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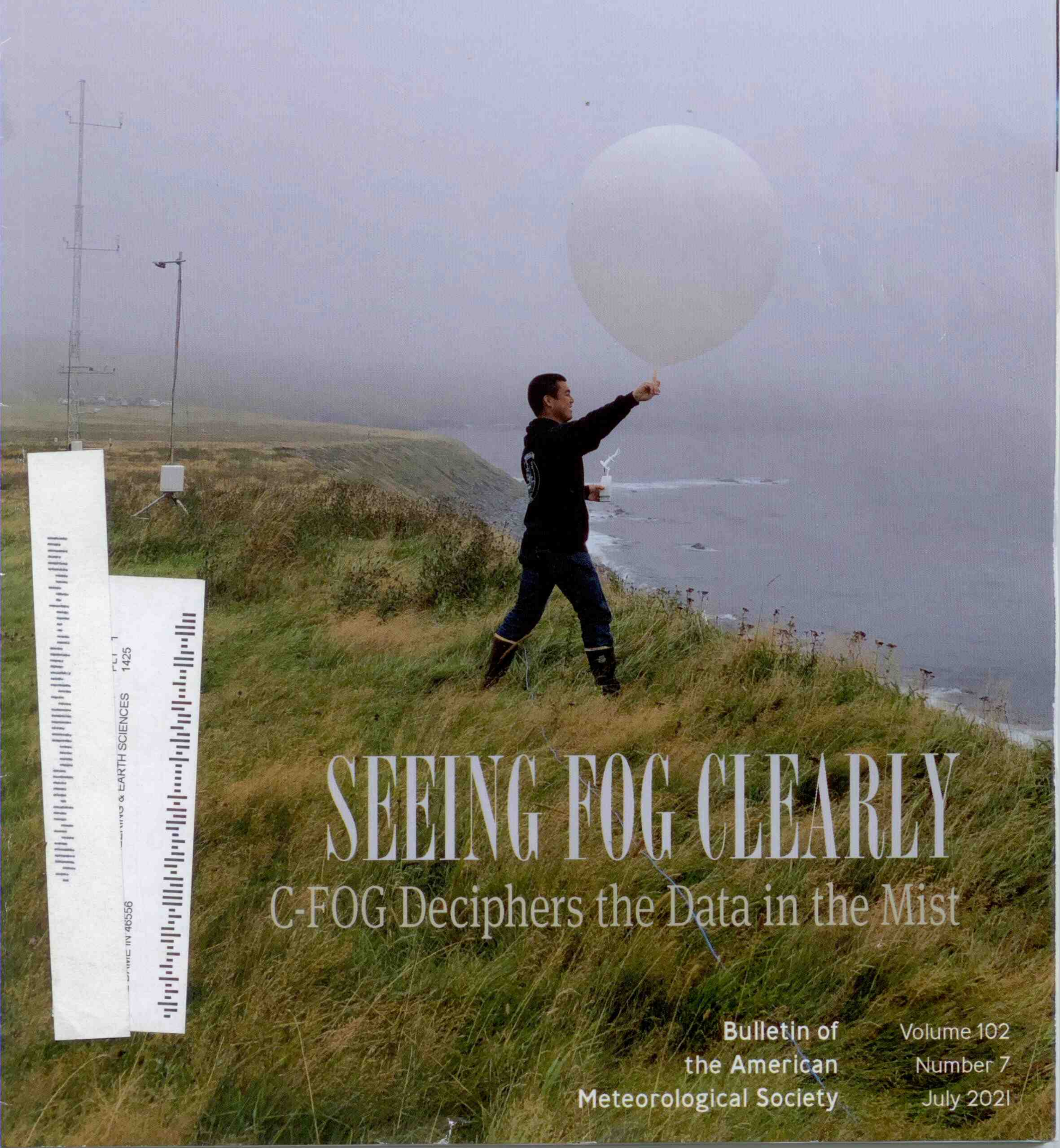

SEEING FOG CLEARLY

C-FOG Deciphers the Data in the Mist

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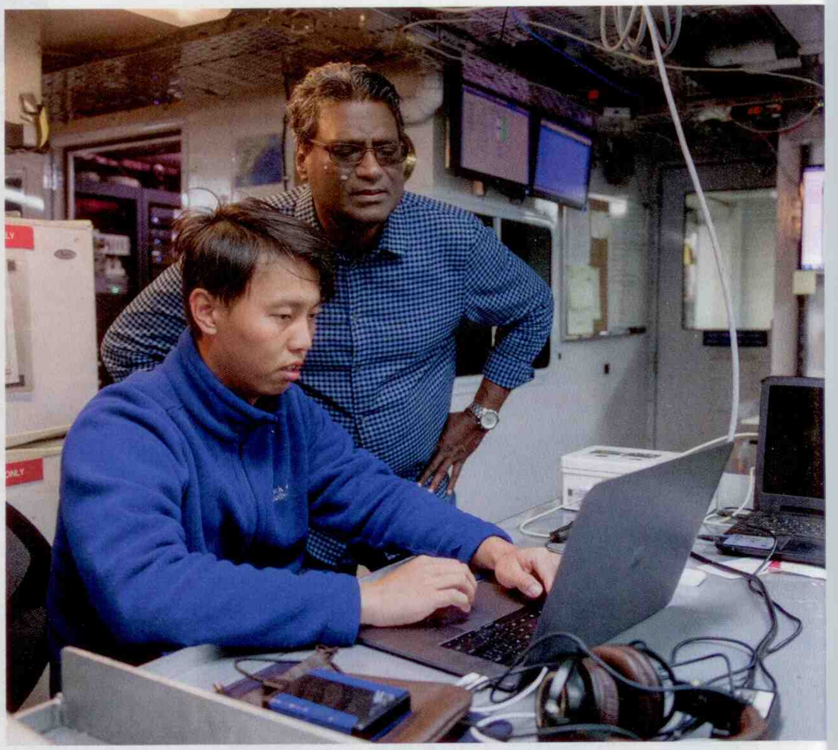


Professor Joe Fernando and Notre Dame graduate student Sen Wang review data aboard the *Hugh R. Sharp* research vessel.

