

Planning aircraft measurements within a warm conveyor belt

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Introduction

Taking aircraft measurements in warm conveyor belts (WCBs) was the ambitious plan of a team of young scientists that came together for a research campaign in October 2012. In addition to the logistical restrictions associated with a crowded European air space as well as technical limitations, the poor predictability of the envisaged weather systems imposed high demands on flight planning and led to the development of a novel chain of forecasting products to be applied for the first time in an airborne field experiment. Here we describe the challenging flight preparation and the application of the planning tools for a selected WCB event.

The Lagrangian perspective on extratropical cyclones has a long history (Browning, 1990) and has added new understanding to the classic cyclone models that describe the spatial structure at successive time-steps. This paradigm was built on improved observational methods, for example radar, satellite and airborne *in situ* observations, with the aim of better understanding cloud and rainfall distribution. The conceptual conveyor belt model describes the cyclone-relative flow by introducing three major coherent air streams: the cold conveyor belt transports colder air westward ahead of the warm front; the dry intrusion describes the descent of dry air from close to the tropopause to lower altitudes west of the cold

front; the third air stream, the WCB, is the focus of this article. From within the warm sector's boundary layer, warm and moist air masses are transported upward and poleward towards the upper troposphere and lower stratosphere. In recent years, the use of steadily improved and better resolved numerical-weather-prediction (NWP) products to drive Lagrangian trajectory models has allowed a detailed characterisation of the WCB (Wernli and Davies, 1997; Eckhardt *et al.*, 2004). Results show that the air masses typically need about two days for an ascent of 500–600hPa, during which diabatic processes occur when the air saturates and clouds and precipitation form. The related latent heating causes a characteristic evolution of potential vorticity along the WCB, as discussed, for instance, by Grams *et al.* (2011). In recent years different experimental studies have provided information about thermodynamic properties in WCBs (e.g. Pomroy and Thorpe, 2000; Vaughan *et al.*, 2003). Other studies have shown uncertainties in the initial moisture distribution, as uncovered by LiDAR observations (Schäfler *et al.*, 2011), and have studied their impact on NWP forecasts. Nevertheless, most of our knowledge on WCBs is based on NWP data and therefore we planned an aircraft experiment to study the diabatic processes in WCBs and the impact of their potential misrepresentation in NWP models on forecast skill.

In a 3-week field experiment from 8 to 26 October 2012, scientists from the Deutsches Zentrum für Luft- und Raumfahrt (DLR), the ETH Zurich and the University of Mainz combined to perform flights with the DLR research aircraft *Dassault Falcon 20-E5* in WCBs, in order to obtain new insight into the structure and evolution of this air stream. The Falcon has a maximum operation altitude of 12.8km, a maximum operation time of about 3.5h and a range of up to 2800km. As the location of the WCBs was not predictable before the campaign, the scientists required maximum flexibility for the flights. The strategy was to fly at various altitudes, drop sondes from high levels, refuel at external airports, adapt the flight pattern to the latest forecast runs and probe the same WCB again in a second flight

separated by only a few hours. Even though the campaign took place in the climatologically very promising month of October, a small chance remained that no WCB would occur within the area of operation – covering central Europe, the easternmost North Atlantic and the western Mediterranean.

Objectives of the T-NAWDEX–Falcon project

Over recent years, research on the improvement of forecast accuracy of high-impact weather on the time-scale of 1 day to 2 weeks has been performed under the umbrella of The Observing System Research and Predictability Experiment (THORPEX), a 10-year international research and development programme of the World Meteorological Organization. The THORPEX North Atlantic Waveguide and Downstream Impact Experiment (T-NAWDEX) is an initiative to investigate the triggering of disturbances along the North Atlantic waveguide, their subsequent evolution, and eventual downstream impacts over Europe by using airborne observations. The T-NAWDEX–Falcon (<http://www.pa.op.dlr.de/tnawdex-falcon/>) project described here is a preparatory campaign for a prospective international field experiment with a well-defined aim: to learn more on how realistically moisture and latent heating along the WCB are represented in NWP models and how diabatic processes modify the structure of cyclones and the upper-level flow. The aim of observing ascending air masses during different stages of the WCB by performing *in situ* measurements of temperature and humidity twice in the same air mass separated in space and time required a Lagrangian matching of consecutively planned flight paths.

