Vertical Air Motion Retrievals From Airborne W-Band Cloud Radar

Haonan Chen, *Senior Member, IEEE*, Christopher W. Fairall, Christopher R. Williams, *Senior Member, IEEE*, and Elizabeth J. Thompson

***Abstract*—In-cloud vertical air motion is a key parameter to describe cloud dynamics and lifecycles. Short-wavelength (Ka- and W-band) radars are often used to observe clouds and extract the vertical air motion from the radar-measured Doppler velocity. However, the vertical air motion retrieval techniques developed using ground-based radar Doppler spectrum may be problematic for airborne cloud radars due to nonideal radar system performance (e.g., receiver saturation) and the Doppler velocity measurement uncertainties caused by aircraft motion, aircraft speed, and the large aircraft motion induced horizontal wind. This article presents a new and simple approach for estimating the in-cloud vertical air motion using airborne W-band radar measurements, which is applicable to cloud measurements without precipitation or with weak precipitation. In particular, a power-law relation between cloud and precipitation particle fall speed and attenuation corrected radar reflectivity is established first. Then, the particle fall speeds estimated from radar reflectivity using the established power-law relation are compared with the radar-measured Doppler velocities to derive the vertical air motions. This technique is demonstrated with W-band airborne radar measurements from the National Oceanic and Atmospheric Administration Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign from January to February 2020, which was designed to investigate atmospheric shallow convection and air-sea interaction in the tropical North Atlantic east of Barbados. The retrieved in-cloud air motion is compared with results reported in the literature for a nearby domain, suggesting that this simple retrieval technique performs reasonably well. Since this approach is applicable for airborne radar measurements with high-frequency noises, it can be used as an effective tool for investigating the mean profile of vertical air motion.**

***Index Terms*—Airborne Doppler radar, air motion retrieval, Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign (ATOMIC), cloud microphysics, W-band.**

Manuscript received 26 August 2023; revised 10 September 2023; accepted 2 October 2023. Date of publication 5 October 2023; date of current version 19 October 2023. The ATOMIC field campaign was supported in part by the National Oceanic and Atmospheric Administration (NOAA) Climate Program Office (CPO) Climate Variability and Predictability Program, in part by the NOAA Unmanned Aircraft Systems Program, and in part by the NOAA Physical Sciences Laboratory. *(Corresponding author: Haonan Chen.)*

Haonan Chen is with the Colorado State University, Fort Collins, CO 80523 USA, and also with the NOAA Physical Sciences Laboratory, Boulder, CO 80305 USA (e-mail: haonan.chen@colostate.edu).

Christopher W. Fairall and Elizabeth J. Thompson are with the NOAA Physical Sciences Laboratory, Boulder, CO 80305 USA (e-mail: chris.fairall@noaa.gov; elizabeth.thompson@noaa.gov).

Christopher R. Williams is with the Ann and H. J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, CO 80303 USA (e-mail: christopher.williams@colorado.edu).

Digital Object Identifier 10.1109/JSTARS.2023.3322346

I. Introduction

Vertical air motion plays a critical role in cloud formation and lifecycle [1]. It is a key parameter used for describing and parameterizing cloud dynamics, thermodynamics, and microphysics [2]. Vertically pointing Doppler radars are efficient tools for investigating vertical air motions in clouds [3], [4], [5]. However, Doppler velocities measured by cloud radars are the combined result of vertical air motions plus the fall speeds of cloud and precipitation particles [6]. In addition, the spectrum of radar Doppler velocity is broadened by turbulence within the radar sampling volume and the finite width of the radar beam [6], [7].

A couple of methods have been developed based on the radar-measured Doppler velocities at each range gate or each range gate's entire Doppler spectra to quantify each of these contributions to Doppler velocity and separate the air motion and particle fall velocity components. For example, Pinsky et al. developed a statistical approach for air motion retrieval using reflectivity and Doppler velocity measurements from an S-band vertically pointing radar (see [8], hereafter referred to as the Pinsky method). The main idea of the Pinsky method was to separate the Doppler velocity into the air velocity and fall velocity of cloud and drizzle drops. In particular, the mean of the measured Doppler velocity was computed as a function of reflectivity. The air motion is estimated as the residual of the observed Doppler velocity times a correlation factor based on the reflectivity dependence of the variance of Doppler velocity [8]. A second method by Shupe et al. assumed that cloud liquid water droplets have negligible fall speed and act as tracers for vertical air motions in vertically pointing Ka-band cloud radar Doppler spectra measurements (see [7], hereafter referred to as the edge method). After correcting for spectrum broadening due to radar beamwidth, turbulence, and wind shear, the air motion velocity is defined as the upward most edge of the spectrum. Zhu et al. [9] improved the edge method by including an additional broadening term that is determined by the signal-to-noise ratio (SNR). These two edge method techniques were demonstrated with ground-based zenith Ka-band radars during two field experiments using observations from the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement facility [7], [9].

Compared to ground-based radar applications, vertical air motion retrieval using airborne cloud radars is rarely done [10], [11]. Therefore, this article presents a new, simple, but effective approach for in-cloud vertical air motion retrievals from downward-pointing airborne W-band cloud radar measurements. The proposed approach is novel since it does not assume zero mean vertical air motion as the Pinsky method did [8], making the proposed technique applicable to broken clouds (i.e., low cloud fraction) where this Pinsky assumption is not valid. In addition, this new approach does not compute the Doppler spectrum broadening factors as required by the edge method. In fact, compared to ground-based zenith radar measurements, airborne nadir radar spectra have larger spectrum widths due to the aircraft's motion and high speed, as well as the induced horizontal wind. These broadening effects are difficult to quantify, posing challenges to practical implementation of the edge method in airborne radar applications.

Nonetheless, it should be noted that extensive comparison between different vertical air motion retrieval methods based on radar measurement from different platforms in different cloud regimes is not the main focus of this study. Rather, this article wants to develop a simple strategy that is effective for airborne radar measurements with high-frequency noise, in support of our investigation of the mean air motion profiles in broken clouds.

