JET STREAMS AND ASSOCIATED TURBULENCE AND THEIR EFFECTS ON AIR TRANSPORT FLIGHT OPERATIONS.

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Abstract

Flight data was used to investigate the effective use of jet stream winds to shorten flight times and conserve fuel, so reducing direct operating costs. Emphasis was placed on the aerodynamic features of modern jet aircraft, and to use these features to utilize the kinetic energy of high speed winds.

Jet stream winds are a constant feature of the earth's global weather pattern and flow mainly from west to east. Their velocity, in excess of 50 m/sec, usually increases during winter months. As modern weather forecasting techniques improve, it will allow flight crews to intercept these winds and make more effective use of them.

Initial results have shown savings of 1-2%, when flying downwind. Savings have also been made flying into strong headwinds, however benefits are not as great as when flying downwind.

Nomenclature

CAS = calibrated air speed
CAT = clear air turbulence
DFDR = digital flight data recorder
D = drag
FL = flight level
g = gravity,
hPa = hecto Pascals
INS = Inertial Navigation System
INS = International Standard Atmosphere
kt = knots
M = mach number
m = metres
nm = nautical miles (1nm = 1852m)
P&W = Pratt and Whitney
STJ = Subtropic Jet Stream
TAS = true airspeed
TAT = total air temperature
T.SFC = thrust.specific fuel consumption
V = velocity
V_G = ground speed
V_T = true airspeed
V_W = wind speed
W = weight
W_f = fuel flow
W/V = wind velocity
δ = pressure ratio
σ = density ratio

1. Introduction

Industry has always strived to have access to a relatively cheap source of energy. Major changes in the price of energy units, ultimately affects the costs of goods produced. Aviation is no exception. whenever the price of aviation fuel is increased, the cost per seat mile is increased. This impacts on direct operating costs.

From the early 1960's, when fuel was just a few cents per gallon, the world has been subjected to a series of fuel crises. In the 1970's fuel price quadrupled, then in 1981, for a few months, the price exceeded US $1.00/US gallon, to a 'Gulf War height' of US $1.28/US gallon (Air Transport World Nov, 1991).

To keep direct operating costs under control, fuel savings must be actively pursued at every level. This paper covers one area, where savings can be achieved by flight crew operating techniques, using aerodynamic features of modern jet aircraft. These techniques enable the aircraft to harness the high speeds and energy of jet stream winds. In doing so, there are immediate savings in fuel used.
Data was collected on a Boeing B747-200 aircraft operating on regular public transport operations on Singapore - London and Manila - London routes. Readings were taken at 'waypoints' as each flight progressed. Where required, adjustments were made for any instrument or calibration errors. To measure the degree of turbulence encountered, the DFDR was read and a series of readings extracted for various atmospheric conditions. All information quoted, that is, weights and fuel flows, reference to optimum height, turbulance margins, and crew operating techniques, pertain to a B747-200 with P&W JT9D engines.

2. Historic Review of Jet Streams

2.1 Sub tropic jet stream (STJ) between Singapore/Manila and London

Jet streams by their very existence are subject to all the physical processes and activities of a dynamic atmosphere. Driven by the impact of solar energy, their position is constantly changing as the STJ stream meanders within the limits of approximately ± 10° to 15° of latitude from its axis.

During the winter months, the STJ moves south, so that the core is centred close to 25° N. A semi-permanent wave pattern results in the core oscillating between 15° N and 35° N, shown by Krishnamurti (1961).[1] In summer, the core is centred at approximately 45° N. In Fig 1 (Jan 1956), the core extends virtually unbroken from Southern Europe across Saudi Arabia, across the Arabian Sea almost to Bombay on the west coast of the Indian Sub-Continent. This path closely follows the airways route 'Red 19' as it was termed at the time when data was collected (it is now known as R 219).

From 1985 - 1990, the height of the STJ core was located between 9500m (≈ 31000 ft), and 10500m (≈ 34500 ft). Core height remains reasonably constant throughout each winter. major level changes of 500 - 1000m occur as the core moves south each year from the summer position of 45° N.

