North Atlantic Waveguide, Dry Intrusion, and Downstream Impact Campaign (NAWDIC)

International Science Plan

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We acknowledge all colleagues who contributed to discussions at and following the first international NAWDIC workshop in November 2020.

Introductory comment: This document is a living document that summarizes the scientific aims and observational strategy for a prospective NAWDIC field campaign. It is based on discussions at a preparatory virtual NAWDIC workshop held in November 2020. The international community has defined contact persons that lead the individual discussions in the national communities and contribute to this document. We acknowledge valuable contributions by many other researchers that participated in the planning workshop.

The acronym NAWDIC was originally defined for the planned German component with the High Altitude and Long Range Research Aircraft (HALO). In the meantime, many components have been added and it needs to be discussed whether a new acronym should be defined for the combined international efforts. Still, in order to cope with uncertainties related to the individual projects, all components will be elaborated as stand-alone projects. This international science plan describes the umbrella for the envisioned individual components.

Planning Wiki: https://internal.wavestoweather.de/campaign/projects/nawdic/wiki

1 Introduction

1.1 Overarching goals

Gale-force wind gusts, wide-spread heavy precipitation, and cold air outbreaks are some of the most severe weather hazards in the midlatitudes in boreal winter. All these types of high-impact weather

(HIW) are related to the evolution and life cycle of extratropical cyclones in the storm track (Fig. 1). Despite considerable progress during recent decades, accurate predictions of the location, timing, and intensity of these typically mesoscale HIW events at sufficient lead time still pose a challenge for state-of-the-art numerical weather prediction (NWP) models. This is due to the multi-scale interactions of physical processes involved in the formation of HIW, ranging from near hemispheric-scale Rossby waves lasting several days to weeks, to momentum transport into the planetary boundary layer (PBL) and cloud microphysics acting on scales of hundreds of meters to micrometers and minutes to seconds. The representation of the same multi-scale interactions is also a challenge for climate modelling and should have an impact on the representation of HIW events in climate models and hence on projection of their future evolution in a statistical sense.

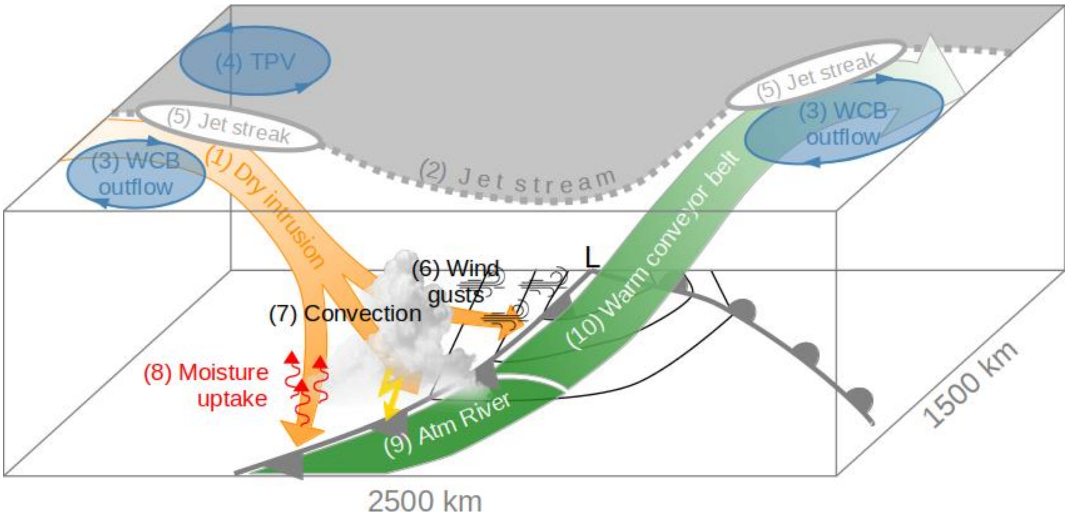

Figure 1: 3-D schematic view of the weather systems, airstreams, and processes of interest to NAWDIC. The shown features are numbered according to the references in the text. "L" denotes the centre of an extratropical low pressure system, "WCB" denotes warm conveyor belt and "TPV" stands for tropopause polar vortex. Science questions concerning the different processes are listed in Sec. 2 of this document.

In 2016, the North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX, Schäfler et al., 2018) successfully investigated how diabatic processes in ascending airstreams (warm conveyor belts, WCBs) affect the upper-level midlatitude jet stream and Rossby waveguide. New observational findings included the systematic under-estimation of vertical wind shear in analyses and forecasts, especially just above the tropopause in the vicinity of the jet stream (Schäfler et al., 2020). New fundamental mechanisms deduced by the NAWDEX team, based on observations, theoretical development and modelling, link diabatic heating in wind shear to local intensification of jet stream strength (Harvey et al., 2020) and the generation of mesoscale perturbations to jet stream structure (Oertel et al., 2020; Blanchard et al., 2021). It was also shown that predictability of weather over the Euro-Atlantic sector during NAWDEX was lower in situations with stronger diabatic influence on advection of the tropopause (Sanchez et al., 2020), building on existing evidence that divergent outflow from WCBs near the tropopause is associated with large forecast uncertainty (Grams and Archambault, 2016; Grams et al., 2018) and rapid forecast error growth (Baumgart et al., 2019). A major issue not investigated in NAWDEX is how the upper-level flow in turn affects the dynamics and predictability of the low-level flow and the mesoscale or convective phenomena that are central to HIW at the surface, especially over land at the downstream end of the stormtrack.

Surface weather can be affected by upper-level disturbances either through direct descent of air masses from upper to lower levels, or through remote influence of tropopause perturbations on the wind and temperature at all levels associated with large-scale balanced flow, mediated by fast wave propagation. A key feature in the air mass transport context is the dry intrusion airstream (label (1) in Fig. 1), which connects perturbations near the upper-tropospheric jet stream (2) to the PBL and HIW near fronts. Dry intrusions emerge from the downstream flank of an upper-tropospheric ridge, which often gets amplified by prior WCB outflow (3). In this region mesoscale anticyclonic and cyclonic perturbations on the tropospheric (3) and stratospheric (e.g., tropopause polar vortices (4)) side of the jet stream, respectively, impact the very sharp tropopause-based gradients of humidity and temperature and contribute to the formation of jet streaks (5). Dry intrusions descend in the cold sector of a downstream cyclone over a horizontal distance of 1000–5000 km within about 2 days. When reaching the lower troposphere the dry intrusion air interacts with the PBL, resulting in destabilization and downward momentum transport, affecting the formation of wind gusts (6) near the surface. Likewise, the destabilization supports the evolution of convectively-enhanced precipitation (7) near the cold front. Although well studied, there are still major uncertainties regarding the dynamics of perturbations along cold fronts, such as cold frontal rainbands and their relation to severe weather, including tornadoes that are relatively common on cold fronts with intense shear (Clark and Parker, 2020). Increasing model resolution is not sufficient to solve these issues, since NWP simulations do not converge with resolution in all aspects compared with observations (e.g., Harvey et al., 2017) and the reasons for these flaws are not understood.