The Falcon was equipped with *in situ* instruments to measure temperature, wind speed and pressure. As humidity was one of the key quantities to be measured, three instruments were operated using different methods to observe both total water and water vapour. Additionally, trace-gas instrumentation was implemented to measure ozone, carbon monoxide, nitric oxides, methane, carbon dioxide and sulphuric

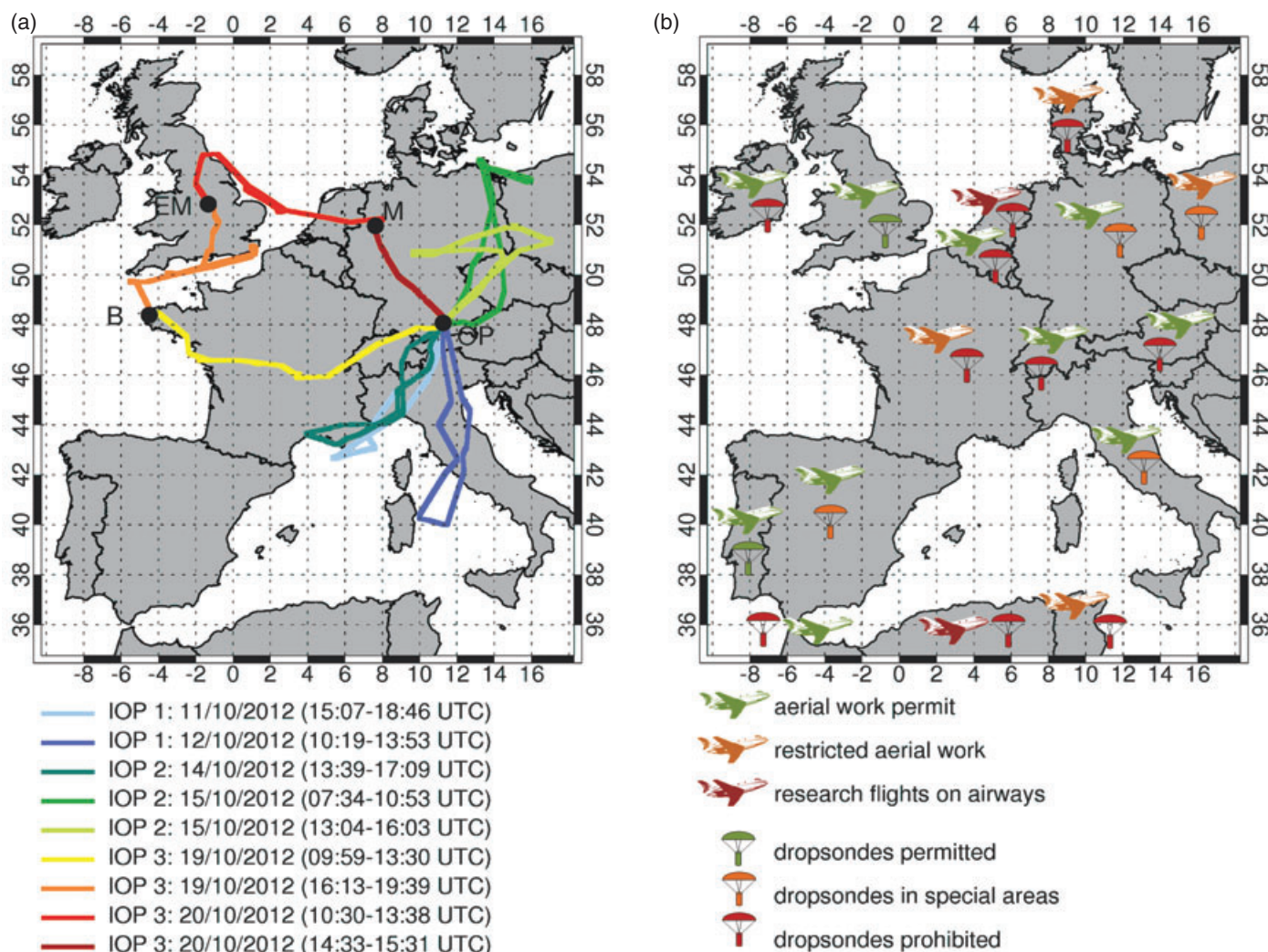


Figure 1. (a) Overview of the T-NAWDEx-Falcon flight tracks. Oberpfaffenhofen (OP), Brest (B), East-Midlands (EM) and Münster (M) airports are marked with black dots. (b) Overview of the permission status for aerial work and dropsonde releases.

dioxide, which are tracers for characterising WCB transport. Underwing instruments from the University of Mainz and the University Blaise Pascal in Clermont-Ferrand were used to measure cloud droplet and ice particles. The payload was complemented by a dropsonde device able to deploy sondes for measuring profiles of temperature, humidity and wind beneath the aircraft.

