The aggregation of shallow convection above cold pools – an observational basis

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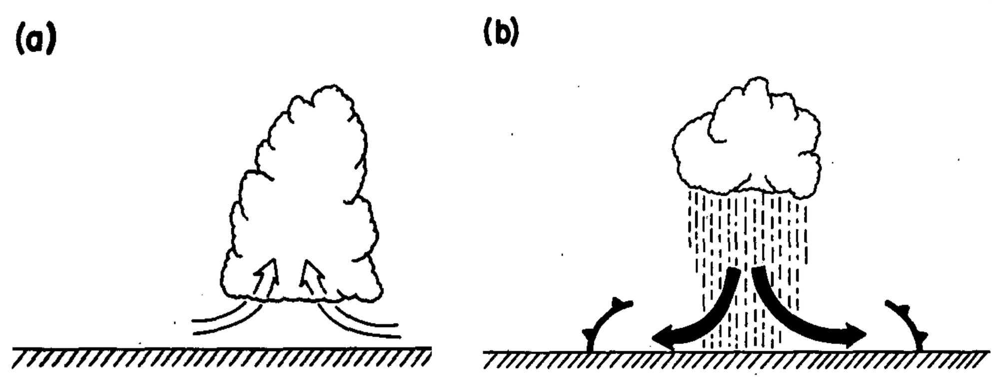
Motivations



(a) (b) Lifecycle of an ordinary precipitating cumuli (Byers and Braham, 1949; Rotunno, 1988)

The evaporation of precipitation below a precipitating cumulus cools the air below it (creation of a cold pool), thus increases its stability. Therefore, once it starts precipitating, a cumulus cloud is naturally short lived.

This is in contradiction with precipitating flowers that have been observed to last for several hours during EUREC4A, despite the presence of a cold pool below them. How can we explain this persistence?

A novel method to detect cold pools in soundings

We define $h_{mix}(\theta_v)$ as the lowest height above ground Z where:

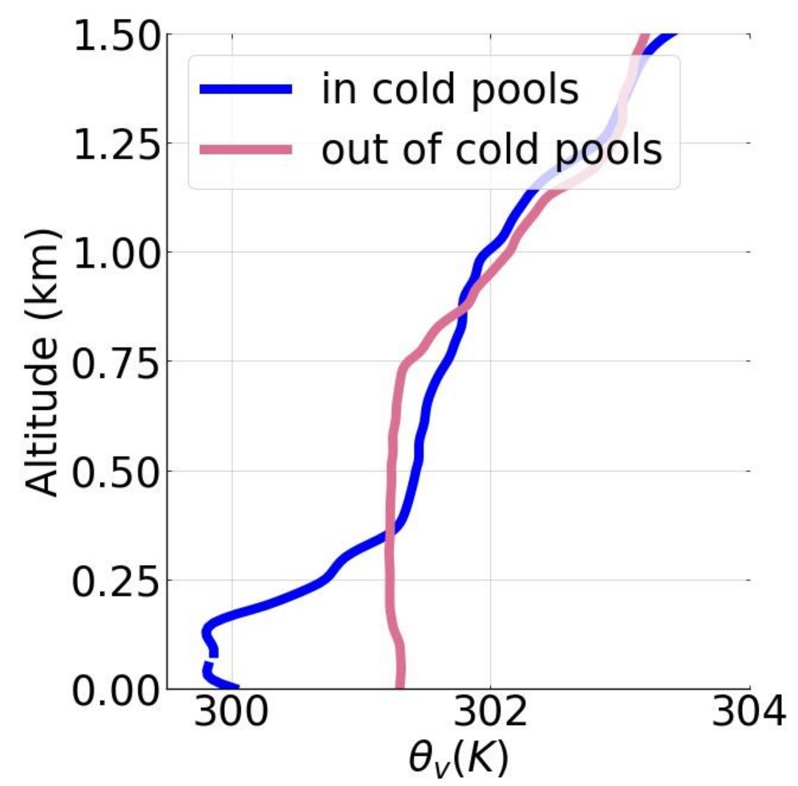
$$\theta_v(Z) \geq \widetilde{\theta_v}(Z) + \epsilon$$

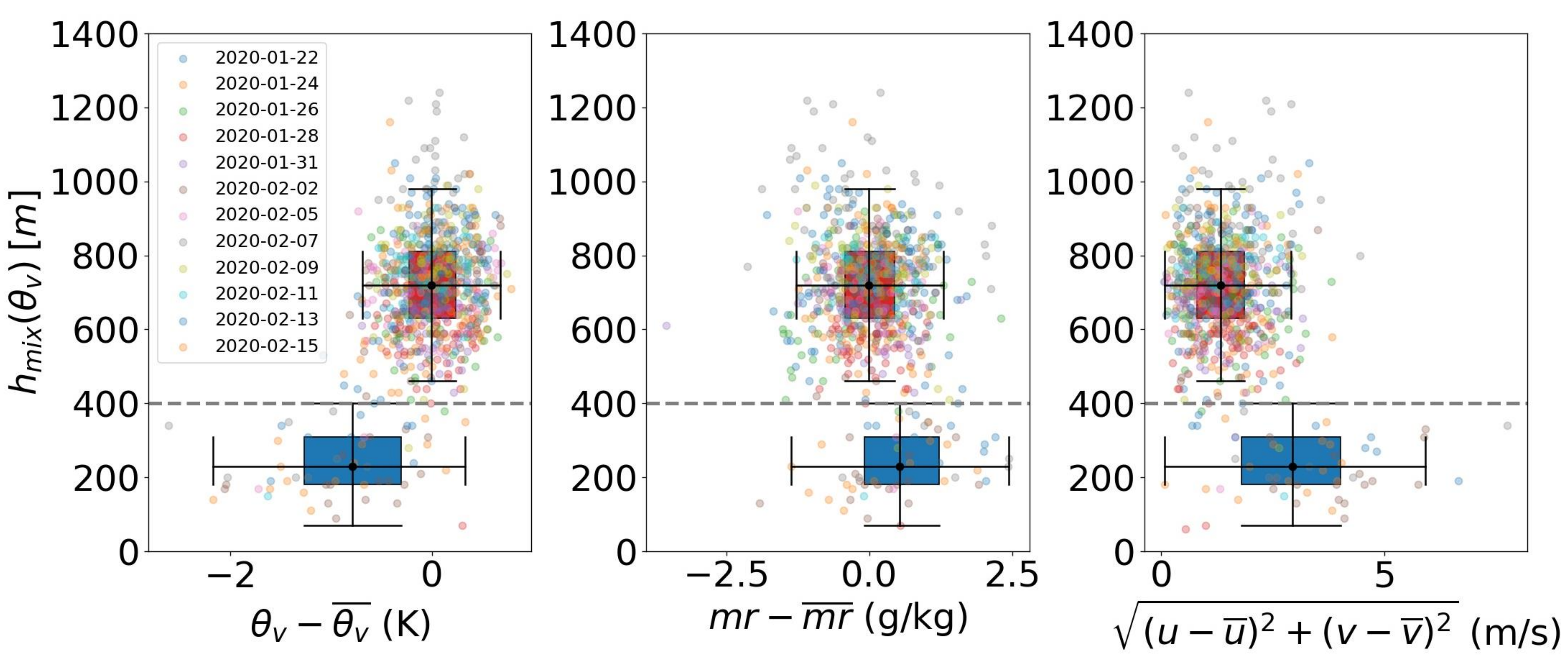
with $\epsilon = 0.2$ K and

$$\widetilde{\theta_v}(Z) = \frac{\int_0^Z \rho(z)\theta_v(z)dz}{\int_0^Z \rho(z)dz}$$

