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Atmospheric structures in the troposphere as revealed by high-resolution backscatter images from MU radar operating in range-imaging mode

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Abstract

VHF band stratosphere/troposphere (ST) radars around the globe are seldom operated in range-imaging mode. As such, the typical range resolution of their backscatter images is about 150 m. The only exception is the Kyoto University's Middle and Upper Atmosphere (MU) radar in Shigaraki, Japan. Range imaging using frequency diversity was implemented there in 2005 and has often been used since then. During the Shigaraki UAV Radar Experiment (ShUREX) campaigns in the spring/summers of 2015, 2016, and 2017, the MU radar was operated in range-imaging mode to provide a range resolution of typically 20 m, for good signal to noise (SNR) ratios. The resulting Capon backscatter images revealed a variety of atmospheric structures in the moist troposphere in great detail. They were also quite useful in deploying in situ sensors on board unmanned aerial vehicles (UAVs) to probe such structures in near real time guided by the images. The goal of this paper is to present and discuss some such structures of interest to atmospheric dynamics collectively, to provide an overarching view. They include Kelvin-Helmholtz (KH) billows generated by shear instability, mid-level cloud-base turbulence (MCT) layers generated by convective instability in a moist troposphere, convective boundary layer (CBL), and sheet and layer (S&L) structures in a stably stratified atmospheric column. Videos of radar images collected during the 2015 and 2016 campaigns are included as Additional file 1 to demonstrate the fascinating, ever-changing evolution of atmospheric structures over the MU radar.

Keywords: VHF radar, MU radar, Range-imaging mode, Unmanned aerial vehicles, UAV, Turbulence kinetic energy, TKE, TKE dissipation rate, Stably stratified flows, Troposphere, Moist troposphere, Convective boundary layer, Mid-level cloud-base turbulence, MCT, Sheet and layer structures

Introduction

The Middle and Upper atmosphere (MU) radar is a Doppler-pulsed VHF radar operating at 46.5 MHz (6.45 m radar wavelength, 3.5 MHz bandwidth and 1 MW peak output power). It is located at Shigaraki, Japan (34.854061° N, 136.105606° E), 378 m above sea level (ASL). During the Shigaraki UAV Radar Experiment (ShUREX) campaigns, the radar was operated in range-imaging mode, using frequency diversity (called FII by Luce et al. 2001) at vertical incidence in 2015 and

three directions in 2016 and 2017, using five closely spaced frequencies between 45.0 and 47.0 MHz switched pulse to pulse, resulting in a high vertical resolution of ~20 m typically, compared to ~150 m in the normal operational mode. Under normal operation (non-range-imaging mode), five principal beams, one zenith, and four 10° off zenith (north, south, east, and west) are used, all at 46.5 MHz frequency. In the range-imaging mode, because the radar controller system imposes that the number of beams must be a multiple of the frequency number used, a total of 10 or 15 beams was programmed: five different frequency (45.0, 45.5, 46.0, 46.5, 47.0 MHz) beams along the zenith and along one or two other off-zenith directions (east in 2015 and east and

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north in 2016) were used. Luce et al. (2018a) have demonstrated that the high-resolution Capon images that range imaging produces are devoid of any “ghosts,” and therefore, the atmospheric features visible in the images are real. Therefore, the fine structures revealed by range imaging, such as the sheet and layer (S&L) structures (see below), are not spurious. This point is essential to the wide-spread acceptance and use of range imaging in routine operations of ST radars around the world.

Methods/Experimental

During all three campaigns (ShUREX 2015, 2016, and 2017), the UAV DataHawk, developed by Prof. Dale Lawrence at the University of Colorado, was flown near and above the radar to gather simultaneous data from the radar and from in situ sensors on the UAV, guided in real time by radar images. Radiosondes were also launched occasionally. The focus of the campaigns was measurement of turbulence in the lower troposphere. However, the resulting rich dataset also contains examples of a variety of atmospheric structures, which will be discussed in the next section. More details about the ShUREX campaign can be found in Kantha et al. (2017) and Luce et al. (2018a, b, c, d). An earlier campaign at Shigaraki called Tanuki 2011 (Wilson et al. 2014) also gathered high-resolution Capon images, but those will not be discussed here.

