

Evidence for a Nimbostratus Uncinus in a Convectively Generated Mixed-Phase Stratiform Cloud Shield

JEROME M. SCHMIDT

Marine Meteorology Division, Naval Research Laboratory, Monterey, California

PIOTR J. FLATAU

Scripps Institution of Oceanography, University of California, San Diego, San Diego, California

PAUL R. HARASTI

Marine Meteorology Division, Naval Research Laboratory, Monterey, California

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ABSTRACT

The structure of a melting layer associated with a mesoconvective system is examined using a combination of in situ aircraft measurements and a unique Doppler radar operated by the U.S. Navy that has a range resolution as fine as 0.5 m. Interest in this case was motivated by ground-based all-sky camera images that captured the transient development of midlevel billow cloud structures within a precipitating trailing stratiform cloud shield associated with a passing deep convective system. A sequence of high-fidelity time–height radar measurements taken of this storm system reveal that the movement of the billow cloud structure over the radar site corresponded with abrupt transitions in the observed low-level precipitation structure. Of particular note is an observed transition from stratiform to more periodic and vertically slanted rain shaft structures that both radar and aircraft measurements indicate have the same temporal periodicity determined to arise visually between successive billow cloud bands. Doppler, balloon, and aircraft measurements reveal these transient bands are associated with a shallow circulation field that resides just above the melting level in a layer of moist neutral stability and strong negative vertical wind shear. The nature of these circulations and their impact on the evolving precipitation field are described in the context of known nimbostratus cloud types.

1. Introduction

One of the more clearly recognizable meteorologically based radar signals is that of the radar reflectivity bright band that forms within mixed-phased stratiform cloud systems near the melting level. After one of the initial studies of the phenomenon by [Ryde \(1946\)](#), research has focused on the radar attributes, microphysical processes, and environmental factors governing the structure of this particular feature ([Atlas 1954](#); [Austin and Bemis 1950](#); [Battan 1973](#); [Fabry and Zawadzki 1995](#);

[Grim et al. 2009](#); [Heymsfield et al. 2015](#); [Klaassen 1988](#); [Knight 1979](#); [Matsuo and Sasyo 1981](#); [Mitra et al. 1990](#); [Ohtake 1969](#); [Stewart 1984](#); [Wexler et al. 1956](#); [Yokoyama and Tanaka 1984](#); [Dutton 2002](#), 274–276). While there is considerable variability from case to case, these studies indicate that, to first order, the formation of the bright band can be attributed to changes in the ice–liquid dielectric values and particle terminal velocities as ice crystals transition to liquid drops across the melting layer.

The importance of the aggregation process on the radar structure near the bright band has been noted in several studies ([Heymsfield et al. 2015](#); [Houze and Medina 2005](#); [Stewart 1984](#); [Willis and Heymsfield 1989](#)). The initial onset in the aggregation is noted to occur approximately 1–2 km above the bright band when temperatures first begin to exceed approximately -6°C . The aggregation rates accelerate below this level

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Corresponding author: Jerome M. Schmidt, jerome.schmidt@nrlmry.navy.mil

as the initial aggregates grow in size and the crystal collection efficiencies further increase in the warmer air below. As shown by [Stewart \(1984\)](#), this leads to an elevated ice crystal concentration maximum near the level of the initial onset of the aggregation process, a steady decrease in the ice concentration and growth in the maximum ice particle size below, and a corresponding change in the slope of the layer-mean radar reflectivity profile in the intervening layers above the bright band. The ice particle sizes are noted to reach their maximum dimension within the bright band at temperatures near 1° – 2°C before further melting leads the supporting crystalline structure to collapse and the subsequent formation of smaller liquid drops ([Klaassen 1988](#); [Knight 1979](#)). The overall depth within which this transformation occurs may be upward of several hundred meters and is further altered by specific microphysical or environmental factors governing depositional growth, sublimation, accretion, collision–coalescence, shedding, secondary ice particle multiplication, particle breakup, type, shape, size, ice water content, lapse rate, and relative humidity features ([Atlas et al. 1953](#); [Fabry and Zawadzki 1995](#); [Grim et al. 2009](#); [Heymsfield et al. 2015](#); [Klaassen 1988](#); [Knight 1979](#); [Matsuo and Sasyo 1981](#); [Mitra et al. 1990](#); [Ohtake 1969](#); [Stewart 1984](#); [Wexler et al. 1956](#); [Willis and Heymsfield 1989](#); [Yokoyama and Tanaka 1984](#)). As discussed by [Hallett and Mossop \(1974\)](#), secondary ice particle production is most prevalent when the ambient temperatures reside between -3° and -8°C and when larger cloud drops coexist with a large number of smaller (diameter $D > 24\text{ }\mu\text{m}$) cloud droplets. For typical stratiform cases such as those examined here, this favored zone would likely lie 0.5–1.3 km above the melting level provided the local dynamics are such as to create water-saturated conditions that support droplet formation and growth.

Given the number of factors involved, it is understandable that considerable differences exist in the observed brightband structure ([Fabry and Zawadzki 1995](#)). Temporal variability in the overall brightband structure has also been noted to arise within a given system as well ([Biggerstaff and Houze 1991](#); [Fabry and Zawadzki 1995](#); [Houze and Medina 2005](#); [Yuter and Houze 2003](#)). Fluctuations within stratiform rainfall occurring over a time span of just a few minutes have been tied to the passage of transient features referred to as rain shafts, fall streaks, or trails ([Fabry and Zawadzki 1995](#); [Houze and Medina 2005](#); [Jameson and Kostinski 2000](#); [Kostinski and Jameson 1997](#); [List et al. 1988](#); [Yuter and Houze 2003](#)). Radar imagery of these transient features are often most pronounced below the melting layer but have been noted to extend above the bright band or even to cloud top in some circumstances ([Fabry](#)

and [Zawadzki 1995](#); [Houze and Medina 2005](#); [Martner et al. 2008](#); [Yuter and Houze 2003](#)).

In a study of the bright band conducted over relatively flat terrain, [Fabry and Zawadzki \(1995\)](#) noted that pockets of increased reflectivity just above the bright band were associated with the rain shafts below. They suggested their presence could be attributed to the impact of accretional processes on wet graupel growth in updrafts formed near the melting layer. Similar reasoning was invoked by [Houze and Medina \(2005\)](#) to explain the observed enhancement of precipitation on the windward slopes of significant orography. Their study revealed a series of small-scale (1–3-km length scale) turbulent eddies extending 1–2 km above the melting layer with Doppler radar–derived velocity perturbations of up to 6 m s^{-1} (their Fig. 12). They attributed these circulations to perturbations forced by stably stratified flow over the underlying irregular mountainous terrain and/or vertical wind shear–induced instabilities resulting from low values of the moist Richardson number [given by $N_m^2 (dU/dz)^{-2}$, where N_m^2 is the squared moist Brunt–Väisälä frequency as defined by [Durrán and Klemp \(1982a\)](#) and U is the horizontal wind speed]. They suggested that these eddies could possibly enhance the production of larger precipitating particles through turbulence-induced increases in the aggregation process above the melting layer. Similar perturbations were evident in the orographically induced stratiform systems examined by [Yuter and Houze \(2003\)](#). They concluded that a clear linkage can develop at times between the precipitation and velocity signatures of the rain shaft below the bright band and the fall streaks of snow located farther aloft. Turbulent mixing near the melting level is also thought to produce favorable conditions for the onset of nimbostratus fractocumulus clouds ([Findeisen 1940](#); [Knight et al. 2004](#)). These cloud systems can alter the structure of the overlying nimbostratus layer aloft because of their vigorous upward growth. These results represent an interesting contrast to other case studies that have shown that the layers above and below the bright band can be dynamically decoupled from one another because of the intervening changes in the static stability ([Willis and Heymsfield 1989](#)).

In this paper, we examine radar signatures similar to those obtained by [Yuter and Houze \(2003\)](#) and [Houze and Medina \(2005\)](#) except that the measurements were obtained near the melting layer associated with a stratiform region of a mesoconvective storm system that formed over relatively flat terrain. In [section 2](#), we describe the instrumentation and data processing methodologies employed in the study. [Section 3](#) describes the observed characteristics of the melting-layer circulation

as revealed by the all-sky camera, the deployed surface data network, and direct in situ measurements of this feature made by the instrumented aircraft. The primary results of the study and a schematic model of the event are presented and discussed in [section 4](#). A summary of the study can be found in [section 5](#).

2. Instrumentation and methodology

The observations used in this study were obtained during a multiagency field experiment held near Cape Canaveral, Florida ([Schmidt et al. 2014, 2012](#)). The U.S. Navy's Midcourse Radar (MCR) served as the centerpiece of the surface-based experimental array. The MCR is a 3-MW peak power, C-band, dual-polarization radar that alternatively transmits two linear frequency-modulated waveforms that provide a choice in the 6-dB range resolution R_6 of either 37 or 0.546 m (henceforth referred to as the narrowband and wideband waveforms, respectively). Both waveforms are composed of a narrow 0.22° beamwidth that can be transmitted at a pulse repetition frequency (PRF) of either 160 or 320 Hz. The data were recorded at an oversampled range-gate spacing of 11.25 and 0.1464 m, respectively, within two independent range windows either 15 km (narrow band) or 120 m (wide band) in length. The two wideband windows were positioned to slightly overlap each other in range to produce a combined high-resolution analysis domain depth of approximately 220 m. For the results presented here, the MCR was held in a fixed vertical orientation and thus set to transmit and receive at the zenith angle exclusively. This scanning strategy captures the time–height structure of the reflectivity and total vertical velocity field ($W_T = w_p + V_T$) that consists of velocity contributions resulting from both the air parcel motion w_p and the particle sedimentation V_T .

The radar was carefully calibrated each day using the orbiting calibration sphere 5398 and the data subjectively edited to remove radar artifacts. The methodology of [Doviak and Zrnić \[2014; their Eq. \(6.24\)\]](#) was used to construct power spectra formed from the FFT of the in-phase I and quadrature Q complex voltage components taken from 128 consecutive raw radar pulses at a fixed range. Because of MCR's small Nyquist interval ($\lambda\text{PRF}/4 = \pm 2.14 \text{ m s}^{-1}$), there was significant aliasing of both the individual spectra velocities and the mean Doppler velocity as slower-falling ice crystals began to melt and accelerate below the melting level. The spectral balancing technique of [Keeler and Passarelli \[1990; their Eq. \(3.12\)\]](#) was used to estimate the mean Doppler velocity corrected for the bias errors due to both white noise and aliased individual spectra velocities. Finally, the resulting mean Doppler velocity

estimates were dealiased using the [Bargen and Brown \(1980\)](#) method, algorithm B, working along segments from the top of the pristine ice cloud region, where mean Doppler velocity estimates were not aliased, downward through to the bottom of the observed rain region.

Ice water content above the melting layer was calculated from the MCR reflectivity factor using the “composite A” relationship shown by [Heymsfield and Palmer \(1986; their Table 2\)](#). Liquid water content (LWC) below the melting layer was calculated from the MCR reflectivity factor using the Marshall and Palmer relationship deduced from [Gunn and Marshall \(1958\)](#). The melting layer is centered at the freezing level with a thickness related to [Boudevillain and Andrieu \[2003; their Eq. \(20\)\]](#). The liquid water content within the melting layer is estimated from a linearly weighted average of the two abovementioned ice and liquid water content relations across the melting-layer depth. The final velocity and derived ice–liquid water content estimates were compared against those derived independently from the Metek K-band Micro Rain Radar (MRR) as a consistency check. Finally, a simple 1–2–1 filter was applied to the reflectivity factor z and various other applied fields in an effort to reduce any residual noise.

Additional surface instrumentation used in this experiment included the Sigma Space Micro Pulse lidar, the Metek Micro Rain Radar ([Löffler-Mang et al. 1999](#)), an all-sky camera that recorded the sky conditions at 1-min intervals, and the Meteorolabor Snow White rainsonde ([Verver et al. 2006](#)). The balloons were typically launched twice a day from the Kennedy Space Center weather station, which is located approximately 15 km to the southeast of the MCR. The K-band Doppler radar (Micro Rain Radar from Metek) was deployed to measure lower-tropospheric vertical profiles of rain rate, liquid water content, and drop size distribution.

