The North Atlantic Waveguide and Downstream Impact Experiment

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1   **The North Atlantic Waveguide and Downstream Impact Experiment**

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Capsule. Multi-aircraft and ground-based observations were made over the North Atlantic in fall 2016 to investigate the importance of diabatic processes for midlatitude weather.

Abstract. The North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX) explored the impact of diabatic processes on disturbances of the jet stream and their influence on downstream high-impact weather through the deployment of four research aircraft, each with a sophisticated set of remote-sensing and in situ instruments, and coordinated with a suite of ground-based measurements. A total of 49 research flights were performed, including, for the first time, coordinated flights of the four aircraft; the German High Altitude and LOng Range Research Aircraft (HALO), the Deutsches Zentrum für Luft- und Raumfahrt (DLR) Dassault Falcon 20, the French Service des Avions Français Instrumentés pour la Recherche en Environnement (SAFIRE) Falcon 20, and the British Facility for Airborne Atmospheric Measurements (FAAM) BAe 146. The observation period from 17 Sep to 22 Oct 2016 with frequently occurring extratropical and tropical cyclones was ideal to investigate midlatitude weather over the North Atlantic. NAWDEX featured three sequences of upstream triggers of waveguide disturbances, their dynamic interaction with the jet stream, subsequent development, and eventual downstream weather impact on Europe. Examples are presented to highlight the wealth of phenomena that were sampled, the comprehensive coverage and the multi-faceted nature of the measurements. This unique dataset forms the basis for future case studies and detailed evaluations of weather and climate predictions to improve our understanding of diabatic influences on Rossby waves and downstream impact of weather systems affecting Europe.

56   Progress in understanding the processes controlling midlatitude weather is one of the factors

57   that have contributed to a continuous improvement in the skill of medium-range weather

58   forecasts in recent decades (Thorpe 2004; Richardson et al. 2012; Bauer et al. 2015).

59   Additionally, numerical weather prediction (NWP) has undergone a revolution in recent

60   years, with the development and widespread use of ensemble prediction systems (EPS) to

61   represent forecast uncertainty (Bauer et al. 2015). However, the short-term prediction of high-

62   impact weather (HIW) events (e.g., strong winds and heavy precipitation), and the medium-

63   range prediction of extratropical cyclones, including their tracks and intensity, is still a major

64   challenge (e.g., Frame et al. 2015). Recent research on midlatitude weather has focused on

65   quantifying model errors and predictability, and in particular on investigating the role of

66   diabatic processes such as those related to clouds and radiation, whose interaction with the

67   dynamics of the flow must be understood and represented more accurately in models in order

68   to further improve forecast quality.

69   Detailed observations are needed to characterize the weather systems and embedded

70   physical processes across a range of spatial and temporal scales that encompass cloud

71   microphysical variability and Rossby waves. In September and October 2016, the North

72   Atlantic Waveguide and Downstream Impact Experiment (NAWDEX) made new multi-scale

73   observations in the North Atlantic basin from eastern Canada to western Europe. Weather

74   features expected to be associated with forecast errors were extensively probed, providing a

75   high-quality set of observations that are not assimilated routinely and thus can be used for

76   validation of the NWP systems.

77   The fall season was chosen for the experiment because diabatic processes are particularly

78   active due to relatively high sea surface temperatures and the jet stream is intensifying as the

79   high latitudes cool. Many of the weather phenomena central to the growth of disturbances on

80   the jet stream and midlatitude predictability are active in fall, such as extratropical cyclones

81   with intense fronts and warm conveyor belts (WCBs), carrying air from the oceanic boundary

82 layer into ridges at the tropopause level. There is also the possibility of North Atlantic tropical

83 cyclones (TCs) recurving poleward into midlatitudes and undergoing extratropical transition

84 (ET) – a process known to be associated with low predictability (Harr et al. 2008). Coherent

85 mesoscale depressions of the tropopause, known as tropopause polar vortices (TPVs, Cavallo

86 and Hakim 2010; Kew et al. 2010), can disturb the jet stream if they move equatorward from

87 the Arctic.

88 NAWDEX contributes to the World Weather Research Program (WWRP) and its High

89 Impact Weather project (Jones and Golding 2015), and aims to provide the observational

90 foundation for further investigating cloud diabatic processes and radiative transfer in North

91 Atlantic weather systems, which will form the basis for future improvements in the prediction

92 of HIW over Europe.

93 **THE ROLE OF DIABATIC PROCESSES.** Weather in Europe strongly depends on the

94 life-cycle of Rossby waves that propagate along the slowly varying part of the North Atlantic

95 jet stream (Martius et al. 2010). The strong meridional potential vorticity (PV) gradient

96 associated with the jet stream serves as a waveguide for propagating Rossby waves.

97 Frequently, small disturbances in the jet entrance region over eastern North America grow in

98 baroclinic weather systems and evolve into large-amplitude features in the European sector

99 (Schwierz et al. 2004). Figure 1 portrays an idealized North Atlantic flow situation that could

100 result in HIW in the form of high winds and heavy precipitation over northern Europe. In

101 addition to Rossby waves amplifying through baroclinic instability, diabatic processes are

102 able to modify upper-tropospheric PV at the level of the midlatitude jet stream, which impacts

103 the wavelength and amplitude of the downstream Rossby wave development (e.g., Massacand

104 et al. 2001; Knippertz and Martin 2005; Grams et al. 2011; Teubler and Riemer 2016).

105 The majority of precipitation and cloud diabatic processes in extratropical cyclones occur

106 within a coherent airstream known as the WCB. It carries warm, moist air from the low-level

warm sector of a cyclone to the ridge at tropopause level within 1-2 days (Browning et al. 1973; Carlson 1980; Wernli and Davies 1997). The boundary layer humidity in the inflow of WCBs (Region 1 in Fig. 1) can impact the outflow height of WCBs (Schäfler and Harnisch 2015). For some WCBs, the inflow region coincides with a filament of strong horizontal water vapor transport, a so-called "atmospheric river", which can contribute to intense rain in the midlatitudes (Lavers and Villarini 2013). During the ascent of WCBs (Region 2 in Fig. 1), latent heating due to cloud microphysical processes, embedded convection and turbulent fluxes influence the level of the outflow layer, the direction taken by outflow air masses, and the shape of the upper-level ridge (Martínez-Alvarado et al. 2014; Joos and Forbes 2016). The latent heating in WCBs is strong both in the early phase of the ascent when condensation dominates and later when mixed-phase clouds are formed and vapor deposition on ice crystals and snow becomes important (Joos and Wernli 2012).

The effect of the heating on the PV structure is to produce a positive PV anomaly in the lower troposphere (Wernli and Davies 1997), which influences the structure and evolution of midlatitude surface cyclones (e.g., Kuo et al. 1991; Davis et al. 1993; Binder et al. 2016). Above the level of maximum latent heating, PV is reduced by cloud diabatic processes leading to negative PV anomalies in the upper-tropospheric WCB outflow region (Wernli 1997; Pomroy and Thorpe 2000; Madonna et al. 2014; Methven 2015). The divergent outflow winds (Region 3 in Fig. 1) tend to amplify the upper-level downstream ridge and to intensify the jet stream by strengthening the PV gradient (Archambault et al. 2013). If the outflow layer is higher, the negative PV anomaly is stronger and more air mass enters the anticyclonic branch of the WCB flowing into the downstream ridge (Grams and Archambault 2016). In addition, a sharp peak in longwave radiative cooling near the tropopause, associated with a step change in water vapor, creates a reinforcement of the positive PV anomaly in upper-level troughs (Chagnon et al. 2013) and plays a key role in maintaining and strengthening TPVs (Cavallo and Hakim 2012).

133   Diabatic processes also play a key role in weather systems that act as triggers to disturb

134   the midlatitude waveguide. Recurving TCs undergoing ET (Jones et al. 2003) can enhance the

135   anticyclonic and divergent flow at upper levels, excite and amplify Rossby waves and cause

136   downstream forecast errors, as well as HIW events (e.g., Agusti-Panareda et al. 2004; Harr et

137   al. 2008; Riemer and Jones 2010). Radiatively maintained TPVs, which are positive PV

138   anomalies above the tropopause, can disturb the Rossby waveguide from polar latitudes.

139   Rossby wave breaking leads to PV filamentation, forming smaller-scale PV anomalies

140   such as PV streamers and cut-off vortices. They form frequently over the eastern North

141   Atlantic and Europe (e.g., Wernli and Sprenger 2007), and several studies have reported their

142   relevance for triggering HIW, in particular heavy precipitation (e.g., Martius et al. 2006;

143   Chaboureau and Claud 2006; Grams and Blumer 2015). Synoptic wave breaking events are

144   also important for the large-scale flow itself as they reinforce weather regimes such as

145   blocking ridges (Michel and Rivière 2011; Spensberger and Spengler 2014). Blocks are also

146   strongly influenced by diabatic processes in air masses ascending from the lower troposphere

147   (Pfahl et al. 2015).

148   Disturbances of the waveguide and associated errors can amplify and propagate

149   downstream, and may cause significant forecast errors over Europe (Madonna et al. 2015;

150   Martínez-Alvarado et al. 2016) (Region 4 in Fig. 1). In NWP models, diabatic processes such

151   as those associated with convection, cloud microphysics and radiation are represented by

152   parameterizations of varying degrees of fidelity and may contain both systematic and random

153   errors that influence forecast skill. A distinct Rossby wave pattern associated with poleward

154   transport of warm and moist air over the eastern US and strong diabatic activity has been

155   identified as a common precursor 6 days before the worst forecast busts over Europe

156   (Rodwell et al. 2013). Upscale error growth experiments in numerical models show that the

157   growth of small-scale perturbations is initially confined to regions where condensation is

158   occurring, with the regions of large error amplitude gradually expanding to affect the

159 synoptic-scale weather pattern (Zhang et al. 2007; Selz and Craig 2015). Doyle et al. (2014)

160 found forecasts of an extratropical cyclone with severe impact in western Europe to be very

161 sensitive to the initial low-level moisture, which influenced the moisture supply in a WCB. At

162 upper levels, global NWP models fail to maintain a sufficiently sharp tropopause, showing a

163 decrease in sharpness with forecast lead time (Gray et al. 2014). This influence on the

164 waveguide can have major implications for the representation of the downstream propagation

165 and amplification of Rossby waves in NWP (Harvey et al. 2015) and the associated prediction

166 of HIW.

167 Previous studies using measurements to study the influence of diabatic processes on the

168 Rossby waveguide have been primarily based on routinely collected observations by

169 operational meteorological services. These observations rely largely on satellite data, which

170 models predominantly assimilate in cloud-free areas, and on sparse in situ measurements, all

171 of which are combined in the data assimilation system using model forecasts as a background

172 estimate. This approach to studying diabatic processes has significant limitations since these

173 processes tend to be strongest in cloudy and precipitating regions, which are particularly

174 challenging for both observation and modeling systems. The processes associated with

175 diabatic heating are characterized by a high-degree of small-scale variability, particularly in

176 the vertical (e.g., sharp vertical gradients of cloud microphysical processes and their

177 interactions with radiative forcing), which are typically poorly resolved by satellite and

178 conventional in situ observations. Furthermore, rapid error growth and systematic model

179 errors lead to large errors in the background forecast in precisely these regions, which are

180 poorly characterized by error covariance matrices based on climatology and/or sampling using

181 an ensemble of limited size. A field campaign has the potential to address some of these

182 difficulties by deploying specialized observing systems with high resolution and the ability to

183 measure both in and around clouds.

184   NAWDEX was proposed with the overarching hypothesis that diabatic processes have a

185   major influence on the jet stream structure, the downstream development of Rossby waves,

186   and eventually HIW. Specific science goals were formulated (Table 1), which require

187   observations of moisture advection in the boundary layer and of the vertical distribution of

188   stability, water vapor, liquid droplets and ice crystals. These observations will be used to

189   investigate spatial variability within clouds and the implications for diabatic processes.

190   Detailed wind measurements in the layer of the divergent outflow of the WCB are needed to

191   investigate the interaction of diabatically modified air masses with the upper-level jet. This

192   includes observations of horizontal and vertical gradients of wind, temperature and humidity

193   as well as hydrometeors in clouds. Accordingly, high-resolution cross-sections of wind,

194   temperature and humidity from the lower stratosphere down to the surface, inside and outside

195   of clouds, are the central observational requirement, which are not available from

196   conventional observations.

197   **EXPERIMENTAL DESIGN AND OBSERVATIONS.** The need for a new field

198   experiment emerged from a series of campaigns coordinated by the World Meteorological

199   Organization's program THORPEX (The Observing-System Research and Predictability

200   Experiment, Parsons et al. 2017). This series includes the Atlantic THORPEX Regional

201   Campaign (ATReC, Rabier et al. 2008), Winter Storm Reconnaissance (WSR, e.g., Szunyogh

202   et al. 2000), the THORPEX Pacific Asian Regional Campaign (T-PARC, Weissmann et al.

203   2011), and the Convective and Orographically induced Precipitation Study/European

204   THORPEX Regional Campaign (COPS/ETReC 2007, Wulfmeyer et al. 2011), which all

205   focused on the impact of additional observations on improving forecast accuracy. This idea

206   was pioneered by the Fronts and Atlantic Storm Track Experiment (FASTEX) in 1997 (Joly

207   et al. 1999) where the concept of targeting observations using sensitive area calculations was

208   introduced. The synthesis of these campaigns and data assimilation experiments denying

209   observations in data rich areas showed that the impact of targeted observations on global

210 forecast systems is weaker than originally anticipated, although they improve forecasts on

211 average (see review of Majumdar (2016)). At the same time, as discussed above, evidence

212 was growing that forecast errors often originate in regions where diabatic processes are

213 strong, and observation and modeling systems are least reliable. This provided the motivation

214 for a new campaign, NAWDEX, that rather than targeting regions of forecast sensitivity,

215 instead focused on observing the processes that are thought to be most uncertain in NWP

216 models.