The goal of this paper is to present and discuss structures of interest to atmospheric dynamics we saw during ShUREX campaigns collectively, to provide an overarching view. Videos of radar images collected during the 2015 and 2016 campaigns are included as Additional file 1 to demonstrate the evolution of these atmospheric structures far better than one or two still images. To our knowledge, no such high-resolution videos displaying fine-scale atmospheric structures have ever been published. The paper also serves as an introduction to the videos.

Results and discussion

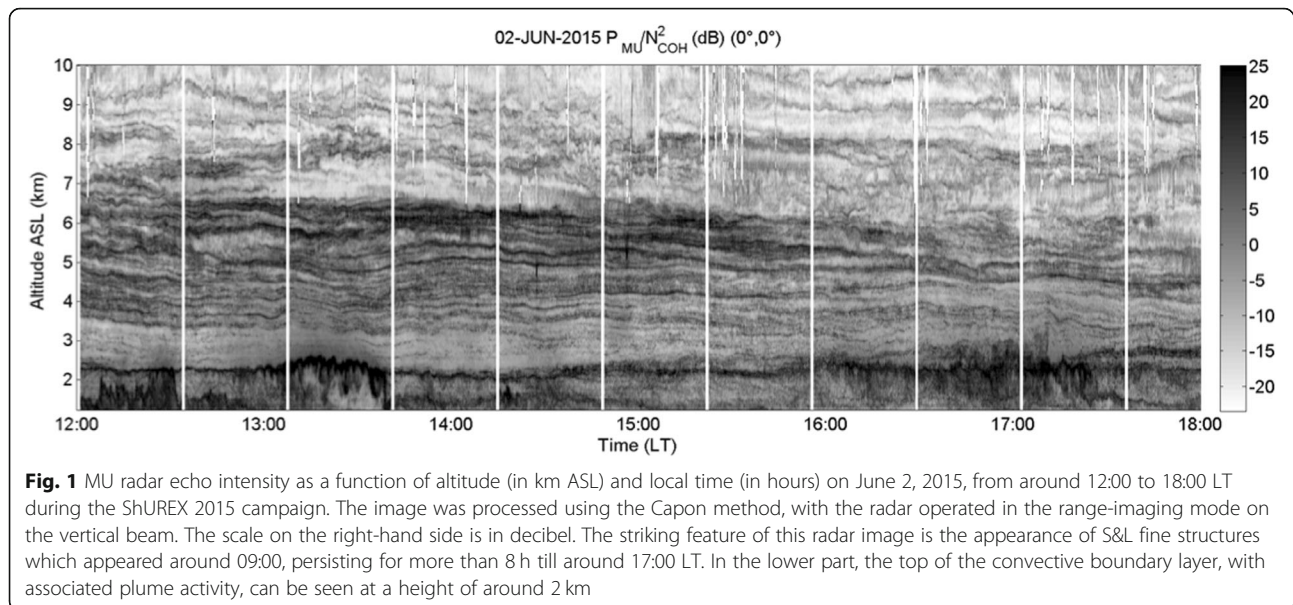
Typical atmospheric structures seen during ShUREX campaigns

The three ShUREX campaigns were conducted during spring/summers of 2015, 2016, and 2017 in the months of May and June, just prior to the onset of the rainy season in Japan. As such, we were able to capture a variety of atmospheric structures in the troposphere and were able to witness their evolution through high-resolution MU radar images. We present and discuss a few of them from the 2015 and 2016 campaigns here. It is important to point out that the dark, thin features seen in MU radar Capon images discussed below and presented in the movies, denote high humidity gradient sheet-like structures, which have high radar reflectivity

characteristics. The MU radar provided excellent high-resolution images extending from about 1.34 km (ASL) to 20 km (ASL) into the lower stratosphere. However, we will focus here on the troposphere only, since the presence of water vapor in the atmospheric column there gave rise to interesting atmospheric structures including, of course, clouds. In contrast, the atmosphere above 10 km consisted mostly and almost always of faint sheet and layer (S&L) structures, described below.

Figure 1 shows S&L fine-scale structures seen between 09:00 and approximately 17:00 LT during the ShUREX 2015 campaign. These structures consist of visually brighter layers of various depths, bounded by thin, dark sheets. The dark sheets result from strong humidity (and hence refractive index) gradients that affect the backscattered radar signal. Such structures were seen frequently and some persisted for hours (occasionally as long as 24–48 h), before dissipating. We do not see any significant gravity wave activity in Fig. 1. Neither do we see any shear-driven Kelvin-Helmholtz (K-H) instability. So the mechanism responsible for the generation (and dissipation) of such fine-scale structures is not clear, to us anyway. The top of the convective boundary layer (CBL) indicated by the dark sheet at an altitude (ASL) of about 2 km, with associated convective plume activity, can be seen throughout the period. A high degree of chaotic activity can also be seen inside the clouds above 6–7 km ASL (above the sheet-like structures).