Weather Modification, Inc., provided a twin-engine Piper Cheyenne II aircraft that operated within ~ 10 km of the radar at all times. This aircraft is capable of climbing at 2710 ft min^{-1} ($\sim 13.8 \text{ m s}^{-1}$) to a ceiling of 31 600 ft (~ 9.6 km) while maintaining an airspeed of 269 kt (138 m s^{-1}). The aircraft was equipped with sensors for measuring GPS location and altitude, pressure, temperature, dewpoint temperature, and vertical velocity. An onboard video camera was also used to document the ambient sky conditions during each aircraft mission. The pressure was measured with either the Setra 270 or 239 probe, which has response times of less than 20 ms and is accurate to within $\pm 0.05\%$ and $\pm 0.14\%$ at full scale, respectively. Temperature was measured with a Rosemount total temperature sensor (model 102 deiced), which operates in a temperature

range from -50° to 50°C with a sampling rate of 32 Hz and an accuracy to within $\pm 0.1^{\circ}\text{C}$. The dewpoint temperature measurements were made with the Edgetech digital dewpoint sensor (model 137), which was mounted through the skin of the aircraft. The model 137 is a chilled-mirror optical dewpoint sensor with a measurement range from -60° to 70°C , an accuracy of $\pm 0.2^{\circ}\text{C}$ and a response time of $1.5^{\circ}\text{C s}^{-1}$. The reported aircraft temperature field was corrected using the methodology outlined by Inverarity (2000) and by accounting for the self-heating and deicing-heating error terms known to arise with the Rosemount 102 deiced temperature probe in subsonic flight conditions (Stickney et al. 1994, p. 22). Based on the reported accuracies of these instruments, the relative humidity can be determined to no better than approximately 10%.

In addition to these sensors, the aircraft was also equipped with the CSIRO–King liquid water probe (King et al. 1978), the Particle Measuring System probes—the Forward Scattering Spectrometer Probe (FSSP; Baumgardner 1989) and the two-dimensional (2D-C) optical array imaging probe (Knollenberg 1981; Korolev et al. 2011). The FSSP measures particles in the 2–47- μm diameter ranges by relating particle size to the amount of light a particle scatters in the forward direction. The response time of the electronics, geometrical arrangement of the probe, and nonsphericity of particles also causes several problems, including undersizing of particles, detection of particles coincident in the beam as a larger single particle, failure to discriminate between ice particles and liquid droplets, and artificial enhancement of droplet spectra in the presence of ice (Fleishauer et al. 2002; Gardiner and Hallett 1985; McFarquhar and Heymsfield 1996). The 2D-C probe measures particles from 25 to 800 μm in steps of 25 μm by illuminating a two-dimensional array of photodiodes with a helium–neon laser. As a particle passes through the beam, a shadow image is cast on the diodes. Significant errors in particle sizing are possible including undersizing and undercounting of smaller particles and missizing of particles because of the discrete nature of the pixel array (Fleishauer et al. 2002; Korolev et al. 1998; Strapp et al. 2001).

The 2D-C particle size distributions shown here were processed using the University of North Dakota's Airborne Data Processing and Analysis Software Package (ADPAA; Delene 2011). This analysis package is based on the "reconstruction" technique described by Heymsfield and Parrish (1978), which has been shown by these authors to provide reasonable estimates of the size spectra distributions for particles' sizes that extend well beyond the upper size limit of the probe itself. To improve the concentration estimates, the ADPAA

processing uses a number of filters to remove suspect particles from the analysis. An initial step includes the removal of particles that are only partially imaged prior to the buffer start time. Each remaining particle is then examined for a maximum dimension and subscribed with the smallest circle possible that fully encompasses the particle. A second rejection criterion is used if the pixel area comprising the particle is less than 0.2 of the subscribed best-fit circle and the particle diameter exceeds 500 μm . A filter to remove particles that have short interarrival times, a signature of particle shattering near the tips of the probes (Baumgardner and Dye 1983; Field et al. 2006; Gardiner and Hallett 1985; Gayet et al. 1996; Heymsfield and Baumgardner 1985), is not currently applied.

The impact of shattering can be significant as neither the 2D-C or FSSP probes used in this study had anti-shatter tips installed. To help mitigate the effect of possible shattering, we removed the lowest three size bins ($D < 105 \mu\text{m}$) where this impact is generally regarded to have its greatest impact. We caution that concentration values in the 100–1000- μm range can also be impacted by shattering particularly in cases where the characteristic particle size (expressed as a ratio of the third moment to the second moment of the distribution) is large (Field et al. 2006; their Figs. 10 and 11). For the distributions shown here, the characteristic sizes ranged from 200 to 1400 μm at all times. Thus, based on their study, this impact on the total concentration is estimated to be on the order of 10%–50%. The impact of shattering on the FSSP data is more difficult to assess. It has been shown by Gardiner and Hallett (1985) that a tell-tale signature of the presence of ice is a rather broad and flat FSSP spectrum that extends across the entire size range. They found that this signature was particularly prevalent when the ambient crystal concentration within the cloud was high ($>300 \text{ L}^{-1}$ in the cases they examined). As shown later, in our study, this is not found to be a persistent characteristic of the FSSP size distributions examined at various levels within the stratiform cloud system. This may partially reflect the relatively low overall crystal concentrations observed on this day, which were, with few exceptions, generally less than 30 L^{-1} .

3. Results

a. System overview

The motivation for this study stemmed from an analysis of the visual structure of the observed cloud field recorded at 1-min intervals by an upward-looking all-sky camera on 24 August 2010 (Fig. 1). The feature of interest in the imagery is the well-defined, regularly



FIG. 1. All-sky camera image of the stratiform rain region observed at 2020 UTC 24 Aug 2010. The MCR dome is evident as the dark oval-shaped structure on the right side (eastern) portion of the image. The northern horizon is on the lower portion of the image. The numbers 1–6 delineate the location of several billow clouds. The billow spacing is estimated to be on the order of 1.3 km. Note the limited transverse spatial extent of the billow clouds. The image was modified to remove the fisheye effect and digitally processed to enhance the contrast.

spaced billow cloud structure (denoted by the numbered bands on Fig. 1) that is shown to be directly over the radar site at 2020 UTC. Inspection of the longer-term record of the all-sky camera images captured on this case day (see the YouTube video from 1930 to 2130 UTC at <https://goo.gl/st2lDO>) reveals that the billow clouds were transient in nature, with several distinct groups propagating across the site during a 2-h period between 1930 and 2130 UTC. The billow clouds were most discernable over the radar in the 2000–2040 UTC time period and, at all other times, were either absent overhead or possibly shielded from view by precipitating particles or intervening cloud layers.

The billow clouds observed between 2000 and 2040 UTC were aligned perpendicular to, and propagated in the direction of, the environmental southwesterly flow. This was determined from a balloon released near 1900 UTC from a site approximately 15 km southeast of the radar (Figs. 2a,b). The humidity trace indicates that the billow cloud layer was likely located near the melting level where nearly saturated conditions were observed (Fig. 2c). This would have placed the cloud layer in a region of strong negative vertical wind shear found just above the core of the 18 m s^{-1} jet axis centered near 3 km (Fig. 2b). The vertical profile of the equivalent potential temperature θ_e indicates the cloud layer may have formed within or near the top of a stable layer present near the melting level. This stable layer separated two nearly moist neutral layers, each approximately 1500 m deep,

found both immediately above and below the melting level (Fig. 2d). A calculation of the moist Richardson number, though inherently noisy when using even a smoothed sounding profile, suggests conditions within the upper moist neutral layer were possibly susceptible to Kelvin–Helmholtz-like instabilities provided saturated conditions were present (Fig. 2e).

Image processing was used to estimate a horizontal separation between successive billow cloud bands of $\sim 1.3 \text{ km}$ and to compute an apparent phase speed of approximately 14 ms^{-1} . These calculations are based on the observed spatial separation near zenith of $\sim 15^\circ$, an assumed cloud base near the melting level ($z = 4.8 \text{ km}$; Fig. 2c), and the $\sim 90\text{-s}$ separation observed between three successive individual billow cloud band images (each separated by 1-min intervals). An analysis of the composite reflectivity field derived from the nearby NWS radar sites, indicates the billow clouds were associated with a quasi-stationary mesoconvective line segment that was also aligned along the local shear vector (labeled A in Fig. 3). Satellite imagery indicates this line segment was part of a much broader cloud field associated with a trough and cold-frontal system that would cross the site during the day (Fig. 4a). A *CloudSat* transect that occurred at nearly the same time as the satellite imagery shows that the cloud band in the vicinity of the MCR site (28.7°N , 80.8°W) was composed of deep convective elements extending to nearly 12 km and an associated stratiform precipitation region (Fig. 4b). Peak reflectivity values of only 25–30 dBZ were found within the well-defined radar reflectivity bright band located near an elevation of 4.8 km. The *CloudSat* overpass transected line segment A along a track that passed nearly directly over the MCR and balloon release point near 1900 UTC (dashed line in Fig. 3a). This line segment would show very little movement over the next 2 h (Figs. 3b,c), during which time it underwent extensive sampling by both the radar and aircraft. It is thus this feature that will serve as the focus of study for the remainder of the text.

b. MCR Doppler radar analysis

An analysis of the narrowband reflectivity and Doppler velocity was undertaken between 1930 and 2130 UTC to determine if the vertically oriented radar scans had possibly captured specific structural details that could be associated with the passage of the observed billow clouds over the experimental network. Possible clues that this was in fact the case are evident in the time–height reflectivity pattern presented in Fig. 5. Of particular interest in this plot is the fundamental shift in the low-level precipitation structure that occurs as the storm transitions from periodic rain shafts to a more

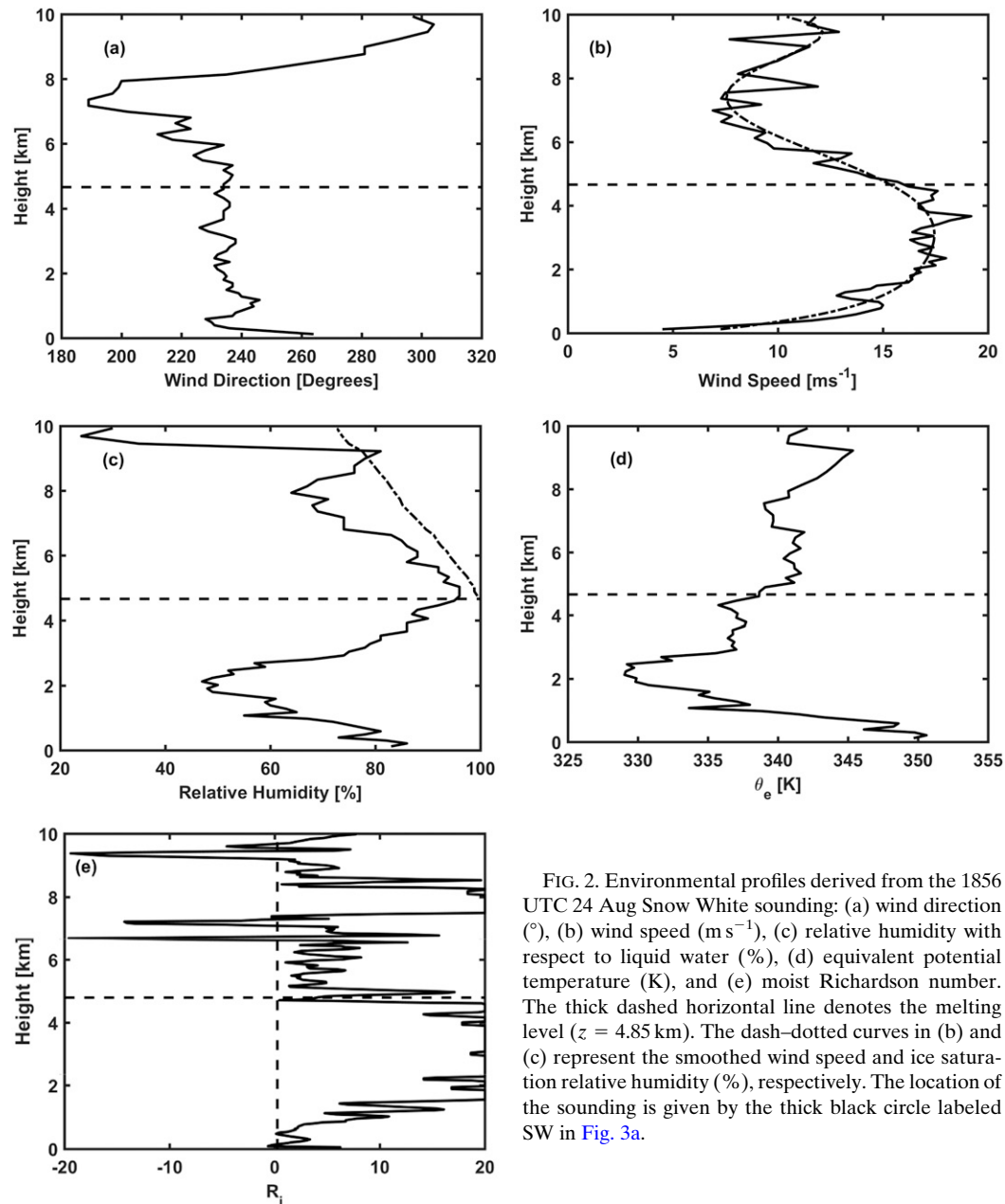


FIG. 2. Environmental profiles derived from the 1856 UTC 24 Aug Snow White sounding: (a) wind direction ($^{\circ}$), (b) wind speed (m s^{-1}), (c) relative humidity with respect to liquid water (%), (d) equivalent potential temperature (K), and (e) moist Richardson number. The thick dashed horizontal line denotes the melting level ($z = 4.85$ km). The dash-dotted curves in (b) and (c) represent the smoothed wind speed and ice saturation relative humidity (%), respectively. The location of the sounding is given by the thick black circle labeled SW in Fig. 3a.

stratiform appearance near 2030 UTC. The rain shafts were vertically coherent for a considerable distance below the melting layer, indicating that a lack of significant turbulent mixing was occurring below cloud base. There is also a notable absence of a corresponding fall streak pattern above the melting level, indicating their formation was localized to that of the brightband region and below. The fluctuations in the precipitation structure after 2030 UTC are much more gradual and appear to be associated with the movement of individual cells. This is particularly evident in the structural

changes in the depth and magnitude of the bright band that occur as the deepest and strongest cell traversed the site between 2040 and 2110 UTC (Fig. 5).

