Sensitivity of Flight Durations to Uncertainties in Numerical Weather Prediction

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***Abstract*—Due to the chaotic nature of weather and limitations in modelling and observations techniques, inaccuracies remain even in state-of-the-art Numerical Weather Prediction (NWP) systems. In aviation, Trajectory Predictions (TPs) are currently based on deterministic METeorological (MET) forecasts and do not make use of the uncertainty information available from Ensemble Prediction Systems (EPSs). The Investigation of the Optimal Approach for Future Trajectory Prediction Systems to Use METeorological Uncertainty Information (IMET) consortium aims to improve the stability and predictability of Air Traffic Management (ATM) systems by exploring the potential benefits of incorporation of MET uncertainties in current TP systems.**

Using a simplified version of the National Aerospace Laboratory of the Netherlands (NLR)'s TP system, we study the variation in flight duration with MET uncertainties along a fixed route from John F. Kennedy International Airport, New York (KJFK) to Aéroport Paris–Charles de Gaulle (LFPG). Initial results suggest that for the fixed route considered, the variation in flight time due to MET uncertainties is generally small ($\leq 1\%$) compared to the total flight time, although it can be significant in specific MET circumstances. We propose diverse ways of visualising MET uncertainties and quantifying their impact on TP. These approaches can be used to integrate MET uncertainties in TPs by developing new cost indices to account for MET uncertainties in the selection of an optimal route.

***Keywords*-air traffic management; ensemble; numerical weather prediction; trajectory prediction; uncertainty**

I. Introduction

Given the chaotic nature of the atmosphere, predicting the weather is a challenging task. Small errors in the specification of initial condition (IC) of the atmosphere in Numerical Weather Prediction (NWP) systems may rapidly evolve into completely different outcomes. The accuracy of NWP is also limited by factors such as observation techniques/coverage, data assimilation methods, model parameterisations and boundary conditions. Even with major advancements in forecast techniques in recent years, inaccuracies remain in NWP results, including the deterministic[1] forecasts for Air Traffic Management (ATM).

Over the last few decades, Ensemble Prediction Systems (EPSs) have been developed to help quantify forecast uncertainties. The core concept of an EPS is to initialise originally identical forecasts by slightly altering the starting condition representing the uncertainty in the initial conditions, yielding an ensemble of forecasts. Data assimilation techniques are often used in EPSs to get the best possible ICs from observations. By considering the ensemble spread, it is possible to assess the uncertainty involved in any given ensemble forecast.

After years of development, EPSs have proved to be an effective way of improving forecast skill and quantifying uncertainties. EPSs are now run operationally in most weather centres such as Met Office, Météo France, European Centre for Medium-Range Weather Forecast (ECMWF) and National Centers for Environmental Prediction. With recent development of EPSs, there is a great potential for use in range of customer applications including ATM, especially in the prediction of flight trajectories. For instance, results from a sensitivity study focusing on the Terminal Manoeuvring Area (TMA) [Schuster and Ochieng(2012)] has shown that METeorological (MET) uncertainty is a key contributor to flight trajectory error.

In the planning phase of ATM [SESAR WP C & partners(2012)], airlines and their Flight Operation Centres (FOCs) upload their flight intentions (in the form of an initial 4D flight trajectory) from six months to weeks before the proposed day of operations. This trajectory is shared with relevant Air Navigation Service Providers (ANSPs) and airport operators, and is progressively refined. It is usually based on users' choice and climatologies, and is referred to as the Shared Business Trajectory (SBT). At 72 hours before execution [EUROCONTROL(2014)], the SBT is finalised into a Reference Business Trajectory (RBT) as short-range [2] MET forecasts become available. At the moment, RBTs are calculated based on deterministic MET forecast, from which no uncertainty information is available. As a result, there is no way of assessing the likelihood of the proposed RBTs from the MET forecast. Even though short-range deterministic forecasts are generally accurate, there have been occasions when large-scale unpredicted events develop in the

[1] A deterministic forecast refers to a single forecast of event of specific magnitude, time and location, with no account of its likelihood to happen

[2] In MET terms, a short-range forecast refers to forecast beyond 12 hours and up to 72 hours [WMO(2010)]

atmosphere [Bowler et al.(2008)]. In such cases adjustments to flight trajectories have to be made at short notice, causing delays and incurring extra fuel costs.

