Can we force convection to aggregate?

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NERC SCIENCE OF THE ENVIRONMENT

ORGANISED CONVECTION

WHAT IS IT?

1. **Convection that is long-lived**
   - Convection that lasts longer than an individual convective cell
   - Generates cold pools which help to initiate new cells
2. **Convection that grows upscale**
   - Covers an area larger than a typical individual convection cell
   - Can be comprised of of a group of convective cells

WHY IS IT IMPORTANT?

1. **Primary contributor of tropical precipitation and significant proportion of tropical cloudiness**
2. **Small changes in organisation with warming could have large impacts on regional rainfall patterns**

CONVECTIVE AGGREGATION:

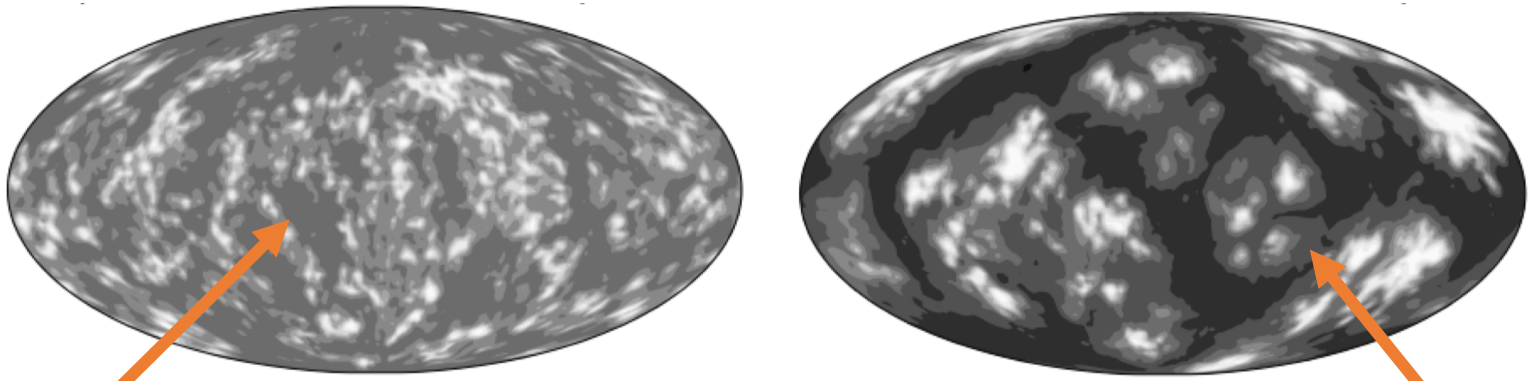
The large-scale reorganisation of convection in radiative-convective equilibrium (RCE) simulations into clusters. Seen in various model types:

2D CRMs | small-domain square 3D CRMs | elongated channel 3D CRMs | regional/global models with parametrised convection | global models with explicit convection

Outgoing longwave radiation on day 210 of simulations

SST = 290K

NOT AGGREGATED



SST = 305K

AGGREGATED

Scattered convection
Lack of large open sky areas

Large clusters of convection
Large areas of clear sky between them

ICON GCM simulation[1,2]
No rotation
Aquaplanet
Globally constant solar insolation

Convective aggregation causes domain-mean changes:

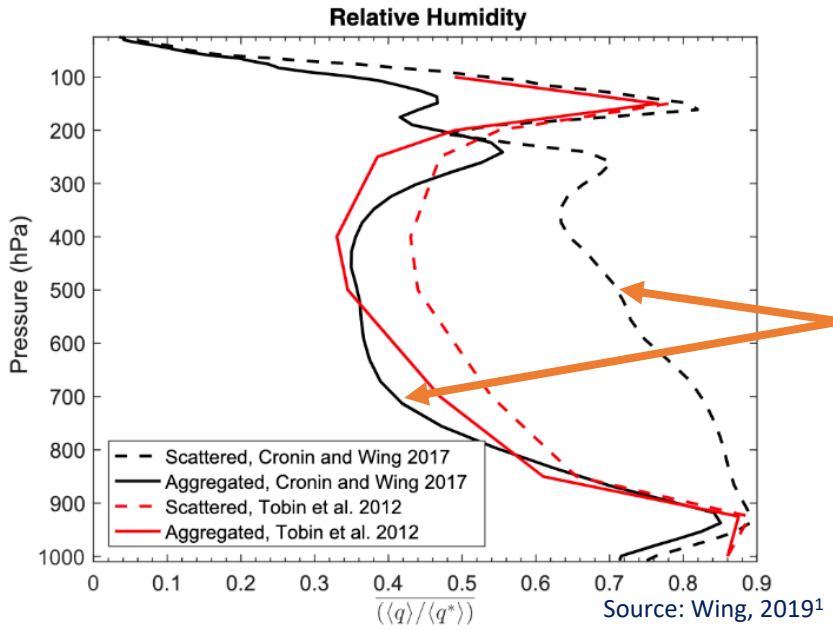


Figure shows relative humidity profiles of observed (red) and modelled (black) convection that is either aggregated (dashed line) or not (solid line)

Source: Wing, 2019[1]

Domain-mean drying when convection is aggregated

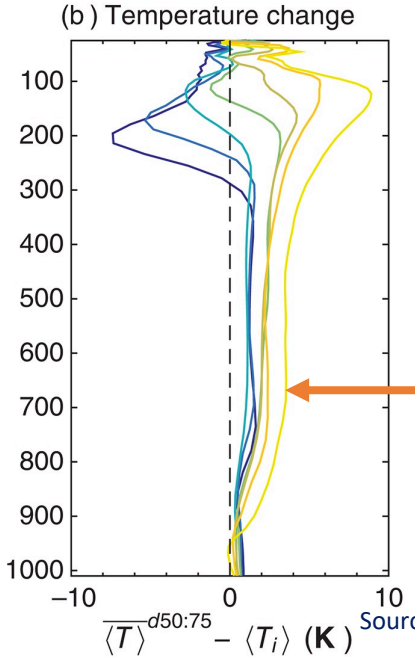


Figure shows temperature change when comparing a non-aggregated situation ($\langle T \rangle_i$) and an aggregated situation ($\overline{\langle T \rangle}^{d50:75}$)

Source: Wing and Cronin, 2016[2]

Domain-mean warming when convection is aggregated

Increased OLR when convection is aggregated

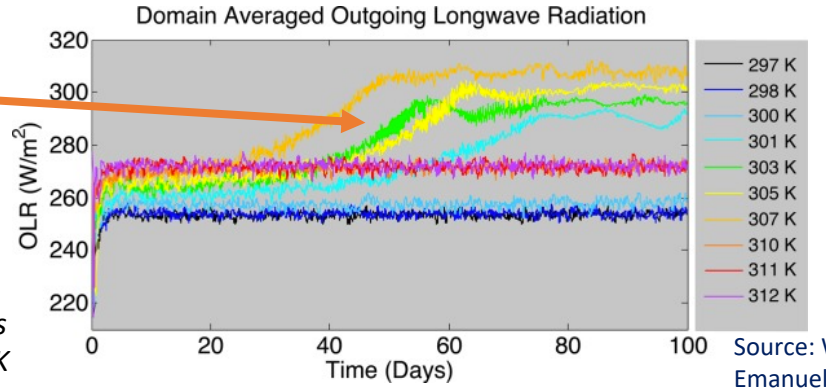


Figure shows outgoing longwave radiation for RCE simulations with different sea surface temperatures (SST). SSTs 301K, 303K, 305K, 307K aggregated

Source: Wing and Emanuel, 2014[3]

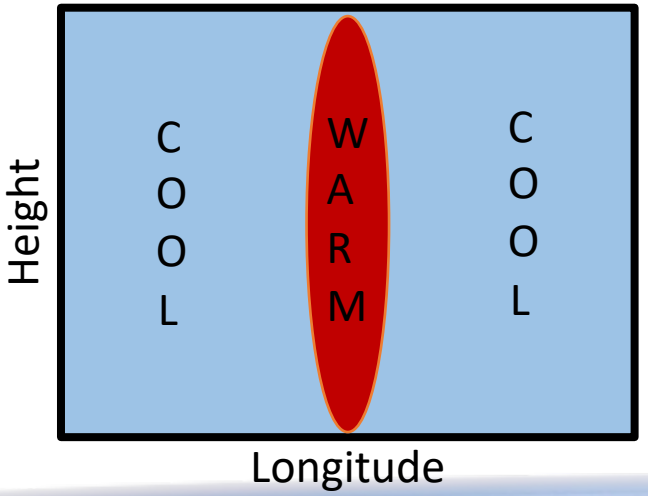
Convective aggregation can therefore have impacts on the energy budget, precipitation, and climate sensitivity