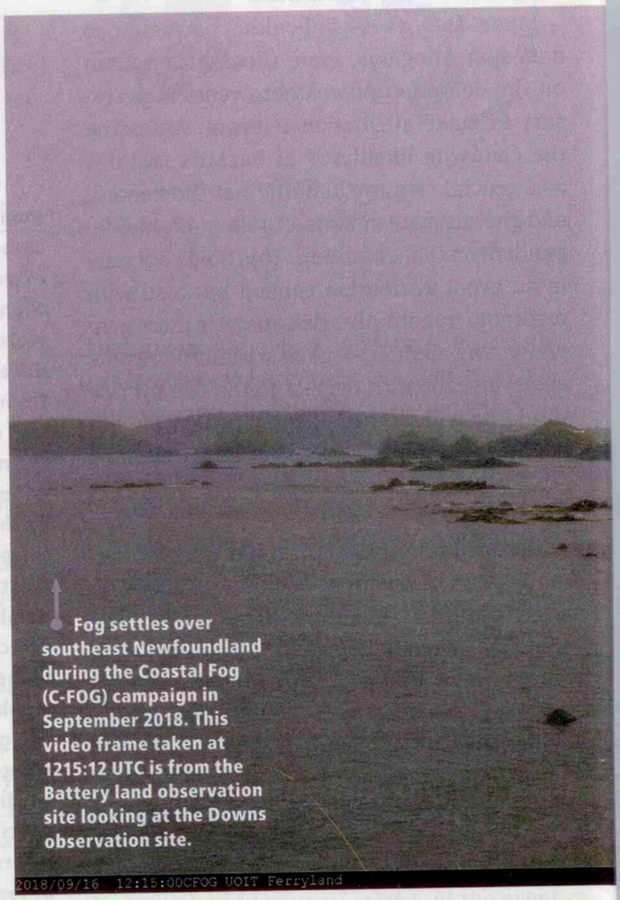
> **“Having grown up along an Indian Ocean coast with a family lineage to fisherman, I was always fascinated by ocean waves and currents. During my senior year in mechanical engineering at the University of Sri Lanka, I realized that fluid mechanics might help one appreciate and quantify the beauty of oceanic flows through a scientific eye. At Johns Hopkins University I was exposed to the true grandeur of oceanic and atmospheric flows and environmental turbulence. The fundamental knowledge I acquired there along with the emphasis on high-tech measurement techniques during my postdoc days at Caltech paved my way to an academic research career.”**
>
> **— H. J. S. Fernando, University of Notre Dame**

PAGE 640

Seeing Fog Clearly

The C-FOG Research Program Addresses Predictability

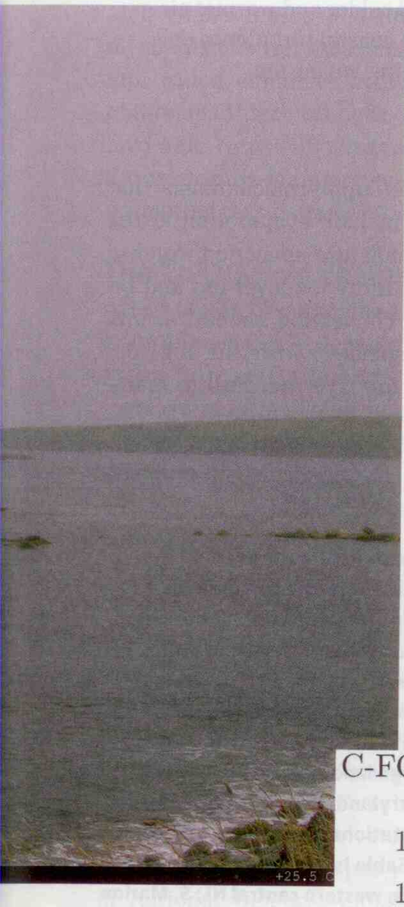
Adapted from "C-FOG: Life of Coastal Fog," by H. J. S. Fernando (University of Notre Dame), I. Gultepe, C. Dorman, E. Pardyjak, Q. Wang, S. W Hoch, D. Richter, E. Creegan, S. Gaberšek, T. Bullock, C. Hocut, R. Chang, D. Alappattu, R. Dimitrova, D. Flagg, A. Grachev, R. Krishnamurthy, D. K. Singh, I. Lozovatsky, B. Nagare, A. Sharma, S. Wagh, C. Wainwright, M. Wroblewski, R. Yamaguchi, S. Bardoel, R. S. Coppersmith, N. Chisholm, E. Gonzalez, N. Gunawardena, O. Hyde, T. Morrison, A. Olson, A. Perelet, W. Perrie, S. Wang, and B. Wauer. Published online in *BAMS*, February 2021. For the full, citable article, see DOI:10.1175/BAMS-D-19-0070.1. For supplemental material see https://doi.org/10.1175/BAMS-D-19-0070.2.



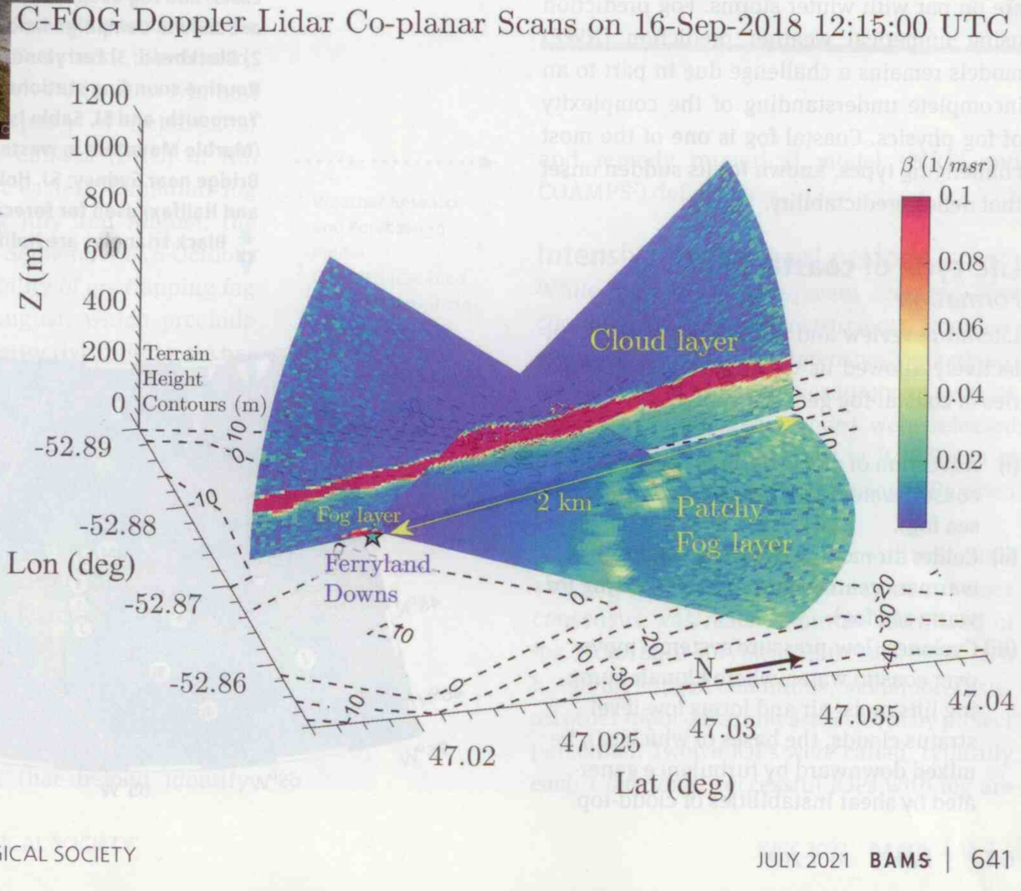
Fog settles over southeast Newfoundland during the Coastal Fog (C-FOG) campaign in September 2018. This video frame taken at 1215:12 UTC is from the Battery land observation site looking at the Downs observation site.

