



ESTIMATING THE IMPACT OF NUMERICAL WEATHER PREDICTION DATA MODELS ON SHORT-HAUL MINIMUM COST TRACKS

Navinda Kithmal Wickramasinghe¹, Yoichi Nakamura² & Atsushi Senoguchi³

^{1,2,3}Air Traffic Management Department, Electronic Navigation Research Institute (ENRI)
7-42-23 Jindaijihigashi-machi, Chofu, Tokyo 182-0012 Japan.
Email: ¹navinda@mpat.go.jp

Abstract

This paper focuses on the impact of using numerical weather prediction (NWP) model variants in flight planning and its influence on aircraft performance. Three NWP models are subjected in this study and a series of Quick Access Recorder (QAR) data and corresponding flight plan data provided by a national airline are used as reference data. To simulate the process of flight planning, a Dynamic Programming (DP) based trajectory optimization model is utilized to generate fuel-optimal flight tracks over the flight route between Tokyo (Haneda) and Fukuoka. Base of Aircraft Data (BADA) Family 4 aircraft performance data from Eurocontrol are used to estimate fuel consumption and a quantitative evaluation is conducted to discuss the potential effects of applying different NWP models in flight planning.

Keywords: flight planning, minimum cost track, weather forecast error, aircraft performance

1. Introduction

In recent years, the airline industry is increasing its attention on achieving efficient air transportation systems to overcome the daunting challenges incurred due to sky-rocketing fuel prices and environmental impact caused by air travel. Similar to the U.S. and European counterparts, the aviation sector in Japan has set its own goals for the sustainability of the society by targeting net-zero CO₂ emissions by 2050 [1, 2]. Efficient flight planning immensely contributes towards the overall performance of an air transportation system, especially in reducing fuel consumption and hazardous emissions. In general, a flight plan is generated by an airline dispatcher several hours before the scheduled departure time (SDT) using a flight planning system (FPS). Depending on the SDT, dispatcher's working shift and degree of workload, the time frame for generating a flight plan may extend up to 15 Hrs. before SDT. Compared to international flights, of which large dispatcher intervention is reflected in route selection, cruising altitude and other performance parameters, domestic flights are relatively less-flexible. Except for last-minute re-routing due to severe weather or significant change in predicted aircraft weight, the flight crew would generally proceed with the original minimum cost track (MCT) provided by the dispatcher (generated by the FPS). FPSs are tailor-made for meeting specific policy requirements of airline operators. However, limitations and restrictions also follow with these systems, such as;

- Nondisclosure of the calculation process and the extent of usage of user-input parameters.
- Limitations in using local products (e.g.: local weather data).
- Difficulties in replacing legacy systems due to their interrelation with other systems/subsystems.

can reduce the flexibility of a dispatcher in achieving efficient flight plans with high flight predictability. Numerical Weather Prediction (NWP) data is one of the key input parameters used in flight planning. As mentioned above, due to the default settings in the FPS, selection of weather data (model

variant and forecast time) may not always be ideal for the subjected flight. The Japan Meteorological Agency continues to upgrade NWP models with higher resolution and update frequency for the Japan region [3] which provide more precise predictions [4]. However, these models are not referenced for operations in the domestic airspace. Reflecting more precise forecast data in flight plan generation can immensely elevate the flight predictability which eventually lead to potential benefits for all stakeholders involved in the aviation industry.

Research have been conducted extensively on strategies to generate fuel/time/range efficient flight tracks. Cruise phase generally consumes the largest percentages of trip time and trip fuel and since is most responsible for the overall efficiency of the flight. A short-haul flight defines a trip time of less than 3 hours and the cruise phase covers between 50-70% of a flight between Tokyo Haneda (ICAO code: RJTT) and Fukuoka (ICAO code: RJFF) with a trip time of less than 2 hours. It is noted that low percentage examples were mainly due to vectoring segments during climb/descent phases. Earlier research showed optimal trajectories consisting only climb and descent phases with constant energy transitions for short-haul flights [5, 6] which is highly unlikely considering the criteria of modern-day operations. Zermelo's navigation problem has been used to treat the flight trajectory optimization in previous research with implicit analytical solutions derived for linearly-varied wind distributions [7, 8]. Dynamic Programming (DP) method is applied in this study and has been a potential solver for flight trajectory optimization related research [9, 10, 11, 12]. Since the main focus here is on the influence of NWP data over the operational efficiency, DP method is feasible since the gridded weather parameters can be directly applied in the optimizer. To elaborate the effect of used weather models, this paper treats a constant-Mach, free final-time optimal control problem considering only the cruise phase and addresses the problem of minimizing the direct-operating-cost (DOC) problem. In this scenario, minimum-fuel solution is identical to the minimum-time solution which is considered as minimizing the DOC in this study. A similar study shows that up to 3% of benefits could be obtained by optimizing the cruise phase of long-haul flights using the grid space search method[13]. Other representative research concentrated on optimizing the cruise phase can be found in [14, 15, 16, 17].

1.1 Contributions of the Paper

This paper focuses on the impact of using NWP model variants in flight planning and its influence on the performance of MCT generated by the FPS. Three NWP models are subjected here, namely Global Spectral Model (GSM), Meso Scale Model (MSM) and Local Forecast Model (LFM). A series of Quick Access Recorder (QAR) data and corresponding flight plan data provided by a national airline are used as reference. To mock FPS-generated MCTs, a DP-based trajectory optimization model is utilized. Flight route between RJTT and RJFF, one of the busiest domestic flight routes in Japan with about 9 million passenger and 150,000 tonnes of cargo movements in 2019 [18], is subjected to investigate the effects of NWP models over the operational efficiency. GSM NWP model data (for global forecasting) are used as baseline data as these data are used as reference data in actual flight planning. MSM and LFM NWP models, focusing on the domestic weather with higher resolution and update frequency, are considered to be more precise in weather forecast. Therefore, MCTs based on these two NWP models will be compared with the MCTs based on GSM NWP model along with the planned flight routes to investigate the discrepancies in aircraft performance. Base of Aircraft Data (BADA) Family 4 aircraft performance model from EUROCONTROL is used to evaluate the aircraft's performance, specifically aircraft drag and fuel flow [19].

