Recommendations on trajectory selection in flight planning based on weather uncertainty

Alan Hally, Jacob Cheung, Jaap Heijstek, Adri Marsman, Jean-Louis Brenguier

SESAR INNOVATION DAYS, 1st-3rd Dec. 2015, Bologna
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- Ensemble Prediction System (EPS)
  - Comparison of EPSs
Overview

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  → Comparison of EPSs

→ Methodology (EPS + TP)
Overview

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Example Case
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Conclusions and Future Work
**Trajectory Predictors** (TP) currently use deterministic meteorological (MET) forecasts

**Deterministic MET** forecasts contain uncertainties due to errors from:

- Atmospheric chaos
- Lack of observations
- Modelling errors

These uncertainties lead to **unknown uncertainty** in the trajectory

**Unknown uncertainty** in flight time and thus **fuel consumption**
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**Approach?**

Use **Ensemble Prediction System** + TP
Ensemble Prediction System (EPS)

How does an EPS capture uncertainty?

- Initial condition with uncertainty
- True state of current weather
- Ensemble forecasts
- Best estimate of current state of weather
- True state of weather in future
- State of weather in future predicted by deterministic forecast
- Forecast uncertainty

$t_0$ to Time
Ensemble Prediction System (EPS)

How does an EPS capture uncertainty?

Maximise **spread** and thus cover whole **envelope** of **future weather scenarios**.
Ensemble Prediction System (EPS)

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Useful in nominal (**uncertainty in winds in the upper-atmosphere**) and non-nominal weather (**convection**)
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Quantify uncertainty in flight planning due to weather
Ensemble Prediction System (EPS)

Maximise spread and thus cover whole envelope of future weather scenarios

Useful in nominal (uncertainty in winds in the upper-atmosphere) and non-nominal weather (convection)

Quantify uncertainty in flight planning due to weather

Lead to a more accurate description of extra fuel needed for flight
Ensemble Prediction System (EPS)

All world-wide weather centres run EPS systems daily
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Met Office Global and Regional Ensemble Prediction System (MOGREPS)
Global, Hor. Res. ~33 km, 70 Vert. Levels, 12 members, 00,06,12 & 18UTC
**Ensemble Prediction System (EPS)**

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<th>SUPER</th>
<th>Multi-model ensemble (mix of all ensembles)</th>
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<td>98 members, 18UTC initialisation time</td>
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Overview

Introduction

Ensemble Prediction System (EPS)
  Comparison of EPSs

Methodology (EPS + TP)

Example Case

Conclusions and Future Work
Comparison of EPSs

Relative Operating Characteristic (ROC) curve

ROC measures the **ability** of the **forecast** to discriminate between two alternative outcomes (yes/no) at different probability thresholds.

ROC is conditioned on the observations (i.e., given that an event **occurred**, what was the corresponding **forecast**?)

The **Area Under the ROC** curve (**AUC**) is the value which is often used.

Want **AUC** close to **1** as possible (translates to high Probability of Detection (**POD**) and low Probability of False Detection (**POFD**))

The **ROC** can be considered as a measure of potential **usefulness**.
Comparison of EPSs

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\[ \text{HIT} = \frac{a}{(a+c)} \quad \text{POFD} = \frac{b}{(b+d)} \]

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<td></td>
<td>Yes</td>
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<tr>
<td>Yes</td>
<td>a</td>
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## Comparison of EPSs

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4 different model configurations compared using AUC score

One month (Jan 2015) of observed AMDAR wind data at FL340 compared to wind forecast by model at 250hPa

Large dataset and thus **statistically robust** verification of model ability

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Domain: 75N-10N, 105W-15E
Comparison of EPSs

AUC score between 0.85 and 0.96 demonstrates excellent model resolution.
Comparison of EPSs

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Dispersion of RCRV score illustrates models’ spread. SUPER (multi-model ensemble) has greatest spread at +36hr lead time.
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Methodology

Probabilistic Trajectory Prediction (PTP)
Methodology

Probabilistic Trajectory Prediction (PTP)