Fog is a collection of suspended small (~1–30 μm) water droplets or ice crystals near the Earth's surface that causes horizontal near-surface visibility to drop below 1 km. Fog forms near the surface and hence dynamic, microphysical, physicochemical, thermodynamic, surface, and environmental processes that regulate moisture in the atmospheric boundary layer (ABL) undergird its formation, evolution (maturation), and dissipation. Societal impacts of fog are profound and include air, maritime, and ground transportation hazards due to low visibility; smog; vast ecological consequences; interruption of terrestrial optical communications; and directed energy applications. It is thought that economic losses due to fog

> **"There it is, fog, atmospheric moisture still uncertain in destination, not quite weather and not altogether mood, yet partaking of both."**
>
> **—Hal Borland**



An interesting case of fog that lasted only tens of minutes occurred on 16 September 2018 during C-FOG. A curious wind shift and increased turbulent mixing dropped the temperature while increasing the humidity to near-saturation. Afterward, winds went calm, indicating the passage of some type of front, and fog began to form as the two air masses mixed. Overall, this can be interpreted as a *mixing fog* event induced by coastal topography.



Co-planar dual-Doppler lidar scans of range-corrected attenuated backscatter ($m^{-1}\,sr^{-1}$) operating from the Downs and Battery sites in southeast Newfoundland. Contours represent the terrain heights (m). High backscatter estimates represent clouds, fog, or a density inversion. The estimated fog layer thickness is ~45 m at Downs. The elevated cloud layer is ~280 m MSL. The scans are mostly over water and the Downs.

CLASSIFICATIONS OF FOG

Three broad categories can be identified: radiation, advection, and mixing. Nocturnal radiative cooling of a moist air layer to or below its dewpoint leads to radiative fog. Advection of warmer air over colder water leads to warm fog (or cold fog, in the opposite case), and both are in the general category of advection fog. Mixing of nearly saturated warm and colder air masses produces mixing fog. Further identified within these are subcategories: steam fog (steam streaks/smoke arising within cold fog), precipitation fog (rain evaporating into drier air), ice fog (at air temperatures $T < 10$°C, and location-based types such as marine fog, valley fog, upslope fog, and land fog. Marine fog includes the categories of coastal fog, sea fog, and open-ocean fog. Some noted coastal fog types include harr in eastern Scotland and England, fret in northeastern England, Labrador fog off eastern Canada, U.S. West Coast fog, and Yellow Sea fog.

are on par with winter storms. Fog prediction using numerical weather prediction (NWP) models remains a challenge due in part to an incomplete understanding of the complexity of fog physics. Coastal fog is one of the most challenging types, known for its sudden onset that defies predictability.

Life cycle of coastal fog

Formation

Literature review and recent observations collectively allowed us to propose these categories of coastal-fog genesis:

(i) Advection of moist warm air over colder coastal waters produces *warm fog* (or cold sea fog).

(ii) Colder air moving over (evaporating) warmer ocean water produces *cold fog* (or warm sea fog).

(iii) Cyclones (low-pressure systems) move over coastal water, where Ekman pumping lifts moist air and forms low-level stratus clouds, the bases of which can be mixed downward by turbulence generated by shear instabilities or cloud-top instability, forming fog. Cold upwelling may also help fog formation.

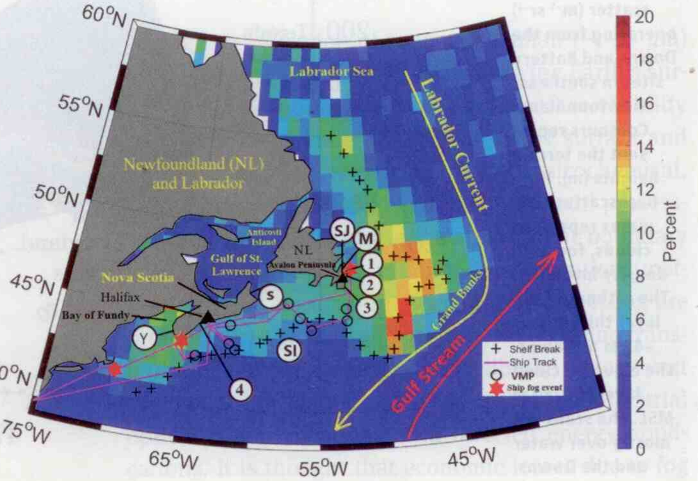
(iv) Subsidence of (warming) air within an anticyclone (high pressure) over a cooler moist marine ABL generates a low-level inversion, leading to slowly descending stratus clouds.

(v) Near-saturated colder and warmer air masses mix by coastal turbulence episodes, generating *mixing fog*.

Persistence

Effective moisture supply mechanisms that help sustain fog include evaporation at the sea surface and moisture advection. Intense radiative cooling at the fog-layer top and resulting turbulent convection beneath it mix the inversion associated with the fog top, thus cooling the fog layer beneath to maintain fog.

A map of North Canadian Atlantic overlaid by 1950–2007 fog climatology as a percentage of time of fog occurrence (color panel). Continental shelf break, major current systems, and prominent land and oceanic areas as well as the R/V track, vertical microstructure profiler (VMP) casts, and fog events encountered by the ship are shown. Campaign land sites are 1) Flatrock; 2) Blackhead; 3) Ferryland; and 4) Osborne Head. Routine sounding stations (M, Mount Pearl; Y, Yarmouth; and SI, Sable Island) and radar stations (Marble Mountain in western central NL; S, Marion Bridge near Sydney; SJ, Holyrood near St. John's and Halifax) used for forecasting are indicated. Black triangles are Halifax and St. John's ports.