Finally, the presence of relatively cool and dry air over the ocean enhances moisture uptake in the cold-sector of a cyclone (8), which could support subsequent cyclogenesis and the formation of or interaction with atmospheric rivers (ARs) (9) or WCB inflow (10). ARs frequently lead to widespread heavy precipitation, particularly when encountering orography. WCB formation will eventually generate upper-level outflow ((3), right) and the cycle might repeat one wavelength further downstream.

NAWDIC aims to advance our understanding of the synoptic- to micro-scale dynamical and physical processes associated with the triggering of severe wind gusts, heavy precipitation, and cold air outbreaks in the North Atlantic, Euro-Mediterranean region and of their representation in NWP models. More specifically, NAWDIC will focus on the physical understanding and quantification of the dry intrusion airstream for the evolution of HIW related to extratropical cyclones in winter. NAWDIC research is structured around three science goals:

1) NAWDIC will make measurements able to characterize the mesoscale structure of the cloud and wind field, including vertical motion, within the jet stream, particularly near jet streaks and in locations where the coherent descent of dry intrusion air masses begins.

2) NAWDIC will strengthen our understanding of momentum transport into the PBL and its role in the formation of severe wind gusts and convection. This will be achieved by high-resolution observations of wind, temperature, all phases of water, and cloud microphysical properties where dry intrusions descend to the top of the PBL, the PBL and surface beneath as well as the neighbouring cold fronts.

3) NAWDIC will clarify the importance of the model representation of surface fluxes in the cold sector and near fronts of extratropical cyclones for HIW and subsequent cyclogenesis, in particular over

the ocean. To this end, detailed observations of turbulent heat, moisture and momentum fluxes at the air-sea interface are planned.

The three science goals close a circle, as the replenishment of moisture and associated sensible and latent heat fluxes from the cold sector support subsequent cyclogenesis and the ascent of a new WCB, which in turn can affect a potential dry intrusion initiation region downstream (see Fig. 1 and Sec. 2).

1.2 Vision for an international field campaign

The idea for NAWDIC as a research campaign in extratropical atmospheric dynamics with the involvement of the German research aircraft HALO developed in 2019 from a discussion at the Karlsruhe Institute of Technology (KIT) and within the Collaborative Research Center "Waves to Weather". The project idea was proposed to the HALO steering committee at a mission selection workshop in autumn 2019, and was considered as a prospective HALO mission after 2025. At the same time interest in coordinated observations to improve the prediction of extreme events in the North Atlantic - European region emerged on an international level (Lavers et al., 2020). When the idea was presented to the community at a virtual international workshop in November 2020, broad interest was expressed and the NAWDIC community grew rapidly beyond the groups involved in NAWDEX. In addition to the European partners, several American colleagues are now involved with the idea to make it a trans-Atlantic field campaign. The international partnerships will allow NAWDIC to collect a comprehensive observational data set. At the same time the collaboration will create momentum for a seamless observational and modelling approach which one group alone would not be able to implement. **Currently NAWDIC is scheduled for winter 2025/2026 with the HALO component planned in Jan / Feb 2026.** A detailed description of the implementation and observational aims will follow in Sec. 3.

We envision NAWDIC as a modular international effort, in which several groups contribute components that are in principle feasible as stand-alone projects. This gives us the necessary flexibility to cope with unavoidable uncertainties in funding, planning, and implementation. NAWDIC forms the umbrella aiming to realize all components together in a coordinated manner in order to maximise synergies between the individual contributions. In that regard the prospective HALO mission is the major envisaged German NAWDIC component. In addition, NAWDIC follows a "seamless" observational approach across scales: high-altitude, long-range aircraft, such as HALO, will characterise the large-scale environment and provide observations with remote sensing and dropsondes covering the spatial extent of a synoptic event. Envisaged observations with mid-range, mid-troposphere aircraft (e.g., UK BAe146; French ATR42, see Section 3.2.1) components will characterise the mesoscale structure and cloud microphysical properties of the descending dry intrusion airstream and the PBL. This will be complemented with ground-based measurement networks that are high resolution in both time and space to observe the mesoscale and convective structures connected to surface weather impact. High resolution (e.g., sub-km in the horizontal) is needed to evaluate convection-permitting, or higher resolution, numerical models that are the cutting edge in NWP.

In our seamless approach, modelling forms an integral part, which will – in collaboration with weather services – directly transfer the heterogeneous but precise observations into a structured model using data assimilation systems across scales. Therefore, the NAWDIC community made an effort to involve weather services already in an early stage of strategic discussions, in order to orientate the scientific goals towards their needs to further improve NWP models. Currently, colleagues from the weather services of Canada (ECCC), Germany (DWD), France (Météo France), the United Kingdom (MetOffice) as well as the European Centre for Medium-Range Weather Forecasts (ECMWF) are actively involved in the planning. The campaign design and its aims follow recommendations by the NWP community that were made at the workshop “Observational campaigns for better weather forecasts” held at the ECMWF in 2019 (Magnusson and Sandu, 2020).

In 2020, NAWDIC was endorsed by the High-Impact Weather Project (HIWeather) within the World Weather Research Programme (WWRP) of the World Meteorological Organization (WMO). HIWeather is a 10-year international research program to advance the prediction of hazards including disruptive winter weather and localized extreme wind. Within HIWeather, NAWDIC will contribute to advance the fundamental understanding of HIW in the research theme predictability and processes.

The rationale of NAWDIC connects with the aim of the newly formed European COST Action on Mediterranean cyclones (CA19109) for enhancing cyclone process understanding to improve their prediction on weather and climate time scales. Therefore, strong links exist between NAWDIC and the Mediterranean COST community.

The NAWDIC community members are hosted at the following institutions:

Canada: Environment and Climate Change Canada (ECCC); McGill University – **France**: Laboratoire d’Aérologie (LAERO); Laboratoire de Météorologie Dynamique (LMD); Météo France; Laboratoire Atmosphères, Observations Spatiales (LATMOS) – **Germany**: German Aerospace Center (DLR), German Weather Service (DWD); Johannes Gutenberg University (JGU) Mainz; Karlsruhe Institute of Technology (KIT); Ludwig Maximilian University of Munich; Free University of Berlin – **Greece**: Hellenic Centre for Marine Research (HCMR) – **Israel**: Weizmann Institute of Science – **Italy**: Institute of Atmospheric Sciences and Climate (CNR-ISAC) – **Norway**: University of Bergen – **Switzerland**: ETH Zürich – **United Kingdom**: ECMWF, Met-Office; University of Exeter; University of Leeds; University of Manchester; University of Reading – **USA**: National Center for Atmospheric Research (NCAR); Naval Research Laboratory (NRL); North Carolina State University; Scripps Institution of Oceanography; University at Albany, SUNY; University of Colorado Boulder; University of Oklahoma - Norman; University of Wisconsin - Madison.

In the remainder of this document we summarise the ongoing discussion about NAWDIC science in more detail (Section 2). Furthermore we outline our vision for the observational and modelling components of NAWDIC in Section 3.