2. Mathematical Formulation and Data Sources

2.1 Mathematical Formulation

This study uses a point-mass model to derive aircraft's motion on the horizontal plane. Zermelo's navigation problem is used to illustrate the aircraft's motion through a region of varying winds and following Equations of motion (EOM) are defined.

$$\frac{d\theta}{dt} = \frac{1}{(R+H)\cos\phi} (V_{TAS}\cos\gamma_a\sin\psi_a + W_x) \quad (1)$$

$$\frac{d\phi}{dt} = \frac{1}{(R+H)} (V_{TAS}\cos\gamma_a\cos\psi_a + W_y) \quad (2)$$

When an aircraft flies at a constant cruise altitude H over a sphere-assumed Earth of radius R , the time derivative of its position given with latitude ϕ and longitude θ can be derived as eqs. 1 and 2 with true airspeed V_{TAS} , flight-path angle relative to air γ_a , heading angle relative to air ψ_a , zonal wind component W_x and meridional wind component W_y . Since the aircraft is at constant-altitude cruise, γ_a is neglected. The objective of this dynamical system is to minimize DOC, therefore it is treated as a non-fixed terminal time optimal control problem. The heading angle is set as the control variable and the optimal values are found by minimizing the cost functional J_{opt} derived in eq. 3.

$$J_{opt} = \min_{\psi(\cdot)} \int_{t_0}^{t_f} FF(t) dt \quad (3)$$

The DOC for a subjected flight is considered as the time integral of fuel flow FF (or the fuel consumption) of the cruise segment between top of climb (ToC) and top of descent (ToD) indicated by start time t_0 and end time t_f . To convert the problem statement to a simplified single-variable function in a fixed interval, the control variable is transformed to the lateral deviation from the great circle route between start and terminal points in a polar coordinate system, defined as the cross-track angle ζ . The state variable is re-defined as the along-track angle η . Conversion to the polar coordinate system also facilitates the direct inclusion of longitude/latitude grid-driven NWP model data in the optimizer. Figure 1 shows how the DP method is applied to an aircraft's 2D-translational motion within the state space grid.

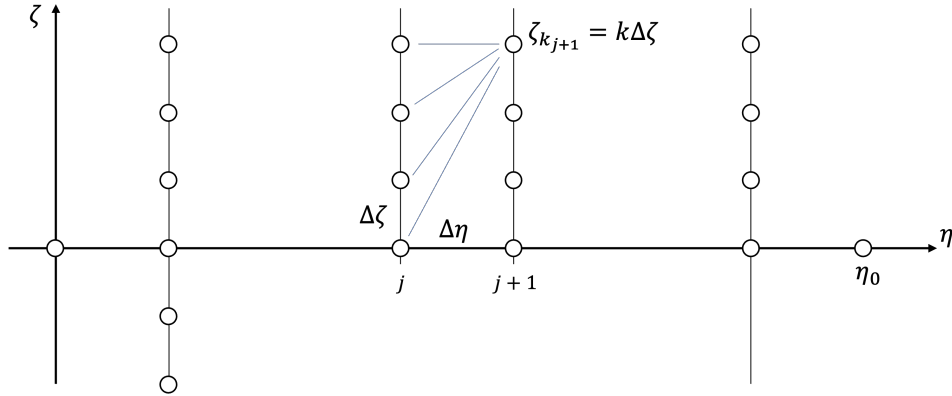


Figure 1 – Application of DP method to aircraft's 2D-translational motion.

The optimal cost function at a waypoint $k + 1$ on the $j + 1^{th}$ segment can be estimated by considering the minimum of the summation of all the combinations between that waypoint and all k on the j^{th} segment and the optimal cost function already given at all k on the j^{th} segment which are given as $J_{opt}(j, k)$. This relationship is demonstrated in eq. 4.

$$J_{opt}(j + 1, k_{j+1}) = \min_{j_k \rightarrow j_{k+1}} [FF|_{j_k}^{j_{k+1}} \Delta t + J_{opt}(j, k_j)] \quad (4)$$

2.2 Numerical Weather Prediction Data

This study uses nowcast/forecast data from three NWP models developed by the Japan Meteorological Agency. Main characteristics of the models are provided in Table 1. The focus here is to investigate how applying NWP data with higher resolution and update frequency can increase the overall performance of operations from the stakeholders' perspective. The gridded data are used directly in the model and piecewise linear interpolation is used to determine the parameters at each grid point of subject along the time, lateral and vertical dimensions. The preliminary study considers only *nowcast* data to investigate the impact of using different NWP models in flight planning.

2.3 Flight Plan and Quick Access Recorder (QAR) Data

Flight plan data and corresponding QAR data for a series of flights conducted between RJTT and RJFF are acquired by a national airline for reference. Figures 2a and 2b respectively illustrate the

flight plan tracks and actual flight trajectories. Relatively large deviations are visible close to the airports which are occurred mainly due to vectoring procedures applied by the Air Traffic Control (ATC) for arrival flights. It is noted that since the flight plan tracks are of past flights, all parameters which are usually available in general flight plans were not accessible. Therefore, boundary conditions of 3D-position, Mach Number and expected fuel burn are extracted from the flight plan data while time related parameters (e.g.: start time (time at ToC)) are obtained from QAR data.