The rest of this article is organized as follows. Section II describes the airborne W-band radar data used in this study. Section III details the proposed air motion retrieval strategy and results. A discussion about practical implementation challenges and limitations of the Pinsky, edge, and proposed methods in airborne radar applications is also presented in Section III. Finally, Section IV concludes this article.

II. Airborne W-Band Radar Observations During Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign (ATOMIC)

To demonstrate the vertical air motion retrieval technique, this article uses W-band (94 GHz) pulsed Doppler radar observations collected from the U.S. National Oceanic and Atmospheric Administration's (NOAA) Lockheed WP-3D Orion research aircraft (abbreviated P3 hereafter) during the ATOMIC [12]. This W-band radar system is described in depth by Moran et al. [3]. It has been successfully deployed from a ship looking up and from the P3 aircraft looking down prior to ATOMIC (see [3], [13], [14]). As part of the larger experiment known as Elucidating the Role of Clouds-Circulation Coupling in Climate [15], ATOMIC aircraft operations were held in the western Atlantic during January 17–February 11, 2020 while a slightly longer period of coincident ATOMIC ship-based and autonomous ocean measurements were also taken nearby [16]. The P3 aircraft obtained 95 h of observations over 11 flights; each flight contained a mixture of sampling strategies. The P3 flight plans, sampling strategies, and observations were summarized in [12].

The airborne W-band radar data were postprocessed to correct attenuation of reflectivity profiles, and adjust the Doppler velocity measurements in regard to aircraft motion and its vertical speed during ascents and descents. Here, a brief summary of the postprocessing strategy is provided. The interested readers can find more details about the corrections of attenuation and aircraft motion in Fairall et al. [14]. For correcting the measured Doppler velocity, the pitch and roll components of aircraft motion are considered. In addition, the vertical speed of aircraft is used to adjust the measured vertical Doppler velocity. The attenuation is mainly contributed by atmosphere gaseous attenuation and rain-specific attenuation. Based on the P3 aircraft flight level data, including temperature, pressure, and computed water vapor density at different heights, the atmosphere gaseous attenuation was computed at 94 GHz using the standard approach from the International Telecommunication Union [17] (www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.676-13-202208-I!!PDF-E.pdf). For rain-specific attenuation, the calculated normalized radar cross section (NRCS) from the return of the sea surface is used as a reference since NRCS is fairly well characterized as a function of wind speed and is independent of radar attenuation. When the aircraft height is low, i.e., the W-band radar beam can reach the sea surface, the difference between the measured and calculated NRCS indicates the path integrated attenuation, which can be incorporated in computing the intrinsic (i.e., attenuation corrected) reflectivity [14], [18]. When the aircraft is high, i.e., the W-band radar beam cannot reach the sea surface, a simple relation $A = 0.047Z^{0.94}$ is applied [14], where A is the specific attenuation (in dB) and Z (in $mm^6\ m^{-3}$) is radar measured reflectivity but after correcting the atmosphere gaseous attenuation.

Fig. 1 illustrates an example of the postprocessed radar observations, including attenuation-corrected radar reflectivity, Doppler velocity after aircraft motion correction, and spectrum width, during the whole flight on January 24, 2020. To highlight details of the cloud pattern and gradient revealed by the P3 W-band radar measurements, Fig. 2 shows a zoomed-in version of the data for 1-h period during this flight. This is a typical event during ATOMIC, which consisted of both broken clouds and drizzle particles. Fig. 3(a) shows a 2-D histogram of Doppler velocities versus radar reflectivity during the same flight, along with the means and standard deviations of the Doppler velocities at different reflectivity intensities from −37 to 23 dBZ with 4 dBZ intervals.

Vertical air motion retrieval and analyzes are performed using the postprocessed W-band radar data for each flight during ATOMIC. It should be noted that six of the 11 flights are excluded from this analysis because they did not contain very many cloud and drizzle samples (flights omitted include January 17, 23, and 31; and February 3, 4, and 5). In fact, almost all the observations on January 31 and February 3 were dominated by clear air radar returns. In addition, since the night flights on February 9 and 10 have few, yet similar radar features in terms of radar reflectivity and Doppler velocity distributions, they are combined together in the retrieval analysis to ensure sufficient samples for investigating this combined flight. As a result of this merging and case selection based on adequate sample size, four total flight segments are included herein to demonstrate the air motion retrieval approach and study the mean profiles of in-cloud air motion during ATOMIC, specifically, January 19 and 24, as well as February 9–11. There are 15 060, 19 565, 13 069, and 13 935 vertical profiles that have