217 Diabatic processes are difficult to measure directly, but can be constrained via their

218 observable effects on the structure and evolution of weather systems. In the decade before

219 THORPEX, detailed diagnostic case studies using aircraft measurements (e.g., ERICA

220 (Experiment on Rapidly Intensifying cyclones over the Atlantic, Hadlock and Kreitzberg

221 1988) and FASTEX) had already shown that diabatic processes, in particular diabatic heating

222 and cooling, can impact the large-scale dynamics via PV modification (Neiman et al. 1993;

223 Pomroy and Thorpe 2000). However, the processes are difficult to accurately quantify since

224 they depend on fine-scale structures (e.g., large gradients) in the water vapor and cloud fields

225 and are influenced by transport and mixing over a wide range of spatial and temporal scales

226 throughout the lifetime of the cyclone (recall Fig. 1). Two single-aircraft field campaigns

227 organized within THORPEX explored how aircraft observations could be used to accurately

228 constrain the impact of diabatic heating in midlatitude cyclones. DIAMET (DIAbatic

229 influence on Mesoscale structures in ExTratropical storms; Vaughan et al. 2015) made

230 airborne in situ measurements of liquid droplets and ice crystals and used them to infer the

231 microphysical processes acting, their positions relative to mesoscale structures (such as fronts

232 and PV anomalies), and their role in the weather system dynamics. Although the observations

233 were limited to the 1-D aircraft flight path, they provided a basis for the modeling studies of

234 Dearden et al. (2014), who obtained estimates of heating rates from various microphysical

235 processes represented by a Lagrangian model initialized with in situ observations of size

236 distributions for cloud droplets and ice particles. However, using a model to extrapolate the

237 measurement information in space and time represents an additional source of uncertainty in

238 the quantification of the processes. The THORPEX-NAWDEX-Falcon project (Schäfler et al.

239 2014) attempted to constrain this uncertainty by carrying out in situ observations of clouds,

240 humidity and wind in ascending WCBs, and trying to re-sample the same air masses at a later

241 time to obtain a Lagrangian estimate of integrated diabatic effects. NAWDEX was conceived

242 to expand upon the design of these previous experiments by combining high resolution remote

243 sensing and in situ instrumentation to provide accurate measurements of atmospheric

244 structures including strong gradients, using multiple aircraft to sample air masses at different

245 stages of the WCB ascent and advection along the tropopause.

246   To allow these observations to be related to the development of weather forecast errors,

247 NAWDEX employed four research aircraft and ground-based stations spanning the northern

248 part of the North Atlantic with the aim of observing the processes influencing the

249 development of disturbances to the North Atlantic waveguide across the Atlantic. This

250 includes upstream triggering of disturbances on the waveguide by phenomena with strong

251 latent heat release, the continuous effects of clouds and radiation near the tropopause, the

252 dynamical interactions between large-scale disturbances, and the potential impact on weather

253 over Europe from the Mediterranean to Scandinavia.

254   ***Airborne platforms and payload.*** NAWDEX employed four research aircraft, the German

255 High Altitude and LOng Range Research Aircraft (HALO) and the Deutsches Zentrum für

256 Luft- und Raumfahrt (DLR) Dassault Falcon 20, the French Service des Avions Français

257 Instrumentés pour la Recherche en Environnement (SAFIRE) Falcon 20, and the British

258 Facility for Airborne Atmospheric Measurements (FAAM) BAe 146. FAAM operated from

259 the UK and HALO and the two Falcon aircraft from Keflavik, Iceland, in an area covering the

260 North Atlantic, north of 45° N, and northern and central Europe. The payloads were chosen to

261 observe the required profiles of wind, temperature, moisture and cloud properties, and in the

262 case of FAAM, in situ cloud microphysics.

263   The strategy was to deploy HALO with its extended range to observe moisture transport

264 and diabatic processes in weather systems upstream of Iceland that impact the midlatitude

265 waveguide. HALO is a modified Gulfstream G-550 ultra-long-range business jet with a

266 maximum flight range of about 10000 km and a maximum endurance of 10 hours

267 (Krautstrunk and Giez 2012; Wendisch et al. 2016), which allows accessing remote regions

268 over the central North Atlantic that are not accessible by other European research aircraft. The

269 high ceiling of almost 15 km in combination with a sophisticated remote-sensing payload (see

270 sidebar and Table 2) allow HALO to fly above the main commercial aircraft routes and to

271 probe features of interest from above. The two Falcon aircraft, with a maximum range of 3000

272 km, a maximum endurance of about 4 hours and a ceiling up to 12 km, aimed to observe the

273 approaching cyclones and evolving jet streams close to Iceland. The DLR Falcon was

274 equipped with two wind lidar systems and the SAFIRE Falcon with a remote-sensing payload

275 for clouds and winds (sidebar and Table 2). The FAAM BAe 146, with a maximum endurance

276 of 5 hours and a ceiling of 10 km, was equipped with a range of in situ instrumentation for

277 meteorological, cloud and chemical measurements together with a downward-pointing aerosol

278 lidar and passive spectral radiometers. Its flights from East Midlands, UK, were aimed at

279 observing microphysics and turbulence in WCBs and the structure of the jet stream.

280   HALO, SAFIRE and the FAAM aircraft were equipped with dropsonde dispensers to

281 measure air temperature, wind and humidity profiles. Global NWP centers could access the

282 dropsonde data from HALO and SAFIRE via the Global Telecommunication System in near

283 real-time. The potential for coordinated application of the various instruments on board

284 multiple aircraft was realized through specific instrument-driven science goals (Table 1 and

285 sidebar). Table 2 indicates which of the research aims listed in Table 1 are addressed by each

286 instrument.

287   In parallel to NAWDEX, the NOAA (National Oceanic and Atmospheric Administration)

288   SHOUT (Sensing Hazards with Operational Unmanned Technology) campaign took place in

289   the tropical and subtropical western North Atlantic. SHOUT utilized the unmanned NASA

290   Global Hawk aircraft with a suite of remote-sensing platforms and dropsondes to study the

291   impact of the observations on TC forecasts. During the campaign, a tropical storm (TS)

292   moved into the midlatitudes and underwent ET, providing an unprecedented scientific

293   opportunity to observe the interaction of such a system with the jet stream using a

294   combination of upstream flights with the SHOUT Global Hawk and downstream flights with

295   NAWDEX aircraft.

296   **[Place Sidebar 1 here: Active remote-sensing observations for future satellite missions**

297   **Aeolus and EarthCARE]**

298   *Airborne observations.* NAWDEX observations took place in the North Atlantic basin

299   between 17 Sep and 22 Oct 2016. Figure 2 shows the tracks of the 47 research flights of the

300   four aircraft, together amounting to 205 flight hours. Performing research flights over the

301   North Atlantic is complicated because of the dense trans-Atlantic air traffic. Commercial

302   airliners are tightly staggered along predefined flight routes, the so-called North Atlantic

303   Tracks (NATs), between altitudes of 9 and 12 km. Operating research aircraft beneath the

304   NATs offers high flexibility for the flight planning; however, the base height of the NATs is

305   often too low to observe the tropopause and jet-related maximum wind speeds. Furthermore

306   the location of the NATs changes from day to day, depending on the forecast wind situation.

307   Height changes and the release of dropsondes from high altitudes are not possible in the NAT

308   area. The requirement of air traffic control (ATC) authorities to have detailed flight plans 2-3

309   days in advance created challenging circumstances in weather situations with reduced

310   predictability, i.e., in situations with large changes between subsequent forecasts. Therefore,

311   NAWDEX combined modern forecasting tools including ensemble and adjoint-based

312 diagnostics, and new visualization techniques to incorporate forecast uncertainty in the

313 planning process (see sidebar on forecast products).

314   HALO covered large parts of the central and eastern North Atlantic and reached flight

315 distances up to 7150 km (~9 h). The flights were performed either at altitudes between 11.5

316 and 14.2 km above the NATs for remote-sensing observations or at ~8 km to release

317 dropsondes beneath the NATs. The two Falcon aircraft remained in radar-controlled air

318 spaces near Greenland, Iceland and the UK. The FAAM BAe 146 flights were north and west

319 of the UK. A total of 289 dropsondes were released (Fig. 3a).

320 **[Sidebar 2: Forecast products to investigate forecast uncertainty]**

321   The research flights occurred within 13 Intensive Observation Periods (IOPs), which were

322 consecutively numbered and had a duration of 1-6 days. Each IOP was associated with a

323 particular weather system development and addressed one or more NAWDEX science

324 objectives (Table 3). For easier communication, the IOPs were given names, which either

325 correspond to the cyclone naming of the Free University of Berlin or the National Hurricane

326 Center, or were invented by the NAWDEX team (Table 3). Some IOPs overlap in time when

327 different weather systems were observed simultaneously by the different aircraft.

328   To exploit instrument synergies and enable direct instrument comparisons, coordinated

329 flights were performed, i.e., the same air mass was near-simultaneously probed by different

330 aircraft on common flight legs. In total, 16 coordinated legs, with a total flight time of 14.5 h

331 and a distance of about 10000 km, were achieved. The longest coordinated leg with the

332 SAFIRE Falcon and HALO on 14 Oct 2016 had a distance of 1365 km (1.8 h). On two

333 occasions the coordination involved three aircraft: HALO and the two Falcons flew together

334 for ~30 min (~300 km) on 9 Oct between the UK and Iceland, and on 14 Oct, FAAM, HALO

335 and the SAFIRE Falcon had a common leg between the Faroe Islands and Scotland (55 min,

336 570 km).

337 ***Ground-based facilities and observations.*** During several IOPs additional ground-based

338 observations were taken to complement the aircraft operations and to enhance the temporal

339 and spatial coverage of routine observations. In total 589 additional radiosondes from 40

340 stations in 14 countries were launched (Fig. 3b and Table 4). Of these launches, 253 were

341 achieved through the cooperation of national meteorological agencies in the European

342 Meteorological Services Network (EUMETNET), complemented by additional radiosondes

343 from Iceland, UK, France and Norway. Launches from land stations or commercial ships

344 were requested daily depending on the predicted evolution of weather systems. Furthermore,

345 two additional radiosondes were launched daily during the campaign from six stations in

346 eastern Canada, upstream of the main NAWDEX area (336 in total).

347   Special ground-based observations were conducted in Iceland, the UK and France (Fig.

348 3b). At Keflavik airport, a radiosonde facility was set up by DLR to increase the frequency of

349 the operational soundings. In cases of orographically induced gravity waves (GWs), large

350 balloons were launched to reach altitudes up to 42 km. Also in Keflavik, a Doppler cloud

351 radar BASTA (Delanoë et al. 2016) allowed several comparisons with its airborne counterpart

352 on board the SAFIRE Falcon during overflights. In the UK, a mesosphere–stratosphere–

353 troposphere (MST) radar, Raman lidar, and radiosondes were operated at Capel Dewi

354 (Wales), together with another MST radar wind profiler at South Uist (Scotland).

355 Additionally, the MST radar at Andøya, Norway, measured tropospheric winds upon request.

356 Two observational sites were active in France during the campaign. The site in Lannion

357 (Brittany) operated a wind profiler, the BASTA Doppler cloud radar and a GPS station. The

358 Site Instrumental de Recherche par Télédétection Atmosphérique (SIRTA) near Paris

359 (Haeffelin et al. 2005) operated radar and lidars, and launched radiosondes.

360 **METEOROLOGICAL CONDITIONS.** The fall of 2016 was a favorable period for

361 observing midlatitude weather over the North Atlantic. The average synoptic situation for the

362 campaign period was characterized by an increased frequency of relevant weather systems

363 compared to climatology (Fig. 4). One of the most prominent features was a long-lasting

364 blocking high and surface anticyclone covering large parts of Scandinavia (Fig. 4a).

365 Extratropical cyclones occurred more frequently than normal south of Iceland and Greenland

366 (Fig. 4b), in the core area of airborne NAWDEX observations. Consistent with the increased

367 frequency of cyclones relative to climatology, the WCB frequency (Fig. 4c) shows increased

368 activity over large parts of the North Atlantic. During the campaign, a succession of events

369 with poleward transport of warm air and ascent of low-PV air into the upper troposphere was

370 observed that appeared to strengthen the downstream anticyclonic anomaly. Most midlatitude

371 cyclones (Fig. 4d) approached Iceland from the southwest, which was favorable for reaching

372 them with Falcon flights from Keflavik. Only a small fraction of the extratropical cyclones

373 moved into central and northern Europe. Six TS occurred during NAWDEX. Ian (12-16 Sep),

374 Julia (13-16 Sep), Karl (14-25 Sep) and Lisa (19-25 Sep) did not exceed TS strength, while

375 Matthew (29 Sep-9 Oct) and Nicole (4-18 Oct) were classified as major hurricanes. Ian, Karl

376 and Nicole underwent ET and moved far into the midlatitudes. TPVs originating over the

377 Canadian polar region were observed twice when they moved southward over the Davis Strait

378 and interacted with the midlatitude waveguide.

379   North Atlantic weather regimes during NAWDEX show Scandinavian blocking to be the

380 dominant regime (blue line in Fig. 5a), corresponding to the anomalous anticyclone activity

381 over northern Scandinavia (Fig. 4a). In late September the block decayed and a short period

382 with a positive North Atlantic Oscillation (NAO) prevailed before the Scandinavian blocking

383 pattern was again established.

384   A broad measure of forecast quality during NAWDEX is provided by the anomaly

385 correlation coefficient (ACC) of the mid-tropospheric geopotential height pattern over the

386 eastern North Atlantic as predicted by the ECMWF Integrated Forecasting System (IFS) in

387 fall 2016 (Fig. 5b). Periods of increased 120-h forecast errors and high spread in the ensemble

388   forecasts are evident, and four of these periods were directly relevant to NAWDEX. Three

389   periods of reduced forecast skill (23 to 27 Sep, 29 Sep to 3 Oct and 5 to 10 Oct) occurred

390   during NAWDEX and two periods of the four were accompanied by a weather regime

391   transition (Fig. 5a). Forecast uncertainty was high on 26 Sep during the onset of a positive

392   NAO phase, and on 1 Oct during the return to the Scandinavian blocking regime. High

393   uncertainty also occurred prior to the campaign, for forecasts initialized between 10 and 14

394   Sep, again covering a regime transition to Scandinavian blocking. This period affected

395   NAWDEX as it complicated the planning of the transfer flight to Keflavik (IOP 1) five days

396   later.

