

Boundary-Layer Meteorology

A review of Coastal Fog Microphysics during C-FOG

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1 **A review of Coastal Fog Microphysics during C-FOG**

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 10 measurements made during the C-FOG (*Toward Improving Coastal Fog Prediction*) field
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 20 wind components, used for fog intensity (visibility) evaluation. Results suggest that
 21 detailed microphysical observations collected at the supersites and aboard the Research
 22 Vessel (*R/V Hugh R. Sharp*) are useful for developing microphysical parameterizations.

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41 each other. The magnitude of 3D-wind fluctuations was higher during the formation and
42 dissipation stages. An array of cutting-edge instruments used for data collection provided
43 new insight into the variability and intensity of fog (visibility) and microphysics. It is
44 concluded that further modifications in microphysical observations and parameterizations
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46 models.

47

48 **Keywords:** Coastal Fog, Eddy Dissipation Rate, Fog Microphysics NWP parameterization, Visibility.

49

50 1 Introduction

51 Coastal fog plays an important role for weather conditions affecting marine environments
52 that include aviation (Gultepe et al 2020), marine shipping (Fernando et al 2020),
53 sporting and social activities (Pezzoli et al 2010), as well as vegetation (Schemenauer et
54 al 2016; Torregrosa et al 2014). The direct consequence of fog is the impairment of
55 visibility, and hence the ‘intensity’ of fog is defined in terms of visibility (Vis).
56 Advection supplies moisture for Atlantic-Canadian coastal fog, while the overhead
57 passage of cyclonic or anticyclonic systems fosters its actual formation (Dorman et al.
58 2020). Other factors such as large-scale subsidence leading to thermal inversions, frontal
59 systems, radiative cooling, topography, tropical cyclones, and turbulence fluxes can also
60 have an impact on the life cycle of coastal fog (Gultepe et al 2007; Toth et al 2011).
61 Intensity of turbulence and turbulence dissipation rate occurred during life cycle of
62 radiation fog were studied by Zhou and Ferrier (2008) and Price (2019) and these
63 suggested that turbulence intensity should be less than a threshold value.

64 Microphysical measurements were performed using a fog measuring device
65 (FMD, FM100) for the first time by Gultepe et al (2007a) during the FRAM project,
66 followed by others (Niu et al 2010; Spiegel et al 2012; Isaac et al 2020). The FM100 was
67 developed using the principles of a forward scattering probe (FSSP), measurements of
68 which were used in developing Vis parameterization by Gultepe et al (2007b). The
69 FM100 provides droplet spectra, which are used to obtain liquid water content (LWC*),

70 -----

71 *Definitions are provided in Nomenclature in the end of paper.
72 mean volume diameter (MVD), effective size (r_{eff}), droplet number concentration (N_d),
73 and the droplet settling rate ($\text{LWC} \cdot V_f$), where V_f is the droplet fall velocity. NWP
74 modeling and evaluation studies of fog have helped to improve forecasting and gain
75 physical insights (e.g. Yang et al. 2009; Gultepe et al. 2007a,b). Warm-fog droplet spectra
76 and its distribution are related to condensation nuclei (CN) and relative humidity with
77 respect to water (RH_w). There have been several studies on this issue, but cloud
78 condensation nuclei (CCN) versus supersaturation with respect to water (S_w)
79 relationships are mostly developed for cloud studies and generally use fixed values of
80 100 cm^{-3} for marine environments (Thompson et al 2008). In reality, such fixed values
81 may not be valid, and therefore we have seen parametric modifications. Prediction of N_d
82 is obtained using prognostic equations that represent processes related to turbulence,
83 droplet growth, radiative heating/cooling, as well as turbulence flux divergence
84 (Storelvmo et al 2014). Based on assumed modified-gamma distributions, either using
85 Kohler theory (Chen 1994) and/or Twomey parameterization (Twomey 1959), N_d
86 predictions can be performed using single or double moment microphysical schemes
87 (Milbrandt and Yau, 2005a,b; Morrison and Gettelman 2008; Schwenkel and Maronga,
88 2019). However, these schemes have been developed for clouds and not for fog.

89 As in Twomey et al (1959), N_d is parameterized based on Kohler theory assuming
90 equilibrium and cooling of an air volume by lifting via the vertical air velocity (w_a). The
91 latter in fog, excluding formation and dissipation conditions, is usually not as strong as in
92 clouds, complicating the application of these parameterizations to fog. Therefore, its
93 usage cannot be verified for all fog types. Another equation for N_d prediction, mainly
94 applicable to climate studies, expresses it as a function of w_a , N_a (aerosol total number
95 concentration) as well as aerosol composition (Abdul-Razzak and Ghan 2000; Ghan et al
96 1998; 2001). In addition to parameters given in Twomey (1974; 1991), this equation uses
97 aerosol composition as an independent parameter. Clearly, environmental conditions such
98 as air temperature (T_a), dew point temperature (T_d) and RH_w , and w_a as well as aerosol
99 and microphysics parameters (CCN and droplet growth rate) play an important role in N_d
100 prediction, thereby affecting Vis estimation (Schwenkel and Maronga, 2019). In this
101 regard, Gultepe et al (2007b) have suggested that accurate predictions of N_d and LWC are

102 critical for Vis prediction, and Vis cannot be accurate if only LWC is used (Kunkel 1984;
103 Stoelinga and Warner 1999). Vis is usually diagnosed in the post processing stage of
104 forecast model outputs using Stoelinga-Warner's method (Stoelinga and Warner 1999),
105 which includes large uncertainties in fog prediction (Gultepe et al 2006, 2007c).

106 Lately, field observations from various projects have been used to improve Vis
107 parameterizations (Gultepe et al 2009; 2014; Haeffelin 2010; Price et al 2018; Wang et al
108 2020) but these are often site dependent because of the nature of N_a spectra and
109 compositional properties (Bergot et al 2005). In this respect, marine fog studies used
110 microphysical parameterizations extensively (Gultepe et al 2009; Gultepe et al 1996).
111 The C-FOG (Toward Improving Coastal Fog Prediction) field project has had better tools
112 to evaluate coastal fog microphysical and dynamical properties, such as droplet and
113 aerosol spectra and turbulence over both the coastal areas and at the ship (Fernando et al
114 2020).

115 Vis parameterizations commonly use only RH_w and/or (T_a-T_d) (called dew point
116 depression) to predict fog coverage but they cannot be used for fog intensity (e.g., Vis)
117 because RH_w (as well as T_a-T_d) indicates only the existence of fog (Toth et al., 2011;
118 Gultepe et al 2009; Dimitrova et al 2020). Therefore, fog microphysical parameters such
119 as LWC and N_d are needed for accurate Vis forecasting, but they are not accurately
120 predicted by models (Pu et al 2016, Dimitrova et al 2020, Gultepe and Milbrandt 2010).
121 In single-moment and double moment microphysical schemes used in NWP models,
122 LWC is usually a prognostic variable and N_d is assumed as a fixed value or obtained
123 either deterministically or prognostically, by making several assumptions on physical
124 terms affecting N_d . If N_d is not fixed, a modified gamma distribution is usually assumed
125 in presenting fog droplet size distribution that is used to obtain N_d .

126 In this work, C-FOG related studies are briefly summarized; WRF fog simulations
127 using various microphysical and surface boundary layer schemes are performed for Vis
128 predictions at the ship and supersite locations. Another microphysics paper is focused on
129 a case of stratus lowering fog over the coastline based on the *R/V Sharp* observations
130 (Wagh et al 2020). Understanding fog microphysics and its impact on Vis, based on a
131 LES model, is provided by Wainwright and Richter (2020). A study using a Tethered
132 Balloon System (TBS) with aerosol and droplet spectral measurements as well as fog

133 thermodynamics is examined by Singh et al (2020). Detailed coastal fog observations at
134 The Downs, Ferryland (Wang et al. 2020) are studied by providing TBS dynamic and
135 thermodynamic profiles and collecting fog-droplet spectra from a CDP modified to
136 increase and measure the instantaneous flow rate. Perelet et al (2020) present a
137 methodology for using a two-wavelength scintillometer system for measuring fog
138 characteristics on scales of 1 km. Wang et al. (2020) also focused on the impact of the
139 fog layer on optical propagation using contrasting measurements at Ferryland and on the
140 US West Coast. In addition, large-scale synoptic events affecting local fog formation are
141 summarized by Dorman et al (2020). An overview of the C-GOG project is given in
142 Fernando et al. (2020).

143 The goal of this paper is to provide an overview of coastal fog microphysical
144 measurements and to evaluate microphysical parameterizations based on the C-FOG field
145 project. In addition, the importance of fog Vis predictions is discussed and challenges are
146 noted when turbulence kinetic energy (TKE) dissipation rates are included. The C-FOG
147 field project has provided microphysical observations from several coastal sites and the
148 *R/V Hugh R. Sharp* (hereafter *R/V Sharp*). The paper organization is planned as follows:
149 Section 2 provides information on observations and project design. Section 3 explains the
150 analysis used in Vis and eddy dissipation rate (EDR) parameterizations. Sections 4 and 5
151 focus on discussions and conclusions, respectively.

152

153 **2 Field Project and Observations**

154 **2.1 Project Location**

155 The C-FOG field campaign took place from 01 September to 07 October 2018. The field
156 campaign took place along the coastlines of Atlantic Canada and the northeastern US. C-
157 FOG is designed to advance our understanding of liquid fog formation, development, and
158 dissipation over coastal environments, and thus improve fog predictability and
159 monitoring. It was designed to capture fog variability in time and space using an array of
160 platforms that included ground, airborne, and shipborne in-situ instruments, remote
161 sensors as well as numerical models. Instruments were located at two supersites (Battery
162 and The Downs sites in Ferryland, NL; Figure 1a,b), four satellite sites, as well as on the
163 *R/V Sharp* (Fernando et al 2020). Figure 1c shows the entire project area overlaid on a

164 satellite SST image for 28 September 2018. A strong SST gradient stands out near the
165 northern region of the project area. In the current study, four cases are presented covering
166 parts of the Intense Operational Periods IOP10 (27–30 Sep 2018) and IOP 12 (03-04 Oct
167 2018) that mainly represent warm advection fog events (Table 1).

168

169 **Table 1** Case studies of coastal fog events studied in the present work. T_a is air temperature and SST is sea
170 surface temperature.

Day	Location	Weather
Sep 28 2018	Battery supersite	T_a , SST, warm air advection
Sep 29 2018	Battery supersite	Warm air advection
Sep 28 2018	R/V Sharp	Warm air advection
Oct 04 2018	R/V Sharp	Advection and tropical depression

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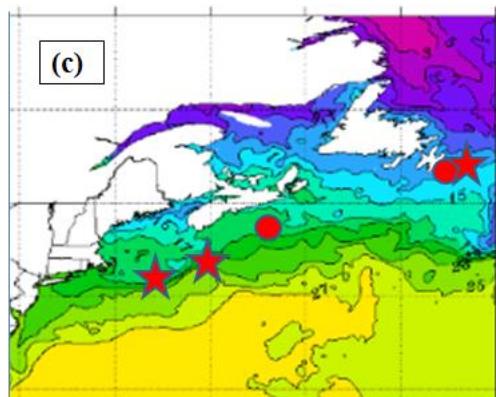
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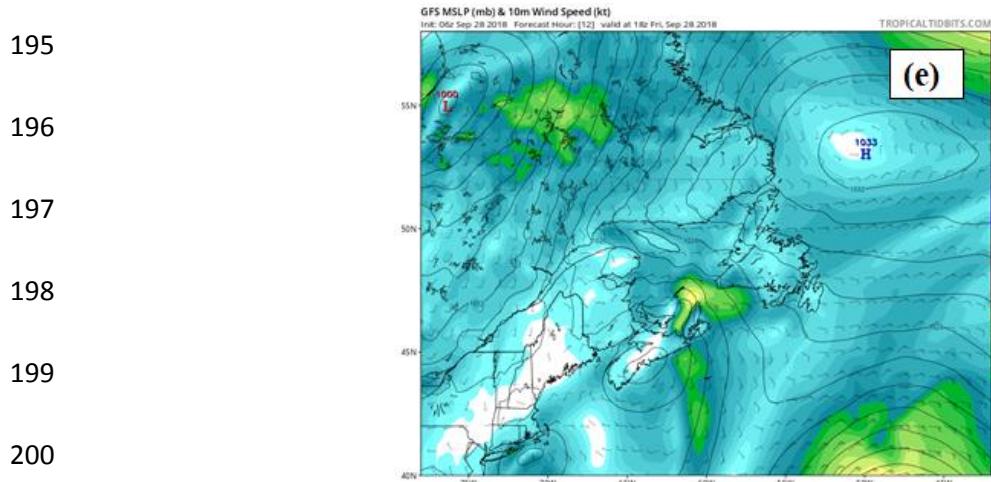
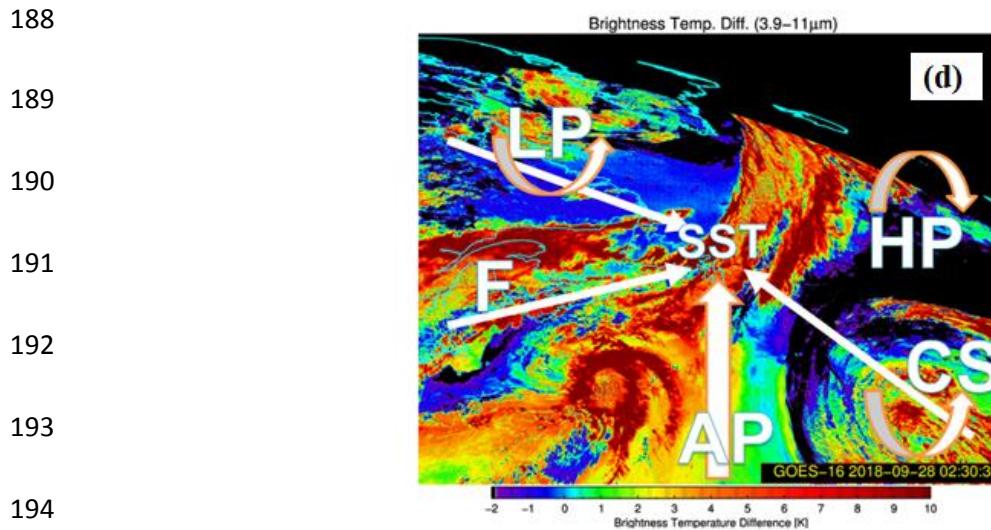
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201 **Fig. 1** Ferryland supersite region (a), Battery supersite (b), NOAA NESDIS Geo-Polar blended 5 km SST
 202 and entire project area with supersites (red circles) and ship locations (indicated by a red star for foggy days
 203 (c), synoptic weather systems affecting project area (d) with LP for “low pressure”, F “front”, SST “sea
 204 surface temperature”, AP “advection process”, HP “high pressure”, and CS “cyclonic system”, and US
 205 NCEP (National Center for Environmental Prediction) GFS (Global Forecasting System) based surface
 206 pressures and wind speed in Knots (e).

207

208 2.2 Synoptic Weather Systems

209 The C-FOG campaign took place at the end of the summer fog season (Gultepe et al 2009).
 210 During this time, various weather systems affect coastal-fog conditions. Figure 1d shows the SST
 211 for the project area and Fig. 1e is the GFS sea-level pressure and 10 m wind vectors on 28
 212 September 2018. The latter shows major weather systems affecting the project area: a low

213 pressure over Nova Scotia in the NW and associated with a warm frontal system (F) in the
214 east, a high pressure (HP) to the NE, and tropical cyclones to the south east (CS), and
215 warm-air advection processes (AP) resulting from T and q_v gradients along a north-south
216 direction. The tropical cyclones usually became tropical depressions when moved to
217 colder northern latitudes and usually they were about 500 km south and southeast of the
218 main project site. During May 25-Oct 31 2018, 16 tropical depressions occurred over 4-
219 months time period and about 4 of them affected physical conditions somehow at the
220 project site. Their advection of SW quadrant of warm and moist air to N and NW
221 quadrants likely played an important role for fog formation 100s of km away from storm
222 center. . The photos in Figure 2 depict fog cases observed at The Downs supersite, and
223 from the *R/V Sharp*, respectively.



224
225 **Fig. 2** The pictures of advection process occurring on Sep 28/29 2018 case at the Downs supersite (a) and
226 on Oct 04 2018 (taken from the RV) (b).

227 **2.3 Microphysical Observations**

228 In this subsection, microphysical and meteorological instruments are summarized. All
229 instruments used are summarized in Fernando et al. (2020). These measurements are
230 related to dynamics, microphysics, radiation, aerosol, and thermodynamic properties of
231 the environment. For particle size thresholds, fog droplets usually cover 1-30 μm , cloud
232 droplets 1-100 μm , drizzle drops 100 (or 30)-500 μm , and drizzle and rain drops >100
233 μm in diameter.

234 Microphysical instruments used during C-FOG are summarized in Table 2 for the
235 *R/V Sharp* and in Table 3 for all ground-based sites. Special sensors (Table 2) were
236 developed for fog microphysics investigations, including a ‘gondola’ shaped assembly
237 (located on the *R/V Sharp*) that contained microphysical sensors such as a cloud droplet
238 probe (CDP) and a backscatter cloud probe (BCP) in a gondola unit for measuring droplet
239 sizes ranging from 1-50 and 5-75 μm , respectively A laser precipitation monitor (LPM)
240 for 100 μm to mm sizes and an optical particle counter (OPC) for sizes of 0.3-20 μm
241 using 16 spectral channels allowed fog and drizzle discrimination (Table 2).

242
243 **Table 2** Microphysical instruments mounted on the *R/V Sharp* during the C-FOG campaign. *Parameters in*
244 *Column 2*: N_d Droplet number concentration, N_a Aerosol number concentration, SV Sampling Volume, S_w
245 Supersaturation with respect to water, and Vis Visibility. *Parameters in Column 4*: UOIT Ontario
246 Technical University, UU University of Utah, Wood Corporation, DU Dalhousie University, and NDU
247 Notre Dame University.

Instrument Name	Measurements	Height (asl, m)	Owner
CDP, DMT, Gondola	N_d , Droplet spectra (1-50) μm	31.8	UOIT
BCP, DMT, Gondola	N_d , Droplet spectra (5-75) μm	31.8	UOIT
OPC N2, Alphasense	N_a , Aerosol Spectra 0.38-17 μm , 16 channels	15	UU
DMT, FM120, near Gondola	N_d , Droplet spectra (1-50) μm	31.6	WOOD
TSI Moudi Impactor 100NR	N_a spectra, 0.18-18 μm , 8 stages, 30 L m^{-1}	37.9	WOOD
Virtual Impactor Inlet	At 20 m, SV=16.7 L min^{-1}	30.1	DU
SMPS 3082, TSI	N_a Spectra, 10-500 nm; SV=1.0 L min^{-1}	30.1	DU
APS 3321, TSI	N_a Spectra, 0.5-20 μm SV=1.0 L min^{-1}	30.1	DU
ACSM, Aerodyne	N_a Composition, <1 μm SV=0.1 L min^{-1}	30.1	DU
CCN-100, DMT	N_a >0.01 μm ; S_w =0.2,0.4,0.8,1% SV=0.5 L m^{-1}	30.1	DU
PWD22- Vaisala	Vis <20 km	10	NDU

248
249 Also, three Scintillometers (Table 3) with measurements in the NIR (Near Infra-
250 Red) and MW (MicroWave) radiation channels were utilized to allow discrimination of

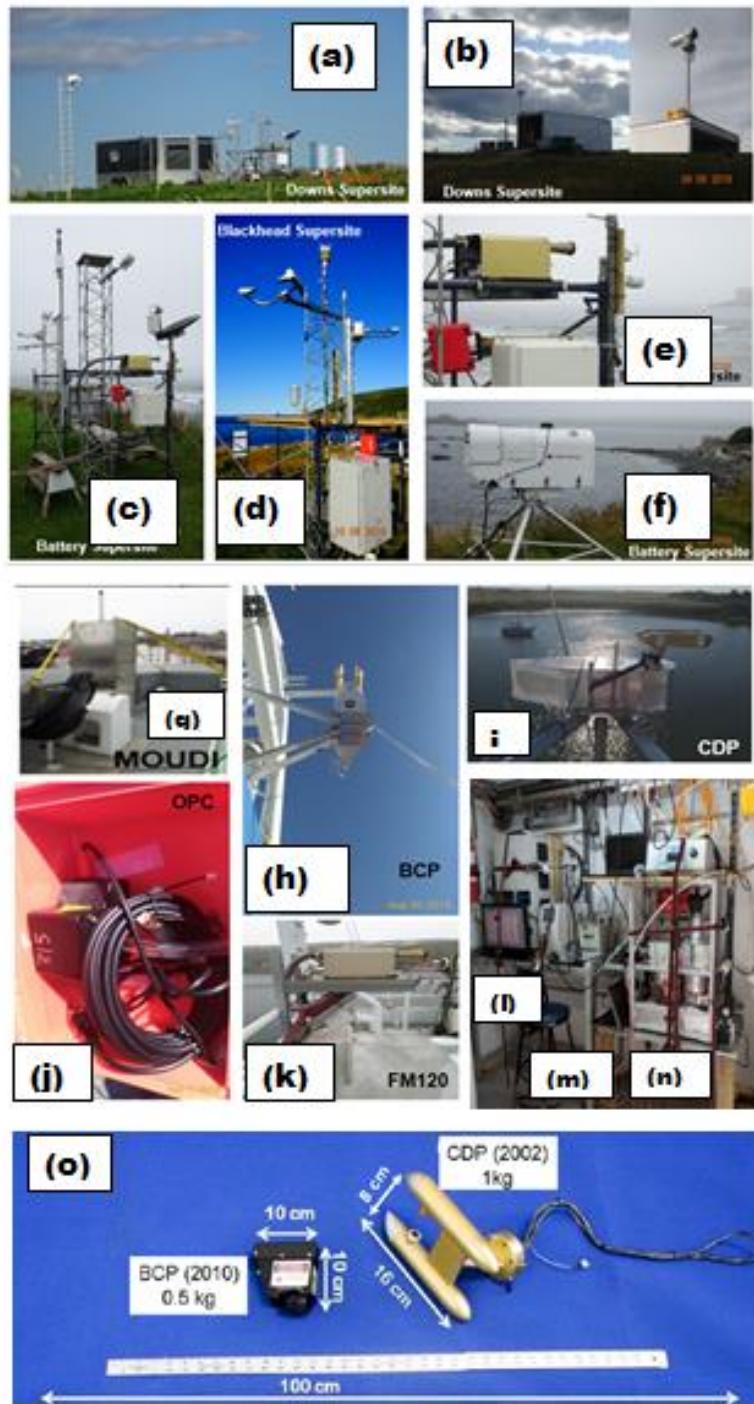
251 fog from rain (Perelet et al. 2020). Figure 3 shows the microphysical, aerosols, as well as
 252 meteorological instruments. Remote-sensing platforms (e.g. microwave radiometer
 253 MWR, ceilometer, Lidar), meteorological towers, tethered balloons, and the GOES-R
 254 (Geostationary Operational Environmental Satellite-R series) Products (fog coverage and
 255 effective droplet size) provided information on horizontal and vertical variability.
 256 Observational products are used for fog-visibility parameterization development, with a
 257 focus on understanding the influence of dynamical processes such as turbulent mixing
 258 and dissipation.

259

260 **Table 3** Microphysical instruments located at the ground sites during C-FOG field campaign. *The*
 261 *parameters in Column 2: Vis Visibility, PR Precipitation rate, IR Infrared, SW shortwave, RF radiative*
 262 *fluxes, LWC liquid water content, Z_e radar reflectivity, V_d Doppler velocity, N_a aerosol number*
 263 *concentration, Z_{cb} cloud base height, β backscattering coefficient, λ wavelength, β_n extinction coefficient,*
 264 *CN condensation nuclei, RH relative humidity, T temperature, U_h horizontal wind, and P pressure.*
 265 *Parameters in Column 7 and 8: BA Battery Supersite, BH Blackhead site, DO Downs Supersite, UOIT*
 266 *Ontario Technical University, UU University of Utah, UND University of Notre Dame, and NPS (Naval*
 267 *Postgraduate School).*

Instrument Name	Measurements	H (agl,m)	Z (agl,m)	Lat [deg]	Lon [deg]	Site	Owner
PWD50-Vaisala	Vis and PR	2	6	47.03443	-52.8782	BA	UOIT
FM100 & FM120	Fog droplet spectra	2	6	47.03443	-52.8782	BA	UOIT
CRN1 Kipp&Zonen	IR&SW up and down RF	2	6	47.03443	-52.8782	BA	UOIT
PMWR MP3017	Profiling, T, RH, LWC	2	6	47.03443	-52.8782	BA	UOIT
MRR, Metek	Z_e & V_d	2	6	47.03443	-52.8782	BA	UOIT
LPM, Metek	Precip. Spectra >100 μm	2	6	47.03443	-52.8782	BA	UOIT
OPC, Alphasense	N_a spectra, >0.3 μm	2	6	47.03443	-52.8782	BA	UU
CL31, Vaisala	Z_{cb} and β	2	6	47.03443	-52.8782	BA	UU
Vaisala PWD 50	Vis (<30 km)	2.9	10	47.52633	-52.6583	BH	UOIT
Vaisala PWD 22	Vis (<30 km)	3	31	47.02181	-52.8731	DO	UND
LPM Metek	Precip. spectra >100 μm	2.74	10	47.52633	-52.6583	BH	UOIT
OPC, Alphasense	Aerosol spect. (0.3-20 μm)	1.37	10	47.52633	-52.6583	BH	UU
DMT CDP	fog droplets (1-50 μm)	3	31	47.02181	-52.8731	DO	NPS
TSI -3563 Nephelometer	$3\text{-}\lambda$ scat& β_n (0.45,0.55,070 μm)	3	31	47.02181	-52.8731	DO	NPS
TSI OPC-310	CN >0.01 μm	3	31	47.02181	-52.8731	DO	NPS
PSAP, Part Soot Abs Photometer	1- λ absorp. at 0.565 μm	3	31	47.02181	-52.8731	DO	NPS
Scintillometer (BLS -900, Scintec AG)	wavelength 0.88 μm extinction	2.9	31	47.02181	-52.8731	DO-BH Tx-Rx	NPS

Scintillometer (BLS 900, Scintec AG)	wavelength 0.88 μ m extinction,	2	6	47.03443	-52.8782	BA-DO Tx-Rx	UU
Scint. MWSC 160, Radio.Phy. GmbH	microwave (wavelength 1.860 μ m extinction	2	6	47.03443	-52.8782	BA-DO Tx-Rx	UU
Met parameters	RH, T, Uh, P	3	31	47.02181	-52.8731	DO	NPS



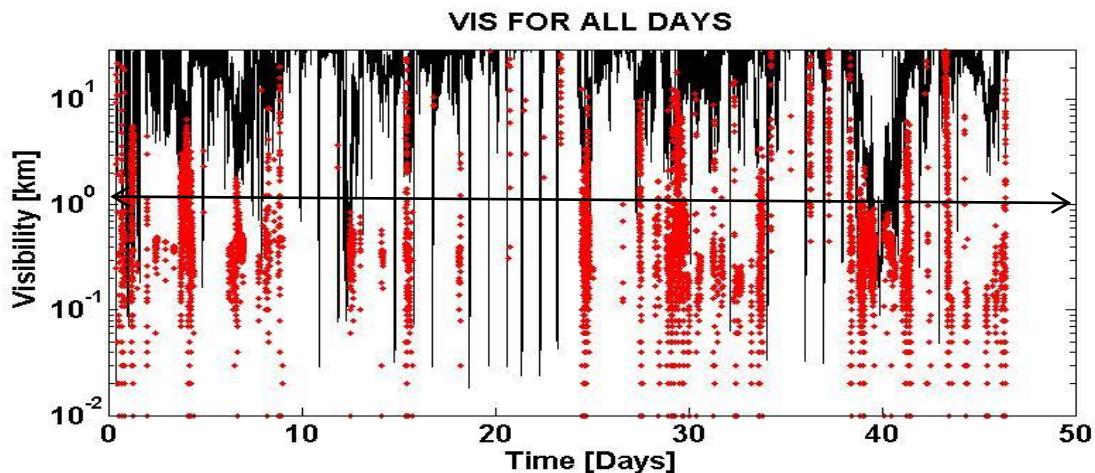
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269 **Fig. 3** Project locations with microphysical probes: The battery site (see Table 3) (a), NPS microphysical
270 sensors mounted on a trailer at the Downs site (b) with CDP2 located in a housing at a mast, FM120, PWD,

271 LPM at Battery (c), PWD, LPM, and OPC at Blackhead (d), a close look of FM120 at Battery (e), PMWR
272 at Battery (f), Wood MOUDI impactor (g), Gondola BCP (h) and CDP2 (i) mounted on Sharp RV, UU
273 OPC (j), Wood Corp FM120 (k), Dalhousie University(DU) CCNC (l), DU SMPS (m), and DU ACSM (n),
274 and Gondola housed CDP and BCP (o) physical characteristics (adapted from Beswick et al. 2014).

275 **2.4 Macro-physical Characteristics**

276 During the installation and campaign period that spanned 7-weeks (Aug 14-Oct 7 2018)
277 various fog conditions existed, as represented by Vis measurements from the Battery site
278 (Fig. 4). This figure shows Vis for 46 days starting from Aug 21 to Oct 7 during which
279 drizzle and light precipitation usually occurred prior to fog. Average fog occurrence
280 during entire campaign was 20-25%.



282 **Fig. 4** Time series of Vis obtained from PWD52 present weather sensor for the entire time period from Aug
283 24 to Oct07 2018. The red dots are for drizzle and black lines are for fog Vis. The line with double arrow
284 indicates Vis level at 1 km.

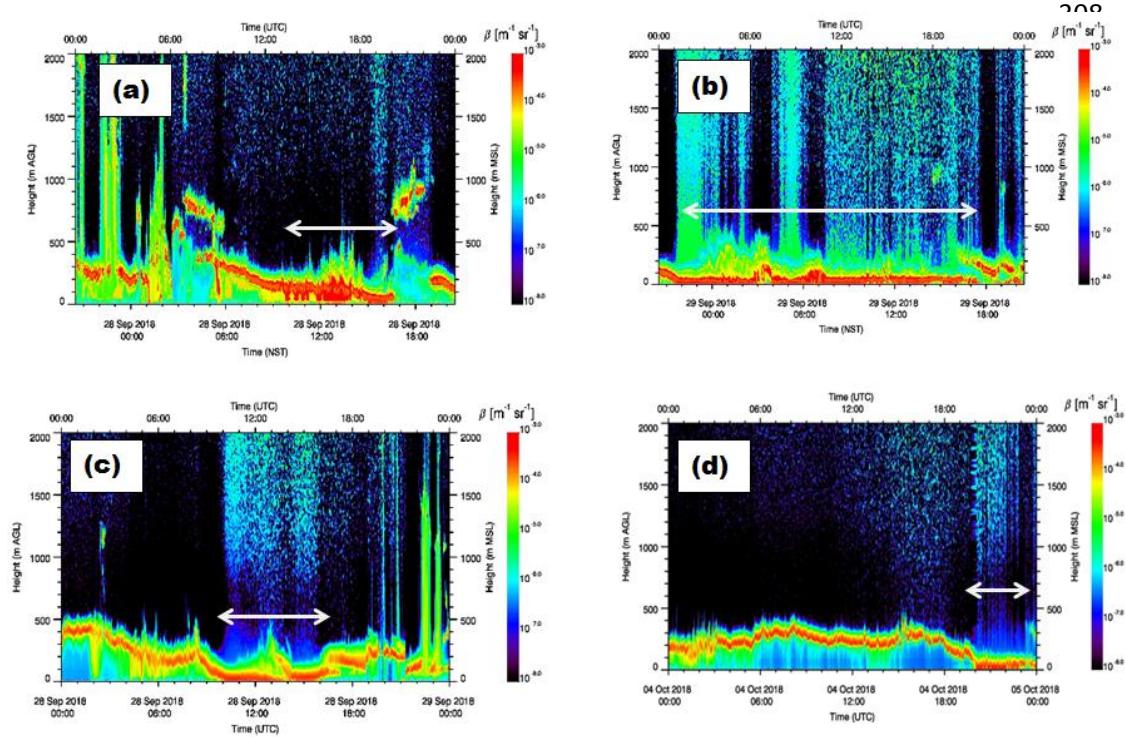
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286 A CL31 ceilometer measured the backscatter ratio (β) time and height cross
287 sections at the Battery supersite and on the *R/V Sharp* for the 4 cases studied, as shown in
288 Fig. 5. Note that the ceilometer-based fog-top heights are not accurate because of its
289 strong extinction when a large number of smaller fog droplets exist. Figure 5a and 5b are
290 for 28 and 29 September cases, respectively, as observed at the Battery supersite and Fig.
291 5c and 5d are for 28 September and 04 October cases, respectively, aboard *R/V Sharp*.

