The quest for water vapour parametrization in weather and climate models

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Extreme Precipitation

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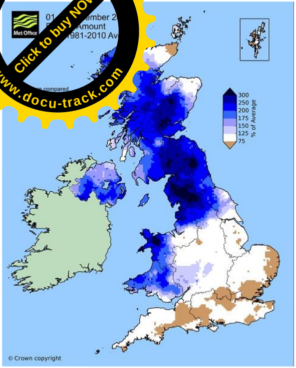


- exceptionally heavy rainfall in November and December 2015
- <u>26th December</u>
  rainfall of up to 120mm fell within 24 hours in the Lancashire and Yorkshire areas
  ≈ average rainfall for the entire month of December (145mm)
- Boxing-day floods in Leeds

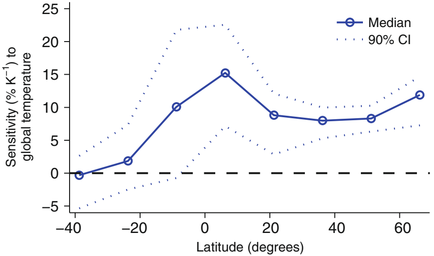
Extreme Precipitation and Climate Change

- Is climate change a contributing factor to extreme precipitation?
- How will precipitation extremes respond to future changes in climate?

We can gain some insights by:

1. looking into past: records of observed precipitation
2. predicting the future: model projection

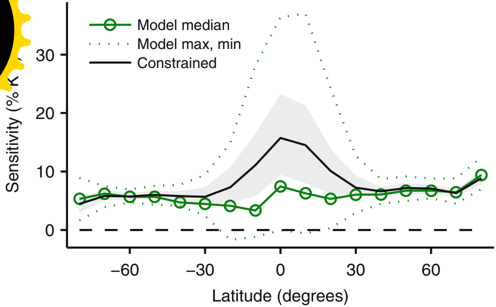
Analysis of observed precipitation extremes



(O'Gorman 2015)

- data from rain gauges over land stations from 1910 to 2010
- maximum daily precipitation rate at each grid box (station) for each year in the record, $P_{\max}(x, y, t)$
- global-mean surface temperature anomaly $\Delta T(t)$ from 1910 to 2010
- regress $P_{\max}(x, y, t)$ against $\Delta T(t)$, regression coefficient $= m(x, y)$
- Sensitivity $= m(x, y)/\langle P_{\max}(x, y, t)\rangle_t \times 100\%$
- averaged over the 15° latitude bands (median)

model prediction



(O'Gorman 2015)

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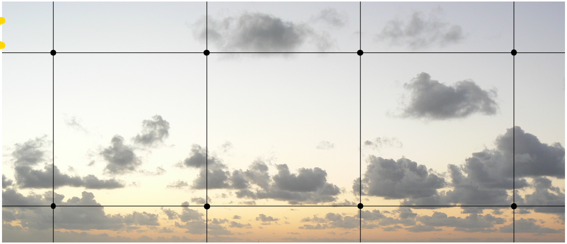
- climate-model simulations using a projected scenario of greenhouse gas concentration into the 21st century (RCP8.5)
- compare results across many different climate models (CMIP5)
- large inter-model scatter in the Tropics ⇒ results unreliable!
  - tropical precipitation depends strongly on small-scale processes that are not resolved in model
  - results sensitive to parametrization of these subgrid-scale processes

Parametrization



- **atmospheric states**: continuous fields governed by differential equations — describe motions on all scales. For example,

  specific humidity field $q(\vec{x}, t)$: $$\frac{\partial q}{\partial t} + \vec{u} \cdot \nabla q = \kappa \nabla^2 q + S - C$$

- **weather/climate models**: numerical solutions of a discrete version of the governing differential equations on a grid
  $\Rightarrow$ cannot describe processes below the grid scale
  subgrid-scale processes affect the atmospheric state on large-scales

- **Parametrization**: technique to represent the statistical effects of subgrid-scale processes in terms of the resolved scales

