N000142112296 : Fatima: Fog and turbulence interactions in the marine atmosphere

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Submitter: Harindra Fernando

Major Goals

In the long term, Fatima [MURI] project seeks transformative leaps of fundamental knowledge as well as prediction and detection capabilities of fog. The project focuses on marine fog where significant knowledge gaps and data paucity exist and applications are timely. In particular, the emphasis will be on Marine Sea Fog that forms over shallow seas and shelves as well as on coastal Ice Fog. The approach is multi-faceted, and includes theoretical analysis, detailed process studies, novel high-resolution numerical simulations, extensive field measurements and predictive modeling in collaboration with practitioners. Fatima draws expertise from a multidisciplinary group of researchers covering the scale continuum from large regional weather systems (synoptic) to fog droplets of micrometer scales that grow on aerosols of nanoscales (microphysical).

The overall science goals are to: (i) deploy leading-edge instrumentation and novel measurements techniques in field campaigns to probe from synoptic to microphysical scales, including the capture of (smallest) scales of atmospheric turbulence where momentum, temperature and moisture fluctuations dissipate and, together with physicochemical properties of aerosols, control the droplet growth; (ii) conduct theoretical and numerical analyses that push the frontiers of multi-phase turbulence, especially nonlinear interactions between fog droplets and turbulence; (iii) elicit earth-surface processes that dictate fog genesis and cause vivid differences between fog and low-level clouds; (iv) identify deficiencies of fog microphysical parameterizations in numerical weather prediction models (NWP) and implement improvements; and (v) understand and model fog and turbulence impacts on optical propagation. Different participants focus on specific aspects that form the building blocks of understanding and prediction of fog life cycle in the overall framework of multiscale-flow (synoptic to turbulence cascade), microphysical (dissipating turbulence, drops), physicochemical (aerosol transformations) and thermodynamical (radiation, heat exchange) processes.

The project consists of two one-month field campaigns during the three-year base period in Grand Banks (Fatima-GB, 2022) and Yellow Sea (Fatima-YS, 2023), which are the two non-polar global fog maxima with different formation mechanisms. Both campaigns and now completed. They deployed research vessels and capitalized on fixed platforms of Fatima international partners, notably, deployments on (i) Sable Island in the outer Canadian Atlantic Shelf, and (ii) Korea Ocean Research Stations (KORS) in the Yellow Sea, in the EEZ of the Republic of Korea (ROK) in collaboration with the Korea Institute of Ocean Science and Technology (KIOST). Multitude of point, profiling and remote sensors pooled from participants conducted measurements across relevant space-time scales, guided by high resolution modeling and NWP forecasts. A number of key hypotheses and associated research questions have been developed that steer the research direction.

University of Notre Dame (UND) with H.J.S. Fernando as the PI (and senior personnel D. Richter and I. Gultepe) leads the project by organizing field campaigns and facilitating the research conducted by co-PIs and partners. The Co-PIs include Naval Postgraduate School (NPS, PI: Qing Wang), University of California, San Diego and Scripps Institution of Oceanography (UCSD, PI: Clive Dorman); University of Utah (UU, PI: Eric Pardyjak) and University of Minnesota (UM, PI: Lian Shen). A large number of US and international collaborators who are funded through other sources are participating in and immensely contributing to the program. They are listed in the project website (https://efmlab.nd.edu/research/Fatima/).

UND PI deployed extensive suite of instruments in Fatima-GB and FY-YS, probing from synoptic to Kolmogorov and Obukhov-Corrsin scales. The goal was to capture the cascading of properties from synoptic to dissipative scales, and develop a general understanding on fog-turbulence interactions and develop physics-based parameterizations. They also identify and analyzed special cases of fog lifecycle that have not been studied hitherto, especially those defy accurate predictions by NWPs. UND senior person Richter utilizes high-resolution simulation techniques for investigating the interactions between aerosol and droplet microphysics and the surrounding turbulent boundary layer. The main tool therein is a Lagrangian Cloud Model (LCM), coupled with large eddy simulation (LES) of the foggy boundary layer (LES-LCM) that allow uncovering important microphysical details at process level. Some examples are the role of droplet collision-coalescence in the activation process, role of vertical gradients of mean aerosol composition, droplet settling tendencies and the transition to drizzle, and the effects of heterogeneous mixtures of CCN size and composition.

The goals of NPS co-PI are two-fold: (i) to understand the physical processes affecting fog evolution, including its interactions with the surface, and (ii) to identify fog microphysics and turbulence parameters affecting optical attenuation to develop more effective parameterizations of attenuation and scintillation of optical signals through the fog layer. The fog layer evolution is impacted by both the microphysical processes associated with thermodynamics and aerosol/cloud physics and the near-surface dynamics of the turbulent boundary layer. The first goal seeks innovative and extensive field deployments and in-depth analyses of observational data in synergy with complementary observations obtained by other Fatima collaborators. NPS also focuses on how boundary thermodynamics and turbulence affect fog development and evolution. The second NPS goal addresses the impacts of fog on important applications such as high-energy lasers (HEL) and free-space optical (FSO) communication systems due to beam attenuation and scatter. This is achieved through analyses of fog microphysical properties and simultaneous measurements of optical attenuation. Existing parameterizations for Meteorological Optical Range (MOR) or Visibility are examined using data from both campaigns.

The UM group addresses how ocean surface processes such as wave-breaking, sea surface temperature (SST), momentum flux and sensible and latent heat fluxes, along with coastal and island land topography, collectively affect marine fog. Precise mechanisms through which oceanic processes and topographic effects influence fog dynamics remain unclear. UM addresses this question by using LES and direct numerical simulations (DNS). They also use an LCM to simulate fog, with evaporation and condensation of sea spray included and fog droplets modeled via Kohler theory. A radiation model accounts for long-wave and short-wave radiation effects on marine fog. The UM group plans to combine this fog model with simulations of moist air, while resolving wave breaking and sea-spray generation.

The UU group continues to analyze Fatima-GB campaign data, for which they play a major role in instrumenting the Sable Island. In the Fatima-YS campaign, they deployed in-house developed liquid water content (LWC) measuring instruments. The UU group emphasizes understanding of the roles of radiative heating and cooling, droplet thermodynamics, vertical profiles of microphysical parameters, dissipative processes, and infrared beam propagation through the fog. The PI from

UCSD leads the climatological analysis component of Fatima, in particular, conduct studies on how synoptic scales drive fog formation through cascading of momentum, temperature and water vapor inhomogeneities. Together with Naval Research Laboratory (NRL), UCSD also played a leading role in providing forecasting support for field studies and providing climatological perspectives during data analyses by different groups.

Accomplishments Under Goals

1. The Second Fatima Investigator meeting was held in the Salt Lake City during 22-24 February 2023. The presentations, agenda, photographs, and advisory committee comments are posted in the Fatima webpage (Fig. 1) [UU, ND]

2. A scouting visit to Busan, ROK by the US PIs during March 24-27, 2023 concerned Fatima-YS campaign planning. Scientists from KIOST, National Institute of Meteorological Services (NIMS), Kyungpook National University (KNU), US Office of Naval Research (ONR), Geosystems Research Corporation (GeoSR), Korea Hydrographic and Oceanographic Agency (KHOA) participated in a meeting at KIOST, followed by informal meetings and a site visit to R/V Onnuri (Fig. 2a,b). A proposal to ONR Naval Vessels Program to support the use of R/V Onnuri was funded in time for Fatima-YS. [ND, NPS, UCSD].

3. Fatima-YS was successfully conducted during 20 June to 9 July, 2023. R/V Onnuri, was the major mobile platform, with additional data streams from three large Ocean Platforms (S-ORS, G-ORS and I-ORS). Scientists from the Korea Precipitation Observations Program (KPOP-MS), from NIMS and KNU, joined the campaign, offering an additional R/V (Gisang-1) at a fixed site and a King Air Research Aircraft, NARA (Fig. 3a). Based on daily weather briefings (0900 am ROK daylight time), eight successful Intense Operational Periods (IOPs) were identified. Aboard R/V Onnuri were eighteen scientists (Fig. 3b). The Fatima-YS modus operandi is shown in Fig. 4. [All]

4. In Fatima-YS, a vast suite of observational tools was deployed, covering synoptic to turbulence (e.g., Fig. 5). NPS's novel C-CAMS system (see 7 below) made synchronous measurements of microphysics, micrometeorology, turbulence, optical visibility, ocean surface wave and SST, measuring vertical profiles at heights 2-12 meters from the ocean surface. Results show strong inhomogeneity of fog (W-Band Radar), SST, cold-water advection over slopes and strong air-sea interactions (Fig. 6). [ND, NPS. NRL].

5. Based on the 35 days of measurements during Fatima-GB, nine Reduced Visibility Events (RVEs) were defined when MOR < 1 km. The data were categorized as: clear, mist, fog, and precipitation. Fig. 7 shows the droplet spectra in all nine RVEs, showing persistent bimodal distributions except for two. Heavy fog (MOR < 400 m) shows different rates of visibility decrease as a function of LWC. Hence, representing both fog and mist using a single power function is misleading [NPS].

6. A collaborative study was conducted on the 'Fog Shadow' behind the Sable Island, discovered in Fatima-GB. Measurements suggest that it is a result of thermal internal boundary layers (IBL) over and past the island that increase air temperature and dissipate fog (Fig. 8 a,b). Simultaneous meteorological profiles (Fig. 9) aptly provided details of boundary layer evolution [ND, NPS, UU, UCSD].