Figure 1(a) shows an overview of the nine completed scientific missions with a total flight duration of 32h. Fortunately, three subsequent WCBs were probed extensively during three intensive observation periods (IOPs).

Operation regulations

The scientists had to deal with many different restrictions during the preparatory phase of this campaign and also when planning the flight routes. The execution of research flights in European air space demands intensive logistical preparation. Air traffic over Europe is generally very dense and a number of authorities need to be contacted and asked for permission to operate

freely away from airways (aerial work permit) and to release dropsondes. To reach the scientific objectives it was crucial to perform measurements away from airways, because the shape and location of WCBs are very variable and forecast uncertainty was expected to be large. Figure 1(b) provides an overview of the permissions obtained from the different countries. The Air Traffic Control (ATC) regulations varied from country to country in terms of lead time for the submission of the flight patterns, and in terms of the area where free operation was permitted. Some countries refused aerial work and required the definition of generic flight patterns with fixed flight routes and altitudes that could be activated during the campaign. Generally, the first announcement to the relevant ATC had to be made 2–4 days in advance. In several countries military training exercises were announced that blocked parts of the air space. It was even more complicated to obtain permission to release dropsondes (Figure 1(b)), as in many countries their laws of aviation forbid the release of any object from an aircraft. Although the danger for aircraft flying beneath and for the population below is minimal, there remains a low

risk. Permission was granted over British territorial waters, in some German and Italian restricted areas, in some Spanish regions, mainly over sea, and over international waters of Maltese air space. Slovakia and Portugal generally allowed the use of dropsondes. We tried to adjust flight routes so that dropsondes could be released whenever possible. Further limitations for the flight planning were airport opening hours and crew duty times, which partly constrained options for sequential flights in a developing WCB.

Refined flight-planning tools

In addition to the limitations imposed by flight regulations, the greatest challenge remained the fact that WCBs and their associated cyclones are typically associated with poor predictability (which was in turn one of the aims to be investigated). This clearly conflicted with the required early flight planning (submission of flight plans 2–4 days before the flight). For preparing meaningful flight plans it was fundamental to have information to answer the following questions:

- From where and to which altitude does the WCB air ascend?
- Where is the WCB ascent located relative to the cyclone and its fronts?
- Can we plan for a Lagrangian matching with the observed air mass during a second flight?
- How do the WCB forecasts change with time and how reliable are they?

Different methods and visualisation techniques have been applied. One approach was to rely on the latest (i.e. the 0000 UTC forecasts from the same day), and presumably most reliable deterministic, forecast at the highest resolution and to monitor the development of the subsequent forecast runs. The other approach was the use of ensemble prediction data and methods, that is, forecasts that start from slightly perturbed analysis fields. To the best of our knowledge, this was a new element in the planning of aircraft missions and allowed a better evaluation of the forecast uncertainty. The products had to be designed such that they could be applied flexibly with respect to the weather situation. Further-

more, a substantial effort was made to minimise the delay of the availability of the products caused by data transfer, trajectory calculation and plotting.

In order to identify WCBs, two different trajectory models were applied that permitted tracing selected meteorological variables forward and backward in time: the first model, LAGRANTO (Wernli and Davies, 1997), calculates 3-dimensional kinematic trajectories; the second model, FLEXPART (Stohl *et al.*, 2005), is a Lagrangian particle-dispersion model that includes parametrisations of turbulent mixing and convection. By selecting trajectories that exceed a threshold in the decrease of pressure over a given period, typically 500–600 hPa in 48 h, the WCB air masses can be identified. For the first time a trajectory-based WCB diagnostic was applied to each of the 51 members of the European Centre for Medium-range Weather Forecasting (ECMWF) ensemble prediction system. From the gridded ensemble WCB data, 'WCB probabilities of occurrence', defined as the relative number (in %) of ensemble members that have at least one WCB trajectory in the

column above a given grid point at each forecast time, were derived. The WCB probabilities were plotted for four different layers that characterised the entire troposphere and the inflow, ascent and outflow regions of a WCB. These products were very helpful in estimating whether WCBs in the ensemble occur in the same region as in the deterministic forecast, and which regions are most likely to be affected by a WCB.

Meteorological charts on standard pressure levels of relative humidity, wind, temperature, equivalent potential temperature, geopotential height and cloud coverage, as well as sea-level pressure, were provided by the open-source 'Mission Support System' (MSS; Rautenhaus *et al.*, 2012). The charts were available via a webpage and a specialised flight planning application.

