A high-level analysis of complex Arctic mixed-phase cloud dynamics

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Scale growth is an inherent property of shallow cumulus convection

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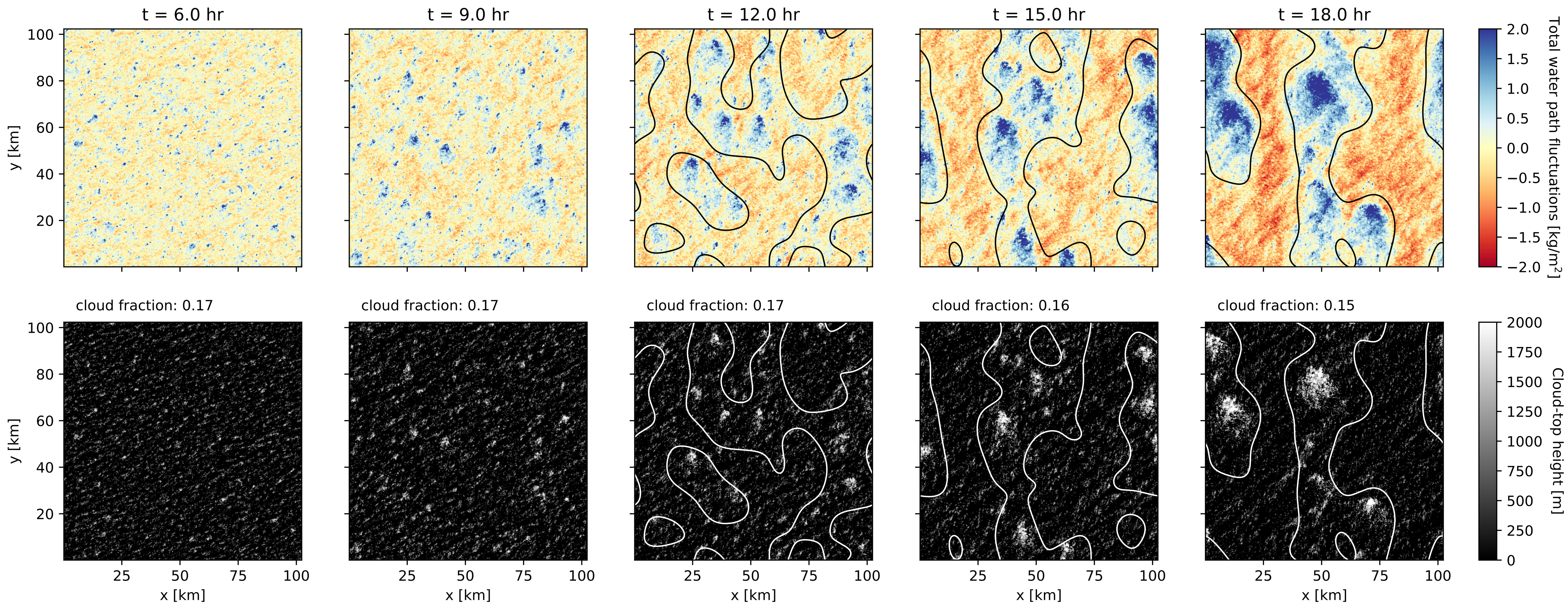
In LES, shallow convection self-organises into mesoscale clusters without cold pools or radiation anomalies



