# Basic Analysis of Winds Aloft Forecast Used for En-Route Trajectory Prediction

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**Abstract** This paper provides the impact of a meteorological forecast model on the trajectory of aircraft for future Air Traffic Management based on trajectory operation. The ground speed of aircraft was calculated under the influences of seasonal wind conditions and meteorological forecast accuracy during cruise flights on the waypoints in the course towards Tokyo International Airport. Aspects of wind conditions of cruise altitude vary from season to season depending on the position of the waypoint, and whether jet stream exists or not. Aircraft ground speed tends to vary based on the direction of aircraft movement in addition to wind conditions. The predictions of ground speed were calculated using meteorological forecast data of 15 h prior or later. The results show that prediction accuracy of ground speed improves if recent prediction data is used. And ground speed prediction accuracy becomes lower and high RMS values overlap when and where wind speed widely varies.

**Keywords** Air traffic management • Meteorological forecast • Trajectory

## 1 Introduction

Trajectory-Based Operation (TBO) is the axis of a global Air Traffic Management (ATM) concept which is being developed by the International Civil Aviation Organization (ICAO) to accommodate a demand for safe, efficient and environmentally-friendly flights through technical advances in the air transport industry with increasing traffic volume [1]. For the purpose of realization of the TBO, prediction of aircraft trajectory is required not only in the aircraft on-board

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system but also in the ground system. One of the applicable aircraft performance models to predict aircraft trajectory is Base of Aircraft Data (BADA), which the Eurocontrol Experimental Centre provides [2]. To create a precise prediction of aircraft trajectory, a prediction model reflecting regional variations is being developed by comparison between predicted trajectory and actual measurement data [3–5].

The impact factors for the prediction of aircraft trajectory are aircraft kinetics, intentions of the pilot or air traffic controller, atmospheric conditions, and so on. The atmospheric conditions such as wind speed, wind direction and temperature are one of the key factors for predicting aircraft trajectory because atmospheric conditions affect aircraft speed during flight. Reflecting close to real conditions where aircraft is passing will help in developing a high-accuracy prediction model of aircraft trajectory, and the advancement of the wind prediction model for aircraft trajectory has been studied [6]. One high-altitude atmospheric condition data to be used is Numerical Weather Prediction (NWP) that the Japan Meteorological Agency (JMA) provides. NWP uses mathematical models of the atmosphere and oceans to predict the weather based on current weather conditions. The NWP model performance is checked whenever new atmospheric models are developed [7]. However, the impact on aircraft speed has never been analyzed. In order to clarify the impact of the meteorological forecast model on the trajectory, aircraft ground speed (GS) during cruise flights were calculated using values in the NWP model.

# 2 Methods

## 2.1 Aircraft Ground Speed Calculation

GS, which is the speed of the aircraft relative to the ground, was calculated in this study. The measurement and indication of airspeed are ordinarily accomplished on board connected to a pitot-static system. True airspeed (TAS) is the speed of the aircraft relative to the atmosphere. Figure 1 shows the vector relationship between the TAS and GS. The formula is as follows:

$$V_{GND} = V_{TAS}\, cos\, \varnothing_D + W\, cos\, (\varnothing_W - \varnothing_T) \tag{1}$$

where $\boldsymbol{V_{GND}}$ is ground speed, $\boldsymbol{V_{TAS}}$ is true airspeed, $\boldsymbol{W}$ is wind speed, $\varnothing_W$ is wind vector angle, $\varnothing_T$ is track vector angle and $\varnothing_D$ is drift angle, the drift angle is calculated as follows:

$$\varnothing_D = sin^{-1}\left(\frac{W}{V_{TAS}} sin\, (\varnothing_W - \varnothing_T)\right) \tag{2}$$

The simplest way to calculate TAS is by using a function of Mach numbers as follows:

$$V_{TAS} = M \times \sqrt{\gamma \cdot R \cdot T} \tag{3}$$

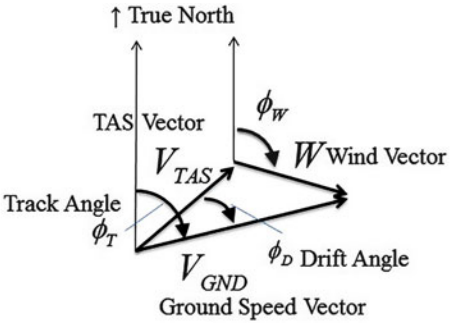


**Fig. 1** Relation between track direction and wind direction

where $M$ is Mach number, $\gamma$ is adiabatic index of air, $R$ is Real gas constant of air and $T$ is Temperature.

Generally, aircraft maintain a constant Mach number during cruise flight. GS was calculated using the constant Mach number 0.84 in this study.

### *2.2 Target Waypoints*

In the case of Japan, air traffic flow concentrates on Tokyo International Airport from each part of the country. Three main traffic flows were targeted in this study, from New Chitose (Sapporo), Fukuoka and Naha to Tokyo. Fixed waypoints, HPE (Hanamaki), IGOSO and SHIBK, located 200–300 NM (1 NM = 1,852 m) from the departure airport, were chosen as the points where GS was calculated, as shown in Fig. 2.

