# The Plant-Craig stochastic convection scheme: How it works and some examples of its application

R. J. Keane [1]

[1]Deutscher Wetterdienst, Germany

26th November 2013

Thanks to: Bob Plant, George Craig, Günther Zängl, Warren Tennant, Christian Keil

Stochastic Physics Week

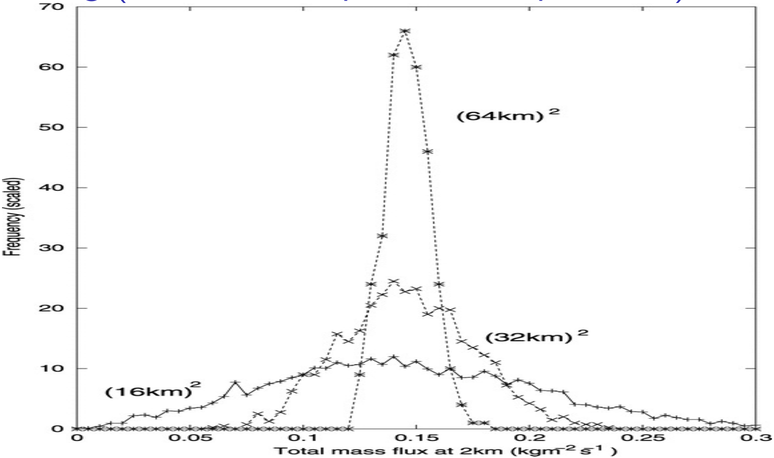
1. Overview of the Plant-Craig stochastic convection scheme

2. Scale-adaptivity of the Plant-Craig scheme in comparison with deterministic schemes, Part I
   - ICON Aquaplanet
   - Effects of the input averaging

3. Verification in MOGREPS

4. Scale-adaptivity of the Plant-Craig scheme in comparison with deterministic schemes, Part II
   - Convective equilibrium experiment

# Variability of convective response to a given large-scale forcing (Convective Equilibrium Experiment)



Taken from Plant & Craig, JAS (2008)

# Plant-Craig scheme methodology (I)

- Average $u$, $v$, $T$, $q$, $q_l$, $q_i$ over a region large enough to contain many clouds, but small enough that it is representative of the current grid box.
- Use this as input to the Kain-Fritsch trigger scheme.

If convection is initiated:

- Use the Kain-Fritsch plume model, extended to allow for an ensemble of plumes, to calculate vertical properties.
    - The plumes are weighted by $p(m)\mathrm{d}m = \frac{1}{\langle m \rangle} \mathrm{e}^{-m/\langle m \rangle} \mathrm{d}m$.
- The model allows for updraft/downdraft pairs with entrainment and detrainment.
- Entrainment decreases with increasing mass flux.
- The total required mass flux is obtained by scaling so that 90% of cape is removed within the closure time scale. This yields the ensemble mean mass flux $\langle M \rangle$. The ensemble mean mass flux per cloud $\langle m \rangle$ is taken as a 'fundamental constant'.

# Plant-Craig scheme methodology (I)

- Average $u$, $v$, $T$, $q$, $q_l$, $q_i$ over a region large enough to contain many clouds, but small enough that it is representative of the current grid box.
- Use this as input to the Kain-Fritsch trigger scheme.

If convection is initiated:

- Use the Kain-Fritsch plume model, extended to allow for an ensemble of plumes, to calculate vertical properties.
  - The plumes are weighted by $p(m)\mathrm{d}m = \frac{1}{\langle m \rangle} \mathrm{e}^{-m/\langle m \rangle} \mathrm{d}m$.
- The model allows for updraft/downdraft pairs with entrainment and detrainment.
- Entrainment decreases with increasing mass flux.
- The total required mass flux is obtained by scaling so that 90% of cape is removed within the closure time scale. This yields the ensemble mean mass flux $\langle M \rangle$. The ensemble mean mass flux per cloud $\langle m \rangle$ is taken as a 'fundamental constant'.

# Plant-Craig scheme methodology (I)

- Average $u$, $v$, $T$, $q$, $q_l$, $q_i$ over a region large enough to contain many clouds, but small enough that it is representative of the current grid box.
- Use this as input to the Kain-Fritsch trigger scheme.