7. Although C-CAMS measurements were from the side of the stationary ship, it was necessary to confirm that airmass is minimally disturbed by the ship. As such, a thorough intercomparison between the C-CAMS data and those from the R/V Atlantic Condor bow mast was made. The consistency between the two sensor suites is shown in Fig. 10. [NPS]

8. A study on the role of radiative heating and cooling and surface radiation balance on marine fog life cycle was completed. Fig. 11 is an example of processes studied using novel data from Sable Island. The profiles are from the up-sounding centered around 0620 UTC and resolve the ~60 m deep fog layer. LWC is calculated from a balloon borne optical particle counter. The changes of the net longwave radiative flux with height correspond to the radiative heating and cooling rates, and resolve the enhanced cooling at the top of fog layer. [UU]

9. Fatima-GB IOP5 data provided a better understanding of spatial (vertical and horizontal) and temporal variability of marine fog during its lifecycle through an analysis of tethered balloon meteorological profiles, droplet spectra, and path-averaged infrared radiation. As illustrated in Fig. 12, the scintillometer signal (infrared radiation propagation) is representative of the integrated droplet spectra from the point measurements. [UU]

10. A lightweight and low-cost LWC sensor was developed (Fig. 13a). A portable wind tunnel (Fig. 13c) was designed and built, capable of varying ambient temperature (18°C to 45°C), wind speed (2 to 10 ms^(-1)), and relative humidity (80 to 97 %) to calibrate the probe (Fig. 13c). The coefficient of determination of regression fit of transfer power across sensor wire and measured electrical power is > 0.99 (Fig. 13b). The field data collected during no-fog conditions helped in-situ dry calibration of the sensor and enhance the probe's accuracy. [UU, UCSD]

11. To validate the LWC instrument in the field, a network of four low-cost hot-wire liquid LWC probes was deployed during (i) Fatima-GB on fixed towers vertically and along a horizontal transect at Sable Island, and (ii) Fatima-YS campaign, vertically on a mast of the R/V Onnuri and a wave glider. The LWC was placed within the sampling volume of a three-dimensional sonic anemometer and co-located with temperature and relative humidity probes to calibrate dry power loss due to the ambient weather conditions Figs. 13d shows preliminary results. [UU, UCSD]

12. A LES-LCM method was developed to study the lifecycle of fog. The code successfully simulated an advection fog event observed during the C-FOG Campaign (Fig. 14). An immersed boundary (IB) method was developed to capture complex land topographic effects at the LES grid resolution. By combining the IB method with an unstructured triangular mesh, topography from LiDAR elevation data could be integrated with LES simulations. [UM]

13. Typical LES use inlet-outlet [periodic] boundary, but this approach is unsuitable for evolving topographies. In addition, to capture well-developed marine fog upstream of the Sable Island in Fatima-GB, the inlet-outlet simulation approach requires an extensive simulation domain. To circumvent such challenges, an alternate approach was developed where periodic and topographic simulations were combined. The efficacy of this approach is currently tested using Fatima-GB data (Fig. 15) [UM]

14. Aerosols can be activated by collection of particles with a comparably small amount of mass. Even if collision does not account for activation, it may be an important source of mass to the aerosols, allowing them to grow faster towards their critical radii and shortening the time needed to activate by diffusion (Fig. 16a). Collision-coalescence and ensuing mixing also acts to homogenize aerosol hygroscopicity. In addition to this work, simulation of Fatima-GB IOP-5 using initial conditions from radiosondes were conducted with LCM-LES to understand the Lagrangian history of aerosols and emerging fog droplets, which show that aerosols remain close to their original altitude during activation (Fig. 16b). [UND]

15. A study conducted to relate local divergence to fog appearance using Fatima-GB data showed that there is a relationship between the two. GFS output (Fig. 17a) and night microphysics images (Fig. 17b) were used for the study. A plausible reason is the lifting associated with surface convergence that brings moist marine air parcels to saturation under stable conditions. [UCSD]

16. Chemical composition of aerosols during fog and non-fog episodes were determined to better understand the association between the composition of aerosol, formation of marine fog, and processing of other atmospheric species in the presence of fog. In the coarse mode of size-resolved aerosol samples (1–100 microns), sodium and chloride had the dominant equivalent ionic loading in both fog and non-fog periods, with similar contributions as expected for sea salt. The results suggest that fog droplets can facilitate aerosols and gases to participate in reactions and gas-to-aqueous partitioning (Fig. 18 a,b).

Plans Next Period

During the 2023-2024, the Fatima Group plans to hold the third Investigator workshop in Jeju Island, ROK, so that KIOST, NIMS and KNU participants of the Fatima-YS campaign can conveniently attend. An ONR Global proposal is being prepared to seek financial support for non-US participants. The UND group continues data quality control and quality assurance (QA/QC) and analysis of instructive cases of the two completed field campaigns. They will take the lead of the BAMS article on Fatima-YS in preparation, submit a proposal to DOE ARM Program for a 2025/26 Ice Fog field campaign in the Northern Slope of Alaska ARM site, complete the theses of selected graduate students, and facilitate the preparation of an overview paper of the Fatima-YS campaign. A data base for the YS program is being developed in consonance with the Geosciences Research Corporation (Fig. 4). David Richter’s group at UND will work with FATIMA aerosol scientists to characterize the full cycle of ambient aerosols through activation and potentially drizzle. Their settling, vertical dispersion, and interaction with turbulence will be inferred from measurements and hopefully confirmed in the modeling environment. This process has recently begun.

The NPS will continue its effort of FATIMA-YS data processing, QA/QC, and initial archiving for collaborative analyses. They will continue data analyses and publication, preparation and submission of C-CAMS results from Fatima-GB, complete a study of boundary layer evolution downwind of Sable Island, and study stable boundary layer characteristics over the island. They also plan to support the analyses of Fatima collaborators and participate in preparing joint publications. The NPS is in the planning stage of a small fog-related project in Watsonville, CA, mainly in support of collaborators from UU in testing the microwave radiometer for a mini-fog measurement campaign. NPS plans to deploy several sensors including a sodar for continuous wind and Cn2 profiling. Following the rigorous validation of their solver against well-established benchmarks, UM Group will apply the code to real-world FATIMA observations. They plan to investigate the sensitivity of the fog lifecycle to physical processes, including turbulent mixing, heat and moisture exchanges, droplet size distribution, and number concentration, using an LES-LCM coupling and leveraging the FATIMA field observations. They also plan to conduct a comprehensive analysis to study the effect of physical and microphysical parameters on the marine fog lifecycle. On the Sable Island land topographic front, efforts are underway to simulate flow and activation of cloud condensation nuclei and development of fog droplets in the combined periodic and inlet-outlet simulations. The computational framework has already been developed, and now it is being validated. For the next reporting period, their aim is to simulate fog development as droplets, and inactive particles are introduced from a well-developed open ocean flow to a topography, focusing on FATIMA-specific locations and terrains.

The UU Group plans to continue the analysis of data from GB and YS campaigns, ramp up writing peer-reviewed journal papers and disseminate results via conferences. Collaboratively with NPS, UU plans to conduct a short-term field experiment in Monterey, CA to (1) better understand the transmission of infrared and microwave radiation in fog and (2) to use the attenuation of infrared and microwave radiation to infer microphysical properties along the path of the scintillometer. These were key science objectives of the original MURI proposal. This experiment was to be conducted on

Sable Island, but due to a major instrument failure, they were unable to get the needed data. To achieve the UU objectives, the scintillometer system will be deployed at the Monterey Bay Academy near Monterey, California. Additional funds and instruments have been requested from NCAR/EOL to help characterize the droplet size distribution (DSD) during the experiment. Specifically, funds were requested for one Ott Parsivel Disdrometer from NCAR and one DMT cloud imaging probe from Ontario Tech. These instruments will be combined with other particle counters to ensure complete characterization of the Droplet Size Distribution (DSD), so that it may be correlated with the scintillometry measurements. With the entire DSD, it is possible to calculate the expected attenuation with the help of Mie Theory. This expected attenuation from the DSD can then be compared with the measured attenuation from the two scintillometers, and then develop relationships between the DSD and attenuation for different hydrometeor types.

The UCSD PI is working on several collaborative research papers, which will be submitted to the Quarterly Journal of the Royal Meteorological Society shortly. A collaborative journal paper on rapid (explosive) formation of fog is in preparation with Darko Koracin (University of Split, Croatia), who visited UND in 2023 for collaborative work. They also plan to submit a manuscript on fog formation in a strong closed low-pressure area over Sable Island

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Results Dissemination

During the reporting period, the results were disseminated by conference presentations as well as submittal of peer reviewed publications. The PI also made several invited presentations at university seminars: University of Bologna (Italy, Summer School on Physical Sensing of the Environment, July 16-21, 2023) and Columbia University (2023).

PI Clive Dorman and collaborators Ismail Gultepe, Darko Kora?in, and Reneta Dimitrova are organizing a special session on “Marine Fog and Multi-Phase Turbulence” at the AGU Fall Meeting in San Francisco, December 11- 15 September, 2023.

News Article on “Korea-US joint exploration of the Yellow Sea … Identification of the cause of sea fog” Can be found in: https://efmlab.nd.edu/news/kiost-reveals-secrets-about-sea-fog/

The journal papers (published, submitted and in preparation), conference papers, and conference/workshop presentations pertinent to the 2022-2023 reporting period is included in the Appendix 1 of the attached file, following the figures.

Honors and Awards

The PI was elected as a Fellow of the International Association for Hydro-Environment Engineering and Research (IAHR), and he delivered the 2023 IAHR Presidential Award Lecture in December 2022.

Training Opportunities

The project offered extensive training opportunities for early career scientists, post-docs, graduate and undergraduate students, as well as technical staff. The graduate students were directly trained under the PIs, and all had opportunities to participate in Fatima Cruises and obtain experience in instrument deployment and data analyses. Since Both Fatima cruises were international, all trainees had an opportunity to travel to international destinations and interact with host-country scientists. An early career scientist was the co-Chief Scientist of Fatima cruises. Student were given opportunity to seek out international internships with partners. Many of the trainees involved participated in national and international workshops and conferences. Collaboration was maintained with DoD personnel about identifying science needs and transitioning of project outcomes to applications.The trainees had an opportunity to interact with DOD laboratories.

Early Career Scientists (4): Jesus Ruiz-Plancarte (NPS), David Ortiz-Suslow, Ryan Yamaguchi (NPS), Francesco Barbano (UU, University of Bologna),

Post-Doctoral Fellows (5): Kelly Huang (UND), Camilo F. Rodriguez-Geno (UND), Han Liu (UM), Alexei Perelet (UU) and Dhiraj Singh (UU).

Graduate Students (13): Thomas Hintz (UND, graduated with MS in 2023), Stef Bardoel (UND), Anne Dowling (UND), Sen Wang (UND), Edgar Gonzales (UND), Fatma Emin (UND, international visiting student), Kelsey Rowe (NPS, graduated with MS in 2023), Matthew Huckins (UU), Anup Barve (UM), Shubham Mittal (UM), Sai Chaitanya Gembali (UM), Leyla Salehpoor (York University), Gianina Massa (Dalhousie University)

Undergraduate Students (3): Jacob Ropp (UND), Eilliott Kirwan (UND), Karolek Suchocki (UND, REU)

Technical Staff (2): Scott Coppersmith (UND), Orson Hyde (UND)

Technology Transfer

A highlight of the project is the close collaboration with DOD Laboratories, which included:

Naval Research Laboratory, Monterey (Saša Gaberšek, who was the lead forecaster of the Fatima-YS project, where he used couple atmosphere-ocean COAMPS model at 1 km resolution and different initialization times to guide IOP predictions; Model-data intercomparisons are being used to identify model deficiencies and remedy them by developing new parameterizations)

Army Research Laboratory, White Sands Missile Range, New Mexico (Ed Creegan, Andrey Grachev, Chris Hocut; Ed Creegan was the Chief Scientists of both Fatima cruises. Grachev and Hocut conducted research on refractive index fluctuations in fog environments with applications to optical turbulence)

Airforce Institute of Technology AFIT (Steve Fiorino and Kevin Keefer; they deployed novel instruments to capture fine aerosols, in particular, the presence of P Syringae in marine aerosols).

Lt. William Griffin and a crew of 4 from the Naval Forces in Korea participated in the mobilization of Onnuri at the Jangmok Port in Busan during Fatima-YS.