### *2.3 Meteorological Model*

The JMA has currently operated several NWP models to cover various types of forecasts. The Meso-Scale Model (MSM) is intended for use in basic data for prediction of disasters and for aviation with higher horizontal resolution. East–west and north–south direction of wind elements and temperature are gained from the Japan Meteorological Business Support Center online data service. Wind speed and wind direction were calculated from east–west and north–south directions of wind elements. Table 1 shows a brief overview of MSM Grid Point Value (GPV). Three pressure altitudes (300, 250 and 200 hPa) which are close altitudes that jet aircraft fly at as a cruising altitude in general, were used for this study. Forecast hours 15, 12, 9, 6, 3 and 0 were used for the meteorological forecast data analysis.

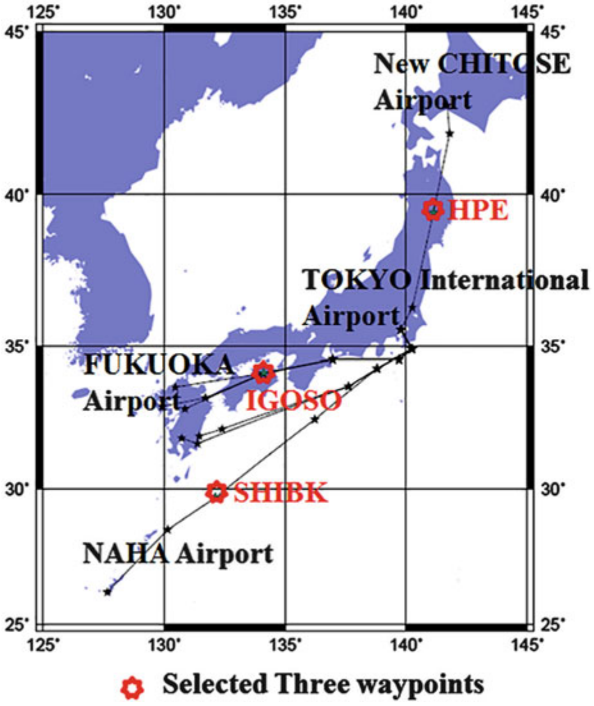


**Fig. 2** Flight course and target waypoints

**Table 1** Summary of MSM (GPV)

| | | | |
|---|---|---|---|
| Delivered range | Northern latitude between 22.4° and 47.6° | | |
| | Eastern longitude between 120° and 150° | | |
| Grid system | Latitude and longitude intervals | | |
| | Latitude 0.1° × longitude 0.125° | | |
| Initial value | 00, 03, 06, 09, 12, 15, 18, 21 UTC (eight times a day) | | |
| Forecast hours | 15 h forecast (00, 06, 12, 18 UTC) | | |
| | 33 h forecast (03, 09, 15, 21 UTC) | | |
| | 3 h intervals | | |
| Pressure altitude hPa (feet in ISA; 1 foot = 0.3048 m) | 100 (53,083 ft) | 150 (44,647 ft) | 200 (38,662 ft) |
| | 250 (33,999 ft) | 300 (30,065 ft) | 400 (23,574 ft) |
| | 500 (18,289 ft) | 600 (13,801 ft) | 700 (9,882 ft) |
| | 800 (6,394 ft) | 850 (4,781 ft) | 900 (3,243 ft) |
| | 925 (2,500 ft) | 950 (1,773 ft) | 975 (1,061 ft) |
| | 1,000 (364 ft) | | |

### 2.4 *Applicable Period*

For the purpose of examination of seasonality in high altitudes, 140 days (4 weeks from each of the five seasons as defined below) of MSM (GPV) data in 2011 were used.

- Winter: January 23 to February 19,
- Spring: April 24 to May 21,
- Summer: July 24 to August 20,
- Typhoon season: September 1 to September 28 and
- Autumn: October 23 to November 19; total 140 days

In the case of Japan, typically four seasons are characterized by atmospheric temperature difference and position of air mass. The months with the lowest temperature are January/February and the highest are July/August, which were defined as winter and summer respectively in this study. In addition to the four seasons, the typhoon season was also considered. Several cyclones with disturbance wind averagely pass through the Japanese archipelago in September. Two typhoons passed through the Japanese archipelago in September, 2011.

Every 3 h of the three pressure altitudes, 3,360 GS were calculated at each waypoint at one forecast hour, totaling 60,480 GS.

## 3 Wind Aspect at High Altitudes

There is a strong westerly wind that is a jet stream near the tropopause where jet aircraft fly at cruising altitude. The width of a jet stream is typically a few hundred kilometers and its vertical thickness is often less than 5 km. The condition of the wind near the tropopause varies due to the influence of the jet stream.

Figure 3 represents the wind speed and wind direction of 250 hPa at each waypoint. The dots are terminal points of one wind vector. The main stream of upper wind at each waypoint is westerly wind. Strong westerly winds are shown in the winter at IGOSO and SHIBK, meanwhile wind at HPE is weak and broadens widely throughout the season.