292 The 28 September case at the Battery site, occurred at about 1000 UTC after the
293 stratus layer base lowered from 500 m to the surface over 3 hrs. Some drizzle was
294 observed (indicated by the spiking cloud base in red colour), which disappeared about

295 1700 UTC. The 29 September case was a continuation of the 28 September case, during
 296 which fog briefly lifted at 1600 UTC and then re-formed at 2200 UTC and lasted until
 297 almost 1800 UTC, which is not likely related solely to a lowering stratus, but was also
 298 likely due to warm-air advection that is verified by using synoptic weather conditions

299 The *R/V Sharp* data for 28 September (Fig. 5c) show that the cloud base
 300 decreased from 500 m at 0000 UTC to almost the surface at 1000 UTC, and then lifted
 301 very quickly at 1330 UTC. After this, the stratus base lowered again to form fog at 1400
 302 UTC. At 1600 UTC, the fog base lifted and eventually disappeared. The *R/V Sharp*
 303 observations for 04 October show that fog formed again due to stratus lowering around
 304 2000 UTC and lasted until 2300 UTC. Note that the lowering cloud base occurred late on
 305 this day and is likely due to IR cooling and/or large-scale subsidence. This might also be
 306 related to drizzle that moistened lower layers, eventually led to fog formation (Singh et al
 307 2020; Wagh et al 2020).



322 **Fig. 5** Time-height cross sections of backscatter coefficient (β) from CL31 ceilometers measurements at the
 323 Battery supersite and onboard the Sharp RV for the 4 cases studied; Sep 28 (a) and Sep 29 (b) cases
 324 observed at the Battery supersite and Sep 28 (c) and Oct 04 2018 (d) cases at the Sharp RV. The white
 325 lines with arrow indicate foggy regions.

326 The general characteristics of these four fog cases at the Battery supersite and *R/V*
327 *Sharp* are presented as a backdrop for the development of microphysical
328 parameterizations. Note that ceilometer measurements cannot unequivocally identify fog
329 regions, and ceilometer inferences should be validated using PWD Vis observations.

330

331 **3. ANALYSIS AND MICROPHYSICAL PARAMETERIZATION**

332 An analysis of the main microphysical and turbulence parameters to be used in the
333 evaluation of fog conditions and for developing parameterizations is provided in this
334 section.

335

336 **3.1 Time Series of microphysical parameters and Turbulence Dissipation Rate (ε)**

337 Time series were obtained based on various microphysical parameters, including Vis, N_d ,
338 LWC, and MVD. Vis was obtained from PWD52 measurements representing various
339 NWS (National Weather Service) codes, droplet spectral measurements of FMD (FM120,
340 in Battery) and CDP and BCP housed in the gondola aboard the *R/V Sharp*. NOAA NWS
341 codes can be found in LPM (2011), based on PR and Vis time series for each
342 hydrometeor type obtained. The FMD was operated at a 1 Hz sampling rate, compared to
343 1-min Vis measurements from PWD52. All meteorological parameters such as T, RH_w ,
344 and wind speed (U_h) and directions were employed as appropriate.

345 N_d is obtained using the corrected ship heading and apparent wind, which
346 includes both ship speed and wind measurements (Gultepe and Starr 1995). It is corrected
347 by computing the cosine of the angle θ between the heading and the apparent wind
348 measured by an anemometer as

$$349 \quad N_d = N_c / (SA * TAS * \Delta t), \quad (1)$$

350 where the true air speed (TAS) is given by

$$351 \quad TAS = U_{ha} \cos \theta. \quad (2)$$

352 In Eq. 1, SA is the sampling area, Δt the sampling interval and N_c the counts of
353 droplets in each bin of the CDP and BCP. N_d is obtained from the FM120 located at the
354 Battery site using a fixed TAS (true air speed) of 5 m s^{-1} for sampling of the
355 environmental air. U_{ha} is the apparent wind speed that includes both ship speed and wind

356 speed. During normal observational conditions, the *R/V Sharp* average speed was about 8
357 m s^{-1} .

358 The TKE dissipation rate (ε_{dis}) is usually calculated based on the spectral slope
359 assumption, representing the inertial subrange (Panofsky and Dutton, 1984). In this work,
360 3D sonic anemometer wind measurements (collected at 20 Hz) at 2 m were used to
361 estimate ε . It should be noted that ε calculation is strongly related to averaging scales and
362 here ε approximately represents scales of 0.3-0.5 km that matches scales of high
363 resolution NWP models. Thus, using a structure function, ε is estimated (Paluch and
364 Baumgardner, 1989; Gultepe and Starr, 1995). Clearly, 1-min averages do not capture
365 inertial subrange scales but a structure function representing 3D scales can be used to
366 calculate ε_{dis} along the mean horizontal wind speed as

$$367 \quad \varepsilon_{\text{dis}} = \frac{1}{2\pi 4.01C} \left| \frac{D_s}{\Delta r^{2/3}} \right|^{3/2}, \quad (3)$$

368 where C is a constant ~ 0.18 , D_s the structure function and Δr the horizontal distance
369 along main horizontal wind, and these are given, respectively, as

$$370 \quad D_s = 0.38(\Delta u^2 + \Delta v^2 + \Delta w^2) \quad \text{and} \quad \Delta r = \Delta t(U_{dx}^2 + U_{dy}^2)^{1/2}. \quad (4)$$

371 In Eq. 4, Δu , Δv , and Δw represent the change in wind components along x, y, and z axis
372 at unit time interval (Δt), respectively; U_{dx} and U_{dy} are wind speed components along x
373 and y axis, respectively, over Δt . Thus, Eq. 3 can then be used in dissipation rate
374 calculations and evaluation of the fog life cycle. For the NWP models, ε is not always an
375 output parameter; therefore, TKE can be calculated from the following equation (or a
376 transformation equation given in Discussion section) that is used to obtain a threshold for
377 fog formation:

$$378 \quad TKE = \frac{1}{2}(u'^2 + v'^2 + w'^2), \quad (5)$$

379 where u' , v' , and w' are fluctuations of wind x, y, and z components that are calculated
380 over 10 min intervals.

381

382 **3.2 Visibility Parameterization**

383 The visibility parameterization is calculated diagnostically, which is a function of various
384 moments of DSD (drop size distribution). In this study, N_d and LWC are used in the Vis
385 parameterization; but N_d is replaced with MVD to emphasize that two microphysical

386 parameters are sufficient to calculate Vis (Gultepe et al 2018). It is emphasized that
387 either RH_w or T_a-T_d can be used to indicate the existence of fog, but not intensity (e.g.
388 Vis).

389

390 **3.2.1 Vis- RH_w Parameterization**

391 The visibility can be parameterized as a function of RH_w , which is measured by a Vaisala
392 HMP 155. RH_w is measured together with T_a from which T_d is estimated. A PWD is used
393 to obtain Vis measurements. The functional relationship between Vis and RH_w is
394 determined by testing various regression fits and selecting the function that ‘best’ fits the
395 observations. Here, humidity data used for the best fit are first bin averaged in 5%
396 intervals. A derived relationship between Vis and RH_w together with a plot is provided in
397 section 4.1.1 and given in Table 3. Note that we do not use T_a-T_d in the Vis
398 parameterization because RH_w is based on both T_a and T_d (Gultepe and Milbrandt 2011).
399 Therefore, fog coverage is obtained when $RH_w > 95\%$, which is further explained in the
400 results section.

401

402 **3.2.2 Vis versus Microphysics Parameters**

403 Fog Vis can be obtained in two ways. The *first* is based on an extinction coefficient
404 measured directly by a probe (e.g., PWD) which is then used to retrieve microphysical
405 parameters assuming certain particle size distributions. The *second* is based on droplet
406 spectral measurements from which LWC and N_d (or MVD) can be used to estimate Vis.
407 Usually, direct measurement of Vis cannot be considered in the same way as those
408 obtained from measured particle size spectra, because of measurement issues. Using
409 warm fog microphysical spectral measurements, Gultepe et al (2006) developed a
410 parameterization that is based on the theory of extinction of visible light in a volume of
411 fog droplets as

$$412 \quad \beta_{ext} = \sum_{r1}^{r2} \pi Q_{eff}(r, \lambda) n(r) r^2 \Delta r, \quad (6)$$

413 where β_{ext} is the extinction coefficient (cm^{-1}), Q_{eff} the extinction efficiency, r droplet
414 radius (μm), λ the visible light wavelength (μm), $n(r)$ the particle number density (cm^{-3}
415 μm^{-1}), and r^2 the droplet surface area. Q_{eff} is usually assumed to be 2, because size

416 parameters ($k=2\pi r/\lambda$) are within the regions where geometric optics apply. For sizes less
 417 than about 5 μm , Q_{eff} can be larger than 2, significantly affecting the extinction of visible
 418 light. Equation 5 can be used for calculating β_{ext} if the particle size spectrum is known for
 419 each time step, when NWP model simulations exist.

420 The extinction coefficient (Eq. 6) can be converted into Vis using the
 421 Koschmieder (1924) relationship as

$$422 \quad Vis = \frac{-\ln(C)}{\beta_{\text{ext}}}. \quad (7)$$

423 For the meteorological observed range (MOR), C is defined as the threshold value that
 424 best fits to conditions whereby the human eye can recognize a target during daytime and
 425 is taken as 0.05 (Gultepe et al 2014). Using Eq. 5 and Eq. 6, the Vis can be obtained as

$$426 \quad Vis = \frac{-\left(\frac{4}{3}\right)\ln(\varepsilon)\rho_w \sum_{r_1}^r n(r)r^3 \Delta r}{Q_{\text{ext}} LWC \sum_{r_1}^r n(r)r^2 \Delta r}. \quad (8)$$

427 Then, Eq. 7 can be simplified as

$$428 \quad Vis = 5.216 \frac{\rho_w r_{\text{eff}}}{Q_{\text{ext}} LWC}, \quad (9)$$

429 where ρ_w is the liquid water density $\approx 1000 \text{ kg m}^{-3}$. Vis can be obtained from Eq. 9 if the
 430 effective radius (r_{eff}) and LWC are known. Mist conditions (defined as $\text{Vis} > 1 \text{ km}$ and
 431 $\text{RH}_w < 100\%$) can also be important for visibility reduction due to swelled aerosols (Fig.
 432 6). A lower limit for mist is usually defined as $\text{RH}_w \sim 80\%$. Haze is composed of dry
 433 aerosols where RH_w is usually $< 70\%$. Lower limit of haze Vis can be down to a few km.

434 Since N_d is inversely related to particle size (e.g. r_{eff}), as r_{eff} decreases N_d usually
 435 increases. Gultepe and Milbrandt (2007) replaced Eq. 9 with the approximate form

$$436 \quad Vis = \alpha \left[\frac{\rho_w}{Q_{\text{eff}} N_d LWC} \right]^\gamma, \quad (10)$$

437 where α and γ are regression constants, and N_d and LWC are obtained from fog DSD,
 438 respectively, as

$$439 \quad N_d = \sum_{r_1}^r n(r) \Delta r \quad (11)$$

440 and

$$441 \quad LWC = \sum_{r_1}^r \left(\frac{4}{3} \right) \pi \rho_w n(r) r^3 \Delta r. \quad (12)$$

442 Assuming that Q_{eff} and ρ_w are constants, Eq. 10 can be rewritten as

$$443 \quad Vis = \alpha (N_d LWC)^{-\gamma}, \quad (13)$$

444 which can be converted to β_{ext} using Eq. 7. For Eq. 13, α and γ are provided in Table 4. In
445 NWP models, Vis is usually diagnosed with post processed model outputs for LWC,
446 which is typically a prognostic output variable. If a numerical forecast model can resolve
447 microphysical processes at small time and space scales, Vis can also be predicted
448 diagnostically. This parameterization does not need droplet spectra at each time step that
449 increases calculation time significantly.

450 Vis parameterizations may not include effective size (or MVD) because N_d is a
451 function of MVD as follows

$$452 \quad N_d = \left(\frac{1}{k}\right) \frac{LWC}{MVD^3} \quad (14)$$

453 where $k=(4/3)\pi\rho_w$. Moreover, replacing N_d in Eq. 13 with Eq. 14, Vis can be rewritten as
454 follows

$$455 \quad Vis = \alpha \left(\left(\frac{1}{k}\right) \frac{LWC}{MVD^{3/2}}\right)^{-2\gamma}. \quad (15)$$

456 This suggests that knowing MVD and LWC, Vis can be obtained prognostically from a
457 NWP model simulation without requirement of N_d . Therefore, the 3rd parameter from a
458 DSD may not be required.

459

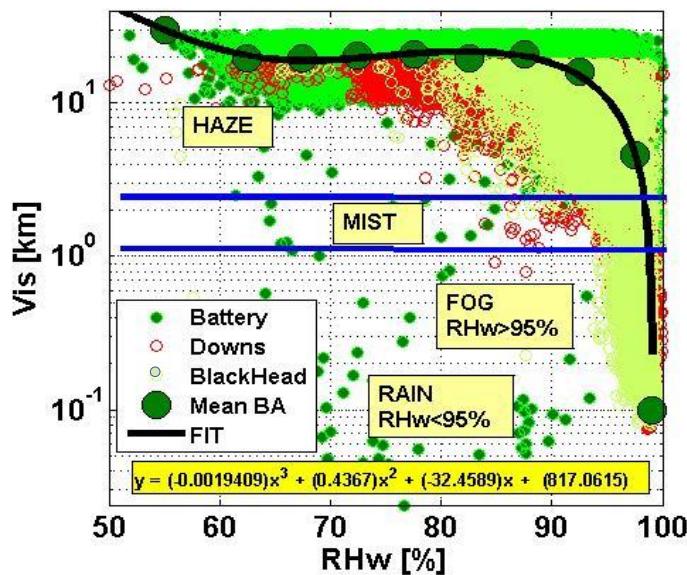
460 **4 Results**

461 **4.1 The 8 September Case (Battery Site)**

462 **4.1.1 Vis-RH_w Parameterization**

463 Vis-RH_w parameterizations are usually derived for fog coverage but not fog intensity,
464 which are obtained based on observations of Vis and RH_w, as well as T_a-T_d differences.
465 RH_w close to 100% indicates the existence of fog layers but does not indicate intensity
466 because of measurement uncertainty in T and T_d measurements and RH_w (Gultepe et al
467 2019). In fact, RH_w is obtained as a function of T_a and T_d so it is redundant to use both
468 T_a-T_d and RH_w in the same parameterization (Gultepe and Milbrandt 2010; Benjamin et
469 al 2010; Smirnova et al. 2000). Figure 6 shows Vis versus RH_w for 3 sites located in
470 Ferryland, including Battery, Blackhead, and the Downs, for 28 Sep 2018. In this figure,
471 fog (Vis<1 km), mist (2>Vis>1 km), and haze layers (Vis>2 km & RH_w<80%) as well as
472 rain data points are shown. Differences among RH_w values are likely related to location

473 and elevation differences. A best fit for the equation for Vis versus RH_w using 5% RH_w
474 bins is also shown in the figure 6 and given in Table 3.



475
476 **Fig. 6** Vis versus RH_w for NWS hydrometeor classification based on PWD instrument measurements at
477 Battery, Blackhead, and Downs sites on 28 Sep 2018. The fit line is applied to bin averaged RH_w values at
478 5% intervals. The equation fitted is shown on the plot together with rain data points.

479 This figure suggests that $Vis < 1$ km corresponds to $RH_w > 95\%$, which can be used
480 as a criterion for detecting fog coverage but not intensity. Note that RH_w measurement
481 accuracy is about 10% (Gultepe et al 2019). Haze and mist layers can occur when $RH_w >$
482 55% up to $RH_w \sim 95\%$ ($Vis > 1$ km). Rain with $Vis < 1$ km occurs when $RH_w < 95\%$.
483 Evidently there is no clear distinction between mist and haze for $Vis > 1$ km. Another
484 point is that Blackhead and Downs had a larger RH_w compared to the Battery site, likely
485 due to their higher elevations (30 m versus 2 m).

486

487 **4.1.2 Time Series of Meteorological Parameters**

488 Time series of Vis, PR, and precipitation types are shown in Fig. 7a based from PWD
489 measurements at 1-min time resolution. Fog and mist are seen mainly in the early
490 morning (segment 1; rectangular box) and later in the day (segment 2). Specifically, a
491 drizzle and light rain event is clearly seen before segment 2, which likely played an
492 important role for BL saturation. During fog events Vis was a few 100s of meters.

493 Fog formation and dissipation are likely related to the TKE magnitude and
494 dissipation rate, which are related to the fluctuations of 3D wind components. The value
495 for ϵ is calculated from Eq. 3 using 3D wind components and a 2D structure function (Eq.
496 4) and utilizing 1-min and 5-min running averages (Fig. 7b). The ϵ during fog is usually
497 less than for fog free conditions (e.g. 0500 and 2000 UTC). The 3D wind components are
498 shown in Fig. 7c. During fog events (see Vis time series in Fig. 7c), the magnitudes of 3D
499 wind components are found to be significantly lower than for fog free conditions. The
500 vertical air velocity (w_a) fluctuations were significantly smaller compared to u and v
501 components for the entire day, indicating the importance of advection processes in the
502 horizontal direction on the fog life cycle. Figure 7d shows 1-minute averaged local
503 accelerations of u , v , and w_a , indicating that the turbulence intensity levels were almost
504 50% less compared to fog-free segments.

505 Results suggest that ϵ is about $3 \times 10^{-4} \text{ m}^2 \text{ s}^{-3}$ in foggy segments compared to
506 $> 1 \times 10^{-3} \text{ m}^2 \text{ s}^{-3}$ in fog-free conditions, which can be used as a criterion for fog formation
507 and dissipation. These values are found to be comparable to those of Downs site
508 (Grachev et al. 2020) who showed that during foggy conditions ϵ_{dis} was between 1×10^{-3}
509 $\text{m}^2 \text{ s}^{-3}$ and $1 \times 10^{-4} \text{ m}^2 \text{ s}^{-3}$. Some differences between their work and current work is that
510 The Downs site at 30 m likely had stronger wind fluctuations compared to current one at
511 sea level. Another reason may arise due to their use of TKE based on averages done over
512 15 mins.

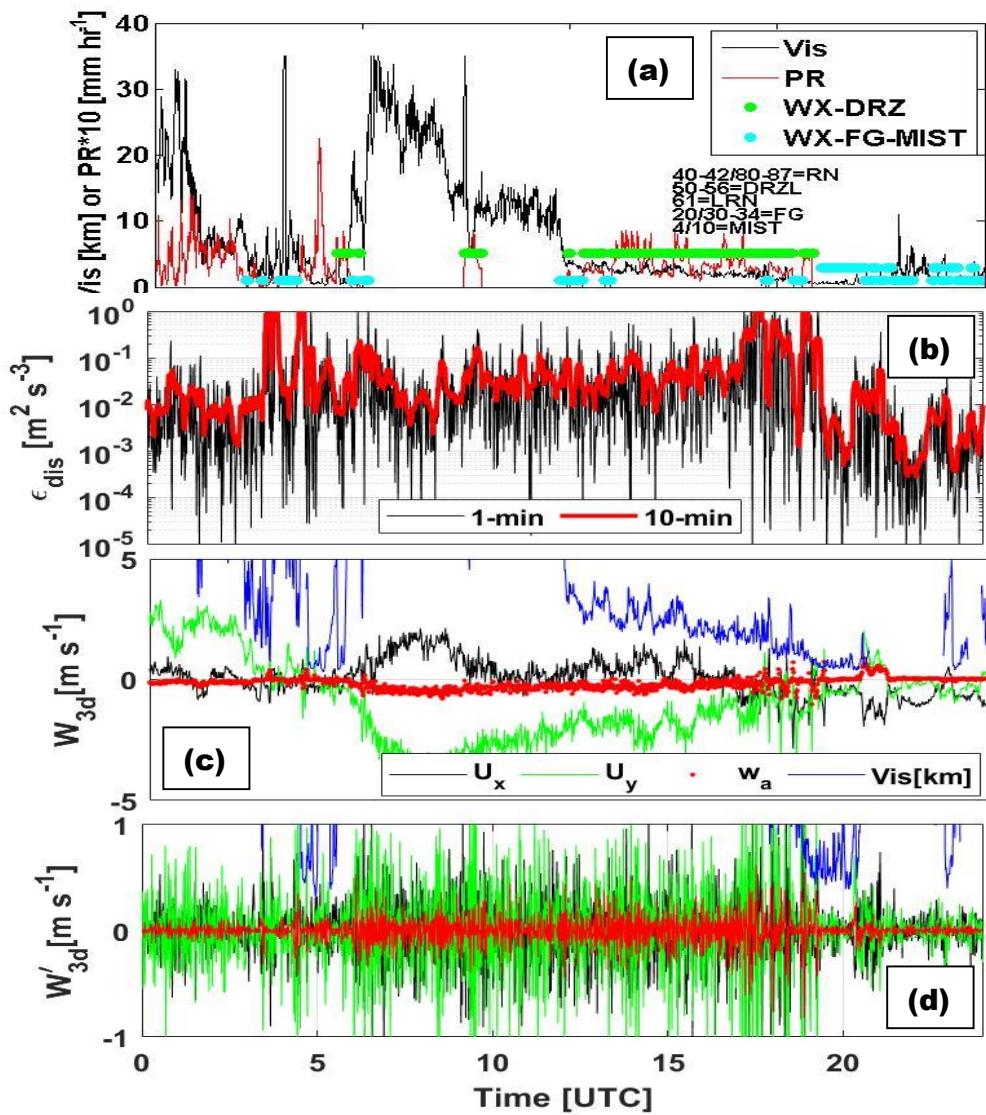
513

514 **4.1.3 Vis parameterization and microphysical parameters**

515 To develop a Vis parameterization, fog microphysical parameters such as N_d , MVD, and
516 LWC are needed because Vis is defined in terms of these parameters. Microphysical
517 parameters are calculated from the FM120 measurements from the Battery site. Figure 8a
518 shows a time series of N_d as a function of LWC, where N_d increases with increasing
519 LWC. N_d time series as a function of $\log(\text{Vis})$ is shown in Fig. 8b where $\log(\text{Vis}) \leq 0$
520 indicates fog conditions. Vis decreases with increasing N_d . These figures suggest that Vis
521 is related to both N_d and LWC (Gultepe et al 2006). Figure 8c shows MVD versus N_d as a
522 function of LWC (colour bar) together with theoretical lines obtained from Eq. 13. The
523 lines ranging from bottom to top in Fig. 8c represent values for LWC = 0.001:0.01:0.1 g

524 m^{-3} with solid lines, and $\text{LWC} = 0.1:0.05:0.3 \text{ g m}^{-3}$ with dashed lines with theoretical
 525 lines calculated using Eq. 13 (c). Clearly MVD is a function of N_d , and decreases with
 526 increasing N_d while LWC increases. This suggests that Vis can be obtained as a function
 527 of either N_d and LWC or MVD and LWC. Figure 8d shows the fit equation for $\text{Vis} =$
 528 $f(\text{LWC}, N_d)$ overlaid on observations, where mean values at dx intervals along x axis and
 529 percentile values are also shown. This equation is obtained from the measurements at
 530 Battery and represents local coastal fog conditions.

531



553 **Fig. 7** Vis, PR, and NWS hydrometeor code time series on 28 Sep 2018 for Battery site (a) with fog regions
 554 shown with light blue data points, ϵ_{dis} (TKE dissipation rate) time series for 1-min and 5-min running
 555 averages are shown in (b), 1-min averaged 3D wind components of u_x , u_y , and w_a as well as Vis time series

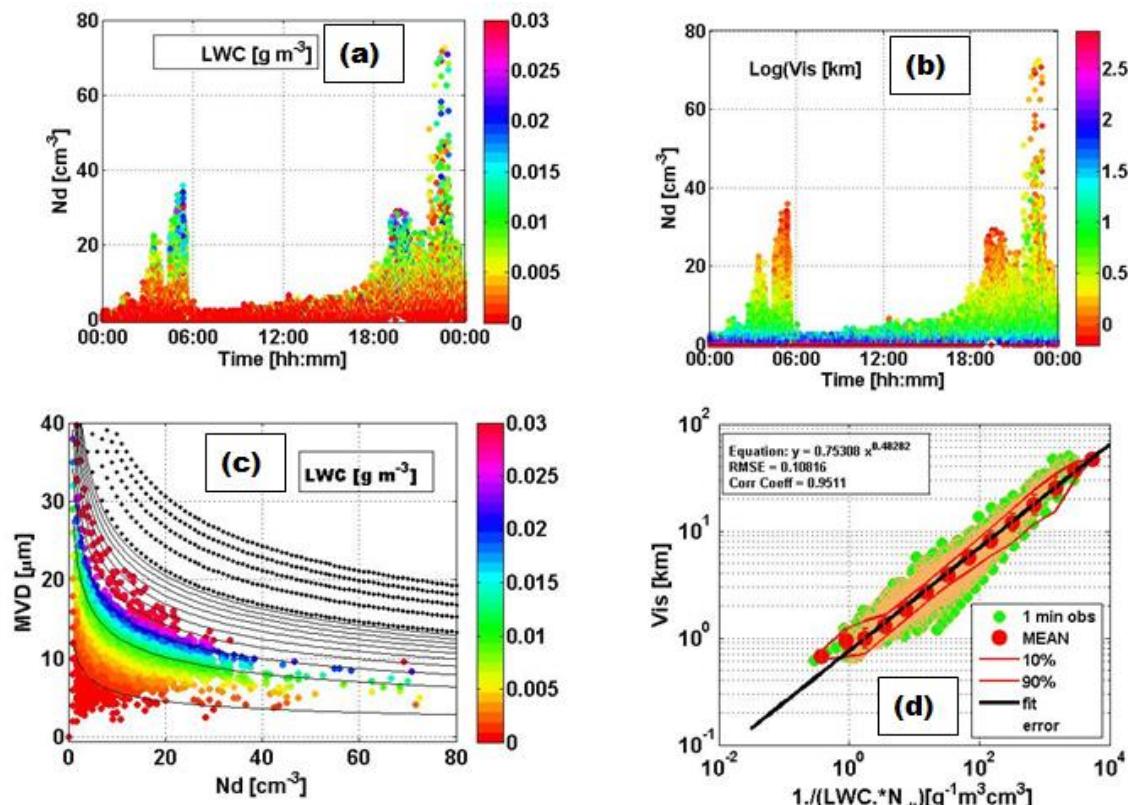
556 (purple line) are shown in (c) with fog regions indicated as blue coloured horizontal bars, and (c), and
 557 acceleration terms du/dt (black line), dv/dt (green line), and dw/dt (red line) with $dt=60$ s and Vis time
 558 series (blue line) are shown in (d). Note that during fog conditions these wind speed changes become
 559 comparable low versus fog free conditions.

560 **4.2 The 29 September case (Battery site)**

561 **4.2.1 Time Series of Meteorological Parameters**

562 Time series of Vis, PR, and precipitation types are shown in Fig. 9a, similar to the 28 Sep
 563 case, representing PWD measurements at 1-min sampling rate. Fog and mist are seen
 564 mainly between 0000 UTC and 1200 UTC early morning (segment 1) and mist and
 565 drizzle mainly later in the day (segment 2; 1300-0000 UTC). A drizzle event is seen
 566 during segment 2. During fog segment 1, Vis is a few hundred meters.

567

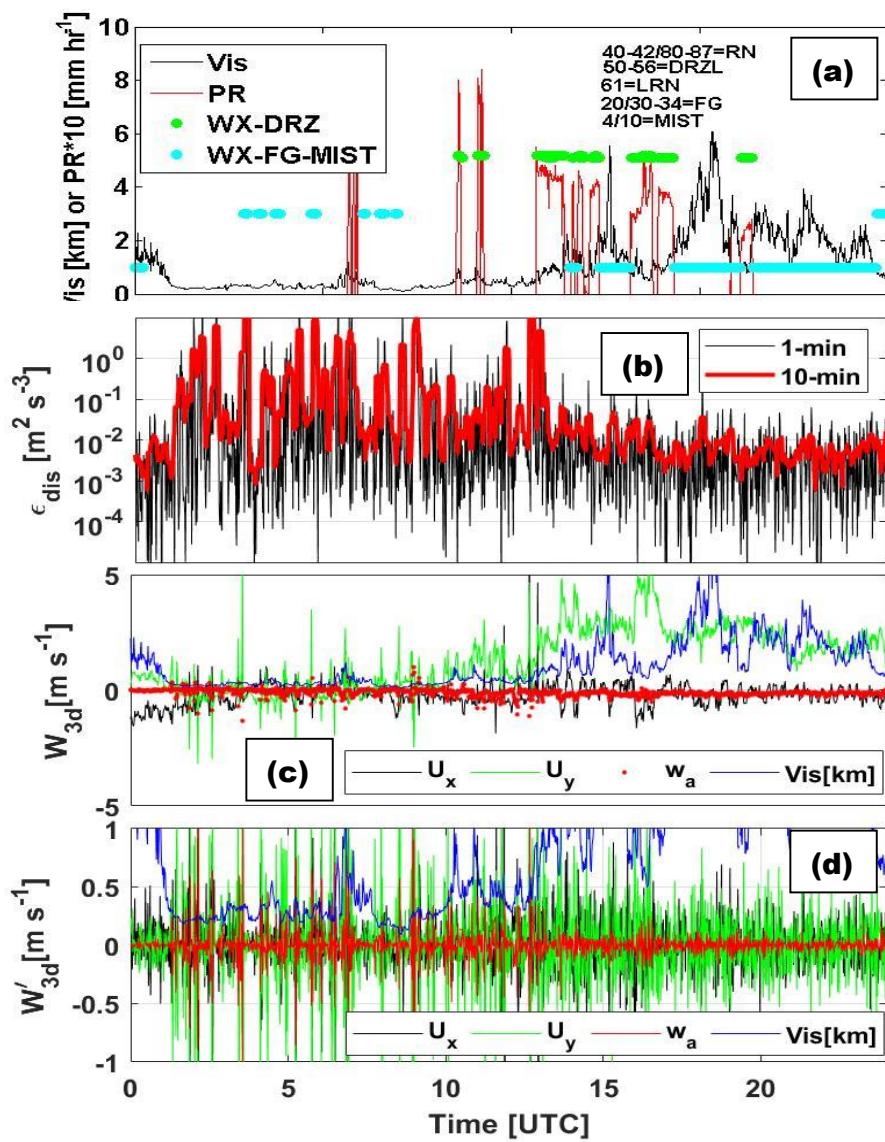


568

569 **Fig. 8** Time series of N_d coloured by LWC (a), N_d coloured by log(Vis) (b), and MVD versus N_d with
 570 points coloured by LWC (LWC=0.001:0.01:0.1 solid lines and LWC=0.1:0.05:0.3 dashed lines) (c) with
 571 theoretical lines calculated from Eq. 13. Vis parameterization as a function of fog index (FI along x axis)
 572 with statistical parameters and fit equation overlaid on observations are shown in (d) for 28 Sep 2018.

573

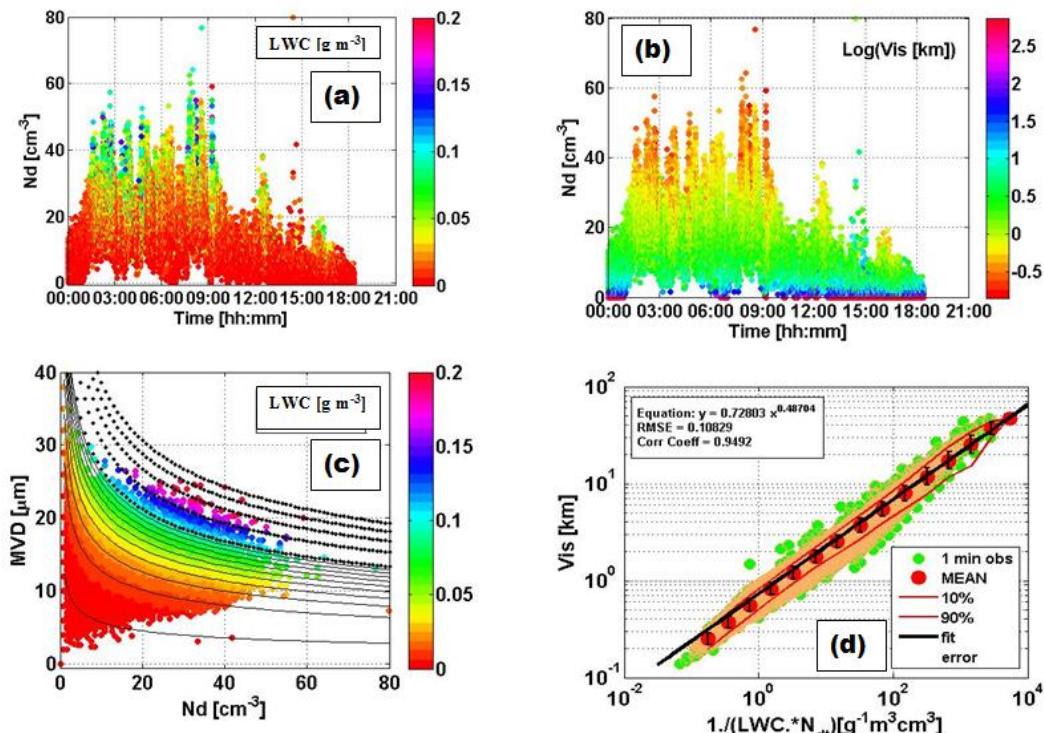
574 The calculation for ϵ is similar to the 28 Sep case, utilizing 1-min and 5-min
 575 running averages (Fig. 9b). The values for ϵ are found to fluctuate more during the foggy
 576 segment 1 (0000-1000 UTC), than segment 2 (1400-2300 UTC) fog and misty
 577 conditions. The values for ϵ change between $1 \times 10^{-2} \text{ m}^2 \text{ s}^{-3}$ and $1 \times 10^{-7} \text{ m}^2 \text{ s}^{-3}$ during the
 578 foggy segment 1, where u_y is highly variable between +1 and -1 m s^{-1} (Fig. 9c and 9d).
 579 Overall, ϵ_{dis} is less than $10^{-5} \text{ m}^2 \text{ s}^{-3}$ for both fog segments. Figure 9d shows 3D wind
 580 components and Vis, where stronger wind fluctuations likely play an important role,
 581 leading to increasing Vis values during segment 2 (light fog).



