NAWDEX Science Plan

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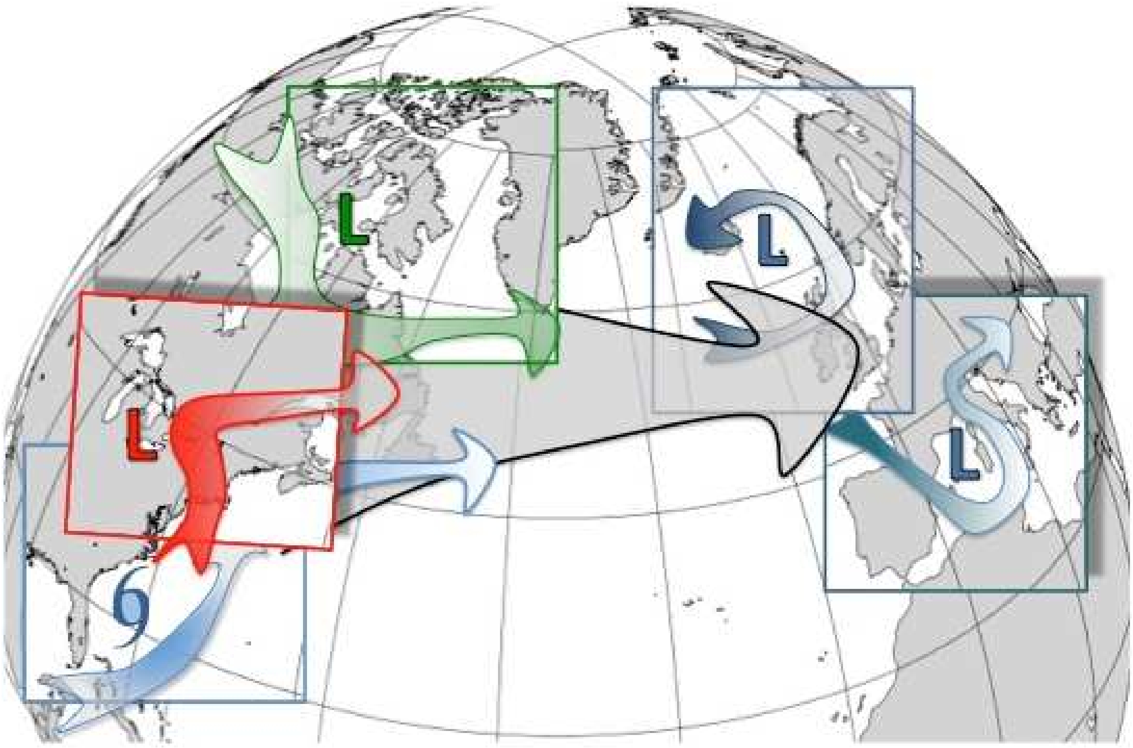

I. Introducing the North Atlantic Waveguide and Downstream Impacts Experiment (NAWDEX)

Recent evidence indicates that the worst weather forecast failures for Europe are associated with distinctive pre-cursor patterns (5-6 days beforehand) that propagate along the jet stream from North America. In addition, the response of regional climate in the mid-latitudes, especially in the European sector, to global warming is highly uncertain due to the large variability associated with the coupled interaction between the North Atlantic storm track and jet stream. It is hypothesized that diabatic processes (involving latent heat release due to condensation in clouds and radiative transfer) are central to both the weather and climate prediction problems in the Euro-Atlantic sector.

The overarching scientific aim of NAWDEX is to increase the physical understanding and to quantify the effects of diabatic processes on disturbances to the jet stream near North America, their influence on downstream propagation across the North Atlantic, and consequences for high-impact weather in Europe. The field campaign will provide a unique observational dataset, sampling the key dynamics and processes associated with the triggering, propagation and downstream impact of disturbances along the North Atlantic waveguide.