In addition, NPS closely works with the Naval Air Warfare Center Weapon Division (NAWCWD), Physics Division, to use the measurement techniques used/developed in FATIMA to support US Navy high energy laser (HEL) weapon testing.

Participants

Name	Role	Person Months
Dorman, Clive E.	Co PD/PI	2
Pardyjak, Eric	Co PD/PI	2

Shen, Lian	Co PD/PI	1
Wang, Qing	Co PD/PI	2
Gultepe, Ismail	Co-Investigator	3
Hoch, Sebastian	Co-Investigator	2
Ortiz-Suslow, David	Co-Investigator	2
Richter, David H.	Co-Investigator	2
Ruiz-Plancarte, Jesus	Co-Investigator	3
Yamaguchi, Ryan	Co-Investigator	2
Bardoel, Stef	Graduate Student (research assistant)	12
Barve, Anup	Graduate Student (research assistant)	9
Dowling, Anne	Graduate Student (research assistant)	12
Emin, Fatma	Graduate Student (research assistant)	4
Gonzales, Edgar	Graduate Student (research assistant)	12
Hintz, Thomas	Graduate Student (research assistant)	9
Huckins, Matthew	Graduate Student (research assistant)	9
Massa, Gianina	Graduate Student (research assistant)	5
Rowe, Kelsey	Graduate Student (research assistant)	3
Salehpoor, Leyla	Graduate Student (research assistant)	2
Shubham, Mittal	Graduate Student (research assistant)	9
Wang, Sen	Graduate Student (research assistant)	6
Coppersmith, Ronald	Other Professional	6
Shoop, Lori	Other Professional	2
Fernando, Harindra	PD/PI	2
Barbino, Francisco	Postdoctoral (scholar, fellow or other postdoctoral position)	1
Huang, Kelly	Postdoctoral (scholar, fellow or other postdoctoral position)	10
Liu, Han	Postdoctoral (scholar, fellow or other postdoctoral position)	6
Perelet, Alexei	Postdoctoral (scholar, fellow or other postdoctoral position)	6
Rodriguez-Geno, Camilo	Postdoctoral (scholar, fellow or other postdoctoral position)	9
Singh, Dhiraj	Postdoctoral (scholar, fellow or other postdoctoral position)	3
Suchocki, Kardek	Research Experience for Undergraduates (REU) Participant	3
Hyde, Jay	Technician	6
Kirwan, Eilliot	Undergraduate Student	3
Ropp, Jacob	Undergraduate Student	2

Figures and Publications Document

Figure 1: The Second Investigator Meeting of the Fatima Project was held during 22-24 February, 2023 at the University of Utah. Co-PI Eric Pardyjak was the host of the meeting. A photograph from the workshop dinner is shown.
For Details, see: https://efmlab.nd.edu/research/fatima/workshops-meetings/ (UND)

Figure 2a: An informal meeting on Fatima-YS cruise planning, after a formal meeting in KIOST during the scouting visit in March 2023.

Figure 2b: The visit to R/V Onnuri for inspection of facilities

Figure 3a: Mobile platforms used for Fatima-YS: R/V Onnuri, R/V Gisang-1, and NARA Research Aircraft with a newly installed Ka Band Radar. KPOP-MS scientists joined Fatima-YS during 20 June to 01 July, 2023.

Figure 3b: Science and ground support Crew of R/V Onnuri before embarking on Fatima-YS. Twelve US and six KIOST scientists were on board during the campaign.

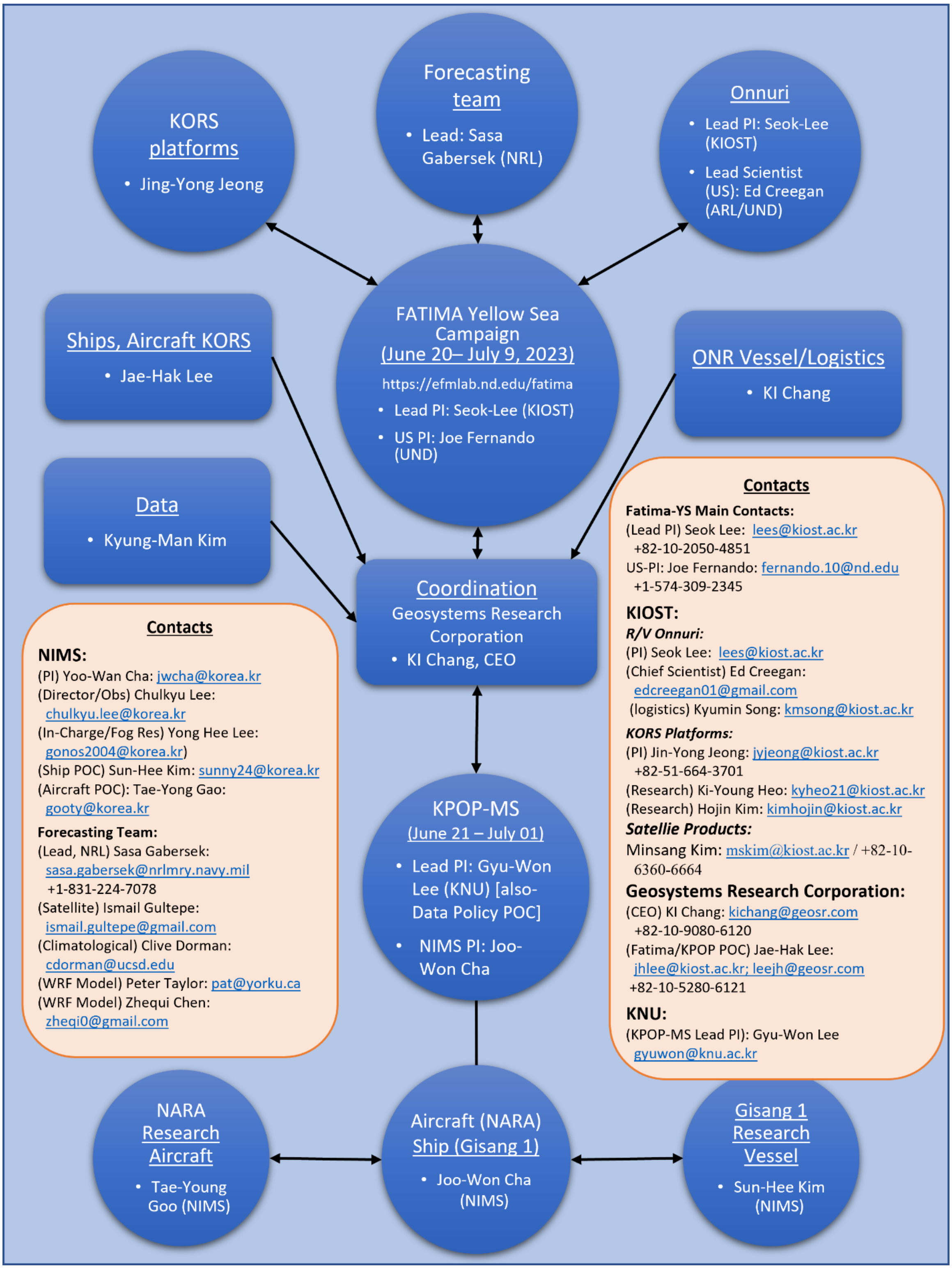

Figure 4: A block diagram of Fatima-YS operations, including personnel in charge of various components. Seok Lee and Ed Creegan were the co-Chief Scientists from KIOST and Fatima, respectively. Drs. KI Chang and Jae-Hak Lee from Geosystems Research Corporation as well as KIOST provided administrative and logistical support for the campaign.

Figure 5: An example of instruments deployed by the UND Group: clockwise – Present Weather Detector FD-70, Microwave Rain Radar (MRR-Pro), motion stabilized scanning Doppler Lidar, VMP-250 microstructure profiler, motion stabilized W-Band Radar, Eigenbrodt-480 Optical Disdrometer, Remote Ocean Sensing Radiometer (ROSR), and Sea Snake array for surface layer temperature. Additional instruments included those for fog droplet size distribution, turbulent perturbations of wind components, temperature, and humidity, visibility, temperature and humidity profiling (microwave radiometer MWR), meteorological profiles (rawinsondes), turbulence, upper-ocean CTD and radiation (bow mast).

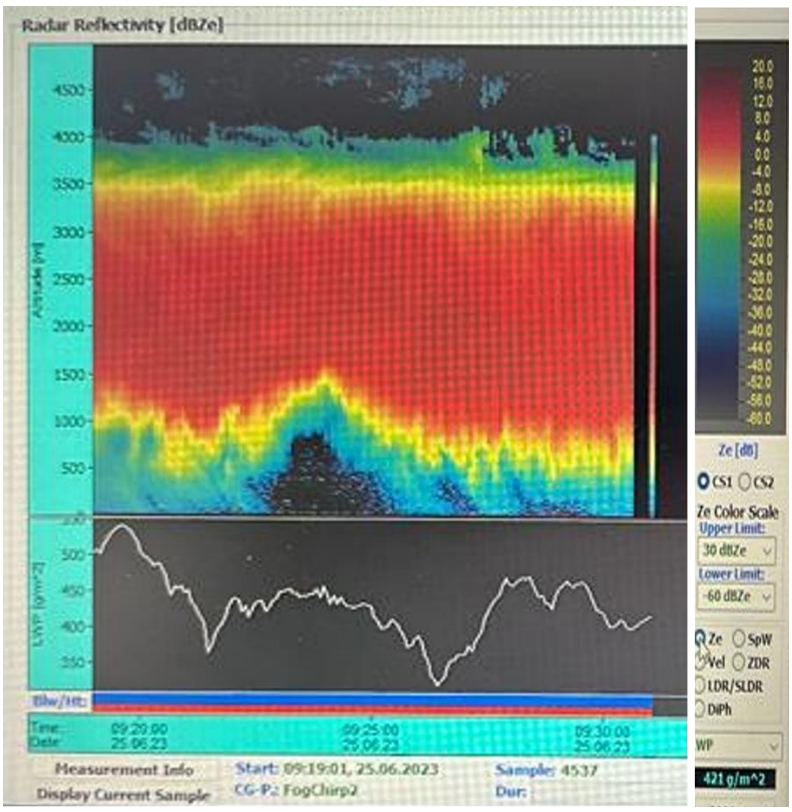

Figure 6: A W-Band Radar reflectivity Image taken during the cruise, showing strong inhomogeneity of fog over YS. Horizontal axis shows the distance travelled.

a)