Figure 2 shows the Capon image on June 30, 2016, from 12:00 to 18:00 LT during the ShUREX 2016 campaign. Intrusion of a dry but warm air mass over the colder, but moist, nearly saturated layer adjacent to the ground around 09:00 LT triggered the formation of the structure seen in the figure between roughly 3 and 4 km ASL. A radiosonde was launched at 14:58 LT, and the UAV itself carries temperature and humidity sensors, which confirm the existence of warm, dry (2% RH) air-mass above the colder, moist (98% RH) air-mass. Normally, one would expect the junction between the two air masses (at a height of 3 to 3.5 km) to consist of a sharp but stable interface, with a sharp change in humidity and hence refractive index. Therefore, we should see a single dark, strong high humidity gradient sheet. Instead, we see a turbulent “layer” sandwiched between two strong, high humidity gradient “sheets” located at 3 and 3.6 km altitude at 12:00 LT and extending to 18:00 LT in the figure, both sheets descending slightly and the sandwiched layer decreasing in depth. The upper sheet denotes the top of the moist air mass. The air above this sheet is nearly dry. The relative humidity (RH) decreases from nearly 100% in the cloudy air mass to nearly 0% above the upper sheet. The lower sheet occurs at roughly 50% RH point in this transition between the nearly 100% RH mass below and the nearly dry air



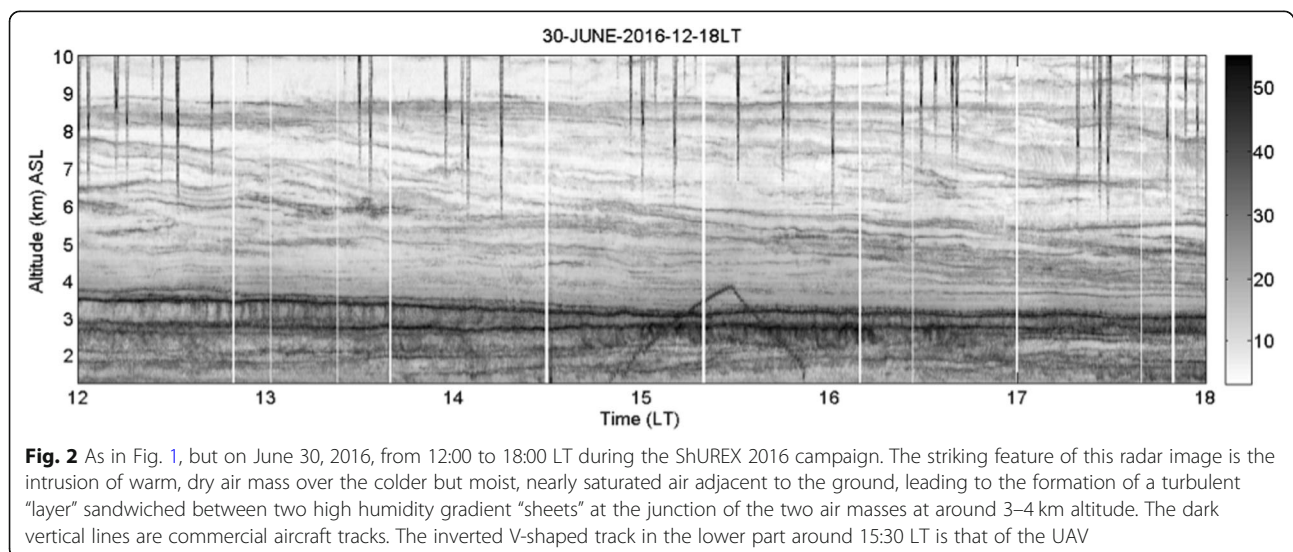
above. This feature persisted for more than 15 h, with the layer and sheets changing slowly with time. A similar feature was also observed during the 2015 campaign. The resulting elevated radar ducts could have an impact on radar propagation characteristics. The mechanism responsible for the generation of these structures is not known.