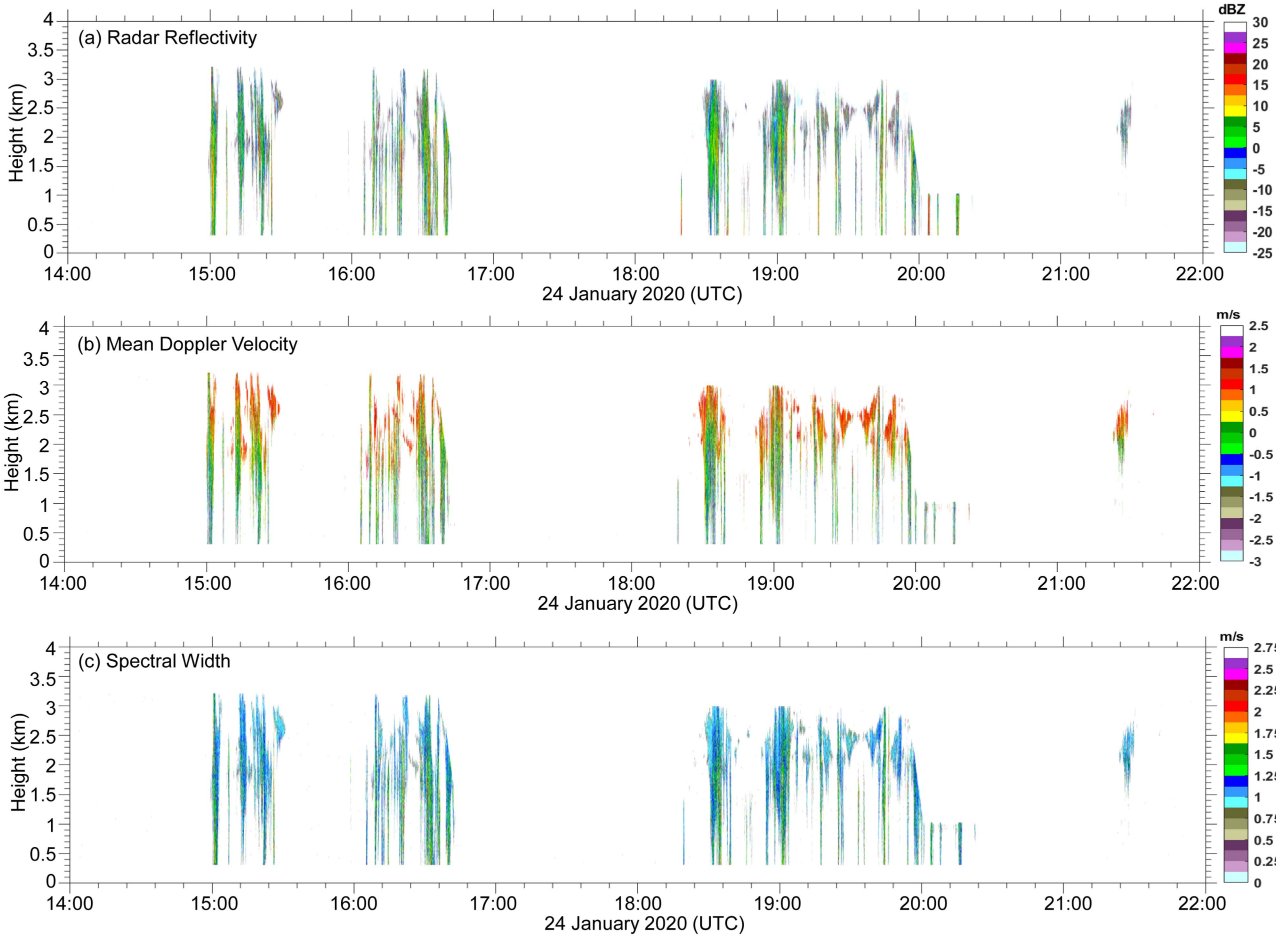


Fig. 1. Observations from the W-band radar aboard the NOAA P3 aircraft during ATOMIC, January 24, 2020. (a) Radar reflectivity after correction for attenuation. (b) Mean Doppler velocity after correction for aircraft motion, with upward motion having positive values. (c) Spectral width.

clouds and/or precipitation echoes during each of the four flight segments, respectively. Since the radar dwell time is 0.5 s, these profiles correspond to 125.5 h, 163.0 h, 108.9 h, and 116.1 h of observations, respectively. The observations and retrieval results for the January 24 flight are extensively used in this article for illustration purposes since other flight segments essentially have similar performance.

III. Methodology, Results, and Discussion

A. In-Cloud Air Motion Retrieval Approach

Air motion retrieval from the radar measurements is achieved through the following three steps.

1) At different heights above sea level, obtain the cloud and drizzle particle fall speeds by subtracting the mean Doppler velocities of low reflectivity clouds from the observed Doppler velocities. An example of low reflectivity clouds is illustrated by the black dashed box in Fig. 3(a), which is near the left end of the Doppler velocity versus reflectivity distribution.

In this study, five height levels are considered based on the cloud height during ATOMIC, namely, 0.5–1.0 km, 1.0–1.5 km, 1.5–2.0 km, 2.0–2.5 km, and 2.5–3.0 km. When we compute the mean Doppler velocities of low reflectivity clouds, range gates with reflectivity between -37 and -33 dBZ are used. If there is no reflectivity samples between -37 and -33 dBZ, the next 4 dBZ interval between -33 and -29 dBZ will be considered, and so on. The fundamental assumption here is that the small cloud droplets have negligible fall speeds with respect to the variations of vertical in-cloud air motions. These small droplets are typically characterized by low reflectivity, < -25 dBZ at W-band. Since low reflectivity echoes with presumably small cloud droplets were commonly observed in the weak shallow convection during ATOMIC, we can easily derive the mean of Doppler velocities of these weak echoes (i.e., populations of small drops).

2) Combine the obtained mean particle fall speeds at all heights with their corresponding reflectivity and establish a power-law relation ($V_{\text{fall}} = aZ_L^b$) between the particle fall speed V_{fall} [ms^{-1}] and radar reflectivity Z_L [mm^6 m^{-3}] through nonlinear least-squares regression.

3) Apply the regression relation derived from step 2) to obtain estimates of the particle fall speed at individual range gates from the time series of radar reflectivity and then estimate vertical air motion at each range gate as the residual between the particle fall speed and the measured Doppler velocity.

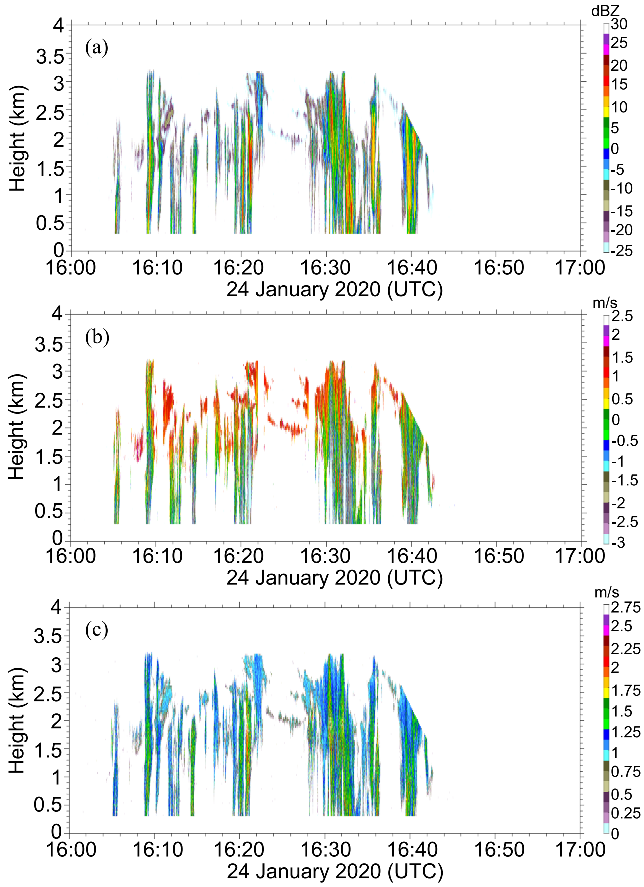


Fig. 2. Same as Fig. 1, but only one hour observations to highlight details of the cloud pattern revealed by the P3 W-band radar measurements.