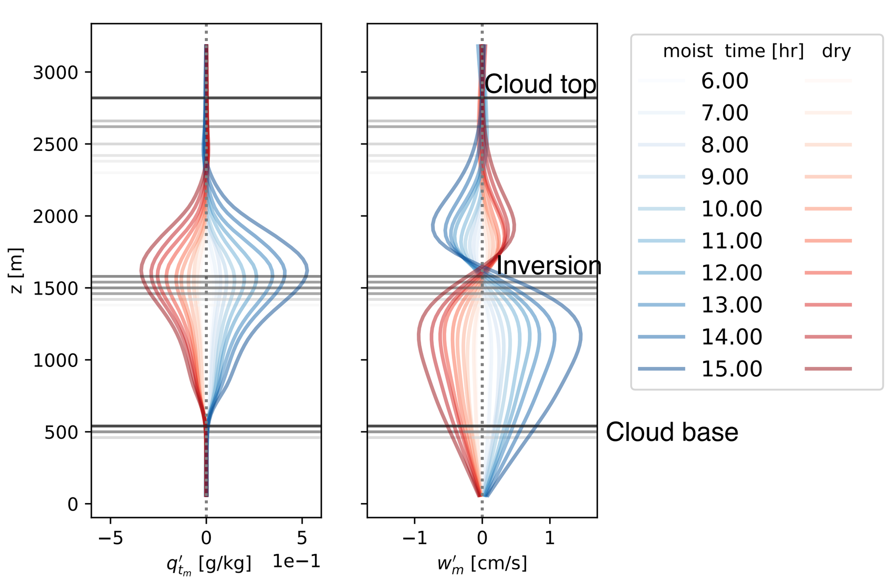
Numerical experiments

- **Case** BOMEX as in Siebesma et al. (2003)
- **Model** Dutch Large Eddy Simulation, MicroHH
- **Domain** $L_x = L_y = 102.4 km$
- **Grid** $\Delta x \in [50, 100, 200] m$, $\Delta z = 40m$
- **Advection** $O(2)$ central differences, $O(5)$ (Wicker & Skamarock, 2002)
- **Physics** Highly idealised setup
  - Imposed, homogenous radiative cooling
  - No precipitation
  - Constant, homogenous surface fluxes

Following Bretherton & Blossey (2017), we diagnose a positive moisture-convection feedback

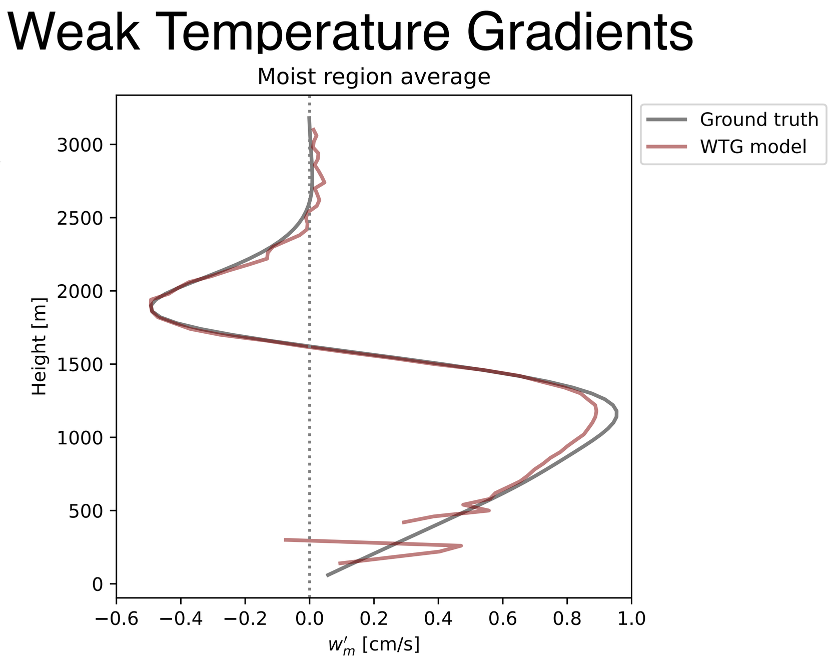
Mesoscale **moisture fluctuations** q'_{t_m} grow in cloud layer on ascending branch of **circulations** w'_m