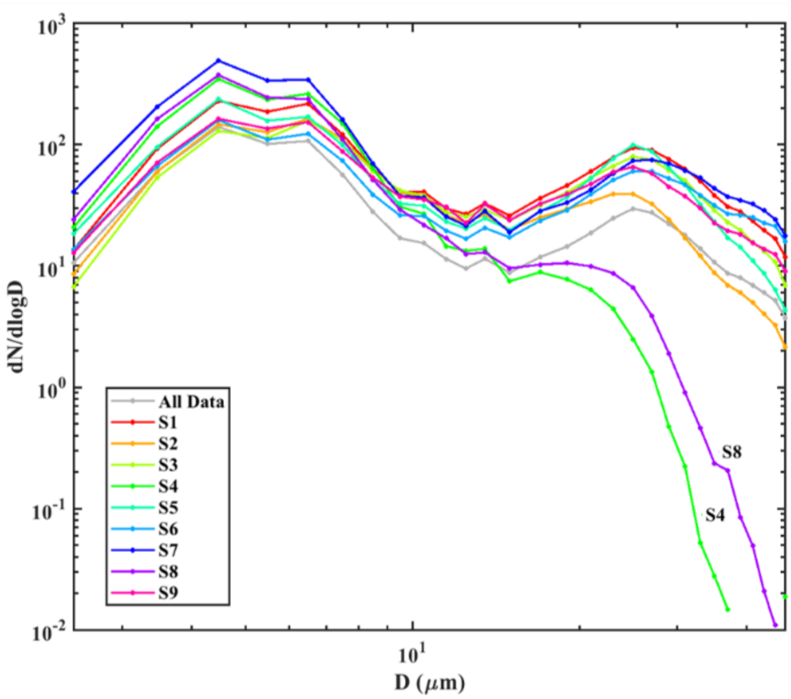

Figure 7: Mean droplet size distribution measured by Fog Monitor FM-120. Legend - nine events selected from the total data set. The two events (S4 and S8) that do not follow the bi-modal distribution were further studied (not shown). Meteorological Optical Range (MOR) or visibility was measured using Present Weather Detector PWD-22, which also provided the hydrometeor classification.

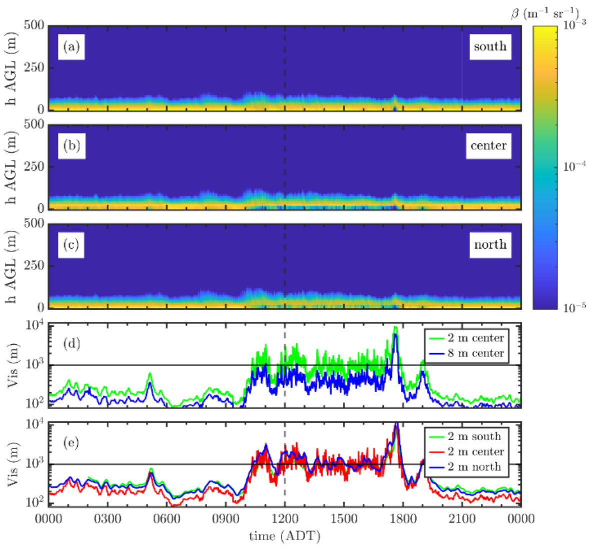

Figure 8a: Sable Island ceilometer backscatter observations at the (a) south tower, (b) center tower, and (c) north tower, (d) visibility at the center tower, and (e) 2 m visibility at the south, center and north tower on 24 July, 2022. Note the progression of visibility reduction on the island in streamwise direction.

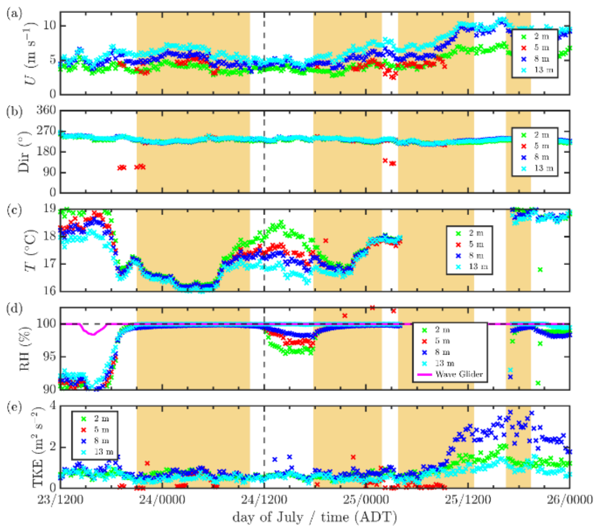

Figure 8b: (a) wind speed, (b) wind direction, (c) temperature, (d) relative humidity, and (e) Turbulent Kinetic Energy (TKE). The shaded regions are foggy conditions. Dashed lines - initial appearance of the fog shadow. The data are from the center tower during IOP10 with upstream temperature measured by the wave glider.

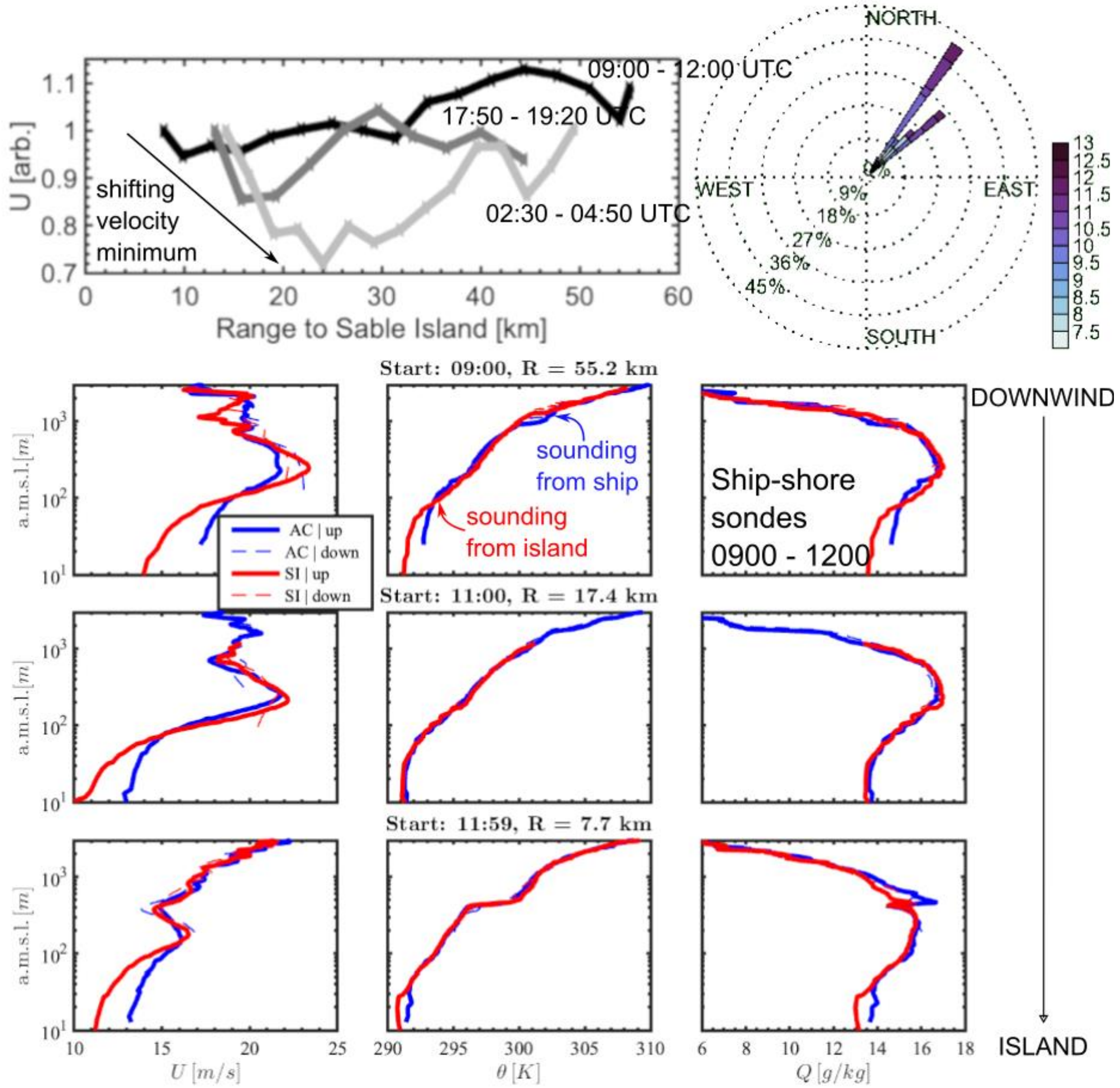

Figure 9: Upper left Time series of surface winds from the R/V *Atlantic Condor* during the study period focused on the fog-island-atmosphere interaction processes. Each curve gives the surface wind (normalized by the value closest to the island at R = 0) during 3 repeated transects starting downwind and heading into the wind. Upper Right Wind rose for study period showing predominantly northeastward winds throughout. Bottom Profiles of wind speed, potential temperature, and specific humidity (left-to-right) for 3 rawindsonde launches made during the first upwind transect during SLOP (black curve in upper left). The red and blue curves show the coordinated soundings from the island and ship, respectively. Note the heating of the profile downstream, where the near-surface velocity increases due to reduction of surface roughness from land to ocean. Also note the moisture pick up during flow acceleration from land to ocean.