Trajectory Prediction (TP) is a cost minimisation problem. In the context of flight TP, assuming safety isn't compromised, the cost to minimise is flight duration while accounting for other constraints such as available airspace capacity and weather hazards. In this paper, the effect of wind on flight time for a specific route is investigated. With deterministic forecasts, it is difficult for the flight crew to estimate how accurate the wind (and other MET parameters) forecasts are compared to the actual situation. As a result, extra fuel has to be taken on board. With the introduction of ensemble MET forecasts, which are currently underused in aviation applications, the Investigation of the Optimal Approach for Future Trajectory Prediction Systems to Use METeorological Uncertainty Information (IMET) project [3], which is part of Single European Sky Air Traffic Management Research (SESAR)'s WP-E Long-term and Innovative Research programme, aims to incorporate MET uncertainties and develop a Probabilistic Trajectory Prediction (PTP) system. PTP differs from existing deterministic ones in the fact that additional costs may be assigned to regions of high MET uncertainty. The PTP algorithm will then try to avoid these regions such that both flight duration and other costs, including course safety, are optimised.

The first step towards the development of a PTP system is to establish an understanding of how uncertainties in MET forecasts translate into variations in flight times such that 'cost' of MET uncertainty can be determined consistently. For example, is it safer and faster to travel through a region of strong but uncertain tail wind or via an alternative region with weak and stable tail wind?

From an ATM point of view, there is no way of assessing the uncertainties of arrival times of all the flights entering the European airspace with deterministic TP. With the improved airspace usage predictability PTP brings, ATM can confidently plan more flights into a given time frame, making a more efficient use of the congested European airspace. PTP also minimises the risk of making last minute changes to the flight plan due to unforeseen weather conditions. On the other hand, airlines will also benefit from better estimates of the minimum amount of contingency fuel required for each flight.

This paper is structured as follows: Sections II describes the EPS used for this study. Section III is dedicated to the description of the method. Results and preliminary conclusions are given in Sections IV and V respectively.

[3]http://www.imet.pro

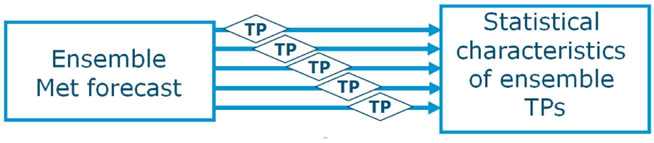

Fig. 1. Schematic of ensemble TP

II. Ensemble MET forecast

The MET forecast used in this paper is that of Met Office Global and Regional Ensemble Prediction System (MOGREPS) [Bowler et al.(2008)]. MOGREPS has been the Met Office's operational EPS since 2008. MOGREPS consists of 12 members (1 control + 11 perturbed) and is run at t=0000, 0600, 1200, 1800 UTC daily. The IC of each ensemble member is generated using the ensemble transform Kalman filter as described in [Bishop et al.(2001)]. Unlike other EPSs (e.g. the one at ECMWF), MOGREPS is designed to represent MET uncertainty in the short range (days 1-2) rather than medium range (days 3-10), which coincides with the time frame in which RBTs are usually determined.

The version of MOGREPS used in this study covers the whole of the globe and has a horizontal resolution of N400 ($\sim$ 33km at mid-latitudes)[4] with 70 model levels in the vertical. The output interval of the model is 3 hours. The dates considered are from 1^{st} May 2013 to 30^{th} April 2014 inclusive.

III. TP using ensemble MET forecast

Other than determining MET uncertainty of TP calculations by introducing probability factors on all MET parameters in a single deterministic forecast (e.g. [Schuster et al.(2012)], [Kaiser M.(2011)]), the IMET project aims to find statistical characteristics of TP calculations from members of an ensemble MET forecast (Figure 1). The main reason for this innovative approach is that MET parameters in a forecast are highly correlated as outcome of the NWP models, thus a lot of information is lost when using non-correlated stochastic MET parameters of a single forecast.