The corresponding perturbation velocity pattern shown in Fig. 6 largely mimics that of the reflectivity field with considerable temporal variability evident within the fall-streak regime (1940 and 2040 UTC) and more gradual transitions arising both before and after this time. This field was obtained by subtracting the MCR-derived layer-mean total Doppler velocity profile shown in Fig. 7a and thus represents perturbation

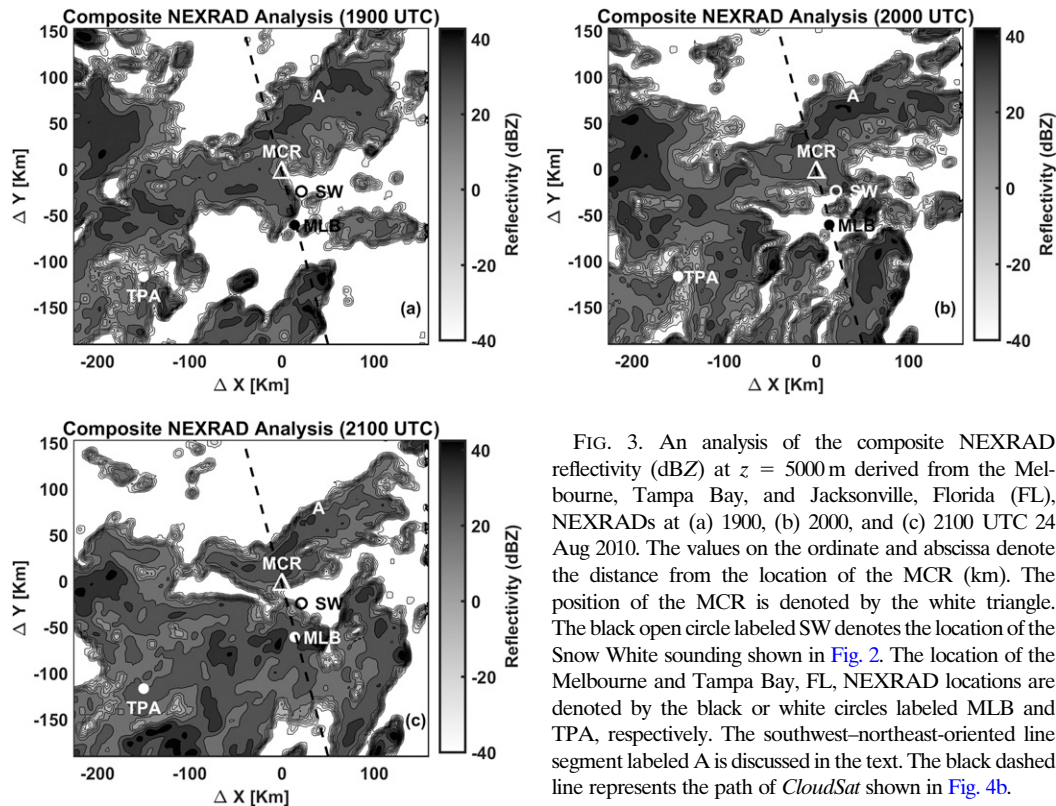


FIG. 3. An analysis of the composite NEXRAD reflectivity (dBZ) at $z = 5000$ m derived from the Melbourne, Tampa Bay, and Jacksonville, Florida (FL), NEXRADs at (a) 1900, (b) 2000, and (c) 2100 UTC 24 Aug 2010. The values on the ordinate and abscissa denote the distance from the location of the MCR (km). The position of the MCR is denoted by the white triangle. The black open circle labeled SW denotes the location of the Snow White sounding shown in Fig. 2. The location of the Melbourne and Tampa Bay, FL, NEXRAD locations are denoted by the black or white circles labeled MLB and TPA, respectively. The southwest–northeast-oriented line segment labeled A is discussed in the text. The black dashed line represents the path of *CloudSat* shown in Fig. 4b.

contributions arising from both the particle terminal velocity and actual vertical air parcel displacement variations. This computed mean is close to the mean hydrometeor terminal velocity derived separately from the Metek Micro Rain Radar above the melting layer (Fig. 7a). This interpretation of the mean velocity is similar to that reached by Orr and Kropfli (1999) in their study of stratiform cloud systems and suggests that the perturbation velocities above the melting layer may be close to the actual updraft and downdraft magnitudes. One notable difference between Figs. 5 and 6 is the clear vertical extension of the velocity anomalies that are evident above the bright band (Fig. 6) during the rain shaft regime. These perturbation velocity couplets first appear to form near the bright band near 2000 UTC and then extend upward and increase in magnitude in time before abruptly fading away between 2030 and 2040 UTC. Similar couplets extend below the bright band as well and again exhibit vertically coherent structure throughout the lowest radar gates.

A closeup view of the velocity perturbation structure presented in Fig. 8 highlights in greater detail the rather remarkable temporal uniformity between successive peaks in the perturbation velocity field. The fluctuations above the bright band are observed to occur approximately every

100 s and appear to be well correlated with similar periodicity within the sub-melting-layer rain shafts. We note that this period is quite similar to that found to arise between successive billow clouds obtained independently from the analysis of the all-sky camera imagery. There is a shift in the orientation of the perturbation field across the melting level with nearly vertically oriented perturbation velocity “cells” above the bright band and a slanted structure below. The velocity cells above the bright band extend through the 1500-m-deep layer previously noted to coincide with the negatively sheared moist neutral conditions found in the environmental sounding (depicted in Fig. 8a by the labeled dashed and solid white vertical profiles, respectively). The negative velocity perturbations below the bright band appear to align well with those above and are further found to correlate well with the position of localized higher-reflectivity maxima that periodically appear within the bright band. This is particularly the case after 2015 UTC as the magnitude and depth of the upper velocity cells reach their peak intensity.

A further refinement of the near-melting-level structure obtained during the active fall-streak regime is derived from the higher-resolution wideband waveform data (Fig. 9). The high-resolution windows were positioned to record a 300-m-deep layer situated just below the radar

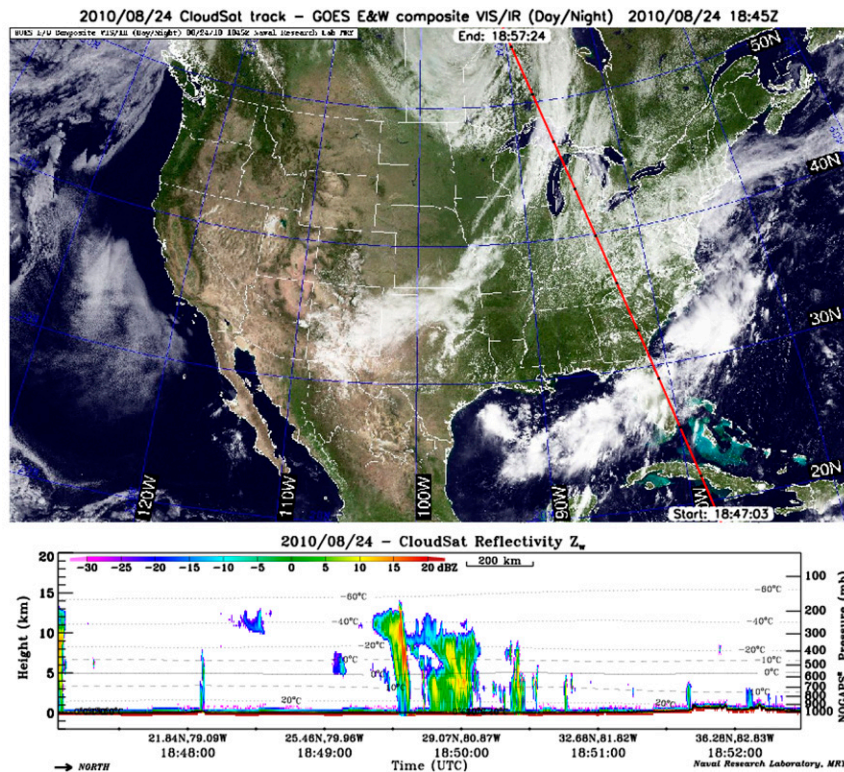


FIG. 4. (top) A visible satellite image at 1845 UTC 24 Aug 2010 showing the main cloud band sampled by the experimental network. (bottom) The *CloudSat*-derived radar reflectivity (dBZ) for the transect depicted by the solid red line overlain on the visible imagery. The *CloudSat* track passed within 1 km of the MCR position near 1850 UTC.

reflectivity bright band. The wideband structure indicates that the broad continuous rain shafts evident in Figs. 6 and 8 are actually composed of numerous and even finer temporally and spatially coherent reflectivity and velocity structures. A rapid acceleration from -2 to -8 m s^{-1} is observed over a very thin transition zone often much less than 150 m thick. Considerable variation in the melting rates is apparent, however, and this leads to the billowy nature of the velocity and reflectivity patterns.

c. Aircraft analysis

The in situ aircraft observations were also examined for evidence of any periodicity that would corroborate that found in the all-sky camera images and radar signatures. As indicated by the thick colored aircraft tracks depicted in Figs. 5, 6, and 8, the aircraft passed through the Doppler-detected perturbation velocity field as it executed a series of stepped descents and horizontal passes through the cloud layer between 2010 and 2040 UTC (labeled L1–L5 in Fig. 8). These specific passes were flown at altitudes ranging from 6.9 to 4.4 km, where the corresponding layer-mean

temperatures were observed to vary between -12° (L1) and 2.0°C (L5). A horizontal plan view of a series of representative flight tracks indicate the aircraft was in cloud the entire time and sampling a series of weak cells located along the southernmost flank of line segment A (Fig. 10). The oval-shaped flight track evident in Fig. 10 was repeated throughout the descent and brought the plane directly over the MCR at roughly 5-min intervals.

