Requirements and Concept for EPS Processing

Deliverable 2.1

TBO-Met

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Authoring & Approval

Authors of the document

Name/Beneficiary	Position/Title	Date
Daniel Sacher / MetSol	Task leader	25/07/2016
Ulrike Gelhardt / MetSol	MetSol contributor	25/07/2016
Alfonso Valenzuela / USE	USE contributor	25/07/2016
Manuel Soler / UC3M	UC3M contributor	25/07/2016
Juan Simarro / AEMET	AEMET contributor	25/07/2016
Thomas Hauf / MetSol	MetSol scientific advisor	25/07/2016

Reviewers internal to the project

Name/Beneficiary	Position/Title	Date
Damian Rivas/ USE	USE contribution leader	17/08/2016
Jürgen Lang / MetSol	MetSol contribution leader	17/08/2016
Manuel Soler / UC3M	UC3M contribution leader	17/08/2016
Juan Simarro / AEMET	AEMET contribution leader	17/08/2016

Approved for submission to the SJU By — Representatives of beneficiaries involved in the project

Name/Beneficiary	Position/Title	Date
Damian Rivas/ USE	Project Coordinator	30/08/2016

Rejected by - Representatives of beneficiaries involved in the project

Name/Beneficiary	Position/Title	Date

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TBO-Met

METEOROLOGICAL UNCERTAINTY MANAGEMENT FOR TRAJECTORY BASED OPERATIONS

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Abstract

The TBO-Met project corresponds to the research topic "Environment & Meteorology for ATM", which is part of the research area "ATM Excellent Science & Outreach" of the SESAR 2020 Exploratory Research programme (call H2020-SESAR-2015-1). TBO-Met is coordinated by the University of Seville (Spain). The rest of the consortium consists by the following members: University Carlos III of Madrid (Spain), University of Salzburg (Austria), MeteoSolutions GmbH (Darmstadt, Germany) and the Spanish meteorological agency AEMET (Agencia Estatal de Meteorología).

In this project we address the problem of analysing and quantifying the effects of meteorological uncertainties in Trajectory Based Operations. In particular, two problems are considered: 1) trajectory planning under meteorological uncertainties and 2) sector demand analysis under meteorological uncertainties, which correspond to two different scales: trajectory (micro) scale and sector (meso) scale. In each problem, two types of meteorological uncertainties are considered: wind uncertainty and convective zones (including individual storm cells). Weather predictions will be based on Ensemble Probabilistic Forecasts and Nowcasts.

At the trajectory scale, the main objective is to assess and improve the predictability of efficient 4D trajectories when weather uncertainty is taken into account, both at the pre-tactical level (mid-term planning) and at the tactical level (short-term planning and execution). To reach this goal, a methodology based on the use of stochastic trajectory optimization will be used.

At the sector scale, the main objective is to analyse the impact of trajectory planning under weather uncertainty (as performed at the trajectory scale) on sector demand. To achieve this objective, a methodology will be developed to measure the uncertainty of sector demand (probabilistic sector loading), based on the uncertainty of the individual trajectories. This analysis will also provide an understanding of how weather uncertainty is propagated from the trajectory scale to the sector scale (this problem of uncertainty propagation between different scales of the system is one of the main

research challenges in the understanding of the effects of meteorological uncertainty in the ATM system).

The expected outcome of the project is two-fold: 1) to enhance our understanding of the impact of meteorological uncertainty in TBO, and 2) to develop methodologies to quantify the impact of meteorological uncertainty in TBO. The methodologies will be evaluated and assessed using advanced air traffic simulation facilities.

To help in achieving the project objectives, a survey among the stakeholders involved (airlines, ANSPs and Network Manager) is to be performed. The main result of the survey will be a first-hand expert description of current practice and future expectations, which will serve as a valuable reference for the project activities.

This project is fully aligned with the objectives of the SESAR 2020 Exploratory Research programme, in particular the following ones related to the "Meteorology" topic: "to enhance meteorological capabilities and their integration into ATM planning processes for improving ATM efficiency" and "to develop 4D trajectories that are optimized to take account of all environmental considerations", and where the following impact is expected: "to enhance ATM efficiency by integrating meteorological information".

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1 Executive Summary

This document is intended to be the basis for the partners to jointly agree upon the meteorological data input to the research topics of WP4 and WP5. It also serves as process design for the development of the software in WP2.2. The document presents the requirements on the data of ensemble prediction systems (EPS) and concepts for data processing. Together with all TBO-Met partners and according to the requirements initially specified, the needed meteorological data sources, i.e., suitable ensemble prediction systems are identified and the necessary processing methods are defined. With respect to the spatial-temporal grid of the model output the processing covers coordinate transformation from hybrid model levels to pressure levels, vertical interpolation, temporal downscaling and interpolation, spatial bilinear interpolation and the extraction of polygons which delimit areas of e.g. deep convection. Further data processing is defined in order to calculate ensemble mean and spread of wind components and temperature which is used to quantify the forecast uncertainty of these meteorological parameters. While wind and temperature data is readily available as model output, information about convection can be derived from numerous parameters. Here detailed information is provided on the definition of suitable indicators to describe convection.

2 Introduction[1]

In the future, ATM system Trajectory-Based Operations (TBO) become the fundamental element to plan air traffic, increase the capacity and efficiency of the system while preserving safety. One key factor that affects the high-level goals set for Single European Sky (SES) is uncertainty which is critical from different perspectives in air transport i.e. safety, capacity, environmental impact and costs.

Weather forecast uncertainty is one of the main sources of uncertainty that affect ATM systems. In this project we focus on the analysis of meteorological uncertainty of wind and convective regions. In Granger et al. [7], the speed uncertainty is identified as the most important factor affecting the en route trajectory predictions and thus the robustness of the pre-synchronized traffic scenarios. According to Zelinski and Jastrzebski [19], convective weather is currently identified as one of the ATM uncertainty factors that most seriously affect the network route structure, and thus the optimal flight trajectory planning.

In this work package, uncertainty of wind fields and convective regions will be derived from Ensemble Prediction Systems (EPS). Ensemble forecasting is a prediction technique that generates a representative sample of the possible future states of the atmosphere. An ensemble forecast is a collection of typically 10 to 50 weather forecasts (referred to as members) with a common valid time, which can be obtained using different Numerical Weather Prediction (NWP) models with varying initial conditions. The spread of solutions can be used as a measure of uncertainty.

This deliverable defines the input to the TBO part of the project, which is to be addressed in WP4 and WP5 (dealing with individual and multiple trajectories, respectively). The results obtained in these two deliverables will be assessed using the results of the project SESAR 11.1.5, project that demonstrates the benefits of using ensemble weather forecasting in trajectory planning.