The visualisation of the WCB evolution is a complex 4-dimensional problem. For a specific WCB starting time, the spatial distribution and the progress of the trajectory positions in time have to be illustrated. However, the ascent does not start at only one point in time. WCB air masses begin to

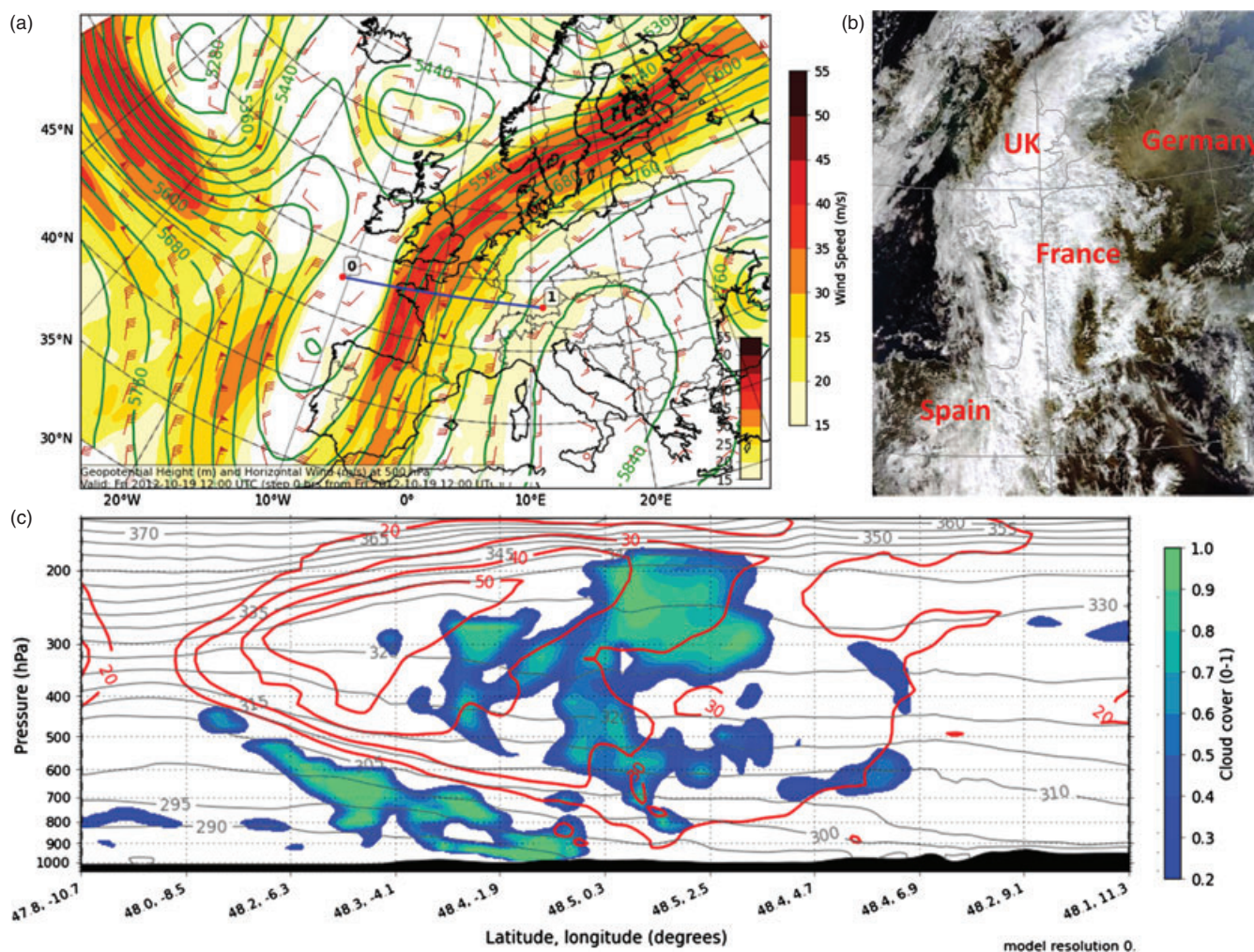


Figure 2. (a) The 500hPa geopotential height (m) and wind speed (ms⁻¹) analysis at 1200 UTC on 19 October 2012, (b) an RGB MODIS image of the AQUA overpass at 1251 UTC (from NERC Satellite Receiving Station, Dundee University, Scotland, <http://www.sat.dundee.ac.uk>) and (c) a vertical section along the blue line in (a) of the ECMWF analysed cloud-cover fraction (colour shading), horizontal wind speed (red contours, ms⁻¹) and potential temperature (grey contours, K).