A summary of the L1–L5 leg-mean particle size distributions obtained from both the 2D-C and FSSP probes is presented in Fig. 11. Comparing the 2D-C profiles for each leg, we find a systematic increase and then decline in the particle concentration across a broad portion of the size spectrum as the aircraft executed its descent through the melting level. Similar to the structure reported in the stratiform cloud systems examined by Stewart (1984), the peak 2D-C values for sizes less than $1000 \mu\text{m}$ were recorded approximately 1 km above the melting level where observed temperatures were near -6°C (see curves labeled L2–L4 in Fig. 11a). The similarity in the 2D-C profiles shown for L3 and L4 (Fig. 11a) resulted from nearly identical aircraft passes through the Doppler-derived velocity

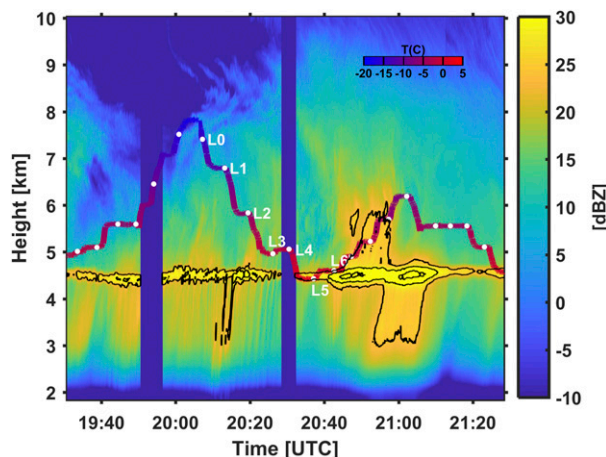


FIG. 5. Vertical time–height plot of the MCR-derived narrow-band reflectivity (shaded; dBZ) as recorded between 1930 and 2130 UTC. The radar reflectivity bright band is evident near an altitude of 4.5 km and delineated by the black contour lines that are drawn at 6-dBZ intervals beginning at a value of 24 dBZ. The thick colored curve represents a time–height plot of the aircraft-recorded temperature ($^{\circ}\text{C}$) as indicated by the color bar inset in the upper-right portion of the plot. The white dots labeled L0–L6 denote the times the aircraft was directly over the radar. The vertical solid blue rectangles represent temporal gaps in the radar coverage.

couplets just 200 m above the melting level. Both of these legs indicate a similar increase in the 2D-C concentration of larger particles in excess of $1500\text{ }\mu\text{m}$, indicating that an active particle growth regime was positioned just above the melting level. The 2D-C concentration for all size categories fell off rapidly below this point, reaching an absolute minimum in the drier air evident in the sounding (Fig. 2c) below the melting level (L5).

The similarity of the L3 and L4 2D-C profiles is also evident in the nearly identical FSSP particle size distributions for these two flight legs. Both of these flight legs show a distinct mode near $8\text{ }\mu\text{m}$ and by far the largest concentration of particles of any other flight leg (Fig. 11b). The size distributions observed during the colder-temperature flight legs L1 and L2 are notably flatter and possibly reflect the impact of ice particles on the recorded concentration or a reduction in the number of drops from accretional or other processes in the supercooled environment found farther aloft. As in the 2D-C data, the L5 leg has the lowest number of particles recorded of any other pass through the cloud system, again likely reflecting environmental changes below cloud base.

Binning the aircraft data into fixed (50-m thick) altitude bands over all flight legs flown between 2000 and 2100 UTC results in the vertical profiles of the various microphysical quantities shown in Fig. 12. The elevated

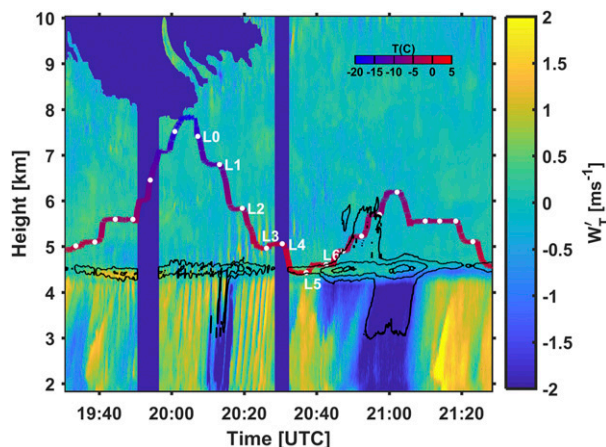


FIG. 6. As in Fig. 5, except that the displayed field represents the radar-derived total vertical velocity perturbation field (shaded; ms^{-1}). The perturbations represent departures from the mean total Doppler velocity profile shown in Fig. 7a.

maximum in the 2D-C concentration above the melting level is clearly evident (Fig. 12a), and its location is found to closely correspond with that found for the peak in the maximum 2D-C particle size concentration (Fig. 12b). This later quantity is computed here as the sum of all particles in excess of $1500\text{ }\mu\text{m}$ in an effort to assess the vertical structure of the growth in the larger particles initially evident in the mean distributions shown in Fig. 11a. Both peaks reside above that of the FSSP concentration, indicating the growth may partially reflect both aggregation and accretional processes (Fig. 12c). Peak ice crystal concentration values within the -3° to -8°C temperature band are found to exceed those expected from primary nucleation processes at the indicated temperature, suggesting that sedimentation from aloft or enhancements to the crystal concentration from secondary ice particle production may have contributed to the placement of this peak (Hallett and Mossop 1974). The profile for the King liquid water content is less coherent but generally shows a bimodal structure with peaks near the melting level and again aloft near 6800 m (Fig. 12d). This profile indicates mixed-phase conditions were present through a deep layer that extended well above the melting level.

A time series plot of the 2D-C and FSSP data acquired in the upper portion of the velocity couplets during L2 is shown as a function of the particle bin size and other aircraft-derived parameters (vertical velocity, relative humidity, and selected particle concentration trends) in Fig. 13. One of the distinguishing features of this pass was the repeated aircraft encounter with collocated spikes in the recorded hand-analyzed needle and computed FSSP concentrations found throughout nearly the entire flight leg (Fig. 13b). A similar association is noted in the 2D-C

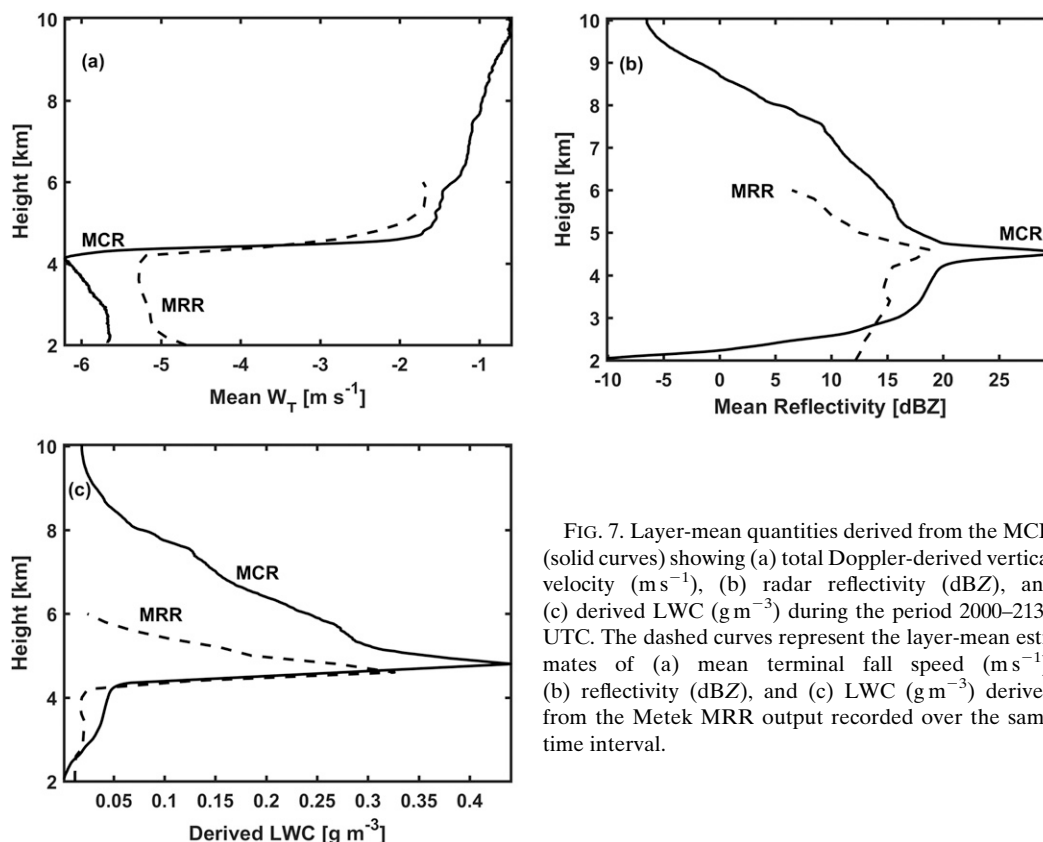


FIG. 7. Layer-mean quantities derived from the MCR (solid curves) showing (a) total Doppler-derived vertical velocity (m s^{-1}), (b) radar reflectivity (dBZ), and (c) derived LWC (g m^{-3}) during the period 2000–2130 UTC. The dashed curves represent the layer-mean estimates of (a) mean terminal fall speed (m s^{-1}), (b) reflectivity (dBZ), and (c) LWC (g m^{-3}) derived from the Metek MRR output recorded over the same time interval.

concentrations, suggesting that most of the needle particles were less than $400 \mu\text{m}$ in length (Fig. 13c). Needles were not observed by the aircraft at temperatures less than -10°C , indicating either a possible sampling issue with the 2D-C probe or that crystals observed at flight level likely formed at altitudes just below the aircraft position. Their association with the elevated FSSP concentrations is significant as it indicates that supersaturated conditions with respect to liquid water were present within at least some portions of the Doppler-derived velocity couplets. This is corroborated by the relative humidity trace (dotted curve in Fig. 13a), which oscillates about the water-saturation value throughout this entire flight segment. Notably, though, these spikes do not necessarily align with the aircraft-measured updrafts at this level (Fig. 13a), indicating sedimentation from aloft, lateral transport, or mixing of needles into the surrounding downdrafts has occurred.

Individual images derived from the 2D-C probe for the selected times (labeled p1–p7 in Figs. 13b and 13c) show the predominance of needles and dendritic growth habits interspersed with small pristine crystals (possibly hexagonal plates) throughout this flight leg (Fig. 14). Most crystals at this level appear to be individual particles that have possibly undergone some level of riming.

A few needle aggregates are interspersed as well, as evident in Figs. 14a–c, and these preferentially occurred where individual peaks in both the FSSP and needle concentrations coincided. Areas between these peaks were found to coincide with larger particles of either irregular or dendritic habits such as evident in p4 and p6. The image p7 was taken as the aircraft was sampling a spike in the FSSP and 2D-C concentrations situated directly over the radar. The crystals consisted mainly of small plates and capped columns or two-layered crystals with frozen drizzle-sized or raindrop centers. The aircraft at the time was within updraft of $\sim 1 \text{ m s}^{-1}$ (Fig. 13a), a value that corresponds well with that inferred from the Doppler-derived perturbation velocity couplets evident at the same time (Fig. 8a).

The temporal structure found within the lower to middle portion of the velocity couplets is shown for L3 in Fig. 15. The most distinctive characteristic of this pass (and that of L4, not shown) are the series of evenly spaced peaks in the FSSP concentration that the aircraft encountered on its inbound leg toward the MCR (Fig. 15b). A time-space conversion using the aircraft's observed 102 m s^{-1} true airspeed indicates a mean horizontal separation between these peaks of approximately $\sim 1.45 \text{ km}$, a value that compares well with the calculated spacing of the

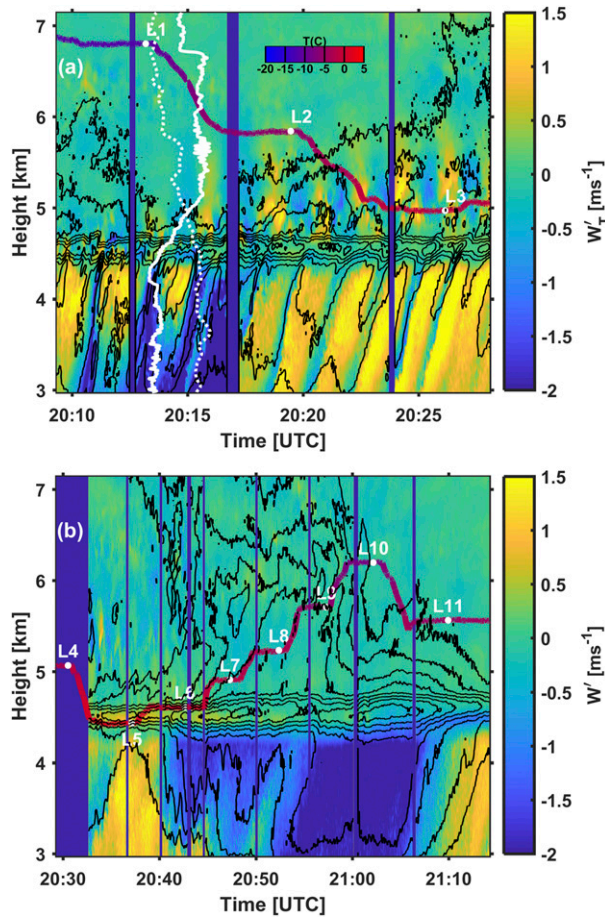


FIG. 8. Vertical time–height cross section of the radar-derived total vertical velocity perturbation field (shaded; ms^{-1}) at (a) 2009:20–2028:08 and (b) 2029:17–2114:00 UTC 24 Aug 2010. The thin black contour lines show radar reflectivity contoured every 3 dBZ beginning at 15 dBZ. The thick colored curve represents temperature ($^{\circ}\text{C}$) along the flight track as given by the color bar inset in the upper portion of (a). The white circles labeled L0–L11 denote times when the aircraft was directly over the radar. The vertical blue bars represent temporal gaps in the radar coverage. The white solid and dashed vertical lines plotted in (a) near 2015 UTC show the scaled vertical structure of the equivalent potential temperature (solid) and horizontal wind speed (dashed) previously shown in Figs. 3b and 3d.