## 4 Seasonal Tendency of Aircraft Ground Speed

### 4.1 *Seasonally-Varying GS*

GS was calculated using values in the NWP. Table 2 shows mean and standard deviations of GS in each season assuming that aircraft maintains Mach number 0.84 during cruise flight at 250 hPa. There is not much difference in GS along each

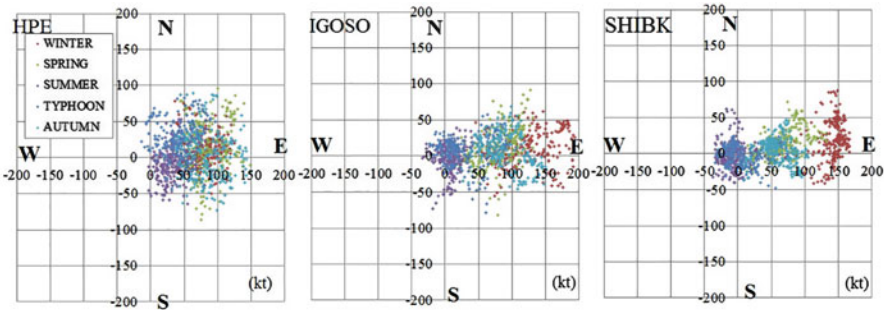


**Fig. 3** Terminal points of wind vectors

**Table 2** Aircraft ground speed at each waypoint at 250 hPa (kt)

| Waypoint | | Winter | Spring | Summer | Typhoon season | Autumn |
|---|---|---|---|---|---|---|
| HPE | Mean | 454 | 449 | 497 | 463 | 461 |
| | SD | 23 | 34 | 25 | 27 | 29 |
| IGOSO | Mean | 613 | 572 | 506 | 531 | 584 |
| | SD | 44 | 32 | 15 | 31 | 28 |
| SHIBK | Mean | 611 | 558 | 493 | 507 | 544 |
| | SD | 32 | 27 | 17 | 22 | 18 |

waypoint during the summer whereas it varies between IGOSO/SHIBK and HPE in other seasons. The variation among these waypoints is caused by flight direction to the destination airport. Especially in the winter, the gap of mean GS between IGOSO/SHIBK and HPE is wide. GS varies widely in the winter in the case of SHIBK and IGOSO, and in the spring in the case of HPE according to standard deviation.

Figure 4 shows distributions of GS at 250 hPa at each waypoint [probability density functions (PDF) and cumulative distribution functions (CDF)]. The peak of GS varies among seasons at IGOSO/SHIBK whereas peaks at HPE do not vary much from season to season. At SHIBK and IGOSO, GS is fast and varies widely especially in the winter.

## 4.2 Ground Speed Change in Three Hours

Table 3 shows the mean and maximum changes in GS over a period of 3 h. GS varies widely in the winter especially at IGOSO (Table 2), and the change in 3 h varies widely in the spring at HPE. The largest change is 57 knots (1 knot = 0.5144 m/s) in 3 h at HPE in autumn.