Ensemble forecast

TP TP TP TP

Ensemble trajectories

Statistical characteristics of ensemble trajectories

Ensemble of trajectories

Represents **uncertainty** related to uncertainty in MET forecasts

Gives a degree of **uncertainty** on important **flight parameters**
## Methodology

### Predicted Trajectory

<table>
<thead>
<tr>
<th>EWF member 1</th>
<th>$T^1$</th>
<th>$T^2$</th>
<th>...</th>
<th>$T^m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EWF member 2</td>
<td>$t_{11}$</td>
<td>$t_{12}$</td>
<td>...</td>
<td>$t_{1m}$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>EWF member n</td>
<td>$t_{n1}$</td>
<td>$t_{n2}$</td>
<td>...</td>
<td>$t_{nm}$</td>
</tr>
</tbody>
</table>

**PDF of $t_{1m}$**

![Histograms for different $T_i$ values]
**Methodology**

<table>
<thead>
<tr>
<th>Predicted Trajectory →</th>
<th>T¹</th>
<th>T²</th>
<th>...</th>
<th>Tᵐ</th>
</tr>
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<tbody>
<tr>
<td><strong>EWF member 1</strong></td>
<td>t₁₁</td>
<td>t₁₂</td>
<td>...</td>
<td>t₁ₘ</td>
</tr>
<tr>
<td><strong>EWF member 2</strong></td>
<td>t₂₁</td>
<td>t₂₂</td>
<td>...</td>
<td>t₂ₘ</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td><strong>EWF member n</strong></td>
<td>tₙ₁</td>
<td>tₙ₂</td>
<td>...</td>
<td>tₙₘ</td>
</tr>
<tr>
<td><strong>PDF of tₙₘ</strong></td>
<td><img src="image" alt="Histogram" /></td>
<td><img src="image" alt="Histogram" /></td>
<td>...</td>
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**High** projected cost (flight time/fuel)

But **low** uncertainty
### Methodology

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<th>$t_{12}$</th>
<th>...</th>
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</tr>
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<tbody>
<tr>
<td>EWF member 2</td>
<td>$t_{21}$</td>
<td>$t_{22}$</td>
<td>...</td>
<td>$t_{2m}$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>EWF member n</td>
<td>$t_{n1}$</td>
<td>$t_{n2}$</td>
<td>...</td>
<td>$t_{nm}$</td>
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**PDF of $t_{mn}$**

**High** projected cost (flight time/fuel)  
But **low** uncertainty

**Lower** projected cost (flight time/fuel)  
But **higher** uncertainty
A 12 member MOGREPS ensemble was used as input to a simple TP system for a case study flight from London (EGLL) to New York (KJFK) on the 25th of January 2015.

Trajectories shown in each panel with the Probability Density Function (PDF) of the flight times for each trajectory shown in the bottom right.

The grey bars represent the standard deviation of the flight times.
Example Case

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Conclusions and Future Work
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Using specific metrics, we have shown that the EPSs are capable of capturing specific nominal weather 36 hours before take-off time. A combination of the EPSs further improves performance.
Conclusions

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A trajectory ensemble was generated using each member of an EPS. A representation of the uncertainty involved in each member of the trajectory ensemble was demonstrated to help in decision making by providing a range of trajectory cost (flight time, fuel) values.
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This would allow TP users to select a suitable trajectory according to their optimum cost distributions.
Our **approach** is currently being validated within **WP11.1**

Extend the approach to the **time interval** close to the **execution** phase using **nowcasting**

Further developments on **Ensemble Weather Forecast (EWF) optimisation**, e.g. ensemble weighting
Thank you for your attention

Met Office

IMET

METEO FRANCE

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SESAR INNOVATION DAYS, 1st-3rd Dec. 2015, Bologna
### Methodology

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<tbody>
<tr>
<td>Cost</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Weather 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t₁₁</td>
<td>t₂₁</td>
<td>...</td>
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**PDF**

**Low** projected cost (flight time/fuel)
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**Higher** projected cost (flight time/fuel)
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