397   The progression of weather systems across the North Atlantic during NAWDEX can be

398   conveniently described as a storyline characterized by *upstream triggers*, their dynamic

399   *interaction* with the jet stream, *subsequent development* of disturbances, and downstream

400   *weather impacts* over Europe. Three such sequences occurred completely within the

401   NAWDEX period, and their timespan is indicated by dark grey shading in Fig. 5. In each

402   case, low predictability was found in 5-day forecasts for the eastern North Atlantic initialized

403   within the *trigger* stage (marked by a drop in forecast skill in Fig. 5b), while the final *impact*

404   stage was associated with significant changes in the weather over Europe at the verification

405   time 5 days later. The snapshots for each sequence in Fig. 6 show that the interaction of the

406   trigger disturbance with the waveguide featured intensification of a surface cyclone, with a

407   diabatic contribution consistent with the first three regions identified in the conceptual model

408   presented in Fig. 1. However, the subsequent development and impact stages differed

409   markedly, with the pattern of low PV in the downstream ridge affecting weather even further

410   downstream than suggested by region 4 of Fig. 1. The temporal continuity between the

411   snapshots in Fig. 6 is shown by labeling several coherent long-lived features (identified in the

412   caption). Prominent ridges (R1-R9) along the North Atlantic waveguide are identified as

northward excursions of the jet stream (and the PV gradient). Since each ridge is characterized by low PV air, the associated flow tends to be anticyclonic.

Sequence A is *triggered* by TS Karl leaving the subtropics and moving northwards into the midlatitudes (Fig. 6, panel A.1). Large ensemble spread and changes between consecutive forecast runs showed that the subsequent evolution was very sensitive to uncertainties in the location and timing of the interaction of Karl with ridge R2, the trough upstream, and the associated weak surface cyclone (not shown). The *interaction* that took place was a merging of Karl with a low-level cyclone, leading to rapid re-intensification and the formation of a cyclonic hook at tropopause level separating ridge R2 from the new ridge R3 (Fig. 6 A.2). The ridge-building is intensified by diabatically produced low PV in the WCB outflow. Hence in the subsequent *development*, the jet stream is unusually strong on its southern flank, forming a jet streak that propagates ahead from Karl reaching Scotland the following day (Fig. 6 A.3). The *impact* on European weather occurs through the formation of a new cyclone Walpurga (W in Fig. 6 A.4), which develops to the west of ridge R3 helping to amplify it. Moisture laden air on the western flank of ridge R3 is drawn around the subtropical high. During IOP 5, HALO observed the moist boundary layer in this atmospheric river type flow that extends to Norway where it causes heavy, persistent rainfall, similar to the case studied in Sodemann and Stohl (2013).

Sequence B begins as sequence A ends, in a southwesterly flow situation with a long PV streamer that formed through the merger of the trough west of R3 and the large cut-off feature C (Fig. 6 A.3-A.4). The *trigger* for this sequence appears to follow from the vortex roll-up of the streamer through shear instability, resulting in a new cut-off over Newfoundland (V in Fig. B.1), which then *interacts* and merges with a large-scale trough west of R5 advancing rapidly from the northwest. Note that ridge R5 and its upstream trough wrap up cyclonically during the development so that the trough catches up with the cut-off to the south of R5. The tropopause was very low just in the very center of this system, which therefore has been

439   named the "stalactite cyclone" (St in Fig. 6 B.2). In the *development* stage, a second cyclone

440   (F in Fig. 6 B.3) intensified rapidly between ridge R6 and the trough to its west. The poleward

441   moving air in R6 crossed Iceland and reinforced the anticyclonic anomaly formed by ridge R5

442   of the stalactite cyclone. The *impact* of the sequence comes not as a classical severe weather

443   event, but through the establishment of a strong blocking anticyclone over Northern Europe,

444   which persisted for the next two weeks.

445   Sequence C begins with two upstream *triggers*. A TPV originating in the Canadian Arctic

446   is carried rapidly southeastward on the poleward flank of the jet stream (T in Fig. 6 B.4 and

447   C.1). It is hypothesized that the TPV locally enhanced the cyclonic circulation about the tip of

448   the large-scale trough (T in Fig. 6 C.1), which eventually wrapped cyclonically over Iceland

449   (Fig. 6 C.2). At the same time the remnants of cut-off C appear to be associated with the

450   emergence of a small surface cyclone, which has been named "Sanchez" (S in Fig. 6 C.1).

451   The European dipole block (cf. Rex et al. 1950) is well established at this time so that the

452   ridge R8 and the cyclonic PV anomaly over Iceland are held stationary and a PV filament

453   forms in the deformation region on their western side. The filament is unstable and

454   experiences vortex roll-up, forming three tropopause-level cyclonic vortices. The key

455   *interaction* in this sequence occurs as the low-level cyclone Sanchez passes the southernmost

456   cut-off, but then phase-locks with the central cut-off resulting in baroclinic intensification (S

457   in Fig. 6 C.2). As the sequence *develops*, the resulting cut-off cyclone progresses slowly

458   eastwards (Fig. 6 C.3) and is responsible for some of the most dramatic high *impact* weather

459   during NAWDEX, with heavy precipitation and flooding across southern France and

460   northwestern Italy in the southerly flow ahead of it (Fig. 6 C.4). But this HIW is not the only

461   significant outcome of Sequence C. Returning to stage C.2, ridges R8 and R9 are similar in

462   horizontal extent, but the tropopause is much higher above R9 than R8 (not shown) with the

463   result that the anticyclonic circulation induced by R9 is stronger and R8 is stretched out

464   meridionally between R6 and R9 (Fig. 6 C.3). As NAWDEX draws to a close, the ridge R9

465 extends rapidly into the Arctic, reinforcing the block and forming a PV anomaly in the shape

466 of the Icelandic character Þ (the first letter of Þor - pronounced Thor - the ancient Norse god

467 of HIW).

468   It is important to note that the large-amplitude ridge building leading to the Thor block is

469 not R8, which developed as part of the interaction phase of Sequence C, but rather R9,

470 associated with a second cyclone that develops to the west (and which may play a role in the

471 cut-off of Sanchez). Indeed for all three sequences, the development stage leading to weather

472 impacts over Europe appears to be associated with a second cyclone that forms in an

473 environment modified by the interaction of the trigger disturbance with the midlatitude flow,

474 and whose development is difficult to predict because of the low predictability of the

475 environment.

476 **HIGHLIGHTS OF NAWDEX.** Observations in NAWDEX were organized in IOPs that

477 focused on key weather systems involved in the longer sequences (Table 5). Several of these

478 IOPs are unprecedented in terms of the phenomena that were sampled or the comprehensive

479 coverage and multi-faceted nature of the measurements. While the analysis of the data is just

480 beginning, a first impression of the results can be obtained from four highlights that illustrate

481 the unique sets of multi-platform and multi-instrument observations that were obtained.

482 *Extratropical transition of TS Karl.* The evolution of TS Karl is the central feature of

483 Sequence A discussed above and IOP 4. It was the first extratropical transition sequence that

484 has been observed with research aircraft through at all stages of development, including TS

485 status, ET, re-intensification with impacts on jet stream strength, moisture transport and

486 downstream HIW (Table 5). By flying over the TS and its northwestern flank twice, the

487 SHOUT Global Hawk observed the development stage that occurred far south of the

488 midlatitude jet stream on 22/23 Sep (Fig. 7a), and the ET phase on 24/25 Sep (Fig. 7b). On 26

489 Sep, HALO observed the interaction with the waveguide and re-intensification phase of the

490   storm by flying over the cyclone center (Fig. 7c), WCB ascent, the low-valued PV air in the

491   WCB outflow and the dry intrusion (not shown). When Karl moved rapidly towards Scotland,

492   decaying in strong horizontal shear on 27 Sep, IOP 5 focused on the intense jet streak at

493   tropopause level and the strong moisture transport along the equatorward side of the jet with a

494   combination of HALO, FAAM and DLR Falcon flights (Fig. 7d).

495   IOP 4 will contribute to answer several of the posed research questions (see Table 1 and

496   3). The large number of dropsonde and special radiosonde measurements that were

497   assimilated into operational forecasts in real-time will provide a basis for observational

498   impact and predictability studies. Detailed airborne remote-sensing observations will allow

499   examination of the role of diabatic processes and their representation in numerical models.

500   Both the synergies of the instruments and the storm-following observational strategy give

501   unprecedented information about this intense and long-lived cyclone and a unique opportunity

502   to analyze forecast error growth due to in situ processes vs. downstream propagation.

503   *Cloud physics in a WCB*. IOP 3 focused on observing the vertical cloud structure and cloud

504   microphysical processes in a WCB that was related to the midlatitude cyclone Vladiana south

505   of Iceland and west of Scotland on 23 Sep 2016 (Fig. 7a and Table 5). The WCB transported

506   moist air northeastward just west of the UK as indicated by the low-valued PV air in the upper

507   troposphere (Fig. 8a).

508   HALO first stayed beneath the NATs at altitudes of ~8 km on the way to the

509   southwestern-most point of the flight (white circle) to begin the first of three sections across

510   the WCB. On this leg to Ireland, 12 dropsondes were released before HALO climbed to ~13

511   km in Irish airspace. Over northern Ireland, HALO and FAAM joined to perform coordinated

512   remote-sensing and in situ observations of the WCB. HALO measured the WCB by remote-

513   sensing from above while FAAM performed 4 in situ legs at different altitudes to measure

514   cloud-microphysical parameters inside the WCB. After the coordinated leg, HALO crossed

515   the WCB a third time and observed the outflow of the WCB between Scotland and Iceland.

516   Figure 8 focuses on the first and second crossing of the WCB. The WALES lidar

517   measured water vapor profiles throughout the troposphere and lower stratosphere in the

518   absence of clouds (Fig. 8b). At the western side of the cross-sections, where HALO was

519   located on the stratospheric side of the waveguide, the post-frontal troposphere was cloud-free

520   except for boundary layer clouds reaching up to 2 km. The water vapor shows high

521   variability, which portrays the dynamically modulated transport of moisture related to cyclone

522   Vladiana. On both crossings of the waveguide, one west-to-east and one east-to-west, a tilted

523   dry layer is visible at altitudes between 5 and 9 km (1110-1125 and 1305-1325 UTC), related

524   to a dry intrusion west of the low-level cold front. The wedge-shaped moist layer on top is

525   associated with high moisture values in the WCB outflow. The second crossing at high

526   altitudes depicts a strong vertical moisture gradient, on top of the elevated moist layer, that

527   marks the tropopause and extends further east into the area where WCB clouds reach high

528   altitudes. A decrease of the tropopause height is detected towards the west on the second leg.

529   The radar shows two vertically (~11.5 km) and horizontally (~400 km) extended and coherent

530   clouds (Fig. 8c) representing the double crossing of the WCB. In between, i.e., on the eastern

531   side of the WCB, cloud tops are lower and the clouds are intermittent. The sharp vertical

532   gradient in radar reflectivity at about 3 km altitude marks the melting layer.

533   On the second transect the FAAM aircraft performed in situ measurements on flight legs

534   beneath HALO (Figs. 8b,c). HALO met FAAM at the beginning of its second WCB leg

535   (purple diamond marker in Fig. 8c) where FAAM started its lowest leg at about 3 km altitude,

536   just above the melting layer, with subsequent legs at 4, 6 and 7.5 km. The in situ observations

537   show that both mixed-phase and ice-only clouds were encountered during the low-level run,

538   but during the high-level runs only ice was observed. The ice water content (IWC) in the

539   WCB shows maximum values of 0.4 g m^{-3} on the lowest two legs (Fig. 8d). Ice images show

540 large differences in the form of the particles at different altitudes. On the lowest leg, large

541 aggregates (~6 mm) dominate close to the freezing level, while on the highest level higher

542 concentrations of small irregularly shaped crystals (< 1 mm) prevail.

543   HALO also observed the interaction of Vladiana's WCB outflow with the jet stream in

544 coordination with the DLR Falcon (not shown). IOP 3 contributes to all research aims (Table

545 3) and future work on the cloud microphysics observations will investigate, e.g., the

546 correlation of increased IWC with particularly high radar reflectivity. Data from liquid and ice

547 particle size distributions will be used to improve the retrieval of cloud properties from the

548 HALO remote-sensing instruments. Overall, this is a unique set of comprehensive and

549 complementary airborne observations of a WCB, its embedded microphysical processes and

550 its outflow interaction with the jet stream.

551 ***Wind observations in the jet stream and outflow of a WCB.*** Figure 6 (panel B.2) shows the

552 stalactite cyclone that formed previously via merging of two near-surface vorticity maxima

553 with a very intense, small-scale, upper-level PV anomaly south of Newfoundland (not

554 shown). The rapid development of the cyclone occurred in the mid-Atlantic between 30 Sep

555 and 2 Oct. On 2 Oct (IOP 6), a coordinated flight of the DLR and SAFIRE Falcons observed

556 WCB ascent and outflow when the stalactite cyclone was most intense (Fig. 9a). The aircraft

557 flew together to intersect the jet stream on the northwestern edge of ridge R5 wrapping

558 cyclonically around the stalactite cyclone. On a common leg between Iceland and Greenland

559 both aircraft crossed the jet stream (Fig. 9b) and made complementary wind observations

560 (Figs. 9c,d). The DWL lidar on the DLR Falcon observed two wind maxima up to 50 m s^{-1} in

561 cloud-free regions and in optically thin cirrus in the WCB outflow. Complementarily, the

562 SAFIRE radar observed in-cloud winds in the region of WCB ascent in the mid and lower

563 troposphere. Only in dry and aerosol-poor air masses over Greenland, i.e., on the stratospheric

564 side of the waveguide, the combination of both instruments provides poor data coverage. The

565 SAFIRE Falcon released 9 dropsondes when crossing the jet stream, yielding further profiles

566 of winds, temperature and moisture.

567 Future research on IOP 6 will be mainly dedicated to predictability issues associated with

568 the blocking formation downstream of the cyclone. The block formed at the time when a loss

569 of predictability in the ECMWF forecasts occurred (Fig. 5b). Winds measured by the two

570 aircraft will help to characterize the role of the WCB outflow in the ridge building. The

571 observed high winds and strong vertical gradients were repeatedly observed on flights across

572 the jet stream with observed maxima up to 80 m s^{-1} and often related to strong vertical wind

573 speed gradients up to 30 m s^{-1} km^{-1}. A unique aspect of this example is the benefit of

574 coordinated flights with complementary instruments to address one the key objectives of

575 NAWDEX (Table 1 and 3) – observing the strong wind shear and PV gradients near a WCB

576 outflow.