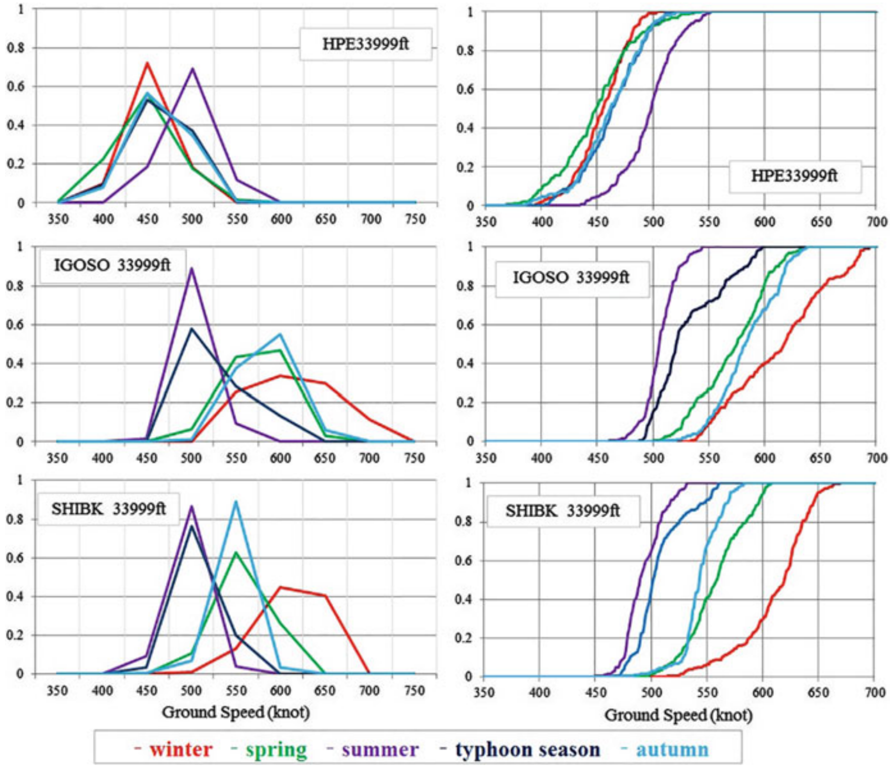


**Fig. 4** GS distributions

**Table 3** Mean and maximum change of GS in 3 h (kt)

| | HPE | IGOSO | SHIBK |
|---|---|---|---|
| *Mean* | | | |
| Winter | 8 | 8 | 6 |
| Spring | 10 | 8 | 6 |
| Summer | 6 | 5 | 5 |
| Typhoon season | 6 | 5 | 5 |
| Autumn | 8 | 5 | 4 |
| *Maximum* | | | |
| Winter | 45 | 33 | 21 |
| Spring | 47 | 42 | 29 |
| Summer | 32 | 32 | 25 |
| Typhoon season | 34 | 27 | 24 |
| Autumn | 57 | 34 | 22 |

# 5 Meteorological Forecast Data Analysis

## *5.1 Weather Prediction Errors*

Meteorological forecast data at zero hour is assumed as a true value in this study. Differences between data of forecast hours (FT = 15, 12, 9, 6 and 3) and zero are regarded as prediction errors. Wind speed prediction errors, wind direction prediction errors and temperature prediction errors are distributed symmetrically and their peaks are almost zero (Fig. 5).

Ninety-five percent of temperature prediction errors are within ±2°. Inside ±7 knots of wind speed, prediction errors are satisfied in 94 % of the FT3 and 76 % of the FT15. Accuracy of wind direction prediction errors drop in the summer and the typhoon season. One of the reasons for lower accuracy of wind direction predictions in the summer and the typhoon season is that the motion of typhoons which bring strong swirling wind is difficult to predict.

## *5.2 Ground Speed Prediction Errors*

Prediction accuracy of GS improves when using weather data predicted in more recent hours. Differences between GS calculated using meteorological forecast hours (FT = 15, 12, 9, 6 and 3) data and that of zero hour data were defined as GS prediction errors in this study. Figure 6 shows the distribution of GS prediction errors of FT15, FT9 and FT3. The mean of prediction error are −0.2 knots in the

