Campaign Implementation Plan for the HALO Component of NAWDIC

NAWDIC 2026

North Atlantic Waveguide, Dry Intrusion and Downstream Impact Campaign

Version 1.1 (24 July 2025)

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Version History

Document Version	Date	Changes
1.0	12 May 2025	Initial version
1.1	24 July 2025	Updated HALO integration schedule (5.3.2), responsibilities of forecasting team (5.4.1), and daily schedule (Tab. 6)

Contents

1. Preface

The North Atlantic Waveguide, Dry Intrusion, and Downstream Impact Campaign (NAWDIC) is a new initiative for an international field campaign aiming to advance our understanding and modelling 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-European region. More specifically, NAWDIC will focus on the physical understanding and quantification of the interactions between mesoscale tropopause structure, dry intrusion airstream, and downstream dynamics near the surface cold front for the evolution of high-impact weather in winter-time extratropical cyclones. Though initiated as a campaign with the German high-altitude, long-range aircraft HALO, NAWDIC has become a major international effort. It involves three European research aircraft (HALO, SAFIRE ATR42, TUBS Cessna) as well as the ground-based instruments that are deployed by different project partners. The research of the individual project partners will benefit from synergies and planned coordination under the umbrella of NAWDIC.

During the six-week core observation period in January and February 2026, the HALO aircraft will operate from Shannon (Ireland) and will be complemented by in-situ and remote sensing instruments onboard of additional mid- to long-range aircrafts as well as dense ground-based measurements at the French Atlantic coast. Further, the observation activities will be accompanied by a modelling component in collaboration with weather services including the assimilation of NAWDIC observations.

This document provides an overview of the scientific background and aims of NAWDIC-HALO, the aircraft and instruments, and logistic aspects. For the campaign preparation, selected case studies and a catalogue of forecast products are presented. The idea and basic structure of this document is mainly based on the corresponding document of the NAWDEX campaign in 2016 (Schäfler et al 2018), which can be found at https://www.pa.op.dlr.de/nawdex/documents/NAWDEX_Campaign_Implementation_Plan_v4.pdf. Some parts that are considered still valid are even boldly copied.

This campaign implementation plan is a living document that reflects the current status in the preparation of NAWDIC. Additional information can be found at the campaign webpage (https://www.nawdic.kit.edu).

2. The mission

2.1 Starting point

In boreal winter, gale-force wind gusts, widespread heavy precipitation, and cold-air outbreaks constitute some of the most severe weather hazards affecting Europe. Advancing our understanding of the synoptic- to micro-scale processes and their representation in numerical weather prediction (NWP) models leading to such hazardous high impact weather (HIW) is the overarching aim of the ground-based and airborne "North Atlantic Waveguide, Dry Intrusion, and Downstream Impact Campaign" (NAWDIC, https://www.nawdic.kit.edu/). The core element of the international NAWDIC consortium is NAWDIC-HALO, which comprises German institutions working on topics of mid-latitude atmospheric dynamics. It is led by the Institute of Meteorology and Climate Research, Troposphere Research (IMKTRO) of the Karlsruhe Institute of Technology (KIT), and further consists of the University of Mainz, Ludwig-Maximilians-University of Munich (LMU) and DLR's (German Aerospace Center) Institute of Atmospheric Physics. It thus brings together scientists who have already collaborated successfully in the "North Atlantic Waveguide and Downstream Impact Experiment" (NAWDEX, 2016, http://nawdex.ethz.ch/) and the DFG Transregional Collaborative Research Center (CRC) "Waves to Weather" (SFB/TRR165, 2015-2024, https://www.wavestoweather.de/). Due to thematic links, also researchers of the DFG CRC "The Tropopause Region in a Changing Atmosphere" (DFG TRR 301, ongoing, https://tpchange.de/) are involved. At an international level, NAWDIC has matured over the past five years into a large pan-Atlantic consortium with scientific partners from 10 countries involving universities, research institutions and weather services. NAWDIC is endorsed by WMO's World Weather Research Programme (WWRP).

2.2 Scientific background

Despite significant advancements of state-of-the-art NWP models in recent decades (Bauer et al 2015), accurately forecasting the location, timing, and intensity of mesoscale HIW events remains a challenge. This is to a large degree due to the cross-scale interactions of physical processes involved in the formation of HIW. In midlatitudes, the processes range from upper-tropospheric Rossby waves covering thousands of kilometers and lasting several days to turbulent momentum transport in the planetary boundary layer (PBL) and cloud microphysical processes acting on scales of hundreds of meters to micrometers and minutes to seconds. A cross-scale airstream that connects upper-tropospheric Rossby waves over North America and the Atlantic Ocean with HIW in Europe is the dry intrusion (DI; Figure 1; Carlson 1980, Browning 1997). During winter months, DIs emerge most frequently from the downstream flank of upper-tropospheric ridges over eastern North America (Raveh-Rubin 2017). From this region (referred to as 'DI inflow'), the DI descends equatorward into the cold sector of a downstream extratropical cyclone over a horizontal distance of 1000-5000 km and reaches the PBL about 2 days later (referred to as 'DI outflow'). The DI outflow is accompanied by intense surface heat and moisture fluxes, elevated PBL heights, changes in PBL cloud cover, and a destabilization of the lower troposphere leading to unusually strong wind gusts and extreme rainfall due to deep convection (Raveh-Rubin 2017, Catto and Raveh-Rubin 2019).

2.3 Planned observations

Most of the time, the involved cross-scale interactions of physical processes relevant to HIW in Europe occur upstream over the Atlantic Ocean and are insufficiently captured by operational observing systems. Accordingly, modern measurement systems on research aircraft are the only way to obtain reliable observations with the necessary high spatial and temporal resolution in these remote regions. With its long range and advanced instrumentation, HALO is optimal to characterize the structure of the DI inflow and outflow, and thus to bridge the scales from the upper-tropospheric Rossby wave to HIW in the PBL. This requires multiple consecutive flights on different days and in two regions of the DI airstream:

1. Two to three days before a forecasted HIW event, HALO will sample the structure of the upper troposphere and lower stratosphere in the DI inflow region (label 1 in Figure 1), which affects the evolution of the DI itself and the downstream development (Section 3.1).
2. Closer to the event, HALO will document mesoscale processes at the DI outflow–PBL and DI outflow–cold front interfaces (label 2 in Figure 1) which are directly linked to HIW and precondition the atmosphere for subsequent cyclone development (Section 3.2).

A tailored payload combining remote sensing and dropsonde observations (Section 4.2) will allow us to sample these regions at unprecedented detail and precision, which is necessary for a targeted evaluation of the quality of operational observing and analysis systems in regions crucial for HIW.

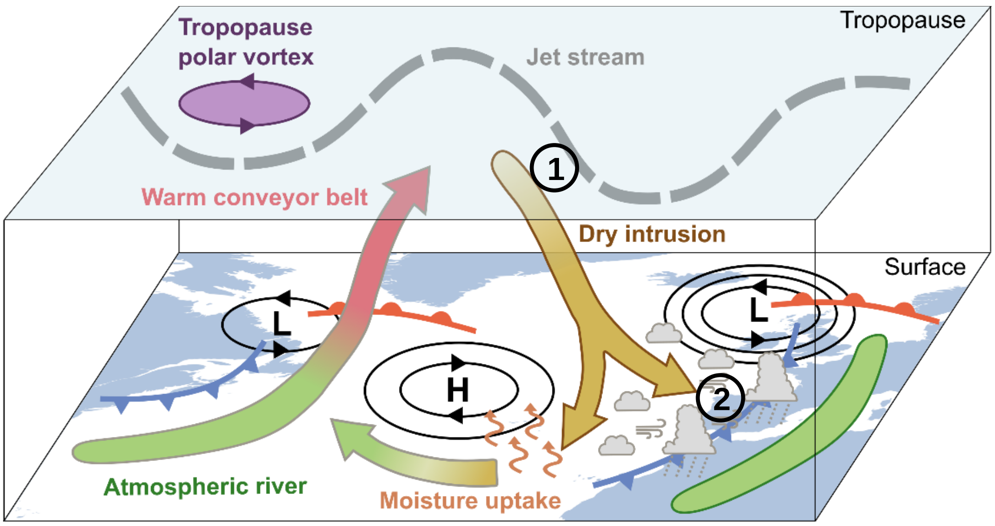

Figure 1: 3-D schematic view of the weather systems and processes of interest to NAWDIC-HALO. Labels 1 and 2 correspond to the DI inflow and outflow regions, respectively (as referenced in the text). “L” denotes the center of an extratropical low-pressure system and “H” denotes the center of the subtropical high-pressure system.

2.4 International dimension

The proposed NAWDIC-HALO campaign is the nucleus of the international NAWDIC initiative which has matured to a pan-Atlantic coordinated measurement effort. The foundation for this was laid at a workshop in November 2020 with 49 participants from 10 countries and 29 institutions, including 5 weather services. Outstanding research issues were identified and published as a joint NAWDIC science plan in July 2021 (https://www.nawdic.kit.edu/73.php). Since then, the international community has been working continuously on modular campaigns: Several groups contribute components that can be realized independently but ideally combine to form a coherent observational chain with coordinated aircraft and ground-based measurements from the western North Atlantic downstream to western Europe (Figure 1). The major projects in addition to NAWDIC-HALO are outlined in the following.

- **AR Recon** is a Research and Operations Partnership (RAOP) with NOAA National Center for Environmental Prediction (NCEP) that employs U.S. Air Force Reserve Command 53rd Weather Reconnaissance Squadron and NOAA aircraft, along with other data collection methods, to fill critical data gaps needed to improve forecasts of landfalling ARs affecting the U.S. West Coast, and western North Atlantic. In winter 2025/2026, additional observations of ARs in these two regions are expected to improve predictions of cyclones and WCBs near the U.S. east coast, which in turn affect the amplification of downstream ridges and the structure of the upper troposphere in the DI inflow region (see Figure 1).
- **NURTURE:** The “North American Upstream Feature-Resolving and Tropopause Uncertainty Reconnaissance Experiment” (NURTURE) aims to advance knowledge of the processes that lead to winter HIW events, such as severe cold air outbreaks, windstorms and hazardous seas, sea ice breakup, and extreme precipitation. NURTURE will be the first National Aeronautics and Space Administration (NASA) campaign utilizing their novel research aircraft Boeing 777. Though the Boeing 777 will be deployed in winter 2026/2027, a NASA Gulfstream 3 complements NAWDIC-HALO measurements by targeting upstream perturbations to the jet stream. Like HALO, the Gulfstream 3 will be equipped with a radar, water vapour lidar and dropsondes. Given the long range of HALO and the Gulfstream 3 instrument intercomparison flights will be feasible.
- **NAWDIC-DICHOTOMI:** The overarching aim of the French component of NAWDIC is to improve the understanding and modelling of downward momentum transport during high-wind events in western Europe by combining airborne observations and numerical simulations at and below the kilometer-scale. Concentrating on the eastern end of the observational chain during NAWDIC, its meso- to micro-scale focus complements the measurement with HALO and the NASA Gulfstream 3. A joint French-German proposal entitled “Dry Intrusion and cloud head winds on top of marine interfaces” (DICHOTOMI) for the deployment of the French SAFIRE ATR42 aircraft and the German Cessna F406 from the Technical University of Braunschweig (TUBS) has been funded by French ANR and German DFG. Both aircraft will be equipped with wind lidar devices so that coordinated flights for the validation of wind measurements can be carried out together with HALO.
- **NAWDIC-KITcube:** The scientific focus of KITcube will be on downward momentum transport during high-wind events associated with DIs. KITcube is a ground-based observation platform for studying processes on the meso- to micro-scale (Kalthoff et al 2013, https://kitcube.kit.edu). With its many in-situ and remote sensing systems, KITcube allows detailed probing of an atmospheric volume with a particular focus on the PBL. By aligning the multiple complementary in-situ and remote sensing instruments from the coast inland along the typical wind direction during DI events, the role of surface inhomogeneities, atmospheric static stability and evaporation in precipitating areas on the downward momentum transport will be studied. 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 west coast.