II. International Context

The idea for NAWDEX was seeded in 2007 and developed by the Predictability and Dynamical Processes (PDP) Working Group of the WMO programme THORPEX. After several aircraft field experiments (FASTEX, ATREC) dedicated to evaluating the potential of targeted observations it was apparent that forecast improvements associated with such an approach (reducing upstream initial condition uncertainty) were small and were not realized in all cases. It was decided that the observational focus should shift to the detailed examination of physical and dynamical processes operating within the weather systems that affect the disturbances on the waveguide, and go on to influence downstream predictability. In this way deficiencies in the representation of processes in models could be identified and, with novel theoretical and numerical approaches, could be used to improve the models used for prediction. As outlined below in more detail, this provided strong motivation to design a trans-Atlantic field experiment and modeling activity to examine different processes that trigger disturbances on the mid-latitude waveguide, propagate downstream modified by diabatic processes at waveguide level, and instigate high-impact weather at the downstream end of the storm-track. Plans for an international NAWDEX campaign, consisting of several nationally funded projects, have been developed since a PDP WG workshop in Erding, Germany, 2009. Due to various reasons related to facilities and funding NAWDEX has been postponed several times, but it is now firmly scheduled for September and October 2016. New theoretical and diagnostic research, and technical developments in forecasting systems during the last decade, make NAWDEX very timely both in terms of available airborne instrumentation and the scientific need to improve our understanding and predictive capabilities of processes along the North Atlantic waveguide.

NAWDEX is a cross-cutting topic for the scientific community focusing on both weather and climate timescales. Since the finish of THORPEX programme at the end of 2014, the leadership from the PDP WG has transferred to the new World Weather Research Programme (WWRP) WG on Predictability, Dynamics and Ensemble Forecasting (PDEF). NAWDEX also has a strong link to the High Impact Weather project, a new activity of the WWRP. It also deals with one of the four key questions posed by the Grand Challenge on clouds, circulation and climate sensitivity of the World Climate Research Programme (WCRP) for the next decade (Bony *et al.*, 2015).

III. Motivation

A. Weather

There is no doubt that the skill of forecasts for extratropical storms has been improving over several decades (Thorpe, 2004). The major short-range (< 2 day) forecast failures in the intensity and track of extratropical cyclones that occurred in the 1980s and 1990s would probably not occur nowadays with the current operational weather prediction systems. Despite these improvements, short-term prediction of high impact weather, such as mesoscale bands of strong winds and heavy precipitation, is still a difficult task. For instance, prediction for the likely location and intensity of peak wind gusts at lead times of 1 to 2 days is only just becoming possible with ensemble forecasts (Hewson *et al.*, 2014; Vaughan *et al.*, 2015). These phenomena depend strongly on diabatic processes, such as cloud physics and turbulence, that are currently parameterized in Numerical Weather Prediction (NWP) models. In particular, a new generation of “convection-resolving ensemble forecasts” with horizontal grid spacings of 1-3 km, have enabled a step-change in capability to simulate weather phenomena and can be run without parameterising convection, a major uncertainty in model formulation. However, the skill of such ensembles for probabilistic forecasts does not necessarily exceed the skill of the global model ensembles in which they are embedded, in part due to the small domain size used at such high resolution.

At upper levels, global NWP models fail to maintain the strong tropopause sharpness and it decreases with forecast lead time (Gray *et al.*, 2014). This can have major implications for the downstream propagation and amplification of Rossby waves in weather forecasts (Harvey *et al.*, 2015) and the associated prediction of high-impact weather.

At the medium range (about one week), the predictability of the weather over Europe is strongly dependent on the characteristics of the slowly-varying part of the jet stream (North Atlantic waveguide) and synoptic Rossby waves propagating along it. Rodwell *et al.* (2013) have shown that the worst 100 forecast busts for Europe over the last decade share a common precursor 6 days beforehand: a distinct Rossby wave pattern with a more prominent trough over the Rockies and a downstream ridge bringing warm, moist air across the eastern USA from the south. They hypothesised that diabatic processes in mesoscale weather systems over the USA are the origin of reduced predictability in these cases and furthermore that these diabatic processes may be misrepresented systematically in forecast models. However, there are other plausible reasons for large forecast error in these cases and hypotheses must be tested through a combination of new in-situ observations, numerical experiments and underpinning theory in order to identify the most fruitful path for model development and improved prediction.