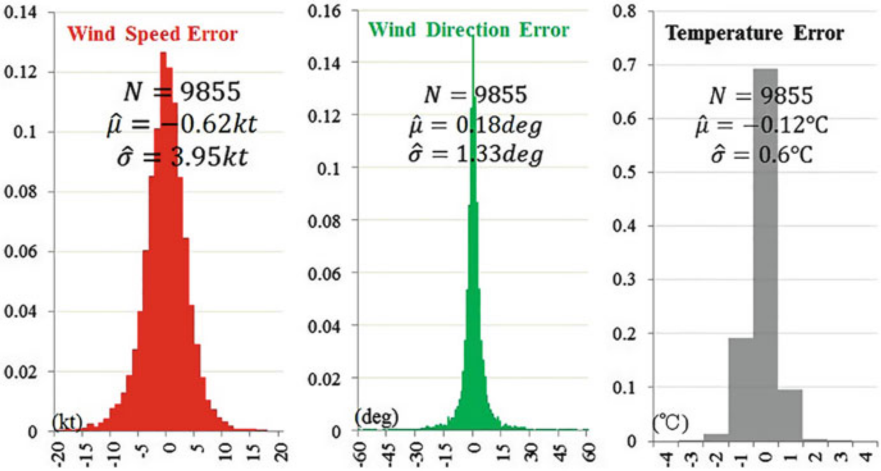


**Fig. 5** Weather prediction error distributions

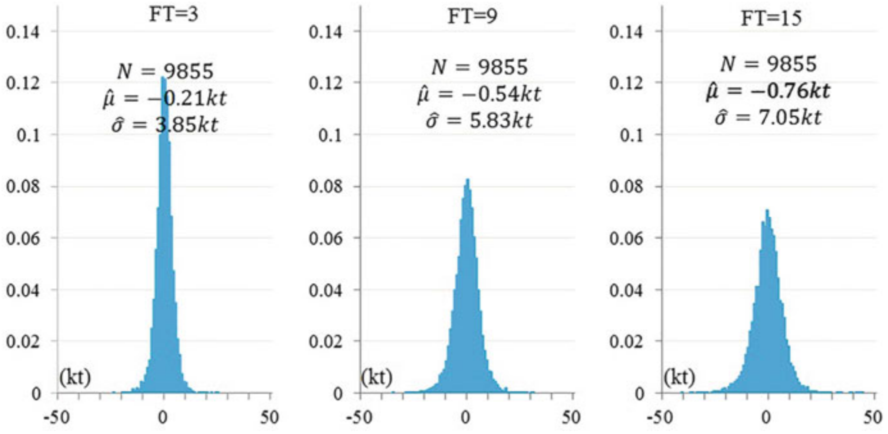


**Fig. 6** GS prediction error distributions

**Table 4** The percentage of prediction errors within ±7 kt

| | Winter (%) | Spring (%) | Summer (%) | Typhoon season (%) | Autumn (%) |
|---|---|---|---|---|---|
| *Wind speed prediction error within ±7 kt* | | | | | |
| HPE | 96 | 91 | 91 | 84 | 93 |
| IGOSO | 90 | 92 | 96 | 94 | 95 |
| SHIBK | 95 | 92 | 96 | 94 | 96 |
| *Ground speed prediction error within ±7 kt* | | | | | |
| HPE | 98 | 94 | 93 | 96 | 97 |
| IGOSO | 88 | 93 | 96 | 96 | 94 |
| SHIBK | 96 | 92 | 94 | 94 | 96 |

FT3, −0.5 knots in the FT9 and −0.8 knots in the FT15 respectively. More than 90 % of GS predictions fit within ±15 knots in the FT15, ±9 knots in the FT9 and ±6 knots in the FT3.

## 5.3 *Seasonal Tendencies of Errors*

Table 4 is the percentage of prediction errors of FT3 data both of wind speed and GS, which are within ±7 knots. Seasonal tendency of wind speed prediction errors are similar to that of GS prediction errors. The lowest-accuracy season is winter at IGOSO in both GS prediction errors and wind speed prediction errors. Table 5 is RMS values of GS prediction errors of FT3 data. The prediction accuracy becomes lower in the winter and RMS values are high.

**Table 5** RMS of GS prediction errors (kt)

| | Winter | Spring | Summer | Typhoon season | Autumn |
|---|---|---|---|---|---|
| HPE | 3 | 4 | 4 | 4 | 3 |
| IGOSO | 5 | 4 | 3 | 4 | 4 |
| SHIBK | 4 | 4 | 4 | 4 | 3 |

**Table 6** Days showing a maximum value of GS prediction error (kt)

| | | FT3 | FT6 | FT9 | FT12 | FT15 |
|---|---|---|---|---|---|---|
| HPE | Date and time | September 28 00Z | September 28 03Z | July 27 06Z | September 5 00Z | September 5 00Z |
| | MAX GS prediction error | 25 | 28 | 35 | 41 | 42 |
| IGOSO | Date and time | November 5 21Z | May 3 03Z | November 5 21Z | September 2 18Z | September 3 03Z |
| | MAX GS prediction error | 24 | 29 | 29 | 38 | 53 |
| SHIBK | Date and time | September 20 06Z | September 20 06Z | May 19 03Z | September 20 06Z | September 20 06Z |
| | MAX GS prediction error | 22 | 34 | 30 | 40 | 44 |

## 5.4 *Large Error Situations*

Days showing high-level GS prediction error are in Table 6. The largest GS prediction error was 53 knots at IGOSO on September 3. A typhoon passed through the Japanese archipelago on that day and the timing of a large error overlapped with the centre of the typhoon as it passed (Fig. 7). Upon viewing other days' meteorological analysis charts, the areas where high GS prediction errors were calculated were areas where air turbulence potentially occurs in most of the cases. Turbulence is caused by unstable atmosphere conditions such as typhoons (tropical cyclones) with a high cumulonimbus cloud, near the trough with horizontal/vertical wind shear along a strong jet stream, convective cloud area caused by unstable air and so on. A large change in wind speed and direction in a short time occur when those unstable atmosphere areas move. The mean of the amount of change in ground speed in 3 h is 23 knots on the days in Table 6. It is three or four times larger than the mean of all the days in Table 3.