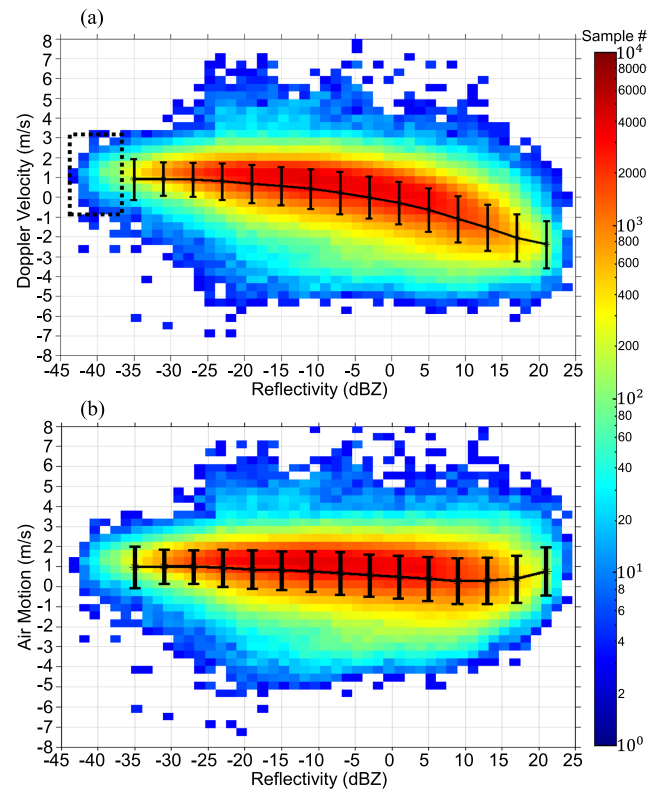


Fig. 3. 2-D histogram of (a) Doppler velocity and (b) derived air motion versus radar reflectivity from the NOAA P3 W-band cloud radar during the flight on January 24, 2020. The black solid lines in (a) and (b) represent mean values for each reflectivity bin (i.e., each 4 dBZ interval from −37 to 23 dBZ), and the black bars indicate corresponding standard deviations. The black dashed box in (a) highlights the low reflectivity clouds near the left end of the distribution (i.e., the first reflectivity bin), which will be investigated in step 1) of the air motion retrieval approach detailed in Section III-A.

The coefficient a and exponent b in the power law relation were derived for each of the four flight segments analyzed here from ATOMIC. In addition, different height levels are considered in step 1) mainly because we are interested in seeing the variation between different heights, and sufficient data samples are available at each height level. We have also tried deriving the power-law relation $V_{\text{fall}} = aZ_L^b$ in step 2) by combining all the data at different heights instead of finding the mean particle fall speeds and corresponding reflectivity at each height level and then taking the mean across five different height levels. The change on a and b is not significant. As such, we highly recommend to use the 3-step procedure for air motion retrievals, with potential adjustment of the height levels in step 1) to guarantee sufficient samples of low reflectivity clouds at each height level.

Compared to the Pinsky method or the edge method, this technique is appealing in airborne radar applications. In fact, neither the Pinsky method nor the edge method was effective for the NOAA W-band data collected during ATOMIC. As mentioned, variations of the mean and standard deviation of the Doppler velocities as a function of reflectivity are key variables used in the Pinsky method (see details in [8]). However, as illustrated in Fig. 3(a), the standard deviation of the Doppler velocity is nearly constant over the observed reflectivity range. The variations of standard deviations during three other flight segments (not shown) were even smaller. This is different from the monodisperse drizzling stratocumulus cloud case presented in [8], likely due to different cloud dynamics and microphysics.

In the edge method, Doppler spectrum broadening due to turbulence, wind shear, and an SNR-based broadening term is estimated and removed from the spectrum's upward edge to obtain the vertical air motion (see details in [7] and [9]). The spectrum broadening due to cross wind within the radar scattering volume was neglected in previous studies, probably because they assumed low horizontal wind speed propagating through the ground-based vertically pointing radar sampling volume. However, this broadening factor should not be ignored for airborne radar applications since the aircraft was flying at high speeds (about 130 m/s during ATOMIC), leading to a high "cross wind" correction. In addition, it is difficult to use airborne radar-measured Doppler velocity to accurately compute the spectrum broadening caused by wind shear since the measured Doppler velocity can have large uncertainties from in flight beam broadening effects, as indicated by the large spread in the Doppler velocity distribution in Fig. 3(a). Thus, the edge method is not suitable for retrieving air motions from an airborne nadir viewing cloud radar with performance characteristics of the NOAA radar system.