2 Science questions and hypotheses

Multi-scale interactions of synoptic-scale weather systems affecting HIW in the Euro-Mediterranean region are organised in the North-Atlantic stormtrack, and thus involve the sequence of extratropical cyclones and anticyclones and airstreams embedded therein. One can view this as a repetitive sequence of interacting airstreams, which connect the regions and meteorological features of scientific interest in NAWDIC, modulated by external factors (illustrated as a circle in Fig. 2): The former NAWDEX campaign in 2016 gained important insight into how the ascending WCB airstream affects the upper-level jet stream and tropopause region. This is also the initiation region of the dry intrusion airstream and open issues remain regarding its representation in NWP models (Goal 1 and details in Section 2.1). The dry intrusion links the upper levels to the PBL and can be involved in the generation of HIW (Goal 2 and Section 2.2 a,b,d). At the same time horizontal moisture transport and uptake might occur in the PBL and near a front associated with an AR (Goal 3 and Section 2.2c). Ultimately, the same air might then ascend ahead of the cold front of a subsequent cyclone as a WCB and affect the upper levels, initiating a new circle of interaction. At the same time external factors such as incoming Rossby wave activity or tropopause polar vortices (TPVs) approaching the jet stream as well as moist processes affect this air mass interaction.

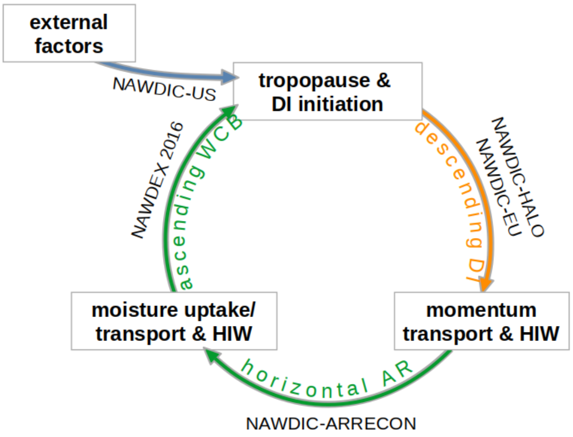

Figure 2: Schematic of the relation between NAWDIC science goals (Section 1.1), regions, and meteorological features, their links via the dry intrusion (DI), atmospheric river (AR), and warm conveyor belt (WCB), and the scope of NAWDEX 2016 and envisaged NAWDIC components. For arrows, the colour coding is the same as in Fig. 1.

The air mass interaction also involves outstanding challenges in the interplay of atmospheric dynamics with moisture and its phase changes: 1) With regard to tropopause structure and dry intrusion origins (Goal 1 and Section 2.1) these are the role of ice and liquid water condensation and evaporation on mesoscale instability and the emergence of coherent banded structure in cloud and winds in the environment of strong shear and curvature beneath the jet stream. 2) With regard to the PBL-dry intrusion interface (Goal 2 and Section 2.2 a, b) these are the mechanisms which enable strong winds above the PBL, especially where dry intrusions descend behind cold fronts, to generate severe wind gusts at the surface. This may involve conditional symmetric instability (CSI) above the PBL, moist thermodynamic profiles within the PBL, and the coupled interaction of motions above the PBL with large eddies within the PBL. 3) With regard to surface fluxes and HIW (Goal 3 and Section 2.2 c, d) these are the influence of surface properties and atmospheric PBL turbulent regime on moisture uptake by ARs and WCBs. It is expected that heavy precipitation in Europe is directly influenced by this moisture, as well as by the properties of WCB latent heating profiles and outflow level (providing a link back to heating in shear and Goal 1).

In the following we detail the NAWDIC science topics.

2.1 Tropopause structure

Hypothesis: Mesoscale circulations oriented across the jet stream axis affect the timing and structure of vertical motion and the coherent descent of air in dry intrusions. An accurate representation of the tropopause structure, dynamics, and parameterized physics in NWP systems is essential for the predictions of the large-scale midlatitude flow and downstream HIW.

a) Features affecting the tropopause structure on the tropospheric side

Latent heat release in the ascending airstreams of mid-latitude weather systems enhances upper-tropospheric divergent outflow, which substantially impacts the structure of the jet (Archambault et al. 2013; Teubler and Riemer 2016; Grams and Archambault, 2016; Quinting and Jones 2016). The ageostrophic circulation in response to heating in the WCB is oriented across the tropopause towards the stratospheric side, tending to displace and sharpen the tropopause potential vorticity (PV) gradient (Harvey et al., 2020). In addition, convective updrafts in a vertically sheared environment lead to the generation of PV dipoles (Chagnon and Gray, 2009; Oertel et al., 2020) that are oriented such that the negative PV side must always be closest to the jet stream core and therefore strengthens the near-tropopause PV gradient and the jet maximum speed (Harvey et al., 2020). This provides a mechanism whereby small-scale processes can influence the large-scale dynamics and predictability.

Prior work has shown that the omission or misrepresentation of diabatic processes in models can lead to considerable differences in the amplitude and intensity of the jet (Baumgart et al. 2019; Berman and Torn 2019; Steinfeld et al. 2020), which translates to uncertainty in the potential for HIW events to develop downstream. Recently Sanchez et al. (2020) have shown that episodes of strong diabatic heating influence on advection of the tropopause are associated with “predictability barriers” (when ensemble mean forecast error grows faster than ensemble spread) over Europe. The inherent predictability of these situations is lower (reflected in the greater rate of ensemble spread) but the faster error growth and link with diabatic processes is unexplained and may reflect NWP model errors. The tropospheric side of the tropopause, on the western flank of trough structures, also hosts the origin region for dry intrusions (Silverman et al., 2021), such that errors in this particular near-tropopause region can lead to misrepresentation of the dry intrusion air mass characteristics.

b) Features affecting the tropopause structure on the stratospheric side

On the scale of individual synoptic and mesoscale features, stratospheric variability may manifest in the vertical gradients near the tropopause which affects the tropopause jet and waveguide. A subset of studies has focused on the three-dimensional nature of Rossby wave propagation along the tropopause waveguide and highlighted the variability in vertical profiles of lower-stratospheric wind and static stability in influencing eddy phase speed (e.g., Chen and Held 2007), eddy length scales (e.g., Rivière 2011), the index of refraction for baroclinic systems (e.g., Simpson et al. 2012), and preferences for cyclonic or anticyclonic wave-breaking (e.g., Wittman et al. 2007). Even if the PV contrast across the tropopause zone is the same, the sharpness of the PV gradient was shown analytically to affect Rossby wave propagation (Harvey et al. 2016). Rossby wave phase speed is a competition between advection by the jet stream and counter-propagation (upstream). If the PV gradient is too smooth in a model, then jet speed weakens more than propagation with the net effect that Rossby wave phase speed is less positive (eastwards). If misrepresented in a model’s initial conditions, the vertical gradients of wind, temperature, and moisture, across the tropopause can produce biases in the evolution of the baroclinic development and Rossby waves downstream (Haualand and Spengler 2021). The high resolution observations across the tropopause (from wind lidar, sondes and stratosphere-troposphere wind radar) during NAWDEX revealed that vertical wind shear is on average much stronger than in analyses and forecasts, especially on the stratospheric side of the tropopause (Schaefler et al., 2020). The ramifications for weather prediction have not been investigated.