"Cold pool" soundings are identified as those where:

$$h_{mix}(\theta_v) \leq 400 \text{ m}$$



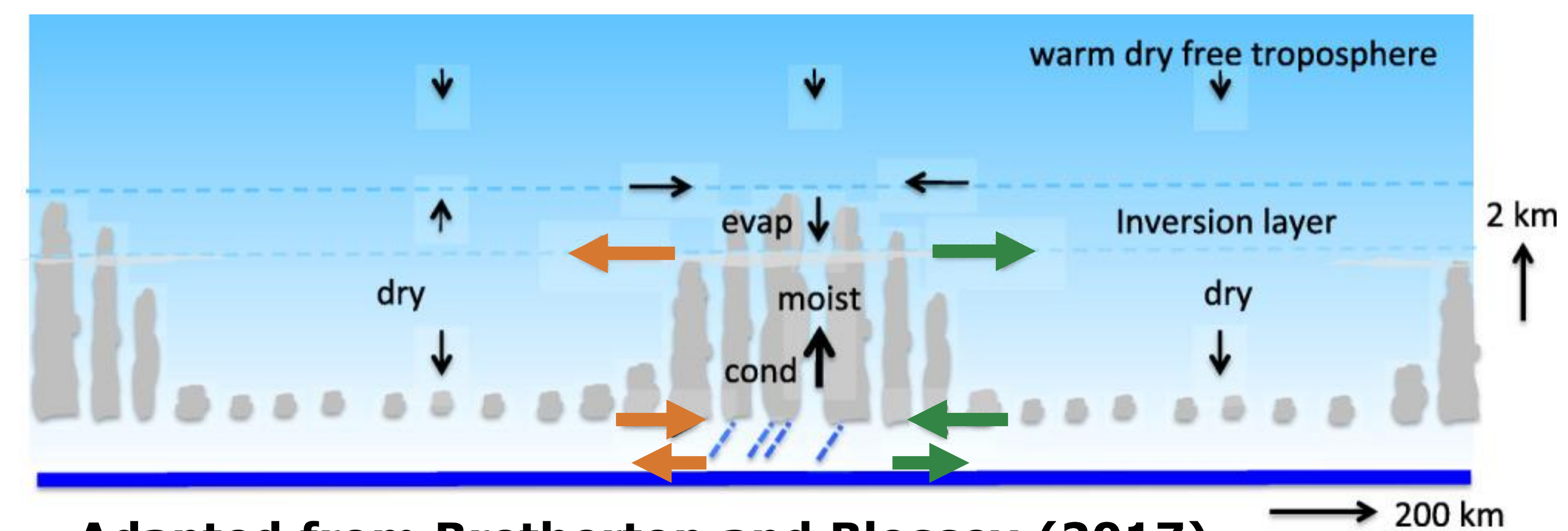


$h_{mix}(\theta_v)$ (as defined above) as a function of the deviation from daily mean virtual potential temperature, mixing ratio, and wind speed measured by dropsondes launched in HALO circles

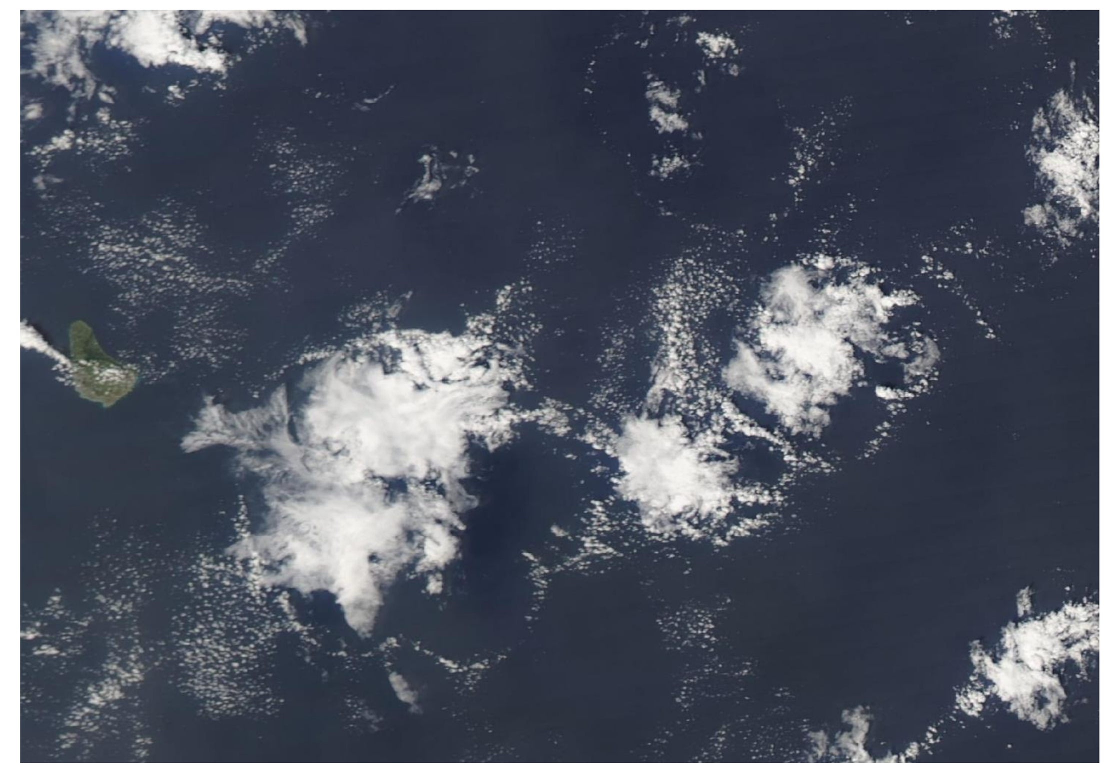
Shallow convective self-aggregation

Based on the analysis of LES simulations, Bretherton and Blossey (2017) develop a simple conceptual model to explain the aggregation of marine shallow cumulus convection.

In this model, convection aggregates quickly mainly because it has negative gross moist stability; the mesoscale vertical motions and moist static energy (MSE) profile tend to converge MSE into moist columns.