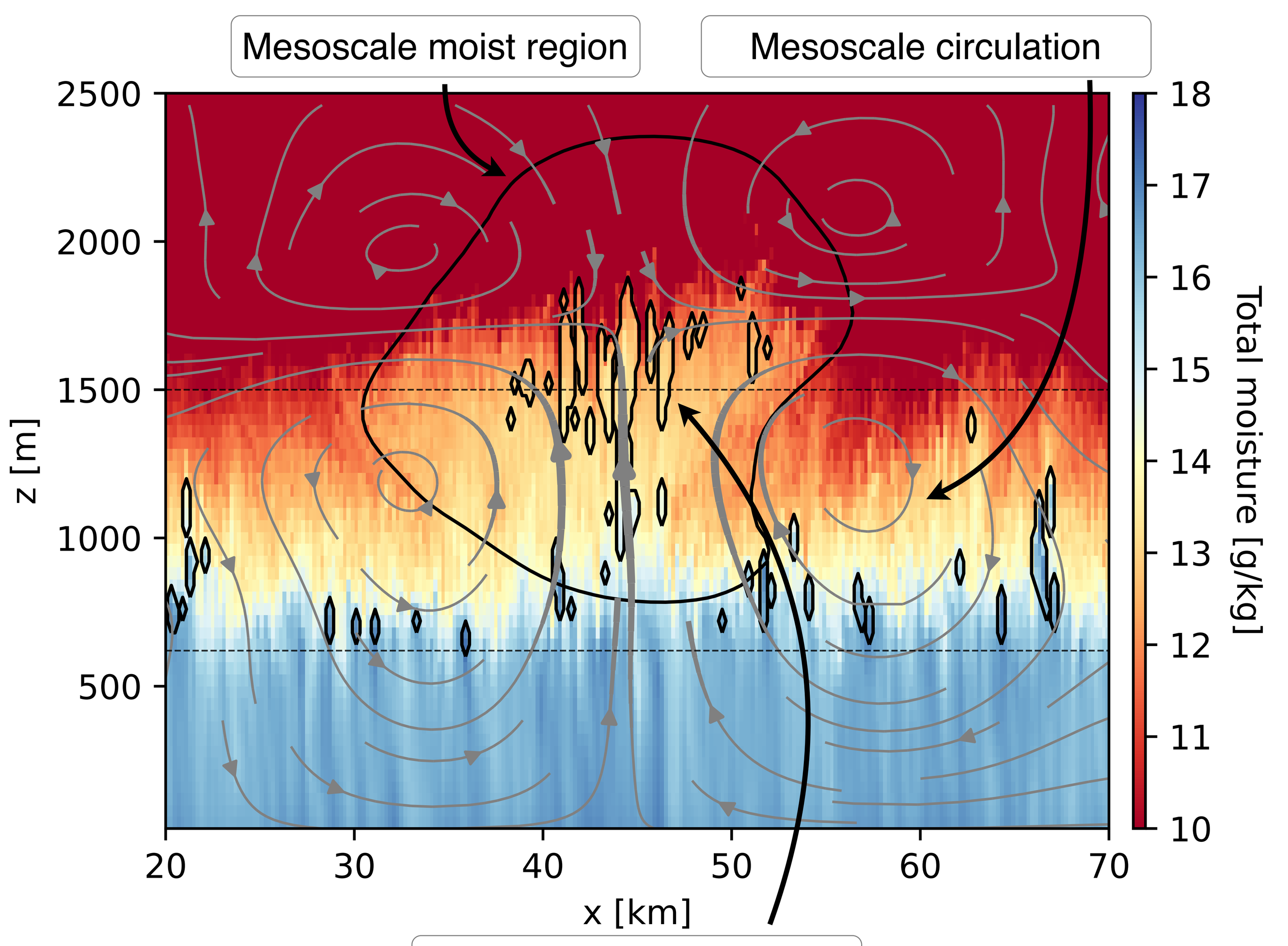
$$\partial_t q'_{t_m} \sim -w'_m \Gamma_{q_t}$$