604 **Fig. 9** Vis, PR, and NWS hydrometeor code time series on 29 Sep 2018 for Battery site (a) with fog
 605 (drizzle) regions shown with light blue (green) data points, ϵ_{dis} time series for 1 min and 5 min running

averages are shown in (b), 1-min averaged 3D wind components of u , v , and w_a as well as Vis time series are shown in (c) with fog regions indicated as blue coloured horizontal bars, and (c), and acceleration terms du/dt (black line), dv/dt (green line), and dw/dt (red line) with $dt=60$ s and Vis time series (blue line) are shown in (d). Note that during fog conditions these wind speed changes become comparable to low versus fog free conditions.

611



612

613 **Fig. 10** Time series of microphysical parameters N_d versus LWC (a), N_d versus $\text{log}(Vis)$ (b), and MVD 614 versus N_d as a function of LWC (c) with theoretical lines calculated from Eq. 13. Vis parameterization as 615 a function of fog index (FI along x axis) with statistical parameters and fit equation overly on observations 616 are shown in (d) for 04 October 2018.

617

618 In summary, most of the ε data points are found below the dissipation rate of 619 3×10^{-5} m 2 s $^{-3}$ during fog segments. The w_a fluctuations in segment 1 are smaller compared 620 to drizzle and fog conditions seen in segment 2. Note that wetting of the sonic 621 anemometer transmitter/receiver may occasionally cause large fluctuations of wind 622 components during heavy fog conditions. Results suggest that, based on 1-min averages, 623 minimum (max) ε is about 1×10^{-6} m 2 s $^{-3}$ (3×10^{-2} m 2 s $^{-3}$) in foggy segment 1, compared to 624 3×10^{-5} m 2 s $^{-3}$ during mist and drizzle conditions (segment 2). Another point is that

625 southerly wind fluctuations (wind coming from south) are likely responsible for warm
626 and moist advection over the region, leading to fog formation similar to 28 Sep case.

627

628 **4.2.2 Vis parameterization and microphysical parameters**

629 Results and parameterizations for this case are obtained similar to that of 28 Sep case
630 (Fig. 10). MVD and N_d are found to be comparatively larger on this day (Fig. 10a,b,c).
631 For example, the maximum MVD reaches 40 μm compared to 30 μm on 28 Sep. The
632 maximum N_d is about 60 cm^{-3} compared to a maximum for N_d of 70 cm^{-3} on 28 Sep.
633 Finally, the Vis fit equation is shown in Fig. 10d. Overall, the slope of the best fit line is
634 very similar to the 28 Sep case but with relatively lower values of observed Vis.

635

636 **4.3 The 28 September Case (RV Sharp)**

637 **4.3.1 Time Series of Vis and RV Wind Components**

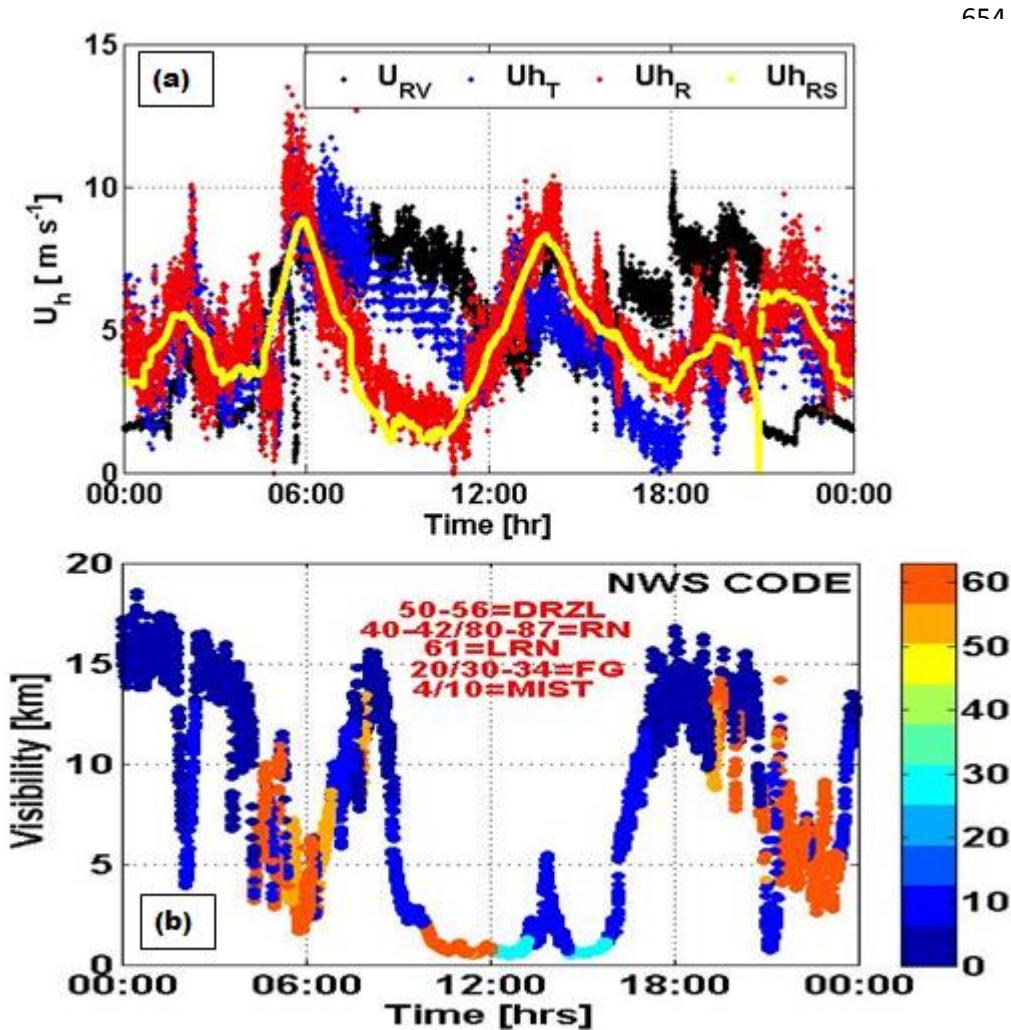
638 Time series of *R/V Sharp*'s navigation parameters obtained from the VectorNav VN100
639 IMU and Trimble BX982 Dual GNSS receiver (Fernando et al 2020) are reported here at
640 1-min intervals (Fig. 11a). This figure shows the *R/V Sharp*'s speed with respect to the
641 ground (U_{RV}), true wind speed (U_{hT}), wind speed with respect to ground (U_{hR}) and
642 smoothed values of U_{hR} over 10 mins intervals. During the fog event between 1000 UTC
643 and 1600 UTC, the *R/V Sharp* was heading 250 deg (SW) until 1300 UTC, then changed
644 to 50 deg NE with U_{RV} at about $5\text{--}8 \text{ m s}^{-1}$. Low Vis was observed between 1000 UTC and
645 1600 UTC, during which Vis improved from 1 km to 5 km after *R/V Sharp* changed
646 direction. After 1600 UTC, Vis increased up to 15 km. Low Vis and haze conditions (Fig.
647 11b) before 1000 UTC likely played an important role later on for drizzle conditions after
648 1000 UTC. Thereafter, drizzle just before fog formation likely led to moistening of the
649 BL and resulted in fog occurrence at about 1200 UTC.

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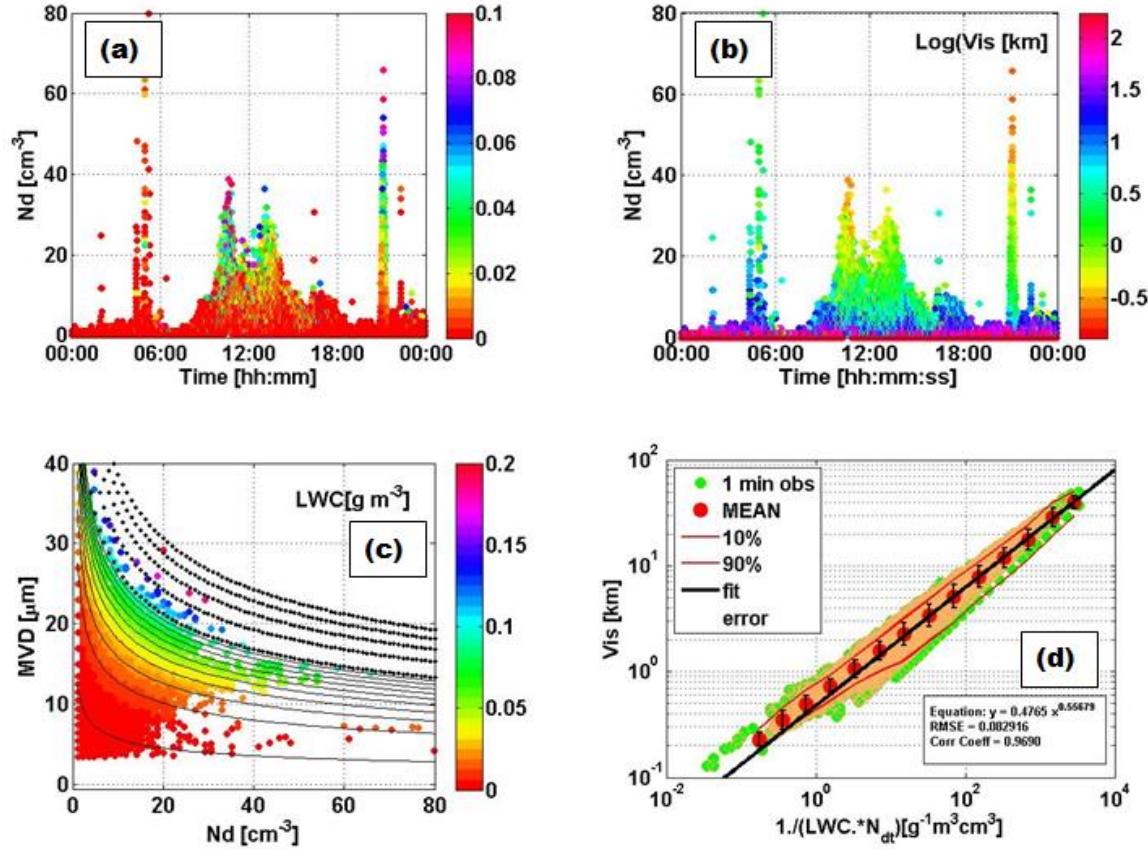
656 **Fig. 11** Time series of U_{RV} , U_{hT} , U_{hR} , and U_{hRS} for 1 min and 10 min running averages are shown in (a) and
 657 Vis, PR, and NWS hydrometeor code time series on 28 Sep 2018 (b) with fog regions shown with light
 658 blue data points.

659

660 **4.3.2 Vis parameterization and microphysical parameters from the gondola**

661 In this subsection, fog droplet spectral characteristics obtained from the CDP and BCP
 662 housed in the gondola (Fig. 2) are investigated. Both CDP and BCP plots were obtained
 663 similar to the Battery plots. Note that BCP (Fig. 12) measurement starts at 5 μm
 664 compared to CDP at 2 μm (Fig. 13) and had the capability for measurements up to 75 μm .
 665 Measurements of N_d , MVD, and LWC are less than 60 cm^{-3} , $40 \mu\text{m}$, and 40 g cm^{-3} ,
 666 respectively. A parameterization is obtained with a power-law form similar to Eq. 12 and
 667 is shown in the figure. The best fit line indicates that increasing fog index (FI

668 $=1/(LWC \cdot N_d)$) results in increasing Vis, which is found to be similar to the fit line
 669 obtained for the Battery site. FI increases with increasing values of either N_d or LWC.
 670 Note that N_d can be replaced with MVD using Eq. 14.



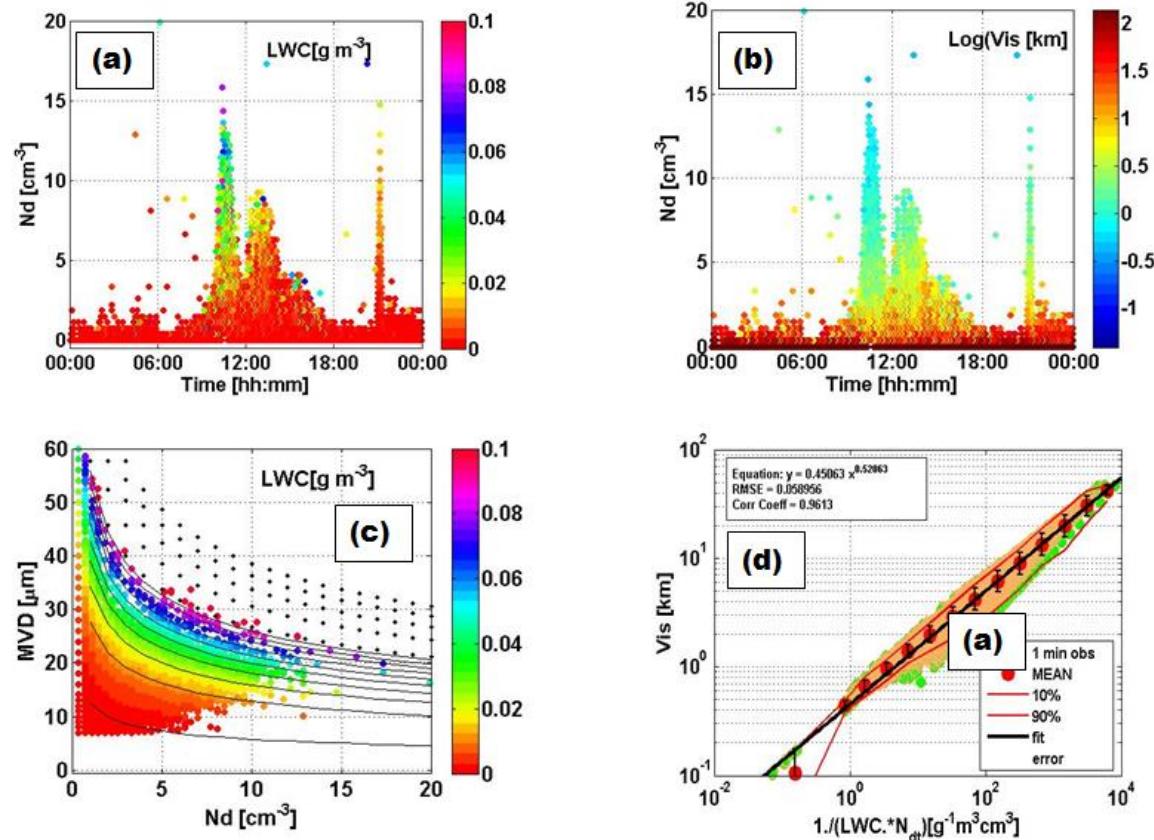
671
 672 **Fig. 12** Time series of microphysical parameters N_d versus LWC (a), N_d versus $\log(\text{Vis})$ (b), and MVD
 673 versus N_d as a function of LWC (c) with theoretical lines calculated from Eq. 13. Vis parameterization as a
 674 function of fog index (FI along x axis) with statistical parameters and fit equation overlaid on observations
 675 are shown in (d) for RV CDP on 28 Sep 2018.

676 Fog-droplet spectral characteristics obtained from the BCP measurements are
 677 shown in Fig. 13. Note that because of missing the first 2 channels in BCP compared to
 678 CDP, N_d , LWC, and MVD cannot have the same values for both probes. N_d and LWC are
 679 based on BCP measurements and therefore, are expected to be less; but MVD is higher
 680 than CDP parameters. Results suggest that max values for N_d are about 15 cm^{-3} , for LWC
 681 about $0.07\text{--}0.08 \text{ g m}^{-3}$, and for MVD~ $60 \mu\text{m}$.

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685



686

687 **Fig. 13** Time series of microphysical parameters N_d versus LWC (a), N_d versus $\log(\text{Vis})$ (b), and MVD
 688 versus N_d as a function of LWC (c) with theoretical lines calculated from Eq. 13. Vis parameterization as a
 689 function of fog index (FI along x axis) with statistical parameters and fit equation overlaid on observations
 690 are shown in (d) for RV BCP on 28 Sep 2018.

691

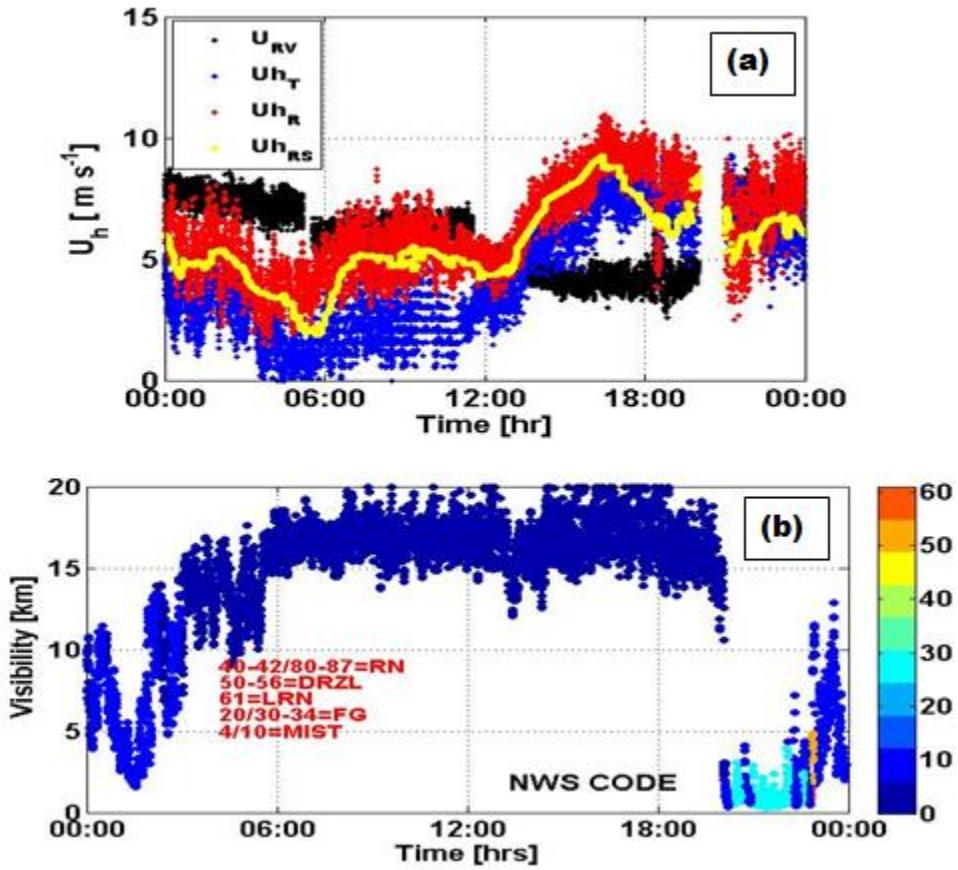
692 4.4 The 4 October Case (*RV Sharp*)

693 4.4.1 Time Series of Vis and RV Wind Components

694 Time series of *R/V Sharp*'s navigation parameters are given in Fig. 14a. This figure also
 695 shows U_{RV} , U_{hT} , U_{hR} , and smoothed values of U_{hR} over 10-minute intervals. Fog occurred
 696 between 1900 and 2300 UTC. Before the fog event at 1900 UTC, the ship was headed
 697 250 deg (SW), and U_{RV} changed from about 4 m s^{-1} to 8 m s^{-1} . U_{hR} was from north during
 698 the fog event (not shown). Low Vis (1 km) was observed between 1900 and 2300 UTC
 699 and Vis improved to 5 km at 2300 UTC. Before 1900 UTC, Vis increased to 15-20 km.
 700 Thereafter, the cloud base lowered to the surface and Vis decreased to <300 m. During

701 low Vis conditions (Fig. 14b) near the end of fog event, drizzle was observed around
 702 2300 UTC. After 1930 UTC, Vis improved significantly.

703
 704



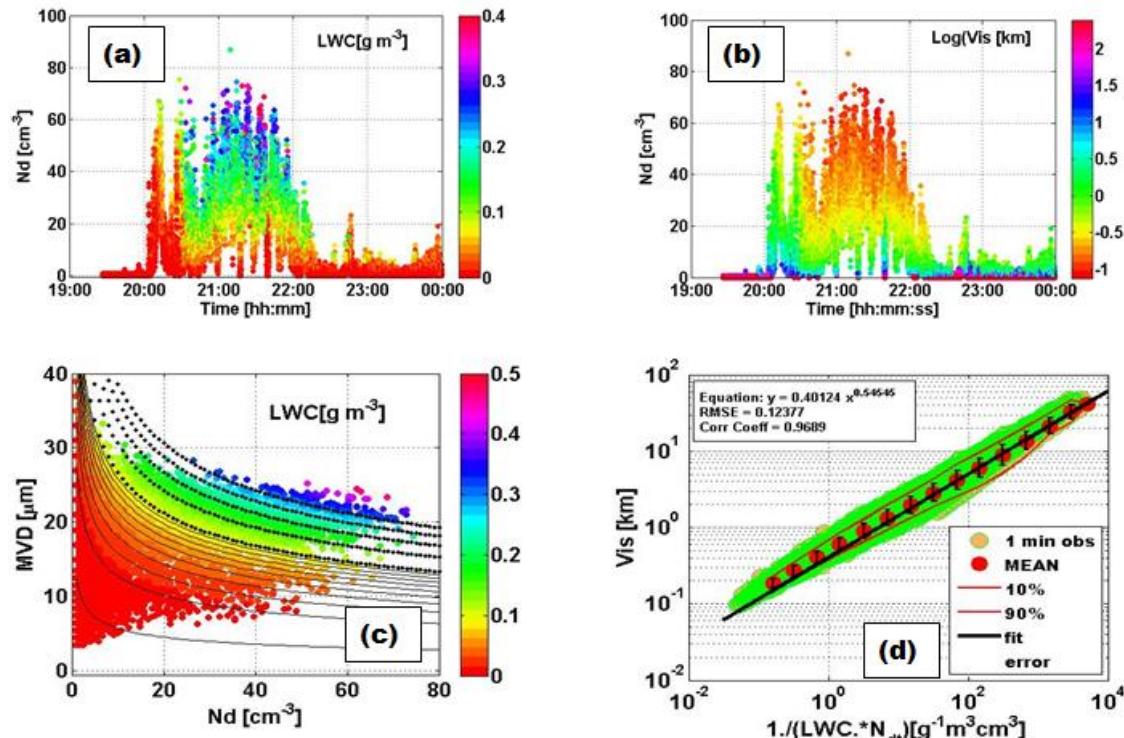
705
 706 **Fig. 14** Time series of U_{RV} , U_{hT} , U_{hR} , and U_{hRS} for 1 min and 10 min running averages are shown in (a) and
 707 Vis, PR, and NWS hydrometeor code time series on 28 Sep 2018 (b) with fog regions shown with light
 708 blue data points.

709 **4.4.2 Vis Parameterization and Microphysical Parameters from the Gondola**

710 Fog droplet spectral characteristics obtained from the CDP and BCP during the 29 Oct
 711 case are shown in Fig. 15 and Fig. 16, respectively. Note that max CDP N_d (Fig. 15a,b) is
 712 about 75 cm^{-3} and LWC reaches 0.4 g m^{-3} . Low Vis, representing fog conditions, is
 713 found between 2000 and 2200 UTC. MVD (Fig. 16c) ranged from a few μm up to $40 \mu\text{m}$
 714 at low LWC and N_d but was at about $22 \mu\text{m}$ when N_d reached a maximum at 70 cm^{-3} .
 715 CDP measurements of MVD and LWC were less than $40 \mu\text{m}$ and 0.45 g m^{-3} ,
 716 respectively. The parameterization obtained based on CDP measurements are shown in

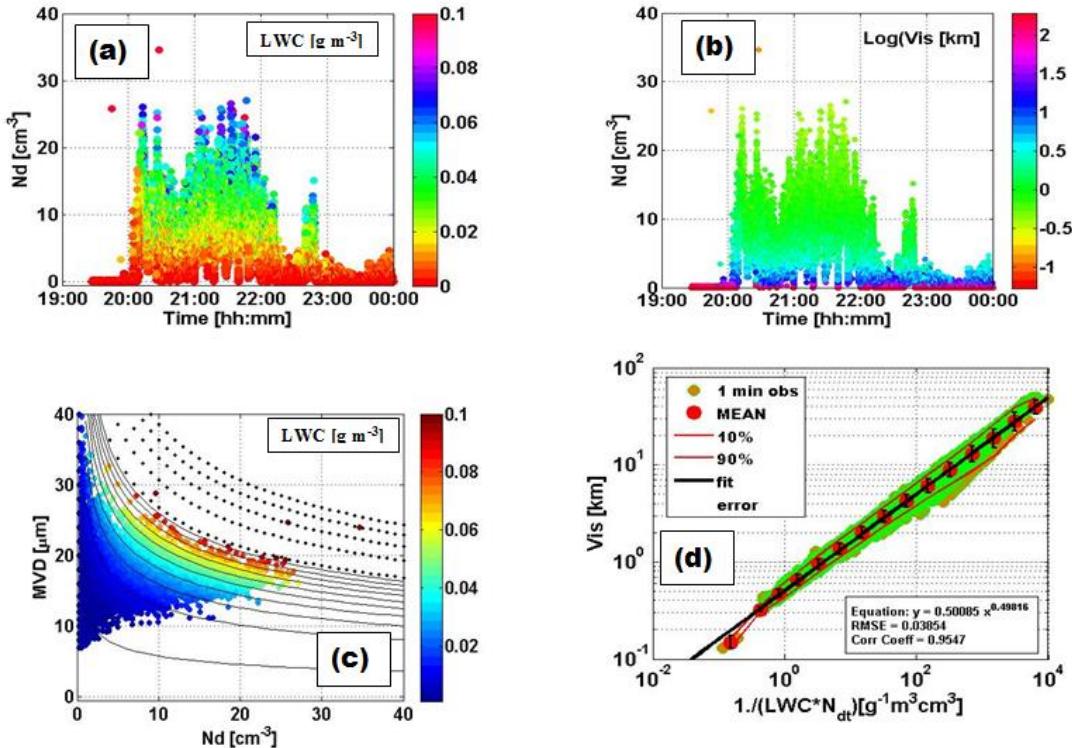
717 Fig. 16d. Similar to previous cases, Vis also increases with increasing values of fog index
 718 ($FI = 1/(LWC \cdot N_d)$) but decreases with increasing LWC and N_d (with decreasing MVD).
 719 The best fit line indicates that increasing FI values result in similar increasing Vis
 720 conditions that represent the Battery site.

721



722
 723 **Fig. 15** Time series of microphysical parameters N_d versus LWC (a), N_d versus $\log(Vis)$ (b), and MVD
 724 versus N_d as a function of LWC (c) with theoretical lines calculated from Eq. 13. Vis parameterization as a
 725 function of fog index (FI along x axis) with statistical parameters and fit equation overlaid on observations
 726 are shown in (d) for RV CDP on 04 October 2018.

727 Fog droplet spectral characteristics based on BCP are shown in Fig. 16. Again,
 728 due to missing the first 2 channels of CDP in BCP measurements, CDP, N_d , LWC, and
 729 MVD cannot be directly compared to those of CDP measurements. As suggested
 730 previously, if there is no drizzle, N_d and LWC based on BCP measurements are expected
 731 to be less compared to CDP parameters; but MVD is expected to be higher because of
 732 larger droplets. Results suggest that max N_d was about 25 cm^{-3} , LWC about 0.4 g m^{-3} ,
 733 and MVD~ $40 \mu\text{m}$. The parameterization for this case based on BCP measurements is
 734 shown in Fig. 16d. Similar to previous cases, Vis increases with increasing FI.



735

736 **Fig. 16** Time series of microphysical parameters N_d versus LWC (a), N_d versus log(Vis) (b), and MVD
 737 versus N_d as a function of LWC (c) with theoretical lines calculated from Eq. 13. Vis parameterization as a
 738 function of fog index (FI along x axis) with statistical parameters and fit equation overly on observations
 739 are shown in (d) for RV BCP on 04 October 2018.

740 4.5 Summary of Vis Parameterizations

741 Vis parameterizations are obtained for each platform (*R/V Sharp* or Battery supersite)
 742 using FM100, CDP, and BCP probes and are summarized in Table 4. The Vis- RH_w
 743 relationships are also provided to emphasize that they are used only as a threshold for fog
 744 formation (e.g. $RH_w > 95\%$ in Fig. 6). Then, fog intensity (e.g. Vis) can be estimated based
 745 on model-predicted values for LWC and N_d (or MVD) (see Eq. 14). Note that the G2007
 746 parameterization (Gultepe et al 2007) was obtained using FSSP measurements based on
 747 low-level flying aircraft observations over the Bay of Fundy, NS taken during the RACE
 748 (Regional Aerosol and Cloud Experiment) campaign. These parameterizations are
 749 discussed in the next section.

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755 **Table 4** Summary of C-FOG Vis parameterizations and previous work. The FI (fog index) is defined as
 756 $1/(LWC \cdot N_{dt})$ with units of $[g^{-1} m^3 cm^3]$.

Case	Parameterization	FMD	Platform location
28 Sep - Battery	$Vis=0.7531(FI)^{0.4828}$	FM100	Ground-C-FOG
29 Sep - Battery	$Vis=0.7280(FI)^{0.4871}$	FM100	Ground-C-FOG
28 Sep -RV	$Vis=0.4765(FI)^{0.5568}$	CDP	Sharp RV-C-FOG
28 Sep -RV	$Vis=0.4506(FI)^{0.5206}$	BCP	Sharp RV-C-FOG
04 Oct -RV	$Vis=0.4012(FI)^{0.5455}$	CDP	Sharp RV-C-FOG
04 Oct -RV	$Vis=0.5009(FI)^{0.4982}$	BCP	Sharp RV-C-FOG
28 Sep - Battery	$Vis=-0.009RH^3+0.437RH^2-2.459RH+817.062$	PWD	Ground-C-FOG
Gultepe et al 2007	$Vis=1.002(FI)^{0.6473}$	FSSP	Aircraft Obs. RACE

757

758 5 Discussion

759 5.1 Overview of Fog Forecasting

760 Fog prediction cannot be done accurately because of rapid changes in its intensity (Vis)
 761 over short time and space scales, as well as non-linear relationships between surface and
 762 atmospheric conditions. There are several methods for fog prediction. These methods
 763 include rule-based techniques (Toth et al. 2007, Zhou and Du 2010), statistical methods
 764 (Claxton 2008, Miao et al. 2012), numerical forecast models (Gultepe and Milbrandt
 765 2010; Bott et al. 1990; Muller et al. 2007, 2010; Bott and Trautmann 2002; Clark et al.
 766 2008; Shi et al. 2012) and integrated nowcasting methods (Golding, 1993; Golden, 1998;
 767 Wright and Thomas, 1998; Haiden et al. 2014). If no persistence exists and turbulence
 768 becomes more dominant, prediction usually fails, unless very short-term data assimilation
 769 techniques are performed. More detailed information on fog modeling issues can be
 770 found in the works of Gultepe et al. (2007a), Wilfried et al. (2008), Croft et al. (1997) and
 771 Fernando et al. (2020).

772

773 5.2 NWP and Microphysical Schemes

774 Prognostic fog forecasting is usually done using model-based prediction of LWC and N_d ,
 775 and that uses detailed droplet nucleation processes described above. In general, a regional
 776 forecast model uses boundary conditions from a global model. As described in Section 1,
 777 assuming a gamma size distribution, visibility can be diagnosed from the size distribution

778 parameters such as N_o (intercept parameter), μ (spectral shape parameter), and λ (slope
779 parameter), or either N_{dt} or LWC or both (Gultepe and Milbrandt 2007b, Milbrandt and
780 Yau 2005a,b). If both LWC and N_d are available as prognostic variables, Vis estimation
781 can be obtained using NWP simulations.

