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

Motivations

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

$$\theta_v(Z) \geq \bar{\theta}_v(Z) + \epsilon$$

with $\epsilon = 0.2$ K and

$$\bar{\theta}_v(Z) = \frac{\int_0^Z \rho \theta_v \, \text{d}z}{\int_0^Z \rho \, \text{d}z}$$

"Cold pool" soundings are identified as those where:

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

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.

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.
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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)

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 10% percentile of the air temperature distribution measured by the research vessel), and "undisturbed" soundings have surface temperature exceeding 27.5°C (40th percentile).

   We propose another criteria based on the height of the mixed layer in $\theta_v$

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

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

   with $\epsilon = 0.2$ and $\overline{\theta_v}(Z) = \int_{Z}^{\infty} \frac{\rho(c)\theta(c)dz}{\rho(c)dz}$

   "Cold pool" soundings are identified as those where:

   $h_{mix}(\theta_v) \leq 1400$ 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

Test on HALO flights

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 EURECA 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 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 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.

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

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 convections on the eastern and western parts (respectively the northern and southern parts) of clouds.

In addition with the 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.

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.
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

References