B. Climate

Some extreme seasons are dominated by persistent weather regimes in Europe that are linked to low frequency variability in the North Atlantic jet stream waveguide. For example, the 2013/14 winter (the wettest on record in the UK, resulting in flooding nationwide) was characterised by a zonal succession of cyclones following the jet stream into Western Europe. In contrast, the 2009/10 winter was characterised by a persistent jet state much further south, associated with exceptionally cold weather across Western Europe and also higher predictability than usual (e.g., Frame *et al*., 2013). The UK Government Pitt Report (2008) cited the flooding of summer 2007 as the “most costly national emergency” since the 1940s and the total rainfall in summer 2012 was even greater. Both summers were characterised by a persistent jet stream wave pattern (and a similar situation occurred in 2008 and 2009). It is not known whether the extreme seasons experienced in Western Europe in the last decade have arisen by chance through the internal variability of the North Atlantic storm track and mid-latitude jet stream, or whether some external factor has influenced the persistent Rossby wave activity. Nevertheless, it is increasingly clear that jet stream variability is central to both the predictability of weather on timescales of a day to weeks, and of regional climate in mid-latitudes on timescales of years to decades.

The same physical processes that are poorly represented in NWP models also constitute a major source of uncertainty in climate model projections and make the prediction of changes in regional precipitation and wind patterns in response to global warming very uncertain. Among them are cloud microphysics, cloud radiative feedbacks, and turbulent boundary layer dynamics, which are parameterized in both NWP and climate models. NAWDEX will help us to improve our representation of these processes by furthering our understanding of how the physical processes influence synoptic-scale dynamics, thereby affecting not only mesoscale sensible weather but also large-scale weather regimes. Only once the physical processes are represented well in models, can the excitation and maintenance of large-scale patterns on seasonal timescales by global teleconnections, or downscaling of climate information for the Atlantic/European sector, be tackled with confidence through numerical simulation.

IV. Scientific hypotheses and questions

Overarching hypothesis: Diabatic processes over North America and the North Atlantic have a major influence on jet stream structure, the downstream development of Rossby waves on the tropopause, and high-impact weather phenomena over Europe.