[1] The opinions expressed herein reflect the author's view only. Under no circumstances shall the SESAR Joint Undertaking be responsible for any use that may be made of the information contained herein.

2.1 Acronyms and Terminology

Term	Definition
ADP	ATFCM Daily Plan
ALADIN	**A**ire **L**imitée **A**daptation dynamique **D**éveloppement **I**nterNational
ANSP	Air Navigation Service Provider
ATFCM	Air Traffic Flow Capacity Management
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATS	Air Traffic Service
CAPE	Convective Available Potential Energy
CP	Convective Precipitation
ECMWF	European Centre for Medium-Range Weather Forecasts
ENS	ECMWF Ensemble Prediction System
EPS	Ensemble Prediction System
EOBT	Estimated Off-Block Time
FPL	Flight Plan
FMS	Flight Management System
GLAMEPS	Grand Limited Area Model Ensemble Prediction System
GRIB	General Regularly-distributed Information in Binary form
HIRLAM	High Resolution Limited Area Model
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
MET	Meteorology
NWP	Numerical Weather Prediction
OR	Operational Requirement
RPL	Repetitive Flight Plan
SES	Single European Sky
SESAR	Single European Sky ATM Research Programme
SJU	SESAR Joint Undertaking
SR	System Requirement
TBO	Trajectory-Based Operations

WGS84	World Geodetic System 1984
WP	Work Package

TBO-Met Consortium

AEMET	Agencia Estatal de Meteorología
MetSol	MeteoSolutions GmbH
PLUS	University of Salzburg
UC3M	University Carlos III of Madrid
USE	University of Seville

3 Data Required for WP4 and WP5

We divide the meteorological requirements from WP4 and WP5 into Operational Requirements (ORs) and System (Integration) Requirements (SRs). The ORs refer to the meteorological information that is needed, whereas the SRs describe some characteristics of this information in order to be integrated with WP4 and WP5, respectively.

3.1 Operational Requirements of WP4

The operational requirements of WP4, related to business trajectory development, sharing, revision, and update, are derived from the different analyses that will be performed in this work package. Two analyses are envisioned:

1. **Pre-tactical analysis (mid-term planning)**

   At the pre-tactical stage, the business trajectory is developed. In the terminology used today, this function can be assimilated to flight planning.

   A flight plan is an aviation term defined by the International Civil Aviation Organization (ICAO) as *"Specified information provided to air traffic services units, relative to an intended flight or portion of a flight of an aircraft."*

   A flight plan is prepared on the ground and specified in three different manners:

   a) as a document carried by the flight crew;

   b) as a digital document to be uploaded into the Flight Management System (FMS);

   c) as a summary plan provided to the Air Traffic Services (ATS).

   It supplies information on route, flight levels, speeds, times, and fuel for different flight phases, alternative airports and other relevant data for the flight so that the aircraft properly receives support from ATS in order to execute safe operations.

   The strategy in regular flights is that each airline files a Repetitive Flight Plan (RPL), typically months/weeks before operation, and sends it to the Network Manager, in particular to the RPL team [8]. One-two days before operation, the RPL team processes the RPL and transforms it into a Flight Plan (FPL), which denotes time of departure as Estimated Off-Block Time (EOBT). This FPL is then submitted to ATFM for its analysis.

   Thus forecasts of 24 to 48 hours of time horizon, which are representative for this phase, would be required.

2. **Tactical analysis (short-term planning)**

Flight planning submission to ATFM dependencies is a recursive process. For IFR flight subject to ATFM, regulation establishes that the flight plan must be presented/submitted 3 hours before EOBT.

Thus, for the tactical analysis, and assuming the EOBT has been set at time t_0, the business trajectory will be studied with weather forecasts ranging from

$t_0 - 3hours$ to $t_0 +$ *duration of the flight*.

For the region of interest (North Atlantic and Europe), maximum durations can be assumed to be 15 hours. Typical durations for a North Atlantic crossing is 6-8 hours, and typical durations for an intra-European flight can be around 3 hours. Those aircraft with maximum endurance, e.g. A350, B787, A380, have endurances around 15 hours as well.

Thus forecasts of 3 to 18 hours of time horizon, which are representative for this phase, would be required.

3.2 Operational Requirements of WP5

The operational requirements of WP5 are derived from the different analyses that will be performed in this work package. Two analyses are envisioned:

a) **Pre-tactical analysis (mid-term planning)**

The ATFCM pre-tactical phase takes place during six days prior to the day of operation, see [14]. This phase studies the demand for the day of operation and compares it with the predicted available capacity on that day. The day before the operation, the ATFCM Daily Plan (ADP) is published with the ATFCM measures to be implemented (e.g. sector configuration management, activation of routing, etc.).

In the pre-tactical analysis, the sector demand will be studied with a forecast time of 24-48 hours, which is representative for this phase.

b) **Tactical analysis (short-term planning)**

The ATFCM tactical phase takes place the day of operation and involves considering, in real time, those events that affect the ADP, and making the necessary modifications to it [15]. This phase is aimed at ensuring that the measures taken during the pre-tactical phase are the minimum required to solve the demand/capacity imbalances.

In this phase, multiple problems with different time horizons arise. For example, the implementation of new ATFCM measures, like level capping or rerouting should be determined at least 3 hours before entering into force.

In the tactical analysis, the sector demand will be studied with a forecast time of 3-6 hours, which is representative for this phase.

3.3 Summary of Operational Requirements (WP4 and WP5)

The operational requirements can be divided into prediction time horizon, coverage area, and meteorological data.

1. Prediction time horizon

Depending on the time scales of the different analyses envisioned in WP4 and WP5 and with regard to the pre-tactical time scale, two different prediction time scales must be taken into account:

OR-1: For the pre-tactical analysis, a prediction time horizon of 24-48 hours is required.

OR-2: For the tactical analysis, a prediction time horizon of 3-18 hours (WP4) and 3-6 hours (WP5), respectively, is required.

2. Coverage area

For each analysis, the area to be covered by the forecast is determined by the trajectories of those aircraft scheduled (WP4) and by the trajectories of those aircraft that may cross the sector under study (WP5), respectively. In the pre-tactical and tactical analysis, complete trajectories will be considered, from origin to destination. Thus, forecasts that cover Europe and the North-Atlantic region are required:

OR-3: For the pre-tactical and tactical analysis, the forecast must cover Europe and the North-Atlantic region.

3. Meteorological data

The analyses foreseen in WP4 and WP5 are based on the computation of individual aircraft trajectories, which are affected by meteorological data; in particular, air temperature, zonal and meridional winds, and convective regions to be avoided by the aircraft (high-risk areas). Forecast products are typically provided at latitude-longitude grids for certain values of altitude and time (reference altitudes and time instants). Therefore, one of the objectives of the processing software is to provide, for each member of the ensemble, accurate and continuous values of the wind components (zonal and meridional) and of the temperature for arbitrarily given values of latitude, longitude, altitude and time, as well as high-risk areas at the same values of time. As coordinate system of the latitude-longitude grid WGS84 is used.