Dissipation

The dissipation of fog may occur when moisture supply is insufficient to maintain saturation conditions against evaporation, deposition, precipitation, and scavenging. Therein, the near-surface layer first becomes slightly unsaturated, leaving stratus clouds aloft (sometimes called *lifted fog*). Another mechanism is the shear instability at the fog top, which enhances turbulent mixing and obliterates the cloud deck. Additionally, unfavorable transient weather (synoptic) conditions for fog maintenance may occur, thus promoting dissipation.

The C-FOG field campaign

A 3-yr (2018–21) comprehensive research program dubbed C-FOG, led by a multidisciplinary group of expert scientists, was designed to increase the predictability of coastal fog via improved understanding of its life cycle, identification of deficiencies of forecasting models, and developing improved microphysical parameterizations.

Considering competing factors, the coasts of Nova Scotia (NS) and Newfoundland (NL) were selected for the C-FOG field campaign from 12 candidate sites for logistical reasons and because they are underrepresented in the literature. Four specific study sites were identified based in part on their propensity for the development of fog: Ferryland, Blackhead, and Flatrock, all on private land in NL, and Osborne Head, a property of Department of National Defence, Canada (DND) in NS. Although the densest eastern Canadian fog climatology is during July and August, the campaign was from 1 September to 6 October 2018 due to the possibility of overlapping fog events in July and August, which preclude the capture of most distinctive differences between various phases of events. A stunning array of in situ, path-integrating, and remote sensing instruments situated on the research vessel (R/V) *Hugh R. Sharp* and at each of the four selected sites gathered data across a swath of space–time scales relevant to the fog life cycle. Satellite and reanalysis products, routine meteorological observations, numerical weather prediction model outputs, large-eddy simulations, and phenomenological modeling underpinned the interpretation of field observations in a multiscale and multiplatform framework that helped identify and remedy numerical model (WRF[1] and COAMPS[2]) deficiencies.

Coastal Fog (C-FOG) Research Program

The Research Program, a 3-yr (2018–21) effort funded by the Marine Meteorology Division of the Office of Naval Research, had the following objectives: (i) improve our understanding of dynamical, microphysical, physicochemical, thermodynamic, terrestrial, and environmental processes underlying the life cycle of coastal fog; (ii) evaluate the efficacy of NWP models in fog prediction; and (iii) improve forecasting model skills. Comprehensive field measurements during 1 September to 8 October 2018 and research-grade large eddy simulations (LESs) supported processes studies. NWP model investigations utilized COAMPS and WRF models. Owing to space–time variability and multiscale complexity, the life cycle of coastal fog remains enigmatic, and fog parameterizations used for NWP codes are largely empirical and leave much to be desired. Lack of rigorous treatment of surface processes, which causes biases in moisture and heat transports as well as energy budgets in models, is a contributor to the current low skill (~50%) of fog prediction. Specifically, the biases are pronounced at the marine–land–atmosphere interface, and addressing the underlying causes is a major task of C-FOG.

Intensive operational periods

While most of the equipment acquired data continuously, special instruments were operational only during intensive operational periods (IOPs), when all measurement systems were a go. Daily radiosondes were released from the coastal sites and the R/V *Sharp* at 0000 and 1200 UTC, except during IOPs when they were released every 3 h.

A go–no-go call for an IOP as well as its start and stop time were made a day ahead once consensus was reached on the likelihood of fog occurrence at typical lead times of 18–36 h based on current conditions, model forecasts, all other input data, and assessment by project personnel. Twelve IOPs were called, typically each 1 day long. Successful IOPs with fog are

[1] Weather Research and Forecasting model

[2] COAMPS (Coupled Ocean/Atmosphere Mesoscale Prediction System) is a registered trademark of the U.S. Naval Research Laboratory.

associated with near saturation of air. On that basis, only 6 out of 12 IOP fog calls were an observational success; 3 of the 6 ship fog alerts were verified.

Hindcasting of IOPs was made using the WRF Model (V3.9). Both COAMPS and WRF were employed to evaluate NWP model efficacy as a forecasting tool, to guide interpretation of flow and fog patterns, and to elicit underlying physical processes.