2.2 Forecasting the STJ

Forecasts detailing the position of jet streams, have a validity extending up to 18 hours, and are issued some 12 hours or more before a flight departs. With most long range flight operations, the forecast will be at least 12 hours out of date during flight. More usually, they are up to 24 hours out of date. There are occasions when a forecast is not available due to breakdown of telex, or communication failure, or industrial dispute. There are many reasons. To counter these deficiencies and take advantage of a tail wind (or avoid a head wind), the following are recognition features used to find, intercept, and stay in contact with this elusive ribbon of wind.

2.3 Recognition features of STJ

i. position shown on significant weather prognosis chart
ii. seasonal location
iii. altitude
iv. static air temperature in cruise
v. temperature gradients - vertically
   - horizontally
vi. relation to the troposphere
vii. wind speed from INS
viii. turbulence entering or leaving jet stream
ix. cloud types if present
x. inflight reports from other aircraft

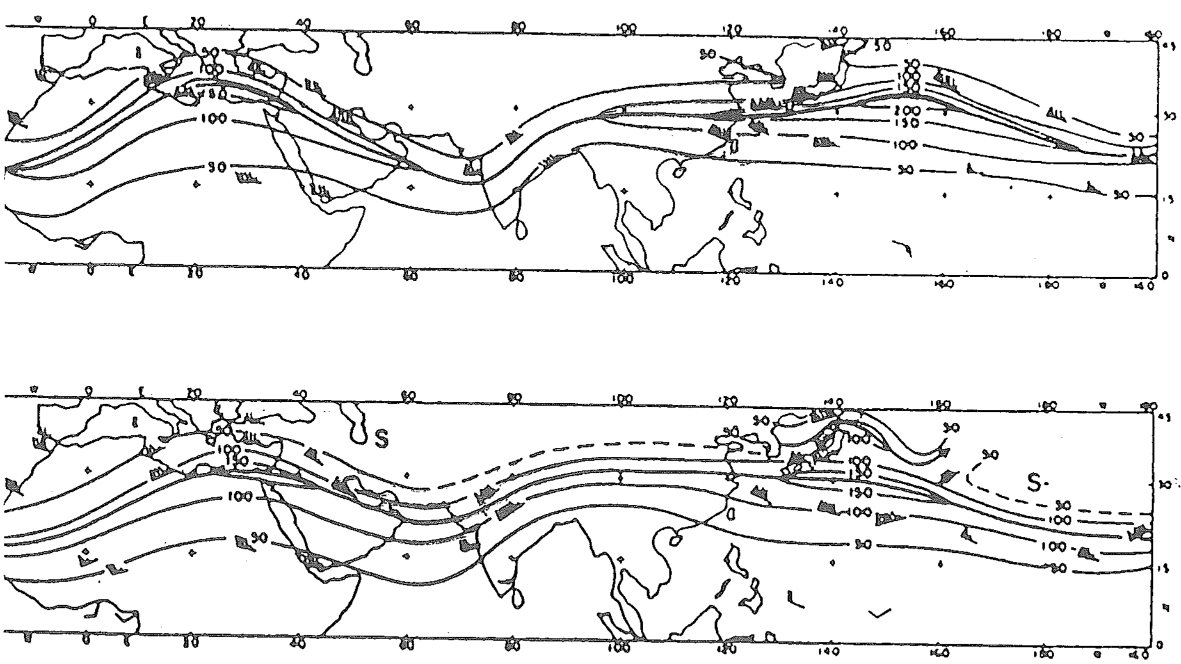

FIG. 1. JANUARY 5 and 6, 1956.(Krishnamurti 1961)

3. Flight Crew Operating Techniques

3.1 Flying down wind

3.1.1 Locating jet stream core

Using information outlined in section 2.3, estimate the location of the jet stream core, and position of the core, in relationship to the aircraft. Knowledge of the cores' position is crucial when positioning the aircraft to gain maximum benefit from the wind. Find the core, then stay as close to the axis as possible.