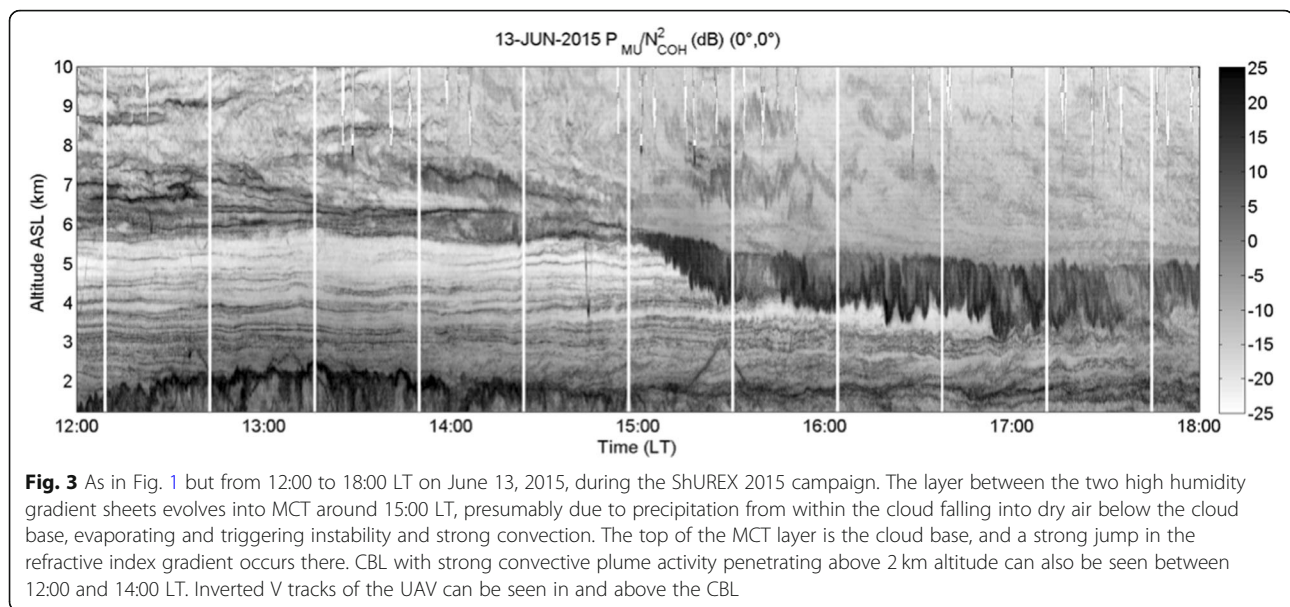
Mid-level cloud-base turbulent convective layers

Figure 3 shows a feature formed by two high humidity gradient sheets, with a turbulent layer in between, evolve into mid-level cloud-base turbulence (MCT) around 15:00 LT on June 13, 2015, during the ShUREX 2015 campaign. The MCT event is triggered by precipitation from within the cloud (hint of which can be seen above the cloud base

in the radar image) falling into the dry air below the cloud base, evaporating and triggering instability and strong convection. The dry air layer below the cloud base prior to the MCT event can be seen clearly between 12:00 and 15:00 LT. The top of the MCT layer is the cloud base, and a strong jump in the refractive index gradient occurs there (and also at the bottom of the MCT layer). Such MCT can persist for a few hours, before convection weakens and ceases. MCTs were routinely observed during the 2015 and 2016 campaigns.

Luce et al. (2010) were the first to present evidence of MCT from lidar and MU radar observations, and Kudo (2013) was the very first to investigate MCT as the probable cause of moderate turbulence encountered by pilots around Japan, under certain conditions during summer.





Through numerical simulations, he showed that such turbulence was not caused by shear instability of the Kelvin-Helmholtz type, but it was more likely due to precipitation below the bases of mid-level clouds, which triggered Rayleigh-Taylor instability due to the sublimation of ice/snow particles and consequent cooling of the drier air mass below the cloud base. Kudo et al. (2015) followed up and presented observations of MCT during the Tanuki 2011 campaign at the MU radar site in Shigaraki, Japan, when some radiosondes launched during the campaign managed to sample the MCT, with the MU radar operating simultaneously in a high-resolution mode to provide vivid images of radar backscatter depicting the MCT structure. MU radar measurements of vertical velocities and turbulence kinetic energy (TKE) were presented along with in situ measurements by the sondes, and compared with numerical simulations.