OR-4-WP4: For each member of the ensemble, air temperature (T) and wind components (zonal and meridional; u and v) must be provided as grid data. For the pre-tactical analysis, a spatial grid resolution of 0.25° (and existing altitudes of model output) and a time step of 3 hours are required. For the tactical analysis, a time step of 1 hour would be desired.

OR-4-WP5: For each member of the ensemble, air temperature (T) and wind components (zonal and meridional; u and v) must be provided as continuous functions of latitude, longitude, barometric altitude and time.

OR-5-WP4: Uncertainties of air temperature (T) and wind components (zonal and meridional; u and v) derived from the ensemble members must be provided as grid data. For the pre-tactical analysis, a spatial grid resolution of 0.25° (and existing altitudes of model output) and a time step of 3 hours are required. For the tactical analysis, a time step of 1 hour would be desired.

OR-5-WP5: Uncertainties referred to the ensemble for air temperature (T) and wind components (zonal and meridional; u and v) are required as continuous functions of latitude, longitude, barometric altitude and time (WP5).

OR-6-WP4: For each member of the ensemble, convection indicators must be provided as grid data (latitude, longitude, time). For the pre-tactical analysis, a spatial grid resolution of 0.25° (and existing altitudes of model output) and a time step of 3 hours are required. For the tactical analysis, a spatial grid resolution of 0.05° (and existing altitudes of model output) and a time step of 15 minutes would be desired. High-risk areas should be provided as vector data (vertices of the convective area) as well.

OR-6-WP5: For each member of the ensemble, convection indicators must be provided for arbitrarily given values of time and as grid data (latitude, longitude). For the pre-tactical analysis, a spatial grid resolution of 0.25° (and existing altitudes of model output) is required. For the tactical analysis, a spatial grid resolution of 0.05° (and existing altitudes of model output) would be desired. High-risk areas should be provided as vector data (vertices of the convective area) as well.

OR-7: Uncertainties derived from the ensemble members of a yet to identify convection indicator must be provided as grid data (latitude, longitude and time).

The previous requirements can be summarized in the following tables:

Table 1: Summary of operational requirements of WP4.

		Pre-tactical analysis	Tactical analysis
Prediction time horizon		24-48 hours	3-18 hours
Coverage Area		Europe and North Atlantic	
Wind components, temperature and corresponding uncertainties	**Spatial resolution**	0.25°	0.25°
	Temporal resolution	3 hours	1hour
Convection indicators and corresponding uncertainties	**Spatial resolution**	0.25°	0.1°
	Temporal resolution	3 hours	15 min

Table 2: Summary of operational requirements of WP5.

		Pre-tactical analysis	Tactical analysis
Prediction time horizon		24-48 hours	3-6 hours
Coverage Area		Europe and North Atlantic	
Wind components, temperature and corresponding uncertainties	**Spatial resolution**	Continuously interpolated	Continuously interpolated
	Temporal resolution	Continuously interpolated	Continuously interpolated
Convection indicators and corresponding uncertainties	**Spatial resolution**	0.25°	0.05°
	Temporal resolution	Continuously interpolated	Continuously interpolated

3.4 System Requirements

The identified system requirements can be divided into precision, performance and units.

1. **Precision**

   The precision of meteorological data will be consistent with the precision of numerical computations in WP4 and WP5. Furthermore, since the meteorological forecasts can be provided in coarse spatial grids (e.g., for global forecasts, 0.25 degrees), providing the high-risk areas with this very resolution may result in additional deviations of the aircraft induced by the discretization. Thus, it is convenient to provide the vertices of the high-risk areas with a higher resolution.

   SR-1: A minimum of 5 significant digits is required for the values of air temperature and wind components.

   SR-2: The coordinates of the vertices defining the high-risk areas must be expressed at least with a precision of 0.25 degrees.

2. **Performance**

   The pre-tactical analysis in WP5 will require the higher computational effort. Each simulation will involve the computation of hundreds of trajectories, each trajectory composed of about a hundred points, and evaluated for each member of the ensemble; it is expected to evaluate each meteorological variable about one million times for each simulation. Therefore, a high computational speed is required.

   SR-3: A high computational speed for the processing of the meteorological data is required.

3. **Units**

   All meteorological variables will be expressed in International System Units, and the location of the vertices of the high-risk areas in degrees.

   SR-4. Air temperature and wind components must be given in SI units.

   SR-5. The coordinates of the vertices defining the high-risk areas have to be expressed in degrees.

4 Data Provided for WP4 and WP5

Ensemble forecasts are model runs typically generated by the same identical model but with physically irrelevant differences in the initial state of some quantities. However, it is also possible to generate an EPS by using different numerical weather prediction models. The individual model runs are referred to as ensemble members. The differences between the various members are a measure of uncertainty. As we need to calculate appropriate measures of uncertainty in this project, using EPS model output is one suitable way to quantify these meteorological uncertainties.

4.1 Model Output Data: ECMWF-EPS and GLAMEPS

In this project we want to focus on the output data of the global ensemble forecast system ECMWF-EPS (ENS) and on the output data of the Grand Limited Area Model Ensemble Prediction System GLAMEPS. AEMET as a project partner has access to data of these two ensemble systems.

1. ECMWF-EPS [12], [15]

   The European Centre for Medium-Range Weather Forecasts (ECMWF) has pioneered a system to predict forecast confidence. This system, operational at ECMWF since 1992, is the Ensemble Prediction System (EPS).

   Since 2010, the EPS probabilistic forecast has been based on 51 integrations with approximately 32-km resolution up to forecast day 10, and 65-km resolution thereafter, with 62 vertical levels.

   The ECMWF-EPS represents uncertainty in the initial conditions by creating a set of 50 forecasts starting from slightly different states that are close, but not identical, to our best estimate of the initial state of the atmosphere (the control). Each forecast is based on a model which is close, but not identical, to our best estimate of the model equations, thus representing also the influence of model uncertainties on forecast error.

   The divergence, or spread, of the control plus 50 forecasts gives an estimate of the uncertainty of the prediction on that particular day. On some days, the spread might be small implying that the atmosphere is very predictable and users can trust that the reality will fall somewhere in the narrow range of forecasts. On other days or in other areas, the 51 forecasts might diverge considerably after just a few forecast days, indicating that the atmosphere is especially unpredictable. The variable ensemble spread gives users potentially very useful information on the range of uncertainty. Having a quantitative flow-dependent estimate of uncertainty allows users to make better informed weather-related decisions.