If convection is initiated:

- Use the Kain-Fritsch plume model, extended to allow for an ensemble of plumes, to calculate vertical properties.
  - The plumes are weighted by $p(m)\mathrm{d}m = \frac{1}{\langle m \rangle} \mathrm{e}^{-m/\langle m \rangle} \mathrm{d}m$.
- The model allows for updraft/downdraft pairs with entrainment and detrainment.
- Entrainment decreases with increasing mass flux.
- The total required mass flux is obtained by scaling so that 90% of cape is removed within the closure time scale. This yields the ensemble mean mass flux $\langle M \rangle$. The ensemble mean mass flux per cloud $\langle m \rangle$ is taken as a 'fundamental constant'.

# Plant-Craig scheme methodology (I)

- Average $u$, $v$, $T$, $q$, $q_l$, $q_i$ over a region large enough to contain many clouds, but small enough that it is representative of the current grid box.
- Use this as input to the Kain-Fritsch trigger scheme.

If convection is initiated:

- Use the Kain-Fritsch plume model, extended to allow for an ensemble of plumes, to calculate vertical properties.
  - The plumes are weighted by $p(m)\mathrm{d}m = \frac{1}{\langle m \rangle}\mathrm{e}^{-m/\langle m \rangle}\mathrm{d}m$.
- The model allows for updraft/downdraft pairs with entrainment and detrainment.
- Entrainment decreases with increasing mass flux.
- The total required mass flux is obtained by scaling so that 90% of cape is removed within the closure time scale. This yields the ensemble mean mass flux $\langle M \rangle$. The ensemble mean mass flux per cloud $\langle m \rangle$ is taken as a ‘fundamental constant’

# Plant-Craig scheme methodology (II)

- Use $\langle M\rangle$ and $\langle m\rangle$ to scale the PDF of cloud mass fluxes:

$$\frac{\langle M\rangle}{\langle m\rangle^2}\mathrm{e}^{-m/\langle m\rangle}\frac{\delta t}{t_L}\delta m.$$

The extra factor $\delta t/t_L$ is to account for the finite lifetime $t_L$ of the clouds ($\delta t$ is the model time step).

- Split this PDF into bins $\delta m$ and choose randomly (based on the probability for that bin) whether or not to initiate a cloud for each bin.
- For each cloud initiated, use the Kain-Fritsch plume model to determine vertical tendency profiles.
- These tendency profiles last for a time $t_L$. Clouds older than $t_L$ are removed and the remaining tendency profiles are summed to give the overall tendency profiles to feed back to the dynamics.

# Plant-Craig scheme methodology (II)

- Use $\langle M\rangle$ and $\langle m\rangle$ to scale the PDF of cloud mass fluxes:

$$\frac{\langle M\rangle}{\langle m\rangle^2}\mathrm{e}^{-m/\langle m\rangle}\frac{\delta t}{t_L}\delta m.$$

  The extra factor $\delta t/t_L$ is to account for the finite lifetime $t_L$ of the clouds ($\delta t$ is the model time step).

- Split this PDF into bins $\delta m$ and choose randomly (based on the probability for that bin) whether or not to initiate a cloud for each bin.
- For each cloud initiated, use the Kain-Fritsch plume model to determine vertical tendency profiles.
- These tendency profiles last for a time $t_L$. Clouds older than $t_L$ are removed and the remaining tendency profiles are summed to give the overall tendency profiles to feed back to the dynamics.

# Plant-Craig scheme methodology (II)

- Use $\langle M\rangle$ and $\langle m\rangle$ to scale the PDF of cloud mass fluxes:

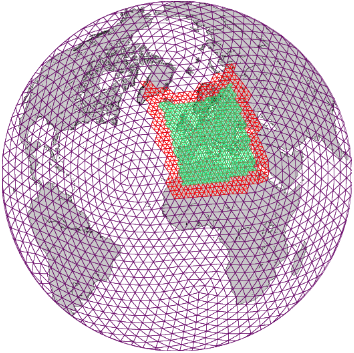
$$\frac{\langle M\rangle}{\langle m\rangle^2}\mathrm{e}^{-m/\langle m\rangle}\frac{\delta t}{t_L}\delta m.$$

  The extra factor $\delta t/t_L$ is to account for the finite lifetime $t_L$ of the clouds ($\delta t$ is the model time step).

- Split this PDF into bins $\delta m$ and choose randomly (based on the probability for that bin) whether or not to initiate a cloud for each bin.
- For each cloud initiated, use the Kain-Fritsch plume model to determine vertical tendency profiles.
- These tendency profiles last for a time $t_L$. Clouds older than $t_L$ are removed and the remaining tendency profiles are summed to give the overall tendency profiles to feed back to the dynamics.