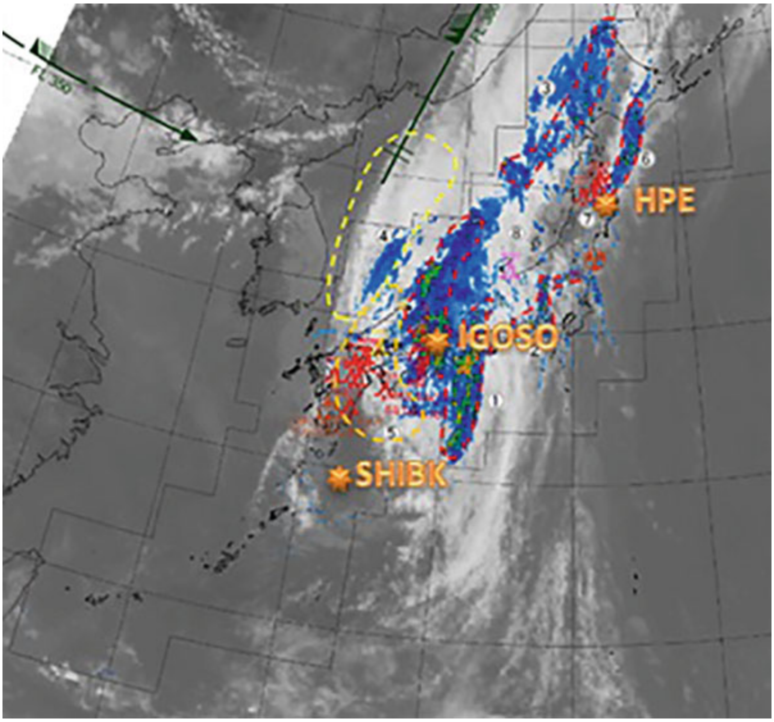


**Fig. 7** Analysis chart for aviation (ABJP) valid 03 UTC of September 3, 2011

## 6 Discussion

Prediction of aircraft trajectory accuracy is the key in the implementation of TBO for future ATM. Meteorological conditions affect aircraft attitude and speed during flight. The purpose of this study is to be able to analyze GS influenced by seasonal changes in atmospheric conditions and meteorological forecast accuracy.

### *6.1 The Impact of Jet Stream*

The existence of a jet stream is important for aviation because of its strong wind speed. Airline industries not only reduce the flight hours but also save fuel when the flight course is set by utilizing a jet stream, especially for east–west long-range flights. It is also known as clear air turbulence (CAT) caused by horizontal and vertical wind shear connected to the jet streams. In the northern hemisphere, the polar jet stream moves southward to approximately 25° at farthest during the winter and northward to approximately 45° during the summer in a meandering shape.

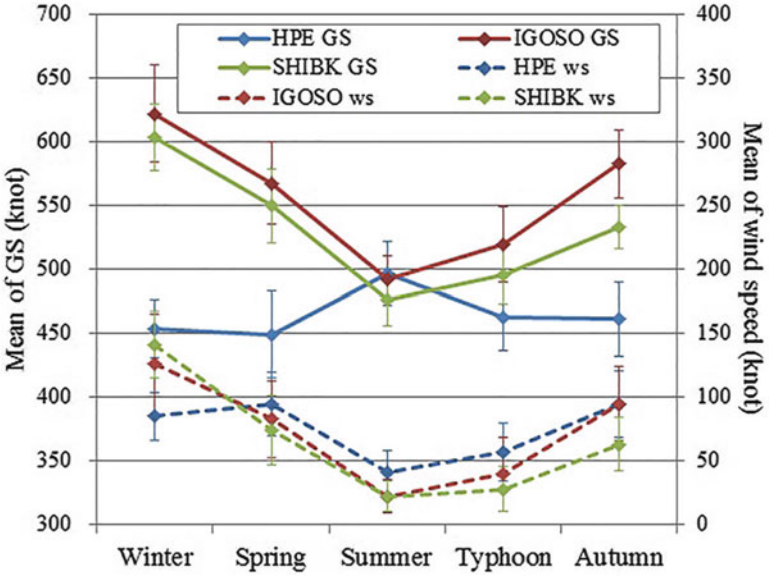


**Fig. 8** Mean of aircraft ground speed and wind speed at each waypoint (250 hPa)

Aspects of wind conditions at cruising altitude vary in each season depending on the position of the waypoint, and whether a jet stream exists or not.

GS during cruising flights varies due to both seasonal changes in wind and flight direction. Figure 8 represents the mean of GS and wind speed in each season in the same chart. GS of IGOSO/SHIBK are shown as lines with similar wind speed at each season, whereas GS of HPE is a contrasting line. The fastest GS was calculated in the winter for east-bound aircraft, and in the summer for southwest-bound aircraft.

## 6.2 GS Prediction Accuracy

GS prediction accuracy improves if recent weather forecast data is used. The mean of prediction error is −0.2 knots in the FT3. The zero hour weather data of MSM (GPV) is not an actual measured value of the atmosphere. It is the calculated value for the default used in predicting future atmospheric conditions, and serves as a useful reference value for determining the average atmospheric condition in the grid area. There are unpredictable atmospheric disturbances such as turbulences occurring in small local areas that do not show up in the MSM. Currently, data-link communication between aircraft during flight and ground-based systems has improved. By reflecting actual atmosphere tendencies from measured meteorological elements by aircraft during flight into algorisms of ground prediction systems, the accuracy of trajectory prediction will improve even more.

It is expected that the required time tolerance will be 30 s at the en-route waypoint in the initial 4D trajectory data link of operations [8]. The difference of 9 or 10 knots during cruise flight rises by approximately 30 s at 200 NM away. And a 7-knot peak of wind vector error is required to satisfy the 6-knot longitudinal error in trajectory accuracy requirements [9]. In en-route phase, the planned TAS by the airline relatively fits with the actual TAS. The mean of the difference between the actual TAS and the planned TAS was −4 knots [10]. GS prediction error shows up as the sum of TAS prediction error and wind prediction error. Although there were a few large GS prediction error areas, the mean of GS prediction error was small and relatively matched within ranges of trajectory prediction requirements, under the no TAS error condition in this study. Therefore, GS prediction error appears mainly to be due to the aircraft kinetic model error such as TAS prediction.