Table 1 – Specifications of NWP Data Models

Model	Local Forecast Model (LFM)	Meso Scale Model (MSM)	Global Spectral Model (GSM)
Area	Longitude: 120°–150°E, Latitude: 22.4°–47.6°N		Global
Resolution	0.05° × 0.04° (601 × 631 grid points)	0.125° × 0.100° (241 × 253 grid points)	0.5° × 0.5° (720 × 361 grid points)
Vertical Layers	16 pressure levels 1000, 975, 950, 925, 900, 850, 800, 700, 600, 500, 400, 300, 250, 200, 150, 100 hPa		
Update (Initial Time, IT)	1Hr. (00, 01, ..., 23UTC)	3Hrs. (00, 03, ..., 21UTC)	6Hrs. (00, 06, 12, 18UTC)
Forecast Horizon	10Hrs.	39Hrs. (IT: 03, 06, 09, 15, 18, 21 UTC) 51Hrs. (IT: 00, 12 UTC)	132Hrs. (IT: 00, 06, 18 UTC) 264Hrs. (IT: 12 UTC)

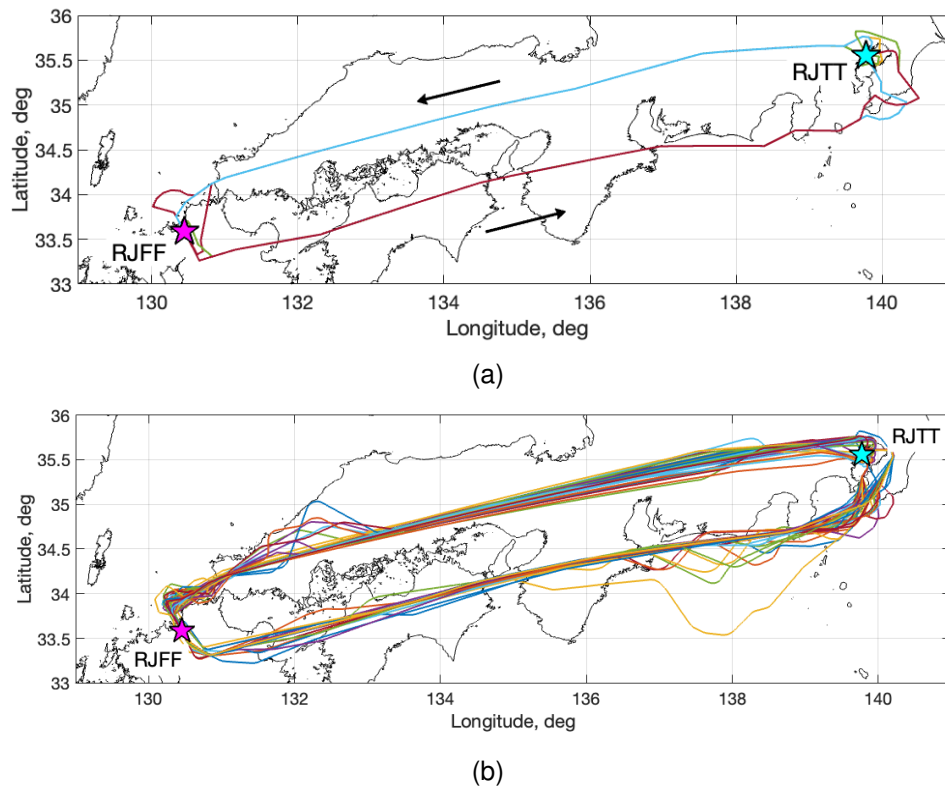


Figure 2 – (a) Flight plan tracks (b) Flight trajectories (QAR data) : RJTT / RJFF flight route.

Furthermore, this study refers to the Base of Aircraft Data (BADA) Family 4 aircraft performance model data as mentioned in subsection 1.1. Since only the cruise phase is subjected in this study, the aircraft thrust is assumed to be equal to the total drag it produces and the parameters were used to estimate the cruise fuel flow.

3. Analytical Results

In this section, two scenarios are considered to introduce the results from the study. The first scenario is the MCTs generated against the cruise segment extracted of each flight plan. The second scenario is a more general discussion focused on the characteristics between MCTs in winter and summer seasons and its distinction depending on the applied NWP model. The Japanese airspace

experiences strong jet-stream winds during winter and this scenario helps to elaborate the maximum impact of utilizing appropriate NWP model in generating MCTs for short-haul flights.

3.1 Performance Evaluation of Minimum-Cost Tracks based on Flight Plan Data

A total of 54 flight cases from RJTT to RJFF and 43 flight cases from RJFF to RJTT are subjected in this analysis. Nowcast data are used from all three NWP models to generate the MCTs. For each flight case, the calculation grid space is set with reference to the Great Circle Route (GCR) between ToC and ToD. Downrange and crossrange directions are respectively discretized with 65km (9 grid points) and 20km (10 grid points on each side of the GCR) segments.

Figures 3a, 3b and 3c respectively show the MCTs generated by using GSM, MSM and LFM NWP models. Each line represents a single flight case and the black dotted line depicts a representative flight path defined at the flight planning stage.