TPVs merging with the jet stream from the polar side can impact the PV contrast across the tropopause zone, the strength of the jet, and can cause a jet streak, and may trigger the initiation of Rossby waves (e.g., Roethlisberger et al. 2018; Johnson and Wang 2021). Although TPVs are typically small in scale relative to the troughs of mid-latitude weather systems, they are long-lived and it has been hypothesised that this might contribute to predictability. The generation of TPVs has not been explored and the role of TPV geometry in the jet interaction process remains unclear. Once TPVs form, there is a self-sustaining intensification process through stronger radiative cooling where the tropopause is lower which acts to enhance PV within the TPV (e.g., Cavallo and Hakim 2012). Biases in the intensity of TPVs may result from too much moisture (Riedel 2020) and the misrepresentation of vertical moisture gradients in the upper troposphere and lower stratosphere (UTLS, see also following paragraph) and the concomitant effect on radiation.

c) Mesoscale instabilities and dynamics at the tropopause

Topics 2.1a and 2.1b concern features of the mid-latitude flow that can emerge and develop remotely but influence the tropopause region through advection of air masses towards the tropopause, both over long distances in the horizontal and also from below as occurs in WCBs. However, mesoscale features in the wind field can also emerge and develop locally in the tropopause region and these may have an important influence on subsequent weather system development. In particular, instability in the flow is likely to reduce predictability due to enhanced sensitivity to initial conditions.

Diagnosing atmospheric instability in the strong shear and curved flow environment, characteristic of cyclones, and the presence of moisture, saturation, and coupling with vertical motion present one of the greatest challenges in atmospheric dynamics. This includes vertical motion within the shear environment of the jet stream and moisture-laden outflow of WCBs and the role of mesoscale descent in the dynamics and predictability of dry intrusion descent.

Major observational challenges relate to the measurement of vertical motion and identifying the aspects that can influence the atmosphere and weather forecasts on time horizons of one day or longer. The latest generation of Doppler lidar and radar can yield measurements of horizontal and vertical components of the wind (or hydrometeor motion), offering new potential for field campaign observations of the mesoscale circulations. Vertical motion in the atmosphere can be partitioned conceptually into a component associated with the balanced flow, described by the evolution of PV and its inversion to obtain the wind and thermal structure of the atmosphere, and unbalanced motion dominated by gravity waves and convection. The unbalanced motions are typically fast and associated with buoyancy oscillations or static instability, while balanced motions are typically slower and larger in horizontal scale and influence longer range prediction.

Research from NAWDEX has shed new light on the role of latent heating in large-scale shear in generating PV structure which is a pathway for moist dynamics coupling between unbalanced and balanced motion. Every heating anomaly generates a PV dipole oriented in the same way due to the large-scale vertical shear (Harvey et al., 2020). If the heating is on a long strip along the flow, as in a WCB, then the PV structure is a dipole band representing stronger shear next to the jet stream core. However, even if the heating is isolated in embedded convective updrafts, the common orientation of the PV dipoles and effects of shear advection result in upscale aggregation into PV strips (Oertel et al., 2020). The differential advection of the two sides of dipoles can also generate a localised jet streak (Oertel and Schemm, 2021). However, the response of the flow associated with the PV bands or a jet streak and the ramifications for dynamics and predictability downstream are unknown, presenting an opportunity for new advances.

Although the arguments above predict how the flow is expected to respond to a heating anomaly in shear, the full problem needs to address why the latent heating anomaly emerges. The theory of CSI (conditional symmetric instability) shows that slantwise motions can emerge and grow even on a large-scale state that is stable to vertical displacements (convective stability) and horizontal displacements (inertial stability). In the absence of humidity saturation and condensation then a necessary condition for symmetric instability is that f*PV is negative (f is the Coriolis parameter) over a large-scale region (Hoskins, 1974). This is unlikely to occur, although PV is observed to be negative in narrow strips (Harvey et al., 2020). However, if the large-scale PV in the region is near zero and there is widespread humidity saturation, the environment may meet the criteria for conditional symmetric instability (dependent on latent heat release) and slantwise mesoscale circulations could emerge (Bennetts and Hoskins, 1979). Thorpe and Clough (1991) presented observations of slantwise structures in vorticity above cold fronts deduced from dropsonde and in-situ aircraft data (from FRONTS 87) and related them to the predictions of CSI theory. However, there are no similar studies investigating CSI in the upper troposphere or in the vicinity of the jet stream.

In NAWDIC we will consider disturbances within the jet stream and near the tropopause generated locally through the coupled dynamics of cloud and wind in the upper troposphere. Also, the non-local response of radiative transfer and heating profiles to humidity and cloud near the tropopause. Finally, turbulent mixing in the tropopause zone and the interaction between turbulence, cloud and radiation are discussed below.

d) Transport and mixing at the tropopause

A common bias in NWP models is that the lower stratosphere is too moist (e.g. Kunz et al. 2014). Humidity data from sondes is not assimilated above the tropopause and so the analysis also has a moist bias. This generates a cold bias in forecasts (Woiwode et al., 2020) as a result of anomalous longwave cooling (Bland et al. 2021, in review). It is hypothesized that the radiative effect of stratospheric water vapor has implications for the sharpness of the waveguide and potentially for the Rossby wave evolution downstream. The exact process that is causing the water vapor excess is still not clear. In some models like the IFS, the moist bias is already present in the initial conditions (i.e., the analysis) and thus support the hypothesis that the cold bias develops as a result of forecast initialization (Woiwode et al. 2020). One explanation is that a combination of lack of observations and numerical diffusion in the region of sharp water vapor gradients may cause a leakage of moist tropospheric air into the lower stratosphere. It was shown that an increase in horizontal and vertical resolution at tropopause level has little impact on the moist bias in NWP models (Woiwode et al. 2020).

Errors in water vapor and temperature in the lower stratosphere may not only contribute to errors in dynamic and thermodynamic relevant vertical gradients, but also contribute to an overestimated transport. Tropopause phenomena, like jet streaks and dry intrusions, are known regions for the vertical exchange between tropospheric and stratospheric air masses (e.g., Stohl et al. 2003, Schäfler et al. 2021). Unresolved small-scale structures of gravity wave breaking or vertical gradients important in diffusion may impact the moist bias. Turbulence can also be greatly enhanced at the top of clouds and cloud-radiation-turbulence interaction is an important and challenging topic (Lane et al., 2012).

Additionally, global models overrepresent ice in the lower stratosphere and sublimation can contribute to the bias in lower stratosphere water vapor (Qu et al. 2020). This bias may also be impacted by the equatorial cold point temperature (e.g., Randel and Park 2019), which is the leading predictor for large-scale lower stratospheric humidity. Assimilating water vapor observations below the tropopause are constrained by high-quality observations, but above the tropopause water vapor is not assimilated due to the lack of well constrained observations (Woiwode et al. 2020). Thus, the assimilation of wind and temperature data above the tropopause impact the derived water vapor content and can also affect water vapor biases.