When it comes to a climbing or descending phase, it has been clarified that the estimate error of wind, especially wind direction, is large under a height of 20,000 ft (1 foot = 0.3048 m) by the estimation of TAS/CAS from radar data [10]. Atmospheric conditions in a climbing or descending phase also have an effect on aircraft trajectory, however there is not much impact in comparison with cruising altitude. The mean and standard deviations of wind speed at 20,000 ft in the winter, the season the wind speed is strongest, were approximately 60 and 20 knots respectively in an additional study. The wind speed was approximately half compared to cruising altitude.

When and where the GS prediction accuracy became lower overlapped with when and where wind speed widely varied. The largest GS prediction error was 53 knots in this study. In most of these large error cases, the area where a high GS prediction error was calculated was where air turbulence potentially occurs. Turbulence is caused by unstable atmosphere conditions. To make short intervals to update the atmospheric conditions forecast with the assistance of actual weather data from aircraft during flight by data-link, the accuracy of predictions will improve in the future. The first step, to examine atmospheric conditions which have the possibility to cause large prediction errors will be helpful to determine an indicator in regard to trajectory prediction accuracy depending on weather conditions.

### *6.3 Comparison of Accuracy Between GS and Weather Prediction Errors*

For the purpose of determining which weather prediction errors impact GS prediction errors, the correlation of the accuracy, which is the percentage of prediction error contained in a certain range of error, of weather prediction errors and GS prediction errors was assessed. Figure 9 shows the correlation between GS prediction accuracy and weather prediction accuracy at IGOSO. Wind speed prediction accuracy shows the most matched linear relationship with GS prediction accuracy rather than that of wind direction and temperature prediction accuracy. Stronger

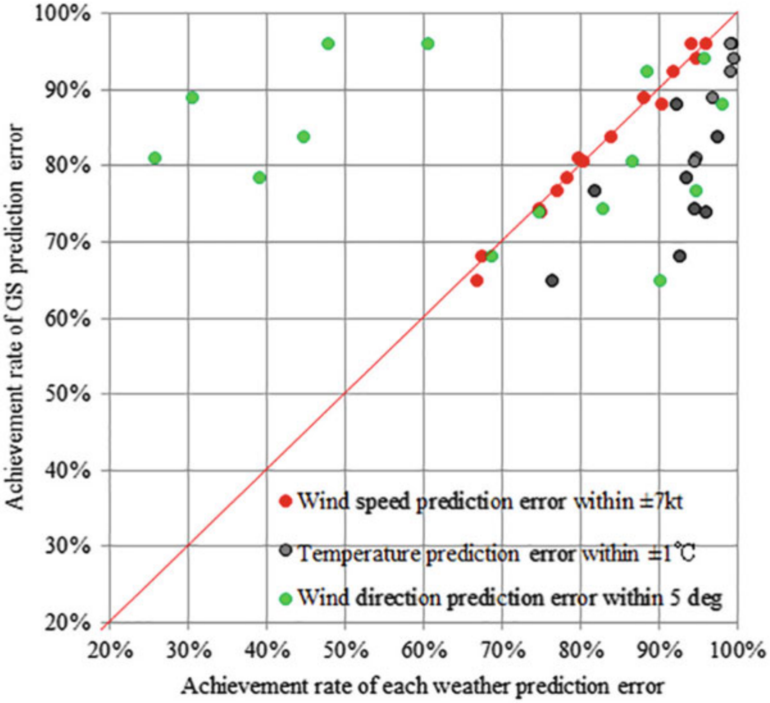
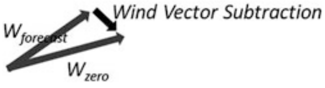


**Fig. 9** Comparison of accuracy between GS prediction errors and weather prediction errors

**Fig. 10** Wind vector subtraction



wind blows at aircraft cruising altitude than at ground height in most of the cases, so wind speed prediction errors have an influence on GS prediction errors at cruising altitude.

A wind vector contains both wind speed factors and wind direction factors. The difference between the forecast hour wind vector ($\boldsymbol{W}_{forecast}$) and the zero hour wind vector ($\boldsymbol{W}_{zero}$) is one degree of exactness of prediction (Fig. 10). As wind vector subtraction ($|\boldsymbol{W}_{forecast} - \boldsymbol{W}_{zero}|$) increases, prediction accuracy lowers. So, a similar analysis was conducted between GS prediction errors and wind vector subtraction. The coefficient of determination ($\boldsymbol{R}^2$) of wind speed prediction accuracy and GS prediction accuracy within ±7 knots was 0.91, 0.99 and 0.96 at HPE, IGOSO and SHIBK respectively. The relationship between the GS prediction accuracy and the wind vector subtraction within ±9 knots was 0.97, 0.91 and 0.96 respectively in a similar analysis. Wind vector subtraction within ±9 knots derived a higher coefficient than that of within ±7 and ±10 knots.

