Modeling and polarimetric radar studies of single- and multi-layered Arctic mixed-phase clouds

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Introduction

Our research objective is to advance the understanding of Arctic mixed-phase clouds through remote sensing observations and multi-scale dynamical and microphysical modeling. In this poster we present three recent studies in our group to reach this objective:

1. **Simulations of a single-layered mixed-phase cloud to examine the response of the supercooled liquid cloud to ice precipitation falling into it from above**
2. **A modelling study to understand the formation mechanism of the lower level cloud in an observed case of multi-layered mixed-phase clouds**
3. **Comparisons of bin microphysical model output with radar observations via a radar forward simulator to evaluate the impacts of vapor depositional growth on the polarimetric radar variables**

Dynamical responses of an Arctic mixed-phase cloud to ice seeding

Motivation

- In multi-layered Arctic mixed-phase clouds, the lower levels are often embedded in ice showers from upper layers.
- In this study we focus on the dynamical response of a single-layered mixed-phase cloud to prescribed ice seeding.

Model

- Regional Atmospheric Modeling System in Large Eddy Simulation mode[1,2] with bulk microphysics for cloud liquid and pristine ice.
- Ice particles represented as spheroids with adaptive habit[3,4].

Experiment

- 100 km by 2 km 2D domain, with resolution of 50 m by 10 m.
- Idealized profile based on Barrow NWS sounding launched at 2013.05.02 23Z[5].
- Seeding starts 3 hr after the beginning of the simulation over central 15 km of the domain at liquid cloud top.
- Thick/Thin clouds seeded with 0.5/1.0 mm/day ice flux.