3. Science objectives

Please note that this section only covers the science objectives of the HALO-related projects of NAWDIC.

3.1 Structure of the upper troposphere and lower stratosphere

Synopsis: Mesoscale circulations affect the jet stream strength as well as the timing and structure of the coherent descent of air in DIs. An accurate representation of the tropopause structure, dynamics, and mixing in NWP systems is key for reliable predictions of the large-scale midlatitude flow and downstream HIW.

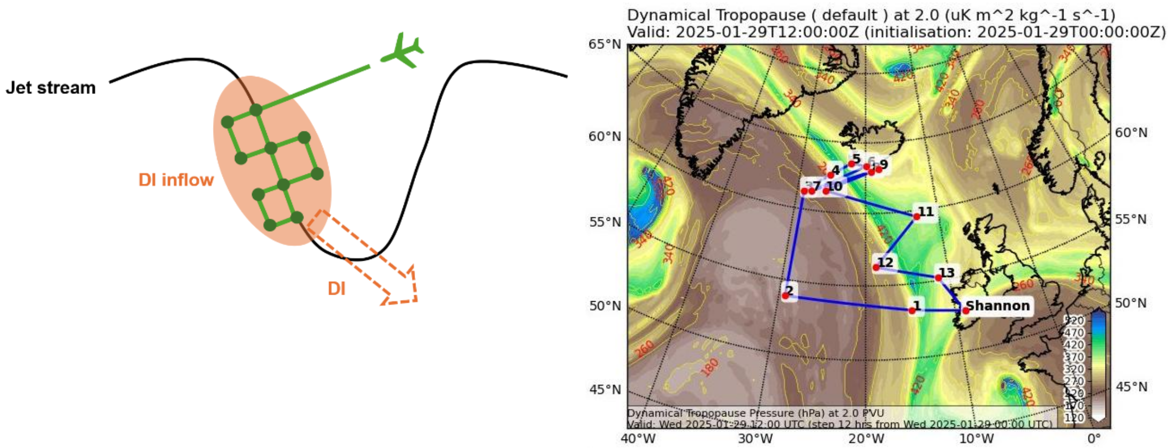

Figure 2: Left: Idealized flight pattern to sample the DI inflow region at the rear flank of an upper-tropospheric trough. Dark green dots represent locations of dropsonde releases. Right: Virtual flight pattern planned during the NAWDIC Dry Run to sample a DI inflow region located north-west of the British Isles on 29 January 2025. Color coding shows the pressure level of the dynamical tropopause at 2 PVU.

3.1.1 Moisture structure in the dry intrusion origin region and its inflow - impact of diabatic processes (NAWDIC-DImoist)

Research questions:	• What is the moisture structure in the DI inflow region? • What processes are responsible for the formation as well as maintenance of moisture gradients in the DI origin region? • Can high-resolution models adequately represent detailed observations of UTLS (meso-scale) moisture structure and its evolution?
Relevant instruments:	WALES, specMACS, UMAQS, FISH, KITsonde
Observation strategy:	Cross-gradient flights in WCB outflow/DI inflow regions (Figure 2)
Aircraft coordination:	Coordinated flights with NASA Gulfstream 3 for air-mass re-sampling

3.1.2 Air mass origin, transport and mixing associated with dry intrusions (ORIGAMI-DI)

Research questions:	• What is the source region and the composition of the air masses entering a dry intrusion? • How strongly are air masses mixed in the upper tropospheric region of a dry intrusion? • How much does stratospheric air affect the composition of a DI? • How coherent is the downward transport within a DI and how much of that air enters the PBL?

Relevant instruments:	UMAQS, WALES/HEDWIG
Observation strategy:	• Tropopause region: sample upper troposphere by flying multiple legs at different altitudes, ideally in a ridge and crossing the tropopause several times • Dry intrusion: crossing the horizontal boundary of the DI at different altitudes, moving down to the lower troposphere (Figure 2)
Aircraft coordination:	Ideally, coordination with upstream measurements of American colleagues to track the composition of an air mass in a quasi-Lagrangian sense

3.1.3 Troposphere to Stratosphere Transport at the WCB outflow

Research questions:	Troposphere to Stratosphere Transport (TST) at the WCB outflow (e.g. Stohl et al. 2003) with a focus on water vapor and ice particles transport into the stratosphere.
Relevant instruments:	FISH (FAIRO, UMAQS, WALES, KITsonde)
Observation strategy:	Fly in the WCB Outflow at the tropopause, sample the lower tropopause up to the lower stratosphere on different stacked flight legs in the area of the WCB outflow (Figure 2; FL 300-450)
Aircraft coordination:	None

3.2 Processes at the DI outflow – PBL and DI outflow – cold front interfaces

Synopsis: The interactions of the DI with the partly cloudy PBL below and with the cold front ahead are key for the evolution of midlatitude HIW locally but also in downstream regions. Errors in the representation of these interactions lead to errors in forecasts of surface conditions in the cyclone's cold sector, at the cold front region, and heavy precipitation further downstream.

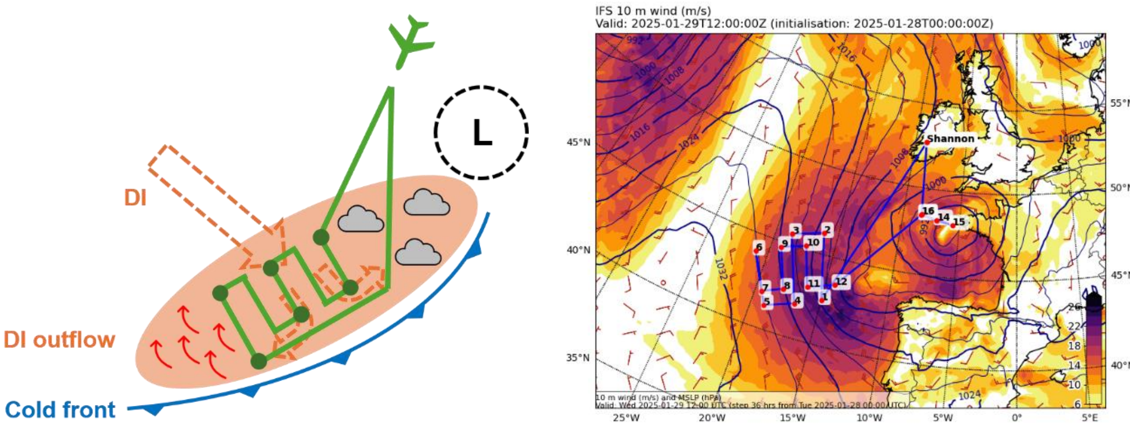

Figure 3: Left: As Figure 2, but for the DI outflow region behind the cold front. Cloud symbols and red arrows represent Cumulus clouds and enhanced turbulent surface fluxes in the cold sector, respectively. Right: Virtual flight pattern planned during the NAWDIC Dry Run to sample a DI outflow region located west of the Iberian Peninsula on 29 January 2025. Color coding and wind barbs show the 10-m wind speed and wind direction, respectively. Isolines represent the mean sea level pressure.

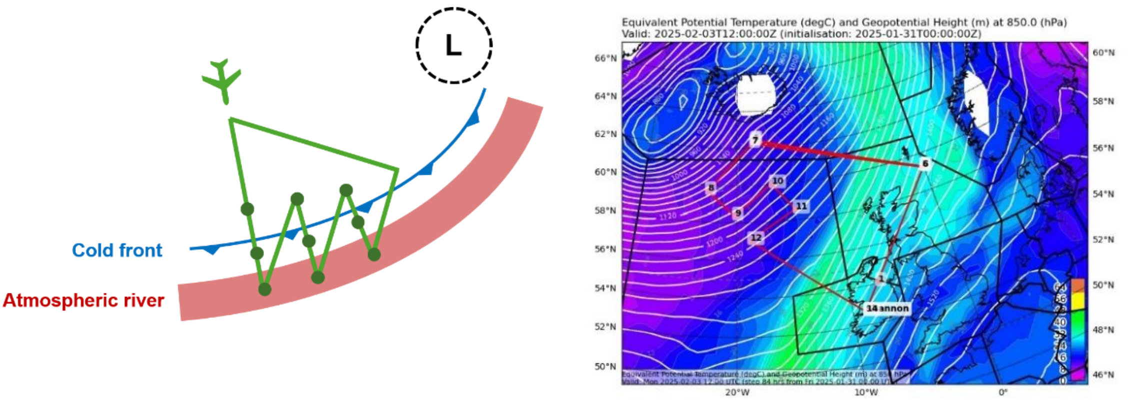

Figure 4: Left: As Figure 2, but for the DI outflow – cold front interface. Right: Virtual flight pattern planned during the NAWDIC Dry Run to sample a DI outflow – cold front interface located north-west of the British Isles on 3 February 2025. Color coding and isolines show the equivalent potential temperature and geopotential height at the 850-hPa level, respectively.

3.2.1 Lidar observations of latent heat flux profiles in cold sectors of extratropical cyclones (NAWDIC-FLUX)

Research questions:	• How can collocated lidar profile observations of water vapor and vertical wind be best used to derive LHFs and to characterize the MBL structure? • What is the spatiotemporal variability of the MBL structure and how is it influenced by surface processes and the DI above? • How well is the moistening of air masses represented by NWP models and what processes drive the diagnosed errors?
Relevant instruments:	HEDWIG, WALES, specMACS
Observation strategy:	Observe hotspots of moisture uptake in the cold sector, ranging from regions of strong near-surface winds close to the cyclone centre, towards regions of only weak winds, therefore sampling wind-driven ocean evaporation vs. humidity deficit-driven evaporation, expected further along the trailing cold front. Survey pattern to map the horizontal wind and water vapour distribution followed by flux pattern with multiple along- and across-wind legs to provide latent heat flux measurements (Figure 3)
Aircraft coordination:	Coordinated flight legs with TUBS Cessna F406 for comparison of in-situ flux measurements and fluxes derived from remote sensing. Further, comparison of HEDWIG with AIRflows (Doppler lidar onboard Cessna)

3.2.2 Dry intrusions and their influence on cloud distributions and cloud microphysics during the NAWDIC-HALO campaign (NAWDIC-CLOUD)

Research questions:	• How do DI events influence cloud cover, cloud top height, and cloud element aspect ratios along the flow under a strengthened PBL inversion in the cold sector behind the front? • What changes will we observe once DI air is mixed into the PBL?