Many airways are ± 10 nm in width, which infers a manoeuvring corridor 20 nm wide to move closer to the core. Some airways are as much as ±20 nm wide, giving an even greater margin in which to manoeuvre.

Monitor the position of the core as flight progresses. Should wind direction vary, make corrections to regain core. This involves a 15° turn left or right, and closely monitoring temperature change, then turning to close on the core again. To get maximum benefit, stay with the jet stream as long as is legally possible.

3.1.2 Height selection

Flights on a easterly heading are limited in their choice of altitudes, to FL 280, 330, 370, 410. Those heights closest to optimum are usually FL 330, or FL 370 (cruise weight 275,000 kg). With the core located between FL 310 and FL 340, for example, the lower level FL 330 would be the initial choice. Should the core be determined to be at approximately FL 350 or higher, climb should be initiated as soon as practicable to FL 370. If the flight remained at FL 330, it would be below optimum, and below the jet core. Additionally as the flight progresses, the aircraft will move further away from optimum resulting in additional fuel usage, rather than saving fuel.

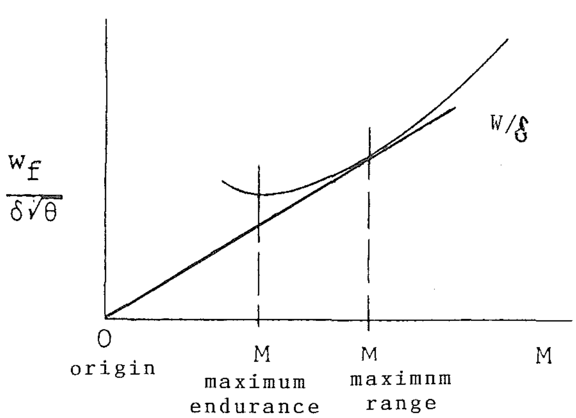

Fig.2. Points of maximum endurance and maximum range.

3.1.3 Speed selection

Having positioned the aircraft as close to the jet stream as governed by airways' width and cruise height, then select a cruise speed for best economy for the wind speed.

Basic equations for maximum range and endurance.

V_T = TAS
V_G = ground speed
V_W = wind speed (+ve for tailwind)
$V_G = V_T \pm V_W$
W_f = fuel flow = (T.SFC).D

Specific range over the ground with tail wind:

$$\frac{V_G}{W_f} = \frac{(V_T = V_W)}{W_f}$$

to minimise $\frac{W_f}{(V_T + V_W)}$

$$\frac{\partial}{\partial V_T} \quad \frac{W_f}{V_T + V_W} = 0 \quad \text{at best range in wind}$$

$$\frac{TSFC \frac{\partial D}{\partial V_T}}{(V_T + V_W)} - \frac{TSFC.D}{(V_T + V_W)} = 0$$

$\frac{\partial D}{\partial V_T} = \frac{D}{(V_T + V_W)}$ best range speed in tailwind, and:

$\frac{D}{V_T}$ for zero wind

$\frac{D}{(V_T - V_W)}$ for headwind situation

Fig 2 drawn for a particular weight/pressure ratio W/δ , illustrated the above. Maximum range speed is where the line from the origin (zero wind) is tangent to the W/δ curve (or thrust required curve). Slope of the line at maximum range being:

$$\frac{W_f}{\delta\sqrt{\theta}\,M}\text{min} = \left(\frac{W_f}{M}\right)\text{min}$$

For a substantial tail wind, as found in a jet stream, the origin is moved towards the left. Slope of the tangent is less, requiring lower speed for maximum range, giving lower fuel flows. It should be noted that V max range will always be higher than V min drag.

Fig 3 illustrates both tail wind and head wind situations where V max range is adjusted +ve and -ve for tail wind and head wind.

Normally tail wind components under the arbitrary lower limit of 58kt for a jet stream are not to be taken into account as the slope of the tangential change is minimal. However as tail wind components move toward 100kt and above, cruising at a lower M number, maintains the cruise speed closer to maximum range.