577 ***HIW related to cut-off cyclone Sanchez.*** Cut-off Sanchez was initiated in the central North

578 Atlantic and reached southern Europe between 12 and 14 Oct 2016 (Fig. 6, Seq. C). On its

579 leading edge moisture was advected northward (Fig. 10a) on 13 Oct when it triggered heavy

580 precipitation and strong winds over France and Italy. The 24-hour accumulated precipitation

581 in the Herault region reached ~250 mm (Figs. 10b), and wind gusts exceeding 100 km h^{-1}

582 were observed along the French Mediterranean coast (Figs. 10c). As in typical Cevenol

583 episodes, strong southerlies brought warm and moist air from the Mediterranean Sea toward

584 the Massif Central and caused heavy orographic precipitation over the mountain ranges of the

585 Cevennes. Upper-level cut-offs like Sanchez are known to be favorable synoptic conditions

586 for triggering convective mesoscale events (Nuissier et al. 2008), which were intensively

587 studied during the recent international field campaign HyMex (Ducrocq et al. 2016). Part of

588 the air masses responsible for the HIW subsequently reached as far north as the SIRTA site

589 near Paris, causing precipitation in the afternoon of 13 Oct (Fig. 10d). This episode illustrates

590   one of the key NAWDEX aims (Table 1) to investigate how HIW events over Europe are

591   associated with complex waveguide dynamics (in this case the formation of a PV cut-off)

592   over the upstream North Atlantic. The combination of the ground-based data with NAWDEX

593   observations both from aircraft and from the many additional radiosondes taken during IOP 9

594   will enable detailed studies of the forecast sensitivity of HIW to upstream initial condition

595   errors.

596   **SUMMARY.** NAWDEX was the first field experiment with synergistic airborne and ground-

597   based observations from the entrance to the exit region of the climatological storm track,

598   taken to investigate the role of diabatic processes in altering jet stream disturbances, their

599   development, and effects on HIW downstream.

600   Because of the operational limitations on research aircraft flights over the North Atlantic

601   and Europe and the need for high-resolution profile measurements of thermal and dynamic

602   properties, NAWDEX focused on airborne remote-sensing observations and the deployment

603   of multiple aircraft. Advanced instruments for remote sensing of wind, water vapor and cloud

604   properties provide an integrated picture of the atmospheric structure in regions where diabatic

605   processes were active, from the synoptic to sub-kilometer scale. The unique combination of

606   the four aircraft and the first deployment of HALO in a campaign focusing on midlatitude

607   dynamics allowed observations in large parts of the North Atlantic. Often, the same weather

608   system could be sampled at different stages of its development, and the interaction of

609   successive weather systems have been observed following the NAWDEX storyline.

610   Additional ground-based observations and an enhanced density of operational radiosonde

611   releases yielded very high coverage with high-resolution vertical profiles from the ground to

612   the lower stratosphere. The region with enhanced atmospheric profiling extended from eastern

613   Canada to most parts of Europe. The coverage and fidelity of the resulting observations will

614   enable future studies to estimate diabatic heating through the use of models and diagnostics

615   constrained by the NAWDEX observations, particularly in situations when the atmospheric

616   flow is especially sensitive to small changes in diabatic heating. Over the 13 IOPs it was

617   possible to address all original campaign objectives (Table 1 and 3). Table 5 lists a number of

618   particular highlights and "firsts" that have drawn the attention of the NAWDEX scientists.

619   The success of the observational campaign was possible because of the favorable

620   meteorological conditions, with many cyclones and WCBs in the vicinity of Iceland.

621   Importantly, the NAWDEX period contained episodes of reduced predictability, indicating

622   that uncertainties originating in the estimated atmospheric state and model formulation grew

623   rapidly. The suggestion that these uncertainties spread via their impact on the lifecycle of a

624   "second cyclone" forming to the west, rather than through a process of downstream

625   development, shows that NAWDEX has the potential to make an important contribution to

626   the study of predictability of midlatitude weather and the representation of uncertainty in

627   EPSs. Since there were also episodes of HIW in Europe connected to disturbances of the

628   North Atlantic waveguide, NAWDEX also is a unique opportunity to explore HIW

629   predictability.

630   To the best of our knowledge, the NAWDEX period provides the most complete set of

631   combined wind, humidity, temperature and cloud profile observations of the North Atlantic

632   jet stream yet accomplished. This dataset will form the basis of detailed case studies and the

633   evaluation of weather and climate prediction models for many years. The widespread

634   coverage of high-resolution multi-variate cross-sections across the jet stream and weather

635   systems developing from one side of the North Atlantic to the other enables examination of

636   the whole chain of processes from the triggering of disturbances on the waveguide to the

637   ultimate impact on weather systems affecting Europe.

638

674   **APPENDIX A: The NAWDEX Team**

675   Table A1

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947 **Sidebar 1: Active remote-sensing observations for future satellite missions Aeolus and**

948 **EarthCARE.** HALO and the SAFIRE and DLR Falcon aircraft were equipped with remote-

949 sensing instruments that are specifically relevant for the future Earth Explorer satellite

950 missions EarthCARE (Illingworth et al. 2015) and Aeolus (ESA 2008) of the European Space

951 Agency (ESA). NAWDEX observations, through coordinated flights of multiple aircraft and

952 of aircraft with satellite overpasses, provide data from comparable airborne instruments for

953 the preparation and future validation of these satellite instruments.

954 HALO was equipped with the High Spectral Resolution (HSRL, 532 nm) and water vapor

955 Differential Absorption Lidar (DIAL) WALES, the HALO Microwave Package (HAMP) with

956 a 35.2 GHz cloud radar and microwave radiometers, the cloud spectrometer (specMACS) and

957 the visible to near-infrared SMART instrument (Table 2). The French Falcon was equipped

958 with the RAdar-LIdar (RALI, Protat et al. 2004) payload consisting of the 94 GHz cloud radar

959 RASTA and the UV High Spectral Resolution lidar LNG (Table 2). These aircraft provide the

960 most complete instrumentation package available at the European level to mimic upcoming

961 EarthCARE measurements and thus provide valuable data for preparing the EarthCARE

962 mission and for future validation. Coordinated flights with both aircraft as well as CALIPSO-

963 Cloudsat underpasses during NAWDEX delivered independent measurements for testing

964 EarthCARE L2 algorithms at different wavelengths and for performing a first rehearsal of the

965 validation/calibration for EarthCARE.

966 Figure SB1a illustrates the complementary character of lidar and radar measurements

967 taken during the HALO research flight on 1 Oct 2016. Optically thin ice clouds at cloud top

968 are only visible in the lidar measurements (green marked curtain), while optically thicker

969 cloud regions are only visible in cloud radar measurements (red marked curtain).

970 The DLR Falcon was equipped with a Doppler wind lidar (DWL) payload consisting of

971 the A2D direct-detection DWL and a 2-µm scanning coherent/heterodyne detection DWL.

972 The A2D is the prototype of the satellite-borne wind lidar instrument on Aeolus and provides

range-resolved line-of-sight wind speeds with high data coverage by exploiting both molecular and particulate backscatter return. With a view to the pre-launch activities for the upcoming Aeolus mission, NAWDEX offered the opportunity to extend the A2D dataset and to perform wind measurements in dynamically complex scenes, including strong wind shear and varying cloud conditions, as well as multiple instrument calibrations, which are a prerequisite for accurate wind retrieval. RALI on board the SAFIRE Falcon complemented the A2D instrument with wind measurements in clouds and aerosol-rich layers.

Figure SB1b shows collocated wind observations from the A2D and the 2-µm DWL from a flight of the DLR Falcon east of Iceland on 4 Oct 2016. The good vertical coverage, limited only by a dense cloud layer, is achieved by combining complementary information from both aerosol backscatter (A2D Mie channel and 2-µm DWL) and molecular backscatter (A2D Rayleigh channel).

985 **Sidebar 2: Forecast products to investigate forecast uncertainty.** NAWDEX focused on

986 weather phenomena that are poorly represented in NWP, so a strong effort to estimate forecast

987 uncertainty was essential for the planning of the IOPs. Deterministic forecasts from the

988 European Centre for Medium-Range Weather Forecasts (ECMWF), the UK Met Office, the

989 Naval Research Laboratory (NRL), Météo France, the Icelandic Meteorological Office (IMO)

990 and the Danish Meteorological Institute (DMI) were available. Additionally, ensemble

991 forecasts from the ECMWF, Met Office (MOGREPS-G) and Météo France (PEARP short-

992 range ensemble) played an essential role.

993 Each day a standard set of synoptic charts and tailored weather products (e.g. PV on

994 isentropic surfaces and WCB trajectories) were produced using a common map projection and

995 pre-defined cross sections. Ensemble diagnostics of mean and spread of several variables, as

996 well as tailored ensemble forecast products for NAWDEX-relevant features (e.g., WCB and

997 cyclone frequencies, and tropopause height) were created. These forecast products were

998 provided via web sites. In addition, an interactive web interface allowed the flight planning

999 team to compute backward and forward trajectories from planned flight tracks, facilitating the

1000 planning of flights to attempt Lagrangian re-sampling of air masses.

1001 Flight planning typically requires cross-section information, e.g., to obtain an accurate

1002 picture of tropopause height, winds speeds and cloud layers, and to assess forecast

1003 uncertainties along hypothetical flight routes. The NAWDEX community had access to

1004 special flight planning tools that allowed an interactive visualization of forecast products.

1005 Central to forecasting and flight planning operations was the "Mission Support System"

1006 (MSS; Rautenhaus et al. 2012). In addition, the interactive 3D forecast tool "Met.3D"

1007 (Rautenhaus et al. 2015a) provided specialized forecast products. Two workstations were set

1008 up at the operation center in Keflavik to run Met.3D and enable the novel ensemble

1009 forecasting workflow described in Rautenhaus et al. (2015b). Ensemble forecasts by ECMWF

1010 could be interactively analyzed in combined 2D/3D depictions. WCB trajectories and derived

1011   probabilities of WCB occurrence could be combined with additional forecast information.

1012   The ability of Met.3D to interactively navigate the ensemble data proved particularly useful,

1013   facilitating analysis of the uncertainty for features such as the predicted tropopause position.

1014   Figure SB2 shows an example of forecast products used for planning the IOP 4 flight. The

1015   +60 h deterministic IFS forecast shows ex-TS Karl as a deep surface cyclone south of

1016   Greenland (Fig. SB2a) with cyclonically wrapped PV contours resulting from an advection of

1017   low-PV air to upper levels in the outflow of a WCB (not shown). High WCB probabilities

1018   with two distinct maxima north and east of Karl indicate that the location of the tropopause

1019   and WCB outflow is predicted with high certainty (Fig. SB2b). Images from Met.3D (Fig.

1020   SB2c,d) show the relation between the jet stream, WCB and tropopause in the ECMWF

1021   ensemble mean along cross sections intersecting the waveguide and the WCB east of the

1022   surface cyclone. A cross section with ensemble mean PV (Fig. SB2c) shows a low tropopause

1023   north of the jet (depicted by an isosurface of wind speed), whereas a high tropopause appears

1024   to the south. This coincides with high probabilities of WCB (Fig. SB2d). WCB trajectories of

1025   a selected ensemble member show two distinct branches (Fig. SB2d). One branch wraps

1026   cyclonically around the cyclone and features a lower outflow compared to the second branch,

1027   which follows anticyclonic pathways at higher elevations, contributing to the elevated WCB

1028   probability maximum there. Real-time adjoint products from COAMPS (Doyle et al. 2014)

1029   were used to identify regions of initial condition sensitivity. At 12 UTC 24 Sep, the maximum

1030   moisture sensitivity is located in the low- to mid-levels and positioned along the eastern

1031   portion of TS Karl (Fig. SB2e). The adjoint sensitivity is computed using a kinetic energy

1032   response function located in a box (450×600 km^2 in the horizontal and extending from the

1033   surface to 700 hPa) centered on the ascending WCB at the 48 h forecast time at 12 UTC 26

1034   Sep when the IOP 4 flights were planned. Optimal perturbations derived from the adjoint

1035   sensitivity show an increase of wind speeds from 30 m s^{-1} to over 45 m s^{-1} in the WCB

1036   highlighting the importance of the mid-level moisture associated with Karl (48 h prior) for the

1037   intensification of the WCB.

Table 1: NAWDEX research aims and science goals. Region numbers refer to Fig. 1			
Aim Nr	Topic	Science Goals	Region
1	Moisture structure in the boundary layer	• Characterization of low-level moisture in atmospheric rivers and WCB inflow regions • Investigation of impact of low-level moisture on downstream weather evolution	1,(2,3),4
2	Mixed phase and cirrus clouds	• In situ and remote sensing measurements of cloud properties and meteorological parameters during WCB ascent and outflow • Comparison of observations and models to quantify latent and radiative heating/cooling in and below WCB • Role of slantwise ascent vs. embedded convection in WCB • Characterization of vertical moisture gradient and cirrus structure in WCB outflow, and effects on radiation	2, 3
3	Potential vorticity	• Quantitative estimate of PV from observations • Verification of PV structures, PV gradients and jet stream winds in numerical models • Structure of negative PV anomalies in WCB outflows and upper tropospheric ridges • Role of divergent outflow of WCBs for ridge amplification • Spatial distribution of turbulence in the free atmosphere and relationship to jet stream and PV structures	3
4	Tropopause waveguide, predictability and consequences for HIW	• Relevance of amplifying small errors at tropopause level for uncertainty in surface weather downstream • Influence of observations within and outside of diabatically active regions on the predictability of downstream HIW	3, 4
5	Instrument-driven aims	• Comparison of measured radiances and retrieved cloud optical properties between SMART-HALO and specMACS • Cloud regime characterization in midlatitude cyclones and analysis of model representation at different resolutions • Radiometer retrieval development for profiles and hydrometeor paths using instrument synergies • Validation of Aeolus calibration and wind retrieval algorithms • Intercomparison of wind and aerosol products from different instruments on DLR and SAFIRE Falcon • First test of EarthCARE calibration and validation strategy	2,3