2. GLAMEPS

Several HIRLAM and ALADIN national meteorological institutes have earlier developed, or are in the process of developing, a variety of techniques for short-range ensemble forecasting in limited domains. The HIRLAM and ALADIN consortia aim to integrate the knowledge, experience, and results from these activities, and incorporate them in an operationally feasible distributed ensemble forecasting system. The major challenge for this system is to provide reliable probabilistic forecast information, on the short range (up to 60h), at spatial resolution of 10-20 km and particularly suited for the probabilistic forecasting of severe, high impact weather.

The aim of the GLAMEPS project is to establish an operational grand limited area ensemble prediction system. In production mode, this will constitute a distributed, multi-model EPS production system. Individual countries from HIRLAM and ALADIN will each produce a subset of ensemble members in a variety of manners. Results from each member will be exchanged in real-time between GLAMEPS participants and added together in a common statistic for probabilistic forecasting. It is anticipated that this will produce ensemble forecasts based on a range of perturbation methods from ~7 HIRLAM countries and ~10 ALADIN countries.

The GLAMEPS ensemble is a 48+4-member multi-model ensemble, with 4 control members plus 48 perturbed members, the latter of which include lagging. GLAMEPS is run over 4 cycles per day for hours 00, 06, 12 and 18 UTC, where each cycle runs a 24+4 member ensemble. The member configuration is such that two consecutive cycles make up a full 48+4 member ensemble.

GLAMEPS comprises following models:

- Hirlam with Straco [16]
- Hirlam Kain/Fritsch [9]
- Alaro SURFEX [10]
- Alaro ISBA [6]

GLAMEPS splits the perturbed ensemble members into two groups, which are run in an alternating manner when moving from one cycle to the next one. This ensemble configuration leads to a full ensemble when combining the perturbed members from two consecutive cycles, and adding the control runs from the newest cycle. This way, GLAMEPS is capable of providing ensemble products every 6 hours, while optimizing the use of available computer resources.

In Table 3 some model characteristics of the ECMWF-EPS (ENS) and GLAMEPS with regard to the project objectives are given:

Table 3: Model characteristics of ECMWF-EPS and GLAMEPS

Model characteristics	ECMWF-EPS (ENS)	GLAMEPS
Coverage Area	Global	North Atlantic and European Area
Forecast length	240h	54h
Spatial resolution	approx. 25km	approx. 11km
Temporal resolution	3h	3h
Update cycle	12h	6h
Number of members	51	52
Wind data	u, v at hybrid levels in approx. 20hPa vertical resolution	u, v at pressure level: 500 hPa
Temperature data	T at hybrid levels in approx. 20hPa vertical resolution	T at pressure level: 500 hPa
Convection data	Total Totals Index, Convective Precipitation, K-Index, CAPE and CIN	Convective Precipitation, CAPE
Convection data (post - processed)		Total Totals Index
Archive	yes	latest 4 cycles available

In the following, we check available data against the defined requirements (see section 3):

a) Model output of ECMWF-EPS:

Advantages:

- In operational use at ECMWF.
- (Archived) data sets available.
- Global model, so the needed area (Europe and North Atlantic) is covered.
- Suitable for wind (especially data at lower pressure levels, i.e. high altitudes (hybrid levels in approx. 20 hPa vertical resolution) is available).
- Different indicators of convection already processed and archived.

Disadvantages:

- With regard to requirements for convection, spatial resolution of 25 km is too coarse.

b) Model output of GLAMEPS:

Advantages:

- Grid size of approx. 12 km is more suitable especially with regard to convection.
- Needed area (Europe and North Atlantic) is covered.

Disadvantages:

- No archived data available, only the latest 4 cycles.
- No data above 500 hPa available.
- Only a few convective parameters available, but e.g. the Total Totals Index could be calculated from other parameters of the model output.

In order to fulfil the requirements of WP4 and WP5 we will consider data of both EPS-models.

The model output data of the ECMWF-EPS is the most appropriate dataset with regard to wind. Here data at upper pressure levels is available where the en route aircraft trajectory is usually located. But for the analysis of convection, we will use data of both models: the GLAMEPS because of its higher spatial resolution, and the ECMWF-EPS in order to provide data for analysis of intercontinental flights.

As convection indicators we will take a combination of two parameters: the Total Totals Index and the Convective Precipitation. Both parameters are provided directly by the ECMWF-EPS as model output. In case of GLAMEPS, the Total Totals Index can be post-processed by using temperature and dew point of different pressure levels provided as model output. Details are described in section 5.3.

In general, time interpolation of convection is not reliable because of its stochastic behaviour. The development of convection in time (and space) is not a continuous process and happens on time scales usually smaller than 3h. Thus, Convective Precipitation and the corresponding uncertainty may only be provided in time resolution of the model output. In particular time interpolation of the Total Totals Index is feasible because of the smooth field of its underlying variables.

In Table 4, a listing of the model output is given which is used as input for the data processing.

Table 4: Selected parameters provided by the ECMWF-EPS (ENS) and GLAMEPS, respectively.

Short name in database	Long Name	Unit	Level (hPa)	Spatial resolution	Time resolution	Model
U	U-Velocity	m/s	Hybrid levels in approx. 20hPa vertical resolution	0.2° x 0.2° lat/lon grid	3 h	ENS
V	V-Velocity	m/s	Hybrid levels in approx. 20hPa vertical resolution	0.2° x 0.2° lat/lon grid	3 h	ENS
T	Temperature	K	Hybrid levels in approx. 20hPa vertical resolution	0.2° x 0.2° lat/lon grid	3 h	ENS
CP	Convective Precipitation	m [3]	Single level	0.2° x 0.2° lat/lon grid	3 h	ENS
TOTALX	Total Totals Index	K	Single level	0.2° x 0.2° lat/lon grid	3 h	ENS
T	Temperature	K	850, 500	0.1° * 0.1° lat/lon grid	3 h	GLAMEPS
TD	Dew Point Temperature	K	500	0.1° * 0.1° lat/lon grid	3 h	GLAMEPS
CP	Convective Precipitation	m [3]	Single l[3]evel	0.1° * 0.1° lat/lon grid	3 h	GLAMEPS

[3] Precipitation is measured in units of length per unit time, typically in millimetres per hour i.e. the depth of rain water that would accumulate on a flat, horizontal and impermeable surface during a given amount of time, typically an hour. One millimetre of precipitation is the equivalent of one litre of water per square meter. As the models use SI units, the unit for convective precipitation is metres.

5 Data Processing

5.1 Wind Data

This section describes the processing of wind data from EPS, fulfilling the requirements of WP4 and WP5 which are specified in section 3.