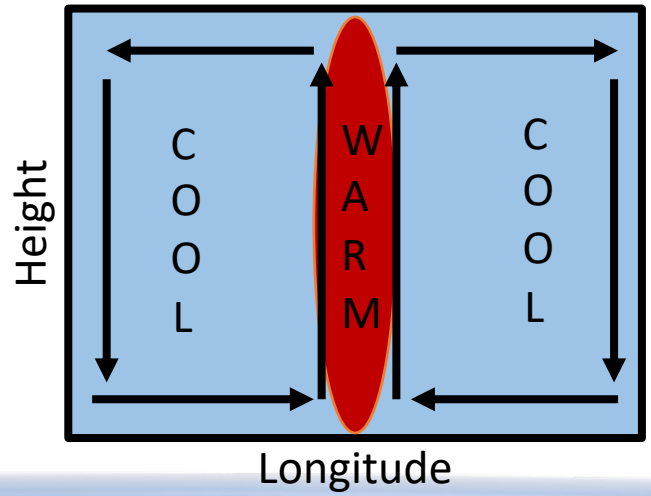
[1]Wing, 2019: Self-Aggregation of Deep Convection and its Implications for Climate. *Current Climate Change Reports*
[2]Wing and Cronin, 2016: Self-aggregation of convection in long channel geometry. *Quarterly Journal of the Royal Meteorological Society*
[3]Wing and Emanuel, 2014: Physical mechanisms controlling self-aggregation of convection in idealized numerical modeling simulations. *Journal of Advances in Modeling Earth Systems*

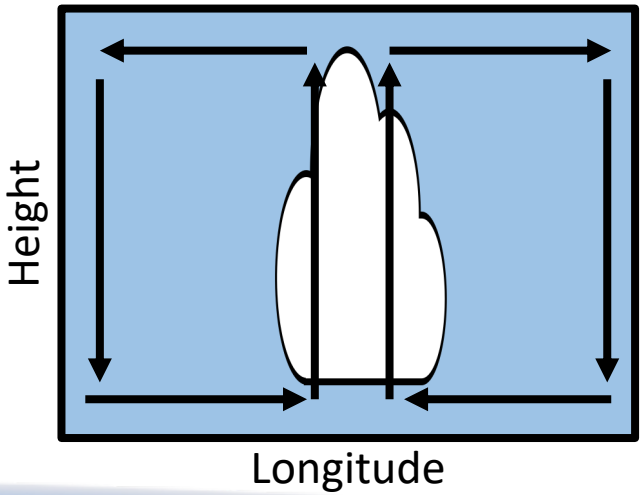
Can we force convection to aggregate?

Idea…

1. **Insert plume of strongly absorbing aerosols somewhere on globe**
   - Using **M**ax-Planck **A**erosol **C**limatology - **S**imple **P**lume model[1,2]
   - Single scattering albedo = 0.8 *(very absorbing aerosols),* Aerosol optical depth = 1.8 *(very large)*
   - Used as an analogue to aerosol radiative effects
2. **Causes a large-scale thermally driven circulation[3]**
3. **Attracts moisture and convection aggregates around plume**







[1]Stevens et al., 2016: Simple plumes: A parameterization of anthropogenic aerosol optical properties and an associated Twomey effect for climate studies . *Geoscientific Model Development*
[2]Stevens et al., 2017: MACv2-SP: a parameterization of anthropogenic aerosol optical properties and an associated Twomey effect for use in CMIP6. *Geoscientific Model Development*
[3]Dagan et al., 2019: Contrasting Response of Precipitation to Aerosol Perturbation in the Tropics and Extra tropics Explained by Energy Budget Considerations. *Geophysical research letters*