782 *Microphysical schemes* are used to evaluate fog prediction conditions using NWP
783 models. Cloud-droplet and fog-droplet size distributions are usually represented by a
784 modified-gamma size distribution in NWP models. The parameters used in a modified
785 gamma size distribution are the N_t (total droplet number concentration), and shape and
786 slope parameters. N_t is obtained either from empirical relationships as a function of
787 aerosol number concentrations (N_a) or from a prognostic equation for N_d with assumed
788 size distribution parameters. The microphysical schemes (MPS) such as MY (Milbrandt
789 and Yau 2005a,b), MG (Morrison and Gettelman 2008), and TO (Thompson et al. 2008,
790 2014) use modified-gamma size distributions and microphysical parameters based on
791 DSD parameters.

792 The N_d can be obtained directly from N_a diagnostically, as stated, or based on S_w
793 (supersaturation) which is function of vertical air velocity (w_a) and N_a as well as its
794 composition (Twomey 1959; Chen 1994; Kohler 1934). The Kohler curve provides a
795 general equilibrium relationship between an aqueous salt solution droplet size and water
796 vapour. S_w can be calculated as a function of both w_a and N_d and that is directly related to
797 size distribution and the composition and mixing state of aerosols. A similar relationship
798 to Twomey (1959) is also suggested by Ghan et al. (1993, 1997) for large-scale cloud
799 formation. Cohard et al. (1998) extended Twomey's power law expression by using a
800 more realistic four parameter CCN activation spectrum with physiochemical properties of
801 aerosols. The most important parameter to estimate N_d is S_w that is obtained using 3
802 methods (Schwenkel and Maronga 2019): 1) saturation adjustment scheme, 2) diagnostic
803 scheme where S_w is diagnosed by the prognostic fields of T and q_v , and 3) a prognostic
804 method (Clark 1973; Morrison and Grabowski 2007; Lebo et al. 2012). These methods
805 are not discussed here, but are listed to emphasize the importance of w_a , CCN, and N_d on
806 S_w .

807 In microphysical schemes, N_d is usually represented with a complete gamma size
808 distribution function as

809 $N_d(D) = N_o D^\mu e^{-\lambda D},$ (16)

810 where D is the diameter, and N_o , μ , and λ_s should also be known to obtain an accurate
 811 droplet spectra. The μ parameter is obtained as a function of CCN (Wilkinson et al.,
 812 2013) or as $\mu = 1/\eta^2 - 1$ with η the dispersion of radius (sd/mean), which is given by
 813 Morrison and Gettelman (2008) as

814 $\eta = 0.0005714 N_d + 0.2714,$ (17)

815 where N_d can be obtained as a function of aerosol number concentration (N_a) (Jones et al.
 816 1994; Martin et al. 1994; Gultepe and Isaac, 1999; Gultepe et al. 2015). But N_d versus N_a
 817 relationships are not unique, and their variability can be large. In Eq. 15, N_o and λ are
 818 usually obtained using a fixed μ and predicted value of total droplet number
 819 concentration (N_{dt}) and water vapour mixing ratio (q_w) as

820 $\lambda_s = \left[\frac{\pi \rho_w N_{dt} \Gamma(\mu+4)}{6 q_w \Gamma(\mu+1)} \right]^{1/3}$ (18)

821 and

822 $N_o = \frac{N_{dt} \lambda^{\mu+1}}{\Gamma(\mu+1)}.$ (19)

823 When models use a single-moment scheme, q_w (e.g. LWC) is predicted but N_{dt}
 824 and μ are fixed. In double-moment schemes, usually both q_w and N_{dt} are prognostic
 825 variables. N_d prediction is an important step in NWP models for accurate fog Vis
 826 estimation.

827 In the MPS, CCN concentration is assumed to be a function of S_w , and N_a for the
 828 ocean (N_{ao}) and land (N_{al}) air masses set as fixed values. The values for CCN
 829 concentration as a function of supersaturation are also given in Fletcher (1966). The CCN
 830 parameterization, given as $CCN = c S_w^k$ where $c \sim 1000 \text{ cm}^{-3}$ and $k \sim 1$ (a unitless constant),
 831 are for continental air masses and $\sim 100 \text{ cm}^{-3}$ and ~ 0.5 for maritime air masses (Feingold
 832 et al 1998). Sometimes, N_d is fixed as 100 cm^{-3} over ocean and 300 cm^{-3} over land
 833 (Wilkinson et al 2013). In reality, as stated in Cohard et al. (1998), the coefficients c and
 834 k change with high S_w . *They suggested that this happens especially in maritime*
 835 *environments.* Therefore, c and k should be matched locally to the activated CN. This

836 suggests that parameterization of S_w and both c and k are critical to improve fog Vis
837 predictions

838

839 **5.3 Scale Issues**

840 Fog usually happens over small areas and dissipates quickly; therefore, NWP models can
841 have difficulty predicting short lived fog conditions. Although fog models can resolve the
842 smaller scales, most of the physics developed for the NWP model cannot be used for high
843 resolution fog models. Due to cloud coverage over the large scales (1-100 km), some dry
844 air pockets result in lower values of RH_w , LWC, and N_d (Gultepe and Isaac, 1999; 2004)
845 and these need to be extrapolated to fog occurrence scales (usually less than 1 km)
846 (Wilkinson et al 2013). The latter study clearly recognizes the issues for better fog
847 prediction on various grid areas. This suggests that further improvement of fog
848 microphysical parameterizations is required for better fog prediction.

849

850 **5.4 Variability in Vis**

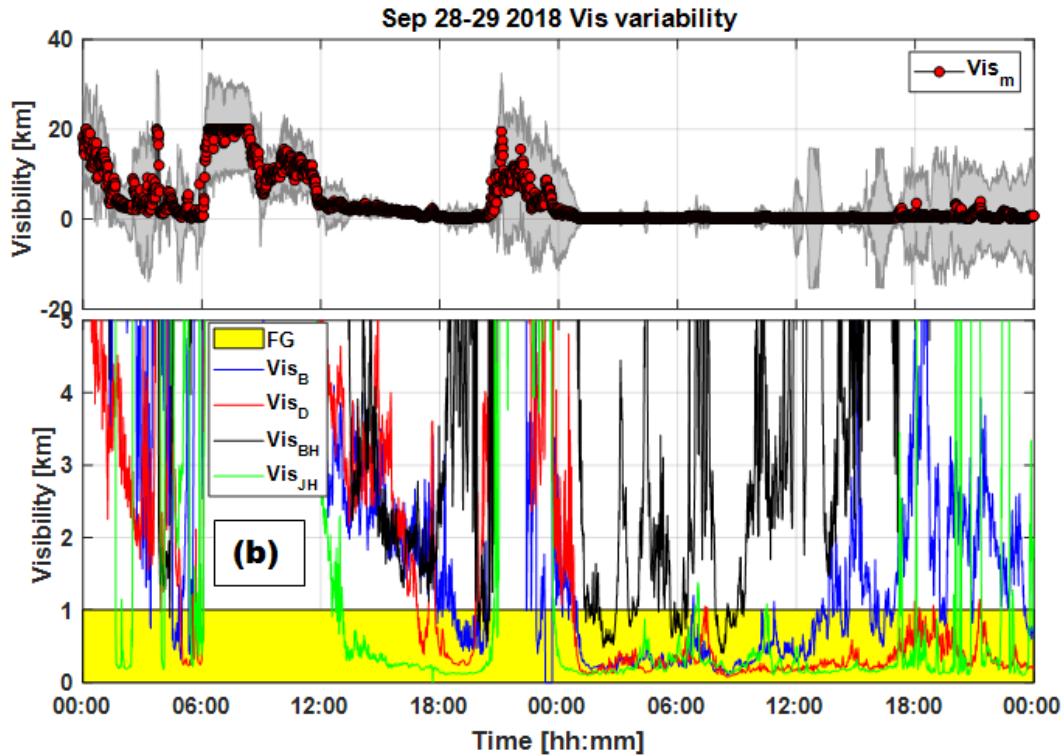
851 Visibility calculation based on observations and NWP model outputs may include large
852 uncertainties due to fog microphysical and BL processes. Variability in Vis based on
853 measurements of PWD located at Battery, Downs, Blackhead, and Judges Hill sites for
854 28-29 Sep is shown in Fig. 17. Figure 17a shows mean Vis from all these sites with a
855 standard deviation. Overall, Vis at Judges Hill had the lowest values compared to the
856 other stations, likely due to its elevation of 129 m (Fig. 17b). The second lowest Vis
857 values are found at The Downs site, at 32 m above sea level. Blackhead and Battery Vis
858 follow, with the next highest values. During dense fog conditions, Vis from Blackhead
859 was much higher than others, likely due to the distance between the Blackhead and
860 Ferryland sites. Vis, representing a scale of about 1.5 km, ranged from 0.2 km up to 1 km
861 for any given time (Fig. 17); therefore, NWPs should be capable of simulating fog
862 conditions at 1 min time intervals and 100 m spatial scales.

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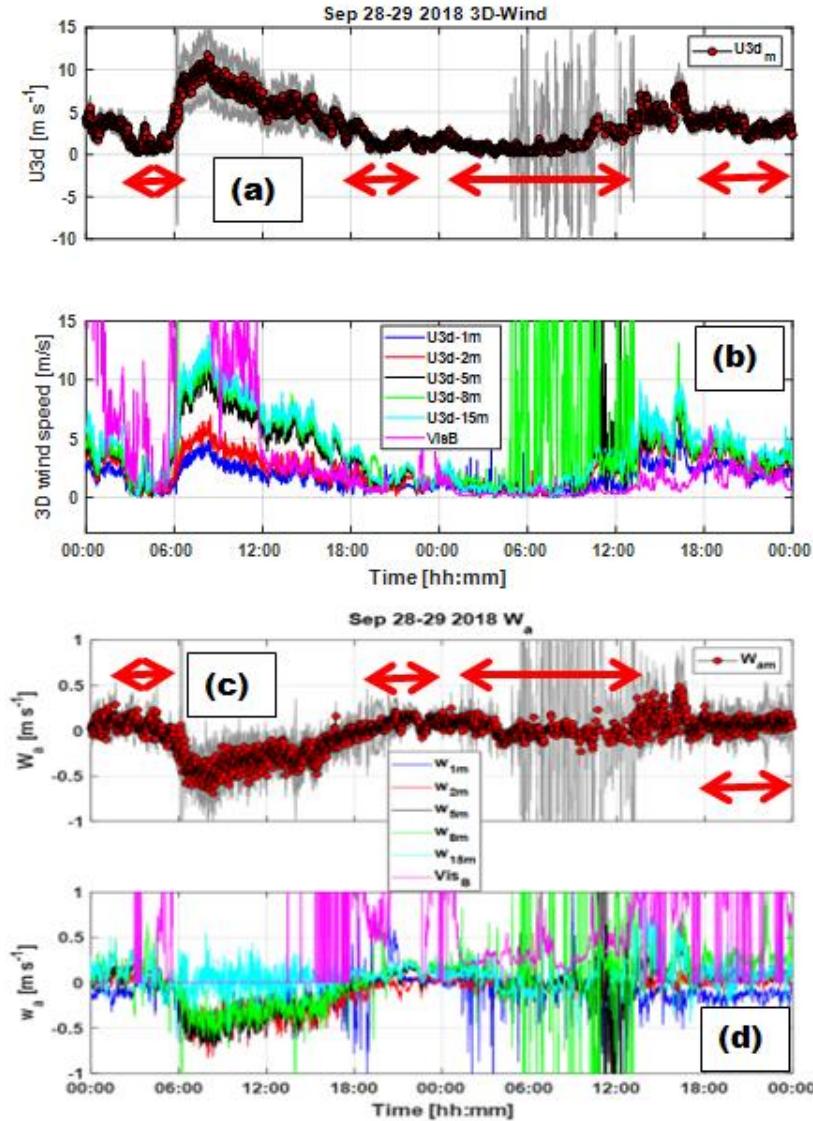
867

868 **Fig. 17** Time series of mean (red filled circles) and sd (gray coloured regions) of Vis based on
 869 measurements of PWDs (indicated in (b)) are shown in (a). Time series of Vis representing Battery (Vis_B),
 870 Downs (Vis_D), Blackhead (Vis_{BH}), and Judges Hill (Vis_{JH}) for 28-29 Sep 2018 are shown in (b). Fog
 871 regions are shown for $Vis < 1$ km (yellow coloured area).

872 **5.5 Variability in sonic anemometer wind components**

873 The 3-D wind component time series of mean and sd obtained from the (20Hz)
 874 measurements of sonic anemometers located at 1, 2, 5, 8, and 15 m levels of the Battery
 875 supersite tower are shown in Fig. 18a for 28-29 Sep cases. Figure 18b shows 3D wind
 876 components and Vis from each of the 5 levels. The U_{3d} values (3-D wind speed) between
 877 0600-1200 UTC indicate some noise in the data and should be ignored because of heavy
 878 condensation on the prongs of the sonic anemometers. The largest U_{3d} fluctuations are
 879 seen at 5, 8, and 15 m levels but these were reduced to lower values during fog events on
 880 May 28 (Fig. 18b). Vertical air velocities (w_a) in Fig. 18c are obtained at the same levels
 881 as in Fig. 18b. Figure 18c shows the mean and standard deviation of w_a obtained from
 882 measurements, representing all levels from 1 m up to 15 m. Clearly, w_a fluctuations were
 883 higher in the fog-free layers compared to foggy layers, indicating greater turbulent heat,
 884 moisture and momentum fluxes in the vertical direction. Note that large fluctuations of

885 w_a at 15 m from 0600 to 1200 UTC in Fig. 18d were likely noise, as noted previously.
 886 The w_a fluctuations within the fog layers were found generally between +0.3 and -0.3 m
 887 s^{-1} , but were more than -0.7 m s^{-1} and +0.7 m s^{-1} in fog-free layers. These suggest that
 888 without estimating wind fluctuations at 3 axis accurately, NWP models cannot properly
 889 handle the fog life cycle.



890
 891 **Fig. 18** Wind components obtained from the sonic anemometers located at 1, 2, 5, 8, and 15 meters levels
 892 of a tower and Vis at 2 m (purple line) are shown in (a) for mean and sd of U_{3d} (3D wind component) and
 893 in (b) for U_{3d} for each level, representing 28-29 Sep cases at the Battery supersite. Mean (red filled circles)
 894 and sd (gray lines) of vertical air velocity (w_a) are shown in (c) and w_a measurements at each level are
 895 shown in (d). Fog layers indicated by red double arrow are obtained from PWD Vis shown in (d) and
 896 previous plots.

897 **5.5 Na Uncertainty and Droplet Spectra**

898 Droplet spectra from CDP, BCP, and FM120 probes include uncertainties related to the
899 calculations of TAS, turbulence, wind speed and ship direction. The aspirator used in
900 FM100 pulls in air at about 5 m s^{-1} but winds coming directly into the inlet can increase
901 (or decrease) the aspirator wind speed. Usually, using a higher TAS compared to a fixed
902 TAS at 5 m s^{-1} set up in FM120 results in a significant decrease (~50-100%) in N_d . For
903 ship measurements, these errors can be much larger. For example, a ship heading north (0
904 degrees) at 8 m s^{-1} plus a wind from NE can result in

905
$$TAS = U_{RV} + U_h \cos\theta. \quad (20)$$

906 Therefore, the error in TAS estimation, applying a derivative of TAS with respect to
907 time, can be written as

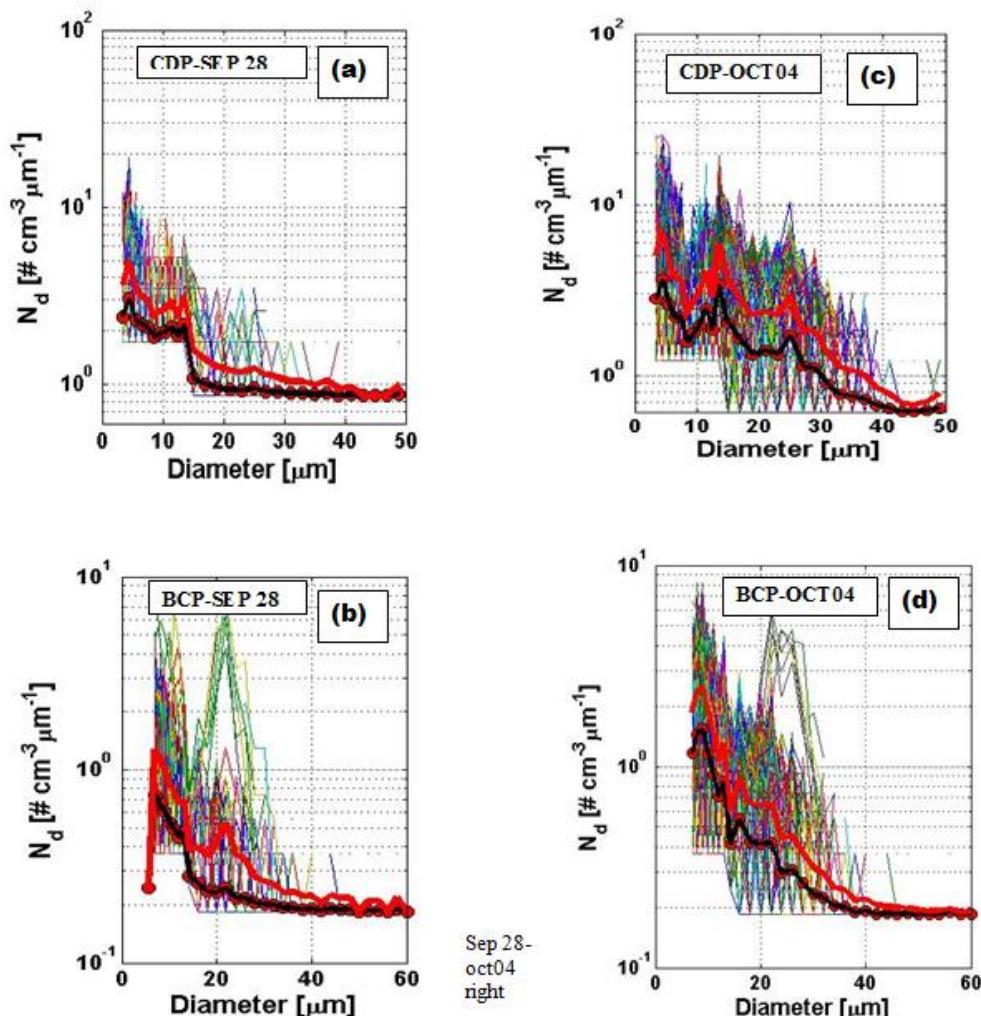
908
$$\varepsilon_{TAS} = \frac{dTAS}{dt} = \frac{dU_{RV}}{dt} + U_h \frac{d\cos\theta}{dt} + \cos\theta \frac{dU_h}{dt}. \quad (21)$$

909 The l.h.s of Eq. 20, ε_{TAS} represents an error in TAS per unit time [$(\text{m s}^{-1})/\text{s}$]. Assuming
910 that error in the first term of the r.h.s of Eq. 20 is approximately 1 m s^{-1} per unit time
911 (e.g., $dt=1 \text{ s}$) at $U_{RV}=8 \text{ m s}^{-1}$, and U_h has an error of 10% say at 0.5 m s^{-1} and wind
912 directional error is about 10 degrees (second term on the rhs), then using $U_h=10 \text{ m s}^{-1}$,
913 $\varepsilon_{TAS}=1 \text{ m s}^{-1} + 10 \text{ m s}^{-1} * (\cos 30 - \cos 40) + \cos(30) * 0.5 \text{ m s}^{-1} = 1.0 + 1.0 + 0.43 = 2.43 \text{ m s}^{-1}$.
914 Absolute error in TAS~ 18 m s^{-1} can then be calculated at about 15%. This means that N_d
915 uncertainty is also about 15%, but likely increases with decreasing TAS. Following
916 works can be suggested for further statistical evaluation of the analysis uncertainty;
917 Moffat (1982) and Kline and McClintock (1953).

918 Figure 19 shows fog droplet spectra obtained from the CDP and BCP probes for
919 Sep 28 (a and b) and Oct 04 (c and d) cases. The mean (black line) and standard deviation
920 (red line) of each bin during fog events of Sep 28 and Oct 4 are shown. Each coloured
921 line represents 1 s spectra. Clearly, Sep 28 droplet spectrum is much different from the
922 Oct 04 droplet spectra, based on both probes. Multi-modes in DSD indicate the various
923 fog regimes that were likely related to droplet fall velocities (V_f) and w_a . For both cases,
924 DSD did not indicate drizzle droplet sizes $> 50 \mu\text{m}$. MVD for the Oct 04 was much larger
925 than for the Sep 28 case. Note that the mean DSD can shift upward if a lower threshold of
926 N_d is chosen to have a higher value (e.g. $1 \# \text{ cm}^{-3}$ instead of $0.1 \# \text{ cm}^{-3}$). In BCP

927 measurements, having a large value for N_d at about 25 μm , may indicate cooling
928 processes leading to increasing values for N_d .

929



930

931 **Fig. 19** Fog droplet spectra vs diameter obtained from CDP and BCP probes for 28 Sep (a and b) and Oct
932 04 (c and d) cases. The mean (black line) and sd (red line) values of each bin during time periods
933 representing fog events of 28 Sep and 4 Oct 2018 are also shown on the plots. Each line with a colour
934 represents 1 s spectra.

935 Sea spray particles can also affect N_d spectra (at 10m) significantly because of
936 breaking waves, especially at small size ranges because of their low settling rates. In the
937 marine environment, droplets can be generated by wave breaking processes, which can
938 then be counted as fog droplets. Entrainment of air at breaking wave crests leads to the
939 formation of a large number of bubbles, which emerge at the ocean surface because of

940 their positive buoyancy and then burst into droplets at the water surface (Troitskaya et al
 941 2018). The spray production due to the bursting of bubbles with sizes smaller than <10
 942 μm has been studied by Blanchard (1963) and Spiel (1995, 1997, 1998). All of these
 943 studies suggest that bursting bubbles are the main source of the ocean spray process,
 944 generating droplets with radii less than $50 \mu\text{m}$ (Wu, 1981).

945

946 **5.6 Impact of TKE Dissipation Rate on Vis**

947 Fog occurs usually at the end of a dynamically unstable environment along coastlines and
 948 marine environments and is augmented sometimes by thermal inversions, keeping
 949 moisture trapped below a stable layer. Thereafter, when the mature fog stage has
 950 developed under dynamically stable conditions, fog dissipates as a result of droplet
 951 growth, increasing turbulence, entrainment, and solar heating. All these factors play an
 952 important role for fog dissipation without considering direct impact of a larger scale
 953 event such as pressure systems and associated fronts. In this work, calculated dissipation
 954 rates suggest that higher ε_{dis} values result in improved Vis conditions. Accuracy of ε_{dis}
 955 will not be discussed here, except in its usage in a fog prediction scheme. TKE
 956 dissipation rate is calculated in NWP models using TKE based on various turbulence
 957 prediction schemes (Mellor and Yamada 1982; Castelli et al 2005; Duynkerke 1988);
 958 therefore, it can be used to improve fog prediction.

959

960 Table 5. Mean and std of TKE dissipation rate calculated using Eq. 3 and Eq. 23, representing 1 hr time
 961 segments based on a 10-min filtering method for Sep 28 and Sep 29 2018 cases. Sep 29 case did not have
 962 wind measurements during heavy fog conditions. Reddish coloured area indicates missing data due to
 963 increased precipitation on the sonic anemometer located at the Battery.

Method	Sep 28 Mean ε_{dis} [$\text{m}^2 \text{s}^{-3}$]	Sep 28 Std ε_{dis} [$\text{m}^2 \text{s}^{-3}$]	Sep 29 Mean ε_{dis} [$\text{m}^2 \text{s}^{-3}$]	Sep 29 Std ε_{dis} [$\text{m}^2 \text{s}^{-3}$]
Using Eq. 3 Foggy	1.23×10^{-2}	1.73×10^{-2}	1.65×10^{-2}	1.19×10^{-2} 965
Using Eq. 26 Foggy	8.73×10^{-2}	24.94×10^{-2}	7.53×10^{-2}	9.21×10^{-2} 967
Using Eq. 3 Clear	7.76×10^{-2}	10.3×10^{-2}	-	-
Using Eq. 26 Clear	20.00×10^{-2}	25.59×10^{-2}	-	-

971 Table 5 is prepared using Eq. 3 and Eq. 26 for mean and std of ε_{dis} during foggy and fog
 972 free conditions, representing means of 1 hr time intervals. It shows that for both Sep 28
 973 and 29, foggy conditions had much smaller ε_{dis} than fog free conditions (excluding Sep 29
 974 case). For fog free conditions on Sep 29, ε_{dis} was corrupted due to precipitation on the 3D
 975 sonic anemometer optics. It is shown based on Table 5 that fog occurs usually when
 976 $\varepsilon_{dis} < 1 \times 10^{-2} \text{ m}^2 \text{ s}^{-3}$ and dissipates for $\varepsilon_{dis} > 10 \times 10^{-2} \text{ m}^2 \text{ s}^{-3}$. Between these two limits,
 977 intermediate fog intensity can likely occur. A conversion equation between ε_{dis} and TKE
 978 (Scully et al 2011) can be obtained using,

$$979 \quad L = C_\mu^3 \frac{TKE^{3/2}}{\varepsilon_{dis}}, \quad (22)$$

980 where L and C_μ are turbulent length scale ($kz=0.41*2$) where k is the Von Karman
 981 constant and z is the height (m) above sea level, and the non-dimensional stability
 982 function, respectively, that is assumed as a constant (0.447). Then, Eq. 22 can be
 983 rewritten for eddy dissipation rate as

$$984 \quad \varepsilon_{dis} = C_\mu^3 \frac{TKE^{3/2}}{kz} \quad (23a)$$

985
 986 Note that ε_{dis} and TKE are function of scales that need to be further evaluated and
 987 developed to improve NWP models based fog Vis predictions. After using the values of
 988 parameters given above, Eq. 23a becomes

$$989 \quad \varepsilon_{dis} = 0.8199 \sqrt[2]{TKE^3} \quad (23b)$$

990
 991 Based on ε time series (Figs. 7 and 9) and equations given in Table 4, we can suggest the
 992 following parameterizations for fog ($Vis < 1 \text{ km}$ & $RH_w > 95\%$), mist ($Vis > 1 \text{ km}$ &
 993 $RH_w > 80\%$), and light fog ($Vis > 1 \text{ km}$ & $RH_w > 95\%$) conditions, respectively, as

994
 995 for $RH_w > 95\%$ & $\varepsilon_{dis} < 10^{-2} \text{ m}^2 \text{ s}^{-3}$;

$$996 \quad Vis = 0.412(LWC \cdot N_d)^{-0.5455} \quad (24)$$

997 for $80\% < RH_w < 95\%$ & $\varepsilon_{dis} < 10^{-2} \text{ m}^2 \text{ s}^{-3}$;

$$998 \quad Vis = -0.0094RH_w^3 + 0.437RH_w^2 - 32.459RH_w + 817.062 \quad (25)$$

999 and

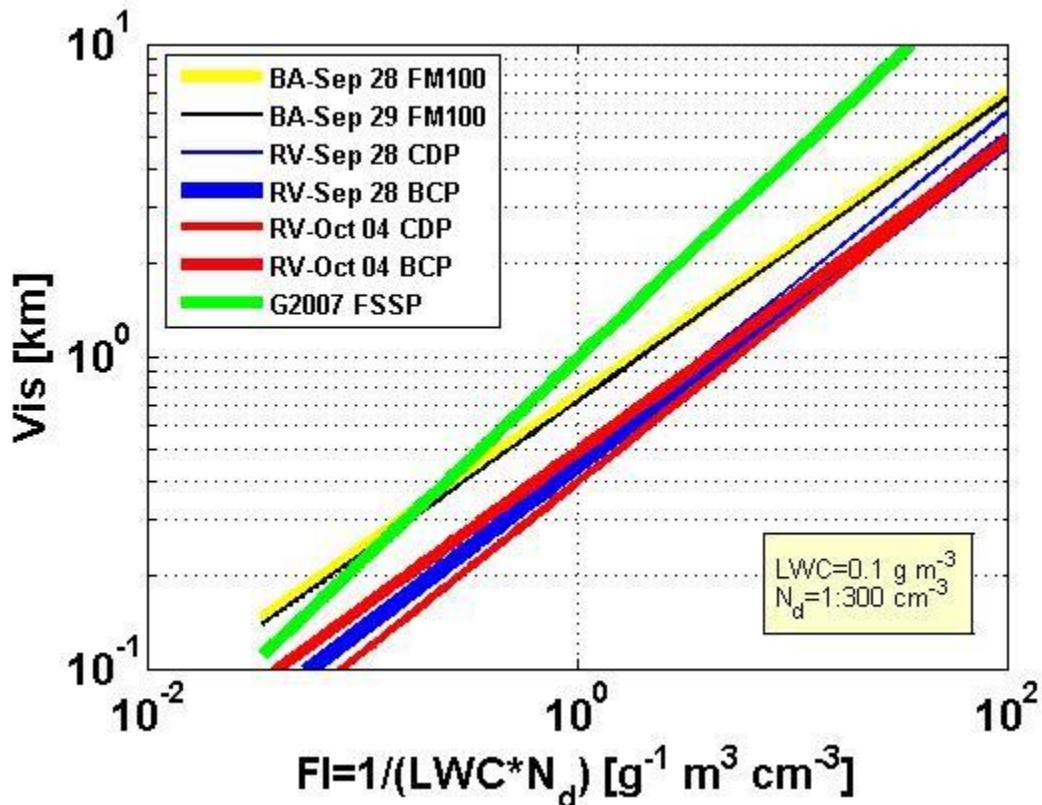
1000 for $RH_w > 95\%$ & $\varepsilon_{dis} > 10 \times 10^{-2} \text{ m}^2 \text{ s}^{-3}$;

1001 $Vis = 1.002(LWCN_d)^{-0.6473}$. (26)

1002

1003 The thresholds for TKE corresponding ϵ_{dis} thresholds for fog and clear air segments are
 1004 estimated as $<4.06 \times 10^{-2} \text{ m}^2 \text{ s}^{-2}$ and $>18.9 \times 10^{-2} \text{ m}^2 \text{ s}^{-2}$, respectively. Between them, fog to
 1005 light fog/mist conditions may occur but this needs further analysis.

1006



1007

1008 **Fig. 20** Vis parameterizations obtained for all the cases based on Table 4. LWC was fixed at 0.1 g m^{-3}
 1009 while N_d changed from 1 to 300 cm^{-3} . RV represents research vessel, BA Battery, G2007 Gultepe et al
 1010 (2007) and FI fog index. FM100, CDP, BCP, and FSSP probes are used for droplet spectral measurements.

1011 6 Conclusions

1012 In this paper, Vis associated with fog environmental parameters such as RH_w , 3D wind
 1013 components, and microphysical parameters, including LWC, N_d , and MVD were studied
 1014 for four cases. Results representing two IOPs from the Battery supersite and two IOPs
 1015 from the *R/V Sharp* are used in Vis parameterization development and to verify the

1016 previous parameterizations. Based on the results of this work, the following points can be
1017 drawn:

- 1018 1. Synoptic weather conditions and ocean-atmosphere interactions are the larger-
1019 scale factors that affect coastal fog microphysics and visibility. The cold ocean
1020 surface off the coast of Ferryland was usually a major reason for fog formation
1021 observed there.
- 1022 2. The main synoptic weather systems that affected fog were usually related to a
1023 high-pressure system located to the NE, a low-pressure system along W-NW, and
1024 a chain of tropical cyclonic motions. This may not be valid early in the fog season
1025 and usually can be valid during the Fall transition period
- 1026 3. Vis is found to be less than 1 km when RH_w is greater than 95%, and this suggests
1027 that the T_a-T_d difference is an important variable indicating fog regions, but not
1028 intensity.
- 1029 4. By decreasing dynamic activity, indicated by smaller 3D wind fluctuations and
1030 lifting, the eddy dissipation rate decreases during mature fog conditions that can
1031 be used for a threshold for prediction of mature fog conditions. Wind
1032 components; u , v , and w_a are relatively smaller in fog-developed regions than in
1033 fog-free regions.
- 1034 5. The w_a fluctuations were 0.1 m s^{-1} during mature fog conditions compared to >0.3
1035 m s^{-1} for fog-free regions. Note that these values can be much larger at the time
1036 scale of 16Hz or 32Hz.
- 1037 6. The TKE dissipation rate was usually $<10^{-2} \text{ m}^2 \text{ s}^{-3}$ during mature fog events
1038 compared to $>10^{-1} \text{ m}^2 \text{ s}^{-3}$ for fog-free regions and can be used for fog prediction
1039 criteria based on NWP models.
- 1040 7. Vis parameterizations that we constructed suggest that the slopes of the Vis versus
1041 fog index (FI) relationships are consistent with each other; but found to be
1042 comparably smaller in magnitude. This can be related to the nature of the
1043 measurement platform, fog season, as well as cloud versus fog measurements.
- 1044 8. Vis is expected to be function of LWC and N_d and this can be replaced with LWC
1045 and MVD without involvement of a 3rd parameter; this can be more generally
1046 applicable for NWP models.