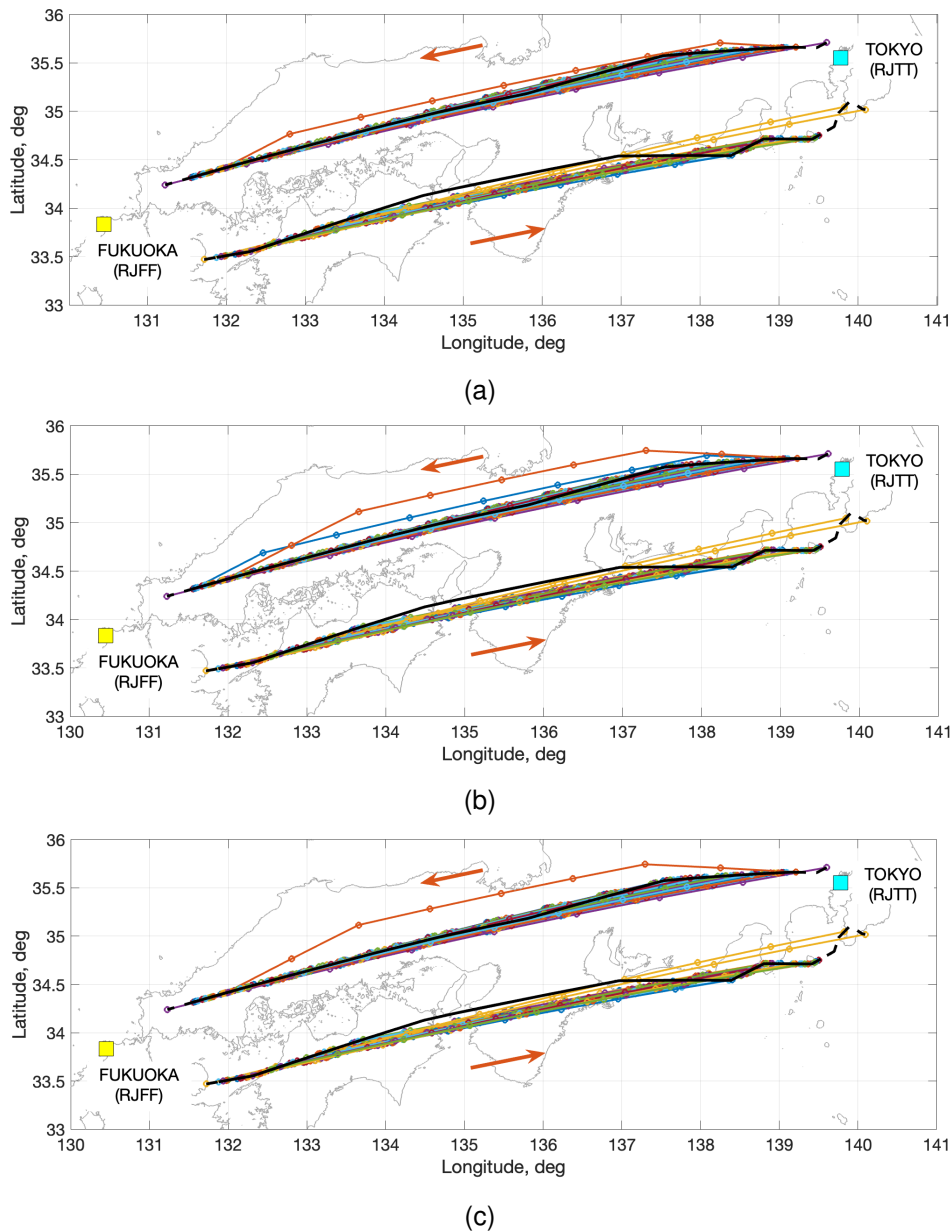


Figure 3 – (a) MCTs with GSM (b) MCTs with MSM (c) MCTs with LFM.

It is noted that majority of the MCTs tend to choose the GCR as the optimal solution for all three NWP models. One plausible reason is that all flight cases discussed in this study were conducted between March and August, a time period where strong jet streams usually do not exist in the upper atmosphere. Hence the influence of wind is considered not to be significant. It is also visible that

unlike MCTs obtained through GSM NWP model, several tracks under MSM and LFM NWP models tend to deviate from GCR. The main reason here is the difference in wind component working at the aircraft motion and it supports the fact that NWP model applied in flight planning can have a potential effect in the resulting flight path.

Then the aircraft performance is compared in presence of each NWP model. First, fuel and time differences between MCTs through each NWP model and corresponding flight plan records are investigated. Figures 4a, 4b and 4c respectively represent the correlation between time and fuel difference, between MCTs from GSM, MSM and LFM models and flight plan records. Left hand side figures depict results of RJTT -> RJFF flight cases and the right hand side figures are for RJFF -> RJTT flight cases.

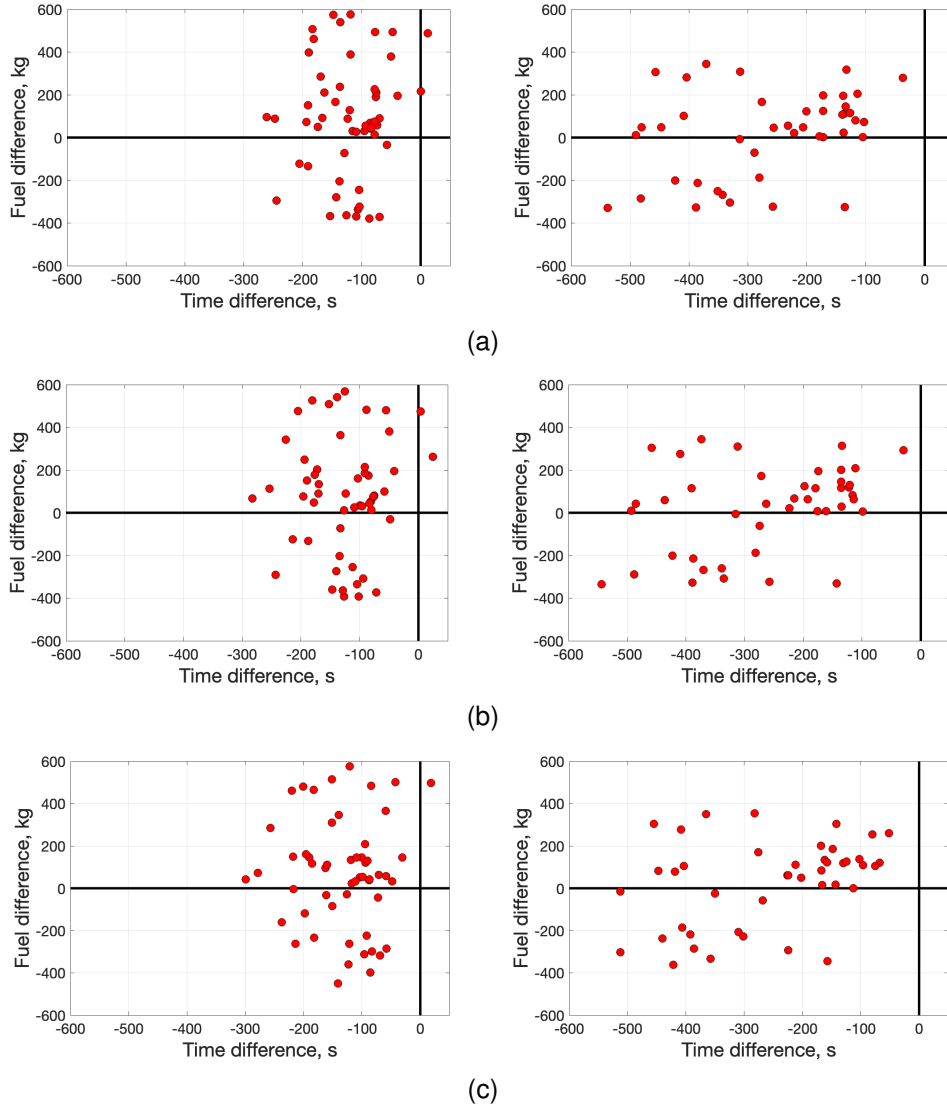


Figure 4 – Fuel difference with respect to flight time difference between MCTs and flight plan data
(a) GSM (b) MSM (c) LFM.