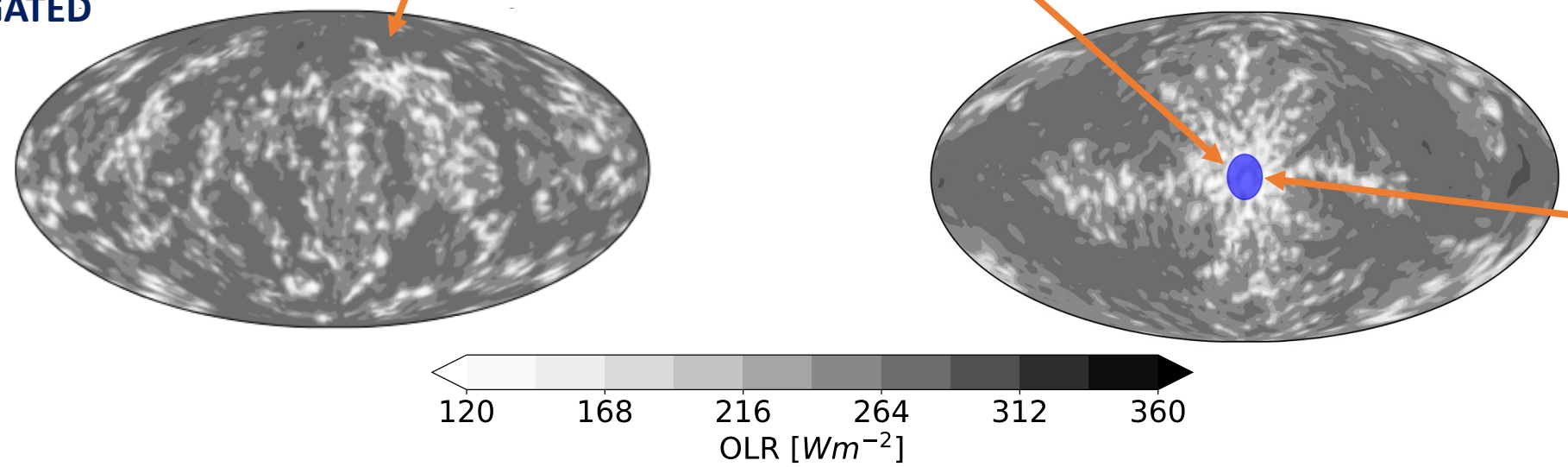
FORCED CONVECTIVE AGGREGATION

Two simulations have the same setup, except for the plume being used on the right.

See how the plume causes aggregation to occur near to it at an SST where aggregation doesn't occur naturally

ICON GCM RCE
SST = 290K
No rotation
Aquaplanet
Globally constant solar insolation
No plume
NOT AGGREGATED

ICON GCM RCE
SST = 290K
No rotation
Aquaplanet
Globally constant solar insolation
Plume included
AGGREGATED



KEY CIRCULATIONS

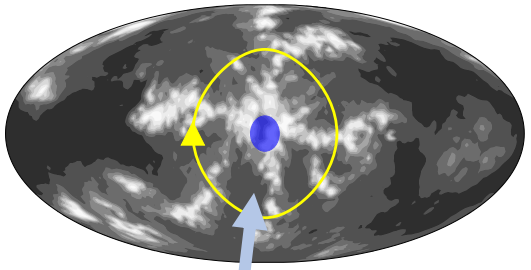


Figure shows daily mean outgoing longwave radiation (day 210) for GCM RCE simulations with SST of 305K with aerosol plume shown by blue circle. Yellow circle shows 50° circle around plume

Convection has aggregated near to plume in star shape

Convective cores transfer converging momentum upwards, so the convection moves towards plume, generating 'star'-like shape

Radial winds show convergence near surface and divergence in upper atmosphere

Tangential winds show circulation between star 'arms', maintaining clear sky between the arms