billow clouds derived from the analysis of the all-sky camera images. Unlike pass L2, the individual FSSP concentration spikes are now found to correlate quite well with the in situ positive vertical velocity and relative humidity anomalies (Fig. 15a). This fact, when taken together with the well-defined mode in the FSSP distribution near $8\text{ }\mu\text{m}$ and peak concentrations in excess of 70 cm^{-3} , suggests that newly nucleated particles were being encountered in updrafts at this flight level in a favorable water-supersaturated environment. The rapid reduction in the FSSP concentration observed

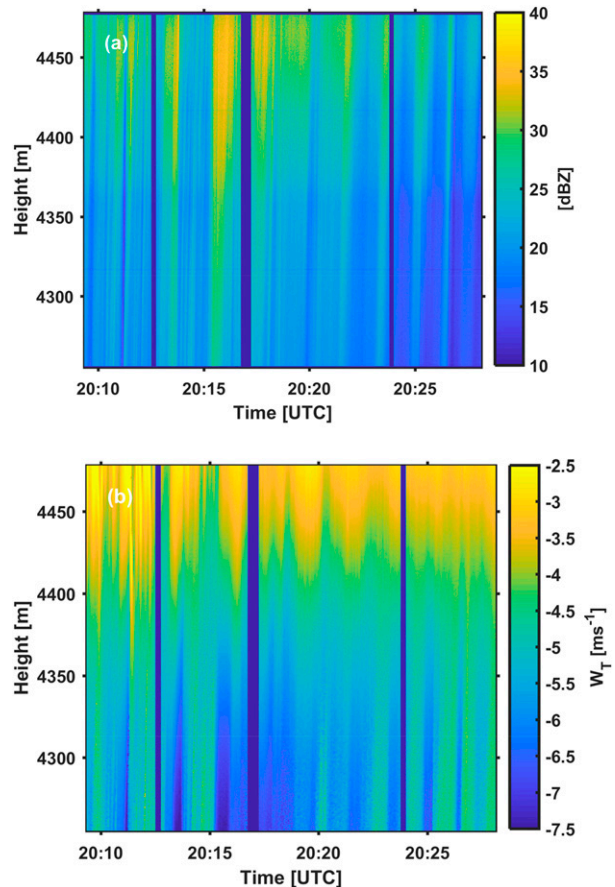


FIG. 9. High-resolution time–height plots showing (a) reflectivity (dBZ) and (b) total vertical velocity (ms^{-1}) derived from the MCR wideband waveform in a thin layer just below the radar reflectivity bright band between 2009:20 and 2028:08 UTC.

between L3 and L2 further suggests a rapid drop-removal mechanism was active between these two layers of the cloud system. The corresponding 2D-C data plot shows that the reduction in peak concentration at this level has occurred primarily over the smaller particle size bins ($<400\text{ }\mu\text{m}$; Fig. 15c). There is also a suggestion in several instances of a subtle shift in position of the local maxima into the downdraft regions (cf. Fig. 15a) and some suggestion that a reduction has occurred in the overall 2D-C concentration in regions where the FSSP peaks reside. This is evident in the three primary maxima that are shown after 2025:30 UTC and suggests that the aircraft is sampling changes in the cloud microphysical properties between the downdraft and updraft regions.

The corresponding individual 2D-C images indicate the presence of a wide variety of crystal habits that included needles, columns, capped columns, and small pristine crystals of unknown type (Fig. 16). As temperatures along L3 were near -1°C , the presence of

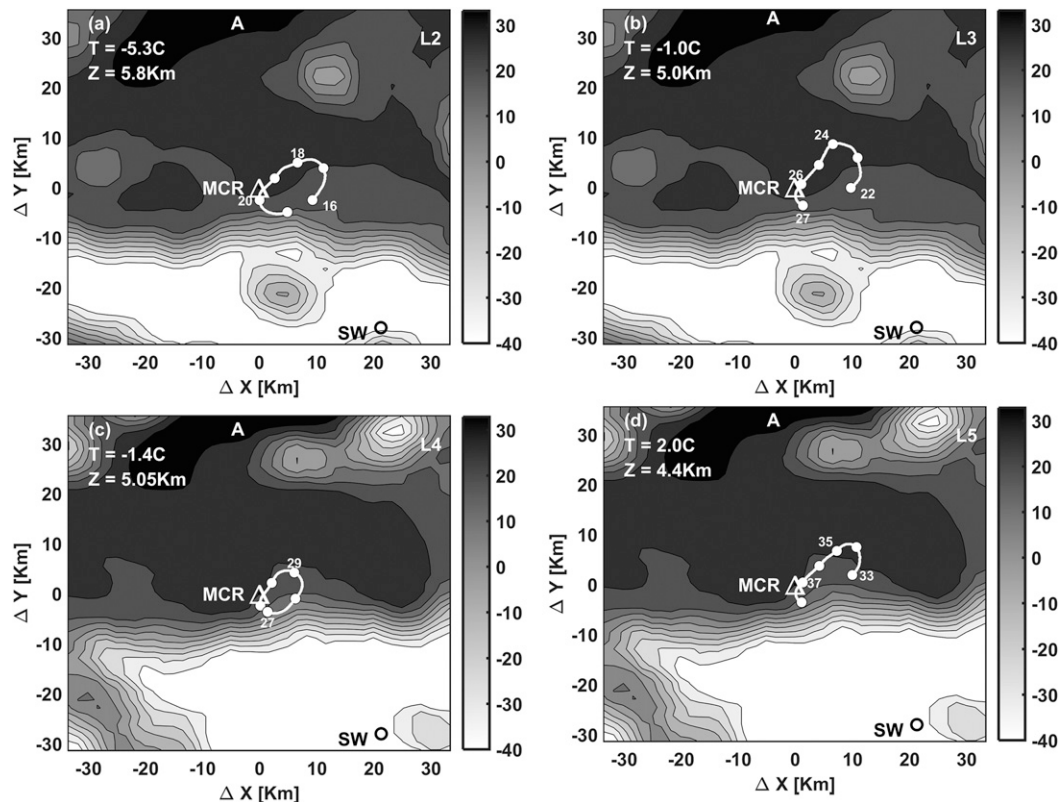


FIG. 10. Horizontal flight tracks (white curves) overlaid on the Melbourne NEXRAD (shaded; dBZ) taken at an elevation of $z = 5000$ m for flight times (a) 2016–2021 (L2), (b) 2022–2027 (L3), (c) 2027–2031 (L4), and (d) 2033–2038 UTC (L5). White labeled dots represent aircraft locations at 1-min intervals. Numeric labeling along the flight track refers to the time in minutes after 2000 UTC. The letters T and Z represent the leg-averaged temperature ($^{\circ}\text{C}$) and aircraft altitude (km), respectively. Values displayed on the axes represent distance from the MCR (km). The black thick circle represents the location of the Snow White rawinsonde (SW). The MLB radar plots shown in (a) and (b) are taken at 2020 and (c) and (d) at 2040 UTC. The letter A represents line segment A as shown previously in Fig. 3.

needles and columns at this flight level indicates that a downward flux of these particles has occurred from a generation zone located farther aloft. Large irregularly shaped crystals that clearly extend beyond the $800\text{-}\mu\text{m}$ size limit of the 2D-C probe are also present, and these account for the increase in the concentration of the larger particles previously shown in flight legs L3 and L4 in Fig. 11a. The presence of these large particles is interesting as they are encountered while the aircraft was flying just above the locations of the localized brightband reflectivity maxima evident in Fig. 8a. The time trace of the larger particles ($D > 1500\text{ }\mu\text{m}$) given by the red curve in Fig. 15c showing pronounced spikes in the regions between the individual FSSP maxima is interesting as they occur while the aircraft was flying just above the locations of the localized brightband reflectivity maxima evident in Fig. 8. This suggests these reflectivity features may have resulted from a

rapid acceleration in large particle production near or just below this flight level or, alternatively, from the continued downward transport of the elevated concentration of particles observed in the $100\text{--}400\text{-}\mu\text{m}$ range (such as that evident near the time of the MCR crossing labeled L3 in Fig. 15c).

The corresponding plots obtained just below the melting level along L5 are shown in Figs. 17 and 18. The FSSP plot shows a distinct mode near $10\text{ }\mu\text{m}$ and several embedded peaks in the concentration that appear randomly distributed in time (Fig. 17b). There is a near absence of particles greater than $15\text{ }\mu\text{m}$ in the FSSP data, perhaps as a result of coalescence below the melting level and a reduction in drop sizes associated with rapid evaporation in the dry air located below the melting level. Several spikes are also evident in the 2D-C imagery shown in Fig. 17c, and these appear randomly distributed as well. Nearly all spikes correspond with

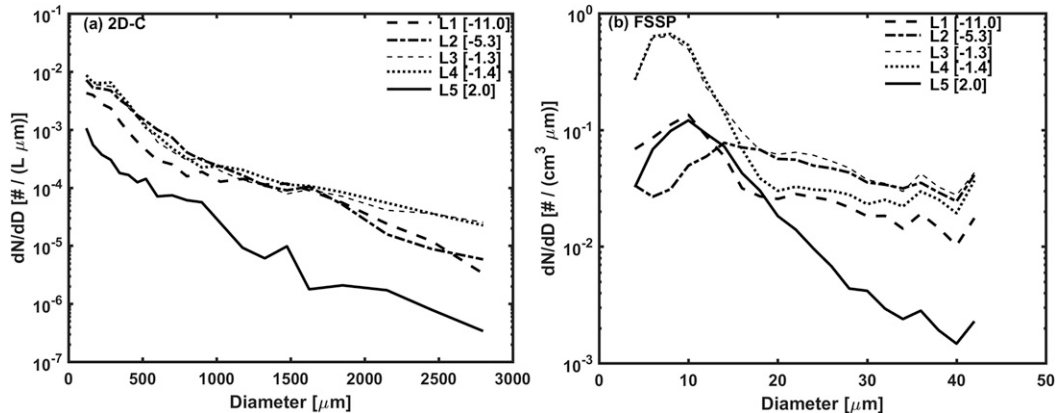


FIG. 11. Leg-mean cloud microphysical properties acquired between 2000 and 2100 UTC 24 Aug 2010 showing (a) the leg-averaged 2D-C size distribution ($L^{-1} \mu m^{-1}$) and (b) the leg-mean FSSP size distribution ($cm^{-3} \mu m^{-1}$). The labels L1–L5 refer to the sequential horizontal flight legs as depicted in Figs. 5, 6, and 8. The number in square brackets in (a) and (b) represents the leg-mean temperature ($^{\circ}C$). The first three size bins were eliminated from the 2D-C plot shown in (a) to reduce impacts from possible shattering on the displayed distributions.

either aircraft-measured downdraft or are found along the updraft–downdraft interface (Fig. 17a). Individual 2D-C images confirm most of the particles are liquid drops at this level (Fig. 18), but these remain interspersed with a few large and highly irregular particles that have yet to fully melt even though the aircraft is sampling at temperatures near $2^{\circ}C$. This is consistent with the structure of the wideband Doppler data shown in Fig. 9, which indicated a highly variable acceleration of the particles in a layer nearly 300 m thick just below the bright band.