Left Hand Side: RJTT -> RJFF, Right Hand Side: RJFF -> RJTT.

Results show that minimum-cost tracks from all three NWP models have similar characteristics over origin/destination with respect to flight plan data. Almost all MCTs indicate shorter flight times, up to 300 seconds for RJTT -> RJFF flight cases and up to 600 seconds for RJFF -> RJTT flight cases. The fuel burn difference varies between -400 and 600 kilograms in general. For such a short-haul flight route, this is about 6-8% (heavy aircraft) or 10-15% (light aircraft) of a cruise segment. The distinction between the applied NWP model data is considered to be one of the key factors contributing to these discrepancies in the obtained results.

3.2 Seasonal Impact on Short-Haul MCTs

The previous section discussed how the application of a certain NWP model can effect present flight planning procedures. However, the time period of the extracted flight plans did not provide sufficient samples of strong/weak wind scenarios to clearly indicate the impact of NWP models. Hence, in this section the study is further extended to understand the maximum potential effects that can be achieved by applying an appropriate NWP model in flight planning. To do so, two months each from Winter and Summer seasons are selected to generate MCTs between RJTT and RJFF using the same calculation procedure. In this scenario, airport locations are set as start / end points in the optimizer. Accordingly, downrange and crossrange directions are respectively discretized with 12 grid points and 10 grid points on each side of the GCR connecting the two airports. Selection of optimal lateral routes during Winter and Summer seasons are respectively displayed in Figs.5 and 6.

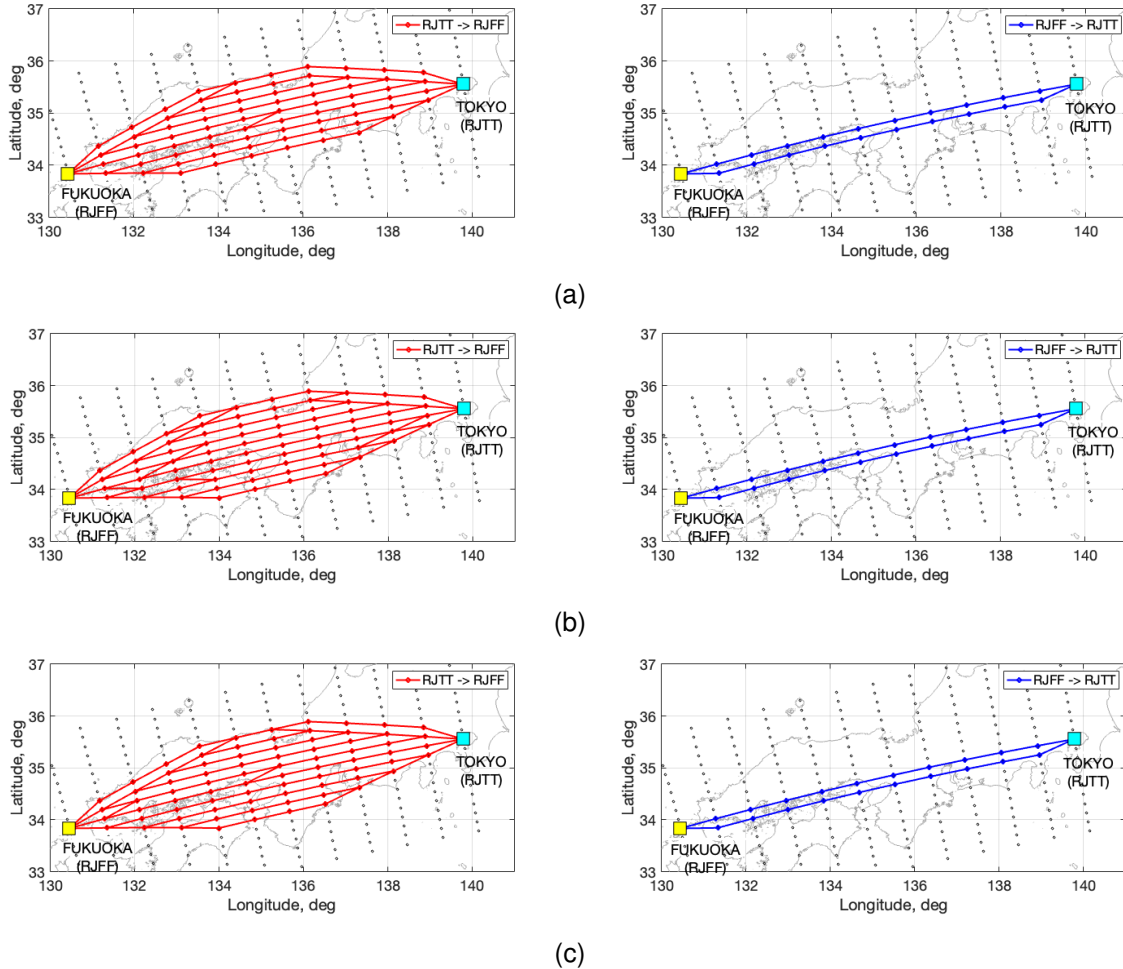


Figure 5 – MCTs for Winter Season (2022/12 - 2023/01) (a) GSM (b) MSM (c) LFM.

Left Hand Side: RJTT -> RJFF, Right Hand Side: RJFF -> RJTT.