Initially the outcome of the TP system of the National Aerospace Laboratory of the Netherlands (NLR) is studied. The TP system conforms to common trajectory prediction structure and capability as described in [FAA/EUROCONTROL(2004)]. The aerodynamics and thrust forces are determined as in the Base of Aircraft Data (BADA) project [Nuic(2010)] throughout the flight and are used to drive the equations of motion. When the time and space coordinates of the next step of the flight is available, the corresponding MET data (pressure, temperature and wind vector) is extracted from the MET forecast for an update of

[4]Horizontal resolutions in MOGREPS are denoted using the notation Nn indicating the model have $2n$ and $(\frac{3n}{2}+1)$ grid points along each latitude circle and longitude respectively

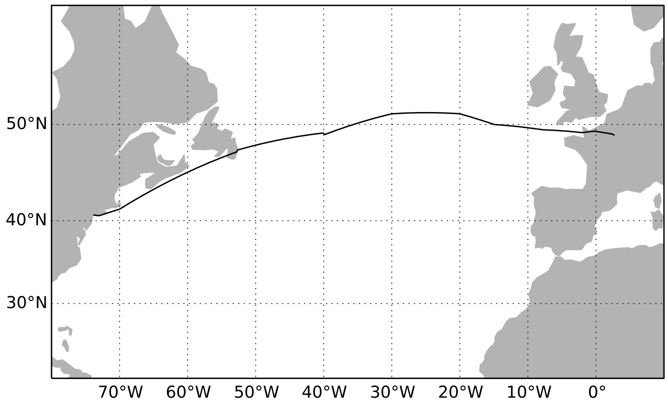

Fig. 2. A typical flight route going from KJFK to LFPG.

the ground speed. Autopilot and autothrust are also simulated in the NLR's TP system to keep the aircraft on track, with the requested speed and altitude profiles.

A fixed eastbound route from John F. Kennedy International Airport, New York (KJFK) to Aéroport Paris–Charles de Gaulle (LFPG) is chosen for this study (Figure 2). The route was flown on 5^{th} July 2013 (and possibly other dates) is very close to the great circle between the airports. Along this route there are 321 points computed, with a constant interval of 10 nautical miles (Nm) (≈18.52 km) between each. In order to investigate the sensitivity of the MET conditions on flight duration, we assume a constant flight level of FL340 (corresponding to air pressure ≈ $250hPa$) throughout the course of flight, with no ascent or descent, as well as a constant Mach number of 0.82.

Given those assumptions, where no optimisation is done with respect to aircraft performance, economic (ECON) speed and altitude, it was found that simple speed formulae would suffice for this study. At any given point along the trajectory, the ground speed V_g and air speed V_a are given by,

$$V_g = \sqrt{V_a^2 - w_X^2} + w_T \quad (1)$$

$$V_a = MS_0\sqrt{T/T_0} \quad (2)$$

where w_X and w_T represent the crosswind and tailwind respectively, T is the temperature and S is the speed of sound. M is the Mach number. Subscript 0 denotes the fact that the specified variable is at sea-level. Using Equations 1 and 2 and the assumptions above, the total flight duration for each ensemble member of a given forecast is determined by summing up the time taken for the aircraft to fly from each of the 321 points to the next.

IV. Results

Figure 3 shows an example of high MET uncertainty and its impact on flight duration along the route indicated in Figure 2. The x- and y-axis represent the distance travelled along the route and forecast range respectively. The top panel shows forecast initiated at $1800UTC$ on the day before flight execution (hereafter F_{18D-1}). The middle and bottom panel show forecasts for $0600UTC$ and $1800UTC$ on the day of flight execution (hereafter F_{6D0} and F_{18D0}) respectively. The x-axes of the panels are aligned such that the validity times of the three ensemble forecasts are matched. For example, the forecast range at 2100 UTC is t+27 for the F_{18D-1} forecast (top), whereas it is t+15 for the F_{6D0} (middle) forecast.

The contour lines in black show the ensemble mean ground speed along the route shown in Figure 2. The colour map represents the standard deviation (σ) of ground speeds among the ensemble. For each take-off time, a blue arrow is drawn to denote the variation (1σ interval) of ensemble flight times (hereafter σ_{FT}). The scale for the blue arrows is located at the right y-axis. Each yellow line tracks the ensemble mean position of flight along the specified route for a given take off time and is directly related to the ground speed. For instance, referring to the top panel of Figure 3, an aircraft taking off 0600 UTC (t+12) would have travelled 1500 Nm from KJFK along the pre-defined route by 0900 UTC (t+15) (see first yellow line from the left). Note that the yellow lines are ensemble means and do not carry any uncertainty information. They serve as an visual aid for observing the link between the variation in ground speeds as a result of MET forecast uncertainty and total flight durations.