2.2 Processes at the dry intrusion-PBL and cold front interfaces and their relation to HIW

Hypothesis: The interactions of the dry intrusion with the PBL below and with the cold front ahead are key for the evolution of weather phenomena near the cold front and for the emergence of HIW. Thus, biases in the representation of these interactions potentially propagate to errors in forecasts of surface conditions in the cyclone's cold sector (including extremes), of HIW at the cold front region, and heavy precipitation further downstream.

a) Dry intrusion influence on the PBL

The dry intrusion air originating from the tropopause region at higher latitudes is often mixed down into the PBL in a cyclone's cold sector (Browning, 1997). In fact, it is usually relatively cold air compared with its surroundings, as it has low potential temperature due to its origin at high latitudes. Typically, the vertical mixing in the PBL is enhanced, resulting in PBL deepening and strengthening of the inversion layer in the presence of dry intrusions (Raveh-Rubin, 2017; Ilotoviz et al., 2021). Despite the dry air, cloud cover in the PBL increases. It is yet unclear how well the clouds and related feedbacks are represented in NWP and climate models and whether such errors propagate upscale.

A key factor controlling the DI-PBL interaction, and the potentially resulting severe surface winds, is the downward transfer of momentum into the PBL and to the surface, which is expected to vary under different vertical shear, PBL turbulence and cloud regimes, and mesoscale organization. It is not generally clear how well the momentum transfer is represented in models, due to the lack of sufficiently detailed wind profile measurements for validation. There is high uncertainty regarding the role of evaporative cooling and the scale of organized structures in controlling downward momentum transfer.

b) Role of mesoscale instability in the lower troposphere and link to severe surface winds

The conditions for CSI (conditional symmetric instability - see Section 2.1c) are known to occur where strong mesoscale banding appears in the lower troposphere and PBL below, but there is still debate as to the importance of instability to the high impact surface weather associated with the mesoscale structures and the nature of the coupling across the wide range of scales involved. Existing theories describing CSI and PBL structural instabilities have so far been developed in idealised situations with limited direct applicability. For example, PV is assumed to be uniform but in practice there are often strong PV gradients. Open questions remain regarding the nature of the mechanisms behind observed banded mesoscale, or smaller, features and whether or not diabatic processes are central to those phenomena.

Observational studies suggest that severe surface winds, as well as maximum wind gusts, are often associated with mesoscale banding in wind coupled with banding in cloud and precipitation. For example, the sting jets, first described by Browning (2004) were identified with several bands in the most intense surface winds within the frontal fracture region of a cyclone (just ahead of the dry intrusion as it descends towards the PBL). The structure of the banding in intense cyclones with damaging surface winds can differ markedly and only some of these cyclones would be identified with sting jets (Clark and Gray, 2018). However, comprehensive high resolution observations of multiple variables (wind components, temperature, moisture and cloud) within and above the boundary layer are lacking except in a very few cases. For example, in the DIAMET project the intense Cyclone Friedhelm was observed (using aircraft, radar and surface stations) as it crossed Scotland. In this case there were distinct rain bands on the south and southwest sides of the cyclone centre (Vaughan et al., 2015) and a descending sting jet air stream was distinguished from the cold conveyor belt using the aircraft measurements (Martinez-Alvarado et al., 2014). However, the wind observations within the BL were insufficient to link the sting jet and cold conveyor belt air streams to the occurrences of strongest winds at the surface and the mechanisms linking them. An open question still is which mesoscale regions (cold front, frontal-fracture region, bent-back warm front) are more favorable to formation of banding structures of wind maxima and precipitation, and why.

<u>Potential destabilization by dry intrusions:</u> A dry intrusion that overruns the surface cold front of an extratropical cyclone may trigger potential instability (Browning and Monk, 1982) – a state of the atmosphere which is well understood theoretically. However, in practice the potential destabilization depends on a number of thermodynamic processes, the interaction of which is still not fully understood. For example, surface latent heat fluxes and surface sensible heat fluxes affect the moisture and temperature in the PBL and thus have a direct impact on the potential instability once the dry intrusion overruns this layer. Further, the dry intrusion air masses may lead to a pronounced inversion at the PBL top, which may inhibit convective activity (Morcrette et al. 2007). Accordingly, convection schemes with CAPE-based closures, which are sensitive to conditional rather than potential instability, may underestimate the convective activity in the area of the overrunning dry air. Hence, it is suggested that a comprehensive thermodynamic analysis of the spatio-temporal evolution of potential instability related to dry intrusions will help to better understand how the process of potential destabilization is handled by NWP models and to what extent is it treated by the resolved dynamics.

c) Dry intrusion influence on surface fluxes and ocean-atmosphere coupling

Upon the descent of dry intrusions into the marine PBL, intense ocean heat loss is triggered through turbulent fluxes of sensible and latent heat (Raveh-Rubin and Catto, 2019, Ilotoviz et al., 2021), further supporting the vertical mixing in the PBL (Slater et al., 2017). Newly evaporated water vapour acts to restore the deficit caused by the intruding dry air and can act as a moisture source for subsequent cyclones and/or ARs, potentially supporting cyclone clustering and/or contributing to heavy precipitation further away (e.g., Winschall et al., 2012, Dacre et al. 2019, Bui and Spengler, 2021).

The wind and thermodynamic profile of the BL and anisotropic eddy structure within the PBL is known to have a major influence on turbulent fluxes over ocean, but there remain significant challenges in the representation of the fluxes, both in the surface layer and in the mixed layer above. The ramifications for the properties of ARs and WCBs and their subsequent influence on heavy precipitation need further exploration.

Errors in representing surface fluxes can propagate upscale and affect precipitation forecasts over Europe and the Mediterranean. Important in this context is the accurate representation of the ocean stratification, mixed-layer depth, heat content and surface roughness, especially under high wind conditions that trigger ocean waves with the frontal passage. The coupling between ocean surface roughness, wind speed, wave conditions and vertical momentum transport is poorly understood, particularly at high wind speeds. Surface stress/drag due to a rough ocean surface or orography is important, as it is incorporated in air-sea interaction feedbacks and PBL recovery mechanisms and shown to introduce large forecast uncertainties (Cook and Renfrew, 2015; Belmonte Rivas and Stoffelen, 2019; Sandu et al., 2020).

d) Dynamics and air mass interactions near the cold front

Horizontal moisture transport: The process of horizontal moisture transport itself is well understood. Strong horizontal moisture transports are typically found in the warm sector of midlatitude cyclones ahead of the cold front. These regions of strong horizontal moisture transport are typically referred to as ARs. However, a comparison of ECMWF forecasts and dropsonde observations reveals that state-of-the-art NWP systems exhibit systematic errors in regions of strong moisture transport in ARs (Lavers et al. 2018). It is hypothesized that these errors are primarily related to uncertainties in the winds near the top of the PBL, although the Ekman spiral is also misrepresented in analyses in some regions (Belmonte-Rivas and Stoffelen, 2019). It has also been found that surface heat and moisture fluxes vary strongly with mesoscale sea surface temperature spatial variability. Still, the exact locations of the errors relative to the AR are not completely clear and it needs to be clarified whether the mesoscale variability of moisture transport is adequately captured by NWP models. Further, the source regions of moisture that eventually lead to HIW events, namely, the relative roles of local fluxes vs. the horizontal transport of moisture over the ocean, potentially feeding an AR of the subsequent cyclone, need to be clarified (Weng et al., 2021).