	• Will we see changes in cloud microphysics reflecting changes in PBL development? • Closer to the front, where will the depth of cells increase - including precipitation development?
Relevant instruments:	specMACS (WALES)
Observation strategy:	behind cold front, probing different cloud regions along their development along flow at mid to high flight levels (Figure **3**)
Aircraft coordination:	Coordinated flights with the ATR42 and comparison with their microphysics in-situ observations

3.2.3 The MESOscale thermodynamic structure near cold fronts and its role for embedded convection (NAWDIC-MESO)

Research questions:	• How large is the mesoscale variability of the thermodynamic and dynamic structure near the cold front and what are the implications for the spatial representativity of individual dropsondes? • How well can numerical models represent the mesoscale variability found in observations and how does it depend on model grid spacing? • Which processes are important for the spatiotemporal evolution of the thermodynamic and dynamic structure on the mesoscale, and in particular, what is the role of DI outflow – cold front interactions in supporting potential destabilization or suppression of convection. • What is the impact of the mesoscale variability near the cold front on surface precipitation and wind characteristics?
Relevant instruments:	KITsonde, WALES, HEDWIG
Observation strategy:	Flight legs across the cold front from DI outflow to AR/WCB inflow; FL280 to allow for KITsonde measurements (Figure 4)
Aircraft coordination:	Coordination with ATR42 for cloud/precipitation structure across the cold frontal region

3.2.4 Improving Atmospheric River forecasts with enhanced observations in moisture source regions (NAWDIC-AR)

Research questions:	• How well are the dynamical and thermodynamic structure of the lower troposphere in moisture source regions and regions of transport represented in models? • What is the impact of additional observations on the predictability of the primary cyclones, the upstream cyclone and their associated Atmospheric Rivers? • What is the added value of additional observations over the North Atlantic for forecasting the impact of cyclones and Atmospheric Rivers in Europe?
Relevant instruments:	KITsondes, HEDWIG, WALES
Observation strategy:	Cold sector of the extratropical cyclones where the DI could have impacts on the enhanced moisture uptake (Figure 3) and also on the warm sector of where the AR is located (Figure 4)

Aircraft coordination:	Simultaneous measurements in ARs to be coordinated with AR Recon

3.2.5 DI-PBL interaction

Research questions:	• How does the DI airmass mix into the PBL? • How does the mixing of DI influence the PBL structure? • How does the incoming DI overcome the inversion layer and, in turn, affect the inversion? • What is the role of surface fluxes feedback in the DI-PBL interaction (in synergy with NAWDIC-FLUX)?
Relevant instruments:	KITsonde, HEDWIG, WALES
Observation strategy:	KITsondes, HEDWIG and WALES lidar profiles in the cold sector and upstream. Interest along the DI flow towards its outflow, where the DI airmass first enters the PBL: focus on mid-level DI object at pressure level 500-700 hPa, as a feature that connects the DI inflow (pressure <500 hPa, generally to the north west), and the DI outflow (pressure >700 hPa, generally to its south east)
Aircraft coordination:	Isotope measurements by ATR42/TUBS Cessna F406 to observe DI interaction with the PBL

3.3 Secondary objectives

3.3.1 Satellite overpasses

- EarthCARE coordination for comparison with WALES and FISH observations

3.3.2 Aircraft-based instrument intercomparisons

- ATR42: WALES, FISH, SpecMACS
- TUBS Cessna F406: UMAQS, HEDWIG (comparison with AIRflows Doppler lidar), FISH
- KITcube: UMAQS (Ozone measurements at the surface are desirable)
- NASA Gulfstream 3: UMAQS (comparison with upstream chemical composition of the atmosphere in the UTLS region)

3.3.3 Verification and data assimilation of moisture

More information to be added.

4. Aircraft and instrumentation

4.1 HALO specifications

The High Altitude and LOng Range Research Aircraft (HALO) research aircraft is based on a Gulfstream G 550 ultra long-range business jet. HALO is funded by the Federal Ministry of Education and Research, the Helmholtz-Gemeinschaft and the Max-Planck-Gesellschaft. The main strengths of HALO are its long range and endurance, high ceiling altitude and large instrument load capacities, which are not available in such combination on any other research aircraft in Europe. Its specifications are summarized in Table 1.

Table 1: Specifications of HALO (Source: https://www.dlr.de/de/fx/forschung-transfer/forschungsinfrastruktur/gulfstream-g550-halo-d-adlr).

Parameter	Value
Wingspan	38.5 m
Length	30.9 m
Height	7.9 m
Max. take-off weight	42.3 t
Tare weight	21.2 t
Fuel capacity	18.7 t
Seating capacity	19 (normally 3 crew members and 5 to 8 scientists and engineers, depending on the instrumentation)
Range	Up to 12 000 km
Max. flight altitude	15 500 m (51 000 ft)
Max. speed	924 km/h (Mach 0.885)
Max. endurance	14 h

4.2 HALO payload

To characterize the mesoscale structure of the DI inflow region as well as the PBL structure in the DI outflow region, DI air masses must be followed with consecutive flights covering the North Atlantic. The payload for NAWDIC-HALO combines in-situ and remote sensing instruments with in-situ trace gas measurements to address the above listed RTs (Table 2). The observations will yield a comprehensive picture of the thermodynamic and dynamic fields from the lower stratosphere to the PBL, including observations of transport and mixing processes in the DI airstream.

Table 2: HALO payload for NAWDIC.

Instrument	Institution	Measured Parameters
WALES	DLR	H_2O, O_3
HEDWIG	DLR	u, v, w
KITsonde	KIT	T, q, u, v
specMACS	LMU Munich	cloud particle phase, particle size, geometry
UMAQS	JGU Mainz	CO, C_2H_6, CH_4, N_2O
FISH	FZ Jülich	H_2O
FAIRO	KIT	O_3
Bahamas	DLR	T, q, u, v, w

4.2.1 WALES

The Water Vapor Lidar Experiment in Space (WALES) lidar is an airborne four-wavelength Differential Absorption Lidar (DIAL; Wirth et al 2009), which was developed at DLR and repeatedly operated onboard HALO during the past decade (e.g., Krüger et al 2022). The water vapour concentration can be deduced by comparing returned signals of two spectrally narrow laser pulses that were emitted to the atmosphere (Table 3). WALES instrument allows to measure profiles over the whole range of water vapour concentrations, often varying by up to four orders of magnitude between the ground and the flight level in the upper troposphere/lower stratosphere region. The observation of water vapour up to the tropopause succeeds by comparing the returned signal of three wavelengths that are sensitive at different water vapour concentrations, i.e., different altitudes, to the reference wavelength at a non-absorbing wavelength. The four wavelengths are located in the water vapour absorption band at 935 nm (Wirth et al 2009). The error is evaluated to be less than 5–7% (Kiemle et al 2007; Bhawar et al 2011). The range-resolved water vapor data has been used to validate NWP models (Krüger et al 2022) and to test the impact of assimilating its observations in NWP models. The combination of H_2O and O_3 profiles will be used to study mixing across the tropopause.

Operational constraints of WALES:

- Best performance if 2 km distance to cloud top is ensured
  - Saturation effects at cloud top for closer distances
  - Higher random error for larger distances
- No data for flight legs within cloud
- System is not frost-proof
- System requires about 3 h to warm up before the lasers can be started and 1 h of laser operation for full performance (especially H_2O)
  - To be considered in case of planned stop-overs
- Maximum power cuts of 5 minutes

Table 3: WALES instrument characteristics.

Parameter	Water Vapour	Aerosol
Wavelength	4 wavelengths @ ~935 nm	532 nm and 1064 nm
Laser energy	40 mJ	
Pulse repletion rate	200 Hz	
Telescope diameter	48 cm	
Observed parameter	Water Vapour mixing ratio, relative humidity (in combination with external temperature data (e.g. ECMWF or dropsonde)	Backscatter coefficient (532 nm and 1064 nm), Color ratio (532 nm/1064 nm) of backscatter, aerosol depolarization (532 nm and 1064 nm), Aerosol extinction (532 nm – HSRL)
Vertical resolution	~200 m	15 m
Temporal resolution	25 s (2.6 – 2.9 km)	1 s (0.22 – 0.24 km)

4.2.2 HEDWIG

The Heterodyne Detection Windlidar Gadget (HEDWIG) is a novel 1.6-µm Doppler wind lidar instrument for HALO. It is a successor instrument to the 2.0-µm wind lidar which has been operated from aircraft and ground since 1999 (Witschas et al 2017, Witschas et al 2023).

Among others, the 2-µm data was used to validate NWP models (Schäfler et al 2020), for NWP impact studies and for satellite validation. HEDWIG is currently set up in the laboratory and already performed the first successful ground measurements reaching up to 20 km. The certification started in February 2024 and is planned to be completed by summer 2025. The primary data product of HEDWIG is the horizontal wind vector below the aircraft which is measured with a vertical resolution of 100 m and a horizontal resolution of a few kilometers by using a conical scan pattern of the emitted laser beam. In addition, HEDWIG may be operated in a nadir pointing mode, enabling it to measure vertical wind speed profiles with a horizontal resolution of about 200 m. The combination of HEDWIG and WALES allows latent heat flux profiles to be measured in the PBL using the eddy covariance method (Kiemle et al 2011).

Cloud-free but aerosol-loaded conditions are ideal for the operation of HEDWIG, although broken clouds are acceptable. The preferred altitude is likely between 9 km and 13 km, depending on the actual weather conditions and aerosol load. Since HEDWIG will operated on HALO for the first time, the dropsonde measurements on board will be useful for validation. Overflights of ground stations or coordination with other aircraft could also be beneficial for specific cases, such as testing certain laser beam scan patterns.

4.2.3 KITsonde

The KITsonde is a modular multi-sensor dropsonde system for high-resolution in-situ profiling of basic atmospheric variables (Kottmeier et al 2024). The system allows to launch up to four measurement probes at the same time, which are released from a discharge container shortly after being dropped from the aircraft. The average fall speed varies between 3 and 8 m s^{-1} and can be individually set based on the parachute size of the probe. Depending on the prevailing wind profile, probes from the same discharge container can spread over several tens of kilometres and capture the mesoscale structure of the upper troposphere and the PBL. Each measurement probe records air pressure, temperature, humidity and horizontal wind at a temporal resolution of 1 s. The receiver unit on board the aircraft can track up to 30 individual probes simultaneously, which allows multiple sonde releases in rapid sequence (Figure 5). Based on measurements collected during the SouthTRAC mission in 2019 and the ASCCI mission in 2025, radio transmission of sonde signals is possible over a maximum distance of about 600 km.

During the NAWDIC-HALO observation phase, the deployment of 110 release containers equipped with a total of 340 meteorological sondes is planned. To allow for adjustment of the required sampling density to different synoptical features, 60 containers filled with 4 sondes and 50 containers filled with 2 sondes will be prepared. Furthermore, the sampled data is planned to be transmitted to the Global Telecommunication System (GTS) of WMO in near-real time for data assimilation applications.