Mid-level cloud-base turbulence (MCT) can occur under synoptic conditions where a moist air mass is advected over a dry one. Around Japan, it occurs typically during the rainy season (Kudo 2013). In spite of the fact that the first article on MCT was published in 2010 (Luce et al. 2010) and was followed up by Kudo (2013), Wilson et al. (2014), and Kudo et al. (2015), very little additional work has been done on MCT until Kantha et al. (2019) cataloged and presented MCT events observed during the 2015 and 2016 campaigns. They also present a one-dimensional, second moment closure-based model of turbulent mixing in the MCT layer, with the event observed on June 13, 2015 (Fig. 3) used as an example.

Kelvin-Helmholtz instability and billow structures

A principal mechanism for generation of turbulence in a stably stratified fluid column is shear instability. When

the governing gradient Richardson number falls below a value of around 0.25, Kelvin-Helmholtz (KH) instability occurs with ensuing billow-like structures, which almost always dissolve into fully developed turbulence. KH instability (KHI) and KH billows were seen frequently during the ShUREX campaigns. Figure 4 shows a textbook example of KH billows generated inside the mid-level cloud just above the cloud base at around 14:40 LT, with MCT occurring concurrently below the cloud base. A similar event that occurred on June 11, 2015, was analyzed and discussed in detail by Luce et al. (2018d).

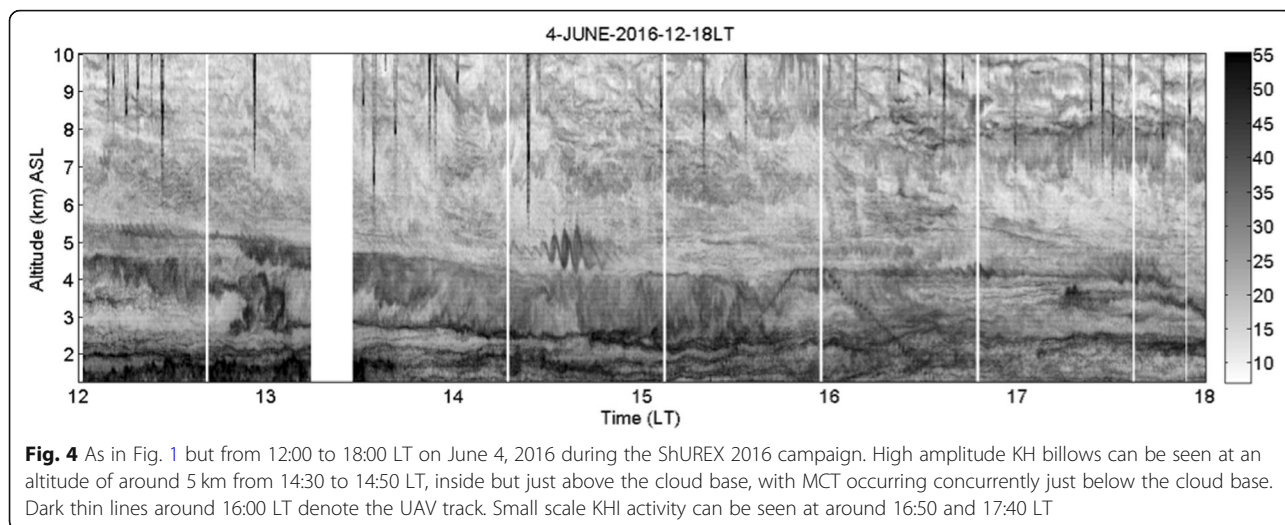
The decay of MCT was often accompanied by small-scale KHI activity at the cloud base. Examples of this can be seen in Fig. 4 at 16:50 and 17:40 LT.

Convective boundary layer

On several days during the campaigns, the solar heating was strong enough to generate vigorous convective activity in the planetary boundary layer. One example of that is shown in Fig. 5, where the top of the CBL has reached just beyond 2 km altitude. It was possible for the UAV to probe that CBL. UAV tracks can be seen as thin lines.