Referring to the top panel of Figure 3, the largest MET uncertainty is located between 1500 - 2700 Nm along the route. The magnitude of ground speed uncertainty starts to grow with time starting from t+21, up to a maximum of 6 ms^{-1} (≈ 2.86% of the ground speed). The variation in flight duration can be approximated by the line integral of the yellow line with the ground speed uncertainty, i.e. the extent to which each of the yellow lines 'overlaps' with regions with high MET uncertainty.

As a result of higher MET uncertainty towards the end of MET forecast, σ_{FT} is also found to increase with the forecast horizon, with a maximum of 4.4 minutes for a ∼400-minute flight (top panel, t+30).

Referring to middle and bottom panel, which are forecasts initiated at a later time (i.e. shorter forecast range for the same validity time), both the uncertainty in MET and flight duration are reduced for flights taking off at the same validity time.

Figure 4 is the same as Figure 3 but for a selected case study with low MET uncertainty, 4^{th} February 2014. Compared to Figure 3, the ensemble mean ground speed is generally stronger but with significantly less variation among the ensemble members. As a result, the flight durations are in general shorter (< 360 minutes) with a low σ_{FT}. Note that even in the F_{18D-1} case, there is no obvious increase in flight time uncertainty even at the t+33 forecast range. In the F_{18D0} case, σ_{FT} of flight time is found to be negligible.