4. Discussion

The data presented thus far points to a commonality in the observed visible and internal cloud structures evident during this particular case study. The temporal fluctuations in the radar-derived velocity couplets near the melting level (Fig. 8a), for example, closely matches that captured in the all-sky camera images of the billow clouds that are thought to arise at nearly the same level (Fig. 1). Likewise, the estimated 1.3-km spatial separation between successive billow clouds determined from the all-sky camera imagery closely matches that calculated to arise between the observed individual peaks in the FSSP time series recorded just above the melting level (Fig. 15b). When taken together, these separate data sources lead us to conclude that the all-sky camera, aircraft, and radar have all captured specific signatures of the observed billow cloud layer and associated circulation field. This possibly accounts for the rather remarkable periodicity

in the observed measurements provided throughout the text.

a. Schematic model

A synthesis of these and other primary features of the observed cloud field recovered from the experimental network lead to the schematic model of the event presented in Fig. 19. The schematic combines the basic properties of the environmental setting (red vertical profiles), the radar reflectivity (black contours) and perturbation velocity fields (shaded), a depiction of the hypothesized circulation (white curves), the spatial placement of the billow clouds (solid gray scalloped regions), and the aircraft-inferred cloud microphysical properties (solid black objects).

b. *Nimbostratus uncinus* structure

The primary perturbation velocity pattern depicted in Fig. 19 is shown as an elliptically shaped circulation with updraft and downdraft centers spaced 1.3 km apart and with peak total velocity anomalies of $\pm 2 m s^{-1}$. Updrafts are depicted to originate within the billow clouds near the bright band and extend upward ~ 1.5 km through a negatively sheared and nearly neutral moist static stability conditions (solid and dashed red profiles, respectively). A thin layer of strong static stability resulting from the melting processes separates the upper moist neutral layer from a separate moist neutral layer below the bright band that contains the slanted rain shafts. Supersaturated conditions with respect to water existed above the melting level within the lower portion of the updrafts leading to a peak in the FSSP

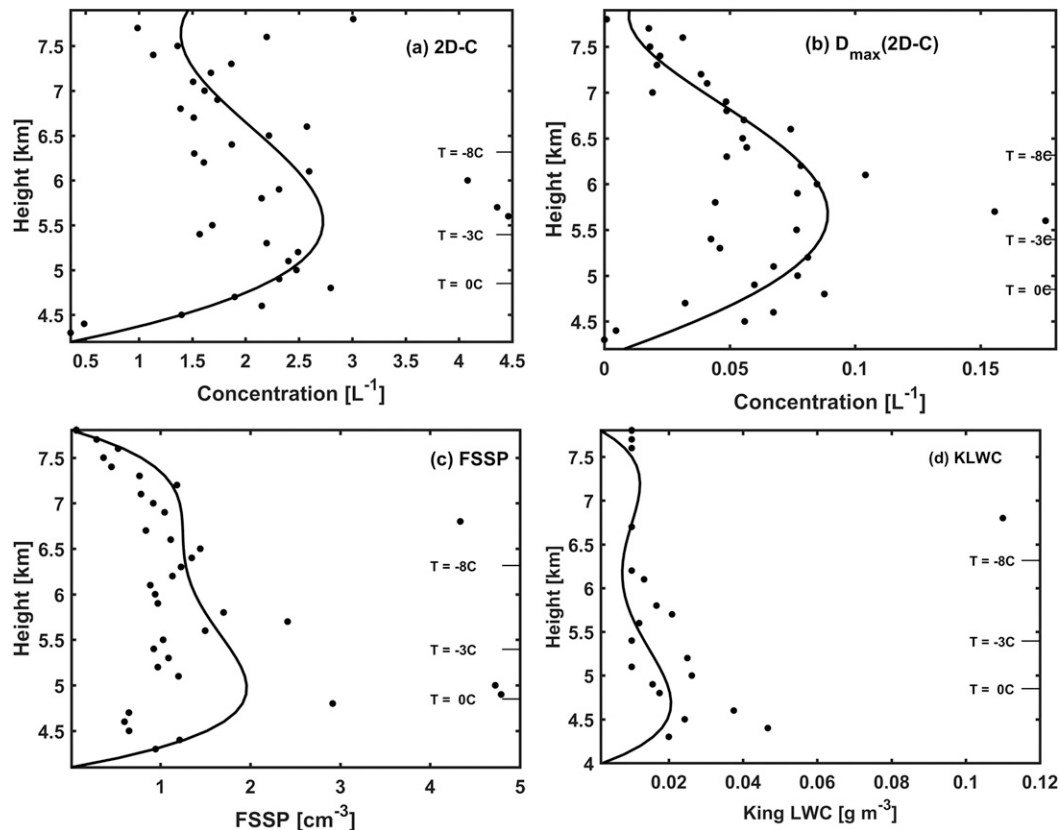


FIG. 12. Cloud microphysical properties acquired between 2000 and 2100 UTC 24 Aug 2010 showing the aircraft-derived layer-mean fields as a function of height for (a) 2D-C concentration for diameters $D > 105 \mu\text{m}$ (L^{-1}), (b) 2D-C concentration for the maximum particle sizes (L^{-1}) determined here as the sum of the 2D-C concentration for particle sizes in excess of $1500 \mu\text{m}$, (c) FSSP concentration (cm^{-3}), and (d) King LWC (g m^{-3}). The layer-mean quantities were computed in 50-m vertical increments in the 4–8-km layer. The level of the 0° , -3° , and -8°C isotherms are depicted along the right ordinate of each panel.

concentration (labeled black dotted curve) and the local generation of needles in their favored nucleation temperature band from -3° to -8°C . The suggested presence of a high concentration of drops and crystals within this temperature zone indicate favorable conditions for the onset of secondary ice particle multiplication processes (SIP) within the narrow updrafts. Secondary ice crystal production and possibly sedimentation may thus explain the higher-than-expected crystal concentration values observed within this temperature band and may also contribute to the location of the peak in the 2D-C concentration.

The circulations from successive updrafts are shown to merge near the top of the intervening downdraft near an altitude of 6 km. This altitude coincides with the location of the observed maximum in the 2D-C concentration (as seen previously in Fig. 12a). It also lies within the layer where the change in slope of the mean radar reflectivity (Fig. 7b) and 2D-C images

(Fig. 14) signaled the onset of larger particle growth and aggregation. Enhanced aggregation is hypothesized to occur near the top of the updrafts as the higher concentrations of particles within the updraft begin to mix with the downward flux of pristine ice crystals arriving from farther aloft (depicted by the thick black arrow). The region of enhanced aggregation is depicted to extend downward through a much deeper layer within the intervening downdraft zones, which observations indicate had a higher overall concentration of particles (Fig. 15c). This is hypothesized to result from the downward vertical transport and sedimentation of the large number of crystals being detrained from adjacent updrafts as depicted in Fig. 19. The higher downdraft crystal concentrations are hypothesized to contribute to the observed correlation between the localized high-reflectivity zones within the melting layer and the negative velocity anomalies that extend well below cloud base within the slanted rain shafts.

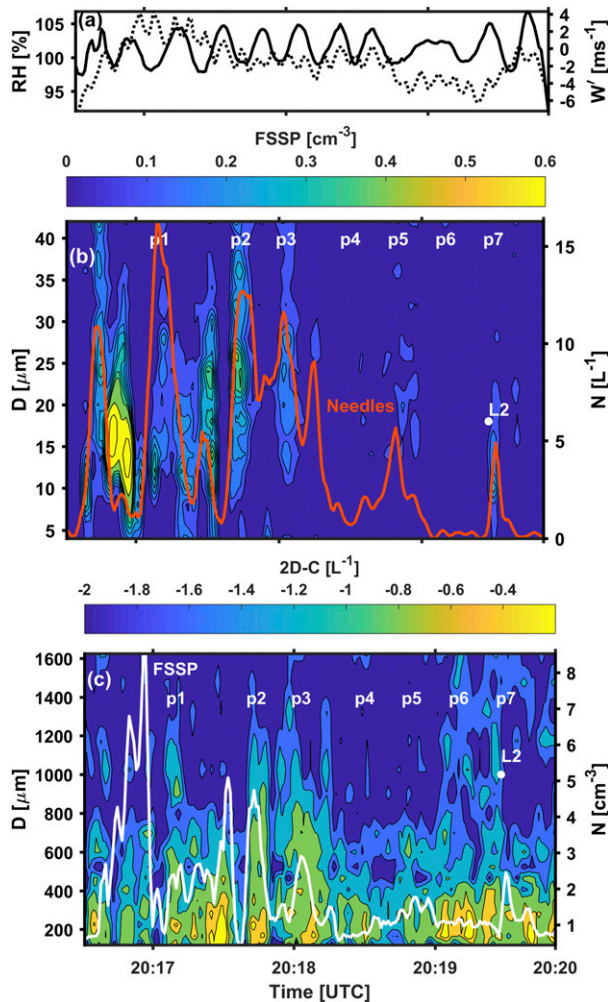


FIG. 13. Aircraft-derived cloud properties near the time of flight leg L2 between 2016:30 and 2020 UTC showing (a) the aircraft-recorded relative humidity (%) (dotted) and perturbation vertical velocity taken about a mean value of 0.0 m s^{-1} (solid), (b) FSSP concentration (shaded; cm^{-3}), and (c) 2D-C concentration [$\log_{10}(N)$; shaded; L^{-1}] for diameters $D > 105 \mu\text{m}$. The orange curve in (b) represents the concentration of needles (L^{-1}) with the values given by the black numbers on the right ordinate. The white curve in (c) denotes the total FSSP concentration (cm^{-3}) with values denoted by the black numbers along the right ordinate. The thick white dot labeled L2 shows the time of the aircraft's closest approach to the MCR. The text labeled p1–p7 denotes the 2D-C images shown in Fig. 14.

This correlation is also hypothesized to have resulted from large particle production within the downdrafts just above the melting layer. The inner closed circulation is meant to suggest possible particle recirculation between the updraft and downdraft centers that, if present, would allow additional particle growth in time through repeated cycles of condensation, riming, secondary ice particle production, and aggregation in a near-water-saturated environment.

Though they differ in appearance, the overall structure of the melting-level eddy circulation and rain shafts presented herein bears resemblance to that found for some cirrus uncinus cells as described by Heymsfield (1975; his Fig. 8a). Similarities include a near-neutral and negatively sheared environment in the generating layer, positive shear below the generating layer, a similar vertical and horizontal length scale for the generating head, velocity perturbations on the order of 2 m s^{-1} , and a sloped precipitation “tail” extending downward from the generating layer. Although we observe the cloud layer to have formed near the base of a nimbostratus layer near the melting level, their smooth visual appearance suggests these clouds do not represent the ragged melting-layer-induced fractocumulus clouds described by Knight et al. (2004) and Findeisen (1940) nor any other known subclass of nimbostratus such as pannus. The additional lack of visual or radar evidence for overturning Kelvin–Helmholtz-type cloud structure lead us to suggest that the combined billow cloud structure and shallow circulation field associated with the slanted periodic rain shafts that extend below cloud base represent a separate subclass of nimbostratus, which we refer to as mixed-phase nimbostratus uncinus.

c. Mechanisms for the periodic billow cloud structure

It is quite intriguing that the shallow circulation structure above the melting layer coincides in time with the observed billow clouds and observations of the periodic rain shaft structure both within and below the melting layer. Other studies have shown oscillatory behavior in the velocity structures to arise near the melting layer and have attributed them to shear-induced Kelvin–Helmholtz instabilities (Houser and Bluestein 2011) or shear-induced turbulent eddies possibly associated with terrain-induced fluctuations in the flow (Houze and Medina 2005; Yuter and Houze 2003). These authors have noted the possible impact of the observed velocity perturbations on the precipitation characteristics due to changes in the microphysical processes related to secondary ice crystal production, riming, accretion, or turbulence-induced changes in the collection kernel. Though the temporal frequency and horizontal length scale of the observed velocity couplets are seen to vary from case to case, all share a commonality in that the observed circulations reside in a 1–2-km-deep layer just above the melting level and, when present, appear to modify the nature of precipitation structure or fall streaks below.

(a) p1 20:17:10



(b) p2 20:17:44



(c) p3 20:18:03



(d) p4 20:18:30



(e) p5 20:18:50



(f) p6 20:19:10



(g) p7 20:19:30



FIG. 14. Selected 2D-C images from 17:10 to 19:30 UTC 24 Aug 2010 taken at an altitude of approximately 5800 m and a temperature of approximately -5.5°C as the aircraft approached the MCR along flight leg L2. Time in each panel runs from left to right and top to bottom and represents less than 1 s of flight data. Start times (UTC) are displayed in the HH:MM:SS format at the top of each panel. The maximum particle size in each subpanel is $800\text{ }\mu\text{m}$ as denoted by the length of the vertical black lines separating each particle. Panels correspond to times (a) p1–(g) p7 as shown in Fig. 13.