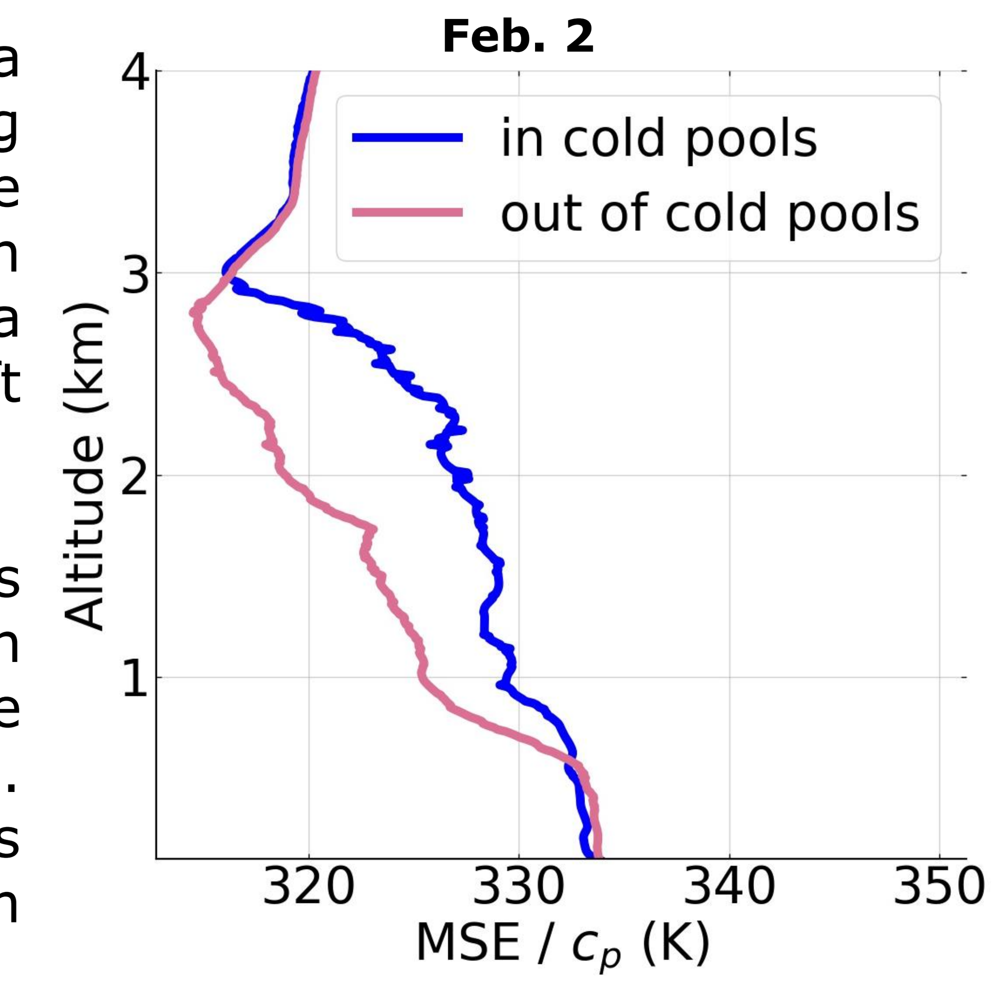
Adapted from Bretherton and Blossey (2017)



Visible image from Aqua off the coast of Barbados on February 2 (source: NASA Worldview)

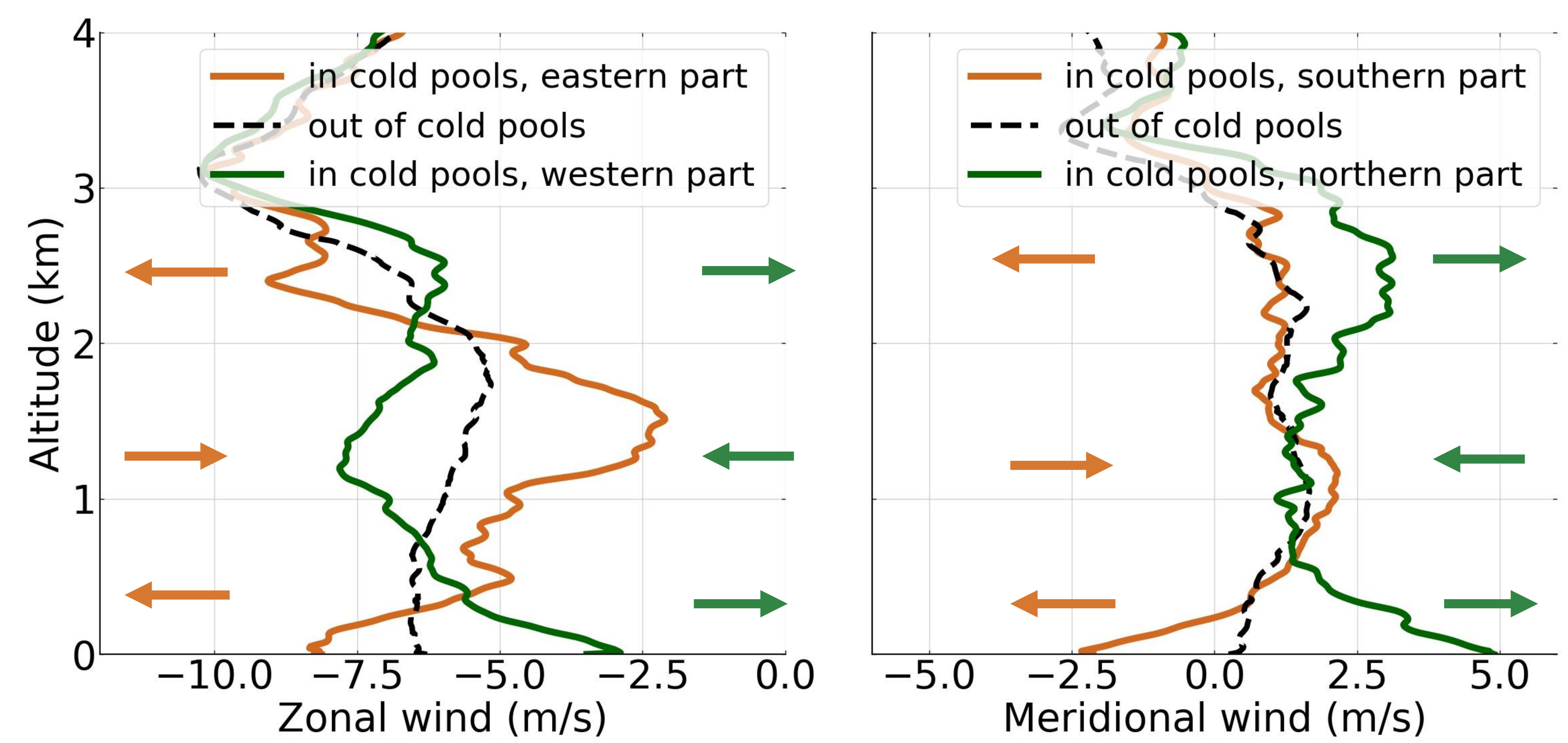
On February 2, we could see a cold pool progressively growing below a "flower" (following the classification introduced in Stevens et al. 2019) in the area where the German aircraft HALO was flying.