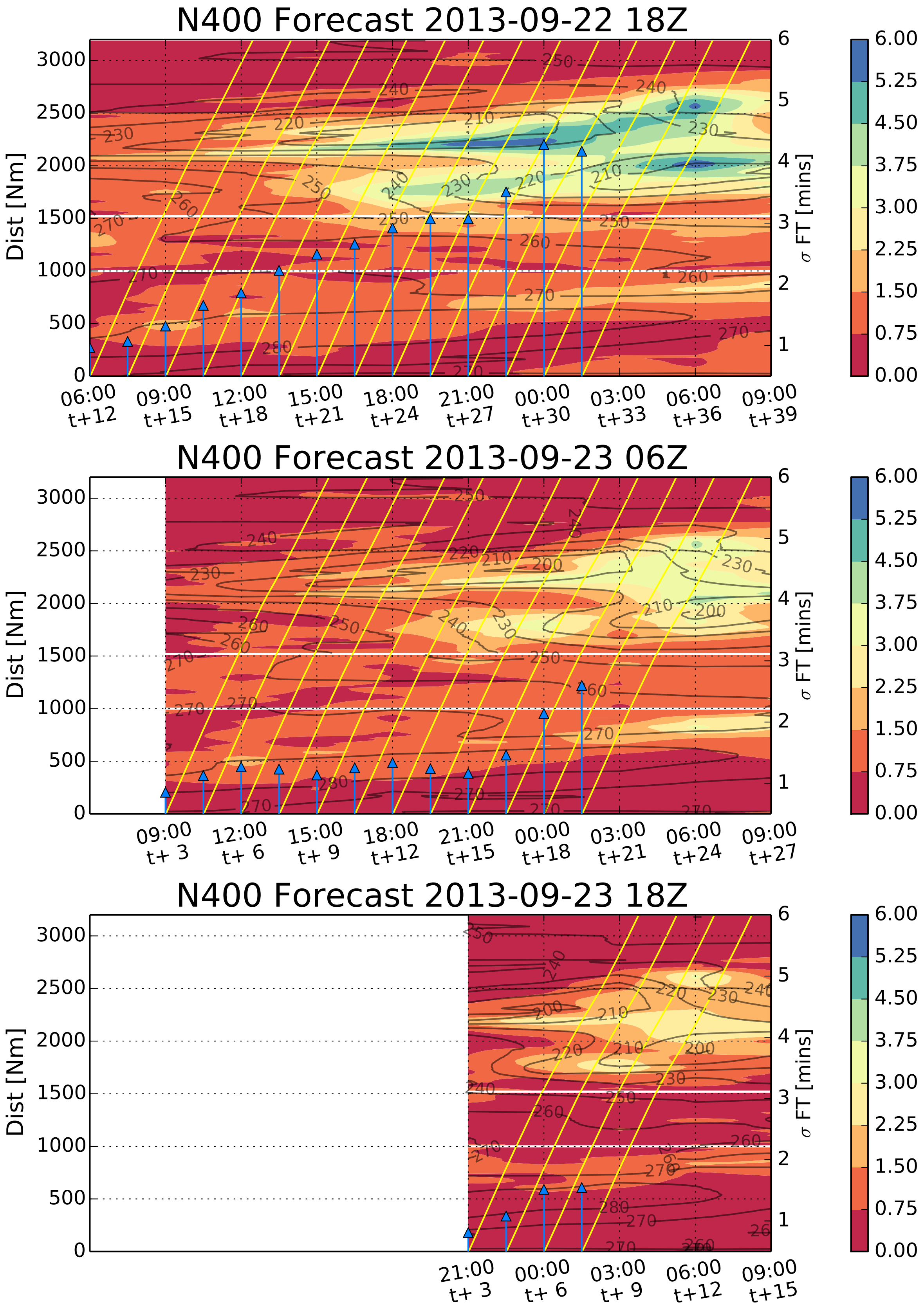

Fig. 3. Case study for 23rd September 2013: Black (coloured) contours show the ensemble mean (standard deviation) ground speed along the route shown in Figure 2. The x- and y-axes (left) denote distance travelled along route and forecast range / UTC time respectively. Top panel is for forecast initiated at 1800 UTC on the day before flight execution; middle and bottom panels are for forecasts initiated at 0600 UTC and 1800 UTC on the day of flight execution respectively. Given a specific take off time, each yellow line shows the position of flight along route at any given time. The blue arrows denote 1σ of flight duration among the ensemble members as a function of take off time. The scale of the flight times uncertainty is marked on the right hand side of the y-axis.