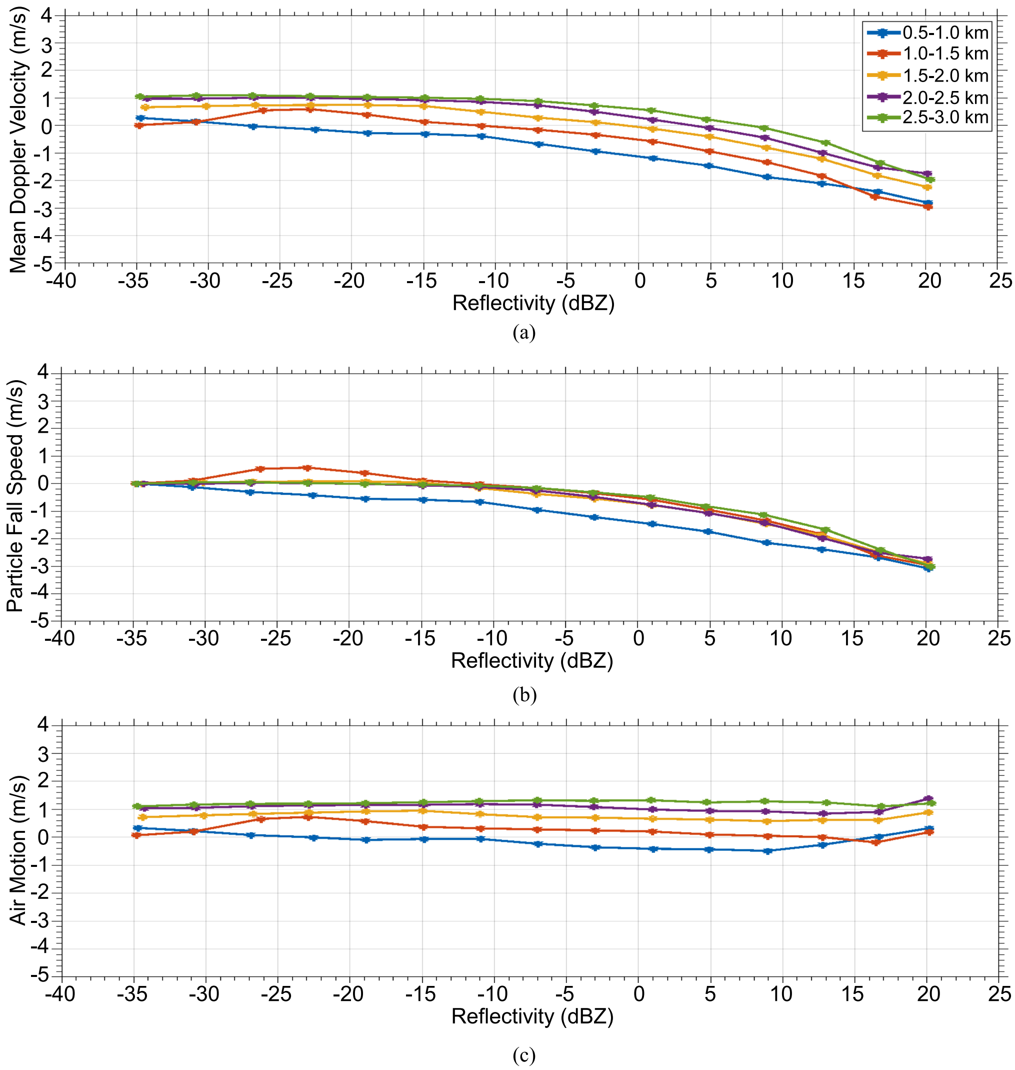


Fig. 4. (a) Mean Doppler velocity, (b) cloud and drizzle particle fall speed, and (c) derived air motion at different reflectivity intensities and different heights above sea level during the NOAA P3 flight on January 24, 2020. Line colors represent observations from above sea level heights shown in (a). Positive velocities represent upward motion.

B. Drop Fall Speed and Air Motion Retrieval Results

For illustration purposes, Fig. 4(a) shows the mean values of postprocessed Doppler velocities at different reflectivity intensities and different heights above sea level during the flight on January 24, 2020. Following the retrieval procedure, Fig. 4(b) shows the particle fall speed obtained from step 1) by subtracting the mean of Doppler velocity measurement for low reflectivity clouds from all other mean Doppler velocities. Then, the mean particle fall speeds as a function of reflectivity averaged across all height levels are calculated, and the results are illustrated by the thin red curve in Fig. 5. Based on these results, a power law relation $V_{\text{fall}}(Z_L) = -0.721 Z_L^{0.316}$ is established for this flight (January 24, 2020, thick red curve in Fig. 5). After applying this relation to the reflectivity measurements to obtain the particle fall speed estimates, the vertical air motions can easily be derived following step 3). For the sake of comparison, Fig. 4(c) shows the means of the retrieved air motions at the same reflectivity intensities for the same height levels as Fig. 4(a) and 4(b).

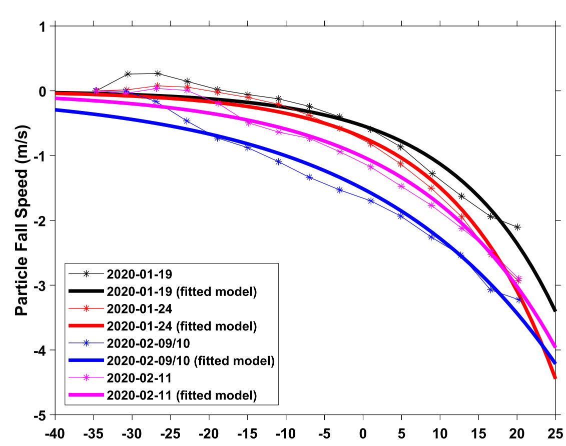
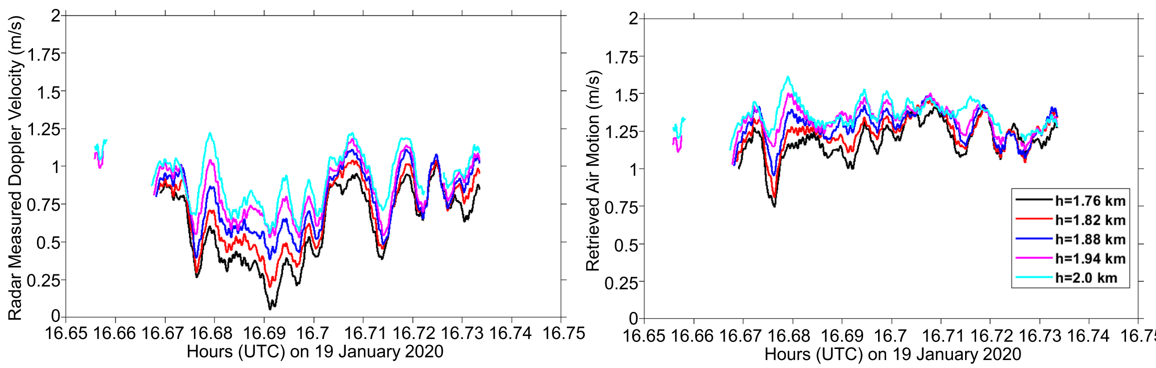


Fig. 5. Cloud and drizzle particle fall speed as a function of radar reflectivity for different NOAA P3 flights during ATOMIC. Negative values indicate that particles are falling downward to the sea surface. Coefficients for the fitted models are summarized in Table I.