ascend over a period of 1–2 days and the starting region changes in accordance with the moving cyclone. A set of operational WCB charts showed the change in pressure and humidity over the following 48h projected onto a particular pressure level, in order to demonstrate the horizontal and vertical extent of the WCB starting regions and their spatial evolution. The WCB trajectories from different starting times that also showed the development of different variables along the ascent (e.g. specific humidity, potential vorticity, liquid- and ice-water content, potential temperature) could be followed interactively on a webpage. For the detailed flight planning, cross-sections along potential flight paths showing meteorological variables and intersections with WCB trajectories helped to adjust the flight altitudes. Forward and backward calculations were made with the FLEXPART and LAGRANTO models in order to determine Lagrangian matching of flight paths from planned and realised flight patterns to optimally adjust flight patterns to allow resampling of the same air masses.

In addition to the standard weather charts, the MSS provided interactive access to available ECMWF data and, in particular, allowed the design of flight routes in direct relation to the predictions. This tool enabled us to easily view vertical sections along a planned flight route and to obtain estimates of the flight performance (in particular the estimated flight time).

Flight planning for IOP 3

Figure 2(a) shows the ECMWF analysis of 500hPa geopotential height and horizontal wind speed at 1200 UTC on 19 October 2012, as obtained from the MSS. An elongated trough, extending far to the south, approached Europe with a distinct jet stream on its leading edge. Figure 2(b) shows clouds below the jet stream extending from Spain towards eastern France and further to the North Sea: also apparent in the vertical section through the ECMWF analysis shown in Figure 2(c). Upstream of the large-scale trough at 40°W/50°N, Hurricane Raphael transitioned into an extratropical low-pressure system during the days before the research flights. The dense clouds over France and the English Channel are related to a WCB that persisted for about 5 days. The use of the above-described forecast products that led to the planning of a double flight on 19 October 2012 is reconstructed in the following.

In preparation for IOP 3 the ensemble WCB-probability product helped to estimate the reliability of the WCB forecasts so that a suitable flight leg over France, which was defined in advance of the campaign, could be activated. The 5-day (+120h) forecast for 1200 UTC on 19 October indicated very high WCB probabilities in the central North Atlantic centred at about 30°W/50°N (Figure 3(a)), due to the predicted outflow of the transforming tropical

cyclone. However, as reflected by the decreasing WCB probabilities to the northwest and southeast of the maximum, there was uncertainty in the ensemble about the actual track of this cyclone and the associated WCB activity over the central Atlantic. Nevertheless, rather high WCB probabilities of up to 50% over western France indicated good potential for a WCB emerging ahead of the elongated trough off the European coast. This led us to activate a predefined low-/mid-level leg over central France and to prepare a flight plan to Brest, well in advance. During the next days the ensemble converged more and more towards a solution with the ex-Hurricane Rafael and its outflow directed to the northwest, towards Greenland (Figure 3(b)–(d)). Consequently, predictability for the position of the trough further downstream along the European coast increased. With +84h lead time (Figure 3(b)), the probability for the WCB ahead of the trough increased to 50% in a larger region, but this region shifted to the southwest – more over Spain and the French coast. Two days prior to the event (Figure 3(c)) the ensemble showed very high probability (80–90%) that a WCB would occur over the French coast, Brittany and the English Channel, which facilitated the detailed flight planning. The latest forecast available before take-off confirmed the scenario (Figure 3(d)), although the WCB core shifted more off the coast.