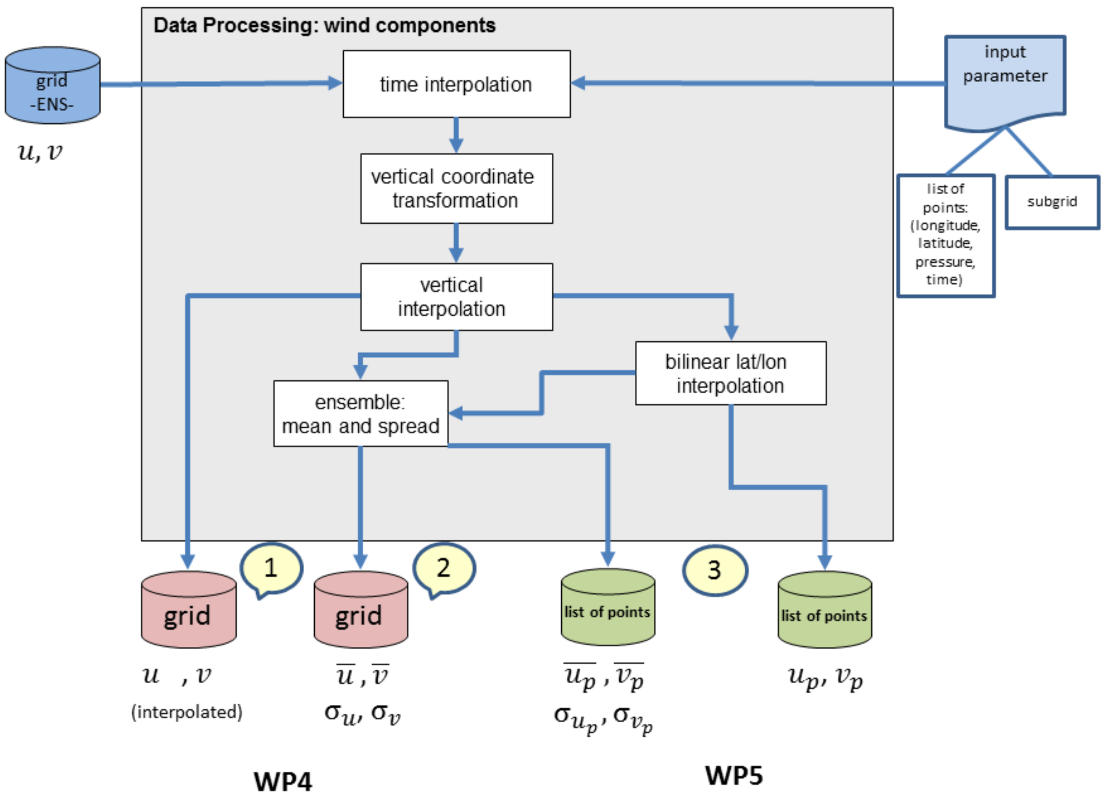

Figure 1: Schematic illustration of the individual wind data processing components, the input data and the final output data. There are 3 different ways of data processing provided (consecutively numbered from 1 to 3). See further information in the text.

In section 4 the ECMWF-EPS (ENS) was identified to be the model that matches the requirements for wind data at most. So, as shown in Figure 1, we use the u- and v- wind components provided in grid data format by the ENS model (see Table 4).

Data retrieval: At first the data will be retrieved from the ECMWF MARS (Meteorological Archive and Retrieval System) data base. The data will be downloaded as files in GRIB format which contain meteorological parameters on a regular latitude-longitude grid and in hybrid vertical coordinates for the desired forecast times. The data will be extracted from the model grid to cover only the desired analysis region in time and space for the flights to be examined. This is done with the purpose of reducing the data amount and thus computation time in all further data processing because the raw EPS output has a large or even global coverage (ENS). The region to be extracted is defined by the minimum and maximum of latitude/longitude, the pressure level where the flights will take place. The extraction of the above defined sub grid can be realized by defining certain request files for the MARS database interface.

Data processing: Once the GRIB files are downloaded, there will be 3 different ways of data processing provided which can be applied individually or in a processing chain (see Figure 1):

1. Temporal downscaling, vertical coordinate transformation and interpolation (requirement of WP4 and WP5):

    a. Temporal downscaling:

    The extracted grids of the u- and v wind components are available from ECMWF in a temporal resolution of 3 hours. As this is too coarse for the research applications in WP4 and WP5, the first step is to downscale it by interpolating to time steps of 1 hour (WP4) or to an arbitrary point in time (WP5). In a first implementation, a linear interpolation algorithm will be used. This will be done before any further processing for the data of each ensemble member.

    For each grid point the following algorithm is run through (here for example: u for zonal wind component):

    1) Get the meteorological parameters $u(t_k)$ and $u(t_{k+1})$ at a given grid point for 2 consecutive points in time t_k and t_{k+1} from the GRIB files.

    2) For linear interpolation between the time steps t_k and t_{k+1} the linear equation

    $$u(t_i) = u(t_k) + \frac{u(t_{k+1}) - u(t_k)}{t_{k+1} - t_k}(t_i - t_k)$$

    has to be solved to get u at point of time t_i.

    b. Vertical coordinate transformation and interpolation from hybrid model levels to pressure levels:

    ECMWF-EPS data is available in high vertical resolution of approx. 20hPa as hybrid model levels. For upper model levels it is straightforward to calculate pressure levels from hybrid model levels:

For each horizontal grid point the hydrostatic pressure p_k at each level $k:1,\ldots,L$ is calculated using:

$$p_k = A_k + p_s B_k$$

with

p_s : Surface pressure

A_k, B_k : Constants that are defined in the header of each GRIB message. These constants are the same for all members of the EPS and all the horizontal grid points.

As p_s is time and space dependent, the same applies to p_k.

Interpolation to pressure level p_i :

For each grid point run the following algorithm:

1) Get the meteorological parameter T_k (for example: u for zonal wind component) at each level $k:1,\ldots,L$ from the GRIB file.
2) Calculate p_k (see equation above) to get the discrete vertical profile $u_k(p_k)$.
3) Determine level k such that $p_k \le p_i < p_{k+1}$
4) For linear interpolation between levels k and $k+1$ the linear equation

   $$u(p) = ap + b$$

   has to be solved using $u(p_k)$ and $u(p_{k+1})$:

   $$a = \frac{u(p_k) - u(p_{k+1})}{p_k - p_{k+1}},\ b = u(p_k) - ap_k$$

5) $u(p_i)$ is then calculated using $u(p_i) = ap_i + b$.

   p_i can be interpreted as a constant pressure level for the grid output or as an arbitrary value according to a single point of the trajectory.