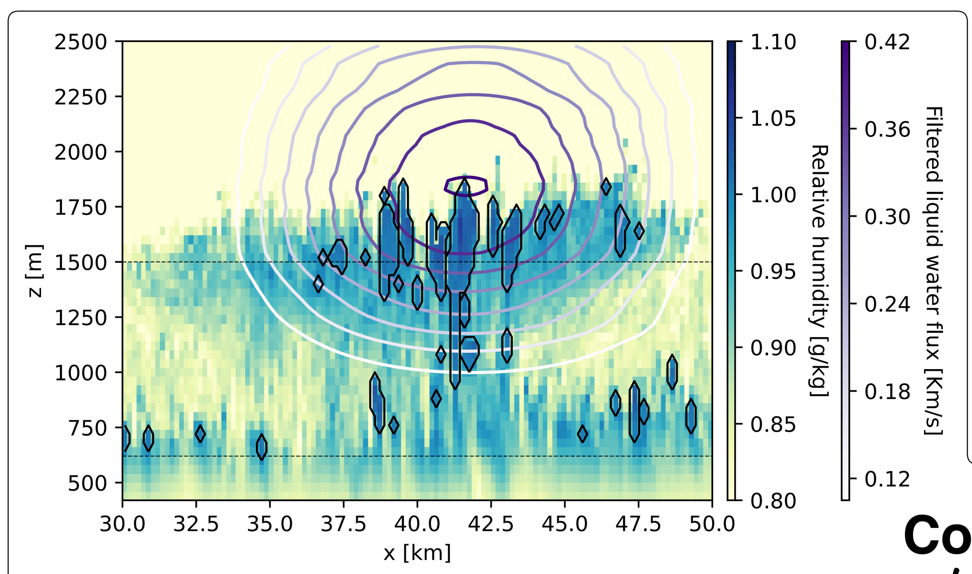


Shallow **circulations** w'_m result directly from **heat flux anomalies** $F'_{\theta_{vlm}}$, assuming Weak Temperature Gradients

$$\partial_t \theta'_{vl_m} \approx -w'_m \Gamma_{\theta_{lv}} - \partial_z F'_{\theta_{vlm}} \approx 0$$



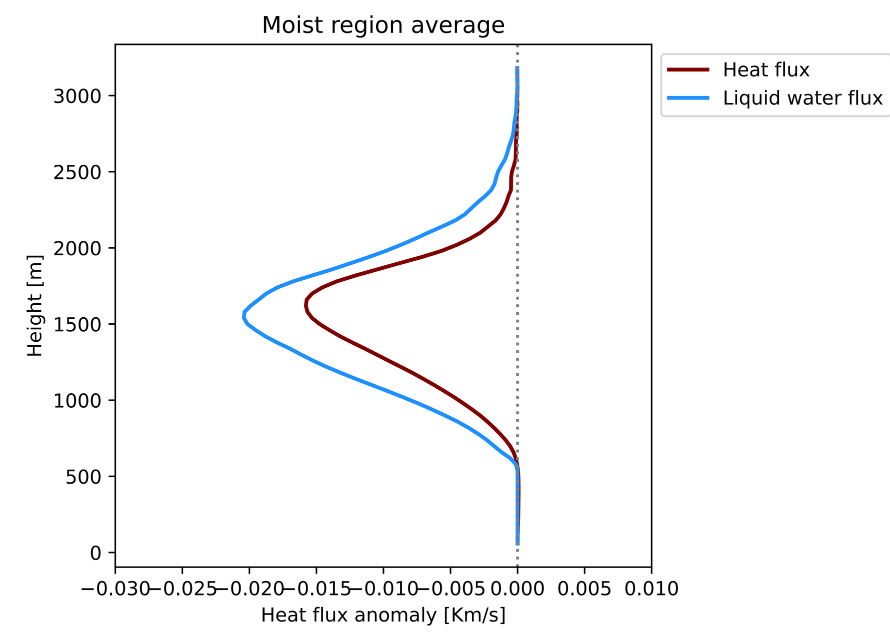




$$C'_m \propto q'_{t_m}$$

Condensation anomalies C'_m result from mesoscale **moisture fluctuations** q'_{t_m}