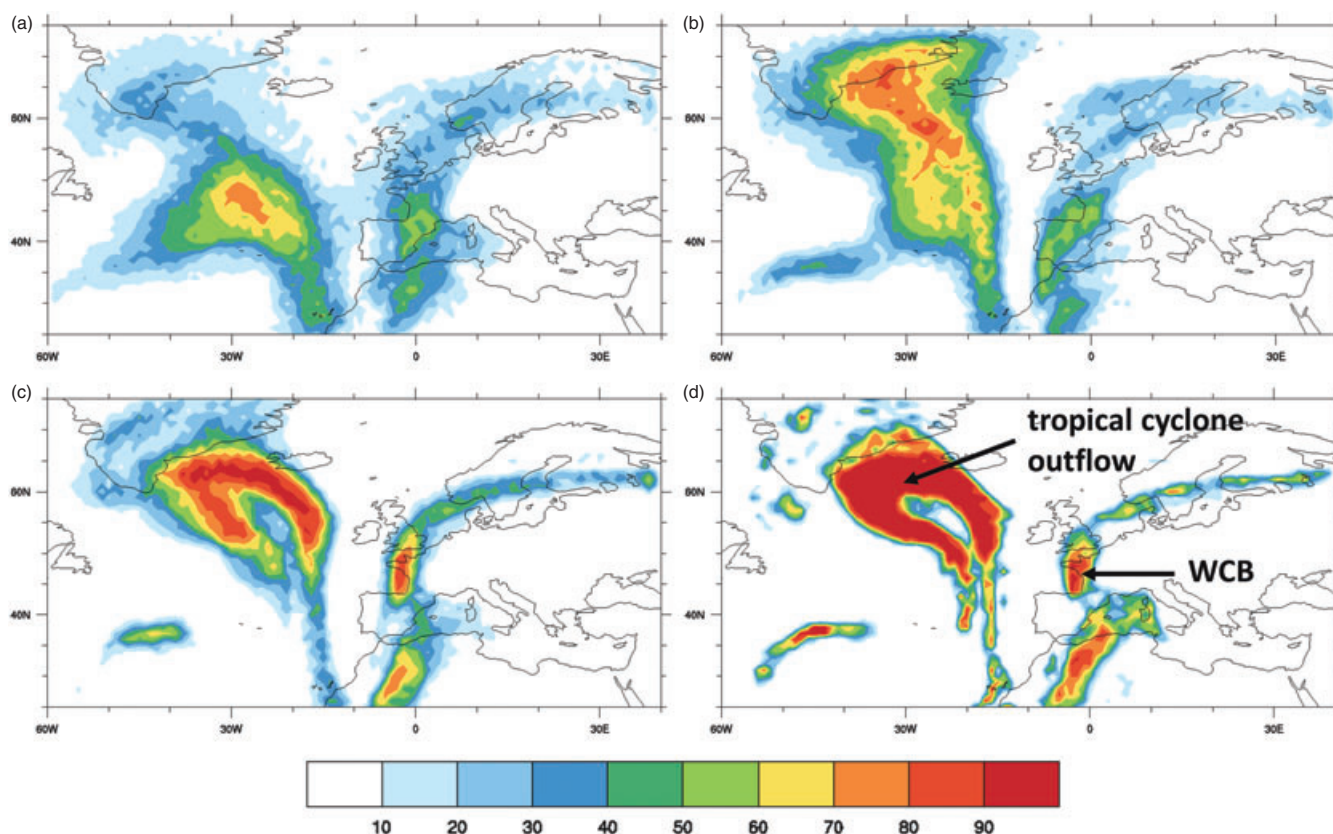


Figure 3. The WCB-ensemble probability of occurrence (in % shaded) for the total layer, valid at 1200 UTC on 19 October 2012, for forecasts initialised at (a) 1200 UTC on 14 October (+120h), (b) 0000 UTC on 16 October (+84h), (c) 1200 UTC on 17 October (+48h) and (d) 0000 UTC on 19 October (+12h).