Over the 80 dropsondes launched from the research flight HALO that day, 16 were detected falling in a cold pool. The figure on the right shows the MSE deduced from dropsonde profiles.



Since cold pools spread isotropically with respect to the mean surface wind, we use the vorticity near the surface of the zonal wind (respectively the meridional wind) to distinguish circulations on the eastern and western parts (respectively the northern and southern parts) of clouds.

In addition to a divergence at the surface due to the cold pool, we see a zone of strong convergence between 0.5 and 2 km (peaking at 1.5 km) and a zone of divergence between 2 and 3 km (peaking at 2.5 km). Consistent with Bretherton and Blossey (2017), these circulations tend to transport MSE into moist columns.



Mean zonal and meridional wind speeds outside cold pools (black, dashed) and inside cold pools (red and blue)

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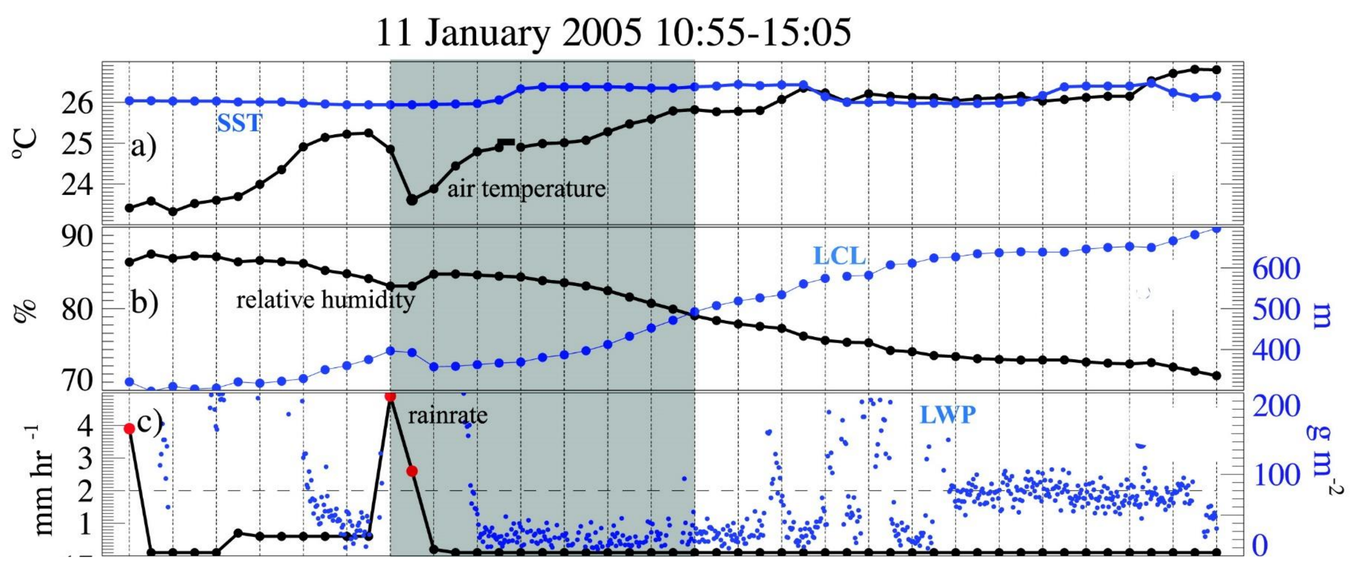
How to detect cold pool in observations?

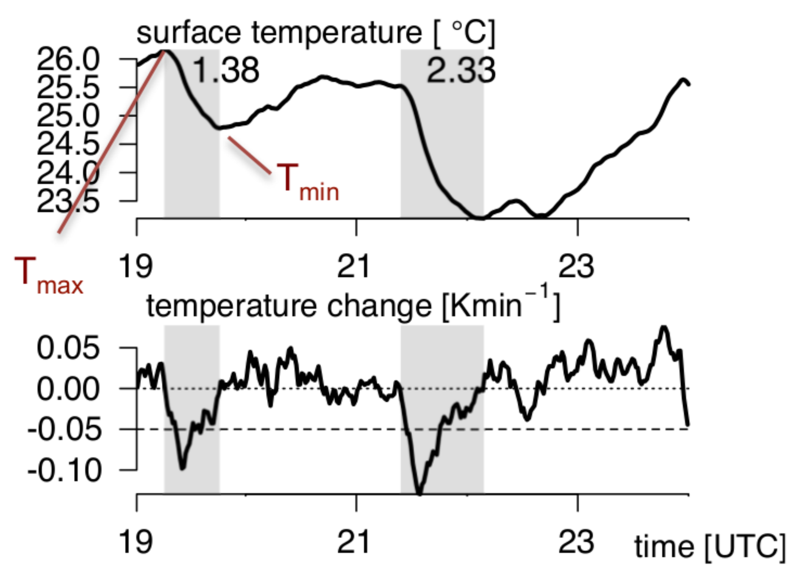
1) From timeseries

- **Zuidema et al. (2012) - detection of cold pools during RICO**



The beginning of a cold pool period is defined by the onset of surface rain and the end of a cold pool time period by the end of the subsequent temperature recovery.

- **Vogel, R. (2017) - detection of cold pools at BCO (see also de Szoeke et al. - 2017)**

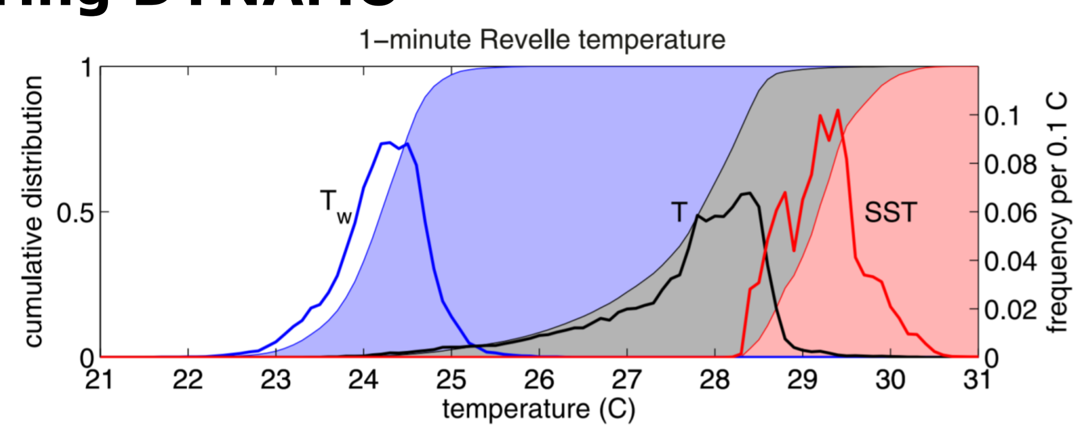


1. Smooth 1-min surface temperature data with 11-min centered linear filter
2. T fil (t)-T fil (t-1) < -0.05 K
3. Identify T max and T min in front
4. retain cold pools with ΔT < -0.5 K
+ more conditions for separating nearby cold pools, defining end of cold-pool wake etc.