From a practical viewpoint, care needs to be exercised in determining the extent of thrust reduction. Lower power limits are governed by Vmin drag, and 1.3 low speed buffet. Example: A B747-200, weight 290000 kg at FL 330, speeds are:
Vmin drag = M 0.79
V1.3 low speed buffet = M 0.72
Normal cruise is M 0.84

As jet streams are invariably accompanied by some degree of turbulence, a low limit of approximately M 0.83 would be prudent. M.83 is on the lower limit of turbulence penetration speed, and gives a safety margin not available with lower mach numbers. In the above example, a savings of 250 to 300 kg/hour are achievable without disrupting airline schedules.

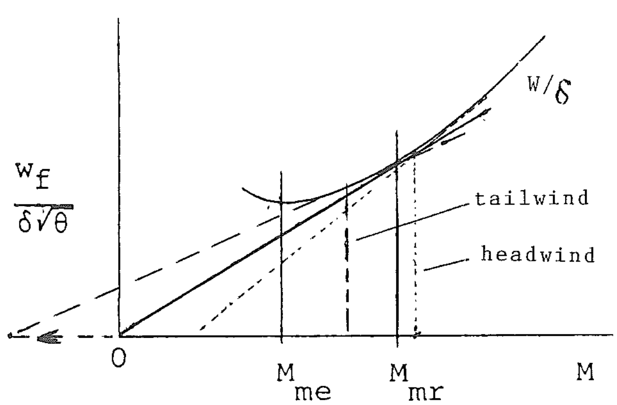

Fig.3. Illustrates reduced point of Max. range for tailwinds and increased Max. range for headwinds.

3.2 Flying into wind

General considerations

Head wind evasion or avoidance is better if taken care of at the flight planning stage. From prognostic charts, determine the influence a jet stream would have on the proposed flight. Should the head wind exceed 100kt for 60 minutes or more, an alternative airway should be considered. To be fully cost effective, select a route that will take the aircraft away from the jet stream, and at the same time, incur only a small penalty of additional miles flown. This pre-planning could save flying into headwinds of 125 knots or more for up to 2 hours, that is, 250 nautical miles saved.

Example: Consider an aircraft scheduled to operate from Dubai to Paris across Saudi Arabia, when a jet stream is positioned over the airways route. An alternate option would be to fly on the airways north west from Dubai, crossing Iran, Iraq and Turkey, completely avoiding high winds and accepting a much lower headwind component of approximately 20-30 kt.

The two routes considered above, join together in Southern Europe after some 1700nm distance, with the Iran/Iraq/Turkey route being 28nm longer. After allowing for the additional distance and adjusting for the 20 - 30kt head wind, an aircraft would fly the longer route in a shorter time of 23 minutes, which is a fuel saving of approximately 4,600 kg.

On the return flight, Paris to Dubai, assuming the same or similar conditions, the trans Saudi route should be flown to take advantage of the strong tail winds.

3.2.2 Locating the jet stream core

If strong headwinds are unavoidable, use the same techniques as outlined in 2.3 and section 3, to determine the position of jet stream core in relationship to the aircraft. When determined, use the width of the airways to move away from the core.

3.2.3 Height and speed selection

On westerly headings, the selection is limited to FL 270, 290, 310, 350 and perhaps 390 if the aircraft's weight is low. On flights departing from Middle East airports (Dubai, Aba Dhabi, Bahrain, etc.) to European destinations, FL 290 offers the best height for heavy aircraft. With a jet stream at FL 290 and M 0.84 ISA conditions, TAS is at a maximum still air speed of 498 kt.

Figure 4 indicates how max TAS can be achieved at FL 290. With a cruise schedule of M 0.82 or 0.83, increase speed to M 0.84 to achieve maximum TAS.

If flying a cruise schedule of M 0.84, hold this speed, any excursions above this value will place the aircraft in the mach drag regime. A mach increase of 0.005 to M 0.845 is shown in Table 1. A comparison can be made with a similar increase of 0.005 from M 0.835 to M 0.840.