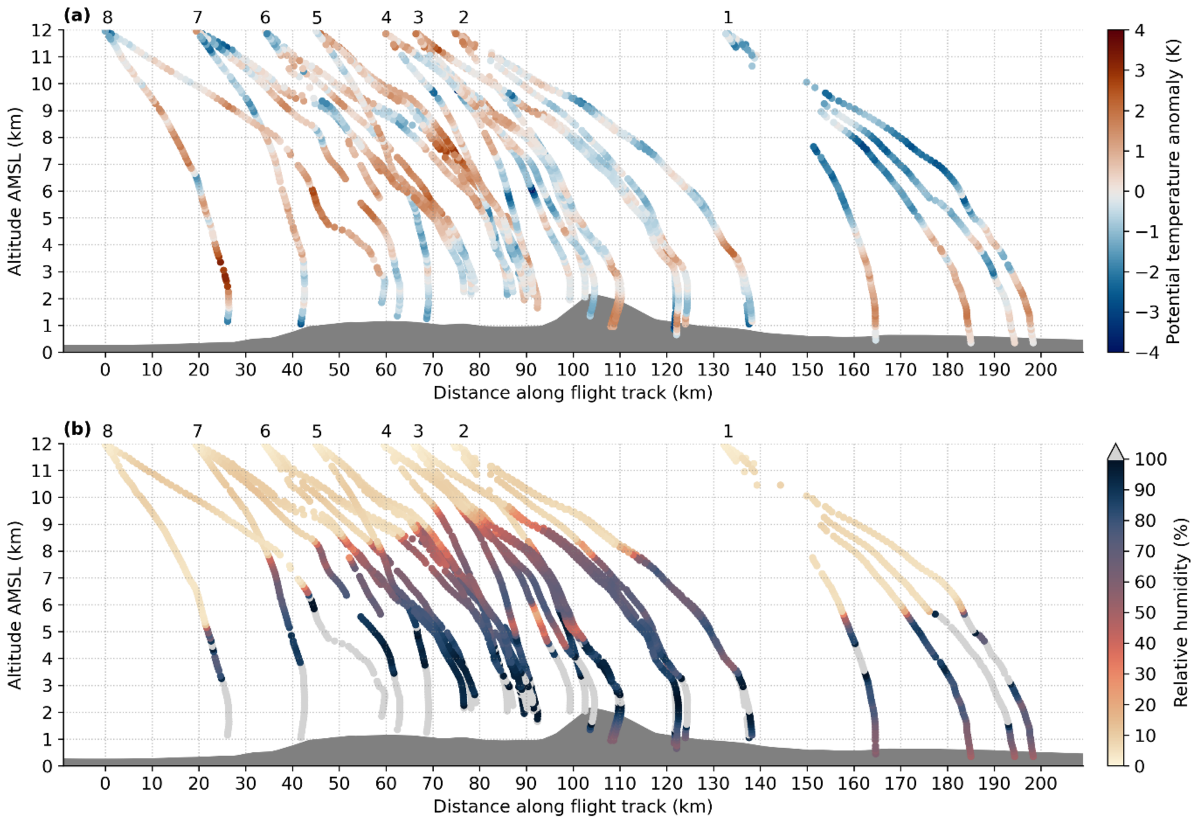

Figure 5: (a) Profiles of potential temperature anomaly (differences from the mean of all shown profiles) and (b) profiles of relative humidity measured by the KITsonde system near Córdoba (Argentina) on 06 November 2019 during the HALO SouthTRAC mission. The numbers on top of the panel indicate the release containers launched between 16:19 and 16:31 UTC. The cloud layers (relative humidity ≥ 100 %) are shaded in light grey. The distance indicated on the horizontal axis is the projection of the positions of the meteorological sondes onto the flight track (left=west, right=east). Dark grey shading represents the surface elevation along the transect.

4.2.4 specMACS

The cloud spectrometer of the Munich Aerosol Cloud Scanner (specMACS) is a spectral and polarized imager covering the solar spectral range (Ewald et al 2016, Weber et al 2024). It consists of two spectral camera systems covering the spectral range between 400 and 2500 nm with a resolution between 3 nm and 10 nm, observing a swath of 34° width (about 30 km) below the aircraft. The system also includes four polarized imaging cameras providing downward horizon-to-horizon imagery along the aircraft track. All subsystems facilitate the observation of cloud macrophysics and microphysics. Cloud microphysics retrievals combine polarized and spectral signals to provide thermodynamic phase, droplet effective size, droplet size distribution shape at or near cloud top. Methods for the observation of cloud cover and cloud vertical extent exist for spectral or polarized sensor parts.

4.2.5 UMAQS

The University of Mainz Quantum Cascade Laser (UMAQS) is based on direct absorption spectroscopy. A continuous quantum cascade laser forms its key component, which operates at a sweep rate of 2 kHz (Müller et al 2015). During recent HALO campaigns, such as WISE, SouthTRAC, and PHILEAS, UMAQS provided 1 Hz measurements of various gaseous trace species such as CO, N_2O, CH_4, CO_2 or OCS, depending on the campaign specific setup. These observations allowed to identify regions of stratosphere–troposphere exchange, mixing processes in the lower stratosphere or sources of air masses, transport pathways into and the composition of the upper troposphere and lower stratosphere. In particular, the measurements of N_2O allow for a precise discrimination of tropospheric and stratospheric air since it is not affected by chemistry like ozone and has a unique tropospheric value. For NAWDIC, UMAQS will measure CO, N_2O, CH_4 and C_2H_6 to study the trace gas composition associated with dynamical processes in regions affected by DIs.

4.2.6 FISH

The Fast In-situ Stratospheric Hygrometer (FISH) is a Lyman-α fluorescence spectrometer. FISH has a forward-facing inlet and measures total water (gas phase plus evaporated ice particles) at a rate of 1 Hz in the range 1–1000 ppmv (Meyer et al 2015). For NAWDIC, the inlet system will be flown for the first time at a position on the bottom fuselage of HALO to ensure undisturbed and correct sampling of ice crystals. The FISH instrument is well established and frequently used as a reference instrument aboard multiple aircraft and on HALO. The water vapor data are used for model comparison studies, for detailed water vapor transport studies as well as cirrus cloud climatologies.

4.2.7 FAIRO

The Fast Airborne Ozone Monitor (FAIRO) is a fully custom-built and compact ozone sensor that combines two measurement techniques: 1) a two-channel UV photometer detecting the absorption of O_3 in the Hartley band around 255 nm (emitted by an UV-LED) and 2) a 10-Hz chemiluminescence sensor (CL; Zahn et al 2012). The measurement precision of both devices is quantum-noise limited and ~0.3% at 10-Hz for the CL detector. FAIRO has been operated during 14 HALO campaigns between 2012 and 2023 and contributed to 30 ISI-referenced publications, primarily regarding chemical processing, transport processes around the UTLS or model evaluation.

4.2.8 BAHAMAS

The basic instrumentation onboard HALO observes in-situ temperature, humidity and winds using HALO’s nose boom and a special inlet for SHARC humidity observations. Temporarily, high-resolution observations (100 Hz) are requested to study turbulence near the jet stream regions.

5. Mission execution

5.1 General information

The NAWDIC-HALO measurement period is scheduled for 6 weeks from 12 January to 20 February 2026. The operation center with all planning activities will be located at Shannon Airport, Ireland (ICAO/IATA code: EINN/SNN, Position: 52.7012°N, 8.9144°W; Figure 6, top left). The reasons for choosing this location as operation basis are: Shannon Airport is ideally placed to reach climatologically preferred regions of both DI inflow and DI outflow (Figure 7):

1. There is a large overlap of aircraft ranges from the different NAWDIC components over the North Atlantic (Figure 7). Accordingly, coordinated flight legs of HALO with aircraft from NURTURE (DI inflow) and NAWDIC-DICHOTOMI (DI outflow) will be possible.
2. The French ATR42 aircraft and the associated science team will be based at Shannon Airport which will ease the flight coordination.
3. DLR flight facility has long experience of conducting flights from Shannon during previous campaigns (e.g., WISE in 2017) and it offers excellent infrastructure including hangar, aircraft handling and offices.
4. Shannon is located at the entry to North Atlantic Tracks, which eases access to the operation regions over the ocean.

A total of 120 flight hours are allocated, which are planned the following way:

- 108 h for science flights from Shannon (approx. 12 flights, 2 per week on average)
- 6 h for test flights HALO’s home airport Oberpfaffenhofen (ICAO/IATA code: EDMO/OBF)
- 6 h in total for direct transfer flights to Shannon and back.

5.2 Infrastructure and logistics

5.2.1 Hangar

- HALO will be based in the ASL Airlines Hangar (good experience during WISE 2017 mission)
- The SAFIRE ATR42 is planned to share the same hangar with HALO (ATR42 is scheduled to arrive on 3 February 2026)

5.2.2 Operations center

- The NAWDIC operations and flight planning center will be based at Treacys Oakwood Hotel (4 km from Shannon Airport; Figure 6, bottom), where two meeting rooms (https://www.treacysoakwoodhotelshannon.com/meeting-rooms.html) will be rented.
- Only limited office space is available inside the hangar. Additional office containers can be rented if needed.

5.2.3 Accommodation

- From experience in 2017, there will be no single campaign hotel. Campaign participants will be distributed all over the place (e.g., the DLR-FX team will stay in Limerick and the KIT team plans to stay in Bunratty; Figure 6, bottom).
- There are plenty of accommodation options available at the airport and in the region (B&B, Hotels, cottages).

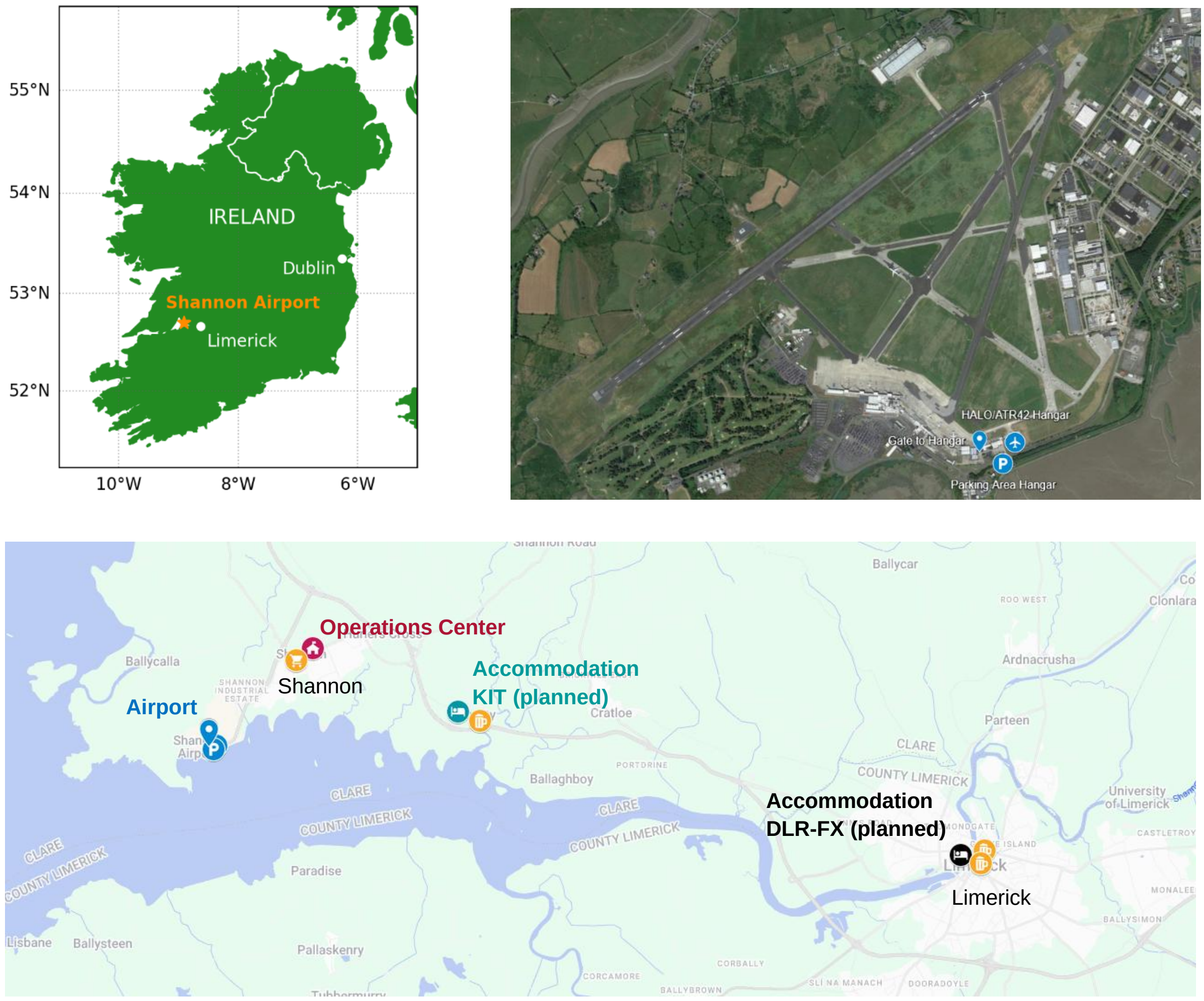

Figure 6: Top left: Location of Shannon Airport in Ireland. Top right: Satellite view of Shannon Airport (Source: 2025 Google Earth). Bottom: Location of airport, operations center, accommodation, and daily supply in the Shannon-Limerick area (Source: 2025 Google Maps). Link to interactive map: https://www.google.com/maps/d/viewer?mid=1xZ4V4KLB6pVYY3FC4W-TIWv3TyAiLcY&ll=52.68967528210898%2C-8.772549600000003&z=12