Subgrid-scale processes

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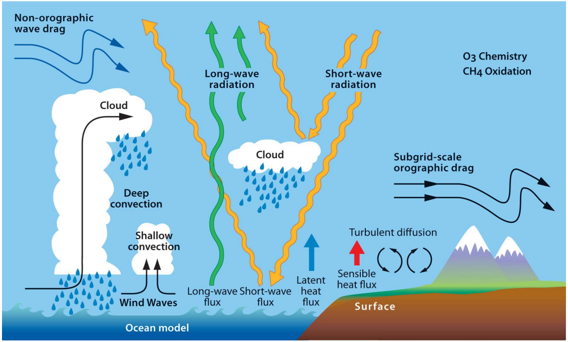
- typical resolution of climate models: horizontal ~ 100 km
  vertical ~ 10 km
- subgrid-scale processes
  - convective cloud ~ 1 km
  - small-scale turbulent mixing ~ 1 mm $-$ 1 m
  - raindrops ~ 1 mm
  - cloud droplets (form by condensation) $\sim 1\ \mu$m



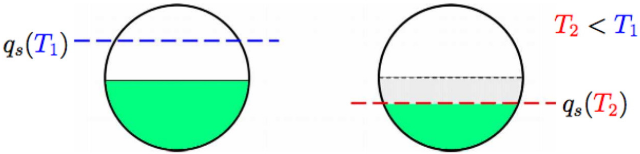
(ECMWF)

Condensation of water vapour

- specific humidity of an air parcel:

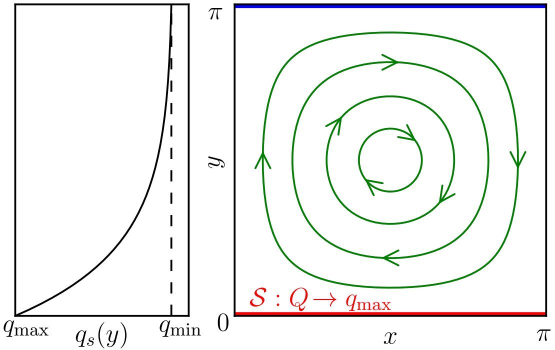
$$Q = \frac{\text{mass of water vapor}}{\text{total air mass}}$$

- saturation specific humidity, $q_s(T)$
  - $Q = \begin{cases} q_s & \text{if} \quad Q > q_s \quad \text{(excessive moisture condensed)} \\ Q & \text{if} \quad Q \leqslant q_s \end{cases}$
  - $q_s(T)$ decreases with temperature T, hence position dependent



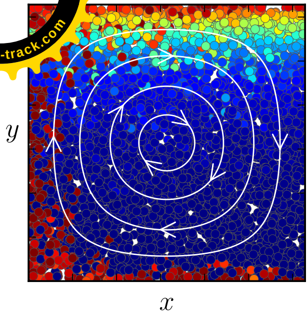
An idealised atmosphere

- bounded domain: $[0, \pi] \times [0, \pi]$, reflective boundaries
- $q_s(y) = q_{\max} \exp(-\alpha y)$: $q_s(0) = q_{\max}$ and $q_s(\pi) = q_{\min}$
- resetting source: $Q = q_{\max}$ if parcel hits $y = 0$
- large-scale cellular flow: $\psi = \sin x \sin y$; $\quad (u, v) = (-\psi_y, \psi_x)$
- small-scale turbulence: Brownian motion

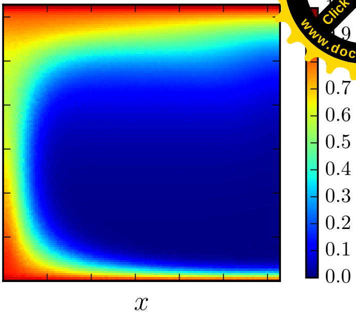


Relative humidity

Snapshot of parcels



“Observation”



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$$\text{relative humidity} = \frac{Q}{q_s}$$

- Observation: divide the domain into small bins and average over parcels in each bin

Parametrization of condensation

- Governing equation for the specific humidity field $q(x, y, t)$:

$$\frac{\partial q}{\partial t} + \vec{u} \cdot \nabla q = \kappa \nabla^2 q + S - C$$

- Numerical solution on a grid: $\overline{q}(i, j, t_n)$ represents the average of the many parcels within a grid box.

  What should be the form of the condensation term C?

1. coarse-grained:

$$C_{\text{avg}} = \frac{1}{\tau}\left[\overline{q}(i,j,t) - q_s(j)\right]$$

2. stochastic:

$$C_{\text{stoc}} = \frac{1}{\tau}\int_{q_s(j)}^{q_{\max}} (q' - q_s)\,\Phi_0(q'|i,j;t_n)\,\mathrm{d}q'$$

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Comparison of parametrization schemes: relative humidity