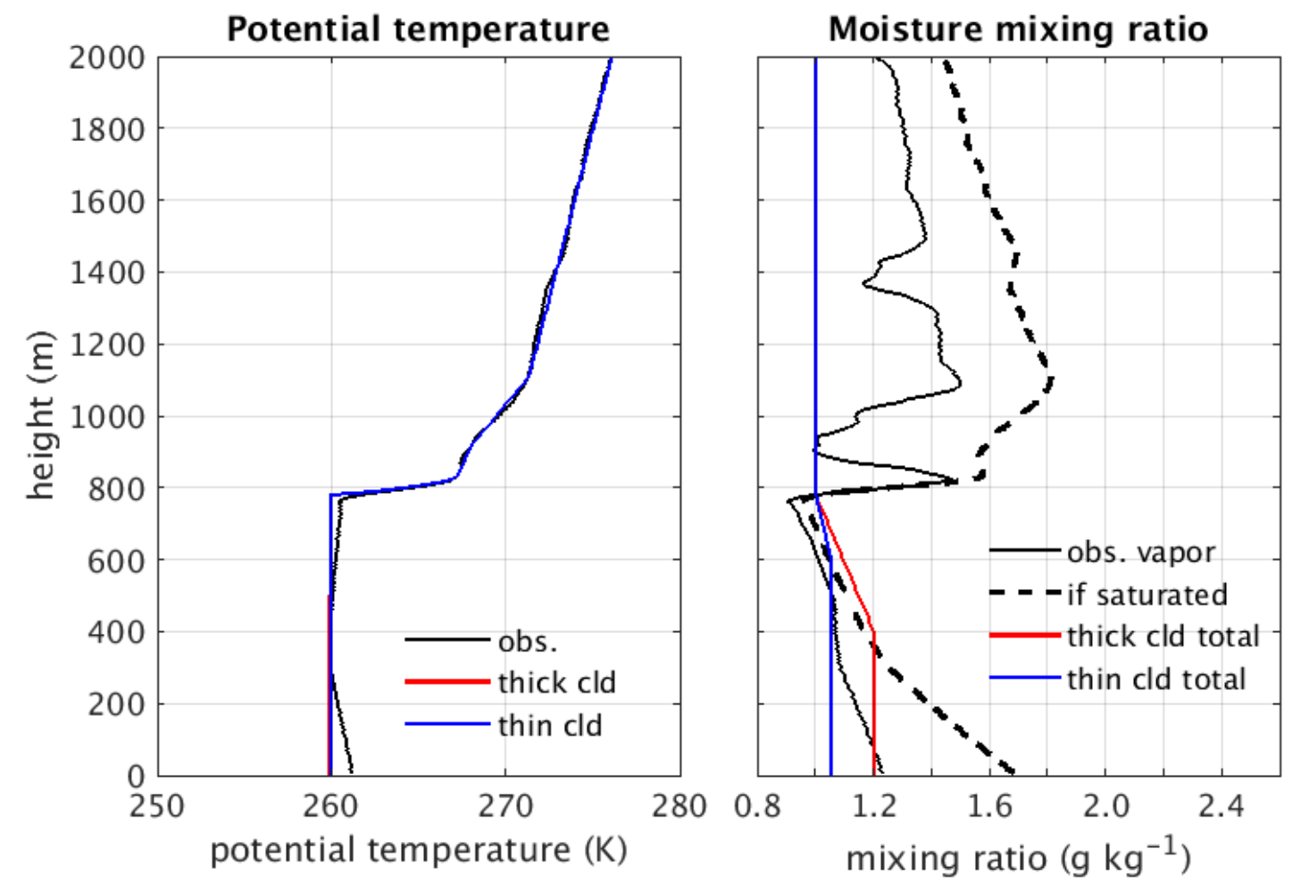

Fig. 1. Observed sounding and idealized profiles for the simulation. The observation is from the Barrow sounding launched around 2013.05.02 23Z at the NWS site near NSA. Horizontal wind is set to zero for simplicity.