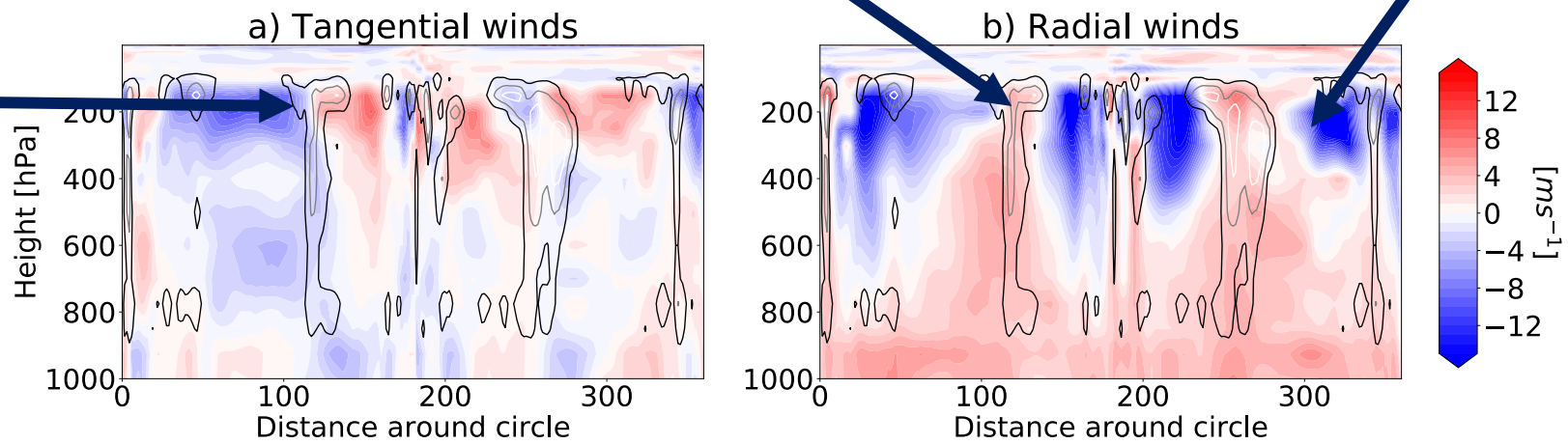
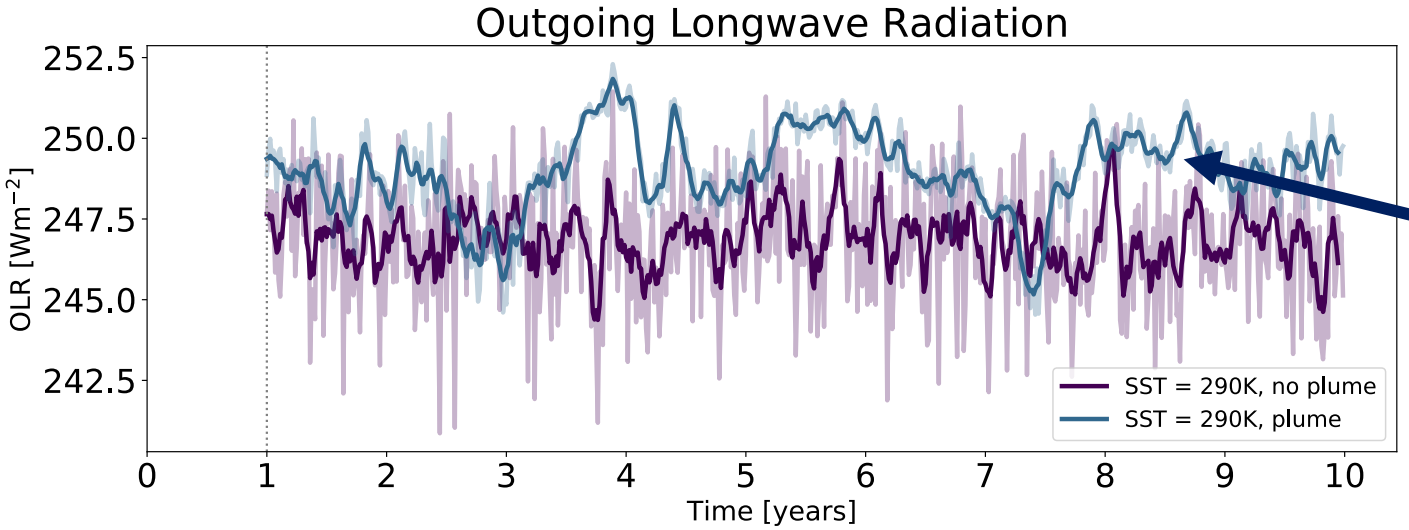