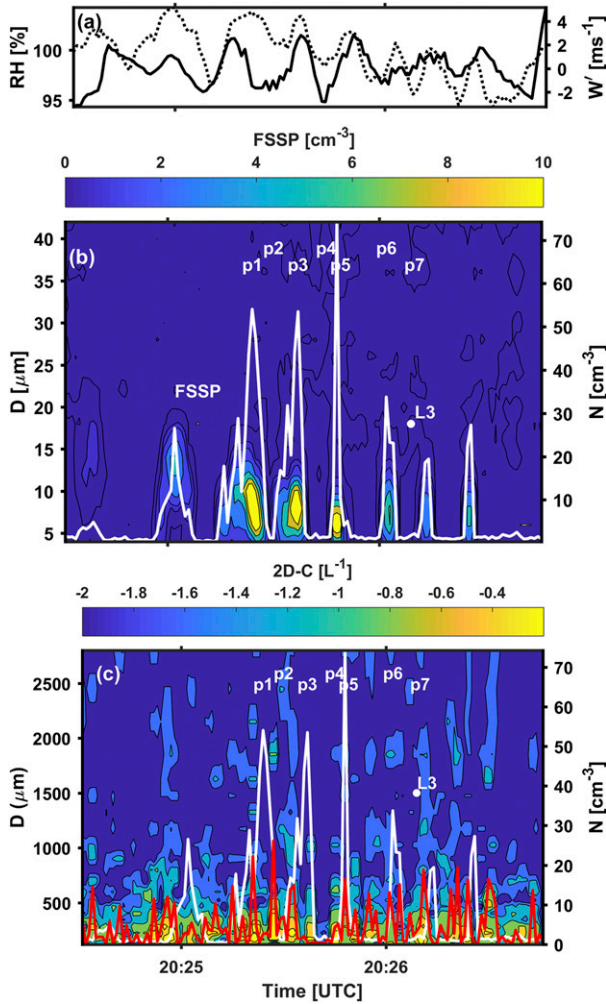


FIG. 15. Aircraft-derived cloud properties near the time of crossing L3 between 2024:30 and 2026:45 UTC showing (a) the relative humidity (%; dotted) and perturbation vertical velocity (m s^{-1} ; solid) about a mean of 0.0 m s^{-1} and (b) the FSSP concentration (shaded; cm^{-3}) and (c) 2D-C concentration [$\log_{10}(N)$; shaded; L^{-1}] for diameters $D > 105 \mu\text{m}$. The solid white curves in (b) and (c) represent the total FSSP concentration (cm^{-3}) as given by the values in black along the right ordinates. The solid red curve in (c) represents the sum (multiplied by 50 for display purposes) of the 2D-C concentration for particles greater than $1500 \mu\text{m}$ (L^{-1}), as given by the black values along the right ordinate. The white circle labeled L3 shows the time of the aircraft's closest approach to the MCR as also indicated in Fig. 8a. The text labeled p1–p7 denotes the times of the 2D-C images shown in Fig. 16.

While the sounding analysis shown in Fig. 2e indicated Kelvin–Helmholtz instabilities could possibly have been supported, we reiterate the lack of visual evidence in all-sky camera images or radar data to confirm that any wave breaking was actually present. An alternative explanation for the observed periodicity may be the presence of internal or vertically trapped gravity waves propagating

along or near the stable melting layer. An assessment of the wave behavior in near-saturated conditions can be undertaken through an analysis of the vertical structure of the moist Scorer parameter $\{l_m^2(z) = N_m^2[U(z) - c]^{-2} - U''(z)[U(z) - c]^{-1}\}$ (Durran and Klemp 1982b; Fovell et al. 2006; Tripoli 1992; Yang and Houze 1995). The expression for l_m^2 is evaluated herein using the definition of the moist Brunt–Väisälä frequency N_m^2 as expressed in Eq. (36) of Durran and Klemp (1982a), the smoothed environmental vertical wind shear and radar-derived liquid water content profiles shown in Figs. 2b and 7c, respectively, and the smoothed temperature and dewpoint temperature field derived from the 1846 UTC Snow White sounding (not shown).

The l_m^2 structure obtained both with and without the inclusion of the impact of the apparent wave phase speed c is shown in Fig. 20. In the $c = 0$ case shown in Fig. 20a, conditions conducive to wave trapping exist above the level of the local peak in l_m^2 that arises near the melting level. The corresponding component analysis indicates that this peak results from a combination of the positive contributions from the buoyancy term $\{N_m^2[U(z) - c]^{-2}\}$ associated with the increased static stability within the isothermal melting layer and the negative curvature in the shear term $\{U''(z)[U(z) - c]^{-1}\}$; shown as the dashed curves labeled l_{mb}^2 and l_{ms}^2 in Fig. 20, respectively]. Reductions to l_m^2 farther aloft are caused by a change in sign of the shear curvature term above the jet axis. As expected, the values of l_m^2 remain lower than that of the standard dry Scorer parameter l_d^2 at all levels, with the greatest difference coinciding with the location of the peak in the shear curvature term found at the 7-km level. The contribution of the total water condensate term to N_m^2 (and thus l_m^2) is relatively minor in this case (Fig. 20b), partly as a result of the low derived liquid and ice water content values. This term is negative throughout most of the column, with the exception of the positive peak that tends to coincide with the sharp increase in the derived liquid water content near the melting level (Fig. 7c). This may be a fairly common signature in mixed-phase stratiform systems, particularly in cases where evaporation in the dry subcloud layer enhances the reductions in the condensate that otherwise result from the acceleration of melting ice particles and raindrops below the melting layer (Fig. 9b).

The basic structure of l_m^2 shown in Fig. 20a bears some resemblance to multilayer wave environments wherein a thin elevated layer of relatively high l_m^2 values is bounded both above and below by much deeper layers in which the l_m^2 values are considerably lower. As shown in Fig. 20c, this impression is further strengthened when the

(a) p1 20:25:24



(b) p2 20:25:30



(c) p3 20:25:37



(d) p4 20:25:45



(e) p5 20:25:49



(f) p6 20:26:02



(g) p7 20:26:10

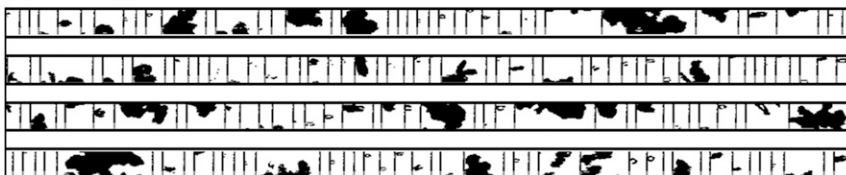


FIG. 16. As in Fig. 14, except the images are recorded between 2025:24 and 2026:10 UTC along flight leg L3 at an altitude of approximately 4960 m and a temperature of -1.0°C .

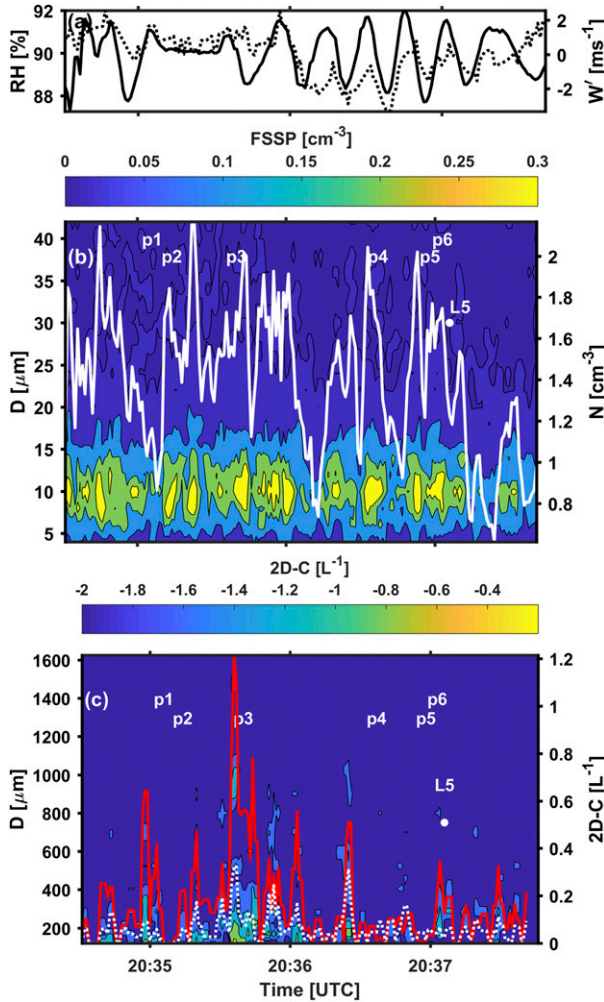


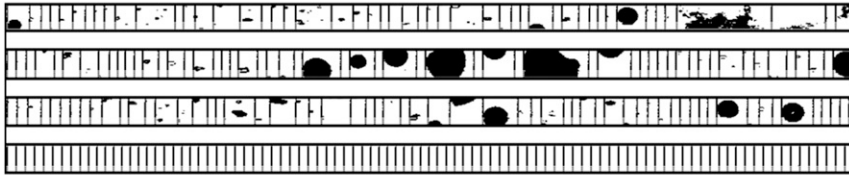
FIG. 17. As in Fig 15, but for the crossing L5 flown between 2034:30 and 2038:00 UTC when the aircraft was near the base of the radar reflectivity bright band showing (a) the aircraft-recorded relative humidity (%; dotted) and perturbation vertical velocity (m s⁻¹; solid) and (b) the FSSP concentration (shaded; cm⁻³) and (c) 2D-C concentration [log₁₀(N); shaded; L⁻¹] for diameters $D > 105 \mu\text{m}$. The white circle labeled L5 in each panel shows the time of closest approach to the MCR, as also indicated in Fig. 8. The solid white curve in (b) represents the FSSP concentration (cm⁻³) as given by the values in black found along the right ordinate. The solid red and dotted white curves in (c) represent the concentration (L⁻¹) of 2D-C particles from 105 to 400 μm and greater than 400 μm , respectively, as given by the values in black found along the right ordinate. The points labeled p1–p6 denote the times of the 2D-C images shown in Fig. 18.

effect of the observed apparent wave phase speed (calculated previously to be $\sim 14 \text{ m s}^{-1}$) is included in the calculation of l_m^2 . In this case, the value of l_m^2 in the stable melting layer greatly exceeds that in the surrounding layers because of the presence of a critical layer that happens to reside at the same level (Fig. 20c).

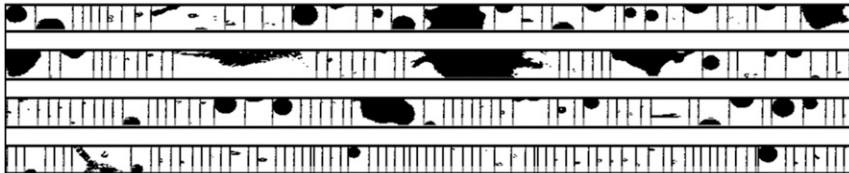
The rapid falloff in l_m^2 both above and below the melting layer indicates the possible formation of a waveguide near the melting level. To provide a qualitative sense of the permissible wavenumber range where trapping may occur, we approximate the atmospheric conditions shown in Fig. 20c as a three-layer system with each layer having a specified depth (h_i , where $i = 1, 3$ specifies the layer index from the lowest to highest layer) and constant values for the layer-mean Scorer parameter l_i^2 . We then numerically solve Eq. (7) of Zang et al. (2007; see also additional references therein) to determine the permissible values of the midlayer depth and Scorer parameter (h_2 and l_2^2) for given fixed constant value of the observed wavenumber k and representative settings for h_1 , l_1^2 , and l_3^2 of the upper and lower layers. The resulting relationship between l_2^2 and h_2 derived using $k = 2\pi/1.4 \text{ (km}^{-1}\text{)}$ is shown in Fig. 21. The plotted curve suggest that values of l_2^2 in excess of 60 km^{-2} and minimum stable-layer depth of h_2 of $\sim 300 \text{ m}$ would be required to allow such short observed wavelengths to become vertically trapped. A comparison of the l_m^2 structure obtained with and without the impacts of the wave phase speed (Figs. 20a,c) suggests that such a constraint would likely require a condition wherein the critical layer, as observed, happens to coincide with the location of the stable melting layer.