The increase from M 0.835 to M 0.84 gives a .73% increase in fuel flow and a gain of 4 kt; compared with M 0.84 to M 0.845 results, a 2 kt increase for more than double the % increase in fuel flow to 1.67%

At M 0.84, the aircraft is within the turbulence speed penetration range, should there be any CAT. Entering a jet stream from below is a known area of increase turbulence and should be respected accordingly. Jursa (1985).[2]

With an aircraft at FL 350 and running into a strong jet stream, consideration should be given to descending or climbing: "to go under or over".

With the prospect of CAT around a jet stream, climbing should be approached with some degree of caution. Climbing from FL 350 to FL 390 will reduce the buffet margins between high speed buffet and low speed stall. In addition, TAS at FL 390 will be reduced 2-3 kt, and may only reduce the head wind component by 10-20 kt. A descent from FL 350 to 310 has the advantage of increasing TAS and increasing the buffet margins. If the airways width allows a manoeuvre, a turn towards the polar side will give maximum benefit from changing

	M.835	M.84	M.845	△	% W_f change	% TAS change
W_f	13650	13750		100	0.73	
TAS	494	498		4		0.81
W_f		13750	13980	230	1.67	
TAS		498	500	2		0.40

TABLE 1. Note % changes in columns 6 and 7 showing at M.845 the aircraft is into the mach drag rise.

height and crossing more isotachs that tend to bunch on the cold side of a jet stream. (See Fig5)

Points to consider when flying into a jet stream:

i) endeavour to transit the higher wind area as quickly as possible by keeping the TAS high
ii) optimum altitude in the presence of high winds is lower than for still air
iii) where possible, move to the polar side of the core

Using the above procedures will not completely negate the effects of adverse winds, however if used, will lessen the loss of fuel and time.

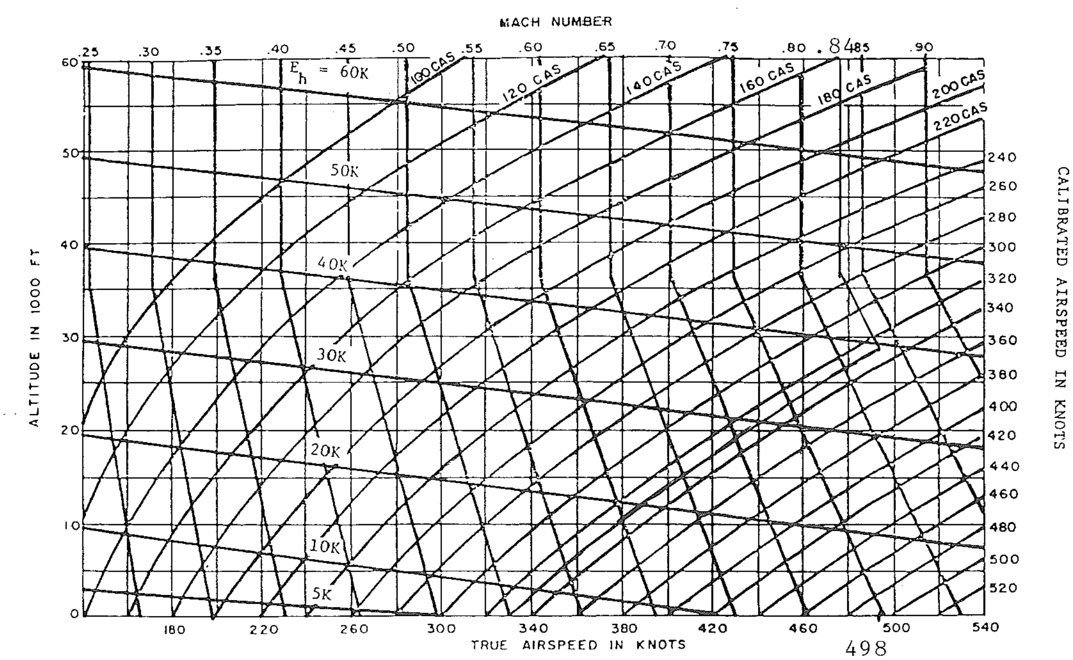

Fig.4 AIRSPEED - MACH NUMBER - ENERGY RELATIONSHIPS (ICAO STANDARD ATMOSPHERE)