5.2.4 Personnel

- Table 4 provides an overview of the estimated personnel on site in Shannon for each of the participating institutions.
- A participants list (planning team, operators) will be drafted as soon as more detailed information on the potential personnel is available

5.2.5 Freight

- DLR-FX will send sea freight containers from Oberpfaffenhofen to Shannon (only limited amount of space available for user freight):
  - Packing of sea freight containers is planned for mid-November 2025
  - Shipping will start in early December 2025. Expected transit time (incl. some buffer) is approx. two weeks (arrival in Shannon ideally before Christmas)
  - Fortunately, no customs issues since Ireland is in the EU, but export control regulations apply
- Air freight should be avoided (very expensive, only limited space)

- User sea freight depends on total amount of freight and needs to be organized by the instrument teams themselves
- HALO board freight during transfer flights is not planned

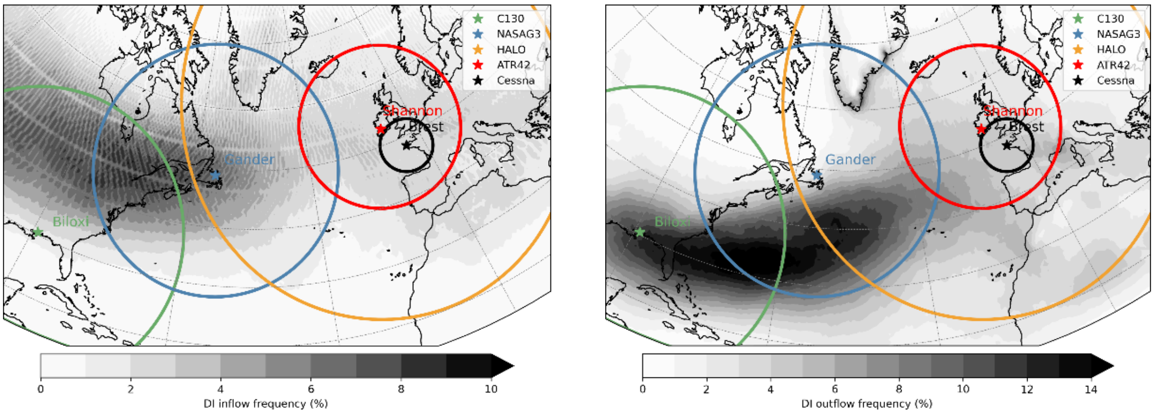

Figure 7: DJF climatological mean DI inflow (left) and DI outflow (right) frequency (shading in %) and range rings for return flights from the respective operating airport with different research aircraft planned to be deployed during NAWDIC.

Table 4: Estimated on-site personnel in Shannon.

Institution	Responsibilities	Number of people
KIT	PIs	2
	Forecasting	2
	KITsonde	1-2
DLR	WALES	3
	Forecasting	1
	HEDWIG	3
	Flight operations (incl. pilots)	10
JGU	UMAQS	2
	Forecasting	1
FZJ	FISH	1
LMU	specMACS	2
	Forecasting	1
WIS	Forecasting	2
ETH	NAWDICiso/Forecasting	3
LMD/Tolouse/SAFIRE	ATR42	14
Scripps	AR Recon	1-2
		Total: 51

5.3 Instrument handling

5.3.1 Certification

- Renewal of certification required:
  - HEDWIG (new certification)
  - specMACS (small revision planned)
  - UMAQS (small revision planned for new pressure reducer)
  - FISH (small revision planned for new inlet)

- No modifications required:
    - WALES
    - KITsonde
    - FAIRO

5.3.2 Integration schedule

- External configuration phase: 3 March – 26 September 2025
- Instrument integration phase: 27 October 2025 – 9 January 2026 (approx.)
- Scientific test flight: 8 – 12 December 2025 (subject to change)

5.3.3 Flight preparation

The approximate handling times for pre-flight preparations (e.g. warm-up) and post-flight work (e.g. data backup) required for each instrument are summarized in Table 5.

5.3.4 Operator seats

- Five operator seats are reserved for WALES, HEDWIG, UMAQS, specMACS, and KITsonde

Table 5: Approximate time line of pre-flight and post-flight instrument handling.

Instrument	-4 h	-3 h	-2 h	-1 h	flight	+1 h
WALES						
HEDWIG				?		?
KITsonde				30 min		
specMACS						
UMAQS						15 min
FISH			90 min			
FAIRO						
BAHAMAS				30 min		

5.4 Flight planning procedures

The NAWDIC campaign's complexity, characterized by multiple objectives and coordinated operations involving up to five aircraft in different regions and over a multi-day period, alongside the ever-changing synoptic conditions, imposes substantial demands on flight planning. Detailed planning, typically starting three to four days before the actual mission, entails discussions on the exact flight strategy including the determination of waypoints, altitudes, and refueling options, while forecast changes from one initialization time to the next have to be monitored. The high demands on the flight planning team are evident when considering scenarios like the simultaneous support for an ongoing HALO mission, the planning of a subsequent HALO flight on the next day in coordination with the international community. Such operations necessitate a robust planning team capable of efficient communication with instrument Principal Investigators (PIs) and flight operations.

5.4.1 Responsibilities

We define the following roles, which will be filled based on a pre-defined (weekly) schedule:

Steering group

- Group of five people that overlook the overall scientific goals, ensure a focused and well-structured planning process, and reach a final decision if needed (in case of different opinions)
- Members: Scientific manager, chief forecaster, instrument manager, two NAWDIC scientific steering group members

Scientific manager

- Central contact person
- Knows all about the planning activities of the upcoming days
- Chairs the general planning meeting
    - guides the decision-making process
- Deliverables:
    - planning matrix (gives an overview of plans for upcoming days)
    - daily schedule (in coordination with DLR-FX operations)
    - responsibilities on Teams page
    - planning summary: a document that summarizes the planning process of the day and discussion at the meetings with focus on plans / changes / discussion topics

Chief forecaster

- Coordinates the forecasting team:
    - collects information from forecasting group
    - provides information to mission scientists
- Chairs the flight planning meeting
- Possibly supported by an assistant
- Deliverables:
    - presentation of weather summary at general planning meeting and flight planning meeting
    - weather summary report on the weather situation of the day

Forecasting team

- Supports a possible active mission with latest satellite and forecast products
- Supports detailed flight planning for next day
- Creates outlook for upcoming days
- Uses latest forecast for:
    - update of tentative flight plans
    - update of plans for the next days
    - file presentation for general planning meeting
- Special tasks that need to be assigned to different members of the forecasting team:
    - Perform forecasts with visualization tool Met.3D (see Section 7.1)
    - Monitor upstream synoptic developments for coordination with NURUTRE and AR Recon

Technical manager

- Organizes the meetings (on-time start, VC infrastructure)
- Takes care of Teams (updates of main page, presentations, summaries, pictures)
- Collects reports

Instrument manager

- Collects information from all instrument PI's on current status
- Ideally a person from the instrument groups
- Deliverables:
    - Instrument summary (summary of the instrument status of the day, describe possible work on instruments)
    - Instrument status table (overview of instrument status that is provided on Teams)

Mission scientists

- 2 persons (1 per aircraft, 1 at the ground) that are responsible for conducting a mission
- Deliverables
    - Pre-flight: Develop the flight plans with pilots and DLR-FX operations, define release locations for dropsondes and request drift estimate from KITsonde instrument PI, provide flight plan to technical manager for upload to Teams page
    - Mission on-board: in-flight decisions HALO, communication with ground, coordination of dropsonde releases with pilots
    - Mission ground: monitors PLANET chat during the research flight, upload of most recent satellite images
    - Post-flight: mission summary (document that summarizes all events during a flight including onboard/ground)

Coordinator for ground-based observations

- Information to all ground-based observation facilities (including extra radiosonde releases)
- activation of additional observations

FX Operation contact person

- Coordination of flights and flight planning with pilots
- sets boundary conditions for flight planning

Campaign reporter

- Creates a short blog contribution for the NAWDIC webpage that shows the day from different perspectives
- Collects the picture of the day

Persons of Trust

- Persons from different hierarchy and experience levels that are on site (ideally) and approachable for campaign participants in situations of high stress (e.g. due to high workload, unusual working times, separation from family and friends, lack of private space, jet lag) or possible conflicts
- For conflict resolution or in the extreme case of harassment, PoTs may contact external colleagues or escalate the case to higher levels
- PoTs are nominated on a voluntary basis and will receive of special training prior to the campaign (organized by HALO-SPP)

To ease the international communication, each project group participating in NAWDIC also nominates a **contact person** who will participate in the planning meeting, report to their group and be approachable in case of questions.

5.4.2 Daily schedule

To streamline the flight planning procedures and ease the international coordination, each campaign day will follow a fixed schedule (Table 6). Individual meetings can be adjusted or canceled according to the current needs.