Atmospheric rivers / dry intrusion outflow interaction: The exchange of air between ARs and dry intrusions at the trailing cold fronts where they meet is not always well represented in models. This is likely due to the diverse processes contributing to the exchange such as mesoscale cross-frontal circulations, frontal rainbands, contrasts in turbulence regime either side of the front, moisture transport and cloud processes. The numerical representation of the frontal region (e.g., its sharpness and along front variability) could be investigated in the framework of NAWDIC. Water vapour and air mass tracers, in combination with water isotopes as indicators will be invaluable tools to better characterize and distinguish transitions between ARs and dry intrusions.

3 Observational strategy

3.1 The phenomenological focus of NAWDIC observations

3.1.1 Upper troposphere

Detailed profile observations of wind, temperature, and humidity are required to observe strong gradients across the tropopause and to quantify the impact of diabatic processes on the waveguide (see section 2.1 a and b; Goal 1). A further focus lies on the mesoscale structure in the origin region of dry intrusions that subsequently descend and interact with the PBL. Such origin regions are anticipated to be located above the remote North Atlantic ocean and Canada. The observed air mass will ideally be traced in a quasi-Lagrangian sense towards the PBL, where it is again observed when it impacts the triggering of HIW.

3.1.2 PBL observations

Preconditioning observations: Many HIW types strongly depend on diabatic processes and in turn on the supply of moisture. NAWDIC will therefore focus on uptake regions of moisture, e.g. in the cold sector impacted by dry intrusions, which are potentially insufficiently represented in NWP models (see section 2.2b-c, Goals 2 & 3). Especially moisture flux profile measurements in source regions of HIW will be obtained to better quantify uncertainties in the PBL moisture structure representation. Water vapor isotope observations may help to quantify air mass exchange and entrainment processes, and to constrain the contribution of local evaporation. Additionally, NAWDIC focuses on the observation of moisture transport from subtropical regions, i.e. AR-type flows that later cause HIW over Europe (see section 2.2c; Goal 3). Observations of horizontal moisture fluxes are only possible with suitable horizontally and vertically resolved wind and water vapor observations to characterize the extent of such moisture plumes in order to reveal biases and quantify their impact on prediction. Ideally, such observations could provide a meaningful moisture budget estimate to be compared against NWP data. NAWDIC envisions observing the poorly understood interaction of dry intrusions with the strong moisture uptake and transport in its vicinity.

HIW observations: NAWDIC will provide local observations of HIW events (Goals 2 & 3). Therefore cross-frontal observations, both with in-situ and remote-sensing instruments will be performed between the dry air, the cold front and the warm sector at several locations along the front (see section 2.2d). A focus lies on turbulent flux profiles in order to gain new insight into how PBL and the ocean or land surface interact. Observations of clouds and boundary-layer winds provide information on the typical scales and intensity of coherent PBL structures related to downward momentum transport, e.g., on convective scales. Ideally, such momentum flux observations are repeated for a broad sample of environments (e.g., clear air and stratocumulus). Ground-based observation sites will be an important backbone to observe local impacts of HIW events.

3.2 Observational facilities

As described in Section 1, NAWDIC observations will be made across multiple scales using airborne and ground-based observations. As shown in Fig. 3, airborne facilities will operate upstream of HIW over the North Atlantic Ocean and in combination with a ground-based observation network that is anticipated to be operated in impacted regions across western Europe (UK, France, and other European countries). In the following the individual observational components are described.

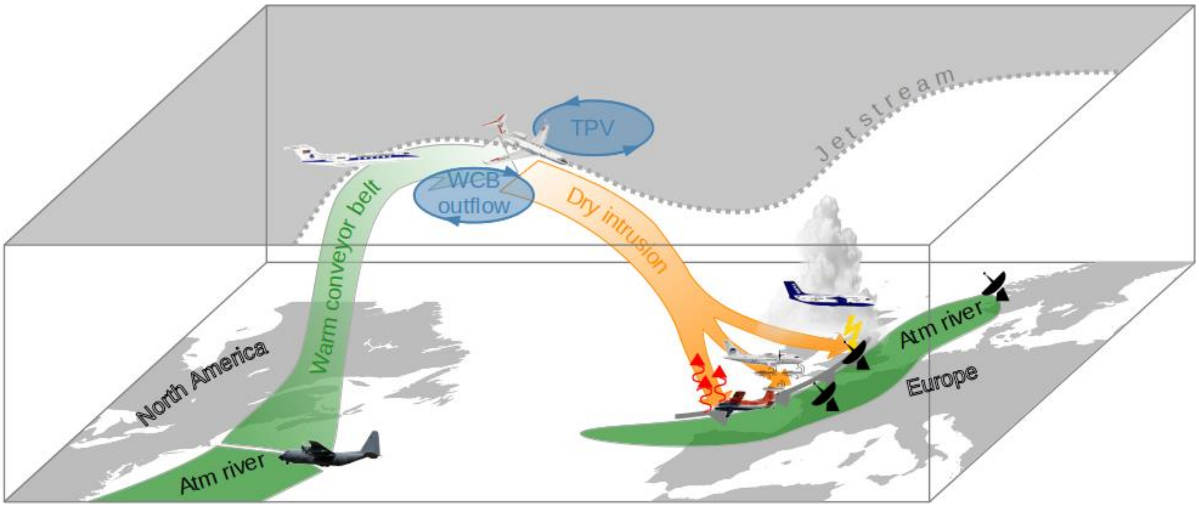

Figure 3: Idealized schematic showing the potential deployment of research aircraft and ground-based observational facilities during NAWDIC.