Results

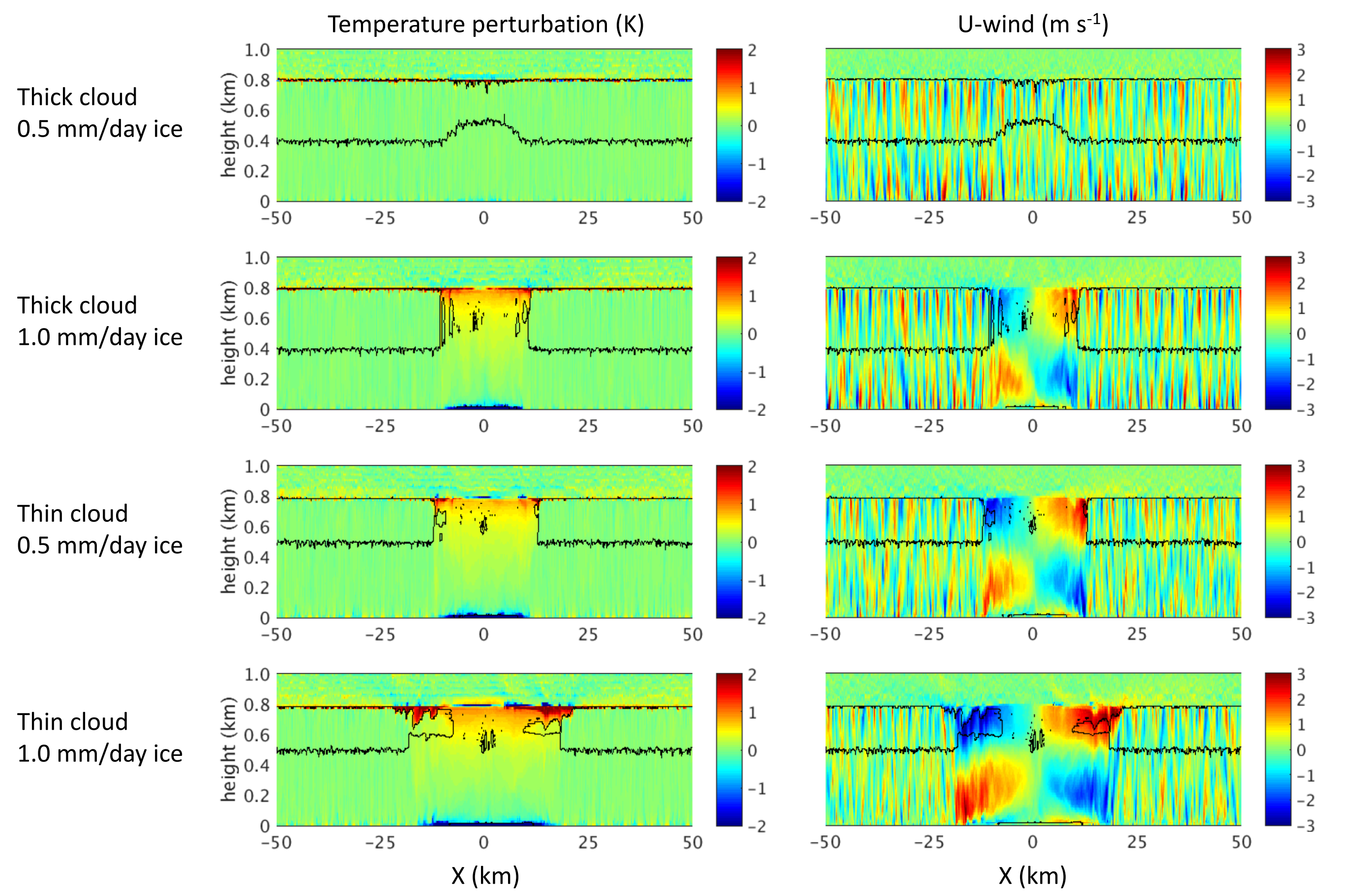

Fig. 2. Temperature perturbation and horizontal wind at 7.5 hr from the simulations of 4 different configurations. Black contours show liquid cloud boundary. 0.5 mm/day ice flux is insufficient to create a gap in thick cloud at this moment. In other three simulations, the seeding results in a warm bubble which then expands. Mixing of warmer air from the inversion layer downward increases the temperature perturbation. The mesoscale horizontal flow accelerates from the center of seeded region towards the unperturbed cloud, forcing a strong downdraft in the neutral air adjacent to the gap.