(a) (b)

Fig. 6. Sample time series of (a) radar measured Doppler velocity and (b) derived air motion at different heights near 2 km during the NOAA P3 flight on January 19, 2020. For each line in (a) or (b), the averages of radar measured Doppler velocity or the derived air motion across two adjacent range gates are used. The height in the legend indicates the center of the two adjacent gates. Upward motions have positive values.

TABLE I
RELATIONSHIP BETWEEN DROP FALL SPEED V_{FALL} AND RADAR REFLECTIVITY Z, FOR EACH P3 FLIGHT DURING ATOMIC

P3 flight date	V_{fall} (m s^{-1}) — Z_L (mm^{6}m^{-3}) Relation
January 19, 2020	$V_{\text{fall}}\,(Z_L) = -0.54 Z_L^{0.32}$
January 24, 2020	$V_{\text{fall}}\,(Z_L) = -0.721 Z_L^{0.316}$
February 9 and 10, 2020	$V_{\text{fall}}\,(Z_L) = -1.513 Z_L^{0.178}$
February 11, 2020	$V_{\text{fall}}\,(Z_L) = -1.019 Z_L^{0.236}$

These relations are also illustrated by the fitted models in Fig. 5.

The power laws between particle fall speed and radar reflectivity for the four flight segments analyzed in this study are shown in Fig. 5 and listed in Table I. Each flight-specific power law was used to derive air motions for each flight. Note that the significance of the variations in the a and b parameters between flights is not known.

To further highlight the contribution of vertical air motion to the radar-measured Doppler velocities and illustrate the application to cloud microphysical investigations, Fig. 3(a) and (b) can be compared or considered together. It can be seen that in the cloud regions (reflectivity < -20 dBZ) the Doppler velocity is mainly contributed by the air motion, but the cloud and drizzle particles understandably contribute more Doppler velocity at higher reflectivity regions, especially when the reflectivity > 10 dBZ, i.e., when light rain was observed by the W-band radar.

Fig. 6 shows sample time series of the W-band radar-measured Doppler velocity (a) and the retrieved air motion (b) at different heights near the middle level of a shallow cloud during the January 19, 2020 flight. This example shows vertical motions that are quite similar and coherent or correlated as a function of height over the 0.25 km intervals plotted, which were collected over a total horizontal scale of about 25 km with roughly eight individual cloud elements sampled. Fig. 6(b) shows that the air motion varied by about 0.25 ms^{-1} across these 1.76–2.0 km height levels, while the mean updraft from these levels was 1.2 ms^{-1}.

C. Discussion

Without in situ measurements of vertical air motion during ATOMIC, it is challenging to quantitatively evaluate the accuracy of this retrieval method. Previous studies on air motion retrievals and cloud microphysics using similar airborne W-band radar are rare, making it difficult for cross comparison. In addition, observations from other stratocumulus clouds are not straightforwardly applicable because their vertical motions and precipitation characteristics vary substantially from stable to unstable conditions and whether the (in)stability in either case is strong or weak.

Nevertheless, the proposed air motion retrieval technique is still appealing because none of the previous retrieval approaches, such as the Pinsky and edge methods would work for airborne radar measurements due to the limitations mentioned previously. The P3 W-band radar measurements during ATOMIC is more complicated because of the radar system performance and high-frequency noise involved in the measurements. Since the ultimate goal of this study is to investigate the mean profile of air motion during ATOMIC, i.e., high-frequency noise is less an issue for this objective, the proposed approach can serve as an effective tool to learn the trend and fluctuation of vertical air motion. To evaluate the results, such as the particle fall speed and radar reflectivity relations derived from the P3 W-band radar measurements with large spread (e.g., Fig. 3), we have simulated radar measurements for a versatile setting of cloud droplet distribution parameters (not shown in this article) to quantify the potential uncertainty of the derived power laws. We have also qualitatively compared the retrieved air motions and their variations at different heights in the context of related previous studies (i.e., [7], [19], [20]). Although the radar frequency, system settings, and synoptic environments are different during ATOMIC from these prior studies and our simulations, it is found that the power-law relations and the retrieved air motion intensity roughly agree with the values reported in those related studies (i.e., the same order of magnitude), which is encouraging.

We also note that although this simple retrieval technique is easy to implement, extra attention should be paid when the radar observations are dominated by precipitating as opposed to nonprecipitating clouds across multiple height levels. In the case of strong or extensive precipitation across time or each vertical height level, there may not be enough cloud samples devoid of precipitation to quantify the statistical spectrum of fall velocities from small cloud droplets, which is required in this retrieval method. In fact, for this reason, the retrieval process may fail if only heavy rain echoes are observed.

Because high-frequency (Ka- or W-band) cloud radars are typically deployed to measure nonprecipitating to weakly-precipitating clouds (< 10 mm hr^{-1}), rather than precipitation mapping over all magnitudes of rain rate, it should be normal to obtain enough samples of non or weakly-precipitating clouds when these Ka- or W-band radars are operating for their designed purpose. Therefore, this retrieval technique should be suitable for cloud radar applications in most weakly- to non-precipitating scenarios. Within those bounds, this technique can also be extended to ground- and ship-based radar observations. Since it was developed with airborne measurements in mind, this method will be useful for ground- and ship-based settings when the uncertainty in the vertical velocity measurements is large for whatever reason.