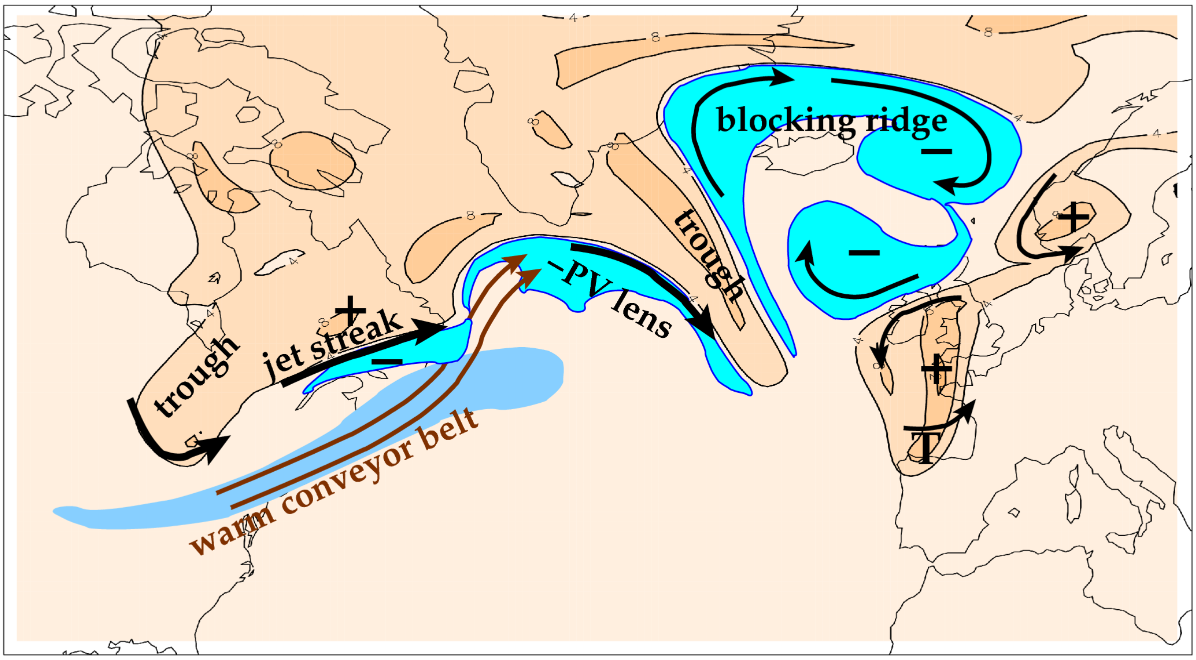

Figure 1: Illustration of disturbances to the jet stream near the tropopause (orange is stratospheric air; cyan marks upper tropospheric potential vorticity (PV) anomalies). The + and – indicate the sign of PV anomalies. Black arrows show upper-tropospheric wind, boldest where the jet stream is strongest. Brown arrows indicate the motion in a warm conveyor belt which ascends polewards from a tongue of low-level warm, moist air (darker blue). T marks the tip of a cut-off vortex that caused extreme flooding across England as it rotated anticlockwise over the following day (20 July 2007).

A. Diabatic processes and impact on potential vorticity and large-scale dynamics

1. Diabatic processes affecting Rossby wave packets (upscale effect):

a) *Warm conveyor belt / latent heating / ridge building:*

The air in the warm sector of each cyclone flows polewards and ascends in a warm conveyor belt (WCB; see Fig. 1) from the boundary layer into the ridge at tropopause level. For North Atlantic cyclones, climatologically the most frequent inflow region of WCBs is along the U.S. East Coast whereas the outflow spreads over the entire central North Atlantic (Madonna *et al.*, 2014). Diabatic processes, such as turbulent fluxes, cloud microphysics and convection in the WCB influence the net heating, the level of the outflow layer and the direction taken by outflow air masses (Martinez-Alvarado *et al.*, 2014a), and has important implications for perturbation growth rates and upscale energy transfer (e.g., Doyle *et al.*, 2014). The effect of the heating on the PV is to strengthen the negative PV anomaly (compared with its surroundings in that layer) in the shallow outflow layer which tends to intensify the upper-level downstream ridge. If the outflow layer is higher, the negative PV anomaly is stronger and more mass enters the anti-cyclonic branch of the WCB flowing into the downstream ridge. The latent heating in WCBs is strong both in the early phase of the ascent when condensation dominates and later when mixed-phase clouds are formed and vapour deposition on snow becomes important (Joos and Wernli, 2012).

b) *Long wave radiation / trough reinforcement:*

A sharp peak in longwave radiative cooling immediately below the tropopause and associated with a step change in water vapour creates a reinforcement of the upper troughs on the stratospheric side in Rossby wave packets (Chagnon *et al.*, 2013). Radiation has also been proposed as an essential process for the maintenance of so-called tropopause polar vortices (high amplitude cyclonic PV anomalies) in the lower stratosphere (Cavallo and Hakim, 2012), which can disturb the Rossby waveguide from the polar side.

c) *PV gradient:*

The combined effects of the low PV in the WCB outflow, the displacement of the tropopause by the divergent outflow, and increased PV contrast due to radiative cooling lead to the creation of a diabatic PV dipole (positive above and negative below the tropopause), a reinforcement of the horizontal PV gradient and amplification of the Rossby wave PV pattern (Chagnon *et al*., 2013).

2. <u>Diabatic processes directly involved in high-impact weather events (downscale influence):</u>

a) *Rossby wave breaking:*

Rossby wave breaking leads to PV filamentation forming smaller-scale PV anomalies such as PV streamers and (isolated) cut-off PV vortices (see the cut-off T over Western Europe in Fig. 1). The eastern North Atlantic and Europe are regions where the formation of PV streamers and cutoffs is particularly frequent (e.g., Wernli and Sprenger, 2007), and several studies reported the relevance of these flow features for triggering mesoscale high-impact weather, in particular heavy precipitation (e.g., Martius et al., 2006; Chaboureau and Claud, 2006). Such synoptic wave-breaking events are also important for the large-scale flow itself as they reinforce weather regimes such as blocking ridges like the one shown in Fig. 1 (Michel and Rivière, 2011; Spensberger and Spengler, 2014).