2. Grid-based ensemble mean and uncertainty (requirement of WP4):

   After linear time interpolation and vertical transformation and interpolation to a constant pressure level we compute the ensemble mean and the standard deviation as an indicator of uncertainty for the zonal and meridional wind components at each node of the sub-grid:

   a. The ensemble mean (= the arithmetic mean of the N ensemble members) of the zonal and meridional wind components u_i and v_i are calculated by using:

$$\bar{u} = \frac{1}{N}\sum_{i=1}^{N} u_i \quad \text{and} \quad \bar{v} = \frac{1}{N}\sum_{i=1}^{N} v_i$$

The uncertainty of the forecast is represented by the spread. Here the standard deviation of the distribution of the ensemble members is often used. So the uncertainty of the forecasted wind components will be estimated by:

$$\sigma_u = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(u_i - \bar{u})^2} \quad \text{and} \quad \sigma_v = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(v_i - \bar{v})^2}$$

3. Trajectory-interpolated u and v components of each ensemble member, mean and spread (requirement of WP5):

   To fulfil the requirements on wind information (components u and v) at an arbitrary location in data space (latitude, longitude, time, pressure), a cascade scheme of linear interpolation processors will be run through. Thus for a given trajectory, i.e. a list of points, this can be used to provide the wind components of each ensemble member linearly interpolated to the needed pressure level and time (as described in temporal downscaling, vertical coordinate transformation and interpolation) and also bilinearly interpolated to the route's latitude-longitude positions.

   Bilinear interpolation to arbitrary location (φ_i, λ_j):

   a) From the GRIB file, find the corner points of the raster field which encloses (φ_i, λ_j) such that

      $\varphi_m \le \varphi_i \le \varphi_{m+1}$ and $\lambda_n \le \lambda_j \le \lambda_{n+1}$, respectively, determine m,n.

   b) For bilinear interpolation of meteorological parameter u (for example: u for zonal wind component)

      within the raster field the interpolant $u(\varphi,\lambda) = \sum_{m=0}^{1}\sum_{n=0}^{1} a_{mn}\varphi^m\lambda^n$ has to be solved by

$$a_{00} = u(\varphi_0, \lambda_0)$$

$$a_{10} = u(\varphi_1, \lambda_0) - a_{00}$$

$$a_{01} = u(\varphi_0, \lambda_1) - a_{00}$$

$$a_{11} = u(\varphi_1, \lambda_1) - a_{00} - a_{10} - a_{01}.$$

   c) The interpolated value is then calculated by

$$u(\varphi_i, \lambda_j) = \sum_{m=0}^{1}\sum_{n=0}^{1} a_{mn}\varphi_i^m\lambda_j^n$$

      with φ_i and λ_i normed to the maximum and minimum coordinates.

Additionally, the ensemble mean and standard deviations of the u and v components at the given trajectory are computed.

5.2 Temperature

The data processing for temperature is done analogously to wind processing. So we can integrate this processing into the workflows already presented for wind as shown in Figure 2.

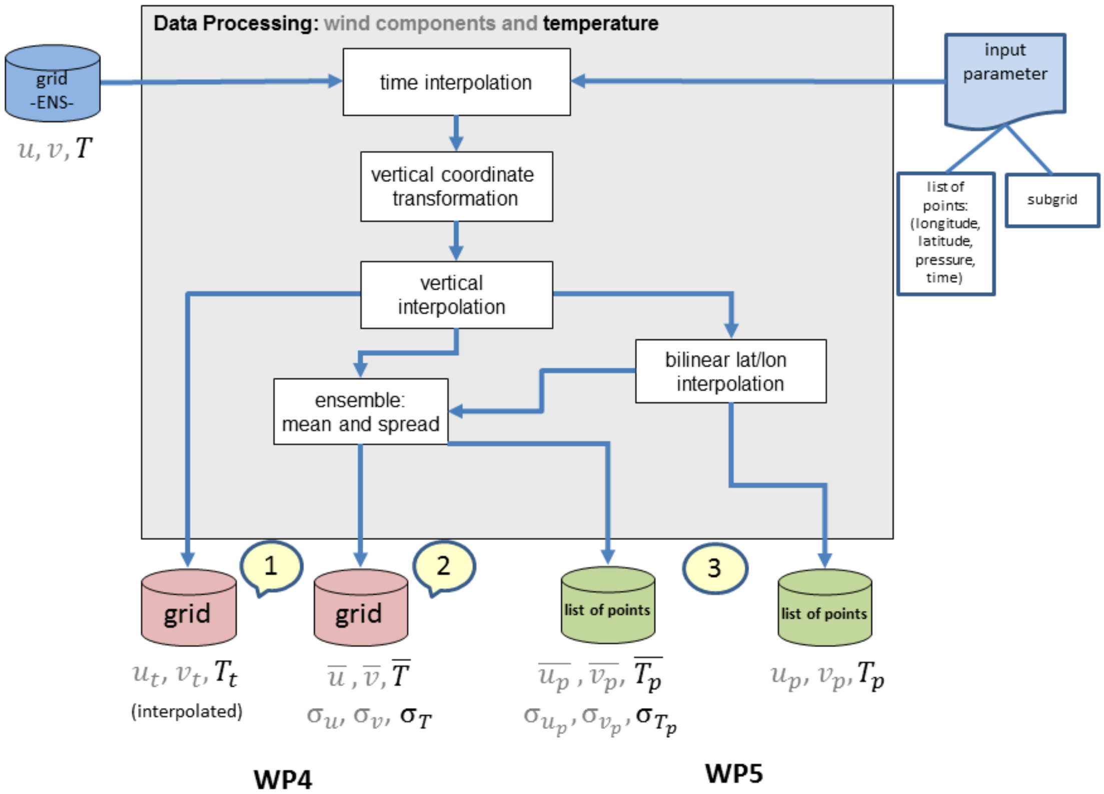

Figure 2: Schematic illustration of the individual components of the data processing for temperature, the input data and the final output data (black). Because this processing is done in analogy to wind processing the output for wind is also shown (grey). There are 3 different ways of data processing provided (consecutively numbered from 1 to 3). See further information in the text.

As described in detail in section 5.1 the following processing steps for temperature are provided:

1. Temporal downscaling, vertical coordinate transformation and interpolation (requirement of WP4 and WP5).

2. Grid-based ensemble mean and uncertainty (requirement of WP4).
3. Trajectory-interpolated u and v components of each ensemble member, mean and spread (requirement of WP5).