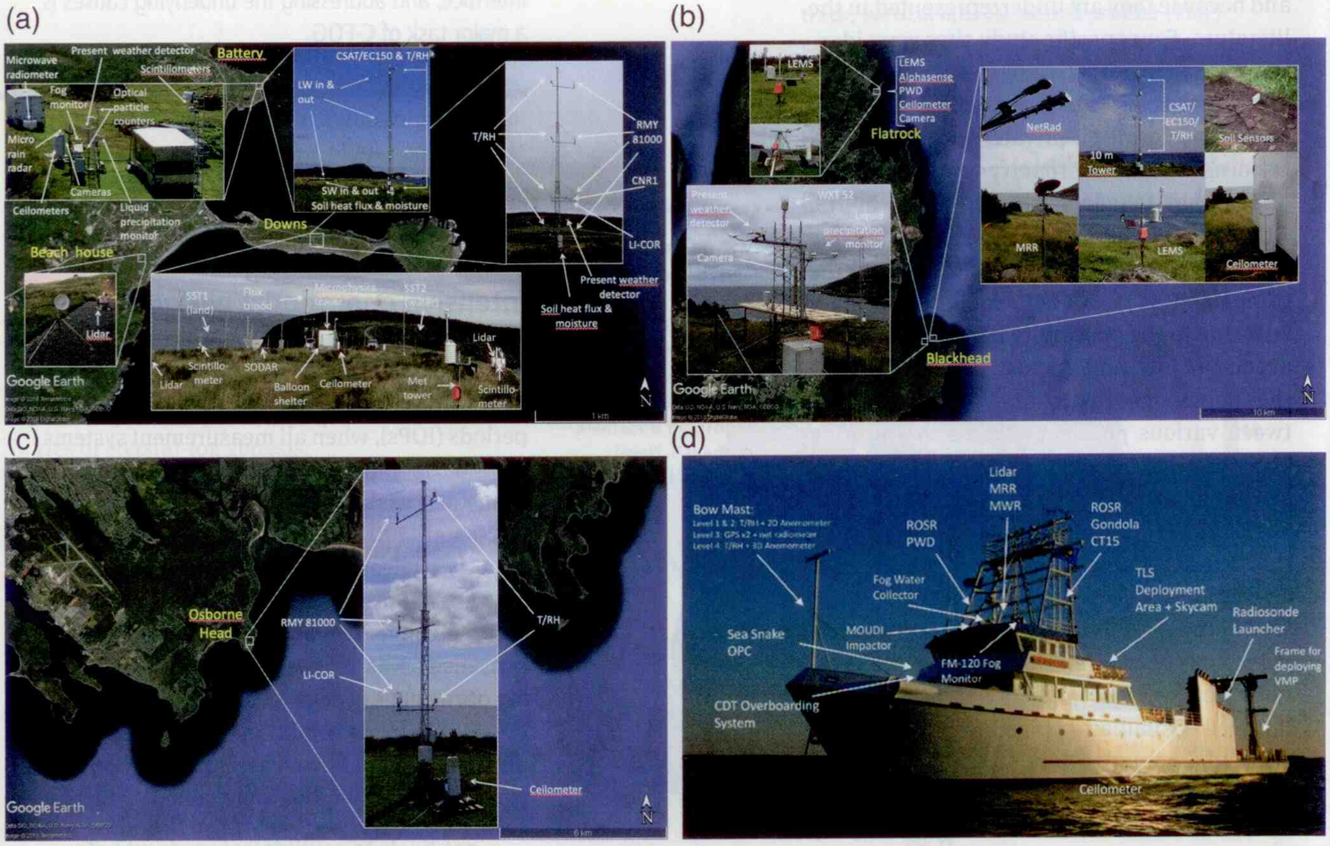
Condensed results

Twelve land-based and three ship-based IOPs were conducted during C-FOG. Although the IOPs were called upon by experienced weather agency forecasters as well as academic researchers, the overall predictability of fog during C-FOG was only ~50%. This low predictive skill can be largely attributed to space–time scale complexity contributed by land–atmosphere–ocean interactions, wherein smaller (micrometeorological and microphysical) scales play a decisive role. Microscales are not resolved by NWPs nor are they well-captured by conventional observing systems. Thus, an important takeaway is that fog forecasting relies heavily on parameterizations (currently with large uncertainties), artificial intelligence techniques, or local operational knowledge.

A major finding is that large-scale (synoptic) weather systems alone are not good prognosticators of fog genesis and evolution, but the details of smaller (meso, micrometeorological, and microphysical) scales generated via scale interactions and aerosol dynamics play a crucial role. Thus, development of high-fidelity subgrid microphysical parameterizations for mesoscale NWP models is key to improving fog forecasts.

Campaign data, notes, and photographs from the C-FOG campaigns are stored at repositories from individual groups as well as in a Google Team Drive at the University of Notre Dame. After full quality control/quality

Photos of land sites and the R/V with instrumentation. (a) Ferryland sites: Downs, Battery, Beach House; (b) Flatrock and Blackhead sites; (c) Osborne Head; and (d) R/V *Hugh R. Sharp*. SST1 and SST2 in (a) are the IR pyrometers for land and water surface temperature measurements.