In each figure, left hand side figures represent results for the RJTT -> RJFF route while the right hand side figures represent results for the RJFF -> RJTT route. From top to bottom, results obtained by applying GSM, MSM and LFM NWP models are depicted respectively. It is apparent that the optimal routes can significantly vary for flight cases over the RJTT -> RJFF route in order to avoid the effect of strong jet stream winds compared to RJFF -> RJTT route and results from the Summer season. It is also understood that results from all three NWP models show similar characteristics in choosing the optimal lateral route. One reason is that the short distance of the subjected flight route. The other reason is the limitations in the proposed study on selecting an optimal altitude or speed. In present flight planning procedures GSM NWP model is used in flight planning systems. As the main objective of this paper, it is important to clarify the distinct performance characteristics by applying different available NWP models in such systems. Hence, MCTs generated by MSM and LFM NWP

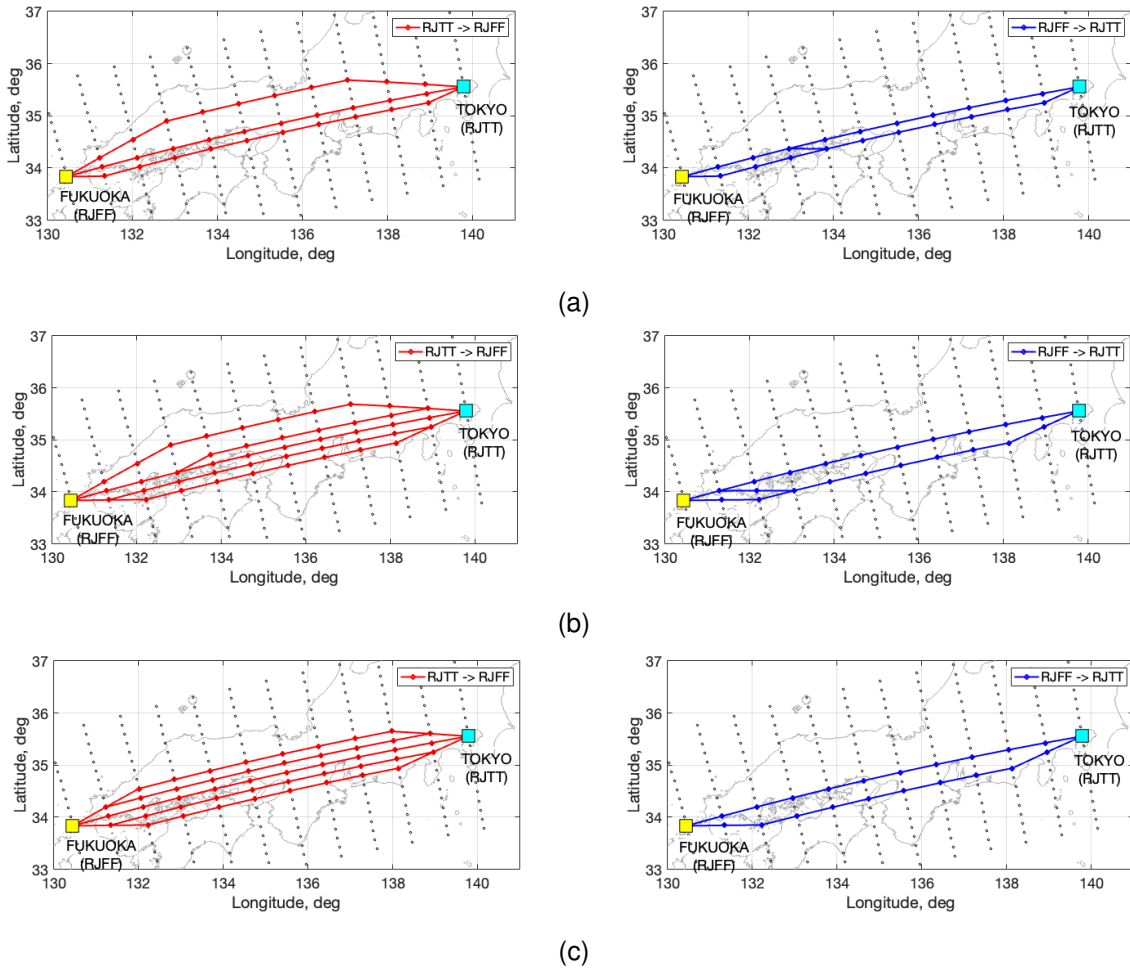


Figure 6 – MCTs for Summer Season (2023/07 - 2023/08) (a) GSM (b) MSM (c) LFM.

models are compared with the MCTs generated by GSM NWP model by investigating the fuel and time differences. Figures 7 and 8 respectively depict the obtained results for Winter and Summer seasons.

In each figure, left hand side figures represent results over the RJTT -> RJFF flight route while right hand side figures show results over the RJFF -> RJTT flight route. Also, in each figure top sub figures compare results between MCTs from MSM and GSM NWP models while bottom sub figures compare results between MCTs from LFM and GSM NWP models. Both figures are plotted with identical x and y axis limits to illustrate the performance distribution due to different operational conditions. MCTs generated from LFM NWP model over the RJTT -> RJFF flight route during Winter season shows the largest distribution, fuel burn difference between -5 to 6 % (about -400 to 500 kilograms) and flight time difference between -6 to 3% (about -300 to 300 seconds). From overall results, it is noted that performance characteristics vary larger between LFM and GSM NWP models compared to characteristics between MSM and GSM NWP models. One key factor contributing to this discrepancy is considered to be the difference of update frequency of the NWP models (LFM update: 1 hour / MSM update: 3 hours) resulting discrepancies in the atmospheric parameters that effect aircraft performance estimation. Results obtained here show the significance of wind conditions effecting aircraft performance estimation and the importance of considering appropriate NWP models in flight planning which could lead to efficient operations.