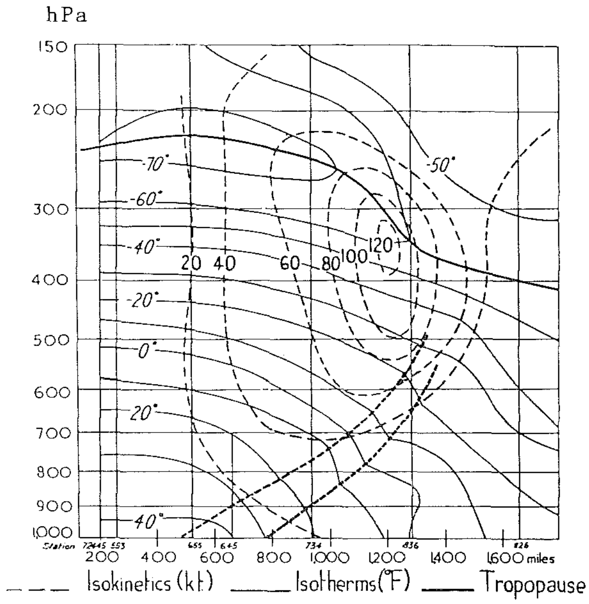

Fig.5. SW-NE cross section of a jet stream over North America 19 Dec.1953 (after Sawyer 1957)

4. Results

Table 2. Using techniques outlined in this paper, the following results were achieved.

Flying downwind

Date	Sector	Fuel gain(loss) (kg)
26.2.88	Riyadh-Manila	2071
25.3.88	Riyadh-Manila	2223
13.4.88	Manila-Honolulu	1139
29.4.88	Manila-Honolulu	3478
27.6.88	Paris-Dubai	3232
14.7.88	Dhahran-Manila	600
16.7.88	Riyadh-Manila	633
18.8.88	Manila-Honolulu	825
01.9.88	Riyadh-Manila	977
14.3.89	Dubai-Manila	1534
21.4.89	Riyadh-Manila	2090
	Total	18802

Flying into wind

Date	Sector	Fuel gain(loss) (kg)
01.3.88	Manila-Dubai	(691)
04.6.88	Honolulu-Guam	2564
12.6.88	Dubai-Rome	2452
12.7.88	Manila-Riyadh	3373
17.7.88	Manila-Riyadh	1680
28.7.88	Manila-Riyadh	1858
14.8.88	Manila-Riyadh	835
23.8.88	Honolulu-Manila	1423
25.8.88	Manila-Riyadh	2305
31.8.88	Manila-Dhahran	2067
26.2.89	Manila-Riyadh	(484)
15.3.89	Manila-Dubai	(385)
21.3.89	Manila-Riyadh	3091
	Total	21648 (-1560)

Gain	40450
Loss	1560
Net gain	38890

5. Conclusions

The major problem of jet stream operations is finding the jet stream, then determining the position of the core. Forecasts of the jet streams' position are at best a guide only, due to the oscillating characteristics. Frequently, the jet streams are not where they are forecast to be located.

There is the problem that it is seasonal and not always readily available. For long range airlines that operate in both hemispheres (such as Qantas and Singapore Airlines), this is not such a problem as the jet stream is blowing in one hemisphere or the other.

Heavy airline traffic on a particular route may restrict the ability to climb and/or descend to make best use of the wind. In these circumstances, make the most of the situation, monitoring other traffic movements, and then move at the first available opportunity.

Manoeuvring in an airways can be 'fiddling', however rewards are there for those that pursue lower fuel consumptions. It is not sufficient to put an aircraft somewhere near a jet stream and expect the wind to do the rest. There is a need to maintain a surveillance for changing temperatures and turbulence, signifying the closeness of a jet stream, which can be utilized to greater advantage.

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