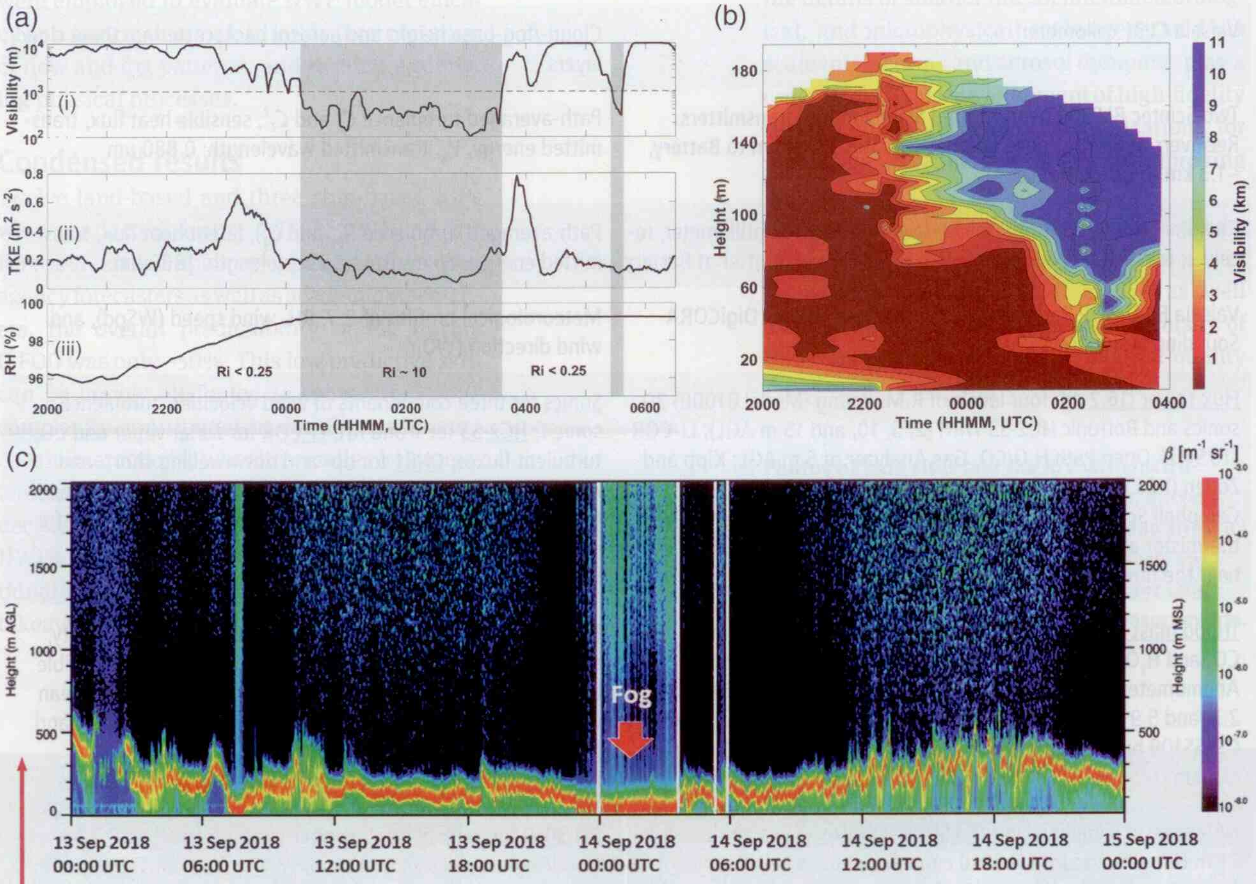


Instrument or instrument system/platform	Measured or retrieved parameters
Two Halo Photonics Streamline^{XR} Doppler lidars, dual-Doppler scanning configuration	Profiles of wind speed and turbulence (horizontal and vertical)
Two MFAS Sodar-RASS systems, separated by 200 m	Wind and temperature profiling
Vaisala CL31 ceilometer	Cloud-/fog-base height and aerosol backscattering, three cloud layers
Two Scintec BLS900 near-infrared Scintillometer transmitters. Receivers at Beach House and Battery sites 1.444 km to Battery, ~1.3 km to Beach House	Path-averaged turbulence C_n^2 and C_T^2, sensible heat flux, transmitted energy, V_R, transmitted wavelength: 0.880 μm
Radiometer Physics GmbH microwave MWS-160 Scintillometer, receiver; MWS-160 is collocated with BLS 900, transmitter at Battery	Path-averaged turbulence (C_n^2 and C_q^2), latent heat flux, transmitted energy, V_R, transmitted wavelength: 1860 μm
Vaisala RS41-SGP Radiosonde Launcher and Vaisala DigiCORA Sounding System MW41	Meteorological profiles of P, T, RH, wind speed (WSpd), and wind direction (WDir)
Flux Tower (16.2 m): four levels of R.M. Young (Model 81000) 3D sonics and Rotronic HC2-S3 T/RH (2, 5, 10, and 15 m AGL); LI-COR LI-7500A Open Path H_2O/CO_2 Gas Analyzer at 5 m AGL; Kipp and Zonen (K&Z) CNR1; Vaisala PWD22 present weather detector; Campbell Scientific Inc. (CSI) CS616 probe, CSI CS109 buried soil thermistor and Hukseflux HFP01 heat flux plate all buried −5 cm near the flux tower	Sonics for three components of wind velocities, turbulence, sonic T; HC2-S3 for T and RH; LI-COR for water vapor and CO_2 turbulent fluxes; CNR1 for up- and downwelling short- and longwave radiation; PWD 22 for visibility and precipitation; CS616 for soil moisture (volumetric water content); CS109 for soil T; HFP01 for soil heat flux
Tripod mast (6 m): Campbell Scientific IRGASON–Integrated CO_2 and H_2O open-path gas analyzer at 5.9 m and 3D Sonic Anemometer; three levels of Vaisala HMP155 and WXT520 (1.5, 2.2, and 5.9 m); Kipp and Zonen CNR1 net radiometer at 3.2 m; CSI SS109 buried thermistor (−0.6 and −6 cm); CSI CCFC field camera	IRGASON for CO_2 and H_2O concentrations, 3D wind velocity, sonic T, bulk T and P, turbulent fluxes of momentum, sensible and latent heat; HMP 155 for mean T, RH; WXT 520 for mean wind, P, T, RH; CNR1 for up- and downwelling shortwave and far infrared radiation; SS109 for soil T
NPS Aerosol Sampling Unit (NASU) Microphysics Trailer: located 21 m from the tripod: TSI 3010 condensation particle counter (CPC); Droplet Measurement Technology (DMT) CDP-2; Radiance Research PSAP; Brechtel TAP soot photometers; TSI 3563 Integrating Nephelometer	TSI 3010 for aerosol total number concentration; CDP-2 for cloud/fog droplet size spectrum; PSAP for aerosol absorption; TAP for aerosol absorption; TSI 3563 for aerosol scattering
Dangling Ultrasonic Micrometeo Balloon-based Observations (DUMBO) tethered system, a 32 m^3 Allsopp Helikite balloon platform: CSI IRGASON, VectorNav VN100 IMU, Rotronic HC2-S3 T/RH; CSI CR6 data acquisition system; Anasphere SmartTether v8 tethersonde system	IRGASON: as above; VN100 for inertial motion unit, linear acceleration, rotation rates, attitude angles; HC2-S3L for T and RH; SmartTether v8: mean wind, P, T, RH.
Local Energy Budget Measurement Station (LEMS): Meter Environment Atmos 22 2D sonic anemometer; Sensirion SHT31 air T/RH probe; Decagon 5 TM soil temperature and moisture sensors; Melexis MLX90614 surface T sensor; LI-COR Li200R global radiation sensors; Bosch BMP280 pressure sensor	Autonomous, solar-powered, Arduino-based low-cost meteorological measurement system: 2 m air and surface temperature, two levels soil moisture (volumetric water content) and temperature (5 and 20 cm); 2 m relative humidity, 2 m pressure, global radiation, 2 m wind speed and direction
Two Heitronics CT15.85 IR pyrometers	Ground temperature (north-pointing) and SST (south-pointing)

Measurement instruments deployed during C-FOG for the Downs land site in southeast Newfoundland (NL). Similar deployments and measurements were made at other C-FOG sites.

Time series of near-surface (i) 5-min-averaged visibility by a present weather detector (PWD), (ii) turbulent kinetic energy (TKE), and (iii) RH.

Contour plot of visibility with time from the surface to 200-m AGL, showing stratus lowering, development of fog near the surface, and penetration of clear air from above down near the surface. Visibility here was derived using the correlations between an optical particle counter suspended on a tethered balloon and a PWD.



Ceilometer backscatter time–height cross section for Blackhead indicating the height of the fog layer/cloud base.

From about 2000 UTC 13 September to 0400 UTC 14 September 2018, the Blackhead site experienced a clear *stratus lowering* event. It followed light precipitation that produced high relative humidity (RH) and mixing, while a nonsaturated layer above the stratus deck radiatively cooled after sunset. This cooling led to cloud-top instability and top-down turbulent mixing, lowering the cloud top to the surface.

assurance, the data will be publicly available in mid-2021. Full technical results, including those separately for the R/V and the four land-based observational sites during selected IOPs, will be described in future archival papers, including a special issue of *Boundary-Layer Meteorology*.