1047 9. Vis<1 km observations showed a large variability, covering an area of a few km^2
1048 (1.5 km^2) up to 20 km^2 , and the difference was very high between a station at
1049 height 129 m (Judges' Hill) compared to one at the sea level, 2 m, (Battery
1050 station) although the horizontal separation distance was only about 1.0 km.

1051 10. BCP droplet number concentration is found to be at least half of the CDP N_d and
1052 this is likely due to BCP's higher threshold of 5 μm ; there were no droplets larger
1053 than 50 μm .

1054 11. There were double and triple peaks for fog DSDs and this can affect the NWP's
1055 fog prediction algorithms and needs to be further researched.

1056

1057 Based on these points, it is suggested that Vis parameterizations can be obtained
1058 using both dynamical and microphysical parameters, but fog droplet spectra
1059 representation for various fog conditions need to be further investigated. Specifically, the
1060 turbulence impact on droplet spectra and the nucleation processes are very critical for the
1061 fog life cycle in low vertical air velocity situations. Moreover, this is the most important
1062 parameter affecting the auto-conversion of fog droplets to drizzle formation.

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1067

1068 **Nomenclature**

1069

BCP: Backscattering Cloud Probe	RF: radiative fluxes
C: A constant ~0.18 in Eq. 3	SA: Sample Area
C: Visibility threshold constant as 0.05	SV: sampling volume
CN: Condensation nuclei	T_a : Air temperature
CCN: Cloud Condensation Nuclei	T_d : T_d : dew point temperature
CDP: Cloud Droplet Probe	TKE: Turbulent Kinetic Energy
D_s : The structure function	u, v, w_a : Measured wind components along x,y, z
DSD: Droplet Size Distribution	u', v', w' : Wind fluctuations
FI: Fog Index	U_{ha} : The apparent wind speed
FSSP: Forward Spectral Scattering Probe	U_{dx} and U_{dy} : wind speed along x and y axis at dt t
FM100: DMT fog measuring device (FMD)	U_{RV} : <i>RV Sharp</i> 's speed with respect to the ground
IR and SW: Infrared and shortwave rad.fluxes	U_{ht} : True wind speed over 10 mins intervals
k: The Von Karman constant as 0.41	U_{hr} : Wind speed with respect to ground
L: Turbulent length scale	U_{3D} : 3D wind component

L: The turbulent length scale	Vis: Visibility
LES: large eddy simulation	V_f : Droplet fall velocity
LWC: liquid water content	V_d : Doppler velocity
MVD: Mean Volume Diameter	Vis_B : Vis at Battery site
$n(r)$: Droplet number spectra	Vis_D : Vis at Downs site
N_a : Aerosol number concentration	Vis_{BH} : Vis at Blackhead site
N_{ao} : Aerosol number conc. over ocean	Vis_{JH} : Vis at Judges Hill site
N_{al} : Aerosol number concentration over land	Z_e : Radar reflectivity factor
N_c : Droplet counts	z : The height (m)
N_d : Droplet number concentration	α and γ : empirical constants in Eq. 13
N_{dt} : total droplet number concentration	μ : spectral shape parameter
N_o : intercept parameter	λ : slope parameter
NWP: Numerical Weather Prediction	β_{ext} : Extinction coefficient
PR: Precipitation Rate	β : Lidar backscatter coefficient
Q_{eff} : Extinction efficiency	η : the dispersion of radius (sd/mean),
r : droplet radius	ρ_w : water density
r_{eff} : Effective radius	θ : Angle between the ship heading and U_{ha}
Δr : The horizontal distance in Eq. 3.	ϵ : Eddy dissipation rate
Δt : Time interval	ϵ_{TAS} : Error in TAS
RH_w : relative humidity with respect water	

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1326

REVIEWER 1

Responses are given in red colored text

Thanks for your constructive points and comments on the importance of this work. We improved the manuscript based on your suggestions. We also improved the text further for clarity.

1. The TKE dissipation rate was found under certain level for C-fog events. This is an important finding of this study. Some other studies, (e.g. Zhou and Ferrier 2008, "Asymptotic analysis of equilibrium in radiation fog" on JAMC, Price2019, "On the Formation and Development of Radiation Fog: An Observational Study" on BLM), also found turbulence intensity must be smaller than a threshold for radiation fog. So turbulence has similar role in C-fog and radiation fog?

Please add these 2 references and some discussion.

1. We included these two papers in the introduction section now. Somehow missed these in introduction. Thanks for the point.

We now discussed this in Discussion section, and stated that this needs to be further researched because rad fog occurs usually in calm conditions. This means that EDR criteria can be still valid for rad fog prediction conditions but lower than this of marine environments.

2. Suggesting TKE dissipation rate in rule-based fog prediction is a good idea. But in regular NWP model, TKE dissipation rate is not output field. Most of NWP models have TKE output. So please also prove a threshold for TKE in the rule.

2. This is provided now in the equation/text. Thanks for the point.

3. Line 114: "LWC and Nd are needed for accurate Vis forecasting, but they are not accurately predicted by models".

Please provide reference(s) for this statement

3. A couple refs is provided now; Gultepe and Milbrandt ; Pu et al

4. Line 174 for the project area and Fig. 1e is the GFS, which model for GFS, is from Canadian or US NCEP's GFS?

4. This is from US NCEP's GFS and text is midified.

5. Line 1154 Wilkinson JM, A. N.F. Porson, F. J. Bornemann, M. Weeks, P.R. Field, and A. P. Lock (2013) Q. J. Roy. 1155, Meteorol. Soc., 139, 488-500. The tile is missing

5. This is added now, was a mistake.

Reviewer #2 Comments on BOUN-D-20-00120

Responses are given in red colored text

Reviewer Recommendation Term: 'Minor Revisions'

Comments to Author:

General comments:

This work studies coastal fog microphysics and its visibility that affect visibility parameterizations. It uses detail in-situ observations representing coastal fog based on a vessel and supersites. Their results suggested that environmental conditions play an important role for late-season fog formation. Visibility (Vis), wind speed (Uh), and turbulence along coastlines are the most critical weather-related parameters affecting marine transportation and aviation. In the analysis, microphysical observations are summarized together with 3D wind components and used for fog intensity (visibility) evaluation. Overall their conclusions stated that EDR is a critical parameter affecting microphysics and that should be part of NWP developments. In addition, they summarized microphysical parameterizations for coastal/marine fog research and clearly provided issues for microphysical measurement biases. In the summary, my comments are usually minor and believe this work will be very useful for coastal/marine fog research related to observations and prediction of fog.

Thank you very much for the points you made, we considered all your points in the text coherently and equally important. We also improved the paper for eqs and figures for clarity.

Major points

* Please prepare a nomenclature for parameters used in the paper because there are many of them and not easy to follow up.

This is prepared now in the end of text.

* In a paper in this C-FOG special issue on coastal fog; this needs to be rewritten to and modified as "In this work, CFOG related studies are briefly summarized; ..."

This is corrected.

* LN 142; Move this after first sentence in parag. In addition, the importance fog Vis predictions is discussed and challenges are noted when turbulence kinetic energy (TKE) dissipation rates are included.

Modified now.

* 3.1 Time Series of Nd and Turbulence Dissipation Rate (ϵ)-change this to "3.1 Time series of microphysics and turbulence....."

It is modified.

Minor points

LN76-may not be valid {, and therefore we have seen parametric modifications} take out the part in brackets

This is done now.

LN84: take out "or specifically coastal fog"

This is done.

LN87: latter in fog is usually not as strong as in clouds; you should say except during formation and dissipation conditions.

This is modified now.

LN105: In this respect, marine fog and cloud studies- change it to "marine fog and BL stratiform clouds"

Corrected.

LN110: take out "Although" and modified sentence, and put "but" before "they"

This is done.

LN116; LWC is a prognostic variable, but not Nd (assumed as fixed). Change this to "LWC is a prognostic variable and Nd is assumed as a fixed value

Modified.

LN138; please take out this sentence "C-FOG is designed to advance our understanding of liquid fog formation, development, and dissipation over coastal environments, and thus improve fog predictability and monitoring"

Taken out.

LN186; In this subsection, microphysical instruments as well as other available sensors-change to "microphysical and meteorological instruments are summarized" Table 2 : col 4, add ASL.

This is improved now.

LN231; Aug 14Oct 7 2018; needs a "-"

Modified.

LN299; normal to stable

Corrected.

LN288; "Uha is the apparent wind speed that includes both ship speed and wind speed", this should go to above.

It is modified now.

LN324; take out "only"

Done.

Results:

These are nice results with comparisons and derivations. Novel work here is that EDR used as criteria for Vis evaluation and this helps advancement of research on fog studies.

Yes it is correct that this can improve the Vis predictions using models.

Discussions: it is a good summary of issues related to coastal fog and its monitoring/predictions.

Conclusions:

Item 5; please explain 1 min versus 20 Hz values, and scale dependency

Improved now.

-References: Please check for refs in case of missing ones/citations.

This is checked and corrected.

Thanks for your improvements on the paper.

[Click here to view linked References](#)

REVIEWER 3

Responses are given in red colored text

Reviewer #3 Comments on BOUN-D-20-00120

Reviewer Recommendation Term: 'Minor Revisions'

Comments to Author:

This study summarizes the microphysical observations carried out during C-FOG field campaign. Using the microphysical measurements along with the 3D wind components, authors have shown the magnitude of 3D-wind fluctuations was higher during the formation and dissipation stages of FOG life cycle. The observations reported in the present study strengthen our current understanding of life cycle of coastal fog and helps in improving the existing microphysical parameterization schemes for accurate fog forecast of NWP models. Overall the study is very good and manuscript is well written. The following minor comments need to be addressed before considering it for publication.

Specific comments:

Lines 56-58: What are anticyclonic storms? Reference has been submitted and hence cannot be checked. I thought fog formed in quiescent conditions. Need clarification.

It is corrected as anticyclonic system, was a mistake. These systems can transport moisture and heat over colder regions of ocean, corrected. Various corrections are also done for the manuscript to improve the quality. Thanks for your points improve the paper.

Line 138: "(Toward Improving Coastal Fog Prediction)" should go to line 119 where C-FOG is first introduced

It is done.

Line 142:"the importance fog Vis predictions" should be "the importance of fog Vis predictions"

Corrected.

Figure 1: color bars too small; parenthesis missing after "days"; vectors in panel (e) cannot be seen; what is the meaning of the two stars in panel (c) and the acronyms in panel (b)? It should be made clear in the caption.

This is improved now.

Line 176: cold front or warm front?

Improved as warm front.

Line 177: how many tropical cyclones? How strong were they and how far away did they get from the measuring sites? This information is needed to gauge their potential impact on the weather conditions at the site.

Over 6 week time period we located at least 4 tropical systems, and they were usually 500 km south or south east of the project location. This is now clarified.

Line 194: the acronym CDP was already defined in line 129, no need to do it again Lines 190-197: for readers that may not be familiar with this, can you please provide the typical radius of droplets in clouds and in fog and drizzle events?

Second definition is taken out, and improved. Droplet sizes are provided as 1-30 micron for fog, 30-100 micron as drizzles, and 1-100 micron for cloud droplets because usually clouds are more active dynamically compared to fog events. This is improved now.

Lines 205-209: define the acronyms NIR, MW, LIDAR and GOES-R

These are defined now.

Table 2: Not sure it is a good idea to have Table 2a and 2b, better to have Table 2 and Table 3. In Table 2b, is Z the height above mean sea-level and H the height aboveground level?

We separate them as 2a and 2b because we cant fit them into 1-page.

Now tables are given as T2 and T3, and text is modified accordingly.

Z and H are defined now.

Figure 3 and others: No need to add "Shows" at the beginning of the caption Line 231: spacing is missing at the end Line

Corrected for all figures and

LN231: It is modified for spacing.

234: "prior to fog, and average" should be "prior to fog. The average"

Corrected now.

Figure 4: Fog is defined as horizontal visibility impaired by water droplets dropping below 1 km. Perhaps a horizontal line corresponding to Vis = 1km can be drawn to better highlight the fog events, or shade as you do in Figure 17.

This is improved now as suggested. Vis=1 km is shown with a line now.

Figure 5: again, very hard to see color bar and labels, please improve the quality of the figure

This is corrected, and we have original figs that will be provided to printing office.

Lines 252-253 and 259-262: can you prove these hypotheses with the available measurements?

Yes, we can, and modified the first sentence but second one is already shown by the given reference.

Section 3: I suggest using a better title as you are describing the theory here. An equation can be provided for Vis-RHw parameterization in section 3.2.1 or at least refer to section 4.1.1 for more details.

Title is modified and Eq. is provided now/refer to section 4.1.1

Line 365: Mist refers to visibility between 1 and 2 km and haze between 2 and 4 km even though different thresholds are used. Stating mist as having a visibility >1 km is incorrect as there is an upper-limit.

These values are not firm unfortunately and need to be further discussed; mist Vis>1 km but <5 km with RH>80%, and haze is usually Vis>5 km with RH<80%, and this is clarified now.

Lines 880-883: TCs do not occur that often in the region, but it is still nice to report on their impacts

Agree and this is slightly modified now.

Thanks for your constructive points.

1 A review of Coastal Fog Microphysics during C-FOG

2
3 *I. Gultepe^{*},^{1a,1b,2}, A.J. Heymsfield³, H.J.S Fernando², E. Pardyjak⁴, C. E. Dorman⁵, Q. Wang⁶, E.*
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5 *Perelet⁴, D.K. Singh⁴, R. Chang¹², B. Nagare¹², S. Wagh², and S. Wang²*

6
7 Received: July 02 2020

8 **Abstract** The goal of this paper is to provide an overview the microphysical
9 measurements made during the C-FOG (*Toward Improving Coastal Fog Prediction*) field
10 project. In addition, we evaluate microphysical parameterizations using the C-FOG
11 dataset. C-FOG is designed to advance understanding of liquid fog formation,
12 development, and dissipation in coastal environments to improve fog predictability and
13 monitoring. The project took place along eastern Canada's (Nova Scotia, NS and
14 Newfoundland, NL) coastlines and open water environments from August-October 2018,
15 where environmental conditions play an important role for late-season fog formation.
16 Visibility (Vis), wind speed (U_h), and turbulence along coastlines are the most critical
17 weather-related parameters affecting marine transportation and aviation. In the analysis,
18 microphysical observations are summarized first and then they are, together with 3D-
19 wind components, used for fog intensity (visibility) evaluation. Results suggest that
20 detailed microphysical observations collected at the supersites and aboard the Research
21 Vessel (*R/V*) *Hugh R. Sharp* are useful for developing microphysical parameterizations.
22 The fog life cycle and turbulence kinetic energy dissipation rate were strongly related to
23 each other. The magnitude of 3D-wind fluctuations was higher during the formation and

24 -----
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41
42 dissipation stages. An array of cutting-edge instruments used for data collection provided
43 new insight into the variability and intensity of fog (visibility) and microphysics. It is
44 concluded—that further modifications in microphysical observations and
45 parameterizations are needed to improve fog predictability of NWP (Numerical Weather
46 Prediction) models.

47
48 **Keywords:** Fog Microphysics. Coastal Fog. Visibility. Eddy Dissipation Rate
49

50 **1 Introduction**

51 Coastal fog plays an important role for weather conditions affecting marine environments
52 that include aviation (Gultepe et al 2020), marine shipping (Fernando et al 2020),
53 sporting and social activities (Pezzoli et al 2010), as well as vegetation (Schemenauer et
54 al 2016; Torregrosa et al 2014). The direct consequence of fog is the impairment of
55 visibility, and hence the ‘intensity’ of fog is defined in terms of visibility (Vis).
56 Advection supplies moisture for Atlantic-Canadian coastal fog, while the overhead
57 passage of cyclonic or anticyclonic systemsstorms fosters its actual formation (Dorman et
58 al. 2020). Other factors such as large-scale subsidence leading to thermal inversions,
59 frontal systems, radiative cooling, topography, tropical cyclones, and turbulence fluxes
60 can also have an impact on the life cycle of coastal fog (Gultepe et al 2007; Toth et al
61 2011). Intensity of turbulence and turbulence dissipation rate occurred during life cycle
62 of radiation fog were studied by Zhou and Ferrier (2008) and Price (2019) and these
63 suggested that turbulence intensity should be less than a threshold value.

64 Microphysical measurements were performed using a fog measuring device
65 (FMD, FM100) for the first time by Gultepe et al (2007a) during the FRAM project,
66 followed by others (Niu et al 2010; Spiegel et al 2012; Isaac et al 2020). The FM100 was
67 developed using the principles of a forward scattering probe (FSSP), measurements of
68 which were used in developing Vis parameterization by Gultepe et al (2007b). The
69 FM100 provides droplet spectra, which are used to obtain liquid water content (LWC^{*}),

70 -----
71 *Definitions are provided in Nomenclature in the end of paper.

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72 mean volume diameter (MVD), effective size (rR_{eff}), droplet number concentration (N_d),
73 and the droplet settling rate ($LWC \cdot V_f$), where V_f is the droplet fall velocity. NWP
74 modeling and evaluation studies of fog have helped to improve forecasting and gain
75 physical insights (e.g. Yang et al. 2009; Gultepe et al. 2007a,b). Warm-fog droplet spectra
76 and its distribution are related to condensation nuclei (CN) and relative humidity with
77 respect to water (RH_w). There have been several studies on this issue, but cloud
78 condensation nuclei (CCN) versus supersaturation with respect to water (S_w)
79 relationships are mostly developed for cloud studies and generally use fixed values of
80 100 cm^{-3} for marine environments (Thompson et al 2008). In reality, such fixed values
81 may not be valid, and therefore we have seen parametric modifications. (Thompson et al
82 2014). Prediction of N_d is obtained using prognostic equations that represent processes
83 related to turbulence, droplet growth, radiative heating/cooling, as well as turbulence flux
84 divergence (Storelvmo et al 2014). Based on assumed modified-gamma distributions,
85 either using Kohler theory (Chen 1994) and/or Twomey parameterization (Twomey
86 1959), N_d predictions can be performed using single or double moment microphysical
87 schemes (Milbrandt and Yau, 2005a,b; Morrison and Gettelman 2008; Schwenkel and
88 Maronga, 2019). However, these schemes have been developed for clouds and not for
89 fog. ~~or specifically coastal fog.~~

90 As in Twomey et al (1959), N_d is parameterized based on Kohler theory assuming
91 equilibrium and cooling of an air volume by lifting via the vertical air velocity (w_a). The
92 latter in fog, ~~excluding formation and dissipation conditions~~, is usually not as strong as in
93 clouds, complicating the application of these parameterizations to fog. Therefore, its
94 usage cannot be verified for all fog types. Another equation for N_d prediction, mainly
95 applicable to climate studies, expresses it as a function of w_a , N_a (aerosol total number
96 concentration) as well as aerosol composition (Abdul-Razzak and Ghan 2000; Ghan et al
97 1998; 2001). In addition to parameters given in Twomey (1974; 1991), this equation uses
98 aerosol composition as an independent parameter. Clearly, environmental conditions such
99 as air temperature (T_a), dew point temperature (T_d) and RH_w , and w_a as well as aerosol
100 and microphysics parameters (CCN and droplet growth rate) play an important role in N_d
101 prediction, thereby affecting V_{is} estimation (Schwenkel and Maronga, 2019). In this
102 regard, Gultepe et al (2007b) have suggested that accurate predictions of N_d and LWC are

103 critical for Vis prediction, and Vis cannot be accurate if only LWC is used (Kunkel 1984;
104 Stoelinga and Warner 1999). Vis is usually diagnosed in the post processing stage of
105 forecast model outputs using Stoelinga-Warner's method (Stoelinga and Warner 1999),
106 which includes large uncertainties in fog prediction (Gultepe et al 2006, 2007c).

107 Lately, field observations from various projects have been used to improve Vis
108 parameterizations (Gultepe et al 2009; 2014; Haeffelin 2010; Price et al 2018; Wang et al
109 2020) but these are often site dependent because of the nature of N_a spectra and
110 compositional properties (Bergot et al 2005). In this respect, marine fog ~~and cloud~~ studies
111 ~~have been used to develop m used m~~ microphysical parameterizations extensively (Gultepe
112 et al 2009; Gultepe et al 1996). The C-FOG ([Toward Improving Coastal Fog Prediction](#))
113 field project has had better tools to evaluate coastal fog microphysical and dynamical
114 properties, such as droplet and aerosol spectra and turbulence over both the coastal areas
115 and at the ship (Fernando et al 2020).

116 ~~Although~~ Vis parameterizations commonly use only RH_w and or (T_a-T_d) (called
117 dew point depression) to predict fog coverage ~~but~~—they cannot be used for fog intensity
118 (~~drop of e.g.~~ Vis) because RH_w (as well as T_a-T_d) indicates only the existence of fog
119 (Toth et al., 2011; Gultepe et al 2009; Renata et al 2020). Therefore, fog microphysical
120 parameters such as LWC and N_d are needed for accurate Vis forecasting, but they are not
121 accurately predicted by models ([Pu et al 2016](#), [Renata et al 2020](#), [Gultepe and Milbrandt
2010](#)). In single-moment and double moment microphysical schemes used in NWP
122 models, LWC is usually a prognostic variable; and but not N_d ~~is~~ assumed as a fixed
123 value or. In double moment schemes, N_d can be or obtained either deterministically or
124 prognostically, by making several assumptions on physical terms affecting N_d . If N_d is
125 not fixed, a modified gamma distribution is usually assumed in presenting fog droplet
126 size distribution that is used to obtain N_d .

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128 In a paper in this C FOG special issue on coastal fog ~~In this work, C-FOG related~~
129 studies are briefly summarized; ([Dimitrova et al 2020](#)), WRF fog simulations predictions
130 using with various microphysical and surface boundary layer schemes are
131 performed tested for Vis predictions at the ship and supersite locations. Another
132 microphysics paper is focused on a case of stratus lowering fog over the coastline based
133 on the *R/V Sharp* observations (Wagh et al 2020). Understanding fog microphysics and

134 its impact on Vis, based on a LES model, is provided by Wainwright and Richter (2020).
135 A study using a Tethered Balloon System (TBS) with aerosol and droplet spectral
136 measurements as well as fog thermodynamics is examined by Singh et al (2020). Detailed
137 coastal fog observations at The Downs, Ferryland (Wang et al. 2020) are studied by
138 providing TBS dynamic and thermodynamic profiles and collecting fog-droplet spectra
139 ~~and aerosol extinction parameters~~ from a ~~cloud droplet probe (CDP) fog measuring~~
140 ~~device in a housing unit~~. Perelet et al (2020) present a methodology for using a two-
141 wavelength scintillometry system for measuring fog characteristics on scales of 1 km.
142 Wang et al. (2020) also focused on the impact of the fog layer on optical propagation
143 using contrasting measurements at Ferryland and on the US West Coast. In addition,
144 large-scale synoptic events affecting local fog formation are summarized by Dorman et al
145 (2020). An overview of the C-GOG project is given in Fernando et al. (2020).

146 The goal of this paper is to provide an overview of coastal fog microphysical
147 measurements and to evaluate microphysical parameterizations based on the C-FOG
148 ~~(Toward Improving Coastal Fog Prediction)~~ field project. ~~In addition, the importance of~~
149 ~~fog Vis predictions is discussed and challenges are noted when turbulence kinetic energy~~
150 ~~(TKE) dissipation rates are included. C-FOG is designed to advance our understanding~~
151 ~~of liquid fog formation, development, and dissipation over coastal environments, and thus~~
152 ~~improve fog predictability and monitoring.~~ The C-FOG field project has provided
153 microphysical observations from several ~~coastal land~~ sites and the *R/V Hugh R. Sharp*
154 (hereafter *R/V Sharp*). ~~In addition, the importance fog Vis predictions is discussed and~~
155 ~~challenges are noted when turbulence kinetic energy (TKE) dissipation rates are included.~~
156 ~~The paper organization is planned as follow:~~ Section 2 provides information on
157 observations and project design. Section 3 explains the analysis used in Vis and eddy
158 dissipation rate (EDR) parameterizations. Sections 4 and 5 focus on discussions and
159 conclusions, respectively.

160
161 **2 Field Project and Observations**
162 **2.1 Project Location**
163 The C-FOG field campaign took place from 01 September to 07 October 2018. The field
164 campaign took place along the coastlines of Atlantic Canada and the northeastern US. ~~C-~~

165 FOG is designed to advance our understanding of liquid fog formation, development, and
166 dissipation over coastal environments, and thus improve fog predictability and
167 monitoring. It was designed to capture fog variability in time and space using an array of
168 platforms that included ground, airborne, and shipborne in-situ instruments, remote
169 sensors as well as numerical models. ~~The field campaign took place along the coastlines~~
170 ~~of Atlantic Canada and the northeastern US.~~ Instruments were located at two supersites
171 (Battery and The Downs sites in Ferryland, NL; Figure 1a,b), four satellite sites, as well
172 as on the *R/V Sharp* (Fernando et al 2020). Figure 1c shows the entire project area
173 overlaid on a satellite SST image for 28 September 2018. A strong SST gradient stands
174 out near the northern region of the project area. In the current study, four cases are
175 presented covering parts of the Intense Operational Periods IOP10 (27–30 Sep 2018) and
176 IOP 12 (03-04 Oct 2018) that mainly represent warm advection fog events (Table 1).

177

178

179

180 **Table 1** Case studies of coastal fog events studied in the present work. T_a is air temperature and SST is sea
181 surface temperature.

Day	Location	Weather
Sep 28 2018	Battery supersite	T_a , SST, warm air advection
Sep 29 2018	Battery supersite	Warm air advection
Sep 28 2018	R/V Sharp	Warm air advection
Oct 04 2018	R/V Sharp	Advection and tropical depressioneyelone

182

183

184 **Fig. 1** Ferryland supersite region (a), Battery supersite (b), SST and entire project location with ship
185 locations (indicated by a red star for foggy days (c), synoptic weather systems affecting project area (d),
186 and GFS (Global Forecasting System) surface pressures and wind speed in Knots (e).

187

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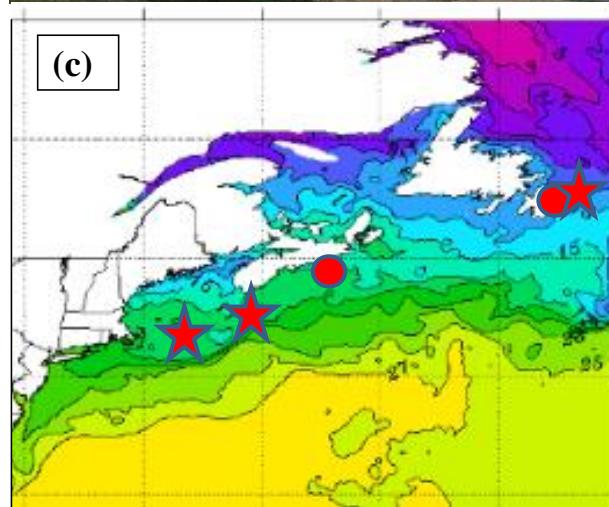
(a)

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(b)

202



(c)

203

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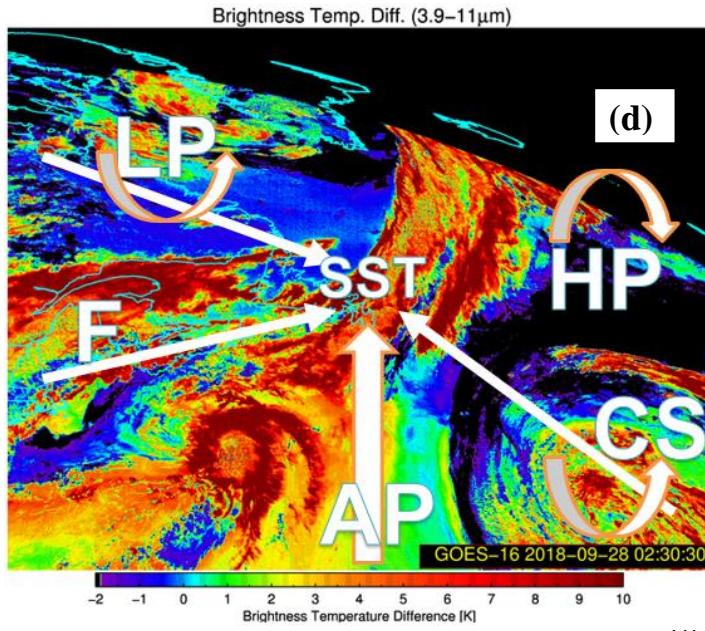
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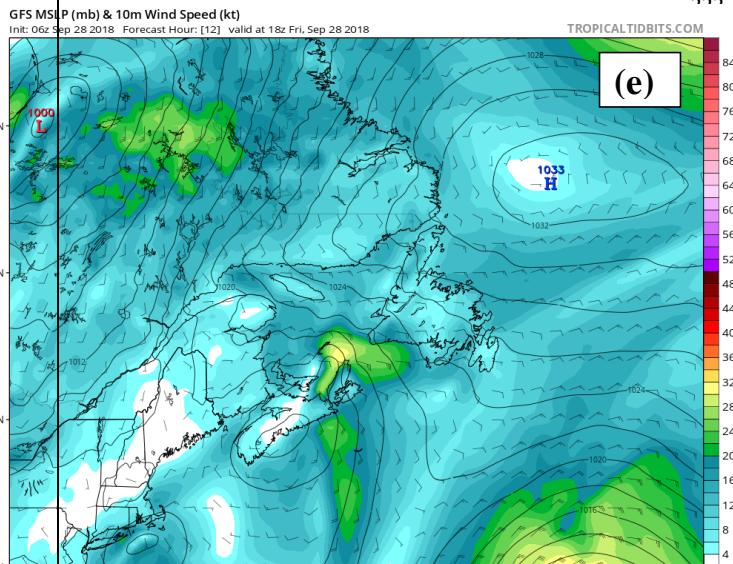
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221



232 **Fig. 1** Ferryland supersite region (a), Battery supersite (b), NOAA NESDIS Geo-Polar blended 5 km SST
 233 and entire project area with supersites (red circles) and ship locations (indicated by a red star for foggy days
 234 (c), synoptic weather systems affecting project area (d) with LP for “low pressure”, F “front”, SST “sea
 235 surface temperature”, AP “advection process”, HP “high pressure”, and US

236 NCEP (National Center for Environmental Prediction) GFS (Global Forecasting System) based surface
237 pressures and wind speed in Knots (e).

238

239

240 **2.2 Synoptic Weather Systems**

241 The C-FOG campaign took place at the end of the summer fog season (Gultepe et al 2009).
242 During this time, various weather systems affect coastal-fog conditions. Figure 1d shows the SST
243 for the project area and Fig. 1e is the GFS sea-level pressure and 10 m wind vectors on 28
244 September 2018. The latter shows— major weather systems affecting the project area: a low
245 pressure over Nova Scotia in the NW and associated with a warm frontal system (F) in the
246 east, a high pressure (HP) to the NE, and tropical cyclones— to the south east (CS), and
247 warm-air advection processes (AP) resulting from T and q_v gradients along a north-south
248 direction. The tropical cyclones usually became tropical depressions when moved to
249 colder northern latitudes and usually they were about 500 km south and southeast of the
250 main project site. During May 25-Oct 31 2018, 16 tropical depressions occurred over 4-
251 months time period and about 4 of them affected physical conditions somehow at the
252 project site. Their advection of SW quadrant of warm and moist air to N and NW
253 quadrants likely played an important role for fog formation 100s of km away from storm
254 center. Figure 1e is an example (Sep 28 case) illustrating the placements of the above
255 mentioned weather systems. The photos in Figure 2 depict fog cases observed at The
256 Downs supersite, and from the *R/V Sharp*, respectively.



257

258 **Fig. 2** shows the pictures of advection process occurring on Sep 28/29 2018 case at the Downs supersite
259 (a) and on Oct 04 2018 (taken from the RV) (b).

260 2.3 Microphysical Observations

261 In this subsection, microphysical and meteorological instruments ~~as well as other~~
262 ~~available sensors~~ are summarized. All instruments used are summarized in Fernando et
263 al. (2020). These measurements are related to dynamics, microphysics, radiation, aerosol,
264 and thermodynamic properties of the environment. For particle size thresholds, fog
265 droplets usually cover 1-30 μm , cloud droplets 1-100 μm , drizzle drops 100 (or 30)-500
266 μm , and drizzle and rain drops $>100 \mu\text{m}$ in diameter.

Microphysical instruments used during C-FOG are summarized in Table 2a for the *R/V Sharp* and in Table 2b-3 for all ground-based sites. Special sensors (Table 2a) were developed for fog microphysics investigations, including a ‘gondola’ shaped assembly (located on the *R/V Sharp*) that contained microphysical sensors such as a cloud droplet probe (CDP) and a backscatter cloud probe (BCP) **in a gondola unit** for measuring

272 droplet sizes ranging from 1-50 and 5-75 μm , respectively. A laser precipitation monitor
273 (LPM) for 100 μm to mm sizes and an optical particle counter (OPC) for sizes of 0.3-20
274 μm using 1620 spectral channels allowed fog and drizzle discrimination (Table 2).