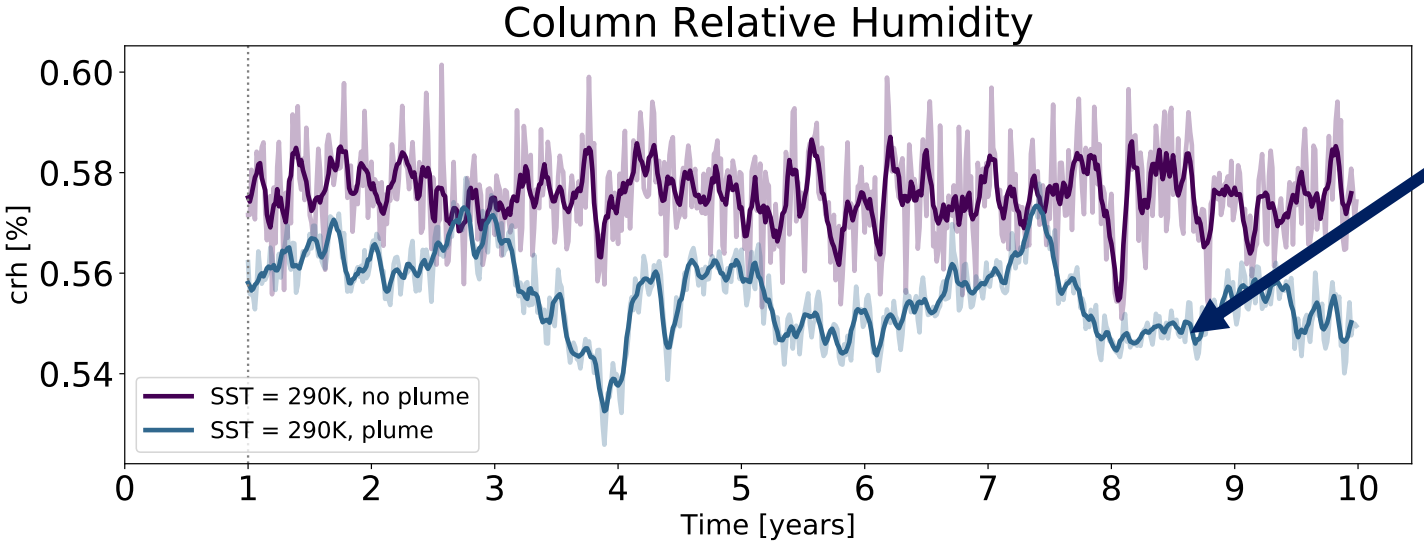