IV. Summary

In-cloud vertical air motion is an important parameter for investigating and parameterizing cloud dynamics, thermodynamics, and microphysics. Short-wavelength radars are typically used to infer cloud properties, such as particle size distributions and vertical air motions. However, previous air motion retrieval techniques were mainly developed using ground radar observations and limited cloud situations, such as precipitating cases. Compared to ground radar measurements, airborne radar vertical velocity measurements involve large uncertainties due to aircraft motion, aircraft speed, and the large aircraft motion induced horizontal wind. This article proposed a 3-step approach for estimating the in-cloud vertical air motion applicable in broken clouds where zero-mean vertical air motion is not ensured. This approach was demonstrated using the airborne W-band radar measurements during ATOMIC 2020 in the Atlantic trade wind region composed of weak shallow convection. The promising performance suggests that this retrieval technique can be used as an effective tool for investigating the mean profile of vertical air motion. This simple retrieval technique is effective in clouds with and without liquid drizzle particles so long as the sampling volume is not dominated solely by precipitation. In addition, the method is presumably applicable to other cloud types observed in other locations as long as small cloud droplets are present. However, collocated in situ or Doppler LiDAR measurements of vertical air motion are needed to further evaluate the retrieval performance quantitatively, although the results in this article are consistent with relatable literature results and methods.

Acknowledgment

The authors would like to thank Dr. Allen White at the NOAA Physical Sciences Laboratory and the anonymous reviewers for providing careful reviews and comments that improved this article. The W-band radar data used in this article are available from the NOAA National Centers for Environmental Information at https://doi.org/10.25921/n1hc-dc30.

References

[1] R. J. Hogan, P. R. Field, A. J. Illingworth, R. J. Cotton, and T. W. Choularton, "Properties of embedded convection in warm-frontal mixed-phase cloud from aircraft and polarimetric radar," *Quart. J. Roy. Meteorological Soc.*, vol. 128, no. 580, pp. 451–476, 2002.

[2] A. Protat and C. R. Williams, "The accuracy of radar estimates of ice terminal fall speed from vertically pointing Doppler radar measurements," *J. Appl. Meteorol. Climatol.*, vol. 50, no. 10, pp. 2120–2138, 2011.

[3] K. Moran et al., "A motion-stabilized W-band radar for shipboard observations of marine boundary-layer cloud," *Bound.-Layer Meteor.*, vol. 143, pp. 3–24, 2012.

[4] L. Tian, G. M. Heymsfield, L. Li, and R.C. Srivastava, "Properties of light stratiform rain derived from 10- and 94-GHz airborne Doppler radars measurements," *J. Geophysical Res.: Atmospheres*, vol. 112, no. D11211, 2007, doi: 10.1029/2006JD008144.

[5] C. R. Williams, R. M. Beauchamp, and V. Chandrasekar, "Vertical air motions and raindrop size distributions estimated using mean Doppler velocity difference from 3- and 35-GHz vertically pointing radars," *IEEE Trans. Geosci. Remote Sens.*, vol. 54, no. 10, pp. 6048–6060, Oct. 2016.

[6] R. J. Doviak and D. S. Zrnić, *Doppler Radar and Weather Observations*. Mineola, NY, USA: Dover, 2006.

[7] M. D. Shupe, P. Kollias, M. Poellot, and E. Eloranta, "On deriving vertical air motions from cloud radar Doppler spectra," *J. Atmospheric Ocean. Technol.*, vol. 25, no. 4, pp. 547–557, 2008.

[8] M. Pinsky, O. Krasnov, H. W. J. Russchenberg, and A. Khain, "Investigation of the turbulent structure of a cloud-capped mixed layer using Doppler radar," *J. Appl. Meteorol. Climatol.*, vol. 49, no. 6, pp. 1170–1190, 2010.

[9] Z. Zhu, P. Kollias, F. Yang, and E. Luke, "On the estimation of in-cloud vertical air motion using radar Doppler spectra," *Geophysical Res. Lett.*, vol. 48, no. 1, 2021, Art. no. e2020GL090682.

[10] Y. Wang and B. Geerts, "Composite vertical structure of vertical velocity in nonprecipitating cumulus clouds," *Monthly Weather Rev.*, vol. 141, no. 5, pp. 1673–1692, 2013.

[11] M. C. Schwartz et al., "Merged cloud and precipitation dataset from the HIAPER GV for the cloud system evolution in the trades (CSET) campaign," *J. Atmospheric Ocean. Technol.*, vol. 36, no. 6, pp. 921–940, 2019.

[12] R. Pincus et al., "Observations from the NOAA P-3 aircraft during ATOMIC," *Earth Syst. Sci. Data*, vol. 13, no. 7, pp. 3281–3296, 2021.

[13] C. W. Fairall, S. Pezoa, K. Moran, and D. Wolfe, "An observation of sea-spray microphysics by airborne Doppler radar," *Geophys. Res. Lett.*, vol. 41, pp. 3658–3665, 2014.

[14] C. W. Fairall, S. Y. Matrosov, C. R. Williams, and E. J. Walsh, "Estimation of rain rate from airborne Doppler W-band radar in CalWater-2," *J. Atmospheric Ocean. Technol.*, vol. 35, no. 3, pp. 593–608, 2018.

[15] B. Stevens et al., "EUREC^{4}A," *Earth Syst. Sci. Data*, vol. 13, no. 8, pp. 4067–4119, 2021.

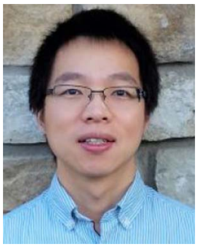
[16] P. K. Quinn et al., "Measurements from the RV Ronald H. Brown and related platforms as part of the atlantic tradewind ocean-atmosphere mesoscale interaction campaign (atomic)," *Earth System Sci. Data*, vol. 13, no. 4, pp. 1759–1790, 2021.

[17] *Attenuation by Atmospheric Gases and Related Effects*, Recommendation ITU-R P.676–13, 2022.

[18] L. Li, G. M. Heymsfield, L. Tian, and P. E. Racette, "Measurements of ocean surface backscattering using an airborne 94-Ghz cloud radar-implication for calibration of airborne and spaceborne W-band radars," *J. Atmospheric Ocean. Technol.*, vol. 22, no. 7, pp. 1033–1045, 2005.

[19] B. W. Orr and R. A. Kropfli, "A method for estimating particle fall velocities from vertically pointing Doppler radar," *J. Atmospheric Ocean. Technol.*, vol. 16, no. 1, pp. 29–37, 1999.