3.2.1 Aircraft and airborne instrumentation

Long-range aircraft

a) HALO

The German airborne contribution to NAWDIC will involve the High Altitude and Long Range Research Aircraft (HALO), which, due to its extended flight range, will be able to provide the large- scale context. HALO allows us to reach the origin regions of dry intrusions over the central and eastern North Atlantic, to follow their descent towards Europe where they impact and trigger HIW events and also to observe large scale moisture fluxes in remote regions over the ocean. The instrumentation is currently under discussion. As pointed out in Sections 1 and 2, observations on the synoptic scale of across-tropopause moisture, temperature, and wind gradients, as well as observations of horizontal and vertical moisture fluxes in moisture source regions are of central interest. A key instrument will be the KIT dropsonde system for high-resolution in-situ profile measurement with up to 30 probes simultaneously. The sondes can contain 1–4 probes and will be deployed for measurements of the tropopause and the PBL. As the operation in transatlantic air spaces is often limited, in-situ observations shall be complemented by remote sensing measurements. It is planned to use a novel combination of well-established lidar instruments onboard HALO, i.e., a Doppler Wind Lidar and a Differential Absorption Lidar (DIAL). This combination of lidar instruments provides the possibility for joint water vapor and wind vector observations beneath the aircraft allowing us to deduce range-resolved horizontal and vertical moisture fluxes (Schäfler et al. 2010). The DIAL that is capable of measuring vertical profiles is able to determine the strong water vapor (and ozone) gradients across the tropopause. In a nadir pointing mode, the wind lidar is able to perform vertical wind measurements beneath the aircraft. The instrumentation will be discussed within the national science community and extended depending on interest. We see the area of operation and the transport processes of interest to be highly relevant to the UTLS and cloud research communities. Additionally, the descent of dry intrusion air may affect cloudiness and mixing in the subtropical PBL, which in turn might affect the transport of moisture to the extra-tropics. This connects well with the research community focusing on the interaction of clouds and circulation in the trade-wind regions (Stevens et al., 2021).

b) NOAA/NCAR aircraft (US academic community)

The primary observing platform for this campaign will likely be the NSF/NCAR GV. The instrument payload will include dropsondes, the Microwave Temperature and Humidity Profiler (MTHP), HIAPER Airborne Radiation Package (HARP), the HIAPER Cloud Radar (HCR) and the High Spectral Resolution Lidar (HSRL) will provide detailed observations of the evolving vertical structure of the UTLS surrounding the tropopause. To date, most knowledge of the structures of interest in the UTLS is dependent on model and reanalysis output that is from a relatively data sparse environment and generally has not been verified, particularly with regards to cloud processes and their impact on tropopause dynamics. Observations of the three-dimensional structure of the cloud and precipitation fields will be important in regard to evaluating the accuracy of model representation of these fields and the impacts of the cloud and precipitation fields on the dynamics and radiative processes in the UTLS. The ability to detect ice versus water clouds with the HSRL will be particularly useful given the radiative importance of clouds containing supercooled water and the impacts of long-wave radiative effects on controlling TPV, jet stream, and stratospheric interactions.

The flight-level observations will also be extremely useful in determining the mesoscale details of features in the UTLS and tropopause, including the intensity of TPVs and jet streaks. Current research suggests that the intensity of TPVs may be underestimated in operational analyses and reanalyses, in part due to the relative lack of accurate and high temporal and spatial resolution observations of temperature and, in particular, water vapor in the UTLS. Together, these measurements will provide details on UTLS winds, PV, vertical motion, and divergent outflow resulting from diabatic heating; profiles of wind, temperature, and water vapor from the lower stratosphere downward. High-resolution estimates of PV will also permit the structure of mesoscale features of interest to be defined over data sparse regions and the subsequent structural transformation in the surface cyclogenesis process. Wind measurements will be augmented by the Radome Gust Probe and All-Weather Gust Pod. The Fast Ozone Instrument will provide observations that will be useful for determining the radiative properties in the UTLS and inside TPVs since ozone also contains absorptive bands in the infrared. These observations of ozone mixing ratio, together with the observations from HARP, dropsondes, and flight-level data, will provide detailed, in-situ measurements of how ozone and water vapor variations around the tropopause impact the radiative budget. Measurements obtained can also be used to compute longwave and shortwave radiative fluxes and heating rates using the Rapid Radiative Transfer Model (RRTM) and the accelerated RRTM model for Global Climate Models (RRTMG) to compare against the radiation measurements from the GV and to validate radiation estimates in numerical simulations and operational prediction models.

mid-range aircraft

c) SAFIRE ATR42

The French ATR42 aircraft is operated by SAFIRE (Service des Avions Français Instrumentés pour la Recherche en Environnement, http://www.safire.fr/), the French facility for airborne research, a public research infrastructure of CNRS, Météo-France and CNES. It is mainly dedicated to observations of the lower and mid-troposphere. Its typical endurance during a field campaign is 3.5 hours and a range of about 1500 km. Its flights will be dedicated to address scientific questions raised in section 2.2 on interactions between the free troposphere and PBL in the regions potentially impacted by HIW events near the western European coastline. The ATR42 payload is composed of remote sensing and in-situ instruments that will measure wind components, turbulence and cloud microphysical properties. The objective is to install the multi beam 95 GHz Doppler radar RASTA (RAdar SysTem Airborne), the Doppler radar BASTA (Bistatic rAdar SysTem for Atmospheric) and the Doppler lidar LNG (Leandre New Generation). In addition to reflectivity measurements, the radar RASTA is capable of retrieving the 3D wind field in cloudy regions, i.e. the three components of the wind on the vertical plane below and above the aircraft (3 antenna configuration looking down and 3 antenna configuration looking up), by combining independent Doppler velocity measurements from the multi-beam antenna system. The radar BASTA will have a pair of antennas looking horizontally to complement the measurements made by RASTA. LNG, in its backscatter configuration, operates at three wavelengths (355 nm, 532 nm, 1064 nm), including depolarization, high spectral resolution and Doppler at 355 nm. It will provide both the determination of optical parameters of aerosol and clouds and along-sight wind in the troposphere. Additionally, the KuROS instrument (Ku-Band Radar for Observation of Surfaces) may be mounted in the ATR42. KuROS provides knowledge of the sea state during lower-tropospheric flights. Finally, the ATR42 can be also equipped with In-situ microphysics probes. The horizontal and vertical distribution of ice crystal and liquid water droplets as well as the scale dependent liquid-ice partitioning can be investigated using the Cloud droplet probe (CDP), the 2D-S stereo imaging probe (or CIP) and the Precipitating Imaging Probe (PIP). These probes cover a complete size range from a few microns up to 6 mm. Parameters such as effective size, ice and liquid water content, number concentrations, ice crystal shapes and cloud phase will be derived from these instruments. A certified rack system for water vapour isotope measurements is available within the consortium for this aircraft.

d) FAAM BAe 146

The BAe146 operated by FAAM (Facility for Airborne Atmospheric Measurements) in the UK, is a converted short-range passenger jet with the potential to carry a large payload of instruments. It has a range of 3500 km and a ceiling of approximately 10 km. It can operate science measurements on very low flight legs (50 feet in clear conditions over sea), for example measuring turbulent fluxes within the boundary layer.