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Aircraft	Instruments	Measured and derived properties	Aim Nr
Table 2: Aircraft and instrumentation for NAWDEX and contribution to research aims (Table1)			
HALO	**HAMP** (HALO Microwave Package) Microwave radiometer with 26 channels spanning the frequency range from 22 to 183 GHz, and Ka-band (35.2 GHz) cloud radar (Mech et al. 2014)	Radiometers: Integrated water vapor, temperature and humidity profiles, liquid and ice water path Radar: profiles of radar reflectivity, depolarization ratio, vertical velocity	2,3,5
	WALES (Water Vapor Lidar Experiment in Space): Four-wavelength Differential Absorption (DIAL) and High Spectral Resolution Lidar (HSRL) (Wirth et al. 2009)	Profiles of water vapor, backscatter coefficient lidar/color ratio, particle linear depolarization ratio, particle extinction coefficient	1,2,4,5
	SMART (Spectral Modular Airborne Radiation Measurement System): Passive cloud spectrometer (Wendisch et al., 2001; Ehrlich et al., 2008)	Spectral nadir radiance, spectral upward and downward irradiance (300-2200 nm), cloud top albedo, cloud thermodynamic phase, cloud optical thickness, effective radius, cloud cover / statistics	2,4,5
	specMACS (Cloud spectrometer of the Munich Aerosol Cloud Scanner): Imaging cloud spectrometer plus 2D RGB camera (+/-35° fov) (Ewald et al. 2015)	Spectral radiance (400-2500 nm), push-broom imaging at nadir and +/- 17° across track, cloud thermodynamic phase, liquid and ice optical thickness, particle size, cloud cover	2,4,5
	Bahamas (Basic HALO Measurements and Sensor System)	In situ observations of pressure, temperature, wind, humidity, TAS aircraft position, attitude, heading, altitude	3,4,5
	Dropsondes Vaisala RD94	Temperature, humidity and wind profiles	1,2,3,4,5
DLR Falcon	**A2D** (ALADIN Airborne demonstrator): direct-detection DWL (Reitebuch et al. 2009, Marksteiner et al. 2011)	Profiles of line-of-sight wind speed and aerosol/cloud layers(20° off-nadir)	3,5
	2-μm scanning coherent/heterodyne detection DWL (Weissmann et al. 2005; Witschas et al. 2017)	Vertical profiles of line-of-sight wind speed, horizontal wind vectors, and aerosol/cloud layers	3,5
	Basic in situ measurements	In situ observations of pressure, temperature, wind, humidity, TAS aircraft position, attitude, heading, altitude	3,4,5
SAFIRE Falcon	**RASTA** (RAdar SysTem Airborne):	Doppler velocity and reflectivity from three antennas (including spectral width), cloud and	2,3,5

	95-GHz Doppler cloud radar (Delanoë et al 2013)	precipitation microphysics (ice and liquid water content), dynamics (horizontal and vertical wind)	
	LNG (Leandre New Generation): high-spectral-resolution lidar (Bruneau et al. 2015)	Three-wavelength (1064, 532, and 355 nm) backscatter lidar with polarization analysis at 355 nm, High Spectral Resolution capability including Doppler measurement, based on a Mach–Zehnder Interferometer, at 355 nm. Radiative properties and dynamics of cloud and aerosol	2,3,5
	CLIMAT infrared radiometer (Brogniez et al. 2003)	Radiances measured simultaneously in three narrowband channels centered at 8.7, 10.8, and 12.0 μm	2,4,5
	Dropsondes Vaisala RD94	Temperature, humidity and wind profiles	1,2,3,4,5
	Aircraft in situ measurements	In situ observations of pressure, temperature, wind, humidity, TAS aircraft position, attitude, heading, altitude	3,4,5
FAAM BAe 146	In situ temperature, Buck CR-2 and WVSS-2 hygrometers, two turbulence probes	Temperature, humidity, and wind and turbulent fluxes	2,3
	PCASP (aerosol size probe), CDP (scattering cloud droplet probe), CIP-15, CIP-100 (cloud imaging probes)	Cloud particle size spectrum: 2 μm-6 mm diameter, cloud droplet spectrum: 3-50 μm	2,5
	Nevzorov hot wire probe	Ice/Liquid water content	2,5
	TECO 49C UV analyser, Aerolaser AL5002, Los Gatos Fast Greenhouse Gas analyser	O3, CO, CH4, CO2	2
	Lidar: downward-pointing Leosphere ALS450 (355 nm, scattering and depolarization)	Position of different atmospheric layers below the aircraft (clear air, aerosols, cloud tops)	2
	ISMAR (International Sub-Millimetre Airborne Radiometer)	Passive radiometer with polarization and multiple channels (118, 243 (V/H), 325, 424, 448, 664 (V/H) and 874 GHz (V/H)) (IOP 11 only)	5
	MARSS (Microwave Airborne Radiometer Scanning System)	Scanning microwave radiometer operating at AMSU-B channels 16-20 (89-183GHz) and pointing both upward and downward (IOP 11 only)	5
	Dropsondes Vaisala RD94	Temperature, humidity and wind profiles	1,2,3,4,5

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Table 3: IOPs, key weather systems and associated flights together with the number of dropsondes from all aircraft. As some of the long-range flights of HALO were related to different weather systems, dropsondes were assigned to the respective IOP. Aims numbered according to Table 1 show contribution to NAWDEX science goals.

IOP	Period	Key Weather systems	Date	HALO	DLR Falcon	SAFIRE Falcon	FAAM BAe 146	Drops	Aim Nr
1	16-17 Sep	Outflow of ex-TC **Ian**, low predictability case	17 Sep	RF01	RF01/02			10	2,3,4,5
2	21-22 Sep	WCB ascent and outflow of extratropical cyclone **Ursula**	21 Sep	RF02	RF03			14	2,3,4,5
3	23-25 Sep	WCB ascent of extratropical cyclone **Vladiana**	23 Sep	RF03	RF04		RF01 (B980)	32	1,2,3,4,5
4	22-28 Sep	Re-intensification phase of ex-TS **Karl** and jet streak forming downstream	26 Sep	RF04				25	2,3,4,5
			27 Sep	RF05	RF05		RF02 (B981)	22	
5	26-29 Sep	Strong WV transport of extratropical cyclone **Walpurga** leading to HIW in Scandinavia	27 Sep	RF05				20	1,3,4
6	1-5 Oct	**Stalactite cyclone** and low predictability over Europe	1 Oct	RF06		RF05		3	2,3,4,5
			2 Oct		RF07	RF06/07		9	
7	4-5 Oct	Strong extratropical cyclone originating as frontal wave near Newfoundland	4 Oct		RF08/09	RF08		5	
			5 Oct			RF09		4	2,3,4
8	6-9 Oct	TPV near Newfoundland and downstream forming cyclone	6 Oct	RF07				20	4,5
			7 Oct			RF10		7	
			9 Oct	RF08	RF10	RF11/12		9	
			10 Oct			RF13		6	
9	9-14 Oct	PV cut-off cyclone **Sanchez** & downstream impact over the Mediterranean	9 Oct	RF08					2,3,4,5
			10 Oct	RF09				20	
10	12-15 Oct	Formation and extension of tropopause ridge **Thor** and the Scandinavian anticyclone	11 Oct			RF14		4	3,4,5
			12 Oct			RF15		8	
			13 Oct	RF10		RF16		26	
			15 Oct	RF12				12	
11	14 Oct	Radar and lidar mission for instrument comparisons and satellite underflights	14 Oct	RF11		RF17/18	RF03 (B984)	15	5
12	15 Oct	TPV over Baffin Island	15 Oct	RF12					4, 5
13	18 Oct	PV streamer over UK	18 Oct	RF13	RF13/14			16	2,3
		Instrument and calibration flights	28 Sep		RF06				5
			15 Oct		RF11/12				
			16 Oct			RF19		2	
			22 Oct		RF15/16				

Table 4: NAWDEX IOPs and periods of increased ground-based observation activities.		
IOP	**Additional Observations**	**Period**
1	Radiosondes from UK, Torshavn and Iceland for a temporal sequence of the arrival of outflow of ex-TC Ian as it extends northeastwards.	16-17 Sep
2	Radiosondes from UK, Iceland and eastern Greenland for a time series during arrival and passage of cyclone Ursula.	21-22 Sep
3	Radiosondes from northern UK to observe rapidly intensifying frontal cyclone Vladiana with strong WCB and ridge building.	23-25 Sep
4	Radiosondes around the northern North Atlantic and Scandinavia to observe the structure and evolution of ex-TS Karl and to observe GWs above Iceland at the jet stream. Jet streak maximum passes directly above MST radar wind profiler on South Uist, Scotland.	26-28 Sep
5	Radiosondes in UK and southern Scandinavia to observe the strong water vapor transport and related HIW. Passage of jet stream over Capel Dewi.	27-29 Sep
6	Radiosondes northwest of Iceland to observe ridge building in relation to the stalactite cyclone. Radiosondes over southern Europe to observe a cut-off downstream. Radiosondes at Iceland to observe GWs in the stratosphere.	1-5 Oct
8	Radiosondes over Iceland and eastern Greenland to observe WCB ascent and cyclone structure. Observation of orographic GWs above Iceland.	6-9 Oct
9	Radiosondes from the western Mediterranean, at Capel Dewi and at SIRTA to observe cut-off Sanchez and related HIW. Passage of outflow from Sanchez over MST radar at Capel Dewi. Radiosondes above Iceland to observe strong GW activity in the stratosphere.	10-14 Oct
8,10	Radiosondes over North Atlantic to obtain a time series of the vertical structure of ridge Thor. MST radar wind observations at Andøya, Norway.	10-15 Oct
11	Radiosondes at SIRTA to observe the downstream impact.	15-16 Oct

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Table 5: NAWDEX observational highlights		
IOP	**Period**	**Specific aspects of the observations**
3	23-25 Sep	Coordinated flights to observe the cloud structure and cloud physics in the WCB ascent related to cyclone Vladiana and the interaction of the WCB outflow with the jet stream.
4	22-28 Sep	First ever observations of a TS from tropical phase and ET (SHOUT observations) through midlatitude re-intensification, jet streak formation, ridge enhancement and HIW over Scandinavia (NAWDEX observations)
5	26-29 Sep	Large-scale strong moisture transport in an atmospheric river type flow upstream of cyclone Walpurga causing HIW over Scandinavia
6	1-5 Oct	Lowest predictability case with observation of the WCB ascent and outflow of the stalactite cyclone and the subsequent influence in the onset of the European block.
8/12	26-29 Sep, 15 Oct	First ever airborne observation of temperature, wind and moisture structure of two TPV events in a phase when they interacted with the midlatitude waveguide
9	9-14 Oct	Roll-up of the positive PV filament giving rise to mesocyclone Sanchez connected to HIW in France and Italy
10	12-15 Oct	Low PV ridge builds and extends into the Arctic reinforcing the anticyclonic part of the block. Profile observations characterizing the low PV anomaly structure.
11	14 Oct	Coordination of three aircraft and joint underflight of the Calipso/Cloudsat satellite path to exploit instrument synergies of radar, lidar and radiometer instruments

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Table A1. Overview of the NAWDEX team members and their roles in the campaign.			
Organization	Country	Participants	Role
Monash University	Australia	Julian Quinting	Flight planning team
Environment and Climate Change Canada (ECCC)	Canada	Ron McTaggart-Cowan	PI Canadian radiosondes, science team
Division Technique, INDU	France	Frédéric Blouzon	RALI team
Institut Pierre Simon Laplace	France	Jean-Charles Dupont	Coordinator of radiosonde launches at SIRTA
Laboratoire d'Aérologie	France	Jean-Pierre Chaboureau	Flight planning team
Laboratoire de Météorologie Dynamique	France	Gwendal Rivière	Science team, flight planning team
Laboratoire Atmosphère, Milieux et Observations Spatiales France	France	Julien Delanoë Jacques Pelon	Science team, flight planning team
		Christophe Caudoux, Quitterie Cazenave, Abdenour Irbah, Mathilde Van Haecke	RALI team (airborne radar-lidar)
Météo France	France	Philippe Arbogast	Science team, flight planning team
		Jean-Marie Donier	UHF radar at Lannion
SAFIRE	France	Jean-Christophe Canonici	SAFIRE coordinator
		Dominique Duchanoy, Guillaume Seurat	Falcon pilots
		Hubert Bellec, Nelly Geil, David Mourlas, Thierry Perrin, Frédéric Pouvesle	Falcon technical support
Deutsches Zentrum für Luft- und Raumfahrt (DLR), Flight Experiments	Germany	Andreas Minikin, Robert Uebelacker, Katrin Witte	HALO and Falcon project management
		Stefan Hempe, Frank Probst	HALO and Falcon operations
		Steffen Gemsa, Michael Grossrubatscher, Stefan Grillenbeck, Philipp Weber, Roland Welser, Matthias Wiese	HALO and Falcon pilots
		Volker Dreiling, Andreas Giez, Christian Mallaun, Martin Zöger	HALO and Falcon sensor and data team
		Michael Kettenberger,	HALO technical support

		Thomas Leder, Florian Gebhardt, Christoph Grad, Stephan Storhas, David Woudsma	
Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institute for Atmospheric Physics	Germany	Andreas Schäfler	Mission coordinator, science team, flight planning team
		Axel Amediek, Andreas Fix, Silke Groß, Manuel Gutleben, Martin Wirth	WALES team
		Christian Lemmerz, Oliver Lux, Uwe Marksteiner, Engelbert Nagel, Stephan Rahm, Oliver Reitebuch, Benjamin Witschas	Wind lidar team
		Florian Ewald, Martin Hagen	HAMP team
		Martina Bramberger, Alenka Senika	Radiosonde team at Keflavik, Flight planning team
Karlsruhe Institute of Technology	Germany	Pila Bossmann, Enrico Di Muzio, Florian Pantillion	Flight planning team
Max Planck Institute for Meteorology (MPI-M) Hamburg	Germany	Björn Brügmann, David Hellmann, Lutz Hirsch, Friedhelm Jansen, Marcus Klingebiel	HAMP team
Technical University Munich	Germany	Marc Rautenhaus	Flight planning team
University of Cologne	Germany	Susanne Crewell, Lisa Dirks, Marek Jacob, Mario Mech	HAMP team
University of Hamburg, Max Planck Institute for Meteorology (MPI-M)	Germany	Felix Ament, Heike Konow	HAMP team
University of Leipzig	Germany	Tim Carlsen, André Ehrlich, Manfred Wendisch, Kevin Wolf,	SMART team
University of Mainz	Germany	Marlene Baumgart, Christian Euler, Paolo Ghinassi, Michael Riemer, Volkmar Wirth	Flight planning team
University of Munich	Germany	George Craig	HALO mission PI, science team, flight planning team
		Florian Baur, Lotte Bierdel, Christian Keil, Julia Mack, Tobias Selz	Flight planning team