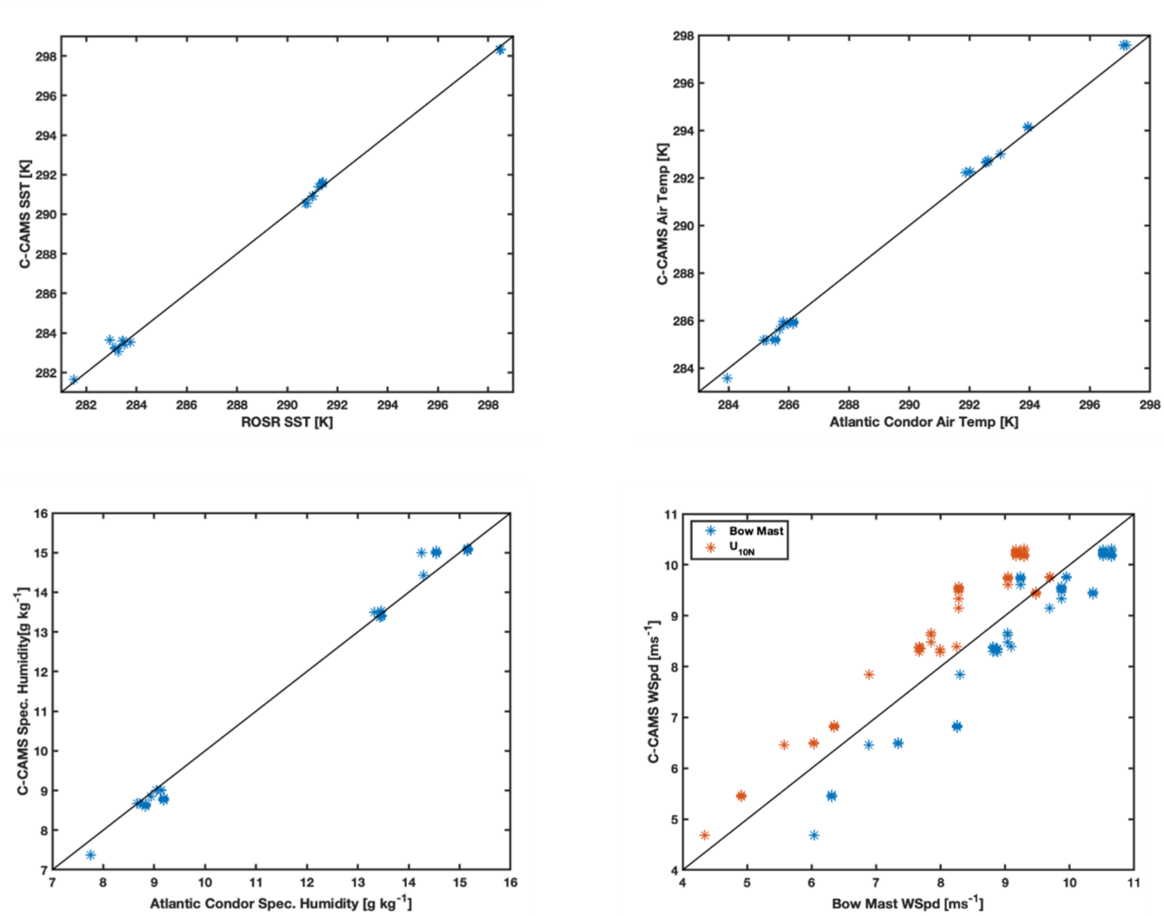

Figure 10: To address the vertical variability of fog microphysics and turbulence near the surface, the NPS-designed new sensor suite - the Crane-deployed Cloud and Aerosol Measurement System (C-CAMS). It was deployed during Fatima-GB. C-CAMS included a suite of aerosol droplet size distribution (microphysics), extinction, and turbulence with electronics housed in a fiberglass container and sensing heads and air inlets on a 10-ft horizontal triangular mast. A comparison of the C-CAMS SST, air temperature, specific humidity, and wind speed from measurements above 7 m to those from the bow mast is shown. The systematic differences in wind speed comparison are likely a result of that the measurements not at the same altitude (the bow mast was at ~18.2 m above the surface while the maximum height above the ocean surface on C-CAMS was less than 10 m). The lower right panel shows high wind speed from the bow mast level. Further study is ongoing at NPS to compare the wind speed calibrated to 10-m height and in neutral conditions.

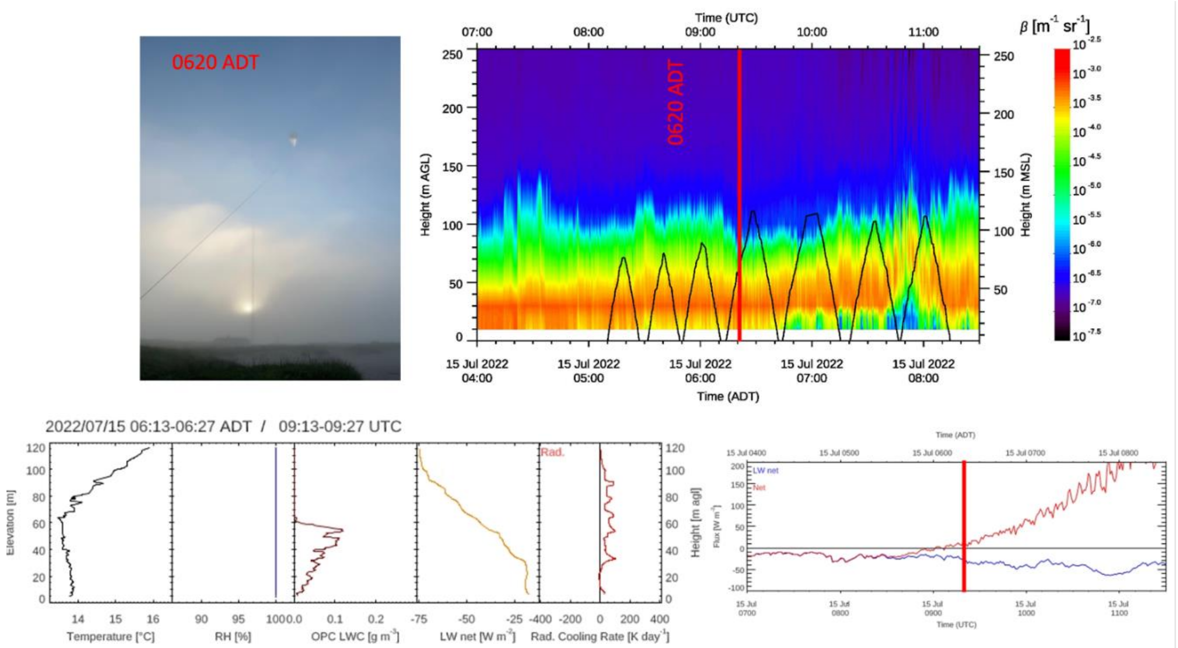

Figure 11: Novel tethered balloon sounding data, ceilometer data, and surface radiation balance capturing the erosion of the marine fog layer from above and below during the IOP 5 morning transition (15 July 2022) at Sable Island. Top right - time-height cross section of atmospheric backscatter, with black lines illustrating the balloon's height. The lightweight gimbal-stabilized pyrgeometer platforms on profiling tethered balloon allowed direct observations of radiative heating/cooling profiles through the fog layer. Note that the fog layer consists of fog plumes of varying sizes and depths advecting over the Sable Island coastline (see web cam image). The time height cross section of backscatter from a ceilometer further reveals the effect of the reversal of the surface radiation balance in the morning which led to the erosion of the fog layer from below.

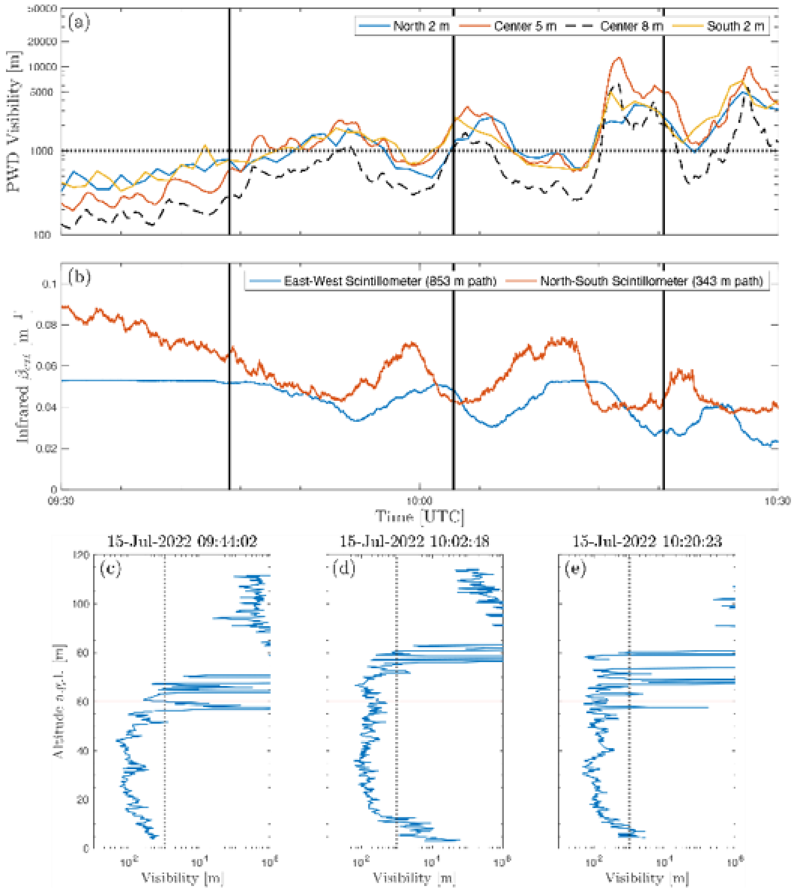

Figure 12: (a) Visibility from PWDs along the North-South transect at West Light site on Sable Island. Temporal variability in the visibility can be seen as patches of fog advected over the island. A lower visibility is seen at 8 m (dashed line) than at 2 m. (b) Extinction coefficient, roughly the inverse of visibility, from the two infrared scintillometers. The North-South scintillometer tracks well with the visibility measurements in (a) while the offset seen in the East-West scintillometer response is due to the horizontal length scales of the advecting patches. (c) Visibility calculated from the OPC-N3 on the tethered balloon for the time periods depicted by vertical lines in (a) and (b).

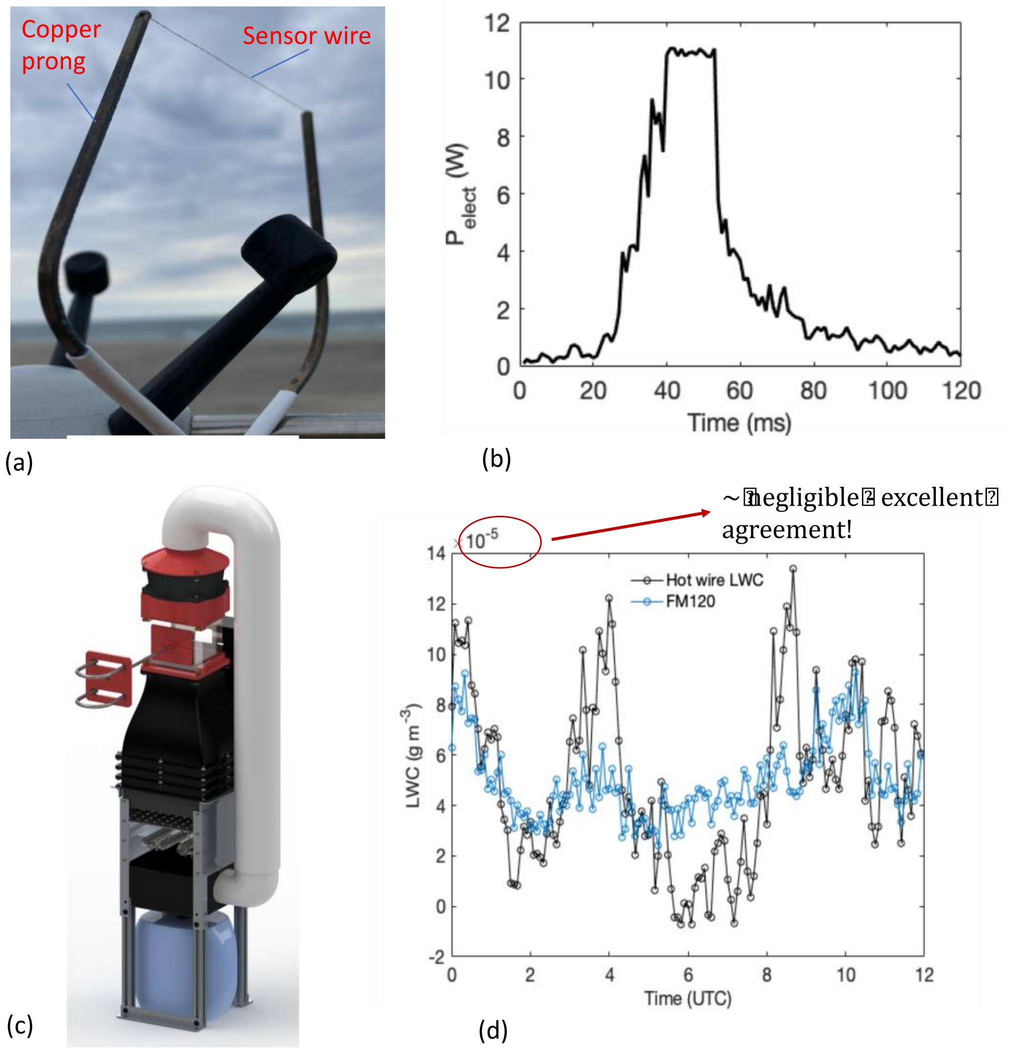

Figure 13: (a) Low-Cost Hot Wire LWC Probe (b) Response time of the LWC circuit (c) Calibration unit (d) Comparison between hot-wire LWC probe and FM120.