2) From soundings

- **de Szoeke et al. (2017) – detection of cold pools during DYNAMO**

"Cold pool" soundings are those with air surface temperatures below 26.5°C (the 10th percentile of the air temperature distribution measured by the research vessel), and "undisturbed" soundings have surface temperature exceeding 27.58C (40th percentile).



- **We propose another criteria based on the height of the mixed layer in θ_v**

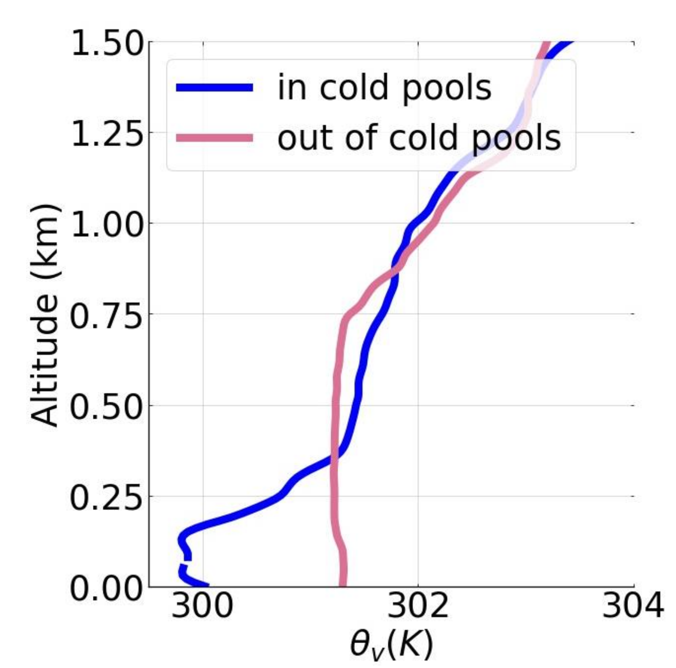
We define $h_{mix}(\theta_v)$ as the lowest height above ground Z where:

$$\theta_v(Z) \geq \widetilde{\theta_v}(Z) + \epsilon$$

with $\epsilon = 0.2$ and $\widetilde{\theta_v}(Z) = \frac{\int_0^Z \rho(z)\theta_v(z)dz}{\int_0^Z \rho(z)dz}$

"Cold pool" soundings are identified as those where:

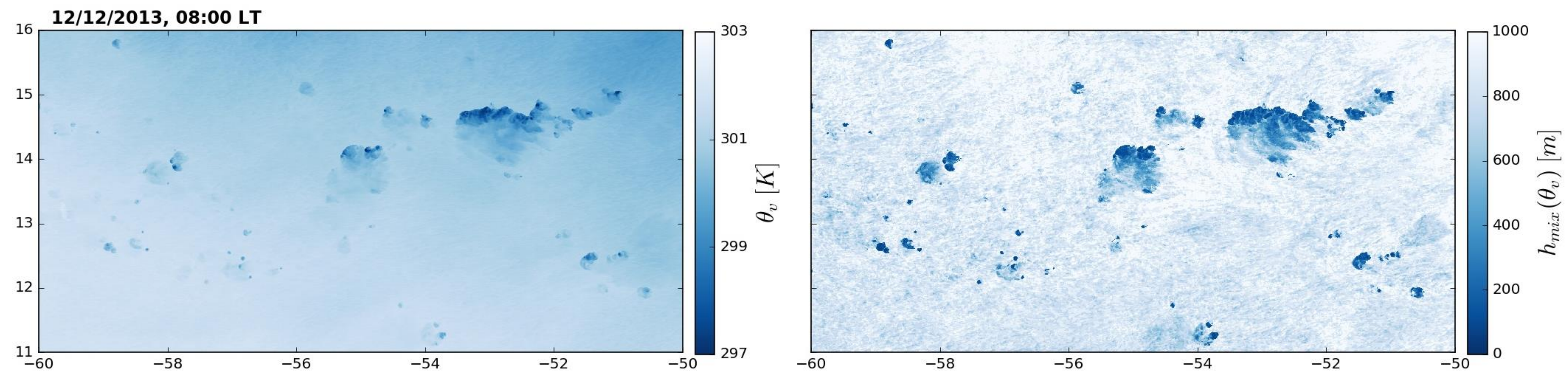
$$h_{mix}(\theta_v) \leq 400 \text{ m}$$



Consistency with LES simulations

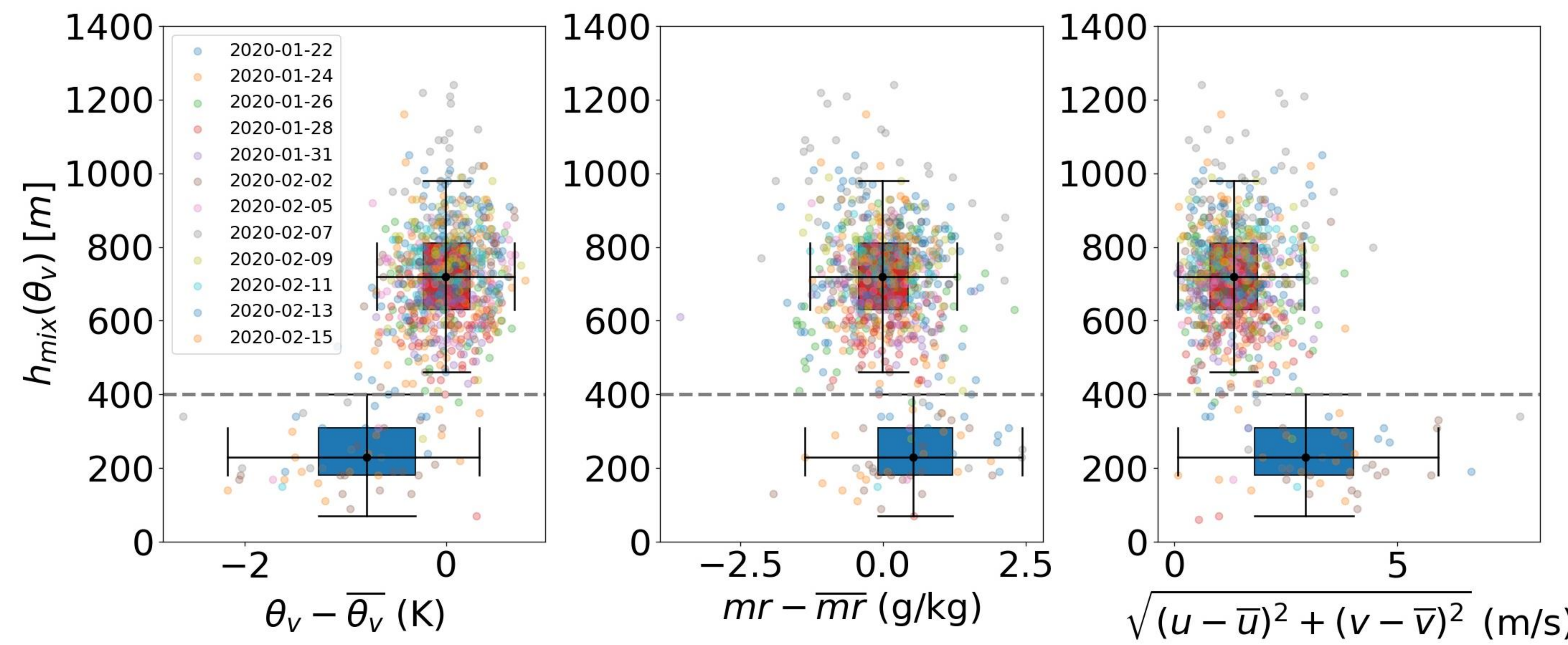
LEM simulations with ICON over Barbados region