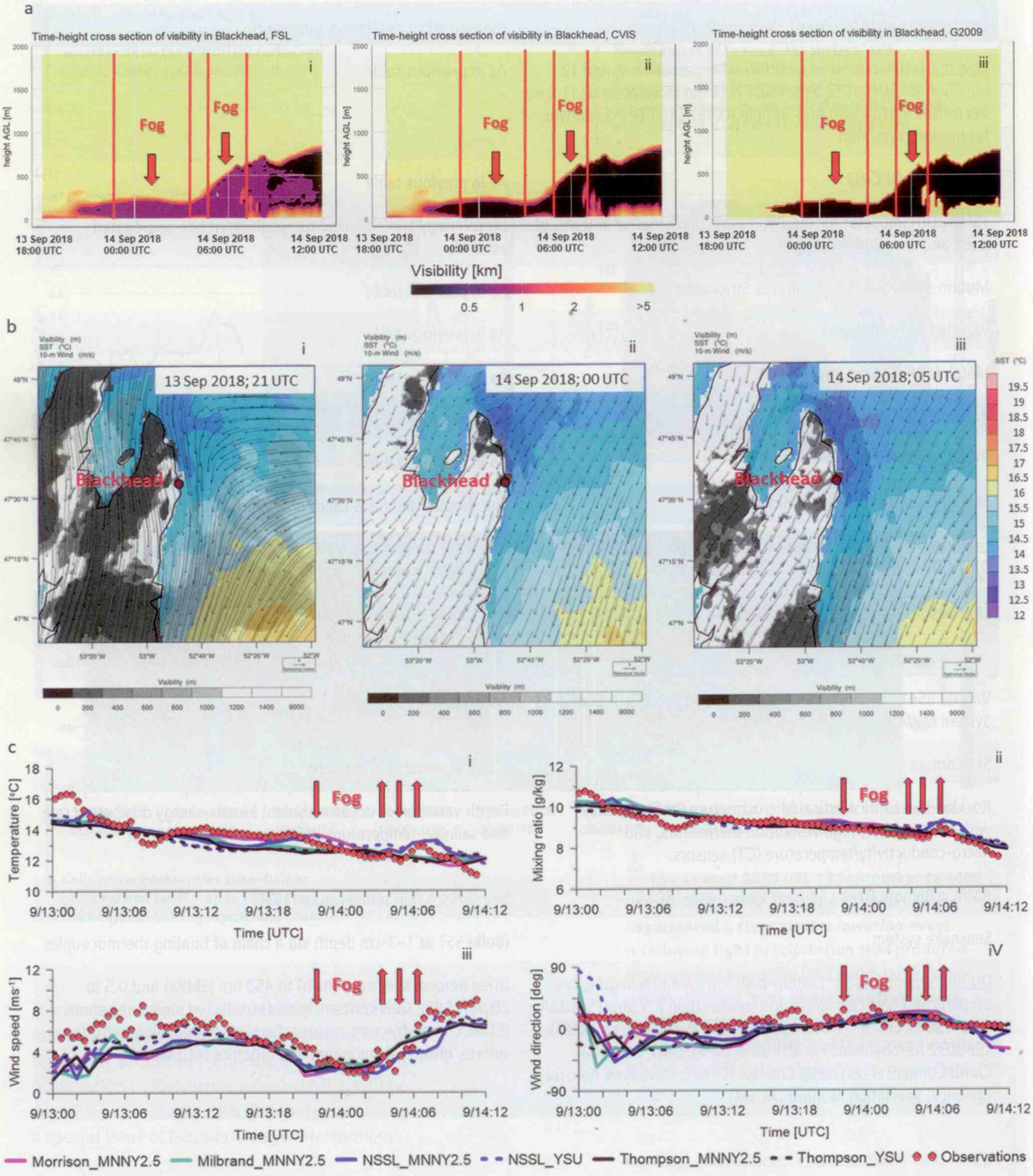
Conclusions

The multipronged approach employed in C-FOG clearly demonstrates that resolvable-(larger) scale motions are much better predicted by NWP models than fog. The life cycle of fog is sensitively determined by details of microscale (surface) processes within the ABL, including turbulence, entrainment, mixing, nucleation, condensation and evaporation, and autoconversion. Parameters that determine such processes, preferably universal (dimensionless) parameters, need to be identified and implemented in NWP models. In addition, C-FOG suggested the possibility of air–sea interaction thresholds that define conditions where the upper ocean plays a significant role in coastal fog life cycle by

Instrument or instrument system/platform	Measured or retrieved parameters
Bow mast: three levels of HMP155 T/RH probes (7, 9, and 12.5 m); CSI IRGASON at 12.5 m; K&Z CNR4 net radiometer at 11.5 m; VectorNav VN100 IMU and Trimble BX982 Dual-GNSS receiver for motion correction	As in previous table
AlphaSense OPC-N2	As in previous table
TSI MOUDI Impactor for sampling particulate matter in terms of mass and chemical content	Morphology and chemical composition of size-segregated aerosols
Motion-stabilized Halo Photonics Streamline^{XR} lidar	As in previous table
Vaisala CL31 ceilometer	As in previous table
Metek MRR-2 Micro Rain Radar	As in previous table
Radiometrics 3000 A MWR	As in previous table
PWD22 visibility sensor	As in previous table
FM120 cloud-particle spectrometer	Fog droplet spectra is used for N_c, r_e, LWC, and Vis
Gondola platform: Combination of two droplet spectrometers, DMT CDP-2; DMT backscatter cloud probe BCP	CDP-2 for droplet spectra and BCP for droplet spectra derived: N_c, r_e, LWC, and Vis
Tethered lifting system (TLS), CIRES/NOAA/ARL, custom made	ABL meteorological profiling, custom turbulence package with fine cold-wire (CW) and hotwire (HW) for turbulence and mean of T and winds. C_T^2 and energy dissipations rate are calculated.
Vaisala RS41-SGP radiosonde launches and DigiCORA Sounding System MW41	As in previous table
Sky camera	Video of weather conditions
Rockland Scientific Vertical Microstructure Profiler (VMP) with shear probes, high-resolution thermistors, and micro-conductivity/temperature (CT) sensors.	Depth variation of ocean turbulent kinetic energy dissipation rate and salinity–temperature–depth to a depth of 250 m
RMRCo Remote Ocean Sensing Radiometer (ROSR)	Sea surface skin temperature (SSST)
Seasnake system	(Bulk) SST at 1–3-cm depth via a chain of floating thermocouples
DU Instrument Cluster: custom-built fog inlet that segregates droplets and particles larger and smaller than 2.5 μm; TSI-DMA model 3081 CPC 3772 Scanning Mobility Particle Sizer (SMPS); TSI-3032 Aerodynamic Particle Sizer (APS); DMT CCN-100 Cloud Condensation Nuclei Counter (CCNC); Aerodyne Aerosol Chemical Speciation Monitor (ACSM)	Dried aerosol spectra from 10 to 450 nm (SMPS) and 0.5 to 20 μm (APS); CCN concentrations at selected supersaturations (CCNC); nonrefractory aerosol chemical composition, reports sulfate, nitrate, ammonium, and organics (ACSM)