Note: The LWC sensor is composed of a single 5-cm long, 125-micrometer diameter platinum wire (see Fig. 13a). and a sensor wire was placed on one of the legs of the Wheatstone balanced bridge circuit. The device was operated at constant temperature, and the design accounts for fog droplet deposition, prong conduction and sensitivity. It has a highly sensitive circuit that measures wind velocities from the order of centimeters to 50 m s^{-1}. The device was set with a positive offset (0.001 V) for circuit stability and used an amplifier that provided a current up to 5.46 A when circuit de-stabilized. The time response was estimated using amplifier characteristics, wire geometry, and thermal properties, and at a given sensor wire temperature 35 ^{o}C response time of 0.02 s was obtained (see Fig. 13b). To enhance the usability of the probes in the field, a portable wind tunnel (Fig. 13c) was designed and built that is capable of varying ambient temperature (18°C to 45°C) wind speed (2 to 10 m s^{-1}), and relative humidity (80 to 97 %). The coefficient of determination (R^2) of regression fit of transfer power across sensor wire and measured electrical power is over 0.99. The field-experiment data collected during no-fog conditions helped dry calibration of the sensor (in situ) and enhance the probe's accuracy. Laboratory tests were conducted with water droplets of known mass applied to the wire using a micro-pipette. These tests resulted in an R^2 value of over 0.99.

The device sensitivity is 0.0001 gm^{-3} (at typical temperatures) and it can measure LWC with accuracy of about 5% at 1 gm^{-3}, 7% at 0.5 gm^{-3} and 11% at 0.01 gm^{-3} using laboratory water droplets test, and it can measure up to approximately 2 gm^{-3}. The LWC probe measurements were validated with a FM120 (Fig.13d), a Vaisala FD70, and a Vaisala Present Weather Detector (PWD).

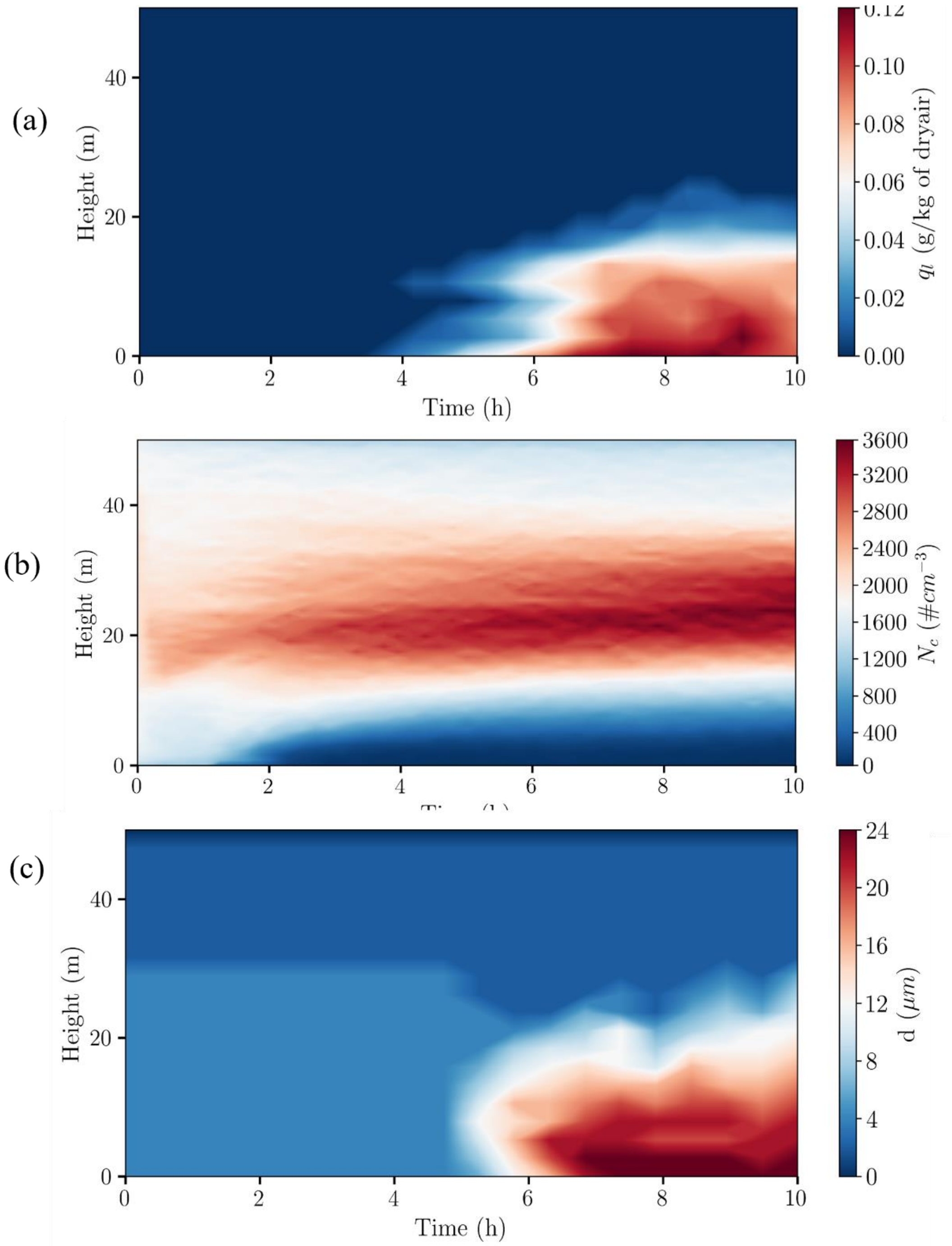

Figure 14: Planar averaged time-height plot of a) liquid water content, b) particle number concentration, and c) average droplet diameter. The figure shows the planar-averaged time-height fog properties from a simulation. The computational domain is a periodic box of 128 m in each direction with a grid resolution of 1m. The geostrophic wind is set to 4 m s^{-1}. The specific humidity is adjusted to maintain 100% saturation at the surface based on the given SST. After an hour, the SST is reduced by 2 °K, after which it takes around 4 hours for the fog to form, as seen in (a), where a threshold of 0.01 g/kg signifies the fog formation. After this, due to longwave cooling, the fog layer continues to deepen until the end of the simulation, which can be observed through an increase in liquid water content. (b) and (c) show the evolution of number concentration and mean droplet diameter, respectively.

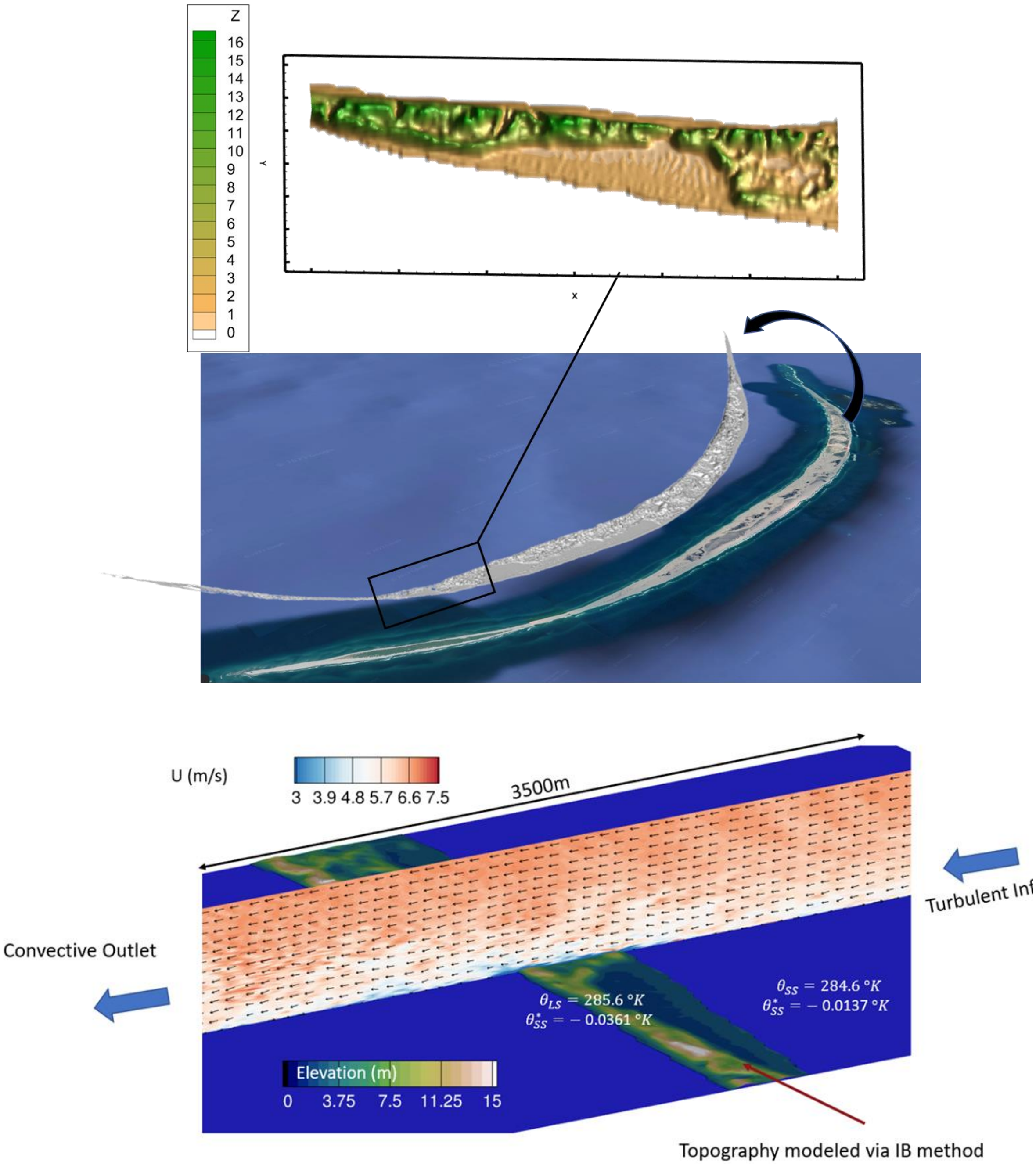

Figure 15: The use of advanced IB method to capture complex geometries in LES simulations. upper: An example of the Sable Island topography included in UM simulations along with its appearance on Google Earth. Lower: Instantaneous wind speed predicted by LES at a horizontal resolution of 24 m. For fog near the island, we use an immersed boundary (IB) method to model the realistic topography in the simulations. The LES grid is clustered in the vertical direction with a minimum resolution of approximately 0.8 m.