275
276 **Table 2a** Microphysical instruments mounted on the *R/V Sharp* during the C-FOG campaign. *Parameters*
277 *in Column 2*: N_d Droplet number concentration, N_a Aerosol number concentration, SV Sampling Volume,
278 S_w Supersaturation with respect to water, and Vis Visibility. *Parameters in Column 4*: UOIT Ontario
279 Technical University, UU University of Utah, Wood Corporation, DU Dalhousie University, and NDU
280 Notre Dame University.

Instrument Name	Measurements	Height (asl, m)	Owner
CDP, DMT, Gondola	N_d , Droplet spectra (1-50) μm	31.8	UOIT
BCP, DMT, Gondola	N_d , Droplet spectra (5-75) μm	31.8	UOIT
OPC N2, Alphasense	N_a , Aerosol Spectra 0.38-17 μm , 16 channels	15	UU
DMT, FM120, near Gondola	N_d , Droplet spectra (1-50) μm	31.6	WOOD
TSI Moudi Impactor 100NR	N_d spectra, 0.18-18 μm , 8 stages, 30 L m^{-1}	37.9	WOOD
Virtual Impactor Inlet	At 20 m, SV=16.7 L min^{-1}	30.1	DU
SMPS 3082, TSI	N_a Spectra, 10-500 nm; SV=1.0 L min^{-1}	30.1	DU
APS 3321, TSI	N_a Spectra, 0.5-20 μm SV=1.0 L min^{-1}	30.1	DU
ACSM, Aerodyne	N_a Composition, <1 μm SV=0.1 L min^{-1}	30.1	DU
CCN-100, DMT	N_a >0.01 μm ; S_w =0.2,0.4,0.8,1% SV=0.5 L m^{-1}	30.1	DU
PWD22- Vaisala	Vis <20 km	10	NDU

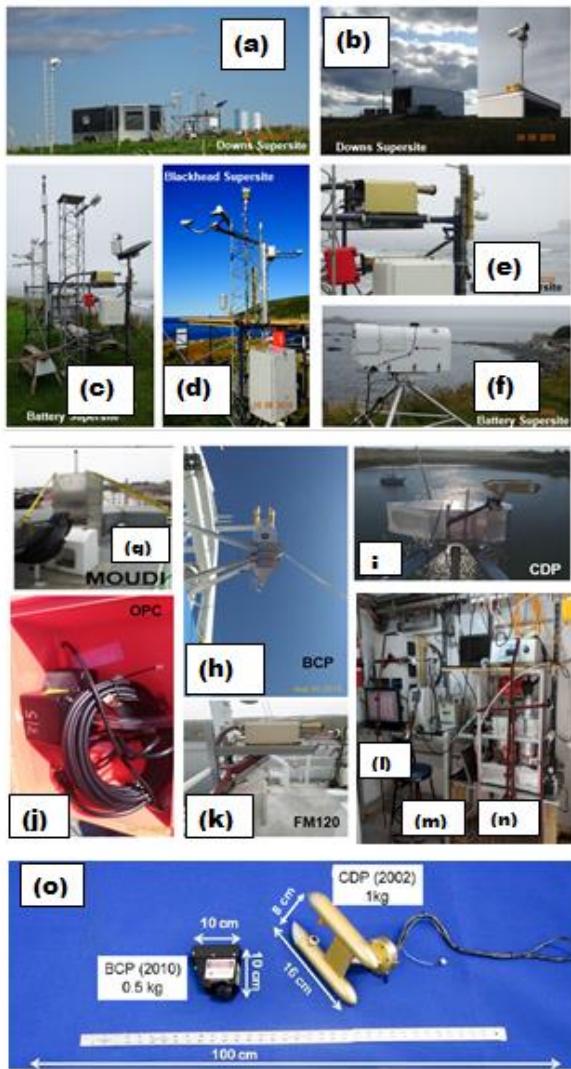
281
282 Also, three Scintillometers (Table 32b) with measurements in the NIR (Near
283 Infra-Red) and MW (MicroWave) radiation channels were utilized to allow
284 discrimination of fog from rain (Perelet et al 2020). Figure 3 shows the microphysical,
285 aerosols, as well as meteorological instruments. Remote-sensing platforms (e.g.
286 microwave radiometer MWR, ceilometer, Lidar), meteorological towers, tethered
287 balloons, and the GOES-R (Geostationary Operational Environmental Satellite-R series)
288 Products (fog coverage and effective droplet size) provided information on horizontal and
289 vertical variability. Observational products are used for fog-visibility parameterization
290 development, with a focus on understanding the influence of dynamical processes such as
291 turbulent mixing and dissipation.

292
293 **Table 32b** Microphysical instruments located at the ground sites during C-FOG field campaign. *The*
294 *parameters in Column 2*: Vis Visibility, PR Precipitation rate, IR Infrared, SW shortwave, RF radiative
295 fluxes, LWC liquid water content, Z_e radar reflectivity, V_d Doppler velocity, N_a aerosol number

296 concentration, Z_{cb} cloud base height, β backscattering coefficient, λ wavelength, β_n extinction coefficient,
 297 CN condensation nuclei, RH relative humidity, T temperature, U_h horizontal wind, and P pressure.
 298 *Parameters in Column 7 and 8:* BA Battery Supersite, BH Blackhead site, DO Downs Supersite, UOIT
 299 Ontario Technical University, UU University of Utah, UND University of Notre Dame, and NPS Navy
 300 Postgraduate School.

Instrument Name	Measurements	H (<u>agl.m</u>) <u>AGL</u>	Z (<u>agl.m</u>)	Lat [deg]	Lon [deg]	Site	Owner
PWD50-Vaisala	Vis and PR	2	6	47.03443	-52.8782	BA	UOIT
FM100 & FM120	Fog droplet spectra	2	6	47.03443	-52.8782	BA	UOIT
CRN1 Kipp&Zonen	IR&SW up and down RF	2	6	47.03443	-52.8782	BA	UOIT
PMWR MP3017	Profiling, T, RH, LWC	2	6	47.03443	-52.8782	BA	UOIT
MRR, Metek	Z_e & V_d	2	6	47.03443	-52.8782	BA	UOIT
LPM, Metek	Precip. Spectra $>100 \mu\text{m}$	2	6	47.03443	-52.8782	BA	UOIT
OPC, Alphasense	N_a spectra, $>0.3 \mu\text{m}$	2	6	47.03443	-52.8782	BA	UU
CL31, Vaisala	Z_{cb} and β	2	6	47.03443	-52.8782	BA	UU
Vaisala PWD 50	Vis ($<30 \text{ km}$)	2.9	10	47.52633	-52.6583	BH	UOIT
Vaisala PWD 22	Vis ($<30 \text{ km}$)	3	31	47.02181	-52.8731	DO	UND
LPM Metek	Precip. spectra $>100 \mu\text{m}$	2.74	10	47.52633	-52.6583	BH	UOIT
OPC, Alphasense	Aerosol spect. ($0.3\text{-}20 \mu\text{m}$)	1.37	10	47.52633	-52.6583	BH	UU
DMT CDP	fog droplets ($1\text{-}50 \mu\text{m}$)	3	31	47.02181	-52.8731	DO	NPS
TSI -3563 Nephelometer	$3\text{-}\lambda$ scat& β_n ($0.45\text{,}0.55\text{,}0.70 \mu\text{m}$)	3	31	47.02181	-52.8731	DO	NPS
TSI OPC-310	$\text{CN} > 0.01 \mu\text{m}$	3	31	47.02181	-52.8731	DO	NPS
PSAP, Part Soot Abs Photometer	$1\text{-}\lambda$ absorp. at $0.565 \mu\text{m}$	3	31	47.02181	-52.8731	DO	NPS
Scintillometer (BLS -900, Scintec AG)	wavelength $0.88 \mu\text{m}$ extinction	2.9	31	47.02181	-52.8731	DO-BH Tx-Rx	NPS
Scintillometer (BLS 900, Scintec AG)	wavelength $0.88 \mu\text{m}$ extinction,	2	6	47.03443	-52.8782	BA-DO Tx-Rx	UU
Scint. MWSC 160, Radio.Phy. GmbH	microwave (wavelength $1.860 \mu\text{m}$ extinction)	2	6	47.03443	-52.8782	BA-DO Tx-Rx	UU
Met parameters	RH, T, U_h , P	3	31	47.02181	-52.8731	DO	NPS

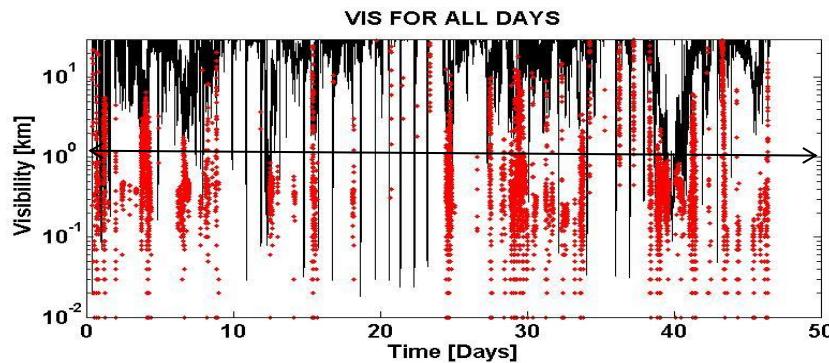
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301
302 Fig. 3 PShows project locations with microphysical probes: NPS microphysical sensors mounted on a
303 trailer at the Downs site (a), CDP2 located in a housing shown in (b), FM120, PWD, LPM at Battery (c),
304 PWD, LPM, and OPC at Blackhead (d), a close look of FM120 at Battery (e), PMWR at Battery (f), Wood
305 MOUDI impactor (g), Gondola BCP (h) and CDP2 (i) mounted on Sharp RV, UU OPC (j), Wood Corp
306 FM120 (k), Dalhousie University(DU) CCNC (l), DU SMPS (m), and DU ACSM (n), and Gondola housed
307 CDP and BCP (o) physical characteristics (adapted from Beswick et al 2014).

308 **2.4 Macro-physical Characteristics**

309 During the installation and campaign period that spanned 7-weeks (Aug 14–Oct 7 2018)
310 various fog conditions existed, as represented by Vis measurements from the Battery site
311 (Fig. 4). This figure shows Vis for 46 days starting from Aug 21 to Oct 7 during which
312 drizzle and light precipitation usually occurred prior to fog, ~~and a Average~~ fog
313 occurrence during entire campaign was about 20-25%.

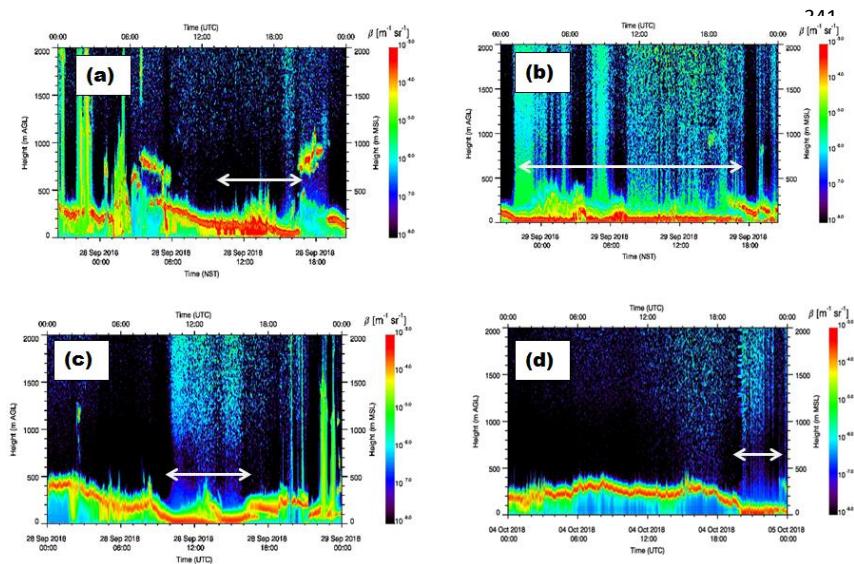


314
315 **Fig. 4** Shows Time series of Vis obtained from PWD52 present weather sensor for the entire time period
316 from Aug 24 to Oct07 2018. The red dots are for drizzle and black lines are for fog Vis. Transition from
317 fog to drizzle cannot be exactly defined. The line with double arrow indicates Vis level at 1 km.
318

319 A CL31 ceilometer measured the backscatter ratio (β) time and height cross
320 sections at the Battery supersite and on the *R/V Sharp* for the 4 cases studied, as shown in
321 Fig. 5. Note that the ceilometer-based fog-top heights are not accurate because of its
322 strong extinction when a large number of smaller fog droplets exist. Figure 5a and 5b are
323 for 28 and 29 September cases, respectively, as observed at the Battery supersite and Fig.
324 5c and 5d are for 28 September and 04 October cases, respectively, aboard *R/V Sharp*.

325 The 28 September case at the Battery site, occurred at about 1000 UTC after the
326 stratus layer base lowered from 500 m to the surface over 3 hrs. Some drizzle was
327 observed (indicated by the spiking cloud base in red color), which disappeared about
328 1700 UTC. The 29 September case was a continuation of the 28 September case, during
329 which fog briefly lifted at 1600 UTC and then re-formed at 2200 UTC and lasted until
330 almost 1800 UTC, which is not likely related solely to a lowering stratus, but was also
331 likely due to warm-air advection that is verified by using synoptic weather conditions.

332 The *R/V Sharp* data for 28 September (Fig. 5c) show that the cloud base
 333 decreased from 500 m at 0000 UTC to almost the surface at 1000 UTC, and then lifted
 334 very quickly at 1330 UTC. After this, the stratus base lowered again to form fog at 1400
 335 UTC. At 1600 UTC, the fog base lifted and eventually disappeared. The *R/V Sharp*
 336 observations for 04 October show that fog formed again due to stratus lowering around
 337 2000 UTC and lasted until 2300 UTC. Note that the lowering cloud base occurred late on
 338 this day and is likely due to IR cooling and/or large-scale subsidence. This might also be
 339 related to drizzle that moistened lower layers, eventually led to fog formation (Singh et al
 340 2020; Wagh et al 2020).



355 **Fig. 5** Time-height cross sections of backscatter coefficient (β) from CL31 ceilometers measurements – at
 356 the Battery supersite and onboard the Sharp RV for the 4 cases studied; Sep 28 (a) and Sep 29 (b) cases
 357 observed at the Battery supersite and Sep 28 (c) and Oct 04 2018 (d) cases at the Sharp RV. The white
 358 lines with arrow indicate foggy regions.

359 The general characteristics of these four fog cases at the Battery supersite and *R/V*
 360 *Sharp* are presented as a backdrop for the development of microphysical
 361 parameterizations. Note that ceilometer measurements cannot unequivocally identify fog
 362 regions, and ceilometer inferences should be validated using PWD Vis observations.

363

364

3. ANALYSIS AND MICROPHYSICAL PARAMETERIZATION

365 An analysis of the main microphysical and turbulence parameters to be used in the
366 evaluation of fog conditions and for developing parameterizations is provided in this
367 section.

368

369

3.1 Time Series of microphysical parameters of N_d and Turbulence Dissipation Rate 370 (ϵ)

371 Time series were obtained based on various microphysical parameters, including Vis, N_d ,
372 LWC, and MVD. Vis was obtained from PWD52 measurements representing various
373 NWS (National Weather Service) codes, droplet spectral measurements of FMD (FM120,
374 in Battery) and CDP and BCP housed in the gondola aboard the *R/V Sharp*. NOAA NWS
375 codes can be found in LPM (2011), based on PR and Vis time series for each
376 hydrometeor type obtained. The FMD was operated at a 1 Hz sampling rate, compared to
377 1-min Vis measurements from PWD52. All meteorological parameters such as T, RH_w ,
378 and wind speed (U_h) and directions were employed as appropriate.379 N_d is obtained using the corrected ship heading and apparent wind, which
380 includes both ship speed and wind measurements (Gultepe and Starr 1995). It is corrected
381 by computing the cosine of the angle θ between the heading and the apparent wind
382 measured by an anemometer as

383
$$N_d = \frac{N_c \epsilon}{(SA * TAS * \Delta t)}, \quad (1)$$

384 where the true air speed (TAS) is given by

385
$$TAS = U_{ha} \cos \theta. \quad (2)$$

386 In Eq. 1, SA is the sampling area, Δt the sampling interval and $N_c \epsilon$ the counts of
387 droplets in each bin of the CDP and BCP. N_d is obtained from the FM120 located at the
388 Battery site was obtained using a fixed TAS (true air speed) of 5 m s^{-1} for sampling of the
389 environmental air. U_{ha} is the apparent wind speed that includes both ship speed and wind
390 speed. During normal normal observational conditions, the *R/V Sharp* average speed was
391 about 8 m s^{-1} .392 The TKE dissipation rate (ϵ_{dis}) is usually calculated based on the spectral slope
393 assumption, representing the inertial subrange (Panofsky and Dutton, 1984). In our work,

394 1-minute averaged data from 3D sonic anemometer wind measurements (collected at 20
 395 Hz) at 2 m were used to estimate ε . This calculation uses an assumption that turbulence
 396 fluctuations do not change over 1 min intervals. It should be noted that ε calculation is
 397 strongly related to averaging scales and here ε approximately represents scales of 0.3-0.5
 398 km that matches scales of high resolution NWP models. Thus, using a structure function,
 399 ε is estimated (Paluch and Baumgardner, 1989; Gultepe and Starr, 1995). Clearly, 1-min
 400 averages do not capture inertial subrange scales but a structure function representing 3D
 401 scales can be used to calculate ε_{dis} along the mean horizontal wind speed as

$$402 \quad \varepsilon \varepsilon_{dis} = \frac{1}{2\pi 4.01C} \left[\frac{D_s}{\Delta r^{2/3}} \right]^{3/2}, \quad (3)$$

403 where C is a constant ~ 0.18 , D_s the structure function and Δr the horizontal distance
 404 along main horizontal wind, and these are given, respectively, as

$$405 \quad D_s = 0.38(\Delta u^2 + \Delta v^2 + \Delta w^2) \quad \text{and} \quad \Delta r = \Delta t(U_{dx}^2 + U_{dy}^2)^{1/2}. \quad (4)$$

406 In Eq. 4, Δu , Δv , and Δw represent the change in wind components along x, y, and z axis
 407 at unit time interval (Δt), respectively; U_{dx} and U_{dy} are wind speed components along x
 408 and y axis, respectively, over Δt , in Cartesian system over Δt (sampling time period).
 409 Thus, Eq. 3 can then be used in dissipation rate calculations and evaluation of the fog life
 410 cycle. For the NWP models, ε is not always an output parameter; therefore, TKE can be
 411 calculated from the following equation (or a transformation equation given in Discussion
 412 section) that is used to obtain a threshold for fog formation:

$$413 \quad TKE = \frac{1}{2}(u'^2 + v'^2 + w'^2), \quad (5)$$

414 where u' , v' , and w' are fluctuations of wind x, y, and z components that are calculated
 415 over 10 min intervals.

416
 417 **3.2 Visibility Parameterization**
 418 The visibility parameterization is calculated diagnostically, which is a function of various
 419 moments of DSD (drop size distribution). In this study, N_d and LWC are used in the Vis
 420 parameterization; but N_d is replaced with MVD to emphasize that two microphysical
 421 parameters are sufficient to calculate Vis (Gultepe et al 2018). It is emphasized that
 422 either RH_w or T_a-T_d can only be used to indicate the existence of fog, but not intensity
 423 (e.g. Vis).

424

425 **3.2.1 Vis-RH_w Parameterization**

426 The visibility can be parameterized as a function of RH_w, which is measured by a Vaisala
 427 HMP 155. RH_w is measured together with T_a from which T_d is estimated. A PWD is used
 428 to obtain Vis measurements. The functional relationship between Vis and RH_w is
 429 determined by testing various regression fits and selecting the function that ‘best’ fits the
 430 observations. Here, humidity data used for the best fit are first bin averaged in 5%
 431 intervals. [A derived relationship between Vis and RH_w together with a plot is provided in](#)
 432 [section 4.1.1 and given in Table 3.](#) Note that we do not use T_a-T_d in the Vis
 433 parameterization because RH_w is based on both T_a and T_d (Gultepe and Milbrandt 2011).
 434 Therefore, fog coverage is obtained when RH_w > 95%, which is further explained in the
 435 results section.

436

437 **3.2.2 Vis versus Microphysics Parameters**

438 Fog Vis can be obtained in two ways. The *first* is based on an extinction coefficient
 439 measured directly by a probe (e.g., PWD) which is then used to retrieve microphysical
 440 parameters assuming certain particle size distributions. The *second* is based on droplet
 441 spectral measurements from which LWC and N_d (or MVD) can be used to estimate Vis.
 442 Usually, direct measurement of Vis cannot be considered in the same way as those
 443 obtained from measured particle size spectra, because of measurement issues. Using
 444 warm fog microphysical spectral measurements, Gultepe et al (2006) developed a
 445 parameterization that is based on the theory of extinction of visible light in a volume of
 446 fog droplets as

$$447 \beta_{ext} = \sum_{r1}^{r2} \pi Q_{eff}(r, \lambda) n(r) r^2 \Delta r, \quad (65)$$

448 where β_{ext} is the extinction coefficient (cm^{-1}), Q_{eff} the extinction efficiency, r droplet
 449 radius (μm), λ the visible light wavelength (μm), $n(r)$ the particle number density (cm^{-3}
 450 μm^{-1}), and r^2 the droplet surface area. Q_{eff} is usually assumed to be 2, because size
 451 parameters ($k=2\pi r/\lambda$) are within the regions where geometric optics apply. For sizes less
 452 than about 5 μm , Q_{eff} can be larger than 2, significantly affecting the extinction of visible

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453 light. Equation 5 can be used for calculating β_{ext} if the particle size spectrum is known for
 454 each time step, when NWP model simulations exist.

455 The extinction coefficient (Eq. 65) can be converted into Vis using the
 456 Koschmieder (1924) relationship as

$$457 \quad Vis = \frac{-\ln(C)}{\beta_{ext}}. \quad (76)$$

458 For the meteorological observed range (MOR), C is defined as the threshold value that
 459 best fits to conditions whereby the human eye can recognize a target during daytime and
 460 is taken as 0.05 (Gultepe et al 2014). Using Eq. 5 and Eq. 6, the Vis can be obtained as

$$461 \quad Vis = \frac{-\left(\frac{4}{3}\right)\ln(\varepsilon)\rho_w \sum_{r_1}^r n(r)r^3 \Delta r}{Q_{ext}LWC \sum_{r_1}^r n(r)r^2 \Delta r}. \quad (87)$$

462 Then, Eq. 67 can be simplified as

$$463 \quad Vis = 5.216 \frac{\rho_w r_{eff}}{Q_{ext}LWC}, \quad (89)$$

464 where ρ_w is the liquid water density $\approx 1000 \text{ kg m}^{-3}$. Vis can be obtained from Eq. 89 if the
 465 effective radius (r_{eff}) and LWC are known. Mist conditions (defined as $Vis > 1 \text{ km}$ and
 466 $RH_w < 100\%$) can also be important for visibility reduction due to swelled aerosols (Fig.
 467 6). A lower limit for mist is usually defined as $RH_w \sim 80\%$. Haze is composed of dry
 468 aerosols where RH_w is usually $< 70\%$. Lower limit of haze Vis can be down to a few km.

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469 Since N_d is inversely related to particle size (e.g. r_{eff}), as r_{eff} decreases N_d usually
 470 increases. Gultepe and Milbrandt (2007) replaced Eq. 98 with the approximate form

$$471 \quad Vis = \alpha \left[\frac{\rho_w}{Q_{eff}N_dLWC} \right]^\gamma, \quad (109)$$

472 where α and γ are regression constants, and N_d and LWC are obtained from fog DSD,
 473 respectively, as

$$474 \quad N_d = \sum_{r_1}^r n(r) \Delta r \quad (101)$$

475 and

$$476 \quad LWC = \sum_{r_1}^r \left(\frac{4}{3}\right) \pi \rho_w n(r) r^3 \Delta r. \quad (124)$$

477 Assuming that Q_{eff} and ρ_w are constants, Eq. 109 can be rewritten as

$$478 \quad Vis = \alpha (N_d LWC)^{-\gamma}, \quad (123)$$

479 which can be converted to β_{ext} using Eq. 76. For Eq. 132, α and γ are provided in Table
 480 34. In NWP models, Vis is usually diagnosed with post processed model outputs for
 481 LWC, which is typically a prognostic output variable. If a numerical forecast model can

482 resolve microphysical processes at small time and space scales, Vis can also be predicted
483 diagnostically. This parameterization does not need droplet spectra at each time step that
484 increases calculation time significantly.

485 Vis parameterizations may not include effective size (or MVD) because N_d is a
486 function of MVD as follows

$$487 \quad N_d = \left(\frac{1}{k}\right) \frac{LWC}{MVD^3} \quad (143)$$

488 where $k=(4/3)\pi\rho_w$. Moreover, replacing N_d in Eq. 123 with Eq. 143, Vis can be rewritten
489 as follows

$$490 \quad Vis = \alpha \left(\left(\frac{1}{k}\right) \frac{LWC}{MVD^{3/2}}\right)^{-2\gamma}. \quad (145)$$

491 This suggests that knowing MVD and LWC, Vis can be obtained prognostically from a
492 NWP model simulation without requirement of N_d . Therefore, the 3rd parameter from a
493 DSD may not be required.

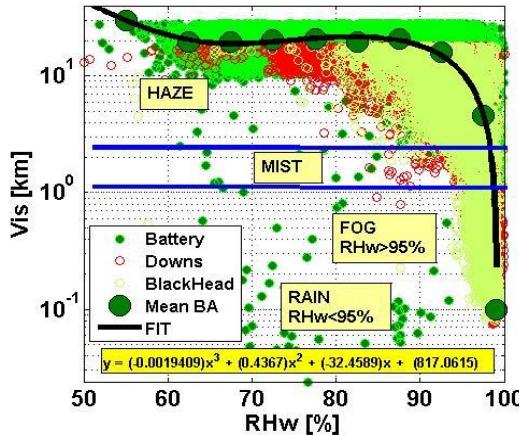
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495 **4 Results**

496 **4.1 The 8 September Case (Battery Site)**

497 **4.1.1 Vis-RH_w Parameterization**

498 Vis-RH_w parameterizations are usually derived for fog coverage but not fog intensity,
499 which are obtained based on observations of Vis and RH_w, as well as T_a-T_d differences.
500 RH_w close to 100% indicates the existence of fog layers but does not indicate intensity
501 because of measurement uncertainty in T and T_d measurements and RH_w (Gultepe et al
502 2019). In fact, RH_w is obtained as a function of T_a and T_d so it is redundant to use both
503 T_a-T_d and RH_w in the same parameterization (Gultepe and Milbrandt 2010; Benjamin et
504 al 2010; Smirnova et al. 2000). Figure 6 shows Vis versus RH_w for 3 sites located in
505 Ferryland, including Battery, Blackhead, and the Downs, for 28 Sep 2018. In this figure,
506 fog (Vis<1 km), mist (2>Vis>1 km), and haze layers (Vis>2 km & RH_w<80%) as well as
507 rain data points are shown. Differences among RH_w values are likely related to location
508 and elevation differences. A best fit for the equation for Vis versus RH_w using 5% RH_w
509 bins is also shown in the figure [6 and given in Table 3](#).



510
511 **Fig. 6** Vis versus RH_w for NWS hydrometeor classification based on PWD instrument measurements at
512 Battery, Blackhead, and Downs sites on 28 Sep 2018. The fit line is applied to bin averaged RH_w values at
513 5% intervals. The equation fitted is shown on the plot together with rain data points.

514 This figure suggests that $Vis < 1 \text{ km}$ corresponds to $RH_w > 95\%$, which can be used
515 as a criterion for detecting fog coverage but not intensity. Note that RH_w measurement
516 accuracy is about 10% (Gultepe et al 2019). Haze and mist layers can occur when $RH_w >$
517 55% up to $RH_w \sim 95\%$ ($Vis > 1 \text{ km}$). Rain with $Vis < 1 \text{ km}$ occurs when $RH_w < 95\%$.
518 Evidently there is no clear distinction between mist and haze for $Vis (>1 \text{ km})$. Another
519 point is that Blackhead and The Downs had a larger RH_w compared to the Battery site,
520 likely due to their higher elevations (30 m versus 2 m).

521
522 **4.1.2 Time Series of Meteorological Parameters**
523 Time series of Vis, PR, and precipitation types are shown in Fig. 7a based from PWD
524 measurements at 1-min time resolution. Fog and mist are seen mainly in the early
525 morning (segment 1; rectangular box) and later in the day (segment 2). Specifically, a
526 drizzle and light rain event is clearly seen before segment 2, which likely played an
527 important role for BL saturation. During fog events Vis was a few 100s of meters.

528 Fog formation and dissipation are likely related to the TKE magnitude and
529 dissipation rate, which are related to the fluctuations of 3D wind components. The value
530 for ϵ is calculated from Eq. 3 using 3D wind components and a 2D structure function (Eq.

531 4) and utilizing 1-min and 5-min running averages (Fig. 7b). The ϵ during fog is usually
532 less than for fog free conditions (e.g. 0500 and 2000 UTC). The 3D wind components are
533 shown in Fig. 7c. During fog events (see Vis time series in Fig. 7c), the magnitudes of 3D
534 wind components are found to be significantly lower than for fog free conditions. The
535 vertical air velocity (w_a) fluctuations were significantly smaller compared to u and v
536 components for the entire day, indicating the importance of advection processes in the
537 horizontal direction on the fog life cycle. Figure 7d shows 1-minute averaged local
538 accelerations of u , v , and w_a , indicating that the turbulence intensity levels were almost
539 50% less compared to fog-free segments.

540 Results suggest that ϵ is about $3 \times 10^{-4} \text{ m}^2 \text{ s}^{-3}$ in foggy segments compared to
541 $> 1 \times 10^{-3} \text{ m}^2 \text{ s}^{-3}$ in fog-free conditions, which can be used as a criterion for fog formation
542 and dissipation. These values are found to be comparable to those of The Downs site
543 (Grachev et al. 2020) who showed that during foggy conditions ϵ_{dis} was between 1×10^{-3}
544 $\text{m}^2 \text{ s}^{-3}$ and $1 \times 10^{-4} \text{ m}^2 \text{ s}^{-3}$. Some differences between their work and current work is that
545 The Downs site at 30 m likely had stronger wind fluctuations compared to current one at
546 sea level. Another reason may arise due to their use of TKE based on averages done over
547 15 mins.

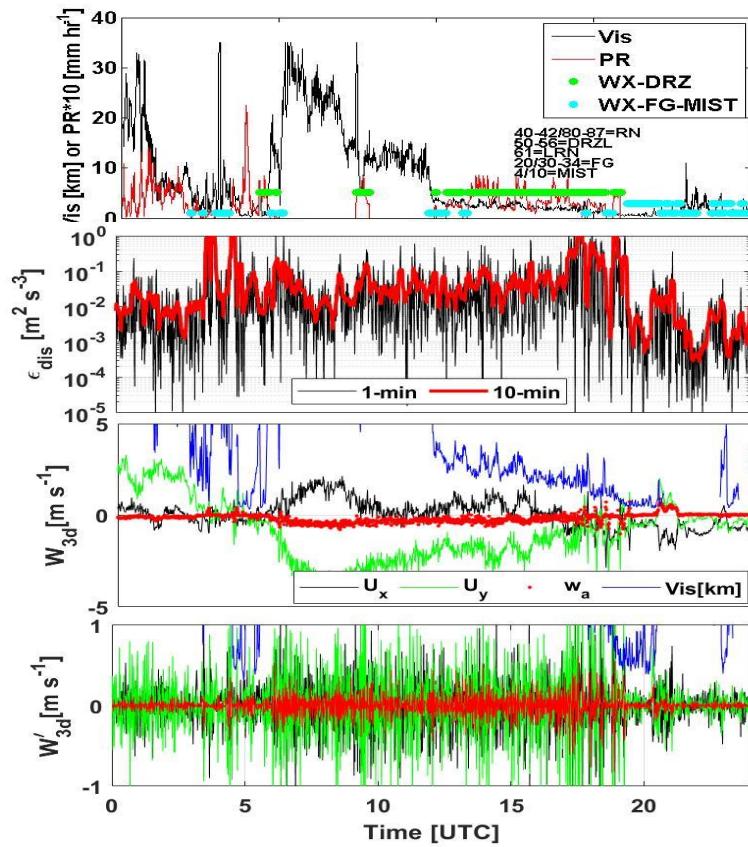
548

549 **4.1.3 Vis parameterization and microphysical parameters**

550 To develop a Vis parameterization, fog microphysical parameters such as N_d , MVD, and
551 LWC are needed because Vis is defined in terms of these parameters. Microphysical
552 parameters are calculated from the FM120 measurements from the Battery site. Figure 8a
553 shows a time series of N_d as a function of LWC, where N_d increases with increasing
554 LWC. N_d time series as a function of $\log(\text{Vis})$ is shown in Fig. 8b where $\log(\text{Vis}) \leq 0$
555 indicates fog conditions. Vis decreases with increasing N_d . These figures suggest that Vis
556 is related to both N_d and LWC (Gultepe et al 2006). Figure 8c shows MVD versus N_d as a
557 function of LWC (color bar) together with theoretical lines obtained from Eq. 13. The
558 lines ranging from bottom to top in Fig. 8c represent values for $\text{LWC} = 0.001:0.01:0.1 \text{ g}$
559 m^{-3} with solid lines, and $\text{LWC} = 0.1:0.05:0.3 \text{ g m}^{-3}$ with dashed lines with theoretical
560 lines calculated using Eq. 13 (c). Clearly MVD is a function of N_d , and decreases with
561 increasing N_d while LWC increases. This suggests that Vis can be obtained as a function

562 of either N_d and LWC or MVD and LWC. Figure 8d shows the fit equation for $Vis =$
 563 $f(LWC, N_d)$ overlaid on observations, where mean values at dx intervals along x axis and
 564 percentile values are also shown. This equation is obtained from the measurements at
 565 Battery and represents local coastal fog conditions.