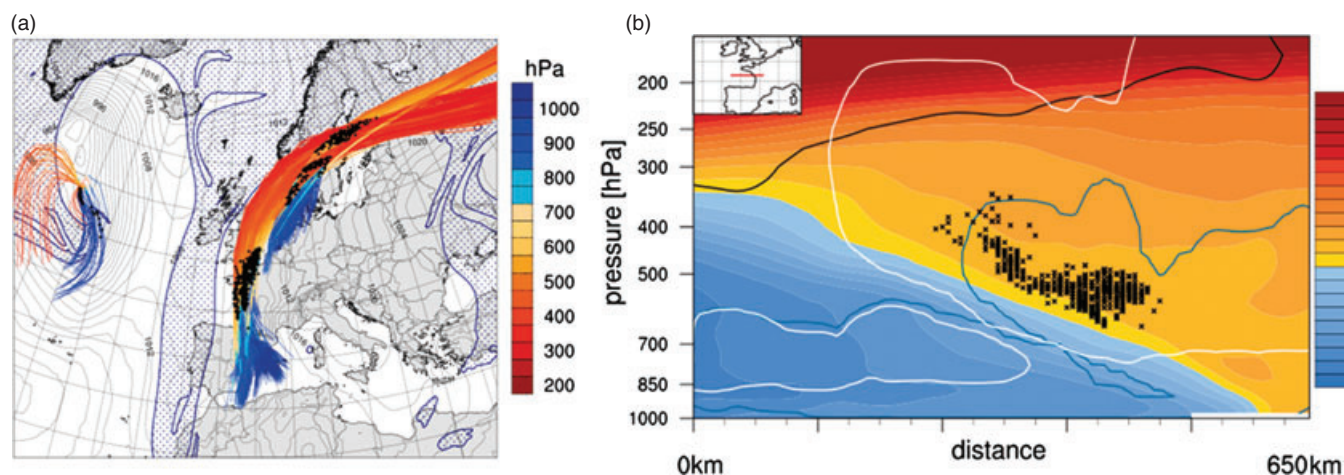


Figure 4. The WCB trajectories and positions at 1200 UTC on 19 October 2012 based on the 1200 UTC 17 October deterministic forecast. The WCB trajectories started at 1800 UTC on 18 October. (a) The WCB trajectories are coloured according to pressure (hPa), grey lines show the sea-level pressure (with an interval of 2 hPa) and the blue stippled area marks stratospheric air (potential vorticity > 2 PVU, where $1 \text{ PVU} = 1 \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}$) at 325 K; black dots show the trajectory positions 18 h (+48 h forecast lead time) after the beginning of the ascent. (b) Cross-section through the WCB showing equivalent potential temperature (colour shading, in K), dynamical tropopause (black contour, 2 PVU), liquid-water content (blue contour, 0.1 g kg^{-1}) and ice-water content (white contour, 0.1 g kg^{-1}), black crosses mark the intersection of the trajectories shown in (a). The panel in the upper left corner of (b) shows the position of the cross-section in red.