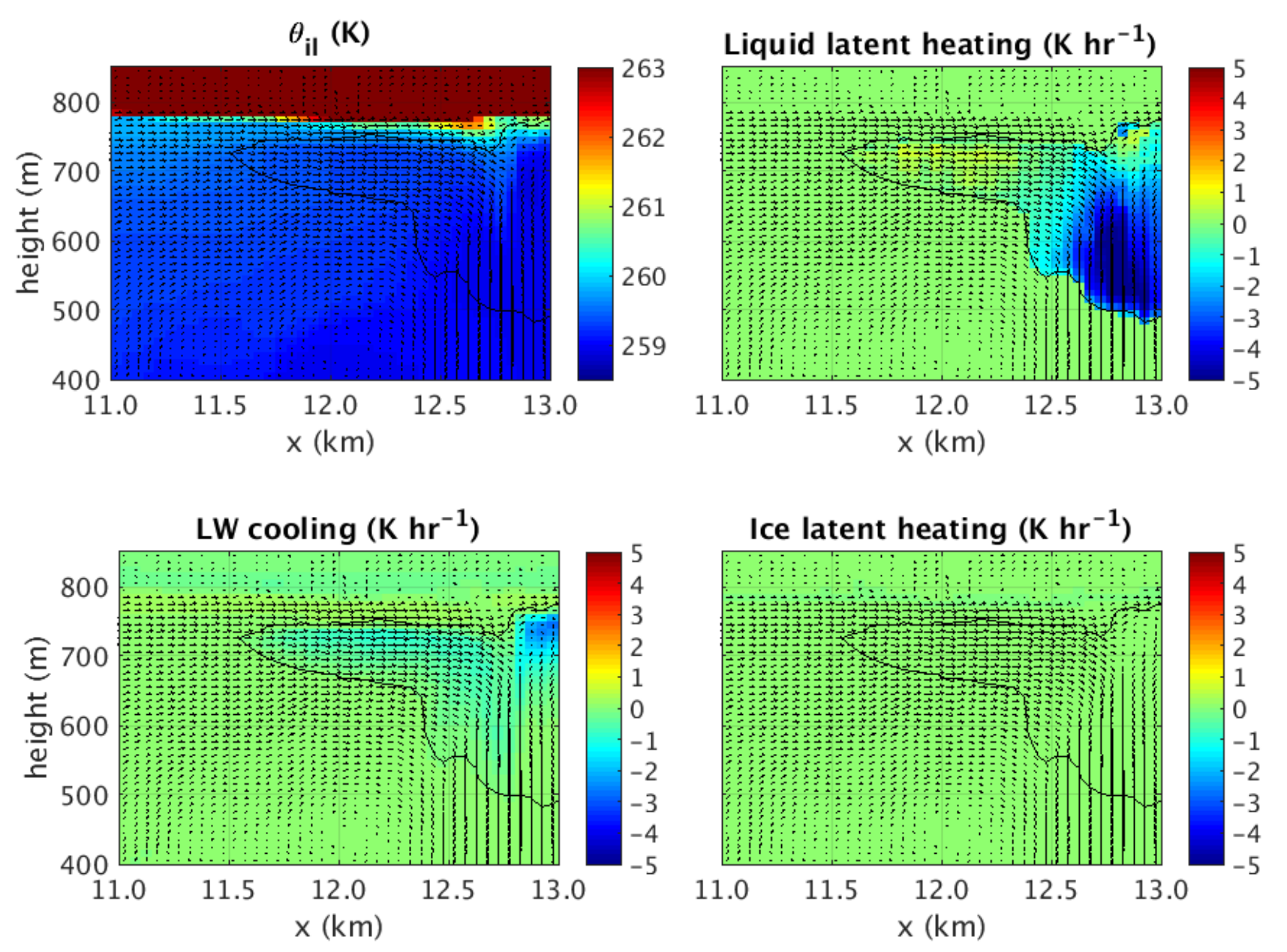

Fig. 3. A subregion in the domain of the simulation for the thin cloud with 0.5 mm/day ice at 7.45 hr. Strong downdraft like the one around 12.75 km vaporizes the liquid cloud. Although the cloud keeps precipitating ice, the associated latent heat is contributing less to the dissipation of liquid. Subsidence and mixing across the inversion base contributes to the warming of the clear air. Since the air below the inversion base has lowest temperature and vapor content, longwave radiation warms it up while cools the upper part of the liquid cloud.

Large eddy simulation of Arctic multi-layered mixed-phase stratocumulus clouds

Objective

Examine the formation of Arctic multi-layered mixed-phase stratocumulus clouds with large eddy simulation (LES) in the Weather Research and Forecasting (WRF) model.

Case Study Period

On 2 May 2013 a weak surface trough extended from the north towards Barrow, Alaska, with Arctic multi-layered mixed-phase stratocumulus occurring from 05:00 UTC to 10:00 UTC on this day.