		Hans Grob, Lucas Höppler, Tobias Kölling, Bernhard Mayer, Tobias Zinner	specMACS team
Norwegian Meteorological Institute	Norway	Rich Moore	NEAREX team
University of Bergen	Norway	Harald Sodemann, Thomas Spengler	NEAREX team
National Institute of Research and Development for Optoelectronics	Romania	Dragos Ene	Flight planning team
ETH Zurich	Switzerland	Heini Wernli	Science team, flight planning team
		Roman Attinger, Hanin Binder, Maxi Boettcher, Bas Crezee, Christian Grams, Jacopo Riboldi	Flight planning team
University of Bern	Switzerland	Matthias Röthlisberger	Flight planning team
Met Office	UK	Richard Cotton, Stuart Fox	FAAM aircraft
NCAS and University of Manchester	UK	Bogdan Antonescu, Hugo Ricketts, Geraint Vaughan	Capel Dewi observations, FAAM aircraft
University of Reading and NCAS	UK	Suzanne Gray, John Methven	FAAM aircraft, NAWDEX-Influence PIs, science team, flight planning team
		Ben Harvey, Jacob Maddison, Oscar Martínez-Avarado, Leo Saffin	Flight planning team
Naval Research Laboratory Monterey, CA and Washington, DC	USA	James Doyle	Science team, flight planning team
		Stephen Eckermann, Carolyn Reynolds	Flight planning team
EUMETNET		Susanne Hafner, Stefan Klink	EUMETNET coordinators
ESA		Dirk Schüttemeyer	ESA campaign section

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Fig. 5. (a) Weather regime indices following the definition of Michel and Rivière (2011): Scandinavian blocking (blue line), positive NAO (red line), negative NAO (green line), and Atlantic ridge (yellow line), identified with a k-means clustering approach (Michelangeli et al. 1995). (b) Time series of ECMWF IFS anomaly correlation coefficient (ACC) for geopotential height at 500 hPa over an area 35 to 75°N and 60 to 0°W for a forecast lead time of +120 h (shown at the initial time of the forecast): IFS deterministic forecast (black line), ensemble mean (red line), 50% of the ensemble members (orange area) and all members (yellow area). (c) NAWDEX IOPs as indicated in Table 3 (red bars). Light grey box depicts the NAWDEX campaign period and the dark grey boxes mark the duration of weather sequences as shown in Figure 6.

Fig. 6. Three sequences that illustrate the NAWDEX storyline from trigger to interaction, development and HIW in Europe (based on ECMWF IFS operational analyses). All panels display PV on 325 K (PV < 2 PVU in white, 2 PVU ≥ PV < 5 PVU in red, 5 PVU ≥ PV < 8 PVU in orange, PV ≥ 8 PVU in yellow), contours of wind speeds (grey contours; 60, 70 and 80 m s^{-1}) and MSLP (blue contours; interval 10 hPa). Some long-lived, coherent features are labelled to enable links from one frame to the next. K refers to TS Karl; W, F, S and St mark midlatitude cyclones observed by NAWDEX; C labels a tropopause level cut-off that persists for 10 days; R1-R9 refer to the prominent ridges along the North Atlantic waveguide, identified as northward excursions of the jet stream and the isentropic PV gradient; T marks a TPV.

Fig. 7. ECMWF IFS operational analyses of wind speed (color shading), 2 PVU (green line) at 325 K and MSLP (blue contours, in hPa) at (a) 12 UTC 23 Sep 2016 with Global Hawk flight track (black line, from 2120 UTC 22 Sep to 2100 UTC 23 Sep), (b) 12 UTC 25 Sep 2016 with Global Hawk flight track (black line, from 1820 UTC 24 Sep to 1715 UTC 25 Sep), (c) 12 UTC 26 Sep 2016 with HALO flight track (black line, from 10 to 19 UTC), and (d) 12 UTC 27 Sep 2016 with HALO (black line, 1130 to 2030 UTC), FAAM (pink line, 0800 to 1230 UTC) and DLR Falcon (purple line, 0930 to 1330 UTC) flight tracks.

Fig. 8. WCB observations on 23 Sep 2016 (IOP 3): (a) ECMWF IFS operational analysis of PV at 325 K (shading) and MSLP (black contours, in hPa) at 12 UTC 23 Sep 2016 with HALO flight track from Iceland (gray / green line; green part corresponds to the section shown in (a) and (b)) and FAAM flight track (gray / black line; black part

corresponds to track in (a) and (b)). The circle and diamond markers indicate the start and end positions of the latitudinal WCB cross-sections. (b) WALES DIAL water vapor mixing ratio (colors) and (c) HAMP radar reflectivity with HALO flight track (green line), FAAM flight track (thick black line, lowest leg was flown first) and dropsonde release positions (thin black lines). Only the part of the FAAM flight track with a spatial collocation to HALO is shown and both aircraft started at the same time, but had a time lag of ~2.5 h at the end of the last upper-most FAAM leg. (d) Ice water content as observed along the FAAM flight track. Differences between the flight tracks in (a,b) and (d) result from interpolation of FAAM position to the closest HALO observation in (a). The longitude axis in (d) was reversed to align with the time axis of the HALO flight track.

Fig. 9. Jet stream observations on 2 Oct 2016 (IOP 6): (a) ECMWF IFS operational analysis of PV at 320 K (shading) and MSLP (black contours, in hPa), and (b) 300 hPa wind speed (colors) and geopotential height (black contours, in dam) at 06 UTC 2 Oct 2016. (a) and (b) include flight tracks of the DLR Falcon (light green line) and SAFIRE Falcon (dark green line). The coordinated part of the flight from east to west shown in panels (c) and (d) is marked with the purple line. (c) DLR Falcon 2-µm DWL wind speeds (colors) and (d) SAFIRE radar-derived wind speeds (colors). Grey area in (c) and (d) marks the topography of Greenland.

Fig.10. (a) ERA Interim moisture fluxes at 850 hPa (arrows, shadings shows magnitude) and surface pressure (black contours, hPa) at 12 UTC 13 Oct 2016. The red star indicates the location of the SIRTA surface observation site. (b) Daily accumulated precipitation (mm) and (c) daily maximum of instantaneous surface wind in southern France on 13 Oct 2016 from the high-resolution climatological network of Météo France surface weather stations. The black areas in (b) and (c) mark topography of the French Pyrenees, the Massif Central and the French Alps. (d) Reflectivity and Doppler velocity (approximately equal to terminal fall speed) at the 25 m resolution of the radar BASTA at SIRTA on 13 Oct 2016.

Fig. SB1. (a) Collocated observations of the vertical cloud structure below HALO, based on lidar (backscatter, along green part of the flight) and radar (radar reflectivity along red line). The underlying true color image was acquired by MODIS Aqua near the time of the flight (Global Imagery Browse Services (GIBS), operated by the NASA/GSFC/Earth Science Data and Information System). (b) Collocated wind

1142   observations on board the DLR Falcon using the A2D direct-detection wind lidar

1143   (along the blue line) and the 2-µm coherent DWL (along the red line). The latter is

1144   horizontally displaced from the actual flight track for clarity (Background picture: ©

1145   2017 Google).

1146   **Fig. SB2.** NAWDEX forecast products for 12 UTC 26 Sep 2016 (lead time +60 h): (a)

1147   ECMWF IFS deterministic forecast of PV on 330 K (color shading) and mean sea

1148   level pressure (MSLP, in hPa). (b) WCB column probabilities of occurrence (color

1149   shading in %), derived from ECMWF ensemble (Schäfler et al. 2014; Rautenhaus et

1150   al. 2015b). Black line indicates location of cross section in Met.3D visualizations in

1151   (c) and (d). (c) Isosurface of ensemble mean wind of 60 m s^{-1} (color indicates

1152   pressure on isosurface in hPa) and MSLP (black surface contours). The cross section

1153   shows ensemble mean PV (color shading) and potential temperature (black

1154   contours). Colored lines represent WCB trajectories of ensemble member 22, starting

1155   at 06 UTC 25 Sep 2016 (colored by pressure). The black vertical poles have been

1156   added to aid spatial perception; they are labeled with pressure in hPa. (d) WCB

1157   trajectories as in (c) but from a different viewpoint and combined with a cross

1158   section showing 3D WCB probabilities (color shading, in %), ensemble mean

1159   potential temperature (black contours) and the 2 PVU isoline (red contour). (e)

1160   COAMPS adjoint 48 h forecast moisture sensitivity at 850 hPa [color shading,

1161   increments every 0.2 m^2 s^{-2} (g kg^{-1})$^{-1}$] and 850 hPa geopotential heights (contours

1162   every 30 m) valid at 12 UTC 24 Sep (initial forecast time).