General planning meeting (0900 UTC, 1000 CET, 0100 PST; hybrid)

- Participants: scientists, instrument PIs, flight facility, pilots
- Duration: max. 45 min
- Aims:
  - inform all participants about scientific plans and tentative flight plans
  - decide all open issues in coordination with the instrument groups and flight facility
- Structure:
  - Short weather summary: information about flight options for the next days and update for planning for the next day with the latest forecast
  - Final discussion about flight pattern for next day (in case of 2 options)
  - Announcement of tentative plans for Day+3
  - Coordination with other aircraft
  - Aircraft status report by FX-Operations
  - Instrument status report by instrument managers
  - Demand of ground-based observations, e.g., EUMETNET radiosondes (organized by ground-based observation coordinator)
  - Key information from previous flight (2 minutes)
- Presentation and discussion led by the scientific manager
- After the general meeting, FX (pilots, operations) and the mission scientists work on filing flight plans

Steering group meeting (1030 UTC, 1130 CET, 0230 PST; every 2 to 3 days or on demand; in person)

- Participants: NAWDIC steering group
- Duration: max. 30 min
- Aim: Discussion on overall flight activities and coordination of general resources

Weather forecast and flight planning meeting (1600 UTC, 1700 CET, 0800 PST; hybrid)

- Participants: scientists
- Duration: max. 60 min
- Aims:
  - Wrap up of the discussion within the forecast team during the day
  - scientific discussion about options for the upcoming days
  - update of flight planning matrix
  - presentation of tentative flight plans (to be filed in detail on next morning)
  - Discussion about coordination of aircraft
  - Decision on responsibilities
- Campaign steering group should be present to decide on what plans will be priority for the next morning
- Weather summary by chief forecaster supported by an assistant

NAWDIC-AR Recon-NURTURE coordination meeting (1730 UTC, 1830 CET, 0930 PST; hybrid)

- Participants: 5-6 persons from NAWDIC and AR Recon steering groups
- Duration: max. 30 min
- Aims:
  - Briefing on current flight activities by each group and plans for upcoming days
  - Short reports of weather situation east and west of the Atlantic
  - Discussion of coordinated flight activities

5.4.3 Digital infrastructure

- The PLANET system of ATMOSPHERE (https://dlr.atmosphere.aero/login; documentation: https://dlr.atmosphere.aero/docs/um/index.html) will be used for in-flight communication between ground and aircraft crew, transmission of live telemetry data, and exchange of small files.
- For general communication between the participants, exchange and storage of files, and online meetings we will use Microsoft Teams.

Table 6: Typical daily schedule of project coordination.

Time (UTC)	NAWDIC	AR Recon	NURTURE
09:00 –10:00	General planning		
10:30 – 11:00	Steering group		
11:00	Submission of final flight plan for Day+1		
12:00			
13:00			Daily weather briefing
14:00			Flight planning discussion
15:00			
16:00 – 17:00	Weather briefing and flight planning	AR Recon briefing	
17:30 – 18:00	NAWDIC-AR Recon-NURTURE coordination		
19:00			
20:00			Flight debriefing

5.4.4 Reports

For documentation purposes, the following reports need to be filed for each flight:

- Weather summary (Chief forecaster and assistant)
- Planning summary (Science manager)
- Mission report (Mission scientist ground/on-board)
- Instrument report (Instrument manager)

5.5 Flight restrictions

The information in this section are based on experience from previous HALO campaigns in the North Atlantic region (mostly NAWDEX 2016 and ASCCI 2025) as well as on exchange with local ATCs at Shannon Airport (AirNav Ireland) in preparation of the campaign.

5.5.1 General remarks

- The pilots have the safety responsibility and decide about the feasibility of the planned flight.
- Flight plans are therefore iterated with the flight facility for many days (at least 3 business days), who also have to get permission of the concerned ATCs.
- Plans get more likely if we consider
    - Significant weather: turbulence, icing, weather during take-off and landing
    - Feasible length of the flight, duty times of crew
    - Restrictions of ATCs in terms of operation (flight altitudes, air traffic, dropsonde observations, instrument operation)
- Data coverage and quality gets better if we consider the restrictions for instrument operation

5.5.2 Flight time limitations

- Everyone flying on HALO is subject to these regulations
- Flight duty time includes time required for preparatory work, flight time, and finishing work
- The unrestricted flight duty time of each crew member between two rest periods is <u>ten hours.</u>
- Within a period of seven consecutive days, the flight duty time according to paragraph 1 <u>may be extended four times by up to four hours</u>, whereby the total of these extensions may <u>not exceed eight hours.</u>
- Each crew member shall be granted a <u>rest period of at least ten hours</u> within a 24-hour period.
- The minimum rest period shall be increased from more than 11 hours to 12 hours, from more than 12 hours to 14 hours
- The operator shall ensure that the minimum rest period referred to in paragraphs 1 and 2 is regularly extended to a weekly rest period in the form of a 36-hour period including two local nights in such a way that there are no more than 168 hours between the end of one weekly rest period and the beginning of the next.

5.5.3 Instrument limitations

The following instrument limitations need to be considered for flight planning:

- WALES:

  - Works best outside thick clouds (attenuated beneath and within optically thick clouds)
  - Maximum coverage at highest flight altitude: ideally 1 to 2 km above clouds
  - Higher horizontal resolution at lower altitudes (lower speed) for PBL observations
  - Operation is permitted only above 7300 m (land) and 6100 m (ocean) due to eye safety restrictions
- HEDWIG:
  - Works best outside of clouds (attenuated beneath and within optically thick clouds)
  - Higher horizontal resolution at lower altitudes (lower speed) for PBL observations
  - Broken clouds are acceptable
  - Better signal if aerosol load is increased
  - Optimal observation mode still needs to be defined (nadir, scanning)
- specMACS:
  - no images possible with Ci clouds
- KITsonde:
  - Maximum distance of 600 km to the dropsonde to ensure data transmission
  - No dropsondes releases above land
  - Individual restrictions by ATCs need to be considered (see following sections)
  - Over the Atlantic Ocean, generally no dropsondes above FL 280 (~8.5 km)
  - In northern latitudes (Norway, Iceland), releases from higher altitudes are possible
  - Permissions towards subtropical regions needs to be negotiated
- UMAQS:
  - Relies on detailed planning of flight altitudes considering air traffic, icing, and turbulence conditions
- FISH:
  - Relies on detailed planning of flight altitudes considering air traffic, icing, and turbulence conditions
- FAIRO:
  - Relies on detailed planning of flight altitudes considering air traffic, icing, and turbulence conditions
- BAHAMAS:
  - Relies on detailed planning of flight altitudes considering air traffic, icing, and turbulence conditions

5.5.4 Air traffic control

The execution of research flights in central European air space demands intensive logistical preparation. Air traffic over Europe is generally very dense and a number of authorities need to be contacted and asked for permissions. The North Atlantic airspace is controlled by the Gander Oceanic Flight information region (FIR) and Shanwick Oceanic FIR. It comprises an area from 44° North to 61° North and partly up to 64° North (Figure 8). This airspace has virtually no land-based navigational aids or communication relays. Operating freely away from airways (aerial work permit) and releasing dropsondes is impossible apart from a few small areas. The further north the flights are located, the more flexibility can be achieved with ATCs due to the reduced air traffic, especially over Scandinavia and Iceland.

- Operational considerations (AirNav Ireland)
    - Domestic airspace: Generally, not a major concern. The bigger challenges are Prestwick (Scotland) and North Atlantic tracks (NATs).
    - Dynamic handling: AirNav dynamically manages airspace by blocking the necessary zones domestically, based on our requirements.
    - Time-dependent availability: Availability is highly time-dependent. Early mornings (until around 5 or 6 AM) tend to be busier.
    - Altitude restrictions:
        - Low-level flights are usually unproblematic.
        - Operating at FL 410 (see Table 7) and releasing dropsondes presents more complexity.
    - Air traffic impact: The higher the flight level, the more aircraft could potentially be affected below.
    - Dropsonde operations:
        - Dropsondes <u>may</u> be allowed to be deployed from altitudes higher than FL 280, depending on the time of day.
        - AirNav must be informed about aircraft presence in drop zones.
    - Traffic forecasting: AirNav typically has a general forecast of traffic conditions for the following days.
    - kml files from Mission Support System (see Section 7.1) should be send to AirNav (will be done by DLR-FX-OPS)
    - Maps with information on dropsonde drift should be provided together with flight plans (will be done by DLR-FX-OPS)
- Shanwick Oceanic
    - Notification Requirement: A 3-day advance notice is helpful. AirNav may be able to block areas down to FL 280. Higher altitudes could be problematic—dropsondes should ideally not be deployed above FL 280.
    - Time Considerations: Air space is usually quieter after 4:00 pm. Also, during winter the air space is generally quieter.
    - Border Area Operations: Flights operating near the boundary between domestic and oceanic airspace can be problematic. Oceanic transitions should be avoided whenever possible. However, when we are out for one hour or two in Shanwick Oceanic then we can also cross multiple times
    - Operational Flexibility: A descent from FL 410 to FL 280 for dropsonde release, followed by scanning at lower altitudes, might be feasible.
    - Dependencies:
        - Depends on the flight heading and current traffic conditions.
        - Operating within a small dedicated airspace block would improve feasibility.
        - AirNav will verify the possibility of securing such a block (Apr 2025). If a block can be secured, this will give us the possibility for level changes in Shanwick air space
- North Atlantic High-Level Airspace (NAT HLA)
    - Dynamic flight routes so called North Atlantic tracks (NATs) for commercial transatlantic traffic are defined depending on the wind situation

    - Generally, flights above the main traffic provide increased flexibility and easier coordination with ATC
    - Flight routes cover FL 285 - FL 420
    - The hours of validity of the two Organized Track Systems (OTS) are normally: day-time OTS (westbound): 1130 UTC – 1900 UTC, night-time OTS (eastbound): 0100 UTC – 0800 UTC
    - NATs are defined only about 17 hours in advance.
- Denmark (Greenland)
    - Despite EASA Membership and former good relationship, approvals and coordination have been very difficult during past campaigns and positive feedback, especially on dropsondes (even over water), can’t be guaranteed.
    - High workload (e.g. risk assessments, lots of questions) and lead time to be expected
    - Local Government of Greenland is now partly responsible for aerial work and dropsondes, that could help.
    - DLR-FX obtained a “High-Risk-Approval” by the German Aviation Authority (LBA).
    - During ASCCI 2025, Greenland still did not permit dropsonde releases
- United Kingdom
    - Long lead time for approval/coordination (28 days+). Expected flight pattern and details required. Single flights to be coordinated ~3 days prior.
    - Military Airspaces / Exercises have priority and can lead to changes in flight planning.
- France
    - Long lead time required and questions/discussions to be expected. Currently each flight (!) has to be announced in detail at least 15 business days prior to operation
    - Rules and workarounds change (seemingly) constantly. We will see how this develops in 2025.

Table 7: Height above ground and mean sea level pressure for selected flight levels assuming the ICAO standard atmosphere.