5.3 Convection Indicators

Within this project it is attempted to delimit high-risk areas due to deep convection and their respective uncertainty. The term convective area is defined here as an area within which individual convective storms may develop, that is an area of potentially developing storms. The latter comprise individual storm cells, multi-cells, mesoscale convective complexes and squall lines. All of them are considered as no-fly zones. Thus within a convective area there is empty space where aircraft can fly through and there are storms which we assume that no aircraft will fly through. The onset and the location of those individual storms are difficult to evaluate for the time being and impossible to determine in many cases. Favourable environmental characteristics and conditions for certain types, however, are known. Some of them are:

- A squall line (at least in Central Europe) very often develops several hundred kilometres ahead of and parallel to an approaching cold front. It is initiated and recognized by a boundary convergence line. Many such lines often occur ~ 10m km apart, but not all of them necessarily develop into a squall line, though some of them do.
- Air mass storms preferably develop in the afternoon. The onset time of first shallow clouds and the development of deep convective clouds can be forecasted by standard meteorological procedures.
- Moderate mid-level shear enhances the storm strength, while too strong shear and no-shear environments are more likely related to weak storms
- Long-lived storms are linked to the renewal and new generation of new cells immediately ahead of a mature cell.
- Storms embedded in a cold front are out of scope of this study as they can be forecasted very well by synoptic forecasts of low pressure systems.
- The structure of the environmental temperature profile (temp) allows deriving certain features of the storm. Maritime dominated storms reveal a temp close to the moist-adiabatic implying weak updrafts, while continental storms exhibit more potential energy to be released. The latter is defined by the area between moist adiabatic and the temperature profile.
- Environmental characteristics are used to derive empirically a range of convective indices, some of them used in this project.

Important to note is that the above characteristics are necessary conditions, but they do not allow the forecast of the precise location and onset. Convective storms need a trigger mechanism. In order to precisely forecast a storm, we therefore need to forecast the trigger mechanisms. To mention but a few:

- Boundary convergence lines
- Boundary layer outflow from existing storms
- Tropospheric gravity waves (λ ~ 10 – 30 km)
- Near tropopause gravity waves (λ ~ 100-200 km)

- Islands
- Mountains
- Land-sea breeze front
- Surface temperature inhomogeneity (cities, sandy areas...)
- Large scale lifting

From the above we conclude that we need an indicator to describe the necessary precondition for the potential development of convection and an indicator which comprises the essential activator in order to develop a storm which has to be avoided by aircraft. As described below this will be done by using a combination of two convection indicators, “Total Totals Index” and “Convective Precipitation”, which are available by the EPSs. When both indicators exceed certain thresholds for a high number of EPS members, the grid point is assumed to lie within the zone of high probability (low uncertainty) of convection which can be interpreted as a no-fly-zone. If only one criterion is fulfilled for a high number of EPS members the grid point is located in a region of convective uncertainty. The boundary of uncertainty areas will delimit convective regions.

Those convective areas may have a persistence or life time of up to 60 hours. Carbone et al. [3] and previous studies investigated precipitation episodes and found much longer life times of that episodes, respectively travelling convective regions, than those of the individual storms developing within. Here we pursue similar thoughts. Convective regions are perceived as areas with a high weather risk, the latter given by always occurring and unpredictable individual storms. Convective regions, therefore, must not necessarily be avoided but require a higher weather situation awareness by pilots and controllers. Also, trajectories passing through a convective area are subject to diversions resulting in increased flight duration and delays. Thus the intersection of a trajectory with a convective region does not imply, as already said above, that the whole area has to be circumnavigated, but rather that delays have to be expected. The dimension of the latter depends, among other factors, on the type of storms embedded in the convective area, density of cells, their orientation, the size of gaps separating the storms and the time of onset.

As said above we decided to combine two indicators for convection:

1. Total Totals Index (attributable to [11]):

   The Total Totals Index (*TT*) is the sum of two indices: the vertical totals (*VT*) $VT = T_{850} - T_{500}$ (temperature gradient between 850 hPa and 500 hPa) and the cross totals (*CT*) $CT = T_{d_{850}} - T_{500}$ considering the moisture content between 850 hPa and 500 hPa by subtracting the temperature in 500 hPa from dew point temperature in 850 hPa.

   $$TT = VT + CT$$
   $$TT = (T_{850} - T_{500}) + (T_{d_{850}} - T_{500})$$

   As a result, TT accounts for both static stability and 850 hPa moisture, but would be unrepresentative in situations where the low-level moisture resides below the 850 hPA level. In addition, convection may be inhibited despite a high TT value if a significant capping inversion is present.

VT = 40 is close to dry adiabatic for the 850-500 hPa layer. However, VT generally will be much less, with values around 26 or more, representing sufficient static instability (without regard to moisture) for thunderstorm occurrence. CT > 18 often is necessary for convection, but it is the combined Total Totals Index that is most important [13].

The risk of severe weather activity is operationally defined as follows (see also [4]):

44-45	isolated moderate thunderstorms
46-47	scattered moderate / few heavy thunderstorms
48-49	scattered moderate / few heavy / isolated severe thunderstorms
50-51	scattered heavy / few severe thunderstorms and isolated tornadoes
52-55	scattered to numerous heavy / few to scattered severe thunderstorm / few tornadoes
>55	numerous heavy / scattered severe thunderstorms and scattered tornadoes

2. Convective Precipitation [5]:

   The Convective Precipitation (CP) is an estimation of the precipitation coming from convective clouds. The total precipitation is the sum of the so-called large-scale precipitation and the convective precipitation.

   The moist convection scheme is based on the mass-flux approach and represents deep (including cumulus congestus), shallow and mid-level (elevated moist layers) convection. The distinction between deep and shallow convection is made on the basis of the cloud depth (< 200 hPa for shallow). For deep convection the mass-flux is determined by assuming that convection removes Convective Available Potential Energy (CAPE) over a given time scale. The intensity of shallow convection is based on the budget of the moist static energy, i.e. the convective flux at cloud base equals the contribution of all other physical processes when integrated over the sub-cloud layer. Finally, mid-level convection can occur for elevated moist layers, and its mass flux is set according to the large-scale vertical velocity. The scheme, originally described in Tiedtke [17], has evolved over time and amongst many changes includes a modified entrainment formulation leading to an improved representation of tropical variability of convection [1], and a modified CAPE closure leading to a significantly improved diurnal cycle of convection [2].

In order to fulfil the desired requirements, the following data processing for convection will be provided which can be applied individually or in a processing chain (as shown in Figure 3).