4. Discussion and Future Works

In this study, the impact of NWP model application in flight planning for short-haul operations was investigated based on a series of flight plan and QAR data. A dynamic-programming based trajectory optimizer was used to generate minimum cost tracks for the cruise segment of these flight

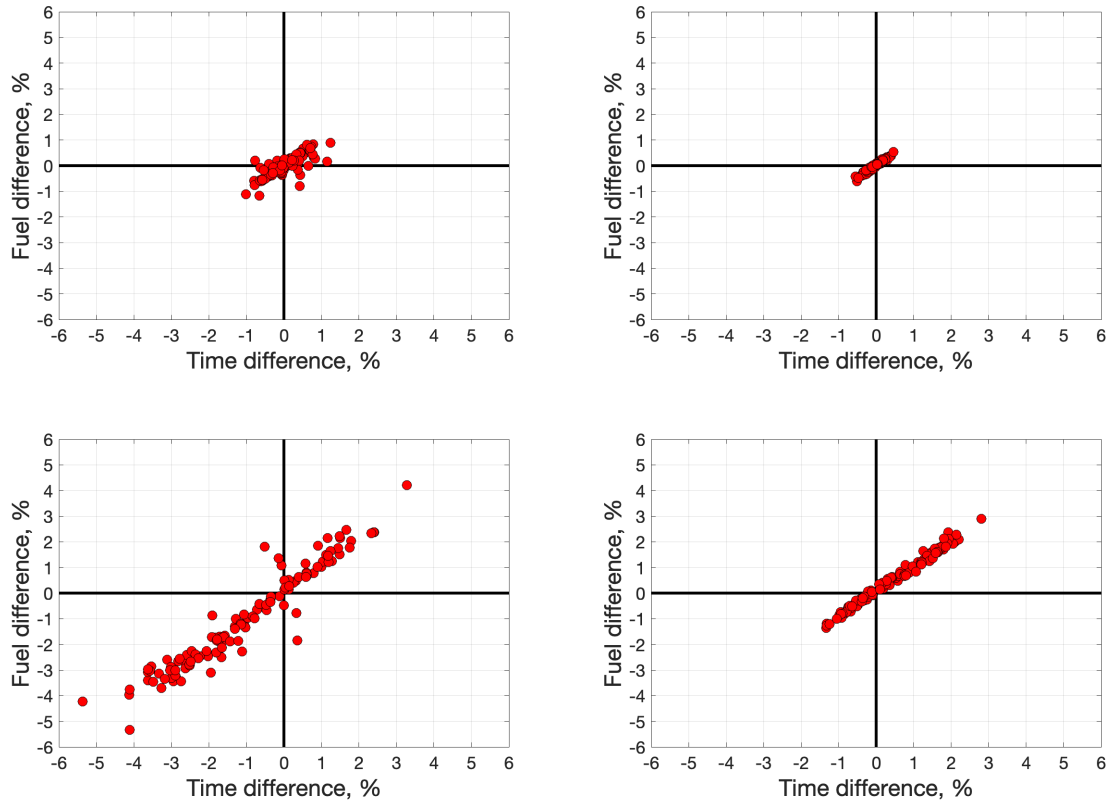


Figure 7 – Fuel and flight time difference with respect to MCTs from GSM NWP model during Winter Season (Top) MSM (Bottom) LFM.

Left Hand Side: RJTT -> RJFF, Right Hand Side: RJFF -> RJTT.

plans between Tokyo Haneda and Fukuoka. The impact of NWP models towards aircraft performance was evaluated by comparing fuel consumption and flight time between MCTs and flight plan data. Comparative analysis between MCTs and flight plan data parameters showed that performance characteristics could vary significantly depending on the NWP model applied in the trajectory planning process. Since current flight planning procedures use GSM NWP model data, performance characteristics were compared between MCTs generated from MSM and LFM NWP models. Obtained results reinforce the fact that performance characteristics can vary significantly depending on the NWP model used for flight planning and should be a key factor when considering potential improvements in flight planning strategies towards efficient operations.

In this study, only the cruise segment was considered with fixed flight altitude and cruise Mach Number with a free final time optimal problem. As an extension of these study, performance characteristics are to be compared when the aircraft is provided the eligibility of selecting an optimal altitude / optimal cruise Mach Number with arrival time constraint and investigate how the application of NWP model variants could effect flight planning strategies in a short-haul operational environment. Furthermore, actual process during flight planning is to be taken into consideration, for example including the flight planning time ahead of a flight and apply the forecast weather data accordingly to compare how the update frequency and resolution of NWP model variants could influence the output of cost minimum flight tracks. Outcome of this study is to be shared with stakeholders in the aviation industry to provide any support that could lead to the improvement of flight planning strategies for a future air transportation system.