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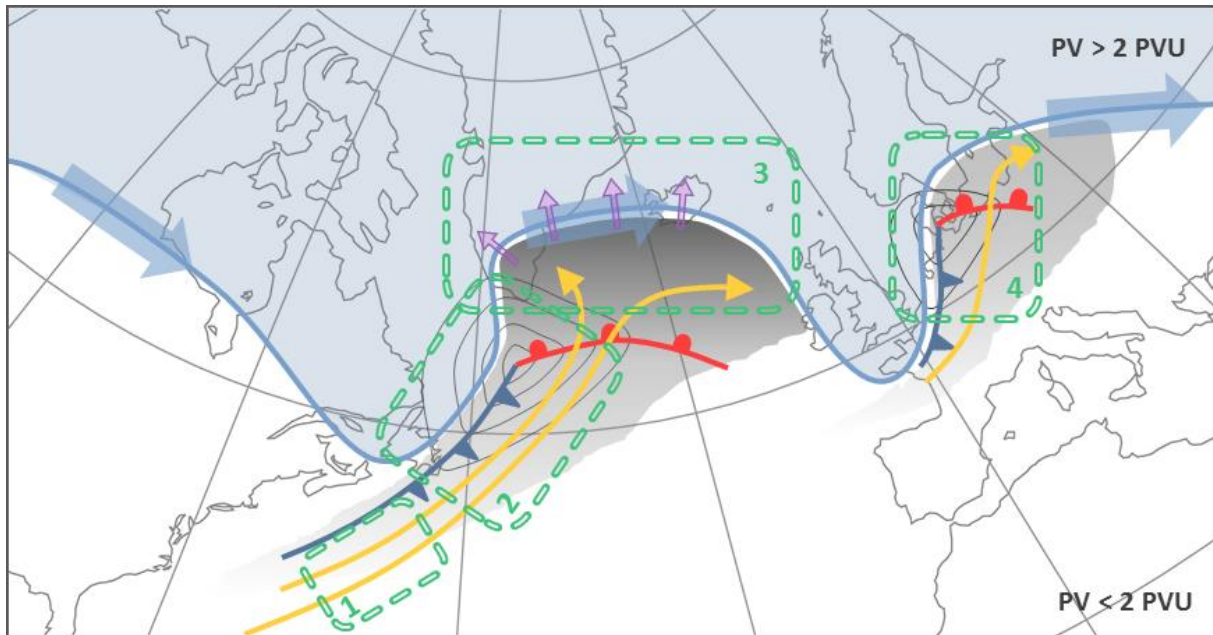
Fig. 1. Schematic of an idealized weather situation during NAWDEX. The blue line marks the location of the waveguide with a strong isentropic PV gradient separating stratospheric (blue background, PV > 2 PVU) from tropospheric air (white background). The jet stream (dark blue arrows) follows the waveguide. Surface lows develop below the leading edge of upper-level positive PV anomalies (black lines indicate sea level pressure and dark blue and red lines surface cold and warm fronts, respectively). Grey shaded areas indicate clouds related to ascending WCBs (yellow arrows). Purple arrows mark divergent outflow at the tropopause. The four green boxes outline the main regions of interest, i.e., the inflow (1), ascent (2) and outflow (3) of WCBs, as well as a region of expected downstream impact (4).
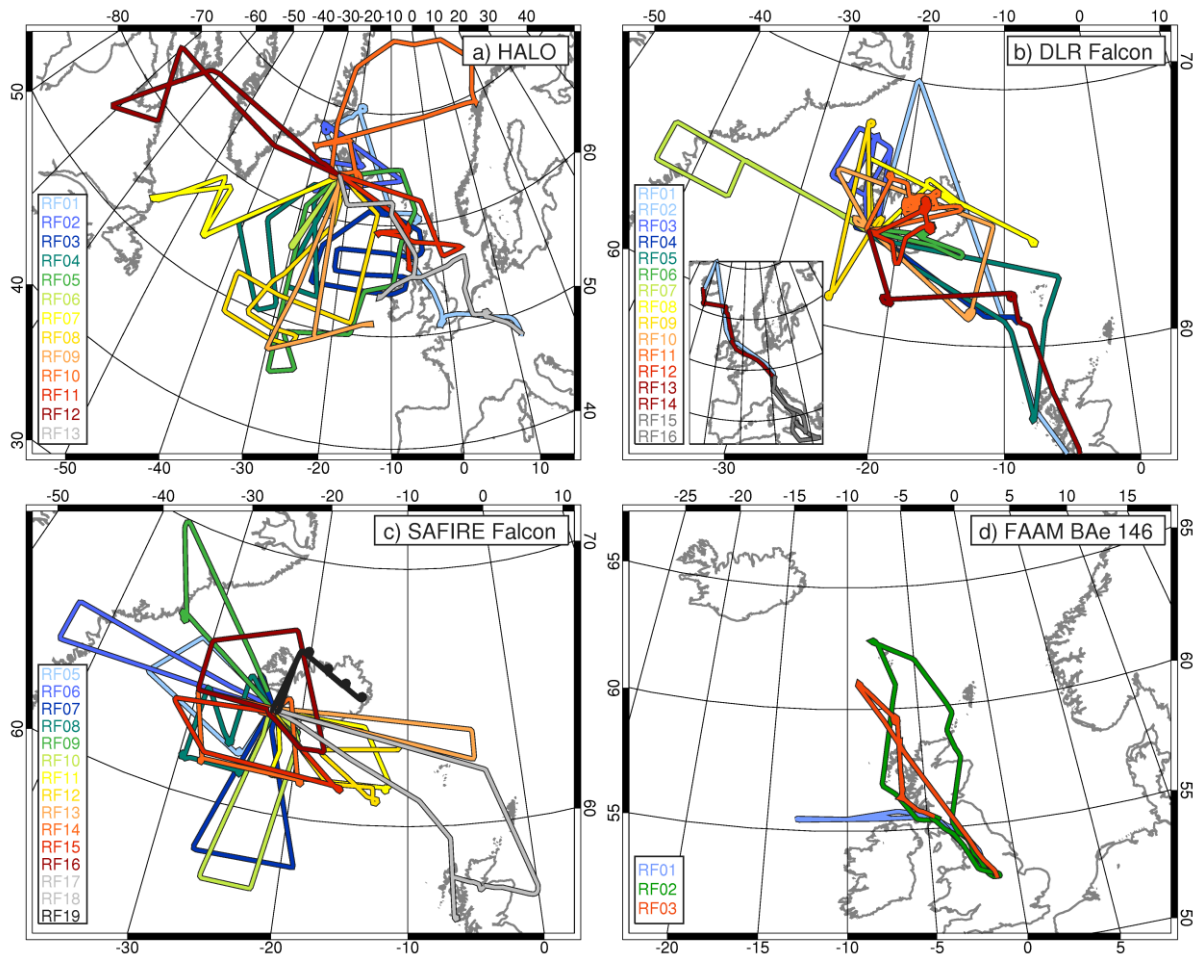
Fig. 2. Tracks of consecutively numbered research flights (RFs) of (a) HALO (97 flight hours during 13 RFs), (b) DLR Falcon (51 flight hours during 16 RFs), (c) SAFIRE Falcon (42 flight hours during 15 RFs; Flights 01 to 04 were made over France just before the campaign to calibrate the instruments), and (d) FAAM BAe 146 (15 flight hours during 3 RFs). The inset in (b) shows the DLR Falcon transfer flights and two flights to the Mediterranean at the end of the campaign.
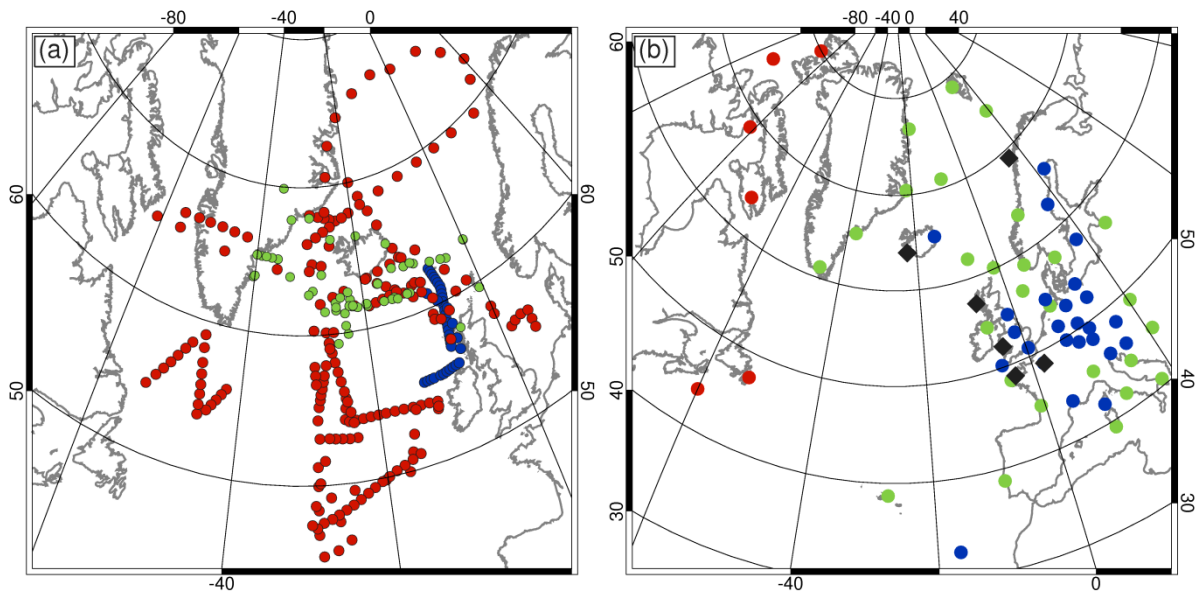
Fig. 3. (a) Dropsondes launched from HALO (red dots, 191 dropsondes), SAFIRE Falcon (green dots, 59 dropsondes) and FAAM BAe 146 (blue dots, 39 dropsondes). (b) Ground-based observation sites during NAWDEX: Canadian radiosonde stations (red dots), European radiosonde stations that performed only operational ascents (blue dots) and those with requested additional radiosonde launches (green dots), and six sites with additional profile observations (black diamonds).
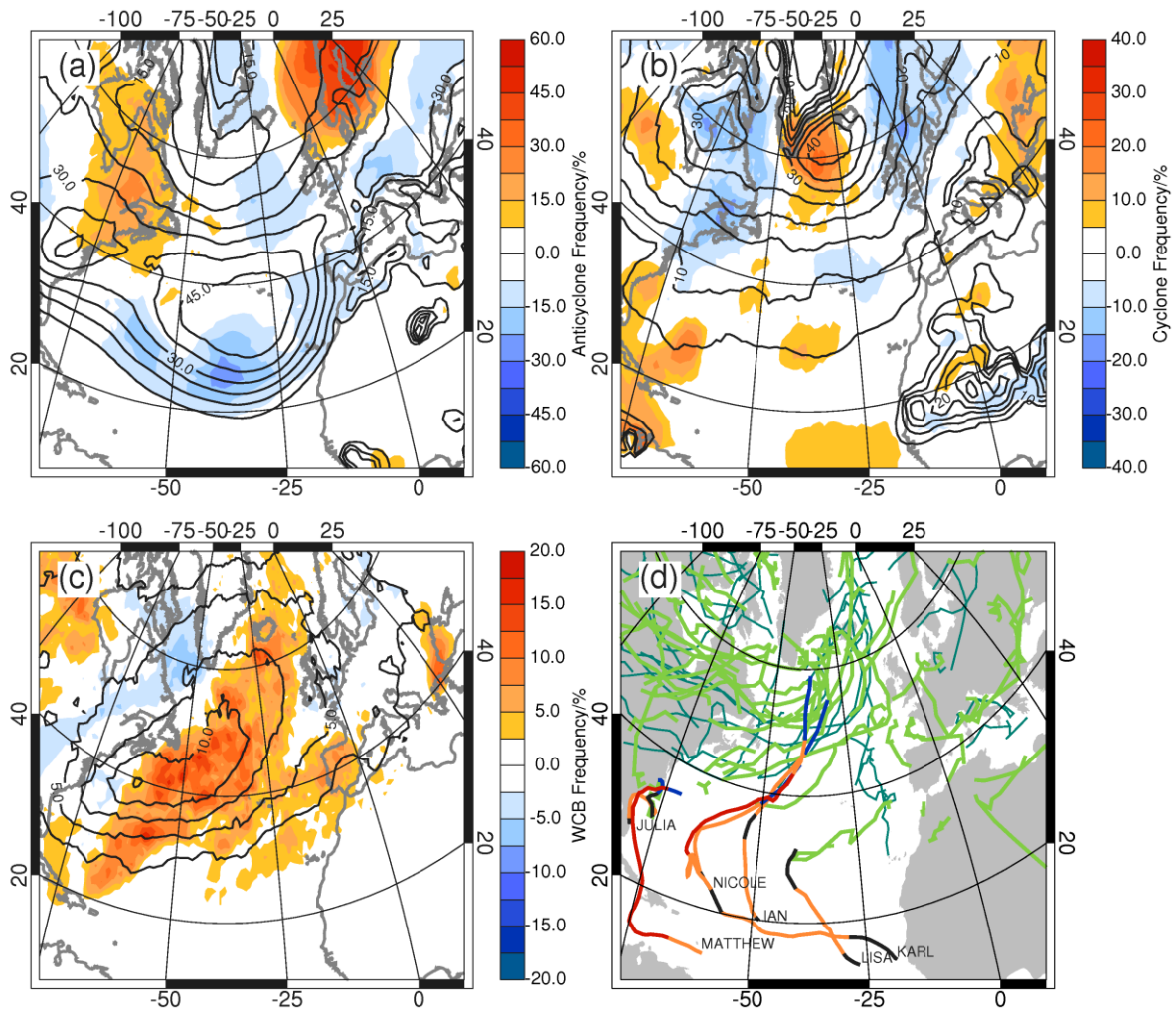
Fig. 4. (a-c) Synoptic-scale conditions during NAWDEX. All panels are based on ECMWF ERA-Interim data (1979-2016) and show in colors deviations of the campaign period in 2016 from the mid-September to mid-October climatology. (a-c) frequencies (all in %) of (a) surface anticyclones, (b) surface cyclones, and (c) WCB. The tracking method is explained in Sprenger et al. (2017). Black contours show the ERA-Interim 37-year climatological mean; (d) best track data (HURDAT2 of the National Hurricane Center) of six tropical cyclones (red sections classified as hurricane, orange as TS and blue as extratropical storm), and cyclone tracks during the NAWDEX period (light green lines) and before/after the campaign period (dark green lines).

Fig. 5. (a) Weather regime indices following the definition of Michel and Rivière (2011): Scandinavian blocking (blue line), positive NAO (red line), negative NAO (green line), and Atlantic ridge (yellow line), identified with a k-means clustering approach (Michelangeli et al. 1995). (b) Time series of ECMWF IFS anomaly correlation coefficient (ACC) for geopotential height at 500 hPa over an area 35 to 75°N and 60 to 0°W for a forecast lead time of +120 h (shown at the initial time of the forecast): IFS deterministic forecast (black line), ensemble mean (red line), 50% of the ensemble members (orange area) and all members (yellow area). (c) NAWDEX IOPs as indicated in Table 3 (red bars). Light grey box depicts the NAWDEX campaign period and the dark grey boxes mark the duration of weather sequences as shown in Figure 6.

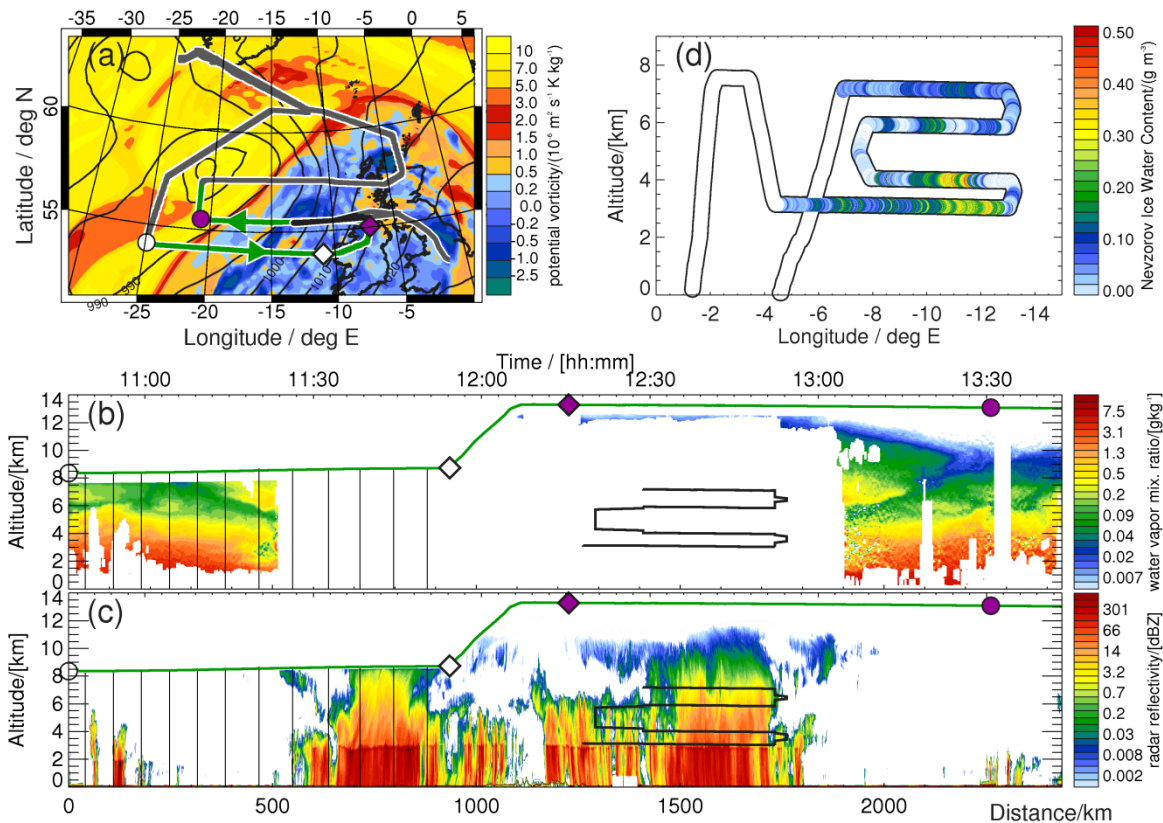**Fig. 6.** Three sequences that illustrate the NAWDEX storyline from trigger to interaction, development and HIW in Europe (based on ECMWF IFS operational analyses). All panels display PV on 325 K (PV < 2 PVU in white, 2 PVU ≥ PV < 5 PVU in red, 5 PVU ≥ PV < 8

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1214   PVU in orange, PV ≥ 8 PVU in yellow), contours of wind speeds (grey contours; 60, 70 and

1215   80 m s^{-1}) and MSLP (blue contours; interval 10 hPa). Some long-lived, coherent features are

1216   labelled to enable links from one frame to the next. K refers to TS Karl; W, F, S and St mark

1217   midlatitude cyclones observed by NAWDEX; C labels a tropopause level cut-off that persists

1218   for 10 days; R1-R9 refer to the prominent ridges along the North Atlantic waveguide,

1219   identified as northward excursions of the jet stream and the isentropic PV gradient; T marks a