Sheet and layer (S&L) structures

Most often, the atmospheric column displayed very stable and persistent S&L structures, with little turbulence activity apparent. This was especially true of the 2017 campaign, when the onset of the rainy season was delayed. One such example can be seen in Fig. 5. The S&L structures were made visible by the high radar reflectivity of the high humidity gradient sheets. Such structures were very persistent and often lasted for more than 24–48 h. Turbulence, if any, in faint layers between

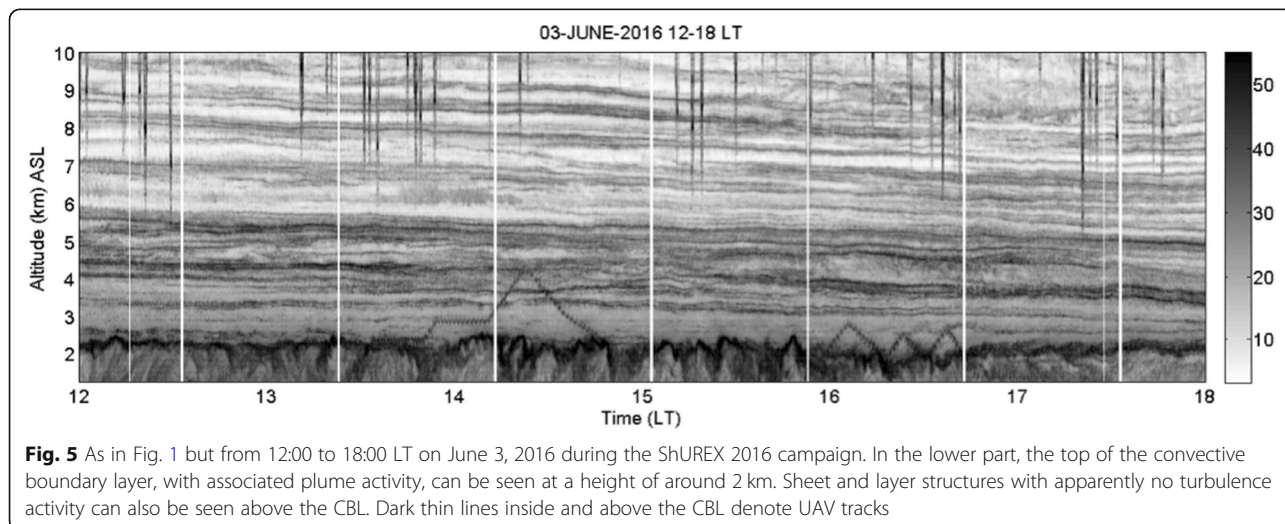


the dark sheets could not be reliably measured by sensors on board the UAVs. The mechanism causing and maintaining such S&L structures and the degree of impact on atmospheric dynamics are not clear to us. Chuda et al. (2007) have advanced a plausible mechanism for S&L structures seen in radiosonde profiles, but it is not clear if it is applicable to at least some of the S&L fine structures observed in the high-resolution radar images during the ShUREX campaigns. Clearly, more studies are needed.

Structures with wave-like oscillations

On one occasion during the three campaigns, on June 9, 2015 (Fig. 6), we saw a strong MCT occur below the cloud base located at 5–6 km altitude (ASL). The lower edge of the MCT layer (dark region with vertical

striations) was located between 3.5 and 4.5 km, with prominent indentations created by convective plume activity inside the MCT layer. Perhaps due to appropriate stable stratification below the cloud base, these indentations produced wave-like structures in the atmospheric column beneath the MCT layer down to 1.34 km (ASL). These wave-like oscillations probably extended all the way to the ground, but the radar is unable to see below 1.34 km. These structures appear to be phase-locked with indentations at the lower edge of the MCT layer caused by vigorous convective plume activity inside the MCT layer. The period of the oscillations ranges between 4 and 8 min. It appears that these are forced oscillations produced by strong convective plume activity inside the MCT. This phenomenon requires further study.