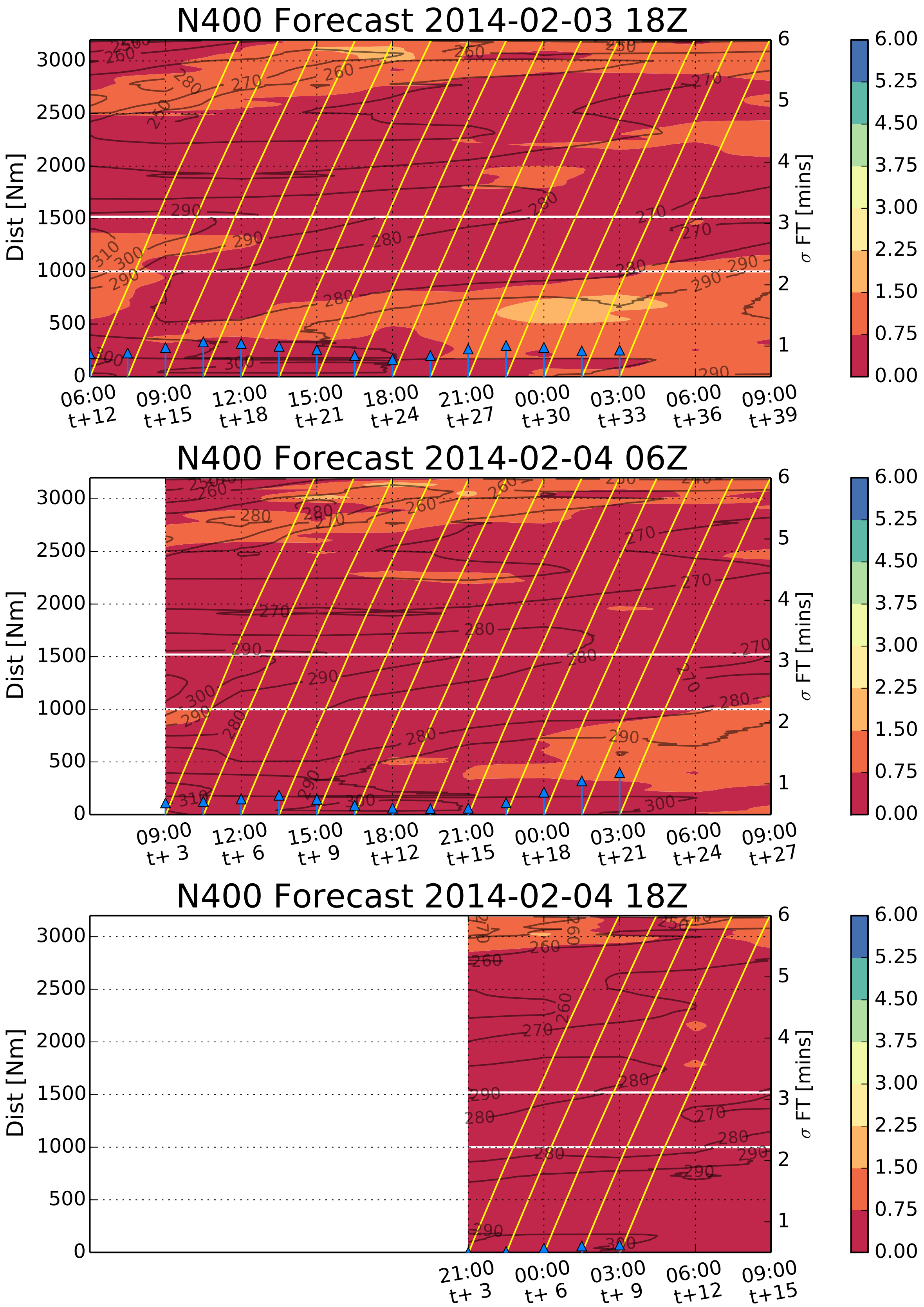

Fig. 4. Same as 3 but for 4^{th} February 2014.

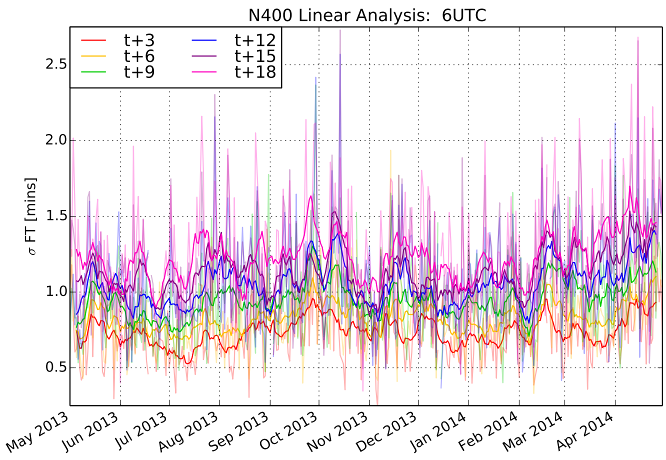

Fig. 5. Variation of ensemble flight times from 1^{st} May 2013 to 30^{th} April 2014. All forecasts are initiated at 0600 UTC on the day of flight execution. Data for flights taking off at forecast range from $t+3$, $t+6$, $t+9$, $t+12$, $t+15$ and $t+18$ is shown. The pale lines show actual data and solid lines show a 9-day moving average.

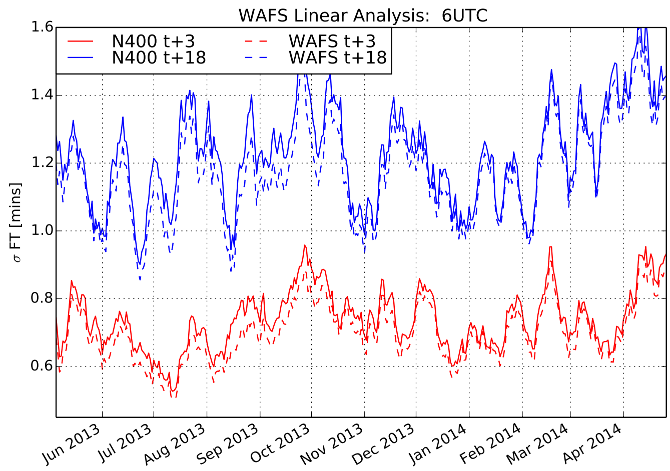

Fig. 6. Same as Figure 5 but only 9-day moving averages for $t+3$ and $t+18$ are shown. Solid and dashed lines show σ_{FT} calculated using high ($N400$,$\sim$33km)and low ($WAFS$, $\sim$140km) resolution respectively.

Figure 5 shows the daily variation of ensemble flight time uncertainties along the route given in Figure 2. It is found that σ_{FT} among the ensemble increases with forecast range which is an expected result. The daily fluctuation of σ_{FT} can be large especially at the t+15 and t+18 forecast ranges. However, no strong seasonal variation for σ_{FT} is found.

As mentioned in Section III, MET data is linearly interpolated on to the points along the chosen flight path. As a result, the resolution of the source data is potentially important for our analysis. Figure 6 compares the variation in σ_{FT} with resolution of MET data. The time series are for 9-day running mean σ_{FT} for flights taking off at $t+3$ (red) and $t+18$ (blue). The solid lines are for MOGREPS operational resolution (i.e. $N400$, corresponding to $\sim$33 km at mid-latitudes) and are the same as the corresponding ones in Figure 5. For the dashed lines, the methodology is the same except MOGREPS output is interpolated to the standard World Area Forecast System (WAFS) grid offline before further interpolating onto the points of the chosen route.