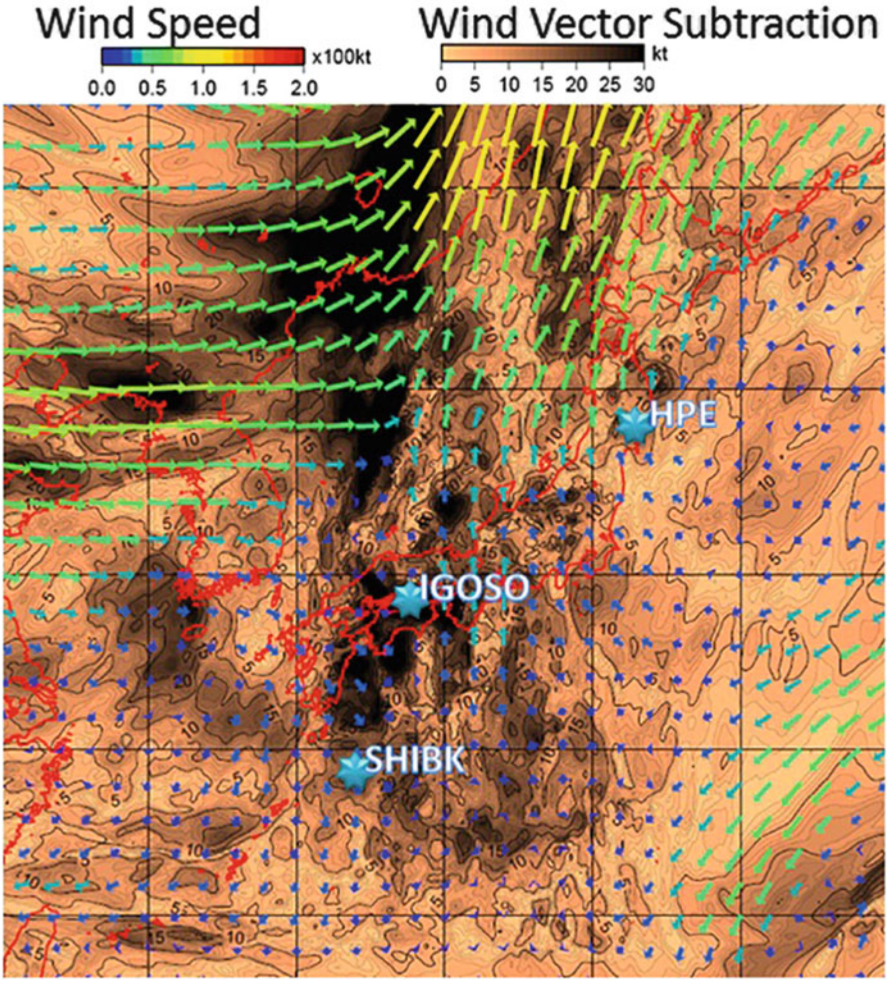


**Fig. 11** Wind vector subtraction between FT15 and FT10

As described above, the wind speed was the most influential component in GS prediction, and the correlation of wind vector subtraction and GS prediction accuracy was also high. Figure 11 represents the contour of wind vector subtraction between FT15 and zero with a brown color scale at the time of the largest GS prediction error (the same day as in Fig. 7). When the wind speed is high, the wind vector subtraction tends to be large. Even when the wind speed is weak, wind vector subtraction tends to be large when whirling wind (i.e. cyclones) moves, because it is difficult to predict the movement accurately.

Wind vector subtraction is capable to express dynamic wind vector change such as cyclones, even when the wind speed is weak. One of the indexes to express weather forecasts uncertainty is “ensemble”, and a time-lagged ensemble of weather model forecasts were estimated and used to estimate the level of uncertainty in hypothetical aircraft trajectory predictions [11]. One possible next step of this study would be inserting the wind forecast uncertainty index into the wind vector subtraction value to define “hot spot” which have the possibility to cause large prediction errors.

## 7 Conclusion

GS was calculated under the influences of seasonal wind conditions and meteorological forecast accuracy during cruise flight on three way points towards Tokyo International Airport from north, west and southwest directions. The prediction of aircraft trajectory at cruising altitude is more likely to be affected by wind factors than during climb or descent phases because of a jet stream, that is a strong westerly wind. Aspects of wind conditions at cruising altitude varied in each season depending on the position of the waypoint, and whether a jet stream existed or not. The tendency of GS varied by direction of aircraft in addition to the wind conditions.

The results showed that prediction accuracy of GS improved by using weather data predicted in more recent hours, as expected. Although there were a few large GS prediction error areas, the mean of GS prediction error was small and relatively matched within ranges of trajectory prediction requirements, under the no TAS error condition in this study. There was also a new finding of relation between prediction accuracy and meteorological conditions, when and where the GS prediction accuracy became lower overlapped with when and where wind speed widely varied.

The wind speed component was the dominant element in making an impact on aircraft ground speed prediction errors among meteorological prediction errors. Also wind vector subtraction is one degree of exactness of prediction. Wind vector subtraction is capable to express dynamic wind vector change such as cyclones, even when the wind speed is weak. The results lead to suggest that one possible next step in this study would be inserting the wind forecast uncertainty index into the wind vector subtraction value to define “hot spots” which have the possibility to cause large prediction errors.

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