b) *Advection of moisture:*

Large-scale advection of lower-tropospheric existing mesoscale humidity anomalies by PV vortices may lead to heavy precipitation events (e.g., Martius *et al.*, 2006). Moisture advection is also important, e.g., in the inflow region of WCBs. Studies by Schäfler et al. (2011) and Schäfler and Harnisch (2015) have shown that low-level humidity in WCB inflows can be poorly constrained by standard observations, and that errors in the low-level moisture can influence the outflow level of WCBs and thereby the waveguide disturbance and downstream flow evolution. Filaments of moisture within low-level jets in WCBs are important regions of initial condition sensitivity and impact the downstream predictability (Doyle *et al.*, 2014).

c) *Frontogenesis, frontolysis, conditional symmetric instability:*

Extratropical cyclogenesis is accompanied by generation of mesoscale structure by frontogenesis, frontal instability and banding through mechanisms such as conditional symmetric instability initiated in saturated air. For example, such processes are invoked to explain the occurrence of sting jets, damaging winds occurring in the frontal fracture region of Shapiro-Keyser type cyclones (Clark *et al.*, 2005; Gray *et al.*, 2011). However, there have only ever been two research aircraft flights into sting jet cyclones, the latest in 2011 (Martinez-Alavarado *et al.*, 2014b; Vaughan *et al.*, 2015), and the mechanisms shaping the structure of the strongest surface winds are not yet known conclusively. However, the frontal structure associated with sting jets often appears for cyclones that have crossed the large-scale jet from its warm-air to cold-air side (Rivière *et al.*, 2015).

B. Potentially misrepresented diabatic processes in models and impact on the circulation :

1. <u>Rossby wave packets:</u>

a) Intensity of the negative PV anomaly and PV gradient:

The amplitude of ridges is often underestimated in current NWP models (Davies and Didone, 2013). Gray *et al.* (2014) have shown that ridge amplitude decays systematically with lead time in the operational forecasts from the Met Office, ECMWF and NCEP. In addition, the PV gradients decrease with lead time suggesting that models cannot maintain the sharpness of the observed waveguide. One possible explanation is that the PV gradient at the tropopause is smoothed by numerical dissipation in NWP models (via the advection scheme and numerical diffusion) and this has the systematic effect of acting to slow down Rossby waves and decrease their amplitude (Harvey *et al.*, 2015). Another origin of the too weak PV gradient in models might come from the representation of long wave radiative cooling, which is sensitive to the vertical profile of water vapour and cirrus clouds near the tropopause. This has ramifications for forecasts of downstream development, since theory tells us that although both the jet stream maximum and westward propagation rate decrease if the PV gradient lessens, the jet effect is stronger and net Rossby wave phase speed decreases. Perhaps more importantly, Rossby wave packets disperse too rapidly downstream. Therefore, diabatic processes, often operating on small scales, can have important consequences for large-scale forecast error. However, the relative importance of the mechanisms outlined above is not known and the aim of the experiment is to quantify the processes using a combination of new observations and model simulations.

b) Vertical structure of the negative PV anomaly:

The negative PV anomaly in warm conveyor belt outflow resembles a thin lens dominated by a static stability anomaly (see e.g., Fig. 1 in the mid-Atlantic). It is hypothesised that forecast models misrepresent the vertical structure of the PV lens which has consequences for the flow "induced" and associated Rossby wave propagation along the waveguide.

c) Displacement of the PV gradient:

Ascent, amplified by heating, is associated with horizontal divergence at the outflow level. On each isentropic surface, the divergent flow has a strong component normal to the tropopause PV gradient, resulting in poleward advection of the tropopause. This acts as a "Rossby wave source" and can initiate Rossby wave packets that propagate downstream.

2. <u>High-impact weather, and downscale influence of Rossby wave packets:</u>

a) Synoptic-scale upper-level forcing of precipitation events:

The advection of mesoscale humidity structures by upper-level PV anomalies gives rise to strong sensitivity of forecasts to the moisture field (Doyle *et al.*, 2014). A better knowledge of the low-level moisture field is required for forecast improvements.

b) Jet streaks:

Localised horizontal PV dipoles (such as shown over Newfoundland in Fig. 1) constitute "jet streaks" where the jet stream is more intense. Jet streaks are often initiated as long-lived polar mesoscale vortices (maintained by radiative cooling) approach the jet stream and can have a direct impact on severe weather through strong baroclinic interaction with the lower troposphere.