- 313m horizontal grid spacing, 150 vertical levels
- Initialization (at 9:00 UTC, 5:00 LT) and nudging of the lateral boundaries (every hour) from 1.25km-resolution runs
- No cloud parameterization; see Dipankar et al. (2015) and Heinze et al. (2017) for the description of turbulence and microphysics schemes



The height of the mixed layer in θ_v is much lower above cold pools (identified as areas of negative virtual potential temperature anomalies near the surface).

Test on HALO flights



$h_{mix}(\theta_v)$ (as defined above) as a function of the deviation from daily mean virtual potential temperature, mixing ratio, and wind speed measured by dropsondes launched in HALO circles

According to our criteria, cold pools (blue boxes) tend to be on average 0.8°C colder, slightly more humid (with a larger spread) and experience more anomalous wind speeds than their environment. These characteristics are consistent with observations of cold pools at BCO during EUREC4A using the same detection method as Vogel (2017) (not shown).

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The mesoscale aggregation of shallow convection in LES

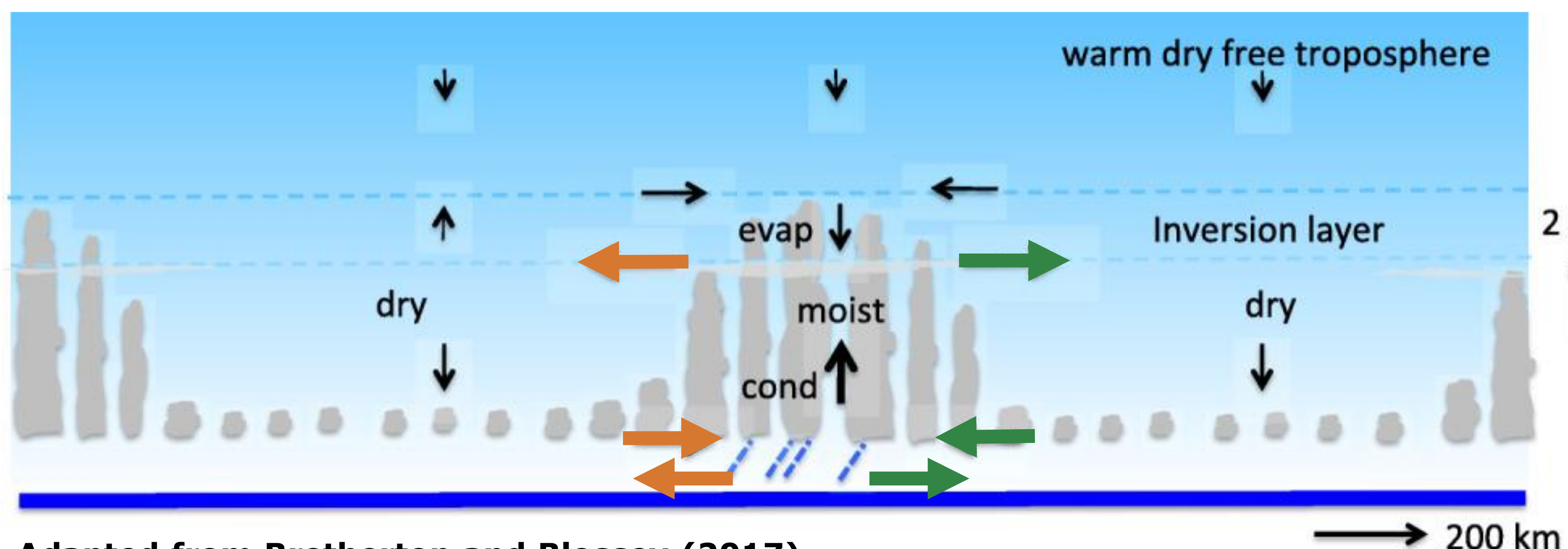
- **Seifert and Heus (2013)**

On a relatively small domain $(25\,\mathrm{km})^2$, with a horizontal grid spacing of 100 m, Seifert and Heus found that without rain evaporation in the subcloud layer (and therefore without cold pools), their simulation shows no sign of organization. On the contrary, cold pools were associated with the formation of mesoscale arcs.

These results led them to claim that the formation of cold pools by evaporation of rain in the sub-cloud layer is a dominant feedback for the organization of trade wind cumulus.