Figure shows slices of the daily mean (day 210) wind field taken around the yellow circle in Vertical proles of winds a) tangentially to the plume and b) radially to the plume are plotted against the distance around the yellow circle. Slice starts at the yellow arrow and moves around the circle in a clockwise direction. Black contours show the 3d cloud area fraction where the darkest to lightest contours show the 0.15, 0.45, 0.75 levels respectively. a) Positive (red) windspeed implies tangential winds moving clockwise, negative (blue) shows tangential winds moving anticlockwise. b) Positive (red) windspeed implies radial winds moving towards the plume, negative (blue) windspeed implies radial winds moving away from the plume.



Can see that, when the plume is added there is an increase in the OLR

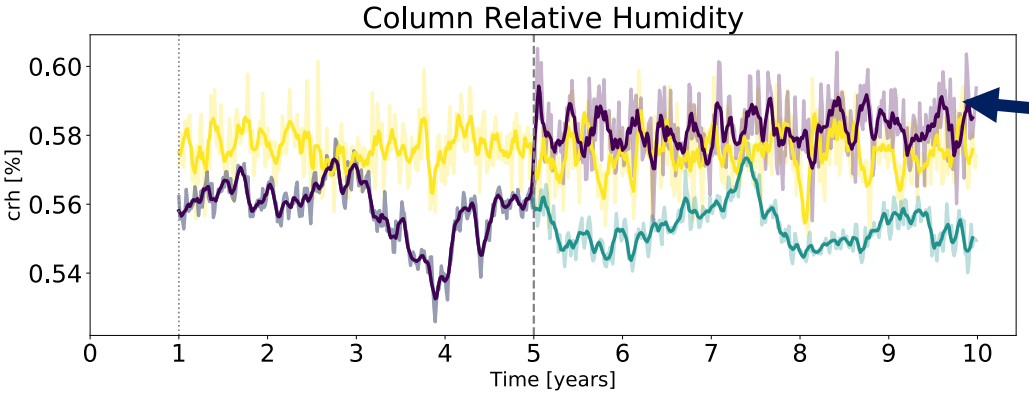


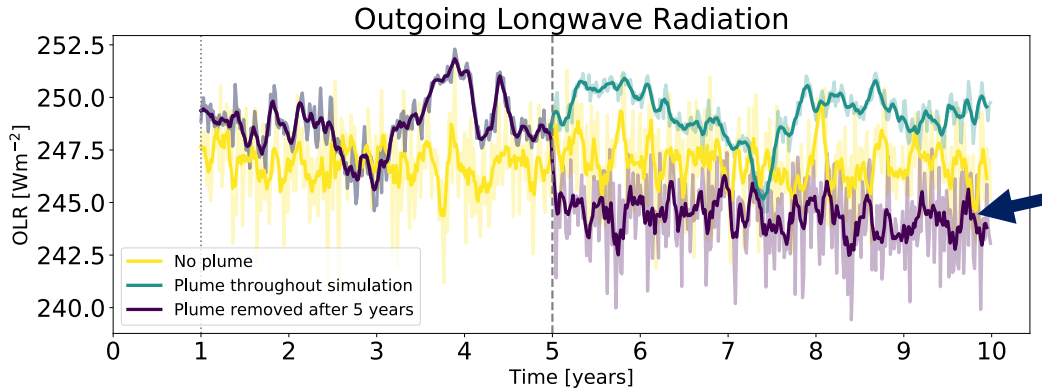
When the plume is added we also get a domain-mean drying

These results are all consistent with the plume forcing convection to aggregate at SST=290K, a temperature at which it didn't aggregate 'naturally'.

Globally averaged timeseries of column relative humidity and outgoing longwave radiation starting after first year of ICON GCM RCE simulation with SST=290K. Faded lines are daily mean output, darker lines are monthly running means. Purple lines are simulations with no plume, blue line has an aerosol plume forcing

Removing the plume



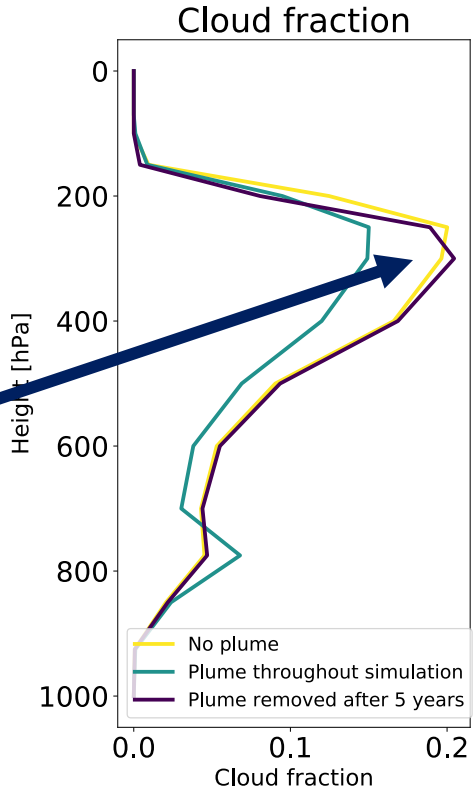


Globally averaged timeseries of column relative humidity and outgoing longwave radiation starting after first year of ICON GCM RCE simulation. Faded lines are daily mean output, darker lines are monthly running means. Yellow lines are simulations with no plume, green line has plume forcing throughout simulation, purple line has plume removed after 5 years of simulation.

If the plume is removed after 5 years the CRH increases slightly compared to the 'original' state after ~1 month

The high cloud fraction moves back to its 'original' state

The OLR falls to slightly lower than 'original' state



Globally averaged vertical profile of cloud fraction, averaged over final four years of a ten year simulation.

Unlike previous studies, forced aggregation doesn't exhibit hysteresis – aggregation is dependent on plume's existence

CONCLUSIONS

- Using ICON GCM in aquaplanet RCE configuration, with idealised aerosol radiative perturbations from MAC-SP model
- Can **force convective aggregation** at SSTs where aggregation didn't naturally occur. This aggregation forms in **'star'-like shapes** - due to two large-scale circulations forming
  1. **Radial circulation**: large-scale convergence near the surface and divergence in the upper atmosphere. **Momentum is transferred upwards** through strong updrafts, moving convection towards plume forcing
  2. **Tangential circulation**: near-surface entrainment and higher detrainment tangentially to the plume forms open-sky pockets. Encourages convection to form in already highly convective regions
- Forced aggregation **doesn't exhibit hysteresis -** convection disaggregates within a month after plume is removed
- Domain mean changes are seen with plume AODs > 0.6 (not shown)
  - Real-world pollution plumes exist with AOD ~ 0.6 and SSAs ~ 0.8. An important analogue of real-world convective aggregation?
  - **Time-scales are too short for global-scale aggregation, but might influence local organisation**