The above analysis is based on simplified assumptions made to make the problem somewhat more tractable. It is recognized that the derivation of N_m^2 as defined by Durran and Klemp (1982b), for example, does not account for the changes in the buoyancy-restoring force due to the ice–liquid-phase precipitation fluxes that could be expected near the melting level of mixed-phase precipitating stratiform cloud systems. The rapid production of numerous secondary ice particles within water-saturated updrafts based near the melting level, for example, could lead to rapid glaciation and the sudden release of latent heat that quickly alters the local updraft strength. Such changes are difficult to quantify analytically as they are dependent on the details of the cloud microphysical processes and the specific thermodynamic path taken by the parcels once they become displaced about their equilibrium levels. It can be anticipated that parcel displacements within liquid-dominated updrafts and ice-dominated downdrafts could lie, however, along separate adiabats and thus experience changes in the restoring force that alter the updraft–downdraft wave symmetry in a manner similar to that found in the liquid-only wave systems examined by Durran and Klemp (1982b). If such adiabats were to be further connected by isothermal

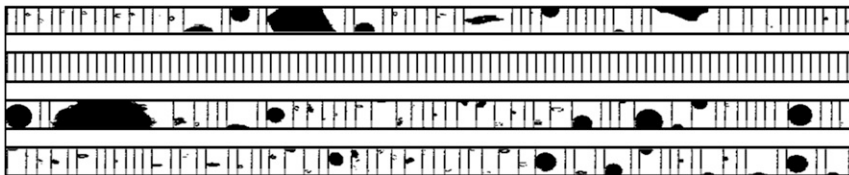
(a) p1 20:35:06



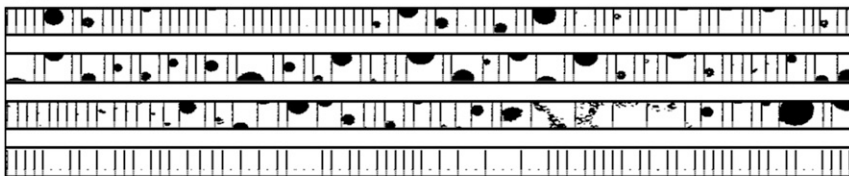
(b) p2 20:35:14



(c) p3 20:35:40



(d) p4 20:36:37



(e) p5 20:36:58



(f) p6 20:37:03



FIG. 18. As in Fig. 14, but for images recorded between 2036:06 and 2037:03 UTC during pass L5 when the aircraft was at an altitude of approximately 4450 m and a temperature of 2.0°C.

expansion and compression paths during the fusion and melting cycles, the circulation would present a reverse Carnot cycle requiring net energy input to maintain the circulation (perhaps from that present in the vertical wind shear). The great multitude of possible thermodynamic paths necessitate the use of

advanced mixed-phase numerical modeling frameworks to better quantify the parameter space governing the onset, structure, dynamics, and evolution of the mixed-phase melting-layer waves of the type presented in this observational study. Such models would further help elucidate the role of vertically

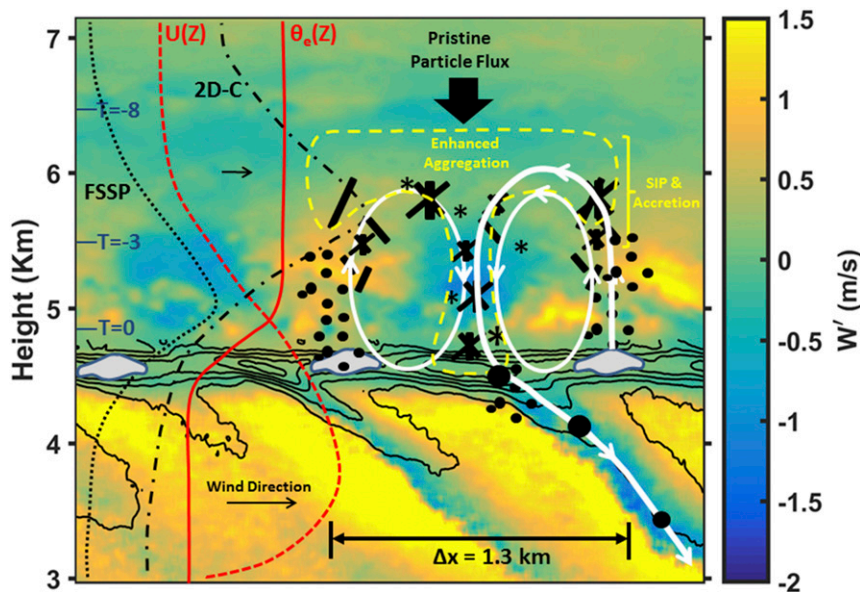


FIG. 19. Schematic model summarizing main observational findings for the 24 Aug 2010 melting-layer eddy structure. The shading represents the MCR Doppler-derived velocity perturbations (m s^{-1}). Solid black contours represent the radar reflectivity field near the bright band (near $z = 4.7$ km). The labeled solid and dashed red curves represent the environmental equivalent potential temperature θ_e and vertical wind shear $U(z)$ profiles, respectively. The labeled dash-dotted and dotted black curves represent the total 2D-C and FSSP concentration profile structures, respectively. The white curves with directional arrows represent the hypothesized circulation and fall streaks. Small and large solid black dots depict cloud drops and raindrops, respectively. Elongated black rectangles denote pristine needles, while needle aggregates and other crystals are denoted by the crossed black rectangles and asterisks. The dashed yellow curve represents the hypothesized zone of enhanced aggregation. The irregularly shaped gray scalloped patterns denote the hypothesized location of the observed billow clouds in relation to the Doppler circulation. The temperature ($^{\circ}\text{C}$) at selected levels is labeled along the left axis. The horizontal scale is shown in the lower-right portion of the plot. The thick black arrow denotes the downward flux of pristine ice crystals of various habits. The label SIP refers to secondary ice multiplication processes.

varying, rather than constant, l^2 profiles as found to arise here with the observed mixed-phase nimbostratus uncinus structure presented above.

5. Summary and conclusions

The structure of a melting layer was examined using a combination of in situ aircraft measurements and a unique Doppler radar operated by the U.S. Navy. High-fidelity radar observations allowed us to notice the structure of small-scale perturbation velocity couplets that developed in a conditionally unstable, negatively sheared layer located just above the level of the observed radar bright band. These couplets are hypothesized to be associated with the billow clouds observed in the all-sky camera images and to contribute to localized centers of enhanced reflectivity in the melting layer that continue downward below as periodic precipitation fall streaks. The coherence of this visual and radar-derived

structure, together with the pronounced sloping fall streaks, led us to refer to the billow clouds as nimbostratus uncinus in analogy to the more readily observed cirrus uncinus cloud structures. Quite surprisingly, this cloud layer may largely be hidden from view in precipitating stratiform cloud systems and was likely only revealed observationally here because of the time-lapse images of the layer that were recorded as a result of the dry intervening subcloud conditions found below the melting layer.

The similarity in periodicity between the observed billow clouds, Doppler-derived velocity couplets, and aircraft anomalies suggests that internal, and possibly vertically trapped, gravity waves generated at or near the melting layer were responsible for the observed structure. Factors governing the wave-trapping conditions of this system were examined and found to depend on a combination of environmental factors that led to a local maximum in the moist Scorer

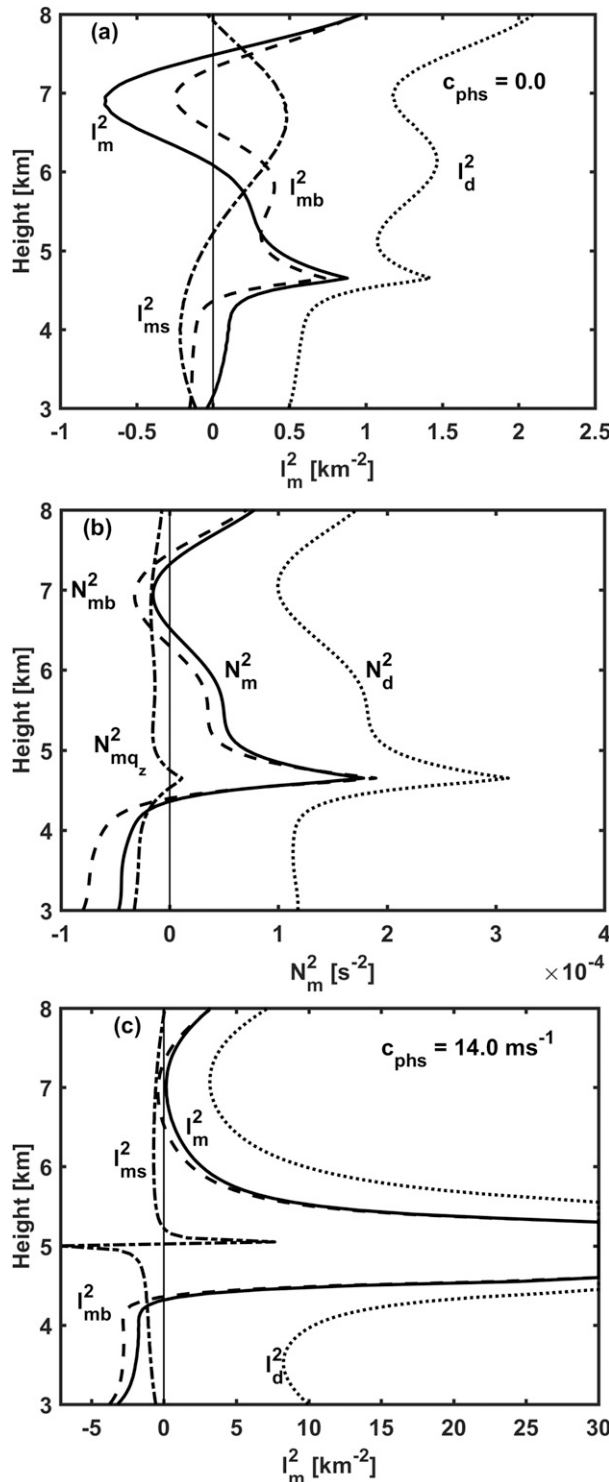


FIG. 20. Vertical profiles of (a) moist Scorer parameter l_m^2 (solid black curve; km^{-2}) with wave phase speed $c_{\text{phs}} = 0.0 \text{ ms}^{-1}$, (b) moist Brunt-Väisälä frequency N_m^2 (solid black curve; s^{-2}), and (c) l_m^2 (solid black curve; km^{-2}) with $c_{\text{phs}} = 14.0 \text{ ms}^{-1}$ for the idealized sounding profiles discussed in the text. Contributions to l_m^2 from the shear curvature $[U''(U-c)^{-1}; l_{\text{ms}}^2]$ and buoyancy

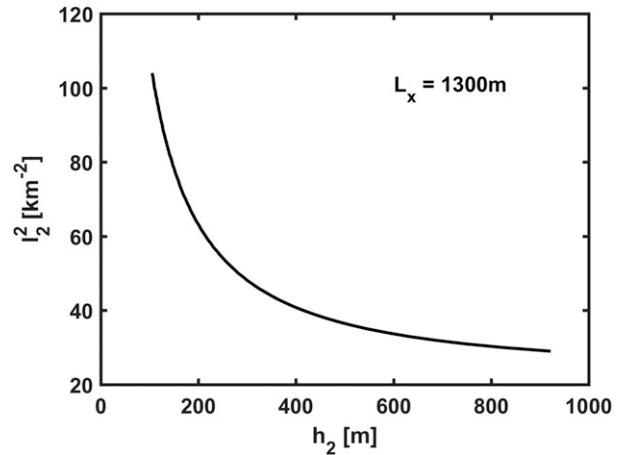


FIG. 21. The values of l_2^2 (km^{-2}) and h_2 (m) needed to support a wavelength $L_x = 1300 \text{ m}$, as derived from a numerical solution of Eq. (7) in Zang et al. (2007). The values of l_1^2 and l_3^2 were set to values of 3.0 and 1.0 km^{-2} , respectively, based roughly on the values shown in Fig. 20c. The solution is not sensitive to the depth of the lower layer h_1 for values in excess of $\sim 600 \text{ m}$.

parameter at the melting level. The results were dependent on the nature of the vertical total condensate profile near the melting level, the shear curvature set up by the environmental flow, and the presence of a critical layer. The structure of the condensate and shear profiles found in this study may not be atypical of other stratiform cases impacted by strong evaporation and diabatic cooling below the melting layer. The parameter space underlying the onset and dynamics of these mixed-phase velocity couplets could be further explored numerically to isolate their properties as well as any impact they may subsequently have on either the periodic nature of stratiform rainfall or overall system evolution.

←

$[N_m^2(U-c)^{-2}; l_{\text{mb}}^2]$ terms in (a) and (c) are given by the labeled dash-dotted curve and dashed curves, respectively. The contributions to N_m^2 in (b) arising from the vertical gradient of the total condensate (dq_w/dz ; N_{mqz}^2) and buoyancy terms $[N_{\text{mb}}^2(T, q_s, \theta)]$ are given by the labeled dash-dotted and dashed curves, respectively. The dry Brunt-Väisälä frequency N_d^2 and Scorer parameter l_d^2 are given by the labeled dotted profiles in (a) and (c). The MCR-derived mean LWC profile shown in Fig. 7c was used to estimate the vertical gradient of the total water content. The maximum value of l_m^2 was greater than 5600 km^{-2} and limited to a value of 30.0 km^{-2} in (c) for clarity. The thin vertical solid line is the zero reference value in each panel.

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