1220   TPV.

Fig. 7. ECMWF IFS operational analyses of wind speed (color shading), 2 PVU (green line) at 325 K and MSLP (blue contours, in hPa) at (a) 12 UTC 23 Sep 2016 with Global Hawk flight track (black line, from 2120 UTC 22 Sep to 2100 UTC 23 Sep), (b) 12 UTC 25 Sep 2016 with Global Hawk flight track (black line, from 1820 UTC 24 Sep to 1715 UTC 25 Sep), (c) 12 UTC 26 Sep 2016 with HALO flight track (black line, from 10 to 19 UTC), and (d) 12 UTC 27 Sep 2016 with HALO (black line, 1130 to 2030 UTC), FAAM (pink line, 0800 to 1230 UTC) and DLR Falcon (purple line, 0930 to 1330 UTC) flight tracks.
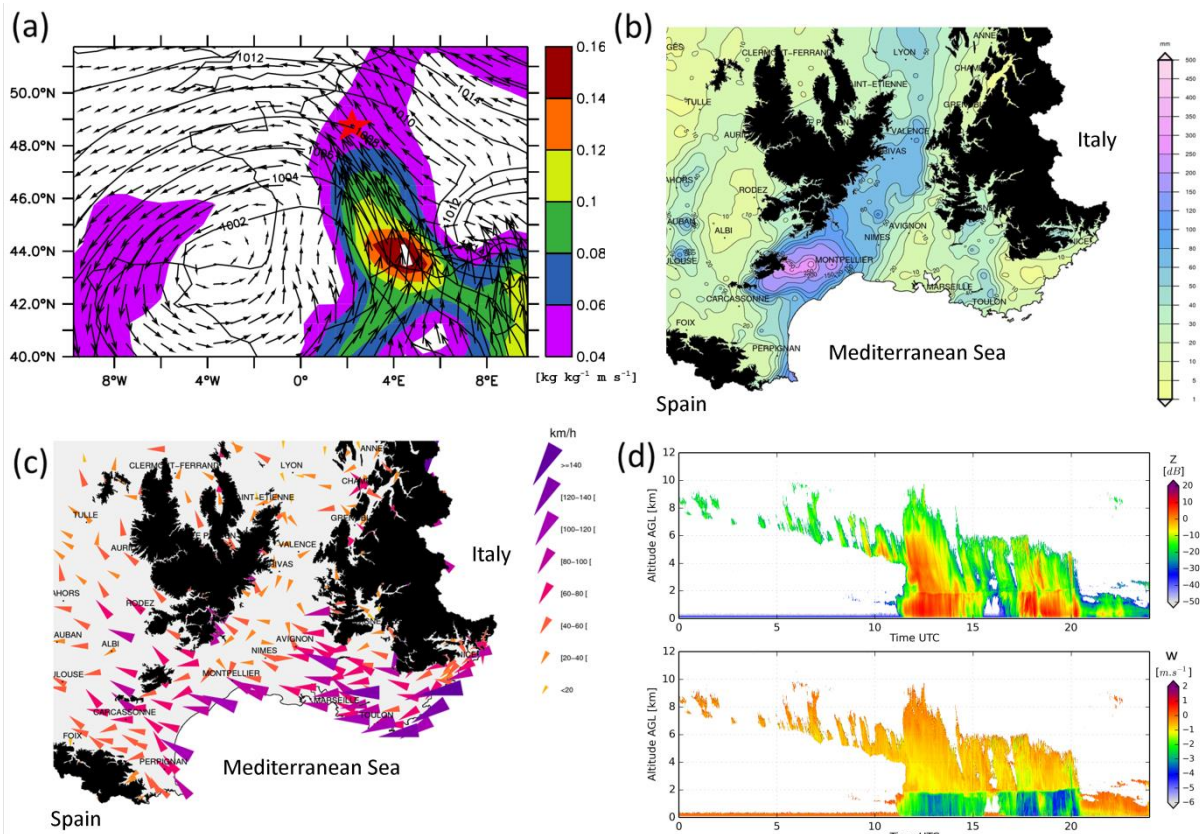
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Fig. 8. WCB observations on 23 Sep 2016 (IOP 3): (a) ECMWF IFS operational analysis of PV at 325 K (shading) and MSLP (black contours, in hPa) at 12 UTC 23 Sep 2016 with HALO flight track from Iceland (gray / green line; green part corresponds to the section shown in (a) and (b)) and FAAM flight track (gray / black line; black part corresponds to track in (a) and (b)). The circle and diamond markers indicate the start and end positions of the latitudinal WCB cross-sections. (b) WALES DIAL water vapor mixing ratio (colors) and (c) HAMP radar reflectivity with HALO flight track (green line), FAAM flight track (thick black line, lowest leg was flown first) and dropsonde release positions (thin black lines). Only the part of the FAAM flight track with a spatial collocation to HALO is shown and both aircraft started at the same time, but had a time lag of ~2.5 h at the end of the last upper-most FAAM leg. (d) Ice water content as observed along the FAAM flight track. Differences between the flight tracks in (a,b) and (d) result from interpolation of FAAM position to the closest HALO observation in (a). The longitude axis in (d) was reversed to align with the time axis of the HALO flight track.

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Fig. 9. Jet stream observations on 2 Oct 2016 (IOP 6): (a) ECMWF IFS operational analysis

of PV at 320 K (shading) and MSLP (black contours, in hPa), and (b) 300 hPa wind speed

(colors) and geopotential height (black contours, in dam) at 06 UTC 2 Oct 2016. (a) and (b)

include flight tracks of the DLR Falcon (light green line) and SAFIRE Falcon (dark green

line). The coordinated part of the flight from east to west shown in panels (c) and (d) is

marked with the purple line. (c) DLR Falcon 2-µm DWL wind speeds (colors) and (d)

SAFIRE radar-derived wind speeds (colors). Grey area in (c) and (d) marks the topography of

Greenland.

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1255 **Fig**.10. (a) ERA Interim moisture fluxes at 850 hPa (arrows, shadings shows magnitude) and

1256 surface pressure (black contours, hPa) at 12 UTC 13 Oct 2016. The red star indicates the

1257 location of the SIRTA surface observation site. (b) Daily accumulated precipitation (mm) and

1258 (c) daily maximum of instantaneous surface wind in southern France on 13 Oct 2016 from the

1259 high-resolution climatological network of Météo France surface weather stations. The black

1260 areas in (b) and (c) mark topography of the French Pyrenees, the Massif Central and the

1261 French Alps. (d) Reflectivity and Doppler velocity (approximately equal to terminal fall

1262 speed) at the 25 m resolution of the radar BASTA at SIRTA on 13 Oct 2016.
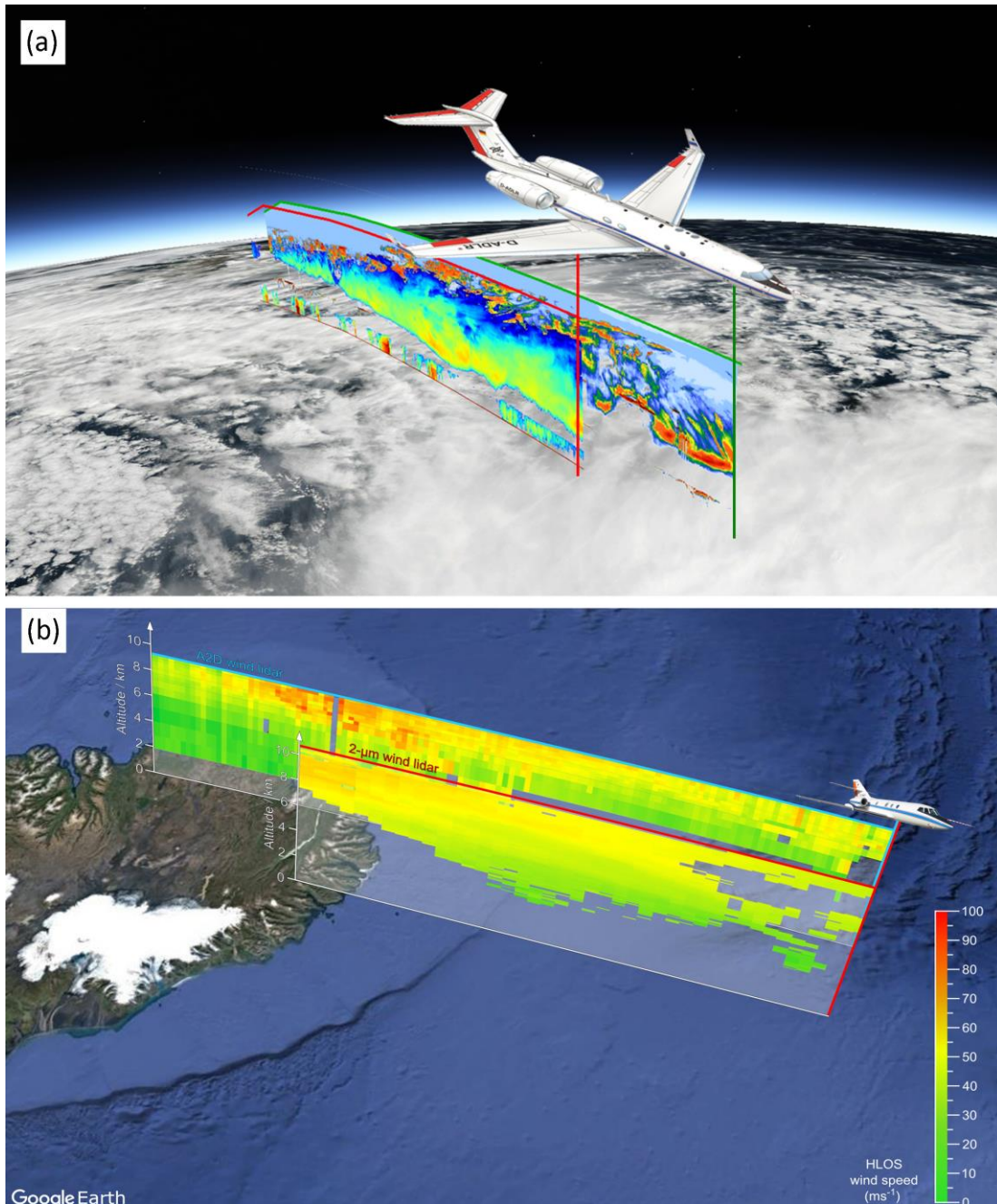
1263

Fig. SB1. (a) Collocated observations of the vertical cloud structure below HALO, based on lidar (backscatter, along green part of the flight) and radar (radar reflectivity along red line). The underlying true color image was acquired by MODIS Aqua near the time of the flight (Global Imagery Browse Services (GIBS), operated by the NASA/GSFC/Earth Science Data and Information System). (b) Collocated wind observations on board the DLR Falcon using the A2D direct-detection wind lidar (along the blue line) and the 2-µm coherent DWL (along the red line). The latter is horizontally displaced from the actual flight track for clarity (Background picture: © 2017 Google).
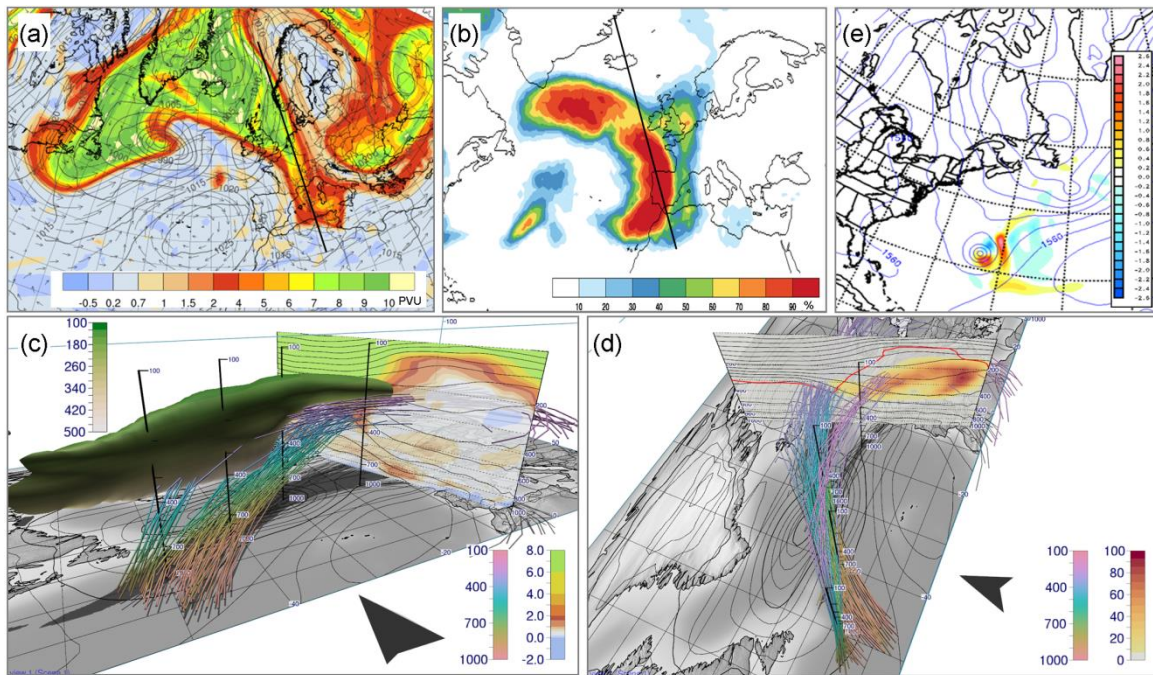
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Fig. SB2. NAWDEX forecast products for 12 UTC 26 Sep 2016 (lead time +60 h): (a) ECMWF IFS deterministic forecast of PV on 330 K (color shading) and mean sea level pressure (MSLP, in hPa). (b) WCB column probabilities of occurrence (color shading in %), derived from ECMWF ensemble (Schäfler et al. 2014; Rautenhaus et al. 2015b). Black line indicates location of cross section in Met.3D visualizations in (c) and (d). (c) Isosurface of ensemble mean wind of 60 m s^{-1} (color indicates pressure on isosurface in hPa) and MSLP (black surface contours). The cross section shows ensemble mean PV (color shading) and potential temperature (black contours). Colored lines represent WCB trajectories of ensemble member 22, starting at 06 UTC 25 Sep 2016 (colored by pressure). The black vertical poles have been added to aid spatial perception; they are labeled with pressure in hPa. (d) WCB trajectories as in (c) but from a different viewpoint and combined with a cross section showing 3D WCB probabilities (color shading, in %), ensemble mean potential temperature (black contours) and the 2 PVU isoline (red contour). (e) COAMPS adjoint 48 h forecast moisture sensitivity at 850 hPa [color shading, increments every 0.2 m^2 s^{-2} (g kg^{-1})$^{-1}$] and 850 hPa geopotential heights (contours every 30 m) valid at 12 UTC 24 Sep (initial forecast time).