c) Lower-tropospheric strong winds:

It is not clear how lower-tropospheric strong winds are dynamically linked to PV anomalies and what the dominant dynamical balances are for these regions of strong winds. The most damaging winds, like sting jets, have been suggested to emanate from the edge or tip of the hooked cloud shield head on the south-western flank of the cyclone, where evaporation of precipitation occurs. However, the role of evaporation of precipitating bands in the formation of sting jets and in the downward transfer of momentum to the surface is not clear yet (Baker *et al.*, 2014; Smart and Browning, 2014).

d) Connection between lower-tropospheric winds and boundary-layer processes:

Destabilization of the boundary layer is required to facilitate downward mixing by convective plumes (Parton *et al.*, 2009). But it is rather difficult to reproduce such a downward transfer of momentum in NWP models under both a real or idealized framework (Parton *et al.*, 2009; Baker *et al.*, 2014). Generally speaking, the interaction between boundary-layer processes and the balanced flow in extratropical cyclones still raises open questions.

V. Experimental design

A. The phenomenological focus of NAWDEX observations

1. Inflow part of WCBs:

Detailed observation of water vapour, low-level winds and surface heat fluxes in the inflow part of the WCBs when air masses are still moving quasi-horizontally in the lower troposphere. Combined measurements of humidity and winds are particularly useful as they allow quantification of the horizontal moisture flux towards the baroclinic zone. This would be clearly needed to better quantify latent heat release in ascending air masses. These observations are relevant to address issues mentioned in sections IV.A.1.a, A.2.b, B.2.a.

2. Jet stream anomalies:

Detailed observation of structure in winds, temperature, water vapour and clouds (liquid and ice water path) near the tropopause in jet stream ridges with particular focus on the thin lenses associated with negative PV anomalies in air that has recently ascended from the lower troposphere to tropopause level (see section IV.A.1.a , IV.B.1a-c). Radiative fluxes near the tropopause will be also quantified (see section IV.A.1.b). It is one of the aims that a suitable combination of wind observations and temperature profiles will permit a meaningful estimate of the potential vorticity structure across the jet stream, in particular in regions where the jet has been modified by diabatic processes.

3. Cloud structures and frontal fracture region:

Detailed observation of hydrometeors within the clouds of cyclones, in particular within the WCB, the cloud head and in the banding cloud structures of the frontal fracture region, including estimating of ice water content. Other fields of interest will be the wind components (both horizontal and vertical), the temperature and the humidity. All this information will serve to estimate evaporation rates at the cloud edges (sections IV.A.2.c, IV.B.2.c-d).

B. Observational facilities contributing to NAWDEX

The observations will mainly rely on airborne facilities over the Atlantic Ocean and ground-based intensified network in the immediate impacted regions (UK, France, and other European countries).

1. Aircrafts and airborne instrumentation

a) HALO / DLR Falcon:

The German, Swiss, UK, and U.S. (NRL) contribution to NAWDEX focuses on the deployment of the two aircraft, HALO and DLR Falcon, such that the wind LIDAR (on the Falcon) and DIAL water vapour (on HALO) can complement one another. The aim is to obtain a comprehensive and unprecedented data set in a region near the tropopause that, so far, was not accessible with smaller research platforms. With the combination of the instrumentation on board HALO (the WALES differential absorption lidar for water vapour, the cloud radar of the Hamburg Microwave Package (HAMP), different radiometers and the dropsonde device) and two wind lidar systems on the DLR Falcon, the three-dimensional structure of water vapour, wind, temperature and cloud properties will be observed. HALO and Falcon will operate over the eastern North Atlantic with base of operations in Iceland. Some flight segments will be together to operate the different remote sensing measurements in tandem. In other situations, the HALO will sample the jet stream towards the upstream end of the waveguide between Iceland and Newfoundland while the DLR Falcon will operate downstream between Iceland and Scotland.

b) SAFIRE Falcon:

The SAFIRE Falcon will be used during NAWDEX as part of the French and Norwegian contributions. The airborne Doppler cloud radar RASTA and the high spectral resolution lidar (LNG) will be operated on-board the SAFIRE Falcon. In addition to the radar, a unique instrumental payload with new in-situ instruments as Robust and CPSD microphysical probes (ice / water discrimination) in addition to already existing ones will be deployed. It will characterize bulk and individual hydrometeor microphysics and thus determine the content of liquid water and ice. The six-beam configuration of RASTA will allow us to retrieve microphysical ice-cloud properties and 3D dynamics of clouds. The lidar measurements will help to characterize aerosols, thin ice clouds and combined with the radar will identify the cloud phase. Furthermore the high spectral resolution lidar has Doppler capability and therefore will help to retrieve the radial component of the wind in clear sky condition. The SAFIRE Falcon is planned to fly in the eastern North Atlantic during a two-week period in October 2016 and to be positioned in Brest (France). The targeted processes are diabatic processes within atmospheric rivers.

c) King air aircraft:

The planned Canadian contribution includes the basic instrumentation of aircraft-of-opportunity that operate routinely over the western North Atlantic. The King Air aircraft have operating ranges up to 2000 km with endurance of 5-6 h. Although these aircraft have a service ceiling of >9 km, the Provincial Aerospace (PAL) missions are primarily for ice reconnaissance, search, rescue and defense, and are thus executed at much lower altitudes (as low as 50 m). These aircraft will be equipped with a ARIM200 Digital Data Probe (ADP), which will provide high frequency in-situ measurements of pressure, temperature and relative humidity in addition to standard flight data. The high quality of the temperature (<0.5 K) and relative humidity (2%) measurements will provide valuable information in this region given the high volume of flights operated by PAL (an average of over 500 h per year, valued at approximately 1M$). These aircraft will be primarily collecting meteorological data while on ice spotting missions during NAWDEX, but routing requests will allow them to be deployed in a strategic manner directly supporting other project aircraft through coordination with the operator.

2. Ground-based observation network

a) UK:

Enhanced ground-based observations across the UK will have two main purposes:

A: to observe the dynamical structure of the negative PV lenses, that have been observed upstream by the German and French aircraft, as they are advected across the UK using additional radiosonde ascents and the UK-based profilers for wind, static stability and humidity.

B: to observe tropopause features that play a leading role in high impact weather in western Europe, and their connection with low-level mesoscale structure in humidity and winds observed in the high-resolution UK analysis from the Met Office which assimilates radar and surface-site obs.

Intensive observations will be made from the MST radar site near Aberystwyth (Wales) used to measure winds and tropopause sharpness. The station also houses the following instruments: an ozone lidar optimised for the tropopause region and a powerful Raman lidar capable of measuring water vapour profiles (Δz~150m) and the static stability profile (Δz~300m).

In collaboration with the Met Office, and subject to funding, there will be additional radiosonde releases (50-60) from any site on their network which can be actioned with less than a day notice. Profiles through the negative PV lenses that have been observed upstream will be a key target for sonde launches. (ii) The new Met Office network of Raman lidars will be operated every 15 minutes throughout the campaign, giving access to static stability profiles as described above (but lower resolution). (iii) Wind profiler observations in the tropopause region are also recorded every 30 minutes by the ST radar on South Uist (NW Scotland). (iv) An opportunity will be exploited with the new MODE-S dataset which consists of horizontal winds retrieved from commercial aircraft flights over the UK, giving good coverage on vertical profiles (3s data) and level flights. (v) The Met Office Doppler radar network and automatic weather station data will be used to examine mesoscale structure at low levels in precipitation and surface winds across the UK.

b) France:

A supersite with intense observations will be settled in Brest (extreme West of France). It will include a wind profiler UHF, a water vapour LIDAR and radiosondes measurements. The project will also benefit from measurements from the observational site SIRTA near Paris where we are planning to launch additional radiosondes on demand. A microwave radiometer profiler, also transportable, which will provide vertical profiles of temperature and the vertically-integrated liquid water content will also be used at Bure (East of France). Finally, wind measurements from permanent radars ST/VHF settled at Lannemezan (Pyrénées) and Clermont-Ferrand will be made available as well.

c) Canada:

On-demand 6-hourly radiosonde launches will be available from several Environment and Climate Change Canada sounding stations during NAWDEX. These ascents will attempt to sample the precursor waveguide disturbances and their immediate surroundings as they approach the project region. Stations prepared to conduct additional soundings include both those that are capable of capturing both southern-stream (WSA, YJT, AYT) and northern-stream (YYR, YVP, YFB) perturbations.