Flight Level	Height (ft)	Height (m)	Pressure (hPa)
270	27 000	8 230	344
280	28 000	8 534	329
290	29 000	8 839	314
310	31 000	9 449	287
330	33 000	10 058	262
350	35 000	10 668	238
370	37 000	11 278	216
390	39 000	11 887	196
410	41 000	12 497	178
430	43 000	13 106	160
450	45 000	13 716	145

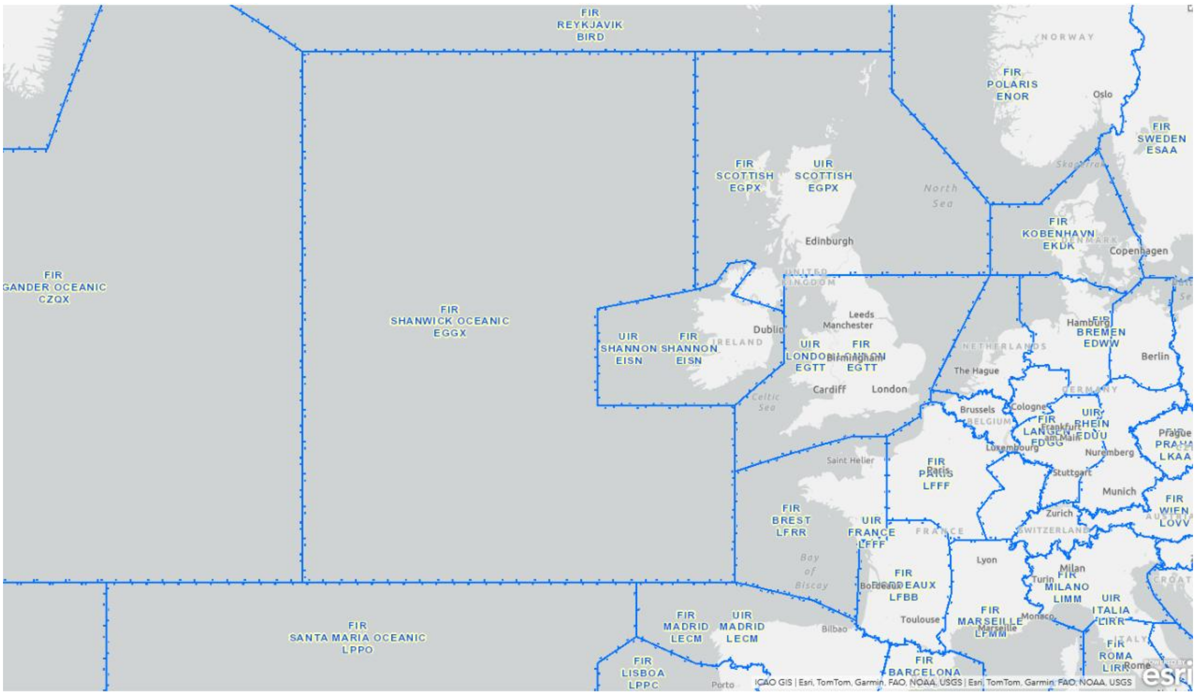

Figure 8: Flight information regions over the North Atlantic and western Europe.

6. Preparation

6.1 Case study "Storm Eunice"

On 18 February 2022, the extratropical cyclone "Eunice" ("Zeynep" in Germany) hit western Europe with hurricane-force winds (maximum wind gust of 196 km h^{-1} in United Kingdom; Volonté 2024a). In Germany alone, the damage was estimated at 900 million Euros and, tragically, a total of three people lost their lives. Three days after "Eunice", cyclone "Franklin" ("Antonia" in Germany) hit the same region. Beyond strong winds, "Franklin" was associated with torrential rain and flooding afterwards. In addition to both systems leading to HIW, we have evidence that the systems are dynamically linked by the occurrence of a DI (Volonté 2024b). At this point, generic flight patterns are illustrated to sample the synoptic evolution of "Eunice" and "Franklin" in collaboration with the international partners.

6.1.1 Structure of the upper troposphere and lower stratosphere

The synoptic situation is characterized by a deep trough over the western North Atlantic on 16 February 2022, 12 UTC (Figure 9, left). Embedded into the trough is a TPV just north of Newfoundland characterized by the lowest potential temperature on the dynamic tropopause. A DI emerges from the western flank of the trough and descends towards the central Atlantic and western Europe within the next two days (Figure 9, right). 48 hours later, the DI air masses that reach southern Great Britain and northern France are associated with severe wind gusts.

The synoptic situation on 16 February 2022 sets the scene, but as hardly within reach for the HALO aircraft, consecutive flights start with NASA's Boeing 777. Departing from Gander, Newfoundland, the Boeing 777 would cross the TPV and jet stream at least two times and the extensive instrumentation will provide profiles of water vapor (DIAL), wind direction and speed (Doppler lidar), and temperature (dropsondes) to characterize the tropopause-level mesoscale structure in the DI inflow region.

24 hours later (17 February 2022, 12 UTC), the trough reaches the central North Atlantic (Figure 10, left) and is within reach for HALO. East of the trough axis, WCB inflow and ascent can be found in a region of locally lowered mean sea level pressure. This region of lower mean

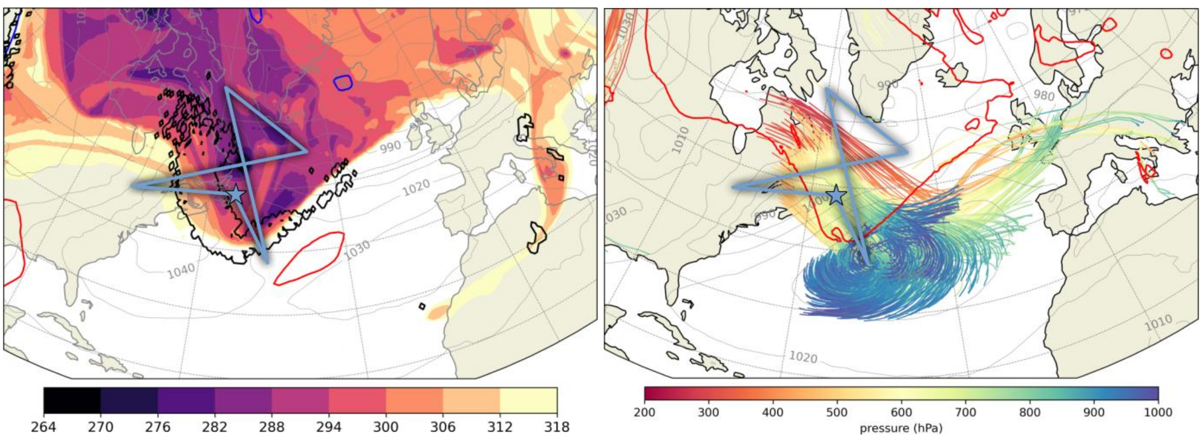

Figure 9: Synoptic situation on 16 February 2022, 12 UTC. Left: Potential temperature on the dynamic tropopause (shading in K), DI inflow (black contour), WCB inflow, ascent, and outflow (red, green, blue contours), mean sea level pressure (grey contours in hPa) and flight track of NASA's Boeing 777. Right: 2-PVU contour on 300-K isentropic surface, 48-h DI trajectories starting on 16 February 2022, 12 UTC (colored by height), mean sea level pressure (grey contours in hPa) and flight track of NASA Boeing 777 (blue line).

sea level pressure constitutes the beginning of the development of cyclone Eunice. West of the trough axis, DI inflow is diagnosed in the upper troposphere (Figure 10, right). Since these air masses are immediately linked to the development of Eunice and reach the near surface levels two days later, the focus of HALO's mission will be on the structure of the upper troposphere in the DI inflow region.

HALO would depart westward from Shannon on 17 February, 12 UTC to cross the tropopause multiple times in the DI inflow region at the highest possible level (~14 km). Measurements with HEDWIG, WALES and KITsonde would sample gradients of winds, humidity and temperature near the jet stream. Repeated across-jet flight legs perpendicular to the wind direction and one leg parallel to the wind direction will further allow to document the mesoscale structure in a region where Cirrus clouds may affect the DI formation through radiative processes.

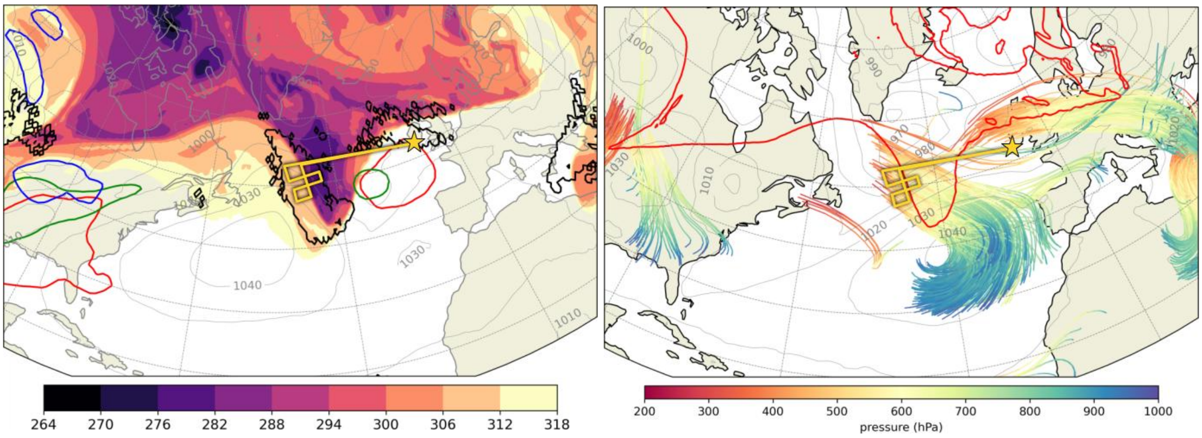

Figure 10: As Figure 9, but for 17 February 2022, 12 UTC with the flight track of HALO (yellow line).

6.1.2 Processes at the DI outflow – PBL interface

DIs that started their descent on 16 and 17 February spread out behind an extended cold front over the central to eastern North Atlantic on 18 February, 12 UTC (red contour in Figure 11, right). The DI outflow is associated with upward fluxes of surface sensible and latent heat indicating warming and moistening of the lowest part of the atmosphere. The DI outflow is further associated with low-level cloudiness changing from scattered to larger cloud and finally to open cells including precipitation. HALO would fly southwestward from Shannon and cross the region of the DI outflow multiple times. The flights would be conducted at mid- to upper-tropospheric levels to document horizontal and vertical moisture transport as well as latent heat fluxes using WALES and HEDWIG. It is the unique combination of these two instruments that allows flux profile measurements by means of remote sensing (Kiemle et al 2011). The flight pattern is further suited to address research questions posed by NAWDIC-CLOUD. DI flow following flight legs allow us to observe the development of the cloud distribution over time. By conducting several of such flight legs across the cold sector, the dependence of the low-level cloud distribution on the environment will be assessed. For example, relatively weak subsidence, higher humidity and a colder PBL favor early transitions from overcast to broken clouds near the low-pressure center (Tornow et al 2023). In contrast, slower transitions are expected further away from the low-pressure center due to stronger subsidence and a warm

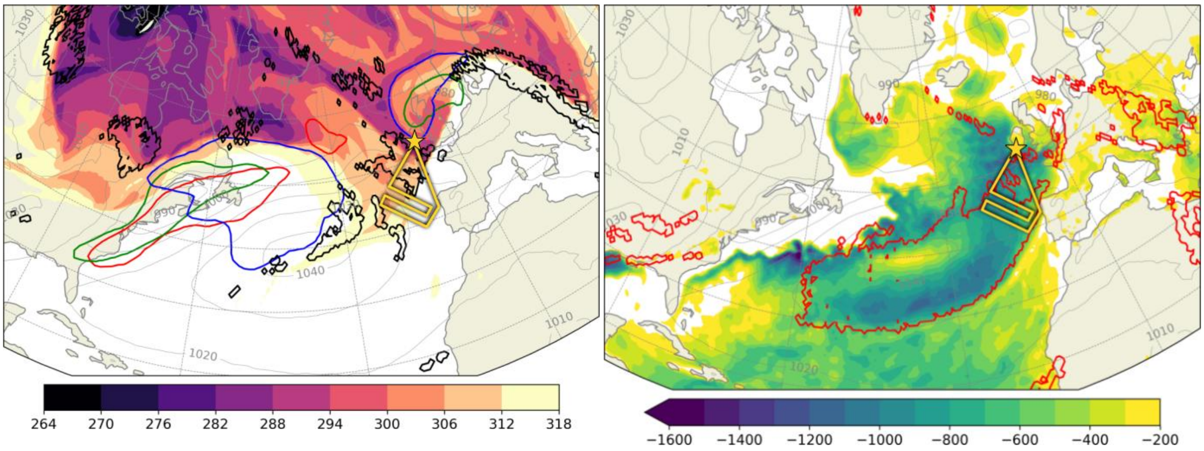

Figure 11: As Figure 9, but for 18 February 2022, 12 UTC. (b) shows upward surface latent heat flux (shading in W m^{-2}), mean sea level pressure (grey contours in hPa) and region of DI outflow (red contour).

and dry troposphere.