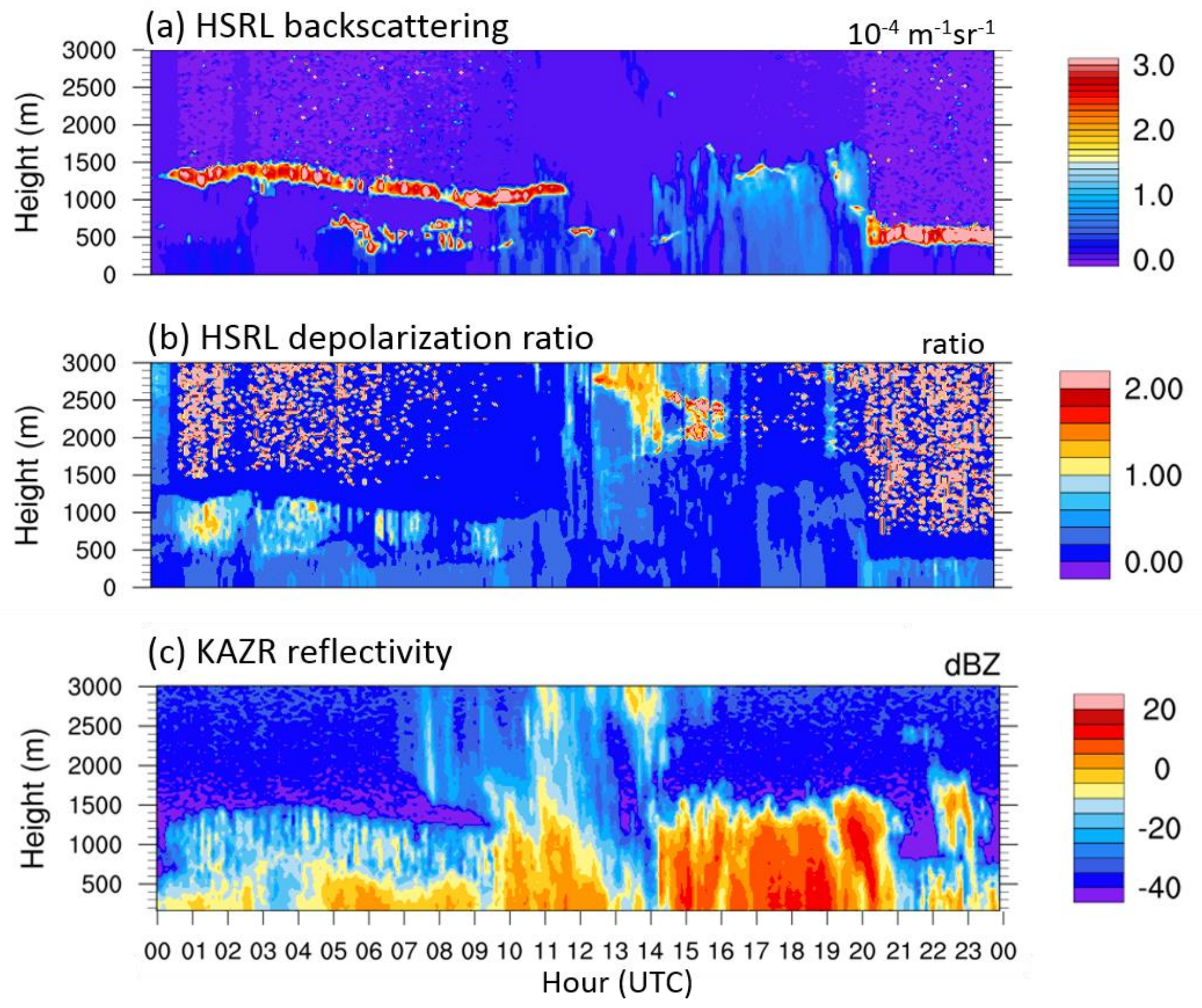

Fig. 4. Height versus time cross sections of (a) HSRL backscattering, (b) HSRL depolarization ratio, and (c) KAZR reflectivity on 2 May 2013.

Model Setup

WRF V3.6.1

- Simulation time: 18:00 UTC 1 May 2013 – 00:00 UTC 3 May 2013.
- Initial conditions: NCEP FNL combined with ERA-interim.
- Horizontal resolution: 4 nested domains with 25 km, 5 km, 1 km, and 0.2 km resolution.
- Vertical resolution: 130 levels with 33-m resolution within the boundary layer.
- The 1-km and 0.2-km resolution domains are LES domains.