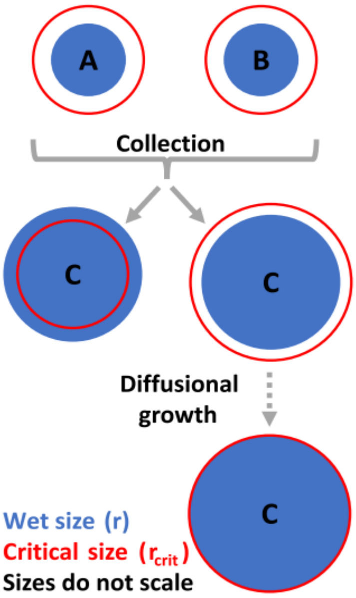

Figure 16a: Schematic of the collisional activation process, where aerosols A and B can collide and either activate based on the new combined size (left path) or speed the process by which diffusion can activate (right path)

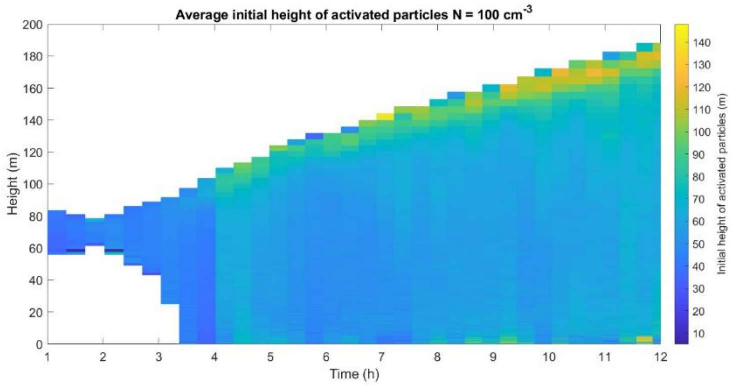

Figure 16b: LES-LCM simulation based on Fatima-GB IOP-5. Contour levels show the average initial height of particles at that current location. The band of yellow at the fog top indicates that newly activated particles were activated at their original altitude, then mixed downwards after becoming droplets.

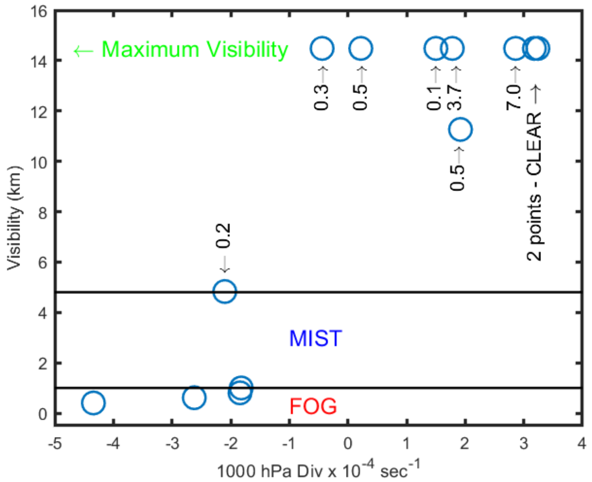

Figure 17a: A plot of visibility versus 1000-hPa divergence (obtained via Global Forecast System GFS) over Sable Island computed for 2-5 July 2022.

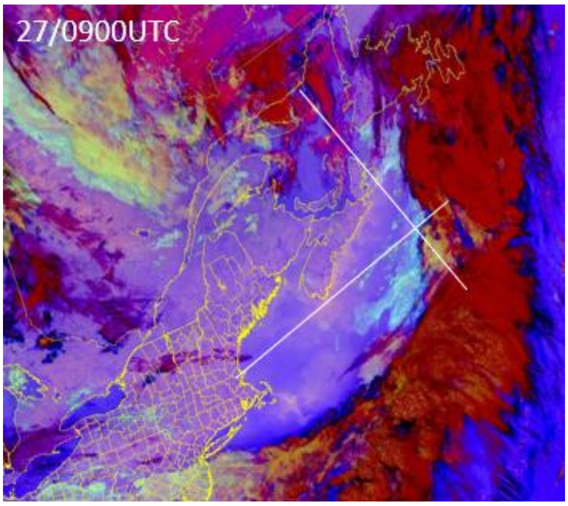

Figure 17b: Night-microphysics image (GOES-R) over Atlantic Canada at 0900 UTC on 27 July 2022. Trailing out of the higher cloud band is a blue surface cloud with a 60 m overcast cloud base and occasional fog. The white lines cross over Sable Island, which had fog at this time.

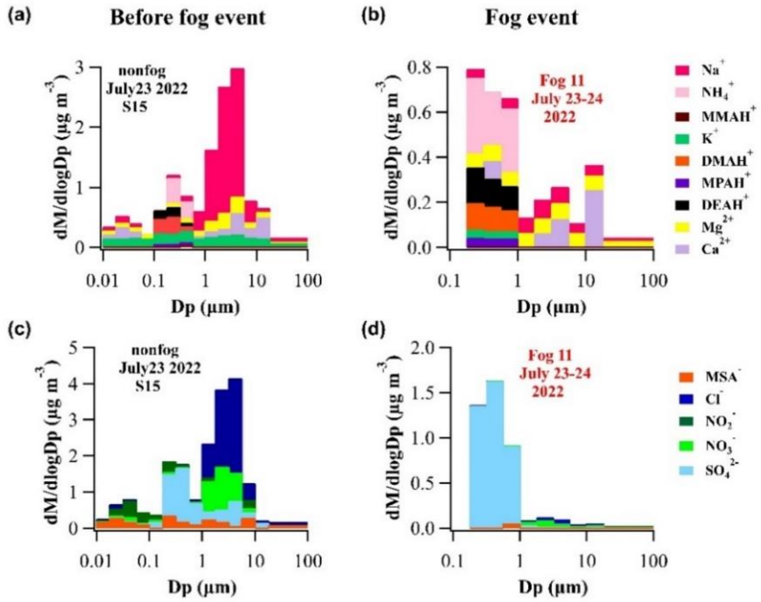

Figure 18a: Ion mass loading (µg m^{-3}) data from nanoMOUDI (non-fog) and MOUDI (fog). Samples were collected prior to (July 23, 2022), during (July 23-24, 2022) near Sable Island. Ion mass loading of major (a) cations and (c) anions during pre-fog events, and (b) cations and (d) anions during the fog formation period. Throughout the fog formation event, coarse-mode sea salt aerosols showed a decrease compared to the pre-fog event, implying the potential role of sea salt aerosols as fog condensation nuclei. Hence, fog typically nucleates on available NaCl particles and grows to sizes above 20 µm.

Note: This study determines the chemical composition of aerosols during fog and non-fog episodes to better understand the association between the chemical composition of aerosol, marine fog, and any processing of other atmospheric species in the presence of fog droplets. In the coarse mode of size-resolved aerosol samples (1–100 µm), sodium and chloride (Na^+ and Cl^-) had the dominant equivalent ionic loading (i.e., moles of species times its charge) in both fog and non-fog periods, with similar contributions as expected for sea salt. In some fog events, the concentration of sea salt ions from the coarse mode decreased compared to pre-fog conditions due to fog scavenging processes. In the fine mode (0.1–1 µm), Na^+ was the dominant cation in non-fog samples; however, ammonium (NH_4^+) was the main cation in the interstitial aerosol during fog events, and non-sea salt sulfate (nss-SO_4^{2-}) at all times. An increase in the sum of total concentration (neq m^{-3}) for: NH_4^+, dimethylamine ($DMAH^+$), diethylamine ($DEAH^+$), methanesulfonic acid (MSA^-), and nss-SO_4^{2-} were observed in fine mode aerosols during fog versus non-fog periods. Within this observation, the average concentration of NH_4^+, $DMAH^+$, $DEAH^+$, MSA^-, and nss-SO_4^{2-} increased during fog events compared to non-fog periods, suggesting that fog droplets can potentially facilitate aerosols and gases to participate in chemical reactions and gas-to-aqueous partitioning. Regardless, these observations show that fog processes may lead to the release of gases or processed aerosol residuals post-fog. In fog water samples, the most prevalent ions were Na^+ and Cl^-, followed by NH_4^+ and SO_4^{2-}, with nss-SO_4^{2-} accounting for 54% of the total SO_4^{2-}. Further analysis is ongoing to elucidate potential interactions between fog water and interstitial fog aerosol composition.

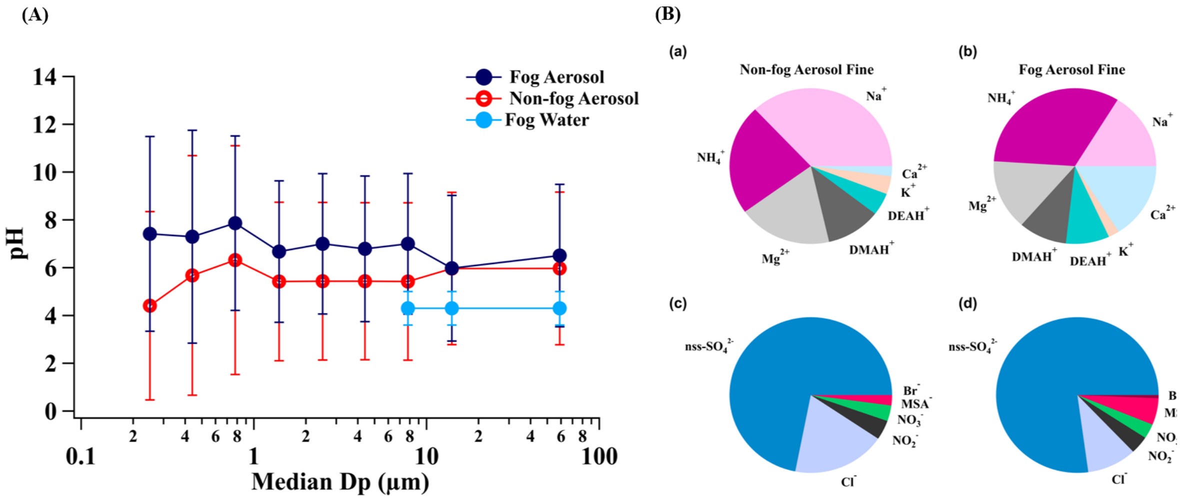

Figure 18b: (A) Comparison of pH values for fog aerosol, non-fog aerosol, and fog water samples (integrated from 20-60 µm) during the entire campaign. (B) The sum of equivalent ionic loadings of fine-mode aerosols: (a) cations in non-fog, (b) cations in fog, (c) anions in non-fog, and (d) anions in fog events. The elevated pH observed in fog aerosol samples in fine mode is consistent with the higher equivalent ionic loading of basic species from fog aerosol samples.