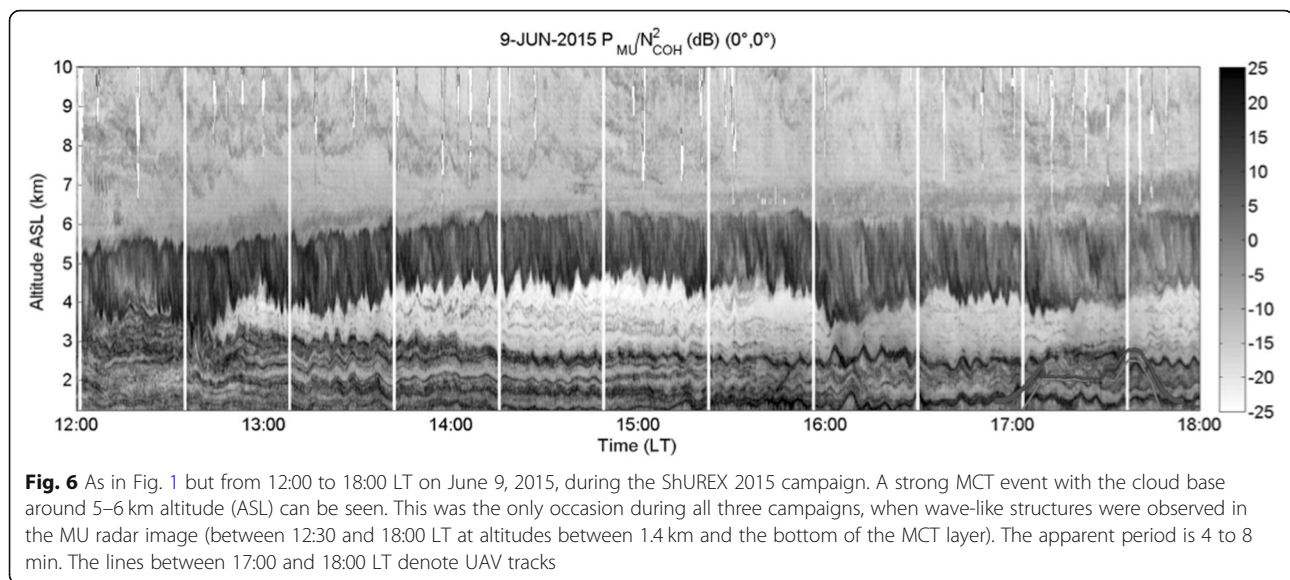


Fig. 6 As in Fig. 1 but from 12:00 to 18:00 LT on June 9, 2015, during the ShUREX 2015 campaign. A strong MCT event with the cloud base around 5–6 km altitude (ASL) can be seen. This was the only occasion during all three campaigns, when wave-like structures were observed in the MU radar image (between 12:30 and 18:00 LT at altitudes between 1.4 km and the bottom of the MCT layer). The apparent period is 4 to 8 min. The lines between 17:00 and 18:00 LT denote UAV tracks

Conclusions

The high-resolution Capon images from the MU radar, operated in range-imaging mode (Luce et al. 2001, Luce et al. 2010, Luce et al. 2018a) during the ShUREX campaigns revealed a variety of atmospheric structures in great detail. It was also possible to see their evolution in time. We have presented and discussed some examples of such structures of potential importance to atmospheric dynamics. However, it is best to see videos of the radar images to appreciate the evolution of these features. As such, we have presented the videos as Additional file 1. It is our hope that these videos persuade ST radar operators around the world to implement range-imaging mode of operation on at least the vertical beam of their radars, so that it is possible to visualize the evolution of atmospheric features above those radars.

Additional file

Additional file 1: Videos of atmospheric structures observed during ShUREX 2015 and 2016. (MOV 1230 kb)

Abbreviations

ASL: Above sea level; CBL: Convective boundary layer; KH: Kelvin-Helmholtz; MCT: Mid-level cloud-base turbulence; MU: Middle and Upper atmosphere; RH: Relative humidity; RISH: Research Institute for Sustainable Humanosphere; S&L: Sheet and layer; ShUREX: Shigaraki UAV Radar Experiment; SNR: Signal to noise ratio; ST: Stratosphere troposphere; UAV: Unmanned aerial vehicle; VHF: Very high frequency

Acknowledgements

LK thanks the Japanese Society for Promotion of Science (JSPS) for providing partial funding for the ShUREX 2016 campaign. The hospitality of RISH personnel and director Prof. Tsuda to their visitors is exemplary.

Funding

This study was supported by JSPS KAKENHI Grant Number JP15K13568 and the research grant for Mission Research on Sustainable Humanosphere from

Research Institute for Sustainable Humanosphere (RISH), Kyoto University. The MU radar belongs to and is operated by RISH, Kyoto University.

Availability of data and materials

MU radar images are available on RISH website as indicated in Additional file 1.

Authors' contributions

HL collected and analyzed the MU radar data and assisted LK in the interpretation of the structures revealed. LK organized and participated in the ShUREX campaigns. HH oversaw the ShUREX campaigns. AD produced the videos from Capon images. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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Received: 1 November 2018 Accepted: 22 February 2019

Published online: 29 March 2019

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