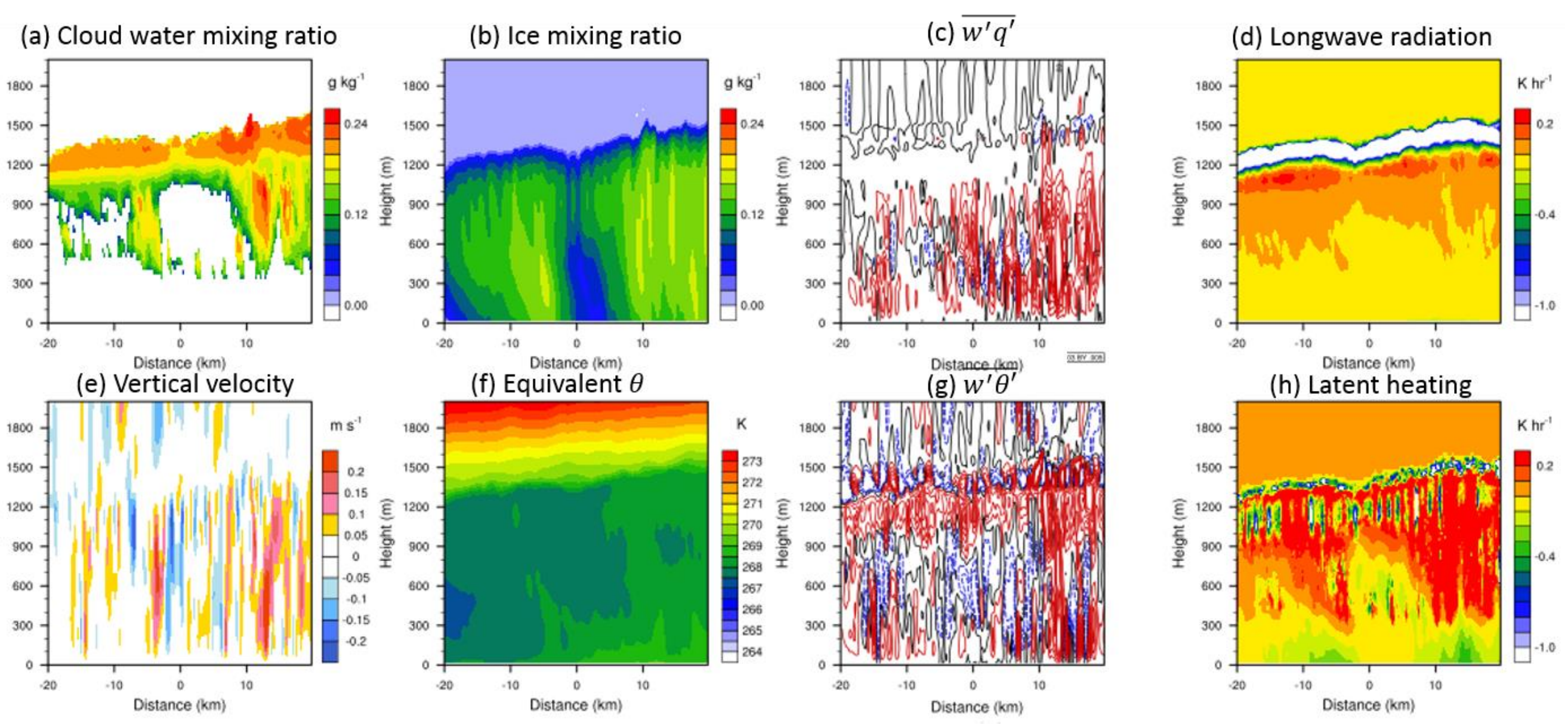

Fig. 5. Height versus latitude (in km) meridional means of (a) cloud water mixing ratio, (b) ice mixing ratio, (c) vertical water vapor flux, (d) potential temperature tendency due to longwave radiation, (e) vertical velocity, (f) equivalent potential temperature, (g) vertical heat flux, and (h) potential temperature tendency due to latent heating from the 0.2-km resolution domain at 0340 UTC 2 May 2013.

Results

- In the 0.2-km resolution domain LES resolved one deep convective line with boundary layer clouds topped by a temperature inversion at 1500 m and one weak convective line with cloud tops at 1200 m and with a second lower layer of clouds around 400 - 600 m.

- Entrainment at the top of the boundary layer caused evaporation of cloud and decreased latent heating. Moreover, there was strong radiative cooling at cloud top. These two cooling processes induced strong downdrafts and stabilized the sub-cloud layer.

- In the stable sub-cloud layer the deep convective line with stronger vertical moisture and heat fluxes extended from the surface to the top of boundary layer, while the weak convective line only extended to 400 - 600 m, forming lower layer clouds.

- To better understand the dynamic and thermodynamic processes that drive the formation of Arctic multi-layered mixed-phase stratocumulus clouds, we will examine how the synoptic scale system initiated these convective lines and formed and maintained the multi-layered mixed-phase stratocumuls clouds.

Observations and simulations of polarimetric radar variables at Oliktok Point, AK

Motivation

- How do the polarimetric radar variables evolve as ice particles grow by vapor deposition in different thermodynamic conditions?

Observations

- Polarimetric radar observations from KaSACR.
- Interpolated soundings (interpsonde product)
- Focus on cases where ice growth is dominated by vapor deposition.

Cloud model

- Bin microphysics for ice particles represented by spheroids whose bulk density and aspect ratio evolve as functions of temperature and ice supersaturation[3].
- 2D fixed flow field consists of vertical cells with maximum updrafts of 0.1 m/s
- Initial lapse rate of 6°C/km, surface temperature of -8°C, and constant RH w.r.t. liquid of 85% based on observations.

Forward model

- Consistent ice particles in scattering calculation and bin model.
- Polarimetric radar variables simulated using the Rayleigh approximation[6].