C. (Bi)-national proposals and their specific objectives

1. German-Swiss :

The consortium will focus on tropopause level flow structures, influenced, e.g., by radiative processes and WCB outflows. In particular, it will investigate the relative importance of balanced flow and ageostrophic flow divergence near the outflow of WCBs and in the downstream ridge. Measurements will be made with the HALO and DLR Falcon aircraft (see section V.B.1.a). In addition to upper-level observations, the humidity structure in the lower troposphere and radar and profile measurements in WCB clouds are of interest for diabatic processes. More information can be found at http://www.pa.op.dlr.de/nawdex. Additional work including analysis of campaign data and associated modeling studies will be performed within the Waves to Weather collaboration (w2w.meteo.physik.uni-muenchen.de).

2. UK-German :

EUFAR have funded 10 hours of additional flight time on the DLR-Falcon aircraft (called NAWDEX-Influence) which will be used to direct the aircraft into PV lenses (shallow negative PV anomalies) that are forecast to pass over the UK-based stratosphere-troposphere profilers. The linked observations will be used to examine the evolution of the PV lenses which present a significant challenge to models due to their shallow structure and the importance of diabatic processes. A second focus will be on the “dry eyes” appearing in satellite imagery that are a signature of cut-off positive PV anomalies and often associated with high impact weather at the surface. The UK is ideally situated, and has an excellent ground-based profiling capability and radar network (see V.B.2) to make the connection between the tropopause evolution and high impact weather across western Europe (collaborating with Météo-France and Met-Norway).

3. U.S. Naval Research Laboratory :

The focus of the NRL program is on diabatic processes associated with the interactions among mesoscale and synoptic-scale disturbances in the waveguide and their impact on predictability of downstream high-impact weather. We will focus on humidity structures and moisture transport in the lower troposphere, with moisture and wind profile measurements within and outside of WCBs in regions of sensitivity of high priority. We are also interested in whether improved analyses and representations of diabatic processes within disturbances that impact the waveguide, as informed by the NAWDEX observations, will increase high-impact weather predictability and links to stratospheric prediction.

4. Norwegian-French:

EUFAR proposal called NEAREX. The proposal plans to study diabatic processes in WCBs, and more specifically on the water-vapor rich part of the WCBs, the so-called atmospheric rivers. Predictability issues on the downstream side of the Atlantic waveguide in Norway will be investigated with a focus on flood prediction associated with atmospheric rivers. Measurements along atmospheric rivers will be made with the SAFIRE Falcon. The airborne Doppler cloud radar RASTA and the high spectral resolution lidar (LNG) will be operated on-board the SAFIRE Falcon. Moreover, a unique instrumental payload with new in-situ instruments as Robust and CPSD microphysical probes (ice / water discrimination) in addition to already existing ones will be deployed. It will characterize bulk and individual hydrometeor microphysics and thus determine the content of liquid water and ice. Observational data will be directly compared to the representation of the atmospheric rivers from both satellite platforms and NWP analyses. Ensemble Prediction Systems will be used, especially a high-resolution EPS centred over Scandinavia.

5. Canadian:

The focus of the Canadian component of NAWDEX is on the precursor disturbances that are responsible for triggering changes to the waveguide. These include features that arrive at the jet entrance region in the northern stream (including tropopause polar vortices and cold air outbreaks) and those that approach in the southern stream (including transitioning tropical cyclones and rapidly developing coastal cyclones). Features in both of these regions will be sampled by proposed on-demand radiosonde launches during the project. The influence of moisture on the growth rates of cyclonic precursors in the southern stream is of particular interest in this component of the project, because it is the intensity of these circulations that largely determines the strength of meridional moisture transport by associated warm conveyor belts. The proposed high quality in-situ temperature and humidity observations made by instrumented aircraft of opportunity during the project will provide unique high density coverage at lower levels over the western North Atlantic. This aspect of the proposal is important for project legacy because the collection of these observations will continue indefinitely.

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