566



588 **Fig. 7** Vis, PR, and NWS hydrometeor code time series on 28 Sep 2018 for Battery site (a) with fog regions
 589 shown with light blue data points, ϵ_{dis} (turbulence-TKE dissipation rate) time series for 1-min and 5-min
 590 running averages are shown in (b), 1-min averaged 3D wind components of u_x , v_y , and w_a as well as Vis
 591 time series (purple line) are shown in (c) with fog regions indicated as blue colored horizontal bars, and (c),
 592 and acceleration terms du/dt (black line), dv/dt (green line), and dw/dt (red line) with $dt=60$ s and Vis time

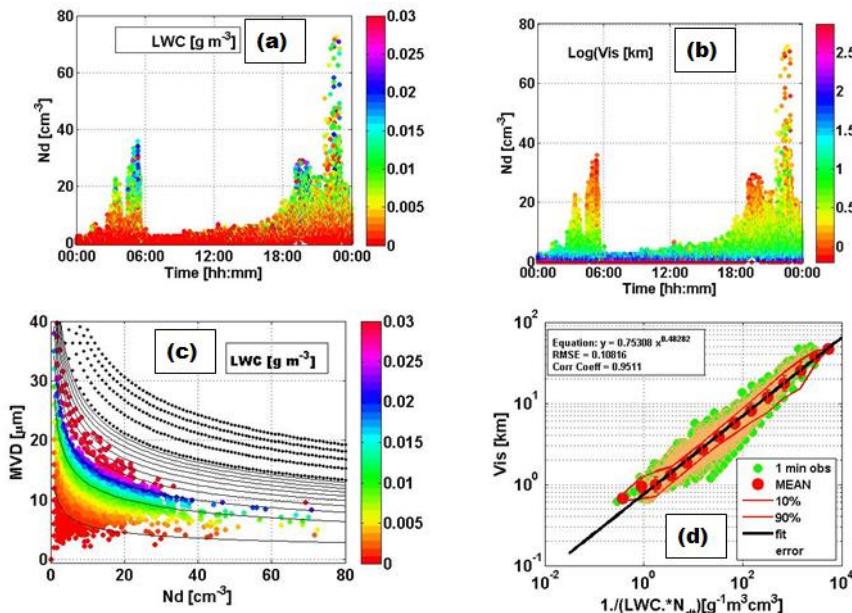
593 series (blue line) are shown in (d). Note that during fog conditions these wind speed changes become
 594 comparable low versus fog free conditions.

595 **4.2 The 29 September case (Battery site)**

596 **4.2.1 Time Series of Meteorological Parameters**

597 Time series of Vis, PR, and precipitation types are shown in Fig. 9a, similar to the 28 Sep
 598 case, representing PWD measurements at 1-min sampling rate. Fog and mist are seen
 599 mainly between 0000 UTC and 1200 UTC early morning (segment 1) and mist and
 600 drizzle mainly later in the day (segment 2; 1300-0000 UTC). A drizzle event is seen
 601 during segment 2. During fog segment 1, Vis is a few hundred meters.

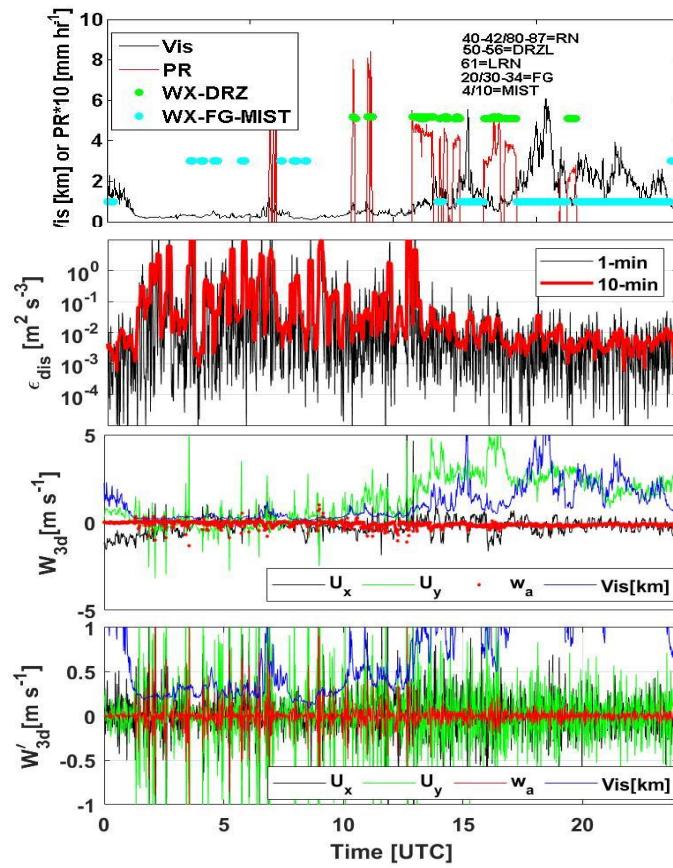
602



603
 604 **Fig. 8** Time series of N_d colored by LWC (a), N_d colored by log(Vis) (b), and MVD versus N_d with points
 605 colored by LWC (LWC=0.001:0.01:0.1 solid lines and LWC=0.1:0.05:0.3 dashed lines) (c) with theoretical
 606 lines calculated from Eq. 13. Vis parameterization as a function of fog index (FI along x axis) with
 607 statistical parameters and fit equation overlaid on observations are shown in (d) for 28 Sep 2018.

608

609 The calculation for ε is similar to the 28 Sep case, utilizing 1-min and 5-min
 610 running averages (Fig. 9b). The values for ε are found to fluctuate more during the foggy
 611 segment 1 (0000-1000 UTC), than segment 2 (1400-2300 UTC) fog and misty
 612 conditions. The values for ε change between $1 \times 10^{-2} \text{ m}^2 \text{ s}^{-3}$ and $1 \times 10^{-7} \text{ m}^2 \text{ s}^{-3}$ during the
 613 foggy segment 1, where u_y is highly variable between $+1$ and -1 m s^{-1} (Fig. 9c and 9d).
 614 Overall, ε_{dis} is less than $10^{-5} \text{ m}^2 \text{ s}^{-3}$ for both fog segments. Figure 9d shows 3D wind
 615 components and Vis, where stronger wind fluctuations likely play an important role,
 616 leading to increasing Vis values during segment 2 (light fog).

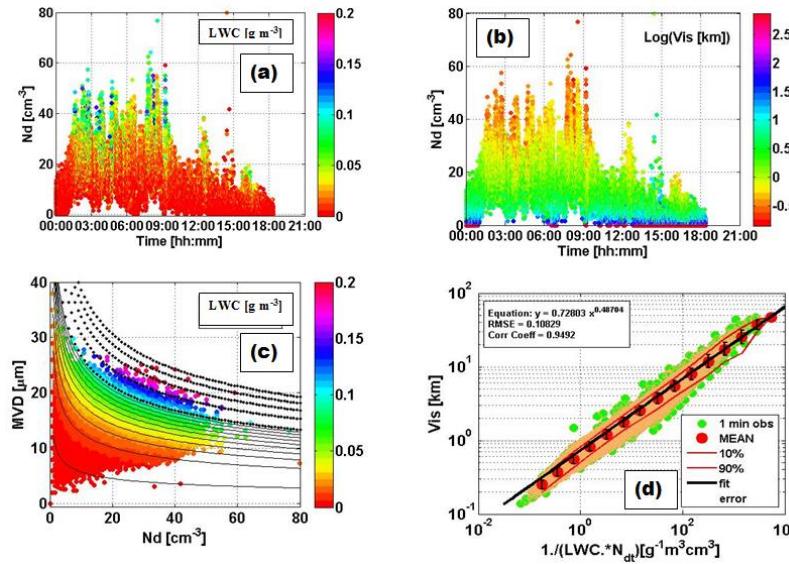


638

639 **Fig. 9** Vis, PR, and NWS hydrometeor code time series on 29 Sep 2018 for Battery site (a) with light blue data points, ε_{dis} (TKE dissipation rate) time series for 1 min and 5 min running
 640

averages are shown in (b), 1-min averaged 3D wind components of u , v , and w_a as well as Vis time series are shown in (c) with fog regions indicated as blue colored horizontal bars, and (c), and acceleration terms du/dt (black line), dv/dt (green line), and dw/dt (red line) with $dt=60$ s and Vis time series (blue line) are shown in (d). Note that during fog conditions these wind speed changes become comparable low versus fog free conditions.

646



647

648 **Fig. 10** Time series of microphysical parameters N_d versus LWC (a), N_d versus log(Vis) (b), and MVD
649 versus N_d as a function of LWC (c) with theoretical lines calculated from Eq. 13. Vis parameterization as a
650 function of fog index (FI along x axis) with statistical parameters and fit equation overly on observations
651 are shown in (d) for 04 October 2018.

652

653 In summary, most of the ϵ data points are found below the dissipation rate of
654 $3 \times 10^{-5} \text{ m}^2 \text{ s}^{-3}$ during fog segments. The w_a fluctuations in segment 1 are smaller compared
655 to drizzle and fog conditions seen in segment 2. Note that wetting of the sonic
656 anemometer transmitter/receiver may occasionally cause large fluctuations of wind
657 components during heavy fog conditions. Results suggest that, based on 1-min averages,
658 minimum (max) ϵ is about $1 \times 10^{-6} \text{ m}^2 \text{ s}^{-3}$ ($3 \times 10^{-2} \text{ m}^2 \text{ s}^{-3}$) in foggy segment 1, compared to
659 $3 \times 10^{-5} \text{ m}^2 \text{ s}^{-3}$ during mist and drizzle conditions (segment 2). Another point is that

660 southerly wind fluctuations (wind coming from south) are likely responsible for warm
661 and moist advection over the region, leading to fog formation similar to 28 Sep case.

662

663 **4.2.2 Vis parameterization and microphysical parameters**

664 Results and parameterizations for this case are obtained similar to that of 28 Sep case
665 (Fig. 10). MVD and N_d are found to be comparatively larger on this day (Fig. 10a,b,c).
666 For example, the maximum MVD reaches 40 μm compared to 30 μm on 28 Sep. The
667 maximum N_d is about 60 cm^{-3} compared to a maximum for N_d of 70 cm^{-3} on 28 Sep.
668 Finally, the Vis fit equation is shown in Fig. 10d. Overall, the slope of the best fit line is
669 very similar to the 28 Sep case but with relatively lower values of observed Vis.

670

671 **4.3 The 28 September Case (RV Sharp)**

672 **4.3.1 Time Series of Vis and RV Wind Components**

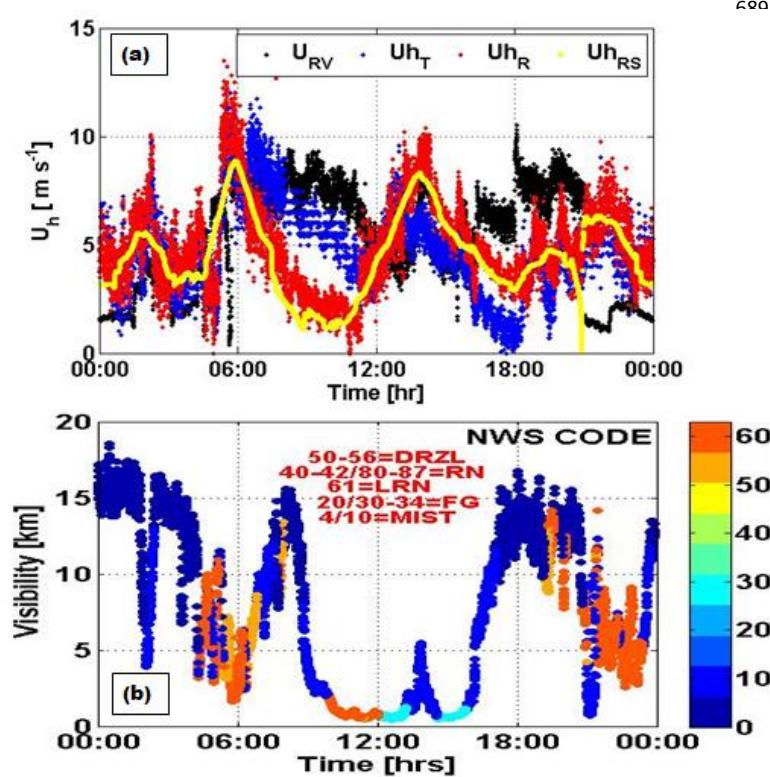
673 Time series of *R/V Sharp*'s navigation parameters obtained from the VectorNav VN100
674 IMU and Trimble BX982 Dual GNSS receiver (Fernando et al 2020) are reported here at
675 1-min intervals (Fig. 11a). This figure shows the *R/V Sharp*'s speed with respect to the
676 ground (U_{RV}), true wind speed (U_{hT}), wind speed with respect to ground (U_{hR}) and
677 smoothed values of U_{hR} over 10 mins intervals. During the fog event between 1000 UTC
678 and 1600 UTC, the *R/V Sharp* was heading 250 deg (SW) until 1300 UTC, then changed
679 to 50 deg NE with U_{RV} at about $5\text{--}8 \text{ m s}^{-1}$. Low Vis was observed between 1000 UTC and
680 1600 UTC, during which Vis improved from 1 km to 5 km after *R/V Sharp* changed
681 direction. After 1600 UTC, Vis increased up to 15 km. Low Vis and haze conditions (Fig.
682 11b) before 1000 UTC likely played an important role later on for drizzle conditions after
683 1000 UTC. Thereafter, drizzle just before fog formation likely led to moistening of the
684 BL and resulted in fog occurrence at about 1200 UTC.

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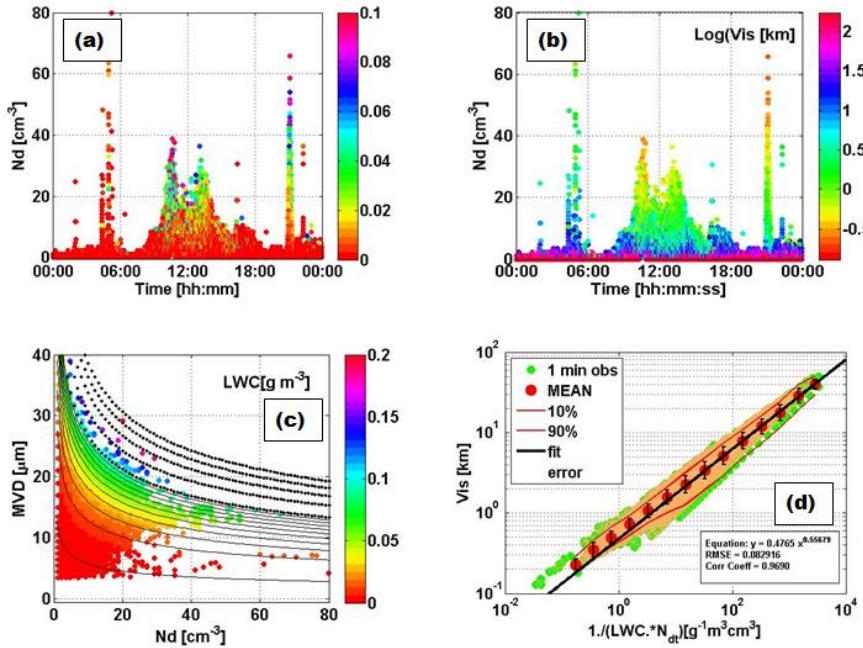


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691 **Fig. 11** Time series of U_{RV} , U_{hT} , U_{hR} , and U_{hRS} for 1 min and 10 min running averages are shown in (a) and
692 Vis, PR, and NWS hydrometeor code time series on 28 Sep 2018 (b) with fog regions shown with light
693 blue data points.

694
695 **4.3.2 Vis parameterization and microphysical parameters from the gondola**
696 In this subsection, fog droplet spectral characteristics obtained from the CDP and BCP
697 housed in the gondola (Fig. 2) are investigated. Both CDP and BCP plots were obtained
698 similar to the Battery plots. Note that BCP (Fig. 12) measurement starts at $5 \mu\text{m}$
699 compared to CDP at $2 \mu\text{m}$ (Fig. 13) and had the capability for measurements up to $75 \mu\text{m}$.
700 Measurements of N_d , MVD, and LWC are less than 60 cm^{-3} , $40 \mu\text{m}$, and 40 cm^{-3} ,
701 respectively. A parameterization is obtained with a power-law form similar to Eq. 12 and
702 is shown in the figure. The best fit line indicates that increasing fog index (FI

703 $=1/(LWC \cdot N_d)$) results in increasing Vis, which is found to be similar to the fit line
 704 obtained for the Battery site. FI increases with increasing values of either N_d or LWC.
 705 Note that N_d can be replaced with MVD using Eq. 14.



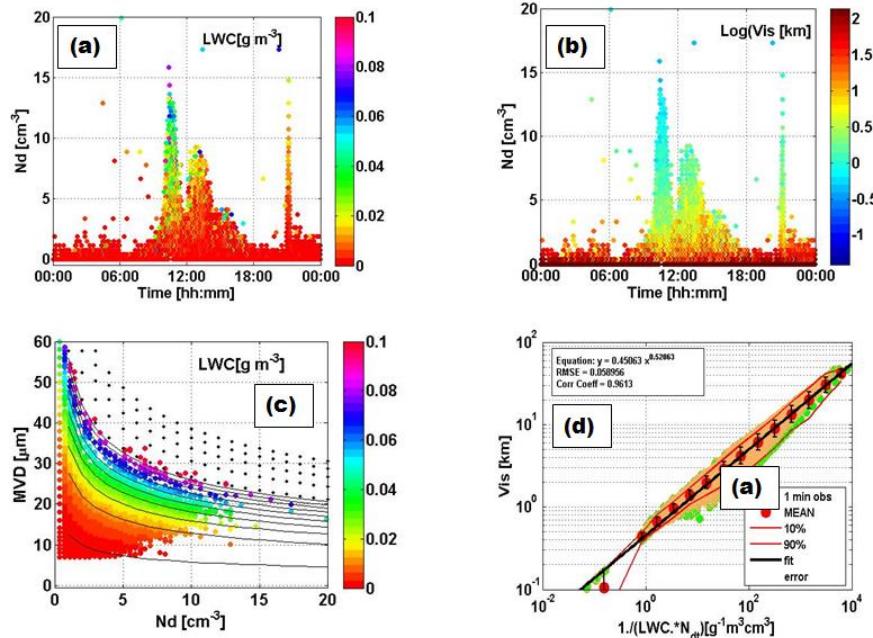
706
 707 **Fig. 12** Time series of microphysical parameters N_d versus LWC (a), N_d versus log(Vis) (b), and MVD
 708 versus N_d as a function of LWC (c) with theoretical lines calculated from Eq. 13. Vis parameterization as a
 709 function of fog index (FI along x axis) with statistical parameters and fit equation overlaid on observations
 710 are shown in (d) for RV CDP on 28 Sep 2018.

711 Fog-droplet spectral characteristics obtained from the BCP measurements are
 712 shown in Fig. 13. Note that because of missing the first 2 channels in BCP compared to
 713 CDP, N_d , LWC, and MVD cannot have the same values for both probes. N_d and LWC are
 714 based on BCP measurements and therefore, are expected to be less; but MVD is higher
 715 than CDP parameters. Results suggest that max values for N_d are about 15 cm^{-3} , for LWC
 716 about $0.07\text{--}0.08 \text{ g m}^{-3}$, and for MVD $\sim 60 \mu\text{m}$.

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721

722 **Fig. 13** Time series of microphysical parameters N_d versus LWC (a), N_d versus log(Vis) (b), and MVD
 723 versus N_d as a function of LWC (c) with theoretical lines calculated from Eq. 13. Vis parameterization as a
 724 function of fog index (FI along x axis) with statistical parameters and fit equation overlying on observations
 725 are shown in (d) for RV BCP on 28 Sep 2018.

726

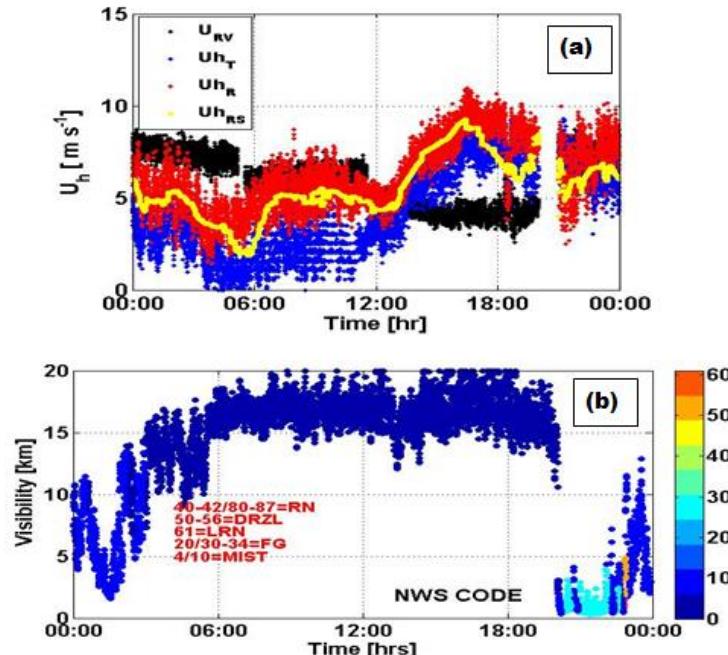
727 4.4 The 4 October Case (RV Sharp)

728 4.4.1 Time Series of Vis and RV Wind Components

729 Time series of *R/V Sharp*'s navigation parameters are given in Fig. 14a. This figure also
 730 shows U_{RV} , U_{hT} , U_{hR} , and smoothed values of U_{hR} over 10-minute intervals. Fog occurred
 731 between 1900 and 2300 UTC. Before the fog event at 1900 UTC, the ship was headed
 732 250 deg (SW), and U_{RV} changed from about 4 m s^{-1} to 8 m s^{-1} . U_{hR} was from north during
 733 the fog event (not shown). Low Vis (1 km) was observed between 1900 and 2300 UTC
 734 and Vis improved to 5 km at 2300 UTC. Before 1900 UTC, Vis increased to 15–20 km.
 735 Thereafter, the cloud base lowered to the surface and Vis decreased to <300 m. During

736 low Vis conditions (Fig. 14b) near the end of fog event, drizzle was observed around
737 2300 UTC. After 1930 UTC, Vis improved significantly.

738
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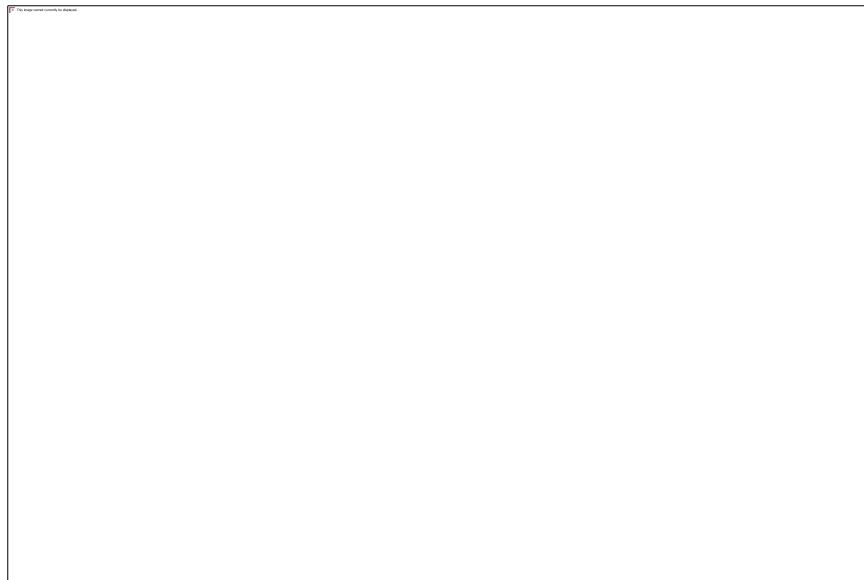
740
741 **Fig. 14** Time series of U_{RV} , U_{hT} , U_{hR} , and U_{hRS} for 1 min and 10 min running averages are shown in (a) and
742 Vis, PR, and NWS hydrometeor code time series on 28 Sep 2018 (b) with fog regions shown with light
743 blue data points.

744 4.4.2 Vis Parameterization and Microphysical Parameters from the Gondola

745 Fog droplet spectral characteristics obtained from the CDP and BCP during the 29 Oct
746 case are shown in Fig. 15 and Fig. 16, respectively. Note that max CDP N_d (Fig. 15a,b) is
747 about 75 cm^{-3} and LWC reaches 0.4 g m^{-3} . Low Vis, representing fog conditions, is
748 found between 2000 and 2200 UTC. MVD (Fig. 16c) ranged from a few μm up to $40 \mu\text{m}$
749 at low LWC and N_d but was at about $22 \mu\text{m}$ when N_d reached a maximum at 70 cm^{-3} .
750 CDP measurements of MVD and LWC were less than $40 \mu\text{m}$ and 0.45 g m^{-3} ,
751 respectively. The parameterization obtained based on CDP measurements are shown in

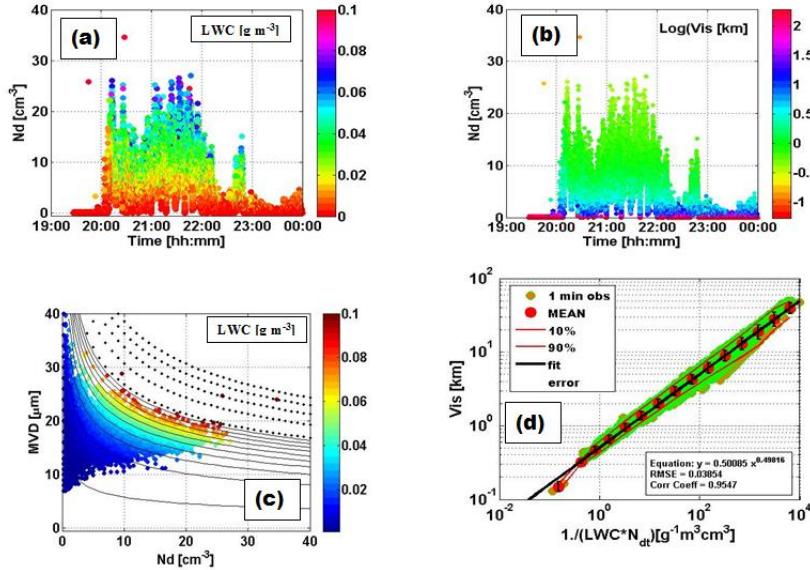
752 Fig. 16d. Similar to previous cases, Vis also increases with increasing values of fog index
753 ($FI = 1/(LWC \cdot N_d)$) but decreases with increasing LWC and N_d (with decreasing MVD).
754 The best fit line indicates that increasing FI values result in similar increasing Vis
755 conditions that represent the Battery site.

756



757
758 **Fig. 15** Time series of microphysical parameters N_d versus LWC (a), N_d versus $\log(Vis)$ (b), and MVD
759 versus N_d as a function of LWC (c) with theoretical lines calculated from Eq. 13. Vis parameterization as a
760 function of fog index (FI along x axis) with statistical parameters and fit equation overlying on observations
761 are shown in (d) for RV CDP on 04 October 2018.

762 Fog droplet spectral characteristics based on BCP are shown in Fig. 16. Again,
763 due to missing the first 2 channels of CDP in BCP measurements, CDP, N_d , LWC, and
764 MVD cannot be directly compared to those of CDP measurements. As suggested
765 previously, if there is no drizzle, N_d and LWC based on BCP measurements are expected
766 to be less compared to CDP parameters; but MVD is expected to be higher because of
767 larger droplets. Results suggest that max N_d was about 25 cm^{-3} , LWC about 0.4 g m^{-3} ,
768 and MVD~ $40 \mu\text{m}$. The parameterization for this case based on BCP measurements is
769 shown in Fig. 16d. Similar to previous cases, Vis increases with increasing FI.



770
 771 **Fig. 16** Time series of microphysical parameters N_d versus LWC (a), N_d versus $\log(\text{Vis})$ (b), and MVD
 772 versus N_d as a function of LWC (c) with theoretical lines calculated from Eq. 13. Vis parameterization as a
 773 function of fog index (FI along x axis) with statistical parameters and fit equation overlaid on observations
 774 are shown in (d) for RV BCP on 04 October 2018.

775 **4.5 Summary of Vis Parameterizations**

776 Vis parameterizations are obtained for each platform (*R/V Sharp* or *Battery supersite*)
 777 using FM100, CDP, and BCP probes and are summarized in Table 34. The Vis- RH_w
 778 relationships are also provided to emphasize that they are used only as a threshold for fog
 779 formation (e.g. $RH_w > 95\%$ in Fig. 6). Then, fog intensity (e.g. Vis) can be estimated based
 780 on model-predicted values for LWC and N_d (or MVD) (see Eq. 14). Note that the G2007
 781 parameterization (Gultepe et al 2007) was obtained using FSSP measurements based on
 782 low-level flying aircraft observations over the Bay of Fundy, NS taken during the RACE
 783 (Regional Aerosol and Cloud Experiment) campaign. These parameterizations are
 784 discussed in the next section.

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788

789

790 **Table 34** Summary of C-FOG Vis parameterizations and previous work. The FI (fog index) is defined as
 791 $1/(LWC \cdot N_{d1})$ with units of $[g^{-1} m^3 cm^3]$.

Case	Parameterization	FMD	Platform location
28 Sep - Battery	$Vis=0.7531(FI)^{0.4828}$	FM10 0	Ground-C-FOG
29 Sep - Battery	$Vis=0.7280(FI)^{0.4871}$	FM10 0	Ground-C-FOG
28 Sep - RV	$Vis=0.4765(FI)^{0.5568}$	CDP	Sharp RV-C-FOG
28 Sep - RV	$Vis=0.4506(FI)^{0.5206}$	BCP	Sharp RV-C-FOG
04 Oct - RV	$Vis=0.4012(FI)^{0.5455}$	CDP	Sharp RV-C-FOG
04 Oct - RV	$Vis=0.5009(FI)^{0.4982}$	BCP	Sharp RV-C-FOG
28 Sep - Battery	$Vis=-0.009RH^3+0.437RH^2-2.459RH+817.062$	PWD	Ground-C-FOG
Gultepe et al 2007	$Vis=1.002(FI)^{0.6473}$	FSSP	Aircraft Obs. RACE

792

793 5 Discussion

794 5.1 Overview of Fog Forecasting

795 Fog prediction cannot be done accurately because of rapid changes in its intensity (Vis)
 796 over short time and space scales, as well as non-linear relationships between surface and
 797 atmospheric conditions. There are several methods for fog prediction. These methods
 798 include rule-based techniques (Toth et al 2007, Zhou and Du 2010), statistical methods
 799 (Claxton 2008, Miao et al 2012), numerical forecast models (Gultepe and Milbrandt
 800 2010; Bott et al. 1990; Muller et al. 2007, 2010; Bott and Trautmann 2002; Clark et al.
 801 2008; Shi et al. 2012) and integrated nowcasting methods (Golding, 1993; Golden, 1998;
 802 Wright and Thomas, 1998; Haiden et al 2014). If no persistence exists and turbulence
 803 becomes more dominant, prediction usually fails, unless very short-term data assimilation
 804 techniques are performed. More detailed information on fog modeling issues can be
 805 found in the works of Gultepe et al (2007a), Wilfried et al (2008), Croft et al (1997) and
 806 Fernando et al. (2020).