ARM-KaSACR RHI – 08 November 2016 12:30 UTC

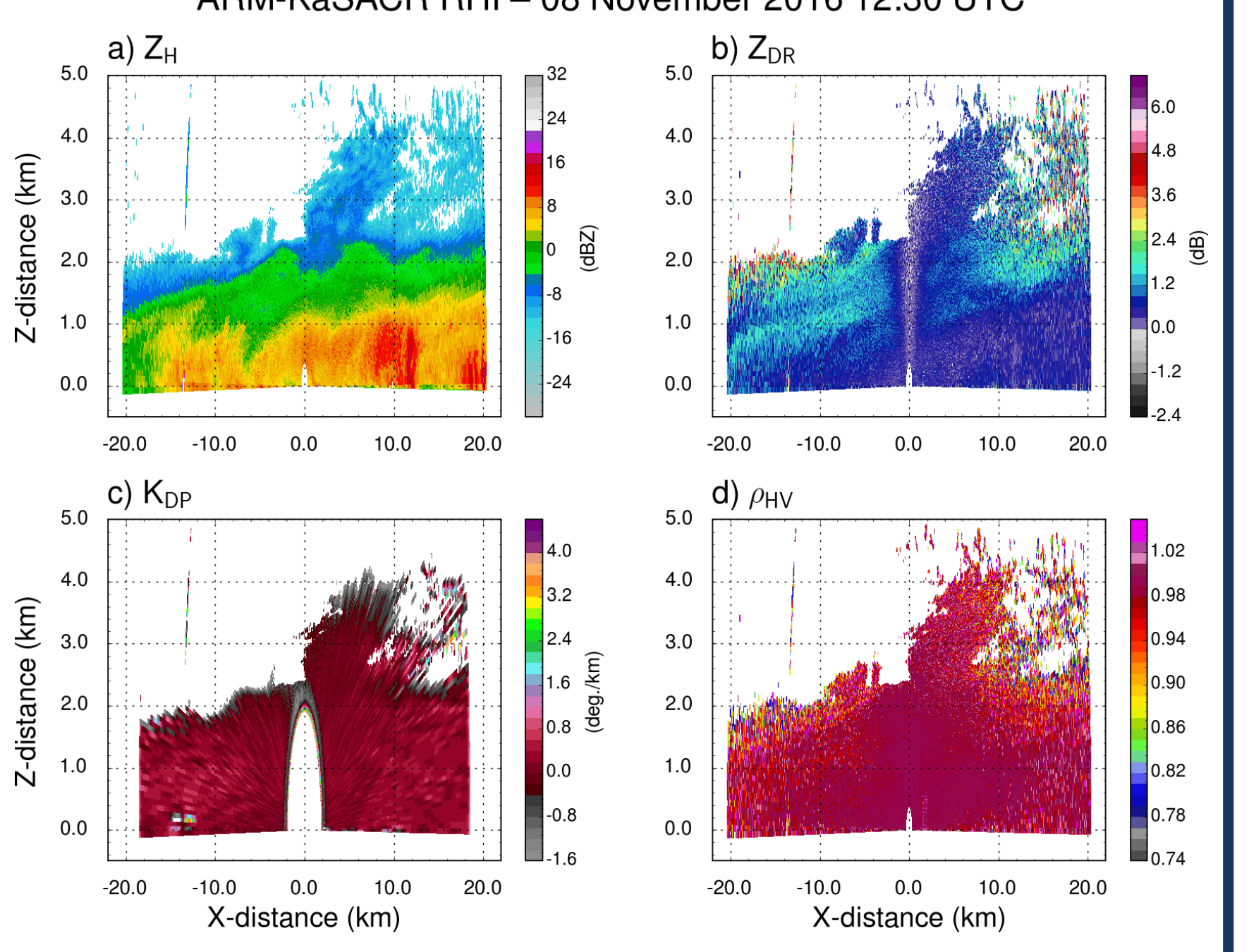

Fig. 6. Images of a) reflectivity at horizontal polarization (Z_H), b) differential reflectivity (Z_{DR}), c) specific differential phase (K_{DP}), and d) co-polar correlation coefficient (ρ_{HV}) from a range height indicator (RHI) scan taken by the KaSACR radar at the ARM Oliktok Point site on 8 November 2016 at 12:30 UTC. Enhanced Z_{DR} between 0.5-2.0 km above radar level (ARL), enhanced K_{DP} between 0.5-1.5 km ARL, and temperatures between -20 °C and -10 °C suggest planar crystal growth.