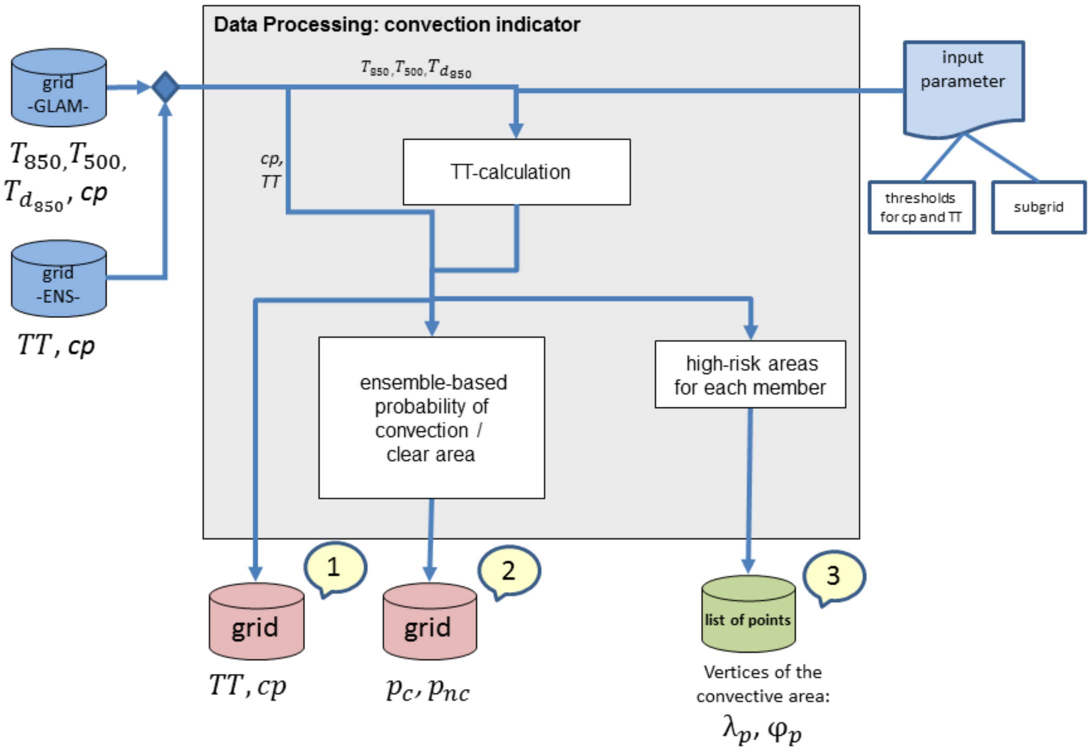

Figure 3: Schematic illustration of the individual components of the data processing for convection, the input data and the final output data. There are 3 different ways of data processing provided (consecutively numbered from 1 to 3). See further information in the text.

1. Grid-based output of the Total Totals Index and the Convective Precipitation:

   For input either model output from the ECMWF-ENS or from the GLAMEPS can be used.

   a) In case of using the GLAMEPS model output at first the Total Totals Index for each member must be calculated from the provided temperature data T_{850} and T_{500} at 850 hPa and 500 hPa, respectively, and the dew point temperature $T_{d_{850}}$ at 850 hPa.

   b) Using the ECMWF-ENS data, both convective indicators, TT and CP are given.

   As already mentioned in section 4, in case of the Total Totals Index a linear time interpolation can optionally be integrated into this workflow.

   The results of this workflow are the TT and CP for each member at the horizontal nodes of the desired sub-grid.

2. Ensemble-based probability of convection / clear air for each grid point:

   With regard to flight trajectories it is important to delimit regions of uncertain weather conditions from regions where the forecast is more reliable. Convective regions of high uncertainty can then be defined as those areas where neither convection nor clear air can be safely predicted. So, the calculation of two quantities is suggested:

   - Probability of convection:
     The ensemble-based probability of convection is the fraction of ensemble members with values above the given thresholds TT_H and cp_H for all TT and cp of the ensemble members. For TT_H we suggest one of the threshold values from the list in 5.3 paragraph 1. For cp_H we suggest 0; that means that any given amount of convective precipitation originates from convective events:

     $p_c = \frac{N_c}{N}$ with $N_c = \sum_{i=1}^{N} i$, where $(TT_i > TT_H) \wedge (cp_i > cp_H)$

     and N : Number of ensemble members.

     High percentage in probability p_c can be interpreted as convection with low uncertainty.

   - Probability of clear air:
     Analogously, we suggest a second value that can show regions of clear air with low uncertainty:

     $p_{nc} = \frac{N_{nc}}{N}$ with $N_{nc} = \sum_{i=1}^{N} i$, where $(TT_i \le TT_H) \wedge (cp_i \le cp_H)$

     and N : Number of ensemble members.

   - Considering both values p_c and p_{nc} at each grid node we are able to divide the focused area into 3 zones (see Figure 4):

     1. Convective zones i.e. high-risk areas with low uncertainty,
     2. Clear air zones with low uncertainty,
     3. Zones with high uncertainty of the predicted weather conditions.

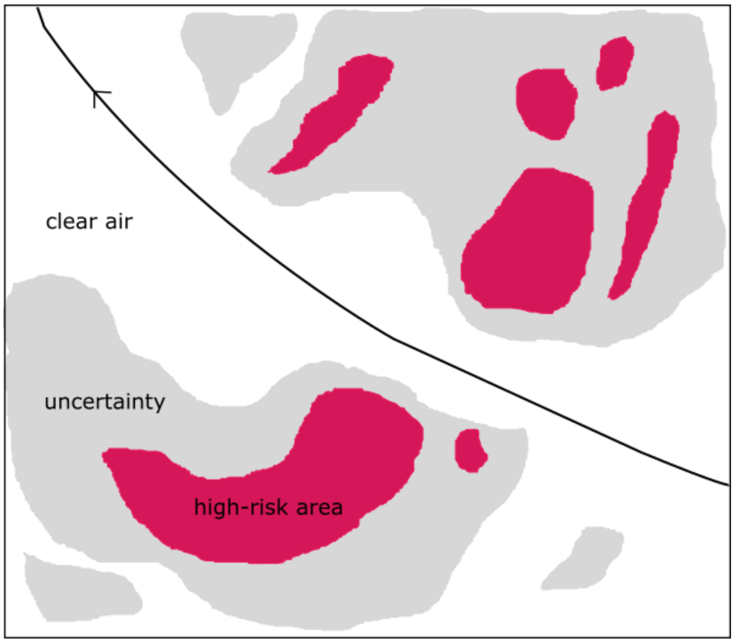

Figure 4: Schematic illustration of the suggested classification of the focused area into 3 different zones: clear air (white), high-risk areas (pink) and uncertainty (grey).

Here we will only provide p_c and p_{nc}. With these two parameters further post-processing like classifications (as described above) can be done.

3. High-risk areas for each ensemble member:

In order to get high-risk areas where each zone is based on the individual prediction of a single ensemble member, we look at the forecasted values of TT_i and cp_i at each horizontal grid node. In analogy to the ensemble-base probability of convection, we define a high-risk area for an ensemble member i as an area where the following condition is fulfilled at each grid point:

$$(TT_i > TT_H) \vee (cp_i > cp_H).$$

That means that a high-risk area is delimited by the regions of low uncertainty which include the regions of high probability of convection.

As the Total Totals Index is a smooth field, we suppose that we get clear structures of convective zones as well. Otherwise morphological operations can be applied to the generated field in order to eliminate unreliable singularities in the convective zones.

Finally the calculated convective zones can be labelled so that the vertices of each polygon can be computed.

6 References

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