[20] K. Lamer, P. Kollias, and L. Nuijens, "Observations of the variability of shallow trade wind cumulus cloudiness and mass flux," *J. Geophys. Res.: Atmospheres*, vol. 120, no. 12, pp. 6161–6178, 2015.



Haonan Chen (Senior Member, IEEE) received the Ph.D. degree in electrical engineering from Colorado State University (CSU), Fort Collins, CO, USA, in 2017.

He has been an Assistant Professor with the Department of Electrical and Computer Engineering, CSU, since 2020. He is also an Affiliate Faculty with the Data Science Research Institute (DSRI), CSU. Before joining the CSU faculty, he worked with the Cooperative Institute for Research in the Atmosphere (CIRA) and the National Oceanic and Atmospheric Administration (NOAA) Physical Sciences Laboratory, Boulder, CO, USA, from 2012 to 2020, first as a Research Student, then a National Research Council Research Associate and a Radar, Satellite, and Precipitation Research Scientist. His research interests span a broad range of remote sensing and multidisciplinary data science, including radar and satellite remote sensing of natural disasters, polarimetric radar systems and networking, clouds and precipitation observations and processes, Big Data analytics, and deep learning. He is the author/coauthor of more than 80 peer-reviewed journal articles in these areas.

Dr. Chen was a recipient of the National Science Foundation (NSF) Faculty Early Career Development Program (CAREER) Award, Ralph E. Powe Junior Faculty Enhancement Award, IEEE Geoscience and Remote Sensing Society (GRSS) Early Career Award, American Meteorological Society (AMS) Editor's Award, and CIRA Research and Service Initiative Award. He is currently an Associate Editor for the *Journal of Atmospheric and Oceanic Technology*, *URSI Radio Science Bulletin*, and IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATION AND REMOTE SENSING.

Christopher R. Williams (Senior Member, IEEE) received the B.S. degree from California Polytechnic State University, San Luis Obispo, CA, USA, in 1985, the M.S. degree from Purdue University, West Lafayette, IN, USA, in 1986, and the Ph.D. degree from the University of Colorado, Boulder, CO, USA, in 1994, all in electrical engineering.

He has been a Research Professor with Ann and H. J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder since 2018. He was with the Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, and the National Oceanic and Atmospheric Administration (NOAA) Oceanic and Atmospheric Research (OAR) laboratories during 1994–2017 through the NOAA Aeronomy Laboratory (1994–2005) and the NOAA Earth System Research Laboratory (2005 to 2017). His research interests have spanned the full research spectrum from designing, developing, and deploying remote sensing hardware to analyzing ground- and satellite-based radar observations to improve global rainfall estimates and understand precipitation processes.

Dr. Williams has been a recipient of several team and individual achievement awards, including the American Meteorological Society Editor's Award from the Journal of Atmospheric and Oceanic Technology in 2014 and the NASA Goddard Space Flight Center Robert H. Goddard Team Award for the category of Exceptional Achievement in Science in 2015.

Christopher W. Fairall received the Ph.D. degree in physics from Michigan State University, East Lansing, MI, USA, in 1970.

He is currently a Physicist with the NOAA's Physical Sciences Laboratory, Boulder, CO, USA. He works in unraveling the mysteries of how the ocean and atmosphere battle as part of the Earth's climate system from El Nino to hurricanes. He has spent decades developing and deploying air-sea interaction observing systems for NOAA ships and aircraft and has participated in nearly 70 research field programs and cruises from the Tropics to the Arctic icecap. His work is devoted to making direct measurements for verifying and improving the representation of air-sea interaction processes in weather/climate models. These measurements include such things as surface evaporation, absorption of heat, generation of waves, and uptake of carbon dioxide. He is the author/coauthor of more than 220 refereed publications in more than 40 different journals. He has led in the development of technologies for the direct measurement of air-sea fluxes, which has produced breakthroughs in, for example, the direct observations of air-sea exchange of carbon dioxide. Other contributions include development of the NOAA COARE community air-sea flux parameterization, major advances in the remote sensing of marine cloud microphysics, improved observations of the net radiative flux over the ocean, and flux parameterizations for hurricane models.

Dr. Fairall was the Chair of the World Climate Research Program Working Group on Surface Fluxes, a member of the Surface Heat Budget of the Artic Ocean Science Steering Committee and the Atmospheric Radiation Measurement (ARM) Science Team Executive Committee, and Chair of the ARM Tropical Western Pacific Science Advisory Committee. He is a Fellow of the American Meteorological Society (AMS), American Geophysical Union (AGU), and University of Colorado Cooperative Institute for Research in Environmental Sciences. He was a recipient of the AMS Sverdrup Gold Medal and NOAA Administrator's Award.

Elizabeth J. Thompson received the B.S. degree in meteorology from Valparaiso University, Valparaiso, IN, USA, in 2010 and the M.S. and Ph.D. degrees in atmospheric science from Colorado State University, Fort Collins, CO, USA, in 2012 and 2016, respectively.

She is currently a Research Meteorologist studying physical processes in the atmosphere, upper ocean, and the air-sea interface. She collects and analyzes measurements of the ocean, air-sea fluxes, and atmosphere to understand the coevolution of atmospheric and oceanic boundary layers. This has included research on precipitation microphysics, and how rain, wind, and sunlight control upper ocean stability. She is now assessing how such ocean variability relate to the growth or inhibition of clouds and precipitation. Her research uses dual- and single-polarization radars, satellites, disdrometers, as well as ocean and air-sea flux instrumentation deployed on ships and autonomous platforms. She has developed algorithms for predicting near-surface ocean stability, estimating precipitation rate from radar, and classifying precipitation type in clouds with radar. Her research activities contribute to greater fundamental understanding of how the ocean and atmosphere interact via processes, such as turbulence, cloud microphysics, precipitation extremes, the global water cycle, atmospheric thermodynamics, ocean stratification, and meteorological phenomena on synoptic- and meso-scales. Her research products support the improvement and evaluation of environmental prediction models, diagnostic nowcasting tools, and operational datasets used to monitor the ocean and atmosphere.