As part of the commitment by UK Research and Innovation (UKRI) to continued funding of the FAAM aircraft for the next 10 years, the aircraft will undergo a major instrument upgrade. This is likely to include a wind lidar, enabling remote sensing of winds beneath the aircraft (although not in precipitating air) and hopefully a 3-channel radar which would have the Doppler capability to measure winds in air with precipitation (or other targets). Improved spectral radiometers are expected to enable retrieval of higher resolution temperature profiles. The core in situ instrumentation will also be upgraded. This includes temperature, water vapour, ozone, carbon monoxide (useful air mass tracers), a turbulence probe (with and without heating to cope with icing) and comprehensive cloud microphysics instrumentation including measurement of cloud droplets, ice particles and particle imagers for ice crystal habit. The scientific focus of this aircraft would be mesoscale structure in cloud, wind and potential temperature above the PBL and its connection with turbulent structure within the PBL.

e) North Atlantic ARRECON (US AR community)

The primary observing platform for this campaign will likely be the US Air Force C-130s, used to deploy dropsondes. During NAWDIC, the aircraft should have the capability to provide dropsonde data in high resolution BUFR format in real time. Other available flight-based observations include stepped frequency microwave radiometer (SFMR) and high density flight level observations of wind, moisture, and temperature. Flight level of the C130s is generally about 7.5-9 km. The C-130s can also deploy additional ocean drifters with pressure sensors, and depending on the stage of development, moisture sensors. Drifter types could include Surface Velocity Program - Barometer (SVP-B) and Directional Wave Spectra - Barometer (DWS-B). SVP-B drifters last approximately 18 months and DWS-B drifters last approximately 8 months. These additions could give the campaign operational longevity to complement the dropsondes and other flight-based observations. The C-130s are also developing the capacity to deploy Airborne EXpendable BathyThermograph (AXBT)s at altitude. AXBTs could help with observations of near-surface ocean temperature profiles that will address science questions in this plan relating to the ocean-atmosphere interface and ocean boundary layer. Exact bases for the aircraft will be determined by the science team in coordination with the Air Force.

3.2.2 Ground-based observation network

a) KITcube

KITcube is a ground-based mobile observation platform for studying processes on the local to meso scale (Kalthoff et al. 2013). With its in-situ and remote sensing systems it allows a detailed probing of an atmospheric volume with a particular focus on the PBL. It is equipped with radiosonde systems, microwave radiometer, Sodar, 5 wind lidars, cloud radar, and X-band radar (see Kalthoff et al. 2013 and https://kitcube.kit.edu for full instrumentation). It is envisaged that KITcube will be deployed at the French Atlantic or French Mediterranean Coast. In coordination with potential ground-based observations performed by the French and UK colleagues, KITcube will be part of a dense observation network along the European coastline, which is designed to sample the incoming weather systems. The exact measurement strategy will be developed jointly by scientists from KIT, French and UK partners, and model developers at the weather centers.

b) France mobile Radars/Lidars

A deployment of up to 4 cloud radars BASTA is envisaged along the French Atlantic and Mediterranean coasts and will be mainly dedicated to observe low-tropospheric-PBL interactions (section 2.2) but can also provide information on the upper-level jet (section 2.1). For the scanning versions the coneshaped scans of these radars can provide reflectivity and wind components over all horizontal directions at a range of about 10 km distance and in the vertical direction over the whole troposphere.

c) UK

Since the last major HIW observational campaign in the UK (DIAMET 2011/12; Vaughan et al., 2015) the observational capability has made a step change, particularly in terms of winds. The Met Office radar network was upgraded to Doppler & dual polarisation in 2012 and the MODE-S data from commercial aircraft gives a dense network of wind observations in the mid to upper troposphere. The radar network spans the UK and Ireland at high resolution (one standard derived product is precipitation rate on a 1 km grid). 3-D reflectivity retrieval from the radar network has also been developed, especially for the aviation sector hazard warning and yields the 3-D structure of precipitating volumes and clouds. In addition, the AWS (automatic weather station) network gives very high temporal (1s) and spatial density of observations and has been used to examine severe weather phenomena, even on very fine scales such as cold frontal rainbands and associated tornado activity (Clark and Parker, 2020). The Met Office runs 6 operational radiosonde stations.

The Atmospheric Measurement and Observations Facility (AMOF) operates the Chilbolton research radar (S. England) which can obtain high resolution S-band Doppler dual polarisation measurements. The MST radar wind profiler at Aberystwyth (Wales) operates continuously retrieving profiles of wind from the boundary layer to the mesosphere, as well as other products such as turbulent dissipation rate in the upper troposphere and lower stratosphere. Together with the Met Office ST wind profiler in South Uist (Scotland), the two profilers are in an ideal situation to measure wind profiles continuously for systems impinging on Europe from the North Atlantic. AMOF also operates a mobile X-band Doppler, dual-polar radar which could be deployed anywhere in the UK, a mobile wind profiler and several Doppler lidars.

d) Norway

At the Geophysical Institute, University of Bergen, measurement facilities for high-resolution measurements of precipitation and microphysical parameters, as well as wind lidars and ocean surface fluxes from instrumented buoys are assembled in place. Previous campaigns have focused on detailed observations of weather and stable isotope parameters during land-falling ARs (Weng et al., WCD, 2021, accepted). Supplemented by installations on off-shore locations, potentially also including wind lidars, airmass transformations downstream of the UK can be surveyed. An important link to be considered at this location will be the connection of HIW to extremes to flooding and landslides in the mountainous coastline.

e) Existing ground and ocean based networks and other platforms

In addition to supersites in the UK and France, we will apply for extra radiosonde observations in the North Atlantic region by EUMETNET, Met Services, and North American universities. We will clarify what additional ocean- and land-based operational observations networks can be included during the campaign. A potential deployment of sail drones for e.g. heat flux measurements were discussed but a coordinator needs to be found.

3.3 Modelling component

NAWDIC has the vision to unite observations and modelling from the preparation phase to campaign implementation and post-campaign data analysis. In the ongoing preparation phase, various groups are investigating data from past field campaigns, in particular NAWDEX 2016, together with model data in order to identify and understand further model deficiencies. In addition, we plan preparatory modelling projects with global modelling and high-resolution regional modelling to refine the science questions. These efforts will inform the design of appropriate missions. During the campaign we plan real-time data assimilation of key observational data, such as dropsondes and lidar measurements. Therefore setups will be developed in a seamless approach from global to LES models. The NAWDIC components coordinated by KIT plan to develop a seamless ICON model suite that allows, in real-time, to assimilate the majority of campaign observations. Namely, the large-scale environmental characterisation by HALO via dropsondes and lidar in global forecasts, mesoscale in-situ, dropsonde, and lidar measurements on mid-range aircraft in higher-resolved nests, as well as high-resolution measurements with the KIT cube in an LES setup. The ICON data assimilation exercise will thus provide timely 4D context to each NAWDIC mission and will also be a powerful information source for the post-campaign analysis. Data denial experiments can help understand the impact of additional observations and point to potential model deficits. Experimental assimilation of non-routine observations (e.g. airborne lidar) is also of interest at ECMWF.

Finally, the flight planning will be supported by DWD via high-resolution ensemble prediction forecasts, as well as dedicated forecast products such as Lagrangian dry intrusion and WCB ensemble forecasts and real-time diagnostics based on global ECMWF ensemble forecast data.

NAWDIC observations will be invaluable for the evaluation of prototype kilometer-scale global weather prediction models, which are currently developed and should be ready for research purposes in 2025 (e.g., https://c2sm.ethz.ch/research/exclaim.html). The explicit treatment of moist convection and the better representation of orography and coastlines in these models are seen as a pathway for strongly improving the quality of NWP models. However, detailed observations of key dynamical processes on small scales - as planned during NAWDIC - are urgently needed for assessing the representation of these processes in forecasts with different resolutions and treatment of moist convection.

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