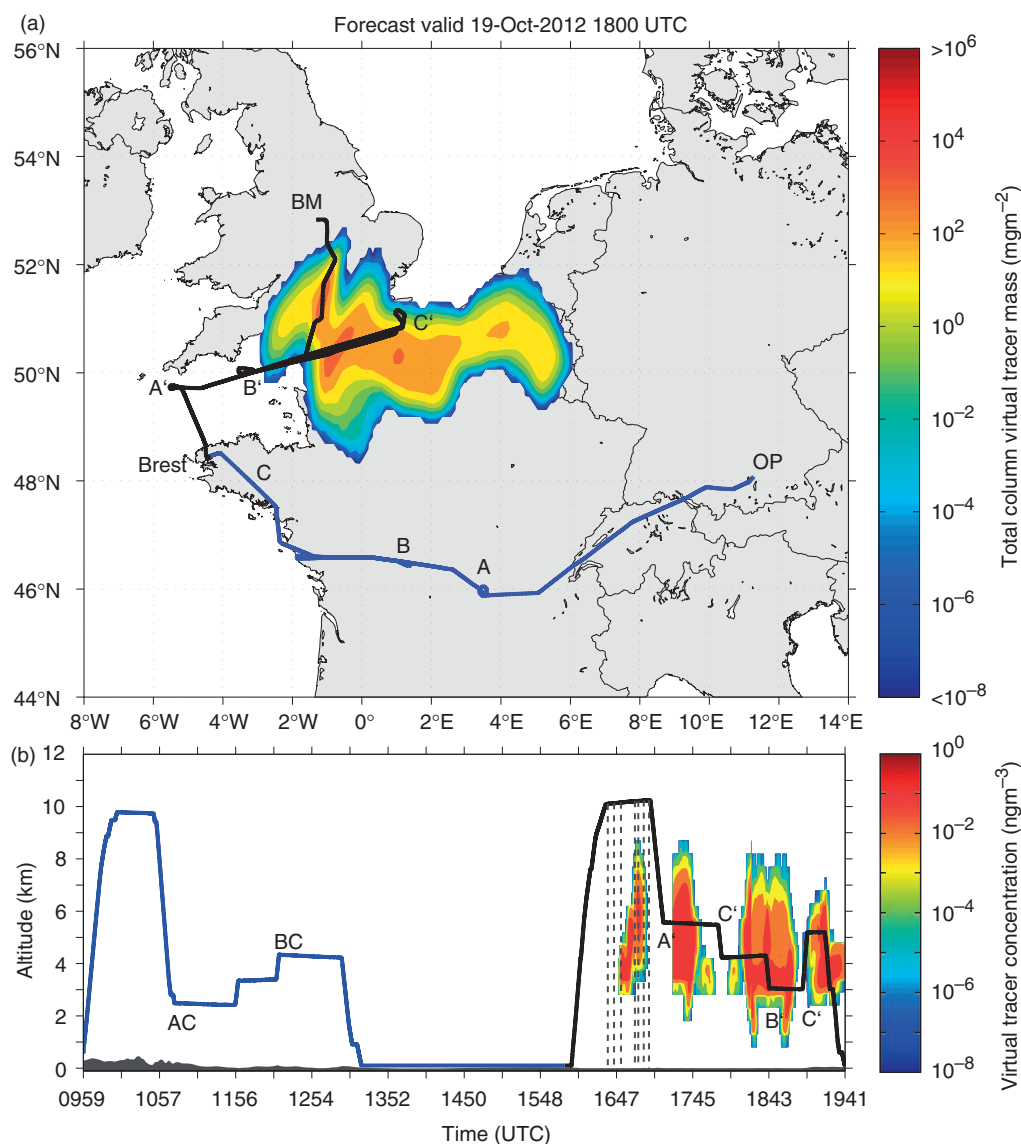


Figure 5. (a) Virtual tracer plume simulated by FLEXPART (shading, total column tracer mass) for releases on flight legs AC, CB and BC of flight 1 (OP, Brest). The previously sampled air mass was predicted to be re-encountered during a second flight from Brest to British Midlands (BM) between 1700 and 1900 UTC according to the operational forecast issued at 0000 UTC on 19 October. (b) Profiles of flight 1 (blue line) and flight 2 (black line) superimposed by the tracer concentration. Dashed vertical lines indicate location of the dropsondes over the English Channel.

When we saw that the ensemble run converged to a solution that appeared convenient to be observed by the requested flight path over western France, we analysed the WCB transport in the deterministic forecasts. Figure 4(a) and (b) shows trajectories for an air mass that was about at the location of the planned flight and that started its ascent on 18 October 2012 (Figure 4(a)). Trajectories in Figure 4(a) indicate the transport of the air over France toward the English Channel. The equivalent potential temperature along an east–west oriented cross-section through the WCB (Figure 4(b)) indicates the tilted frontal zone close to the Atlantic coast and the associated moist-adiabatic ascent of the WCB air masses. The model fields show a thick cloud with increased liquid-water content up to ~400hPa. Ice-water content increases above about 700hPa and shows high values up to the tropopause. The trajectories that represent the part of the WCB with a specific release time and an ascent rate of more than 600hPa in 48h cross the plane between 600 and 400hPa. We also expected moist air masses located at the front at lower levels to ascend after the time of the observations. Due to these additional investigations, the predetermined flight legs that were restricted to lower levels over France could be adjusted slightly to 750, 670 and 600hPa for the flight to Brest a few hours before take-off.

To adjust flight levels for the second flight in the UK air space to possibly resample the same air mass, forward calculations with the FLEXPART model using the available forecast data at the time of flight planning were considered. Figure 5 shows the concentration of a virtual tracer that was released in 10-s intervals along relevant legs of the first flight and advected using ECMWF's operational forecast data. The flight track of the second flight was planned so that it would provide maximum overlap with the virtual plume location from 1700 to 1900 UTC, and match the structure of the forecasted WCB. The time interval was chosen to allow for dropsonde observations over the English Channel. Figure 5(b) shows that with the adjusted flight legs and the dropsondes we were able to sample the forecasted WCB air mass during the second flight over the English Channel.

Conclusion and outlook

The aim of this paper was to summarise the demands for the planning and completion of research flights in WCBs over Europe and to show the complexity of Lagrangian flight planning. The variable forecasts, as well as the operation regulations, strongly affected the planning. The constraint to submit flight plans up to 4 days ahead often needed a simultaneous planning of upcoming WCB events and a fine adjustment of the flights for the next day. The general synoptic

pattern was very suitable and enabled us to observe three WCB events in about 2 weeks. After this period large-scale subsidence associated with a persistent anticyclone hindered further flights.

The description of the planning for two flights during IOP 3 illustrated the challenges due to forecast uncertainty. However, we should add that we tried to adjust flight altitudes up to the latest possibility, which meant that in some situations the pilots asked for flight-level changes during the flight. In summary, the application of a novel chain of forecast products, including deterministic and ensemble-forecast-based WCB diagnostics proved to be valuable. The WCB-probability product was very useful in providing guidance for WCB prediction several days in advance. It helped us to assess whether we could rely on the more detailed deterministic forecast or whether there was large uncertainty linked to a particular scenario.

The T-NAWDEX–Falcon dataset is now being investigated extensively with respect to the mesoscale structure of WCBs and their representation in NWP models. The flights are being analysed for Lagrangian matches of air masses. The humidity and cloud probe data are being used to analyse the observed type of clouds, which will be compared with cloud fields produced by NWP models. Additionally, the T-NAWDEX–Falcon period is investigated with respect to forecast uncertainty because, for example, the extratropical transition of Hurricane Rafael complicated the prediction in the Atlantic–European sector in mid-October 2012. Finally, we are using the forecast data for research into uncertainty visualisation in order to further improve the utilisation of ensemble predictions during flight planning.

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