It is observed that in the WAFS case, which is the standard resolution for MET forecast in the aviation industry, σ_{FT} is generally underestimated compared to that of the $N400$ case. This is possibly due to the fact that small scale features are averaged out. Note that Figure 6 shows only 9-day running means of σ_{FT}. In the extreme case, the daily difference in σ_{FT} between the two resolutions can be as large as 30% (not shown).

V. Conclusions and Final Remarks

Despite the success of EPSs over the last few years, flight TPs are based on deterministic MET forecasts and do not take uncertainty into account. This paper establishes an insight of how uncertainty in MET forecasts could impact on flight durations, and provides a crucial step towards the development of a new PTP system.

In this paper we focused on a fixed route going from KJFK to LFPG. Using ensemble MET forecasts from a state-of-the-art EPS, the duration for a flight with fixed Mach and flight level was calculated for each ensemble member of the MET forecast. Two case studies, which highlight scenarios of opposing level of MET uncertainties, were presented.

We found that the variation of ensemble flight times σ_{FT} is generally small compared to the total flight time ($\leq$ 1%) for the route considered. Also, the spread of flight duration is found to be underestimated when MET data of a coarse resolution is used (i.e. WAFS gridded forecasts). However, in some cases, we found that uncertainty is large enough for the variation in flight duration to become significant in terms of fuel consumption and punctuality.

In conclusion, we have explored various approaches of visualising areas of high MET uncertainty and quantifying their impact on TP. Forecast uncertainties derived from ensemble forecasts can now be integrated in TPs to measure the cost of MET uncertainties in the selection of the optimal route.

We are fully aware that flight optimisation with TP calculations are far more complex than presented herein (economical speed, optimum altitude, etc). Another aspect of MET forecast is the uncertainty with respect to adverse weather (i.e. thunderstorm, clear air turbulence) that could impact the spread of TP. This will be investigated in the next phase of the IMET project.

Acknowledgement

This work is co-financed by EUROCONTROL acting on behalf of the SESAR Joint Undertaking (the SJU) and the EUROPEAN UNION as part of Work Package E in the SESAR Programme. Opinions expressed in this work reflect the authors' views only and EUROCONTROL and/or the SJU shall not be considered liable for them or for any use that may be made of the information contained herein.

References

[Bishop et al.(2001)] CH Bishop, BJ Etherton, and SJ Majumdar. Adaptive sampling with the ensemble transform Kalman filter. part I: Theoretical aspects. *Monthly weather review*, 129(3):420–436, 2001.

[Bowler et al.(2008)] NE Bowler, A Arribas, KR Mylne, KB Robertson, and SE Beare. The MOGREPS short-range ensemble prediction system. *Quarterly Journal of the Royal Meteorological Society*, 134(632):703–722, 2008.

[EUROCONTROL(2014)] EUROCONTROL. European network operations 2014-2018/19. http://www.eurocontrol.int/sites/default/files/publication/files/european-network-operations-plan-2014-2018-2019.pdf, 2014.

[FAA/EUROCONTROL(2004)] FAA/EUROCONTROL. Generic Trajectory Predictor Structure, Action Plan 16 https://acy.tc.faa.gov/cpat/tjm, 2004.

[Kaiser M.(2011)] Identification of stochastic parameters *UTOPIA deliverable*, E.02.15-D02, 2011

[Nuic(2010)] A Nuic. User manual for the base of aircraft data (BADA) revision 3.10. *Atmosphere*, 2010:001, 2010.

[Schuster and Ochieng(2012)] W Schuster and W Ochieng. Trajectory prediction algorithms. *TESA deliverable*, E.02.07-D03, 2012

[Schuster et al.(2012)] W Schuster, M Porretta, and W Ochieng. High-accuracy four-dimensional trajectory prediction for civil aircraft. *AERONAUTICAL JOURNAL*, 116:45–66, 2012.

[SESAR WP C & partners(2012)] SJU / SESAR WP C & partners. European ATM master plan, edition 2. https://www.atmmasterplan.eu/download/29, 2012.

[WMO(2010)] WMO. Manual on the global data-processing system. http://www.wmo.int/pages/prog/www/DPFS/documents/485_Vol_I_en.pdf, 2010.