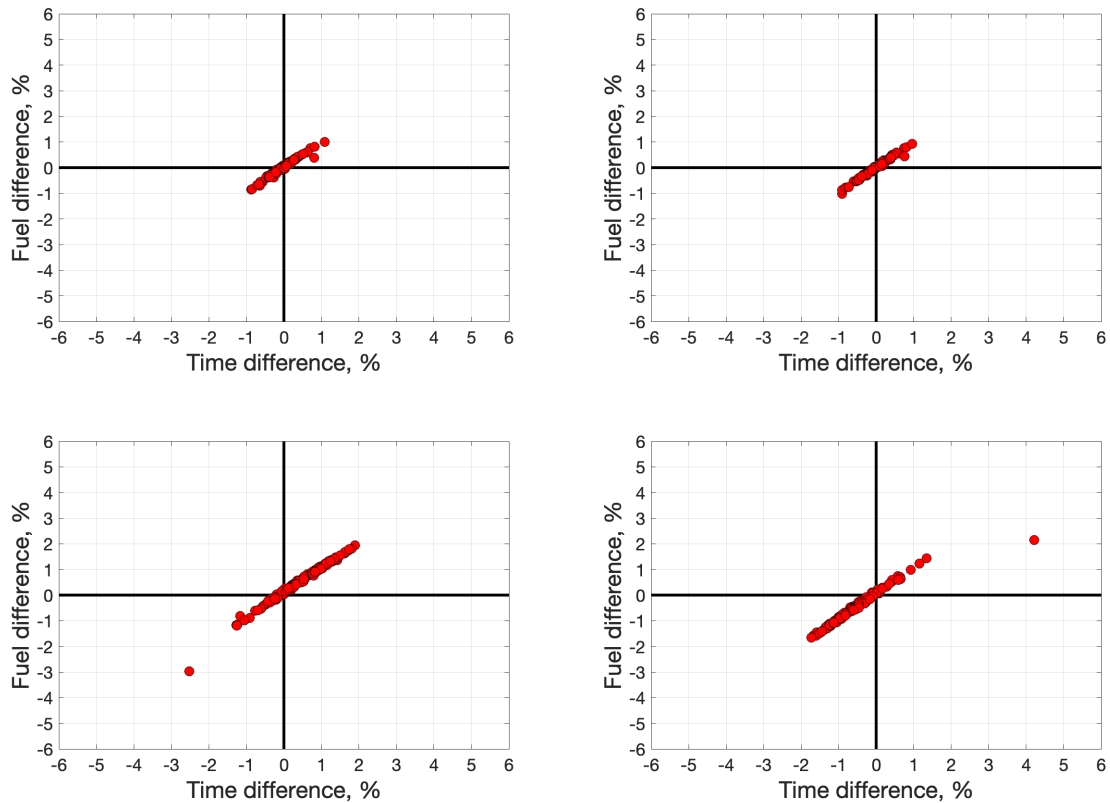


Figure 8 – Fuel and flight time difference with respect to MCTs from GSM NWP model during Summer Season (Top) MSM (Bottom) LFM.

Left Hand Side: RJTT -> RJFF, Right Hand Side: RJFF -> RJTT.

5. Contact Author Email Address

mailto: navinda@mpat.go.jp

6. Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.

References

- [1] Japan Airlines. Addressing Climate Change. <https://www.jal.com/en/sustainability/environment/climate-action/>, October 2023.
- [2] All Nippon Airways. ANA Group ESG Commitments. <https://www.ana.co.jp/group/en/csr/commitment/>, October 2023.
- [3] Chapter 3: Numerical Weather Prediction Models. Japan Meteorological Agency. https://www.jma.go.jp/jma/jma-eng/jma-center/nwp/outline2022-nwp/pdf/outline2022_03.pdf, March 2022.
- [4] Wickramasinghe N K, Nakamura Y and Senoguchi A. Evaluating the Influence of Weather Prediction Accuracy on Aircraft Performance Estimation. *The Proceedings of the 2021 Asia-Pacific International Symposium on Aerospace Technology (APISAT2021)*, South Korea, Vol. 2, pp 755-770, 2021.
- [5] Barman J F and Erzberger H. Fixed-range Optimum Trajectories for Short-Haul Aircraft. *Journal of Aircraft*, Vol. 13, No. 10, pp 748-754, 1976.

- [6] Erzberger H and Lee H. Constrained Optimum Trajectories with Specified Range. *Journal of Guidance and Control*, Vol. 3, No. 1, pp 78-85, 1980.
- [7] Jardin M R and Bryson Jr. A E. Neighbouring Optimal Aircraft Guidance in Winds. *Journal of Guidance, Control and Dynamics*, Vol. 24, No. 4, pp 710-715, 2001.
- [8] Bijlsma S J. Optimal Aircraft Routing in General Wind Fields. *Journal of Guidance, Control and Dynamics*, Vol. 32, No. 3 pp 1025-1028, 2009.
- [9] Hagelauer P and Mora-Camino F. A Soft Dynamic Programming Approach for On-line Aircraft 4D-Trajectory Optimization. *European Journal of Operations Research*, Vol. 107, No. 1, pp 87-95, 1998.
- [10] Wang S X, Yang Y S and Jing Z L. Optimal Flight Path Planning of Cruising Phase with No-Fly Zone Constraints Based on Dynamic Programming Algorithm. *Advanced Materials Research*, Vol. 433-440, pp 5911-5917, 2012.
- [11] Miyazawa Y, Matsuda H, Shigetomi S, Harada A, Kozuka T, Wickramasinghe N K, Brown M and Fukuda Y. Potential Benefits of Arrival Time Assignment - Dynamic Programming Trajectory Optimization applied to the Tokyo International Airport. *Eleventh USA/Europe Air Traffic Management Research and Development Seminar*, 2015.
- [12] Nakamura Y and Senoguchi A. Modeling of Aircraft Routes under Severe Weather Conditions. *AIAA SCITECH 2022 Forum*, pp 2022-0434, 2022.
- [13] Mendoza A M and Botez R M. Lateral Navigation Optimization Considering Winds and Temperature for Fixed Altitude Cruise using the Dijkstra's Algorithm. *Proceedings of the ASME 2014 International Mechanical Engineering Congress & Exposition*, 2014.
- [14] Filippone A. Cruise Altitude Flexibility of Jet Transport Aircraft. *Aerospace Science and Technology*, Vol. 14, pp 283-294, 2010.
- [15] Franco A, Rivas D and Valenzuela A. Minimum-Fuel Cruise at Constant Altitude with Fixed Arrival Time. *Journal of Guidance, Control and Dynamics*, Vol. 33, No. 1, pp 280-285, 2010.
- [16] Girardet B, Lapasset L, Delahaye D and Rabut C. Wind-optimal Path Planning: Application to Aircraft Trajectories. *2014 13th International Conference on Control Automation Robotics & Vision*, pp 1403-1408, 2014.
- [17] Jung H and Clarke J-P. Optimal Cruise Airspeed Selection and RTA Adjustment in the Presence of Wind Uncertainty. *Transportation Research Part C: Emerging Technologies*, Vol. 162, pp 104613, 2024.
- [18] Year 2019: Passenger Movements by Aircraft (in Japanese). Ministry of Land, Infrastructure, Transport and Tourism. <https://www.mlit.go.jp/report/press/content/001333684.pdf>, March 2021.
- [19] User Manual for the Base of Aircraft Data (BADA) Family 4. EEC Technical/Scientific Report No. 12/11/22-58, *Eurocontrol Experiment Centre*, Ver.1.3, 2016.