review of the forecast and analysis valid 24 hours later showed that the forecasts were highly accurate, but flight plans based on an intervening forecast, such as the 1800Z, resulted in error segments. It is possible that in these few cases there were no forecast errors at all but rather that the flight planning algorithm or the analysis methodology somehow resulted in forecast winds being compared to actual winds valid at a different time.

Average Winds in Areas of Sharp Gradient

The methodology by which these airlines develop the average winds for a flight plan segment may have resulted in some "forecast errors". Both airlines use some scheme to determine an average wind for a flight plan segment from adjacent Marsden Square data. Since some flight plan segments can traverse more than one Marsden Square, in areas of sharp gradient flight plan winds may be developed by averaging very light winds with very strong winds, depending on the algorithm being used. This averaging process appears to have resulted in some apparent forecast errors on the flight plans, which do not appear when one visually compares the forecast and analysis charts.

This problem applies equally to situations with a pronounced wind direction gradient. Many forecast error segments were found near the centers of highs, lows, ridges or troughs where the wind direction changes rapidly with distance.

Mid-East Errors

Significant "forecast errors" were noted on 11 days in the Mid East area by BLUE Airlines. Even on other days there were usually some error segments but they were judged to be relatively insignificant and not worth further analysis. Often these "errors" were on the same routes day after day - routes through Yugoslavia, Turkey, Syria, Iraq, and Iran. The charts that were available did not extend far enough east to be of help in explaining the forecast errors in this area. However, it is believed that the persistent, almost daily, occurrence of forecast errors in this area is significant on its own even if the significance of the individual daily errors cannot be determined. Since it is difficult to explain how a forecast error should occur in the same location so often, it was assumed that this was the result of some anomaly in the BLUE Airlines system.

8. METHODOLOGY AND DATA REDUCTION

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8.1 METHODOLOGY

Numerous flight plan data were provided by NASA on magnetic tape for the analyses conducted during this study. In Task I alone, for example, up to 20,000 flight plans were included in the data base.

The methodology required that data be extracted from the flight plans and identified. Appropriate groups of data would then be compared and the results presented. Specific procedures peculiar to any one task were discussed in the previous sections of this report that discussed the results of each task. In general, however, the first and most difficult task was to extract the data from the various flight plan formats included in the input magnetic tapes.

Flight plans for Task I were presented in the appropriate output format of either the RED or BLUE Airlines, while plans for Task III were copied on magnetic tape from the teletype output queue and included such extraneous data as message switching codes and line control characters. These tapes also included flight plans which were not relevant to this study. The SRI flight plans in Task II and the AIDS data presented two more formats to decode.

Computer programs were developed to scan the input tapes and to extract and identify relevant data. Data such as date, origin, destination, flight time, fuel burn, wind component and temperature were identified from each flight plan and stored in files for subsequent comparisons between the various flight plan groups. In some cases the data were not presented on the flight plans and had to be derived from available data, such as winds from the wind correction angle and true air speed on the BLUE Airlines flight plans.

The comparisons between groups of flight plans were then processed by computer and the statistical results output in graphic form. Figure 8-1 is a sample of the typical output format. In each task and sub-task the objective was usually to determine differences in some parameter between plans based on one set of conditions and plans on some other conditions. As Figure 8-1 shows the mean value of the difference was determined, along with the variance, standard deviation and 90 percent confidence limits. An histogram depicted the frequency of occurrence of incremental values of the differences between the two groups.

8.2 DATA ANOMALIES

Since the data used in these analyses were collected during 1979 and some preliminary processing was conducted by NASA during 1980, it was not possible during this project in 1981 to rerun, correct, or recreate any erroneous or missing data. As a result of procedural anomalies during data collection or other factors which are no longer known, there was

Figure 8-1

SAMPLE OUTPUT

```
 300                                    +
 290
 280
 270
 260
 250                                    +
 240
 230
 220
 210
 200                                    +
 190
 180
 170
 160
 150                                    +
 140
 130
 120
 110                                    *
 100                                    +
  90                                    *
  80                                    *
  70                                    *
  60                                    *
  50                                    +
  40                                    *
  30                                    ***
  20                                  *****  *  *
  10                            * *****************   *
       ----+----+----+----+----+----+----+----+----+----+----+
               -20       -10        0        +10       +20
```

```
Mean                        2.16
Variance                   34.61
Standard Deviation          5.88
90% Confidence Limits      -7.52 to 11.84
Total Occurrences          384
```

Total Fuel Consumed -Hundreds

Operational Forecast Vs. Re-Analysis

Carrier: BLUE   Direction: Eastbound   Region: All some loss of data for some of the tasks and a corresponding reduction in the size of the statistical sample. However, sufficient reliable data were left to form valid conclusions from the analyses.

In Task I, several features inherent in the BLUE Airlines flight planning system, the NWS analysis model, and NASA's input procedures caused some anomalies in the data base. Three of these were somewhat significant.

First, an error checking procedure in the NWS software caused pilot reports and AIDS data submitted by NASA to be ignored, and resulted in the verifying analyses being always identical to the forecasts in equatorial regions and the Southern Hemisphere. As a result data from some flights in these regions had to be discarded.

Second, AIDS recreated flights in the BLUE system used direct, great circle routes between the origin and the oceanic entry point while the minimum time track plans were restricted to airways. This resulted in a distance bias generally favoring the AIDS flights which sometimes gave a fictitious indication of fuel savings when AIDS flights were compared to minimum time tracks.

Third, since NASA's inputs to the BLUE system tried as closely as possible to recreate the original conditions under which AIDS flights operated, flight levels were restricted to those used by the AIDS flight while minimum time track plans were calculated at optimum levels. This resulted in fuel burn differences which were attributed to the flight level difference rather than weather data differences.

Adjustments were made manually to the computer output to correct the findings for these anomalous data. The adjustment factors were determined from the actual distance differences between the airways and direct routes used by all of the flights in Task I and from the actual flight level differences between the plans.

Another procedural problem during data collection resulted in a substantial reduction in the size of the sample in Task III. In Task III AIDS observations of winds and temperatures were compared to those on the flight plan of the flight which observed those data. This required the airlines to retain copies of the flight plans during the data collection period. The BLUE Airline accomplished this by periodically dumping the output queue from its flight planning system on to magnetic tape. During the Task III analysis it was discovered that this "dump" was apparently not done frequently enough and substantial numbers of flight plans were lost. It was estimated as a result that up to 50 percent of the possible segment comparisons were lost because the flight plan corresponding to the AIDS flight could not be found.

However, sufficient data were still available to form valid conclusions and, in fact, a supplemental run which nearly doubled the sample size through relaxed error checking criteria resulted in negligible changes to the results.