Bin model output (1 hour) - simulated radar variables at Ka band

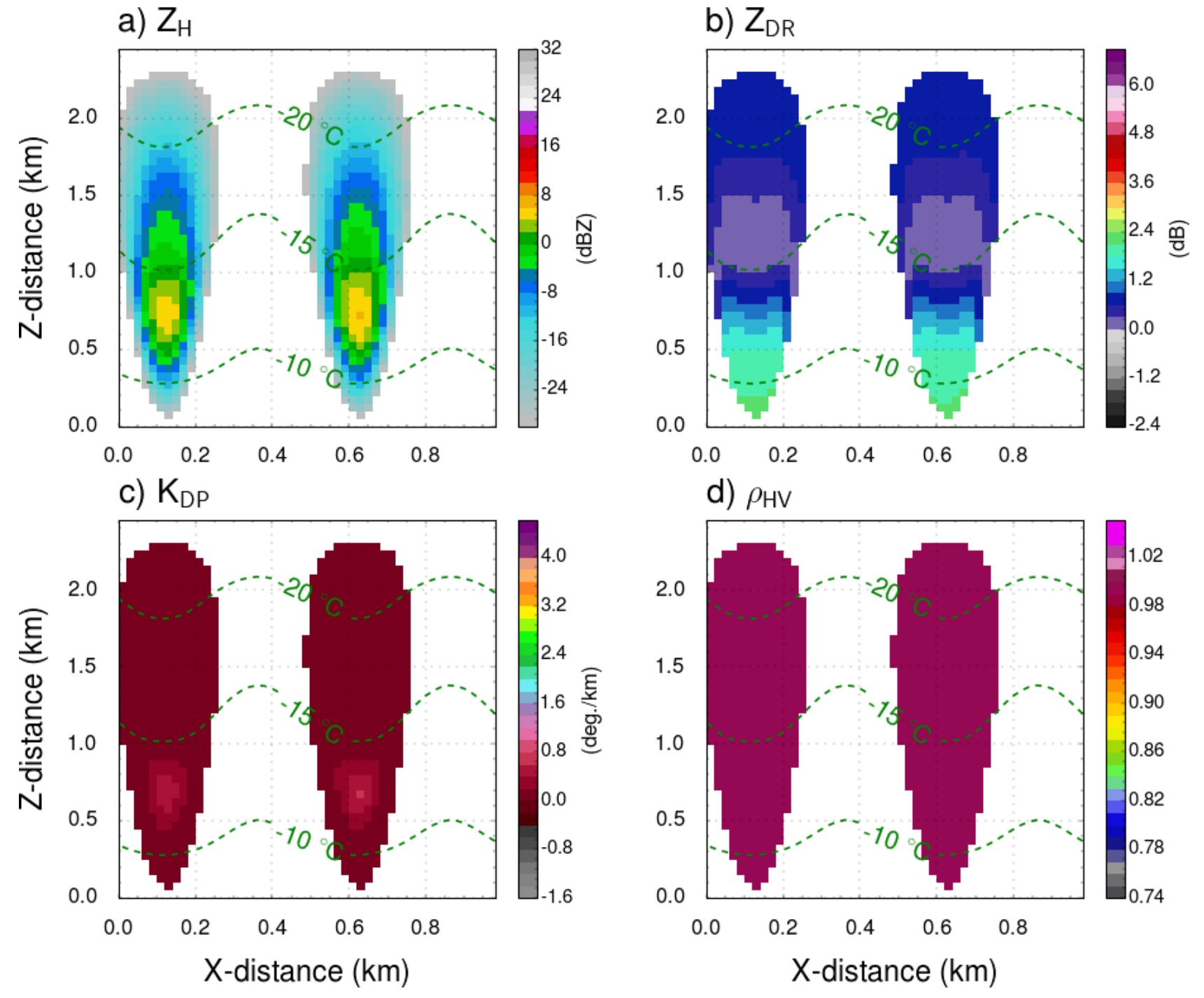

Fig. 7. Images of simulated a) Z_H, b) Z_{DR}, c) K_{DP}, and d) ρ_{HV} from a one-hour simulation of vapor deposition using the bin model. Contours of temperature are indicated by the green dashed lines and are labeled as indicated.

Results

- The bin model-simulated radar variables show increasing Z_H, Z_{DR}, and K_{DP} towards the ground near -15°C, similar to the KaSACR observations.

- The simulated Z_H is lower than the observed Z_H and simulated Z_{DR} values increase towards the ground; observed Z_{DR} values decrease towards the ground.

- These differences may be a result of aggregation and riming during this case (not included in our model) increasing the size of the largest particles, decreasing Z_{DR} and increasing Z_H.

- More realistic scattering calculations are needed to understand these errors in the forward operator and improve comparisons with the radar observations.

- We also plan to explore the sensitivity of the simulations to perturbations in the thermodynamic conditions and the flow field.

References

1. Petters *et al.* (2012), Radiative-dynamical feedbacks in low liquid water path stratiform clouds. *J. Atmos. Sci.*, **69**, 1498—1512.
2. Ovchinnikov *et al.* (2014), Intercomparison of large-eddy simulations of Arctic mixed-phase clouds: Importance of ice size distribution assumptions. *J. Adv. Model. Earth Syst.*, **6**, 223—248.
3. Harrington *et al.* (2013a), A method for adaptive habit prediction in bulk microphysical models. Part I: Theoretical development. *J. Atmos. Sci.*, **70**, 349—364.
4. Harrington *et al.* (2013b), A method for adaptive habit prediction in bulk microphysical models. Part II: Parcel model corroboration. *J. Atmos. Sci.*, **70**, 365—376.
5. Oue *et al.* (2017), Manuscript in preparation.
6. Ryzhkov *et al.* (2011), Polarimetric radar observations operator for a cloud model with spectral microphysics. *J. Appl. Meteor. Climatol.*, **50**, 873—894.

Acknowledgements

The presented work is supported by the U.S. Department of Energy via Grant No. DE-SC0013953.