- **Bretherton and Blossey (2017)**

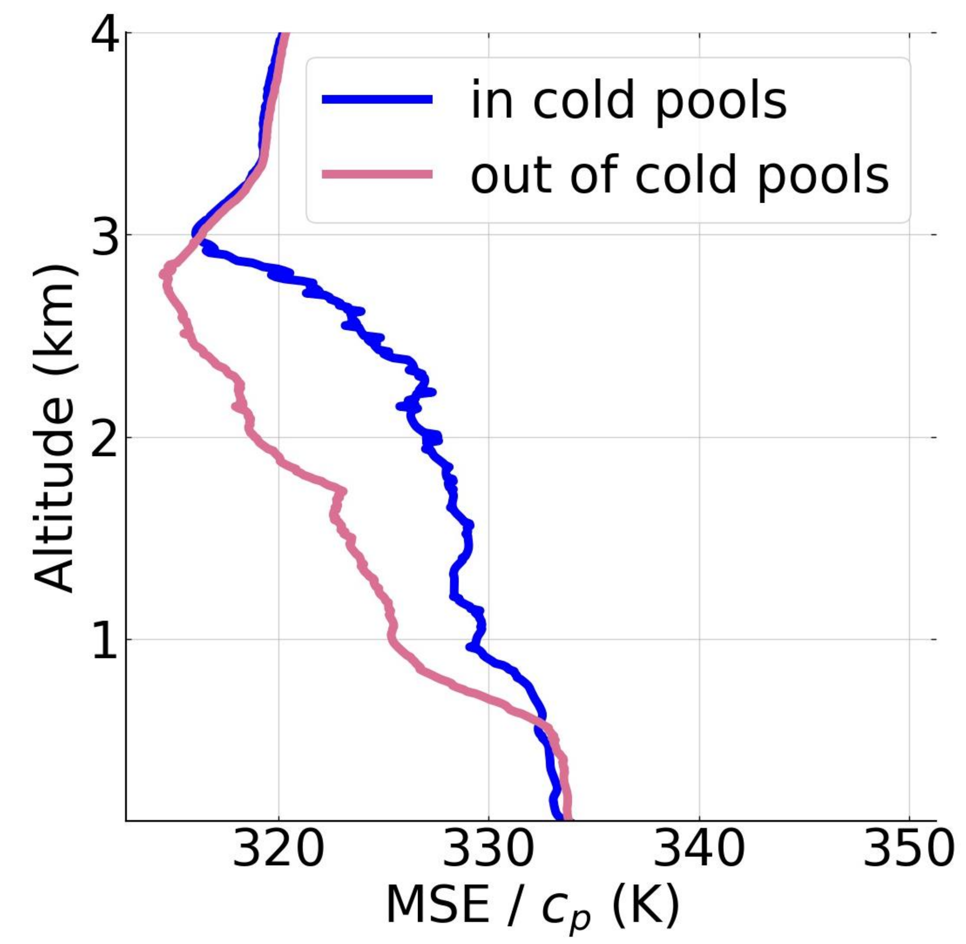
Bretherton and Blossey (2017) consider a larger domain $(128\,\mathrm{km})^2$ than Seifert and Heus (2013), with a coarser horizontal grid spacing (250 m). They found that shallow cumuli self-aggregate relatively quickly, with one major cluster appearing within one to three days. In their simulations, self-aggregation is affected by precipitation and mesoscale feedbacks of radiative and surface fluxes, but still occurs without them. Contrary to Seifert and Heus (2013), cold pools are therefore not a dominant feedback for the organization of trade wind cumulus in their simulations.



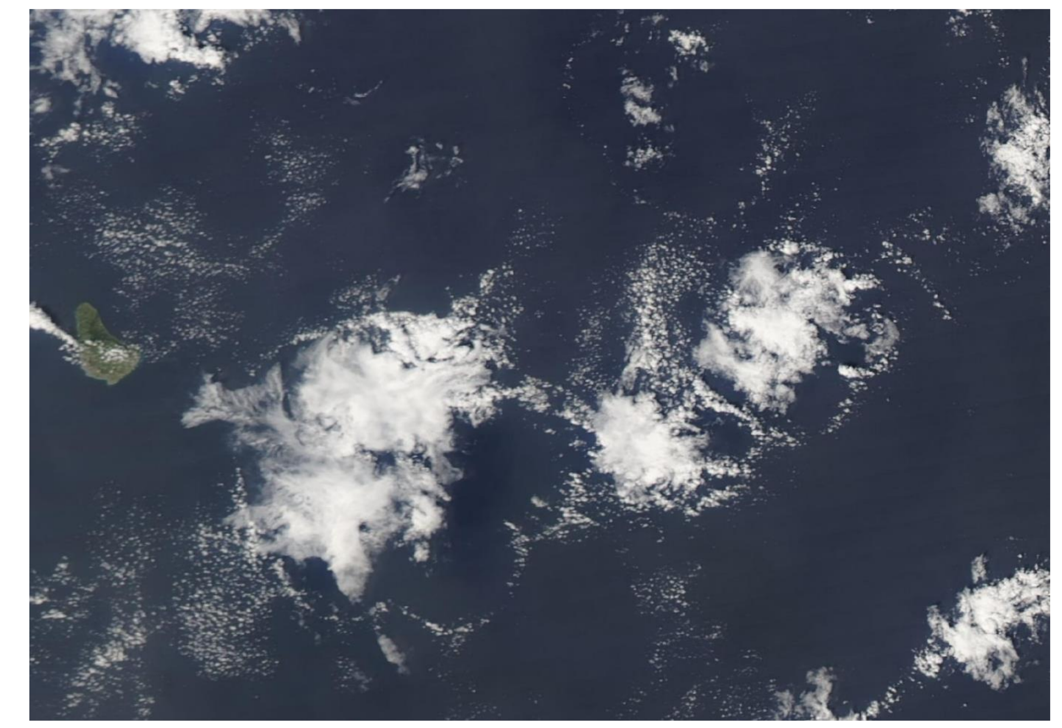
Adapted from Bretherton and Blossey (2017)

To explain the aggregation of shallow convection, Bretherton and Blossey propose the conceptual model above. In the moist patch at the center of the diagram, cumulus updrafts lose less buoyancy to entrainment-induced evaporative cooling, so they deepen into the inversion layer. The latent heat released in these cumulus clouds induce mesoscale upward motion within the moist patch, thus horizontal convergence in the lower part of the boundary layer and divergence at the inversion base.
Due to the decrease of the MSE profile with height in these regions, these circulations tend to transport MSE into moist columns, thus promoting the self-aggregation of shallow cumuli.

February 2 – a case study for studying the mesoscale aggregation of shallow convection during EUREC4A



During EUREC4A, on February 2, we could see a cold pool progressively growing below a "flower" (following the classification introduced in Stevens et al. 2019) in the area where HALO was flying. This flower lasted until after 10 pm (LT) despite the presence of a persistent cold pool below, first observed before noon.