807

808 5.2 NWP and Microphysical Schemes

809 Prognostic fog forecasting is usually done using model-based prediction of LWC and N_{d1} ,
 810 and that uses detailed droplet nucleation processes described above. In general, a regional
 811 forecast model uses boundary conditions from a global model. As described in Section 1,
 812 assuming a gamma size distribution, visibility can be diagnosed from the size distribution

813 parameters such as N_o (intercept parameter), μ (spectral shape parameter), and λ (slope
814 parameter), or either N_{dt} or LWC or both (Gultepe and Milbrandt 2007b, Milbrandt and
815 Yau 2005a,b). If both LWC and N_d are available as prognostic variables, Vis estimation
816 can be obtained using NWP simulations.

817 *Microphysical schemes* are used to evaluate fog prediction conditions using NWP
818 models. Cloud-droplet and fog-droplet size distributions are usually represented by a
819 modified-gamma size distribution in NWP models. The parameters used in a modified
820 gamma size distribution are the N_t (total droplet number concentration), and shape and
821 slope parameters. N_t is obtained either from empirical relationships as a function of
822 aerosol number concentrations (N_a) or from a prognostic equation for N_d with assumed
823 size distribution parameters. The microphysical schemes (MPS) such as MY (Milbrandt
824 and Yau 2005a,b), MG (Morrison and Gettelman 2008), and TO (Thompson et al. 2008,
825 2014) use modified-gamma size distributions and microphysical parameters based on
826 DSD parameters.

827 The N_d can be obtained directly from N_a diagnostically, as stated, or based on S_w
828 (supersaturation) which is function of vertical air velocity (w_a) and N_a as well as its
829 composition (Twomey 1959; Chen 1994; Kohler 1934). The Kohler curve provides a
830 general equilibrium relationship between an aqueous salt solution droplet size and water
831 vapor. S_w can be calculated as a function of both w_a and N_d and that is directly related to
832 size distribution and the composition and mixing state of aerosols. A similar relationship
833 to Twomey (1959) is also suggested by Ghan et al. (1993, 1997) for large-scale cloud
834 formation. Cohard et al. (1998) extended Twomey's power law expression by using a
835 more realistic four parameter CCN activation spectrum with physiochemical properties of
836 aerosols. The most important parameter to estimate N_d is S_w that is obtained using 3
837 methods (Schwenkel and Maronga 2019): 1) saturation adjustment scheme, 2) diagnostic
838 scheme where S_w is diagnosed by the prognostic fields of T and q_v , and 3) a prognostic
839 method (Clark 1973; Morrison and Grabowski 2007; Lebo et al. 2012). These methods
840 are not discussed here, but are listed to emphasize the importance of w_a , CCN, and N_d on
841 S_w .

842 In microphysical schemes, N_d is usually represented with a complete gamma size
843 distribution function as

844
$$N_d(D) = N_o D^\mu e^{-\lambda D}, \quad (156)$$

845 where D is the diameter, and N_o , μ , and λ_s should also be known to obtain an accurate
 846 droplet spectra. The μ parameter is obtained as a function of CCN (Wilkinson et al.,
 847 2013) or as $\mu = 1/\eta^2 - 1$ with η the dispersion of radius (sd/mean), which is given by
 848 Morrison and Gettelman (2008) as

849
$$\eta = 0.0005714 N_d + 0.2714, \quad (167)$$

850 where N_d can be obtained as a function of aerosol number concentration (N_a) (Jones et al.
 851 1994; Martin et al. 1994; Gultepe and Isaac, 1999; Gultepe et al. 2015). But N_d versus N_a
 852 relationships are not unique, and their variability can be large. In Eq. 15, N_o and λ are
 853 usually obtained using a fixed μ and predicted value of total droplet number
 854 concentration (N_{dt}) and water vapor mixing ratio (q_w) as

855
$$\lambda_s = \left[\frac{\pi \rho_w N_{dt} \Gamma(\mu+4)}{6 q_w \Gamma(\mu+1)} \right]^{1/3} \quad (187)$$

856 and

857
$$N_o = \frac{N_{dt} \lambda_s^{\mu+1}}{\Gamma(\mu+1)}. \quad (188)$$

858 When models use a single-moment scheme, q_w (e.g. LWC) is predicted but N_{dt}
 859 and μ are fixed. In double-moment schemes, usually both q_w and N_{dt} are prognostic
 860 variables. N_d prediction is an important step in NWP models for accurate fog Vis
 861 estimation.

862 In the MPS, CCN concentration is assumed to be a function of S_w , and N_a for the
 863 ocean (N_{ao}) and land (N_{al}) air masses set as fixed values. The values for CCN
 864 concentration as a function of supersaturation are also given in Fletcher (1966). The CCN
 865 parameterization, given as $CCN = c S_w^k S_k$ where $c \sim 1000 \text{ cm}^{-3}$ and $k \sim 1$ (a unitless constant),
 866 are for continental air masses and $\sim 100 \text{ cm}^{-3}$ and ~ 0.5 for maritime air masses (Feingold
 867 et al 1998). Sometimes, N_d is fixed as 100 cm^{-3} over ocean and 300 cm^{-3} over land
 868 (Wilkinson et al 2013). In reality, as stated in Cohard et al. (1998), the coefficients c and
 869 k change with high S_w . *They suggested that this happens especially in maritime*
 870 *environments.* Therefore, c and k should be matched locally to the activated CN. This

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871 suggests that parameterization of S_w and both c and k are critical to improve fog Vis
872 predictions

873

874 **5.3 Scale Issues**

875 Fog usually happens over small areas and dissipates quickly; therefore, NWP models can
876 have difficulty predicting short lived fog conditions. Although fog models can resolve the
877 smaller scales, most of the physics developed for the NWP model cannot be used for high
878 resolution fog models. Due to cloud coverage over the large scales (1-100 km), some dry
879 air pockets result in lower values of RH_w , LWC, and N_d (Gultepe and Isaac, 1999; 2004)
880 and these need to be extrapolated to fog occurrence scales (usually less than 1 km)
881 (Wilkinson et al 2013). The latter study clearly recognizes the issues for better fog
882 prediction on various grid areas. This suggests that further improvement of fog
883 microphysical parameterizations is required for better fog prediction.

884

885 **5.4 Variability in Vis**

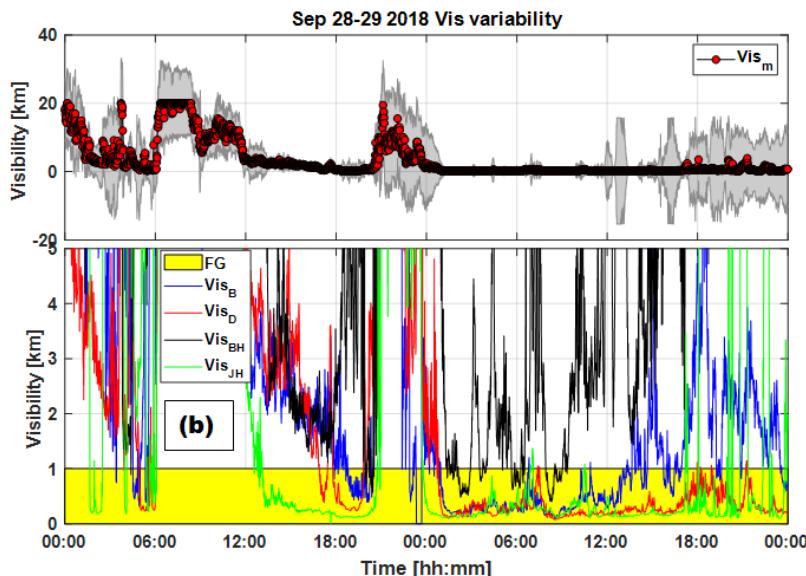
886 Visibility calculation based on observations and NWP model outputs may include large
887 uncertainties due to fog microphysical and BL processes. Variability in Vis based on
888 measurements of PWD located at Battery, Downs, Blackhead, and Judges Hill sites for
889 28-29 Sep is shown in Fig. 17. Figure 17a shows mean Vis from all these sites with a
890 standard deviation. Overall, Vis at Judges Hill had the lowest values compared to the
891 other stations, likely due to its elevation of 129 m (Fig. 17b). The second lowest Vis
892 values are found at The Downs site, at 32 m above sea level. Blackhead and Battery Vis
893 follow, with the next highest values. During dense fog conditions, Vis from Blackhead
894 was much higher than others, likely due to the distance between the Blackhead and
895 Ferryland sites. Vis, representing a scale of about 1.5 km, ranged from 0.2 km up to 1 km
896 for any given time (Fig. 17); therefore, NWPs should be capable of simulating fog
897 conditions at 1 min time intervals and 100 m spatial scales.

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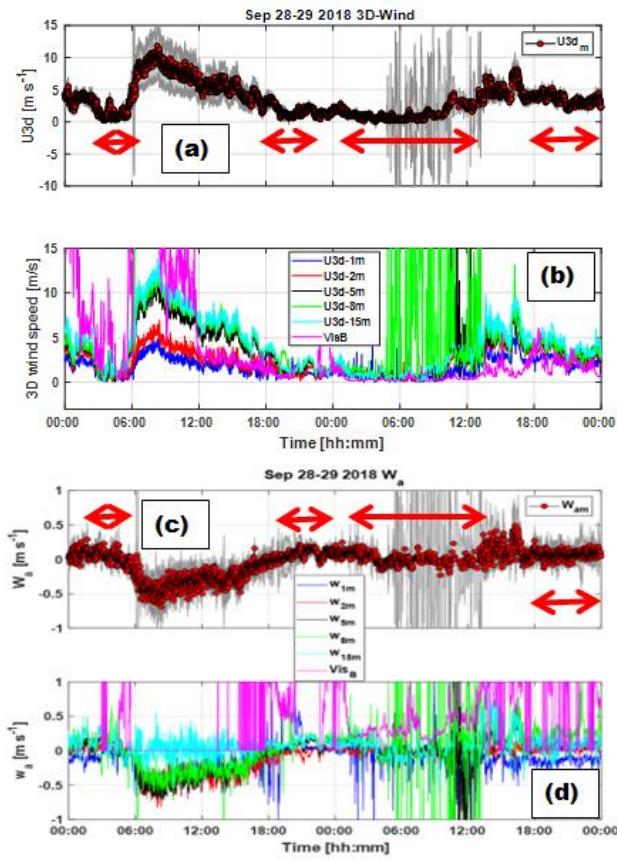


902
903 **Fig. 17** Time series of mean— (red filled circles) and sd (gray colored regions) of Vis based on
904 measurements of PWDs (indicated in (b)) are shown in (a). Time series of Vis representing Battery (Vis_B),
905 Downs (Vis_D), Blackhead (Vis_{BH}), and Jack Hill (Vis_{JH}) for 28-29 Sep 2018 are shown in (b). Fog regions
906 are shown for Vis<1 km (yellow colored area).

907 **5.5 Variability in sonic anemometer wind components**

908 The 3-D wind component time series of mean and sd obtained from the (20Hz)
909 measurements of sonic anemometers located at 1, 2, 5, 8, and 15 m levels of the Battery
910 supersite tower are shown in Fig. 18a for 28-29 Sep cases. Figure 18b shows 3D wind
911 components and Vis from each of the 5 levels. The U_{3d} values (3-D wind speed) between
912 0600-1200 UTC indicate some noise in the data and should be ignored because of heavy
913 condensation on the prongs of the sonic anemometers. The largest U_{3d} fluctuations are
914 seen at 5, 8, and 15 m levels but these were reduced to lower values during fog events on
915 May 28 (Fig. 18b). Vertical air velocities (w_a) in Fig. 18c are obtained at the same levels
916 as in Fig. 18b. Figure 18c shows the mean and standard deviation of w_a obtained from
917 measurements, representing all levels from 1 m up to 15 m. Clearly, w_a fluctuations were
918 higher in the fog-free layers compared to foggy layers, indicating greater turbulent heat,
919 moisture and momentum fluxes in the vertical direction. Note that large fluctuations of

920 w_a at 15 m from 0600 to 1200 UTC in Fig. 18d were likely noise, as noted previously.
 921 The w_a fluctuations within the fog layers were found generally between +0.3 and -0.3 m
 922 s^{-1} , but were more than -0.7 $m s^{-1}$ and +0.7 $m s^{-1}$ in fog-free layers. These suggest that
 923 without estimating 3D wind fluctuations accurately, NWP models cannot properly handle
 924 the fog life cycle.



925
 926 **Fig. 18** Wind components obtained from the sonic anemometers located at 1, 2, 5, 8, and 15 meters levels
 927 of a tower and Vis at 2 m (purple line) are shown in (a) for mean and sd of U_{3d} (3D wind component) and
 928 in (b) for U_{3d} for each level, representing 28-29 Sep cases at the Battery supersite. Mean (red filled circles)
 929 and sd (gray lines) of vertical air velocity (w_a) are shown in (c) and w_a measurements at each level are
 930 shown in (d). Fog layers indicated by red double arrow are obtained from PWD Vis shown in (d) and
 931 previous plots.

932 **5.5 N_d Uncertainty and Droplet Spectra**

933 Droplet spectra from CDP, BCP, and FM120 probes include uncertainties related to the
934 calculations of TAS, turbulence, wind speed and ship direction. The aspirator used in
935 FM100 pulls in air at about 5 m s^{-1} but winds coming directly into the inlet can increase
936 (or decrease) the aspirator wind speed. Usually, using a higher TAS compared to a fixed
937 TAS at 5 m s^{-1} set up in FM120 results in a significant decrease (~50-100%) in N_d . For
938 ship measurements, these errors can be much larger. For example, a ship heading north (0
939 degrees) at 8 m s^{-1} plus a wind from NE can result in

940
$$TAS = U_{RV} + U_h \cos\theta. \quad (20)$$

941 Therefore, the error in TAS estimation, applying a derivative of TAS with respect to
942 time, can be written as

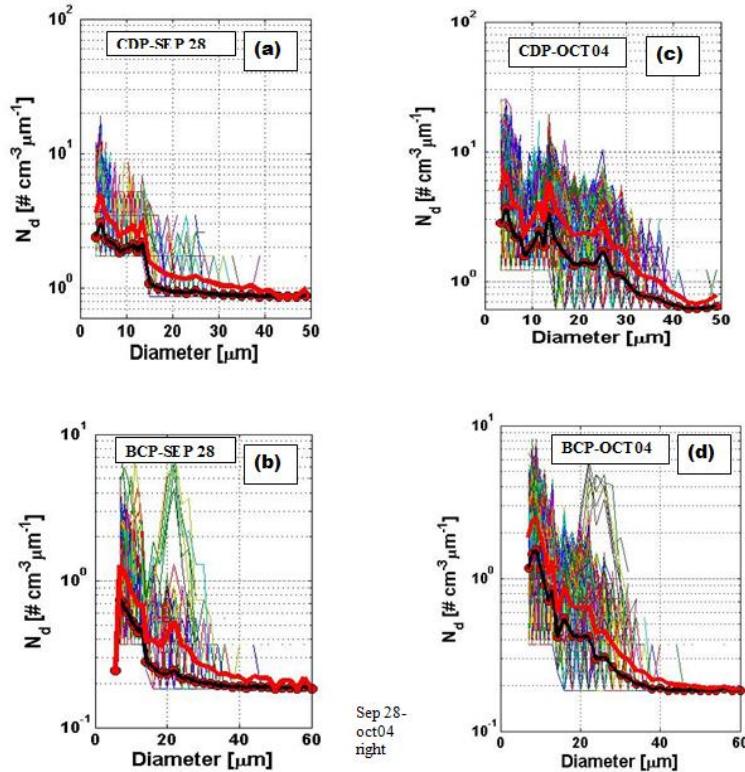
943
$$\varepsilon_{TAS} = \frac{dTAS}{dt} = \frac{dU_{RV}}{dt} + U_h \frac{d\cos\theta}{dt} + \cos\theta \frac{dU_h}{dt}. \quad (21)$$

944 The l.h.s of Eq. 20, ε_{TAS} represents an error in TAS per unit time [$(\text{m s}^{-1})/\text{s}$]. Assuming
945 that error in the first term of the r.h.s of Eq. 20 is approximately 1 m s^{-1} per unit time
946 (e.g., $dt=1 \text{ s}$) at $U_{RV}=8 \text{ m s}^{-1}$, and U_h has an error of 10% say at 0.5 m s^{-1} and wind
947 directional error is about 10 degrees (second term on the rhs), then using $U_h=10 \text{ m s}^{-1}$,
948 $\varepsilon_{TAS}=1 \text{ m s}^{-1} + 10 \text{ m s}^{-1} * (\cos 30 - \cos 40) + \cos(30) * 0.5 \text{ m s}^{-1} = 1.0 + 1.0 + 0.43 = 2.43 \text{ m s}^{-1}$.
949 Absolute error in TAS~ 18 m s^{-1} can then be calculated at about 15%. This means that N_d
950 uncertainty is also about 15%, but likely increases with decreasing TAS. Following
951 works can be suggested for further evaluation of errors related to TAS calculations;
952 Moffat (1982) and Kline and McClintock (1953).

953 Figure 19 shows fog droplet spectra obtained from the CDP and BCP probes for
954 Sep 28 (a and b) and Oct 04 (c and d) cases. The mean (black line) and standard deviation
955 (red line) of each bin during fog events of Sep 28 and Oct 4 are shown. Each colored line
956 represents 1 s spectra. Clearly, Sep 28 droplet spectrum is much different from the Oct 04
957 droplet spectra, based on both probes. Multi-modes in DSD indicate the various fog
958 regimes that were likely related to droplet fall velocities (V_f) and w_a . For both cases, DSD
959 did not indicate drizzle droplet sizes $> 50 \mu\text{m}$. MVD for the Oct 04 was much larger than
960 for the Sep 28 case. Note that the mean DSD can shift upward if a lower threshold of N_d
961 is chosen to have a higher value (e.g. 1 # cm^{-3} instead of 0.1 # cm^{-3}). In BCP

962 measurements, having a large value for N_d at about 25 μm , may indicate some cooling
963 processes leading to increasing values for N_d .

964



965

966 **Fig. 19** shows fog droplet spectra obtained from CDP and BCP probes for 28 Sep (a and b) and Oct 04 (c
967 and d) cases. The mean (black line) and sd (red line) values of each bin during time periods representing
968 fog events of 28 Sep and 4 Oct 2018 are also shown on the plots. Each line with a color represents 1 s
969 spectra.

970 Sea spray particles can also affect N_d spectra (at 10m) significantly because of
971 breaking waves, especially at small size ranges because of their low settling rates. In the
972 marine environment, droplets can be generated by wave breaking processes, which can
973 then be counted as fog droplets. Entrainment of air at breaking wave crests leads to the
974 formation of a large number of bubbles, which emerge at the ocean surface because of

975 their positive buoyancy and then burst into droplets at the water surface (Troitskaya et al
 976 2018). The spray production due to the bursting of bubbles with sizes smaller than <10
 977 μm has been studied by Blanchard (1963) and Spiel (1995, 1997, 1998). All of these
 978 studies suggest that bursting bubbles are the main source of the ocean spray process,
 979 generating droplets with radii less than 50 μm (Wu, 1981).

980

981 **5.6 Impact of TKE Dissipation Rate on Vis**

982 Fog occurs usually at the end of a dynamically unstable environment along coastlines and
 983 marine environments and is augmented sometimes by thermal inversions, keeping
 984 moisture trapped below a stable layer. Thereafter, when the mature fog stage has
 985 developed under dynamically stable conditions, fog dissipates as a result of droplet
 986 growth, increasing turbulence, entrainment, and solar heating. All these factors play an
 987 important role for fog dissipation without considering direct impact of a larger scale
 988 event such as pressure systems and associated fronts systems. In this work, calculated
 989 dissipation rates suggest that higher ϵ values result in improved Vis conditions. Accuracy
 990 of ϵ will not be discussed here, except in its usage in a fog prediction scheme. TKE
 991 dissipation rate is calculated in NWP models using TKE based on various turbulence
 992 prediction schemes (Mellor and Yamada 1982; Castelli et al 2005; Duynkerke 1988);
 993 therefore, it can be used to improve fog prediction.

994

995 Table 5. Mean and std of TKE dissipation rate calculated using Eq. 3 and Eq. 26., representing 1 hr time
 996 segments based on a 10-min filtering method for Sep 28 and Sep 29 2018 cases. Sep 29 case did not have
 997 wind measurements during heavy fog conditions.

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<u>Method</u>	<u>Sep 28</u> <u>Mean ϵ_{dis} [$\text{m}^2 \text{s}^{-3}$]</u>	<u>Sep 28</u> <u>Std ϵ_{dis} [$\text{m}^2 \text{s}^{-3}$]</u>	<u>Sep 29</u> <u>Mean ϵ_{dis} [$\text{m}^2 \text{s}^{-3}$]</u>	<u>Sep 29</u> <u>Std ϵ_{dis} [$\text{m}^2 \text{s}^{-3}$]</u>
<u>Using Eq. 3</u> <u>Foggy</u>	<u>1.23×10^{-2}</u>	<u>1.73×10^{-2}</u>	<u>1.65×10^{-2}</u>	<u>1.19×10^{-2}</u>
<u>Using Eq. 26</u> <u>Foggy</u>	<u>8.73×10^{-2}</u>	<u>24.94×10^{-2}</u>	<u>7.53×10^{-2}</u>	<u>9.21×10^{-2}</u>
<u>Using Eq. 3</u> <u>Clear</u>	<u>7.76×10^{-2}</u>	<u>10.3×10^{-2}</u>	<u>—</u>	<u>—</u>
<u>Using Eq. 26</u> <u>Clear</u>	<u>20.00×10^{-2}</u>	<u>25.59×10^{-2}</u>	<u>—</u>	<u>—</u>

999

1000
1001
1002 Table 5 is prepared using Eq. 3 and Eq. 26 for mean and std of ε_{dis} during foggy and fog
1003 free conditions, representing means of 1 hr time intervals. It shows that for both Sep 28
1004 and 29, foggy conditions had much smaller ε_{dis} than fog free conditions (excluding Sep 29
1005 case). For fog free conditions, Sep 29 had larger values of ε_{dis} that likely was contributed
1006 by wetting of the 3D sonic anemometer optics. It is shown based on Table 5 that fog
1007 occurs usually when $\varepsilon < 1 \times 10^{-25} \text{ m}^2 \text{ s}^{-3}$ and dissipates for $\varepsilon > 1 \times 10^{-24} \text{ m}^2 \text{ s}^{-3}$ (see figures for
1008 time series of ε). Between these two limits, intermediate fog intensity can likely occur. A
1009 conversion equation between ε and TKE (Scully et al 2011) can be obtained using,

1010
$$L = C_\mu^3 \frac{TKE^{3/2}}{\varepsilon}, \quad (22)$$

1011
1012 where L and C_μ are turbulent length scale ($kz=0.41*2$) where k is the Von Karman
1013 constant and z is the height (m), and the nondimensional stability function, respectively,
1014 that is assumed as a constant (0.447). Then, Eq. 25 becomes approximately as

1015
1016
$$TKE = 0.876 \sqrt[3]{\varepsilon^2}. \quad (23)$$

1017
1018 Note that ε and TKE are function of scales that need to be further evaluated and
1019 developed to improve NWP models based fog Vis predictions.

1020 Based on ε time series (Figs. 7 and 9) and equations given in Table 4, we can

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1021 suggest the following parameterizations for fog ($Vis < 1 \text{ km}$ & $RH_w > 95\%$), mist ($Vis > 1$
1022 km & $RH_w > 80\%$), and light fog ($Vis > 1 \text{ km}$ & $RH_w > 95\%$) conditions, respectively, as

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1023
$$RH_w > 95\% \text{ & } \varepsilon < 10^{-25} \text{ m}^2 \text{ s}^{-3} \text{ & } Vis = 0.412(LWC \cdot N_d)^{-0.5455} \quad (24)$$

1024
$$80\% < RH_w < 95\% \text{ & } \varepsilon < 10^{-42} \text{ m}^2 \text{ s}^{-3} \text{ & }$$

1025
$$Vis = -0.0094RH_w^3 + 0.437RH_w^2 - 32.459RH_w + 817.062 \quad (25)$$

1026 and

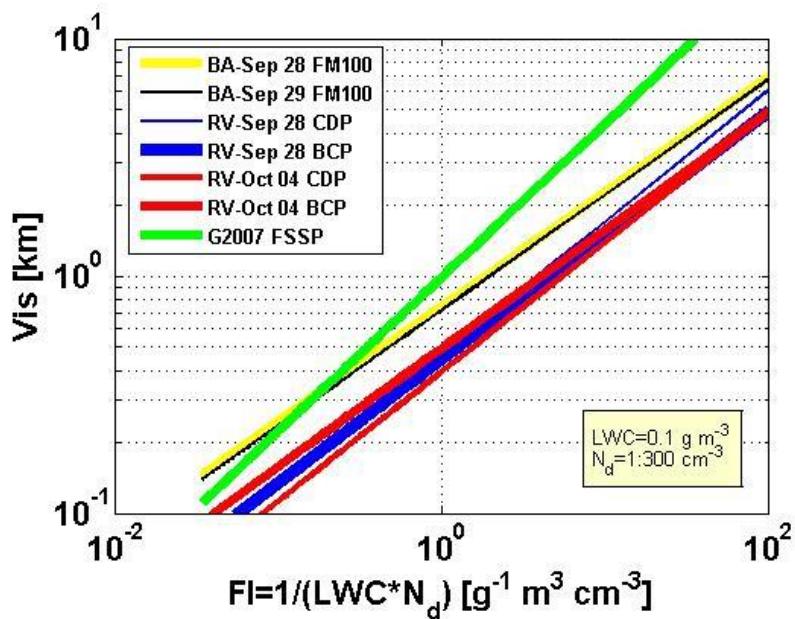
1030 $RH_w > 95\% \text{ & } 10^{-4} < \varepsilon < 10^{-52} \text{ m}^2 \text{ s}^{-3} \text{ & } Vis = 1.002(LWCN_d)^{-0.6473}.$ (236)

1031
1032
1033 The thresholds for TKE corresponding ε thresholds is estimated as $<4.06 \times 10^{-2} \text{ m}^2 \text{ s}^{-2}$,
1034 $>1.88 \times 10^{-2} \text{ m}^2 \text{ s}^{-2}$, and between them for Eqs. 24, 25, and 26, respectively. These values
1035 are calculated using Eq. 23. Note that these criteria need to be further checked and
1036 developed to improve NWP model based fog Vis predictions.

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1038

1039

1040 **Fig. 20** Vis parameterizations obtained for all the cases based on Table 34. LWC was fixed at 0.1 g m⁻³
 1041 while N_d changed from 1 to 300 cm⁻³. RV represents research vessel, BA Battery, G2007 Gultepe et al
 1042 (2007) and FI fog index. FM100, CDP, BCP, and FSSP probes are used for droplet spectral measurements.

1043 **6 Conclusions**

1044 In this paper, Vis associated with fog environmental parameters such as RH_w , 3D wind
1045 components, and microphysical parameters, including LWC, N_d , and MVD were studied
1046 for four cases. Results representing two IOPs from the Battery supersite and two IOPs
1047 from the *R/V Sharp* are used in Vis parameterization development and to verify the
1048 previous parameterizations. Based on the results of this work, the following points can be
1049 drawn:

- 1050 1. Synoptic weather conditions and ocean-atmosphere interactions are the larger-
1051 scale factors that affect coastal fog microphysics and visibility. The cold ocean
1052 surface off the coast of Ferryland was usually a major reason for fog formation
1053 observed there.
- 1054 2. The main synoptic weather systems that affected fog were usually related to a
1055 high-pressure system located to the NE, a low-pressure system along W-NW, and
1056 a chain of tropical cyclonic motions. This may not be valid early in the fog season
1057 and usually can be valid during the Fall transition period.
- 1058 3. Vis is found to be less than 1 km when RH_w is greater than 95%, and this suggests
1059 that the T_a-T_d difference is an important variable indicating fog regions, but not
1060 intensity.
- 1061 4. By decreasing dynamic activity, indicated by smaller 3D wind fluctuations and
1062 lifting, the eddy dissipation rate decreases during mature fog conditions that can
1063 be used for a threshold for prediction of mature fog conditions. Wind
1064 components; u , v , and w_a are relatively smaller in fog-developed regions than in
1065 fog-free regions.
- 1066 5. The w_a fluctuations were 0.1 m s^{-1} during mature fog conditions compared to ≥ 0.3
1067 m s^{-1} for fog-free regions. Note that these values can be much larger at the time
1068 scale of 16Hz or 32Hz.
- 1069 6. The TKE dissipation rate was usually $< 10^{-5} \text{ m}^2 \text{ s}^{-3}$ during mature fog events
1070 compared to $> 10^{-4} \text{ m}^2 \text{ s}^{-3}$ for fog-free regions and can be used for fog predictions
1071 criteria based on NWP models.

1072 7. Vis parameterizations that we constructed suggest that the slopes of the Vis versus
 1073 fog index (FI) relationships are consistent with each other; but found to be
 1074 comparably smaller in magnitude. This can be related to the nature of the
 1075 measurement platform, fog season, as well as cloud versus fog measurements.

1076 8. Vis is found to be function of LWC and N_d and this can be replaced with LWC
 1077 and MVD without involvement of a 3rd parameter; this can be more generally
 1078 applicable for NWP models.

1079 9. Vis $< 1\text{km}$ observations showed a large variability, covering few km^2 (1.5 km^2)
 1080 up to 20 km^2 , and the difference was very high between a station at height 129 m
 1081 (Judges' Hill) compared to one at the sea level, 2 m, (Battery station) although the
 1082 horizontal separation distance was only about 1.0 km.

1083 10. BCP droplet number concentration is found to be at least half of the CDP N_d and
 1084 this is likely due to BCP's higher threshold of $5 \mu\text{m}$; there were no droplets larger
 1085 than $50 \mu\text{m}$.

1086 11. There were double and triple peaks for fog DSDs and this can affect the NWP's
 1087 fog prediction algorithms and needs to be further researched.

1088 Based on these points, it is suggested that Vis parameterizations can be obtained
 1089 using both dynamical and microphysical parameters, but fog droplet spectra
 1090 representation for various fog conditions need to be further investigated. Specifically, the
 1091 turbulence impact on droplet spectra and the nucleation processes are very critical for the
 1092 fog life cycle in low vertical air velocity situations. Moreover, this is the most important
 1093 parameter affecting the auto-conversion of fog droplets to drizzle formation.

1095 **Acknowledgments:** This research was funded by the Office of Naval Research Award # N00014-
 1096 18-1-2472 entitled: Toward Improving Coastal Fog Prediction (C-FOG).

1097 **References**

1099 **Nomenclature**

BCP: Backscattering Cloud Probe	RF: radiative fluxes
C: A constant ~ 0.18 in Eq. 3	SA: Sample Area

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C: Visibility threshold constant as 0.05	SV: sampling volume
CN: Condensation nuclei	T _a : Air temperature
CCN: Cloud Condensation Nuclei	T _d : Td: dew point temperature
CDP: Cloud Droplet Probe	TKE: Turbulent Kinetic Energy
D _s : The structure function	u, v, w: Measured wind components along x,y, z
DSD: Droplet Size Distribution	u',v',w': Wind fluctuations
FI: Fog Index	U _{ha} : The apparent wind speed
FSSP: Forward Spectral Scattering Probe	U _{dx} and U _{dy} : wind speed along x and y axis at dt t
FM100: DMT fog measuring device (FMD)	U _{RV} : RV Sharp's speed with respect to the ground
IR and SW: Infrared and shortwave rad. fluxes	U _{HT} : True wind speed over 10 mins intervals
k: The Von Karman constant as 0.41	U _{HR} : Wind speed with respect to ground
L: Turbulent length scale	U _{3D} : 3D wind component
L: The turbulent length scale	Vis: Visibility
LES: large eddy simulation	V _f : Droplet fall velocity
LWC: liquid water content	V _d : Doppler velocity
MVD: Mean Volume Diameter	Vis _B : Vis at Battery site
n(r): Droplet number spectra	Vis _D : Vis at Downs site
N _a : Aerosol number concentration	Vis _{BH} : Vis at Blackhead site
N _{aO} : Aerosol number conc. over ocean	Vis _{JH} : Vis at Jack Hill site
N _{aL} : Aerosol number concentration over land	Z: Radar reflectivity factor
N _c : Droplet counts	z: The height (m)
N _d : Droplet number concentration	α and γ : empirical constants in Eq. 13
N _{dt} : total droplet number concentration	μ : spectral shape parameter
N _o : intercept parameter	λ : slope parameter
NWP: Numerical Weather Prediction	β_{ext} : Extinction coefficient
PR: Precipitation Rate	β : Lidar backscatter coefficient
Q _{eff} : Extinction efficiency	η : the dispersion of radius (sd/mean).
r: droplet radius	ρ_w : water density
r _{eff} : Effective radius	θ : Angle between the ship heading and U _{ha}
Ar: The horizontal distance in Eq. 3.	ϵ : Eddy dissipation rate
At: Time interval	ϵ_{TAS} : Error in TAS
RH _w : relative humidity with respect water	

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