Note: Aerosol pH as a function of size and composition was calculated using the Extended Aerosol Inorganics Model (E-AIM IV) and constrained using the range of observed total reduced N: NHx = ammonia (NH_3) + NH_4^+. Specifically, all ammonium was to be present in the gas phase and allowed free partitioning to establish the subsequent gas-particle equilibrium, eliminating concerns about excess NH_4^+ in the resulting charge balance, although observations found this ion in excess (likely balanced by organic acids that or carbonate ions that were not quantifiable). In parallel, bulk fog water pH was directly measured immediately after collection. During fog events, the interstitial aerosols had average pH values of 6.66 in the coarse mode and 7.52 in the fine mode, which were notably higher than the measured pH of fog water at 4.3, a sharp and unexpected chemical contrast. These results are being subject to further sensitivity tests and quality control to understand their viability and drivers under these unique global conditions. Comparatively, aerosols in non-fog conditions displayed more typical pH values, with the coarse mode at 5.61 and the fine mode at 5.46. These observations suggest that fog events are associated with higher interstitial aerosol pH levels, possibly due to the uptake of basic species facilitated by additional water and/or an abundance of basic gases in the Grand Banks and Sable Island atmospheres.

Appendix 1:

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Fernando, H.J.S., Wang, S., Huang, K., and Creegan, E., Fog-Laden Density Staircases in the Marine Atmospheric Boundary Layer, *Environmental Fluid Mechanics*, 23, 489-510, https://doi.org/10.1007/s10652-023-09914-4

Grachev, A., Fairall, C.W., Blomquist, B.W., Fernando, H.J.S., Leo, L.S., Otárola-Bustos, S.F., Wilczak, J.M., and McCaffrey, K.L., A Hybrid Bulk Algorithm to Predict Turbulent Fluxes over Dry and Wet Bare Soils, *Applied Meteorology Climatol*ogy, 61(4), 393-414. https://doi.org/10.1175/JAMC-D-20-0232.1.

Huang, K.Y., Katul, G.G., Hintz, T.J., Ruiz-Plancarte, J., Wang, Q., and Fernando, H.J.S., Fog Intermittency and Critical Behavior, *Atmosphere*, *14*(5), 875, 2023. https://doi.org/10.3390/atmos14050875.

Kit, E. and Fernando, H.J.S., Small-scale anisotropy in stably stratified turbulence; Inferences based on katabatic flows, **2023**, *14*(6), 918. https://doi.org/10.3390/atmos14060918 7.

Krishnamurthy, R., Fernando, H.J.S., Alappattu, D., Creegan, E., and Wang. Q., Observations and Models of offshore Internal Boundary Layer, *J. Geophys. Res*. (Atmospheres), Geophysical Research: Atmospheres, 128, e2022JD037425. https://doi.org/10.1029/2022JD037425.

Singh, D. K., S.W. Hoch, I. Gultepe, and E.R. Pardyjak, A case study of the life cycle of a stratus-lowering coastal-fog event in Newfoundland, CA, under revision, *Quarterly Journal of the Royal Meteorological Society*, accepted.

Hintz, Thomas J., Kelly Y. Huang, Sebastian W. Hoch, Stef L. Bardoel, Saša Gaberšek, Ismail Gultepe, Jesus Ruiz-Plancarte, Eric R. Pardyjak, Qing Wang, Harindra J. S. Fernando: A Mechanism for Coastal Fog Genesis at Evening Transition, *Quarterly Journal of the Royal Meteorological Society*, under revision.

Barbano, F. and Pardyjak, E.R., Potential-temperature variance budget in a saturated coastal-fog environment, *Quarterly Journal of the Royal Meteorological Society*, Submitted 2023.

Bardoel, S., Hoch, S., Ruiz-Placarte, J., Lenain, L., Gultepe, I., Grachev, A., Gaberšek, S., Wang, Q., Fernando, H.J.S., Study of fog dissipation in an internal boundary layer on Sable Island. *Quarterly Journal of the Royal Meteorological Society*, Submitted.

Gultepe, E., Wang, S., Blomquist, B., Fernando, H.J.S., Kreidl, O.P., Delene D.J., and Gultepe, I. 2023: Machine Learning Analysis and Nowcasting of Marine Fog Visibility Using FATIMA Grand-Banks Campaign Measurements, *Frontiers in Earth Science*, Atmospheric Science Section, Submitted.

Huang, Kelly, Hintz, T., and Kit, E., and Fernando, H.J.S., An Equilibrium Radius of Fog Droplets in Turbulent Environments, *Submitted*

Rodriguez-Geno, C.F., Richter, D.H., 2023: The role of collision and coalescence on the microphysics of marine fog, *Quarterly Journal of the Royal Meteorological Society*, in review.

Rowe K., Ruiz-Plancarte, J., Yamaguchi, R.T., Ortiz-Suslow, D., Pardyjak, E., Fernando, H.J.S., and Wang, Q., 2023: Characteristics of summertime marine fog observed from a small remote island, to be submitted to QJRMS, *Quarterly Journal of the Royal Meteorological Society*, In Preparation.

Yamaguchi, R. T., Kalogiros, J.A., Ortiz-Suslow, D., Ruiz-Plancarte, J., Bloomquist, B., Chang, R., Creegan, E., Fernando, H.J.S., and Wang, Q., 2023: A crane-deployed shipboard measurement suite for turbulence and fog microphysics, *Quarterly Journal of the Royal Meteorological Society*, In Preparation.

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Gultepe, E., Sen Wang, S., Blomquist, B., Fernando, H.J.S., Kreidl, O.P., Delene, D.J., Gultepe, I., 2023: Generative Nowcasting of Marine Fog Visibility in the Grand Banks area and Sable Island in Canada, Workshop on Tackling Climate Change with Machine Learning at NeurIPS.

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Bardoel, S., Dimitrova, R., and Fernando, H.J.S., Internal Boundary Layers and Fog Past Mid-Ocean Islands, 75th Annual Meeting of the Division of Fluid Dynamics (Abstract L33.00008), Indianapolis, Indiana, USA, November 20–22, 2022.

Chang, Rachel, Edward Creegan, Clive Dorman, Sasa Gabersek, Ismail Gultepe, Luc Lenain, Eric Pardyjak, Qing Wang, Harindra J.S. Fernando, Highlights from the Fog and Turbulence in the Marine Atmosphere 2022 field campaign, Fifth bi-annual conference of the Sable Island Charity Friends, Delta Dartmouth on October 20-21, 2023.

Dimitrova, R.N., Fernando, H.J., Silver, Z., and Bardoel, S.L., Aerosol WRF-LES Numerical Simulations of a Mixing Fog Event during C-FOG Campaign, 6B.4, 103rd AMS Annual Meeting, 8 to 12 January, Denver, Colorado, 2023.

Dorman, C. E., Koračin, D.R. and Dimitrova, R., A Fall Fog Bank Along Nova Scotia Generated by Air, Sea, and Land Turbulent Processes. Abstract (A34D-06) presented at 2022 AGU Meeting, 12-16 Dec., 2022

Dorman, C. E., D. Koračin I. Gultepe, An Atlantic Canada July 2022 Advected Cloud and Extended Fog Event during FATIMA. 21st Symposium on the Coastal Environment, 103rd American Meteorological Society Annual Meeting, Denver, 9-13, January 2023 Abstract ID: 412411

Dorman, Clive, Darko Koračin and Ismail Gultepe (2023) Examination of a Fog Event Related to a Large-Scale Cyclone at Sable Island During Fatima Campaign. Submitted to 9th International Conference on Fog, Fog Collection and Dew at 2023 July 23-28, Fort Collins, Colorado State University.

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Fernando, H. J., Creegan, E., Dorman, C., Gabersek, S., Gultepe, I, Lenain, L., Pardyjak, E. and Wang, Q. (2022) The Fog and Turbulence in Marine Atmosphere (Fatima) 2022 Field Campaign. Abstract (A46C-02) presented at AGU Meeting, 12-16 Dec., 2022.

Fernando, H.J.S., Creegan, E., Dorman, C., Gabersek, S., Gultepe, I., Lenain, L., Pardyjak, E., and Wang, Q., Highlight of the 'Fog and Turbulence in the Marine Atmosphere (FATIMA)' 2022 Field Campaign, IFDA 9th International Conference on Fog, Fog Collection, and Dew (FOGDEW 2023). 23-28 July 2023, Fort Collins, Colorado, USA.

Giacosa, G., Robinson, L., Gauvin-Bourdon, P., Salehpoor, L., Crilley, L., VandenBoer, T., Ortiz-Suslow, D.G., Yamaguchi, R., Wang, Q., Creegan, E.D., Fernando, H.J.S., and Chang, R., Aerosols Size and Droplet Distributions during the Fatima Fog Study in the Northwest Atlantic Ocean, 16A.2AEROSOL, 103rd AMS Annual Meeting, 8 to 12 January, Denver, Colorado, 2023.

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Gultepe, I., H.J.S. Fernando, Q. Wang, E. Pardyjak, S. W. Hoch, A. Perelet, R. P. Jesus, S. Wang, J. Komar, E., Villeneuve, and M. Agelin-Chaap: Comparisons of Marine Fog Microphysics during FATIMA: Turbulence Impact on Fog Microphysics. IFDA 9th International Conference on fog, fog collection, and dew. 23-28 July 2023, Fort Collins, Colorado, USA

Gultepe, I., Fernando, J. H., Pardyjak, E., Wang, Q., Hoch, S., Perelet, A., Jesus, R.-P., and Dorman, C., 2023: Profiling of Shallow Marine Fog using a UAV and Remote Sensing Observations over the Sable Island during FATIMA, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-10484, https://doi.org/10.5194/egusphere-egu23-10484.

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Koracin, Darko and Clive Dorman (2023) Effects of Synoptic Forcing on Formation of marine fog at Sable Island, Nova Scotia, 9th International Conference on Fog, Fog Collection and Dew at 2023 July 23-28, Fort Collins, Colorado State University.

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Perelet, A.O., Singh, D.K., Garrett, T., Gultepe, I., Hoch, S.W., and Pardyjak, E.R., Discriminating Between Liquid Water and Ice Crystal Precipitation Using Ground-Based Extinction at Microwave and Infrared Wavelengths, 103rd Annual AMS Meeting, 8-12 January 2023, Denver, CO, Presentation 16A.5.

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