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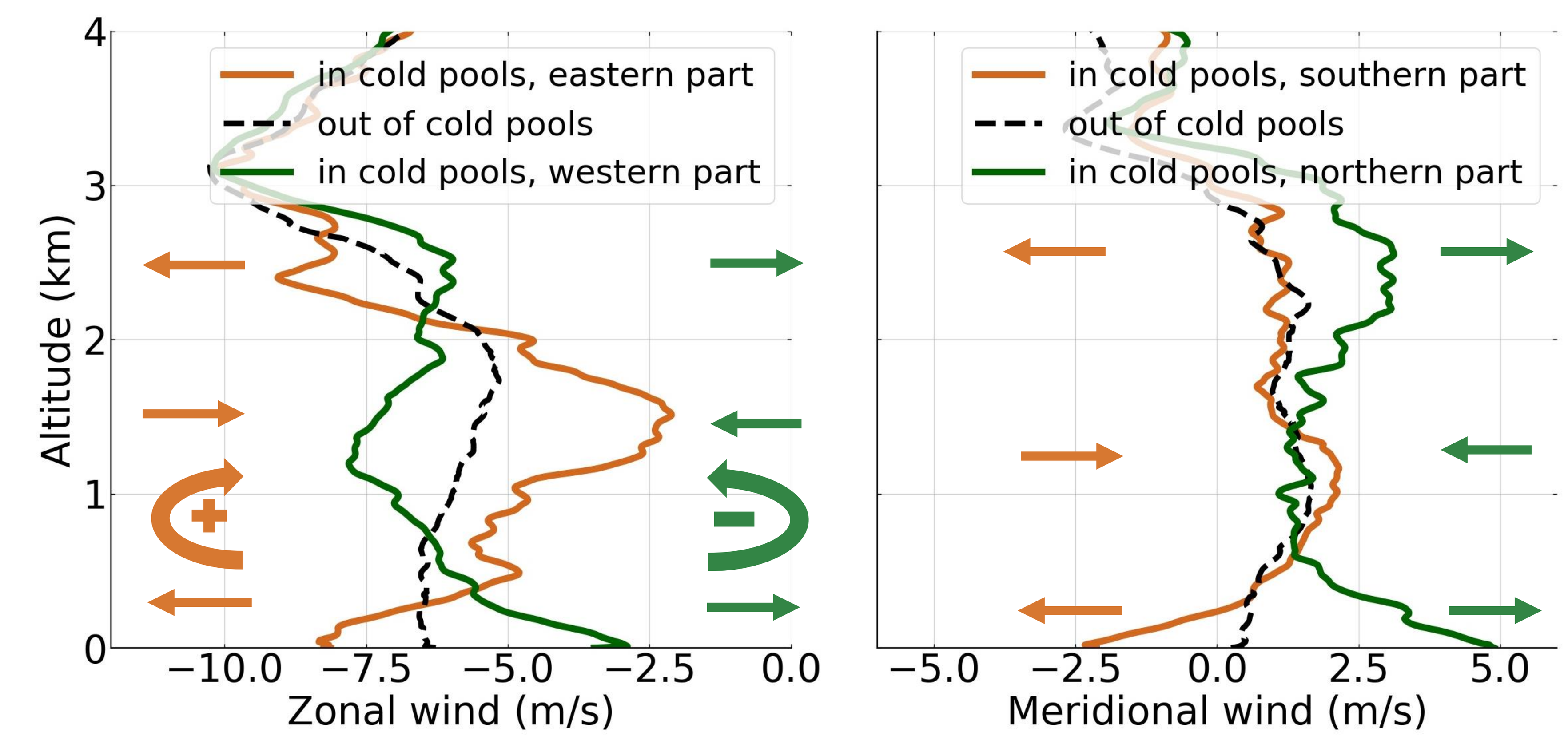
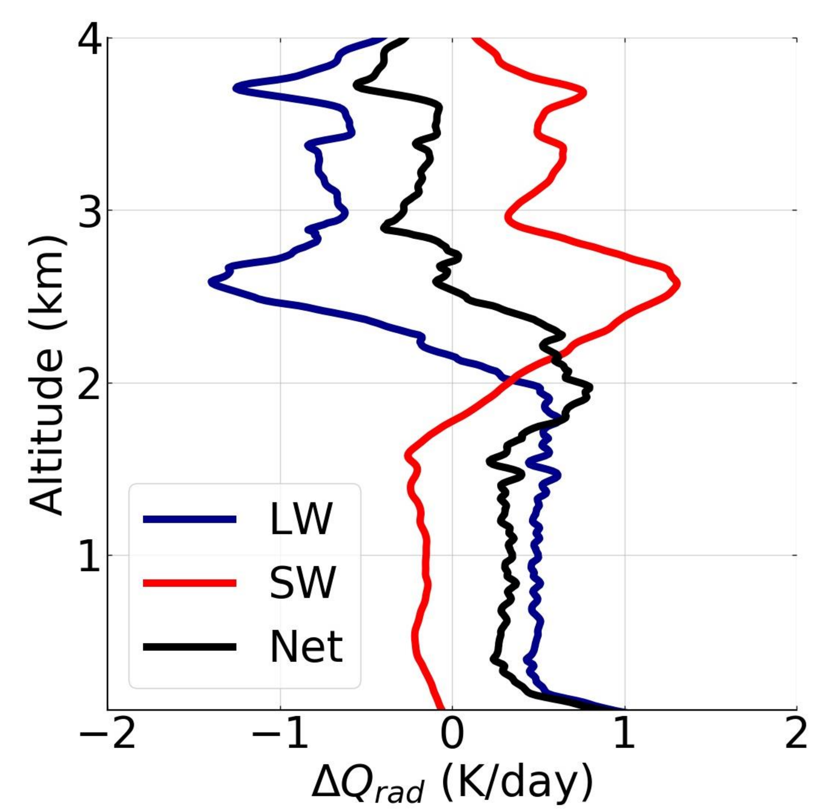


Mean zonal and meridional wind speeds outside cold pools (black, dashed) and inside cold pools (red and blue)



To test the sensitivity of self-aggregation to local radiative feedbacks, Bretherton and Blossey (2017) perform a sensitivity study in which they homogeneize horizontally radiative heating rate. Under these conditions, their simulations also aggregate, but more slowly, which suggests a positive feedback of local radiative heating rates on self-aggregation.
For February 2, we plotted (figure on the left) the difference between the mean radiative profile in cold pools and in their environment (using the radiative code rte-rrtmgp). In average, the extra radiative cooling above cold pools is positive, acting therefore as an MSE source. Moreover, the anomalous radiative cooling in the inversion layer compared to the boundary layer stimulates more cumulus convection in moist columns, thus promoting the circulations exposed previously. Consistent with Bretherton and Blossey (2017), these results suggest a positive feedback of radiation on self-aggregation.

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Summary

- This preliminary work introduced a novel method to detect cold pools from soundings over tropical oceans, using the height of the mixed layer in the virtual potential temperature to distinguish cold pools and their environment.
- Due to the isotropical spreading of cold pools, we showed that the vertical vorticity near the surface of the zonal wind (respectively the meridional wind) could be used to distinguish circulations on the eastern and western parts (respectively the northern and southern parts) of precipitating clouds.
- Using February 2 as a case-study, we showed that circulations around "flowers" (following the classification introduced in Stevens et al. 2019) were consistent with LES simulations of self-aggregation from Bretherton and Blossey (2017). Local radiative effects were also briefly studied as potential feedbacks on self-aggregation.

A picture of a "flower" taken from the Barbados Cloud Observatory on February 2. Photo credit: M. Ringel

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