6.1.3 Processes at the DI outflow – cold front interface

The sequence of HALO flights ends by targeting the processes occurring at the DI – cold front interface. On 20 February 2022, 00 UTC the synoptic situation features an AR on the southern flank of cyclone “Franklin” (Figure 12, left). Extending the DI trajectories starting on 16 February 2022, 12 UTC forward in time, it becomes apparent that these air masses were transported around the subtropical anticyclone (Figure 12, right). The considerably increasing specific humidity along the DI trajectories indicates moisture uptake inside the PBL and a contribution of this moisture to rainfall that was associated with the AR in large parts of Great Britain.

In such a situation, HALO would depart from Shannon in westerly direction first measuring water vapour (WALES) and winds (HEDWIG) to derive the moisture transport at high spatial resolution which contributes to the rainfall in Great Britain. Inside and below clouds, the deployment of KITsondes will complement the remote sensing measurements. HALO would then conduct multiple flight legs across the cold front. The deployment of dropsondes at a high frequency would sample the mesoscale structure in a region where a subsequent DI may overrun the surface cold front (not shown). Further, precipitation forecasts have been shown to be particularly sensitive to uncertainties in regions of strong gradients along the cold front (Reynolds et al 2019). Thus, measurements of moisture and wind with HALO provide additional observations in these sensitive regions to improve downstream precipitation forecasts.

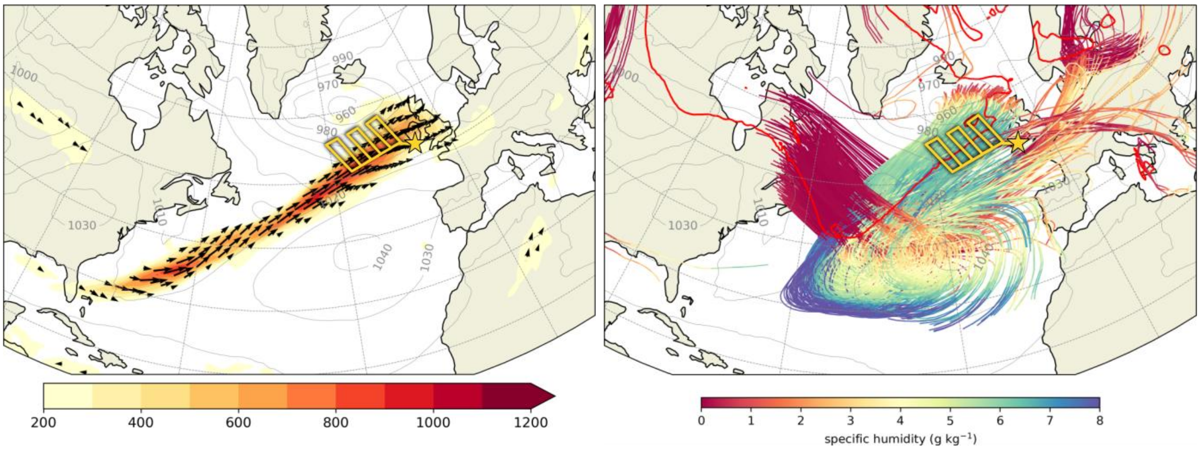

Figure 12: Synoptic situation on 20 February 2022, 00 UTC. Left: Vertically integrated water vapour transport (shading in kg m-1 s-1) and mean sea level pressure (grey contours in hPa). Right: 84-h DI trajectories coloured by specific humidity (g kg-1) starting on 16 February 2022, 12 UTC and ending on 20 February 2022, 00 UTC. Further shown is 2 PVU contour (red) on 300-K isentropic surface and mean sea level pressure (grey contours in hPa).

6.2 Dry run

In a two-week NAWDIC "Dry Run", that took place from 27 January to 7 February 2025, forecast products and practice planning procedures (as described in Section 5.7) were tested under realistic conditions and in collaboration with the international community. The lessons learned from the dry run will help to adjust and optimize the planning procedures during the actual mission period in 2026.

6.3 ASCCI campaign

The KITsonde is a central observing system during NAWDIC-HALO which has been successfully deployed during the SouthTRAC campaign. To characterize the capabilities the system and test different measurement strategy, the KITsonde has been deployed during the “Arctic Springtime Chemistry Climate Investigations” (ASCCI) campaign in March 2025, where HALO operated from Kiruna (northern Sweden). In total, 24 containers equipped with 72 meteorological sondes were successfully released.

7. Forecasting Products

7.1 NWP forecasts

7.1.1 Basic weather charts

- ECMWF forecasts (DLR): https://www.pa.op.dlr.de/missionsupport/classic/forecasts/forecasts2/
- ECMWF forecasts (ETH): https://iacweb.ethz.ch/staff/lpapritz/forecasts/arctic/index_nawdic.html
- Windy: multiple models for comparison (kml overlay possible) https://www.windy.com/?850h,50.735,7.111,5,i:pressure,m:eRZafRr
- NCEP Integrated Water Vapor Transport (IVT) Analyses and Forecasts: https://cw3e.ucsd.edu/ivt_northernhemisphere/

7.1.2 Mission Support System

The Mission Support System (MSS) is a Web-Map-Service-based system that allows an interactive planning of flight routes in the context of ECMWF's operational forecasts (further data sources can be integrated). Various products can be visualized for desired geographical sections and vertical levels. The tool calculates cross sections along planned flight routes. It also contains a flight performance calculation for HALO. Further information can be found in Rautenhaus et al 2012.

7.1.3 Met.3D

Met.3D is an open-source visualisation tool for interactive, three-dimensional visualisation of numerical ensemble weather predictions and similar gridded atmospheric datasets. Met.3D uses state-of-the-art computer graphics technology and implements several recently proposed ensemble visualization methods to facilitate interactive 3D visual data analysis in a novel way (https://met3d.wavestoweather.de/met-3d.html). Met.3D Test Products can be found here: https://wx.hcds.uni-hamburg.de/.

7.1.4 KITsonde simulator

The KITsonde simulator is a tool developed at IMKTRO of KIT that simulates fall trajectories of dropsondes with different fall velocities using operational ECMWF forecast data. These simulated trajectories can be either used to fulfil ATC requirements by estimating drift distances of planned KITsonde releases or to facilitate the optimization of flight tracks and release strategies to sample the mesoscale variability.

7.2 Lagrangian products

- Moisture source diagnostic: To be implemented
- Warm conveyor belt diagnostic: http://www.kit-weather.de/wcb_probability_maps.php

7.3 Ensemble sensitivity products

https://www.atmos.albany.edu/student/pcapute/ar_sens.php

7.4 Satellite images

- Windy (Geostationary IR, VIS): https://www.windy.com/de/-Satellit-satellite?satellite,49.268,-31.025,4,i:pressure,m:eS2afWQ

- EUMETSAT Eumetview (Geostationay Meteosat, MTG products): https://view.eumetsat.int/productviewer?v=default
- EUMETSAT's EUMeTrain ePort (Meteosat, NWP overlays): http://185.254.223.166/ow-maps/
- Icelandic met office
  - Geostationay Meteosat Atlantic composite: https://en.vedur.is/weather/observations/satellites/#type=atlantic
  - Seviri Archive (IR; WV, VIS, Composites): http://brunnur.vedur.is/myndir/seviri/
- Norwegian meteorological institute (Meteosat, VIS, IR animation): met.no/vaer-og-klima/satellittbilder
- Kachelmannwetter (Meteosat): https://kachelmannwetter.com/de/sat/grid-europa-afrika/satellit-nature-15min.html
- National Oceanic and Atmospheric Administration (NOAA): GOES-E North Atlantic: https://www.star.nesdis.noaa.gov/GOES/sector.php?sat=G16&sector=na
- National Aeronautics and Space Administration (NASA) Worldview, Geostationary (GOES-E/W, HIMAWARI) and polar orbiting (NOAA 20/21, Aqua, Terra): https://worldview.earthdata.nasa.gov/
- EarthCARE predictions:
  - https://www.engr.colostate.edu/~jhaynes/orbits/earthcare/
  - https://evdc.esa.int/orbit/

7.5 Radar images

- European composite:
  - Meteoradar: https://www.meteoradar.co.uk/en-gb/continent/eu
  - Kachelmannwetter: https://kachelmannwetter.com/de/regenradar/europa.html
- UK composite (Met Office): https://weather.metoffice.gov.uk/maps-and-charts/rainfall-radar-forecast-map
- Ireland (Kachelmannwetter): https://kachelmannwetter.com/de/regenradar/irland.html

7.6 Soundings

7.6.1 Observations

- University of Wyoming: https://weather.uwyo.edu/upperair/europe.html
- Wetteronline: https://www.wetteronline.de/?gid=euro&pcid=pc_modell_expert&pid=p_modell_expert&sid=Radiosondes

7.6.2 Predictions

- Wetterzentrale (GFS, WRF for selected cities): https://www.wetterzentrale.de/show_soundings.php?lat=48&lon=-4&model=gfs&var=120&run=6&lid=OP&h=0&time=0
- NOAA Real-time Environmental Applications and Display sYstem (Ready): https://www.ready.noaa.gov/READYcmet.php

7.7 Flight restrictions and North Atlantic Tracks

- Skyvector Aeronautical Charts: https://skyvector.com/?ll=52.46850446825682,-42.36914061641109&chart=301&zoom=14
- French Aeronautical Information Service: https://www.sia.aviation-civile.gouv.fr/
- Portuguese Aeronautical Information Service: https://ais.nav.pt/wp-content/uploads/AIS_Files/eAIP_Current/eAIP_Online/eAIP/graphics/eAIP/LP_ENR_6_01-9_en.pdf

8. Data handling

8.1 Data policy

All research data of NAWDIC and newly developed software will be made available to the public. Detailed information about data management will be summarized in a research data management plan which will be agreed on and shared with all NAWDIC partners before the start of the campaign.

8.2 Data repository

Aircraft data will be archived in the HALO database which is operated at DLR-IPA (https://halo-db.pa.op.dlr.de/). Data usage will follow accepted best practices as defined in the usual HALO Data Protocols, which will apply to all national and international partners. These protocols treat data analysis, deadlines for data storage to the database and access to the data and follow the DFG (German Science Foundation) codex of good scientific practice. Following the CF metadata conventions and assigning a digital object identifier will make the data findable, accessible, interoperable and reusable. Software code will be versioned using Git and the web-based code sharing platform Gitlab at KIT (https://gitlab.kit.edu/).

We also plan to establish a de-centralized data browser (similar to https://orcestra-campaign.org/data.html), where all available data products related to NAWDIC are collected.

8.3 Conventions

Before the start of the campaign, we plan to agree on common data format, meta data, and naming conventions among all NAWDIC partners to facilitate the exchange of campaign data and future collaborations.

To ease the communication about flight planning and interpretation of campaign data, we plan to define IOPs (intensive observation periods) as days on which one of the three aircraft involved in NAWDIC (HALO, SAFIRE ATR42, TUBS Cessna) is in operation and name it according to the date. Additionally, each research flight of the aircraft will be named according to an Irish city.

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