Heat flux anomalies $F'_{\theta_{vlm}}$ result from **condensation** anomalies C'_m in clouds at **small scales**



$$C'_m \approx \partial_z F'_{q_{lm}} \; ; \quad F'_{\theta_{vlm}} \propto F'_{q_{lm}}$$

We frame the model as a linear instability, whose conditions are satisfied by the convection itself

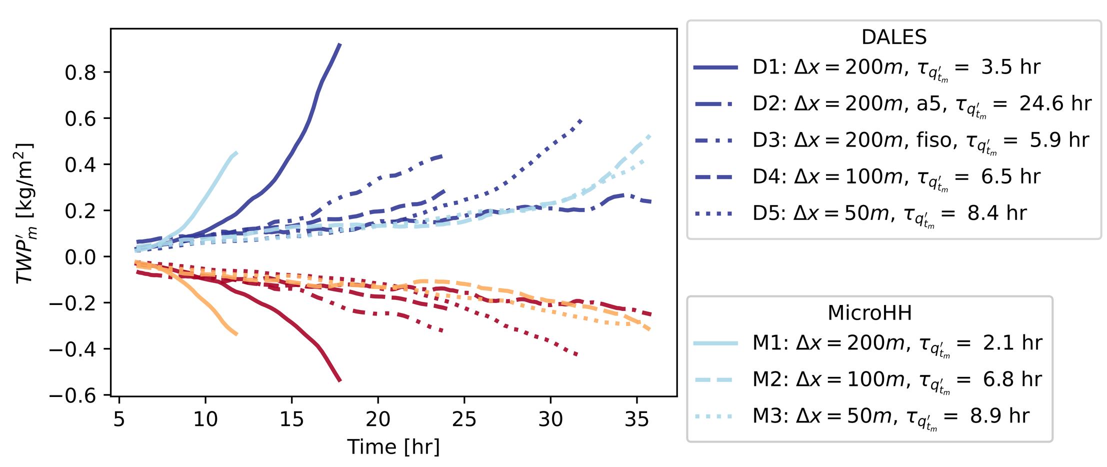
Model for column-integrated mesoscale moisture anomaly $\langle q'_{t_m} \rangle$:

$$\partial_t \langle q'_{t_m} \rangle \approx \frac{\langle q_{t'_m} \rangle}{\tau_{q'_{t_m}}}, \qquad \tau_{q'_{t_m}} \propto \frac{1}{w^* \partial_z \left(\frac{\Gamma_{q_t}}{\Gamma_{\theta_{lv}}} \right)}.$$

- $w^* > 0$ is a convective velocity scale
- $\partial_z \left(\Gamma_{q_t} / \Gamma_{\theta_{lv}} \right) > 0$ requires the mean states to be curved and convex. This is facilitated by transition- and inversion-layer curvatures in mean-state fluxes, and not by radiative cooling, as suggested by Bretherton & Blossey (2017).

Any cumulus layer able to sustain itself may be expected to be unstable to scale growth.

The feedback roots in small-scale energetics, making it sensitive to numerical choices



- Different grid spacing (Δx), advection scheme (a2, a5), filter width (fiso) and even model give different $\tau_{q'_{t_m}}$
- Heat fluxes (w^*, $F_{\theta_{vlm}}$) governed by sub-kilometre cumulus dynamics are to blame
- High resolutions or accurate convection parameterisations are likely needed to get small-scale influence on mesoscale cumulus patterns right

How does this picture fit observations?

- Circulations present on most EUREC^{4}A days (George et al., 2022)
- Transition layers are usually curved, convex and possibly due to very shallow clouds (Albright et al., 2022)
- Variability in cloud-base mass flux relates to variability in mesoscale vertical velocity (Vogel et al., 2020).

How much of this is due simply to self-induced variability cumulus convection?

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