Measurement instruments deployed during C-FOG for R/V *Hugh R. Sharp*.

ways of air–sea fluxes, SST, ocean upwelling, and fog condensation nuclei injection. It also stressed the need for improved understanding of fog-microphysical processes as well as spatial (especially vertical) variation of microphysical parameters of ABL, measurements of which are virtually nonexistent. This is an aspect that conspicuously lags the progress of its cloud-microphysical counterpart. While current fog microphysical parameterizations are hinged on developments in cloud microphysics, which is a prudent first step, it appears that great strides in fog modeling are possible by understanding, quantifying, and



(a) Vertical WRF (with NSSL-2 microphysics) cross sections covering the onset, intensification, and dissipation of fog. Visibility algorithms used included (i) FSL (NOAA Forecast Systems Laboratory), (ii) CVIS, and (iii) G2009. (b) 10-m wind velocity, SST, and fog (Vis < 1 km; in gray) for three selected times corresponding to conditions (i) that preceded fog formation, (ii) at fog onset, and (iii) at fog dissipation. (c) Near-surface 30-min-averaged observed (hydro-) meteorological parameters compared with simulations for Blackhead. Microphysical schemes are used with YSU and MYNN2.5 PBL schemes. Downward arrows represent fog appearance and vice versa.

implementing in NWP models how ABL attributes intrinsic to coastal marine and terrestrial environments, such as surface dynamical processes (e.g., fluxes, shear, stratification, stability, topographic), physicochemical characteristics (e.g., composition, transport, and transformations of fog condensation nuclei), thermodynamics (e.g., convection, radiation, phase changes), and their spatiotemporal variability, determine the life of coastal fog. The authors hope that fundamental knowledge gained from C-FOG will help address factors that currently stymie reliable fog forecasting. ⁂

METADATA

BAMS: What would you like readers to learn from this article?

H. J. S. Fernando (JF, University of Notre Dame): *With a few exceptions, fog is an uncommon phenomenon, but when it forms it can have potentially disastrous impacts such as the crippling of transportation and communication networks and even some critical military defense hardware. Despite this threat, our scientific knowledge of fog is sparse, and current numerical weather prediction (NWP) models still grapple with reliable fog predictions that are currently accurate only about 50% of the time. The main challenge for prediction is our meager understanding of physical, chemical, dynamical, and thermodynamic processes and their complex interactions responsible for fog formation. The processes underlying coastal fog are particularly intricate, given simultaneous involvement of land, ocean, and atmosphere.*

An unprecedented array of atmospheric instruments, satellite products, and NWP and high-resolution modeling allowed us to pin down the crucial role of the atmospheric boundary layer process in fog prediction. Contrary to the common belief that synoptic conditions are a good prognosticator of coastal fog, our work clearly demonstrated that inaccurate representation of meter-scale processes can thwart reliable fog predictions even though mesoscales are well-captured by NWP models.

BAMS: How did you become interested in the topic of this article?

JF: *Having lived in Tempe, Arizona, for a long time, I developed an interest in atmospheric visibility, spurred by the local brown cloud of air pollution and dust storms. When we were awarded the MATERHORN project to study complex-terrain weather in 2011, the field campaign was based near Salt Lake City, where visibility impairment by fog is an issue. Thus, we included fog as a research theme in MATERHORN, despite our group lacking expertise in critical microphysical measurements. During the 2012 AMS Annual Meeting, I met Dr. Ismail Gultepe from Environment and Climate Change Canada, who generously offered expertise and instrumentation for a full-fledged fog field campaign. Our exposure during the campaign to the richness of physical, dynamical, and thermodynamic processes underlying fog was exhilarating. Toward the end of MATERHORN, we learned that the Office of Naval Research (ONR) also has an interest in coastal fog, a scientifically deeper challenge—and the rest is history.*

BAMS: What surprised you the most about the work you document in this article?

JF: *While we were confident in the conventional fog prediction methods employed in C-FOG — synoptic analysis, WRF and COAMPS modeling, satellite products, and Artificial Intelligence, all employed with some success in C-FOG— there were cases of egregious defiance of nature to what we thought were confident predictions of fog. Comparison of model and observational results for these cases indeed diagnosed favorable confluence of large-scale processes needed for fog genesis, but the setback was the failure of the models to trigger small-scale (subgrid) processes generally needed for fog formation. Realization of the multiple roles of the atmospheric boundary layer was intriguing, which makes fog starkly different from low-level clouds.*

As for fog in coastal Newfoundland, we expected advection fog from the south, prompted by warm, humid air arriving from the Gulf Stream region via large-scale weather systems. Surprisingly, this was an oversimplified scenario.

BAMS: What was the biggest challenge you encountered while doing this work?

JF: *Our biggest challenges were designing a research program that addressed critical science questions across a mammoth range of space–time scales; assembling a multidisciplinary team with appropriate but complementary expertise, instrumentation, synergy, and numerical skills; and garnering funding. We were fortunate to have a U.S.-Canadian international multidisciplinary team from universities, national laboratories, industry, and government agencies, and the support of the Marine Meteorology Program of ONR in many ways.*

Graduate student Nipun Gunawardena (University of Utah) reviews data from a meteorological instrument at the Flatrock C-FOG site in Newfoundland, Canada.

Joe Fernando (left) checks the motion-stabilized Doppler lidar with Notre Dame scientist Charlotte Wainwright and field technician Jay Orson Hyde on a top deck of the *Hugh R. Sharp* research vessel docked at St. John's Harbor in Newfoundland, Canada.

Alexi Perelet, a trained graduate student from the University of Utah, climbs the 15-m flux tower for C-FOG to mount an infrared gas analyzer and sonic anemometer. (PHOTO: Sebastian Hoch)

> **"We would like to better understand and quantify small-scale details, from nanometers to 100-meter scales, undergirding fog formation. Turbulence and physicochemical transformations appear to be crucial. As well, their parametrization in NWP is imperative for high-fidelity predictions. While aerosol measurements are reaching nanometer-scale resolution, direct measurement of momentum, temperature, and liquid water fluctuations of submillimeter scales are still untenable, and we will strive to develop instruments and theoretical ideas to deal with such fog-spawning scales."**
>
> **—H. J. S. Fernando, University of Notre Dame**

PAGE 640