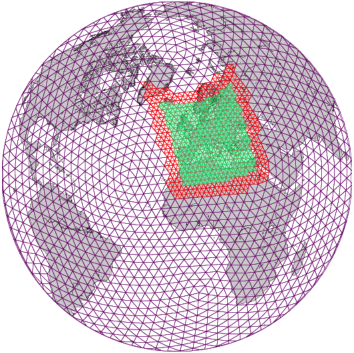
# German Icosahedral Nonhydrostatic General Circulation Model (ICON)

- Jointly developed by DWD and the MPIM in Hamburg.
- The results shown here are for different constant resolutions (40 km to 160 km), to determine how the rainfall variability varies with resolution.
- Input averaging (equivalent length 80 km) is applied for the 40 km run; the effects of varying this averaging are also shown.
- The Aquaplanet setup is used here in order to isolate variability due to different schemes.



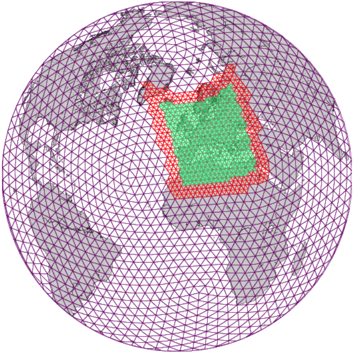
# German Icosahedral Nonhydrostatic General Circulation Model (ICON)

- Jointly developed by DWD and the MPIM in Hamburg.
- The results shown here are for different constant resolutions (40 km to 160 km), to determine how the rainfall variability varies with resolution.
- Input averaging (equivalent length 80 km) is applied for the 40 km run; the effects of varying this averaging are also shown.
- The Aquaplanet setup is used here in order to isolate variability due to different schemes.



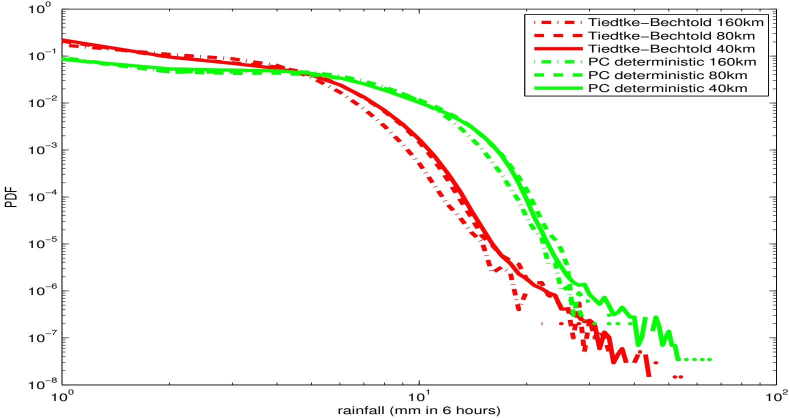
# German Icosahedral Nonhydrostatic General Circulation Model (ICON)

- Jointly developed by DWD and the MPIM in Hamburg.
- The results shown here are for different constant resolutions (40 km to 160 km), to determine how the rainfall variability varies with resolution.
- Input averaging (equivalent length 80 km) is applied for the 40 km run; the effects of varying this averaging are also shown.
- The Aquaplanet setup is used here in order to isolate variability due to different schemes.



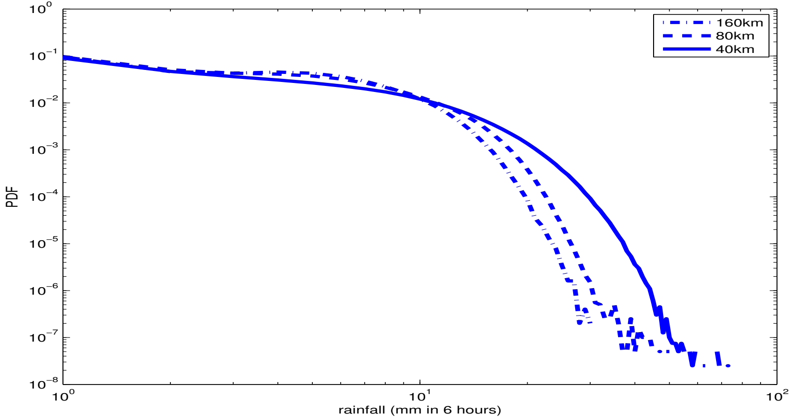
# PDFs of 6-hour rainfall accumulation for the two different deterministic schemes, at three different resolutions.

- Every 6 hours for 3–6 months, between ±20 degrees latitude.



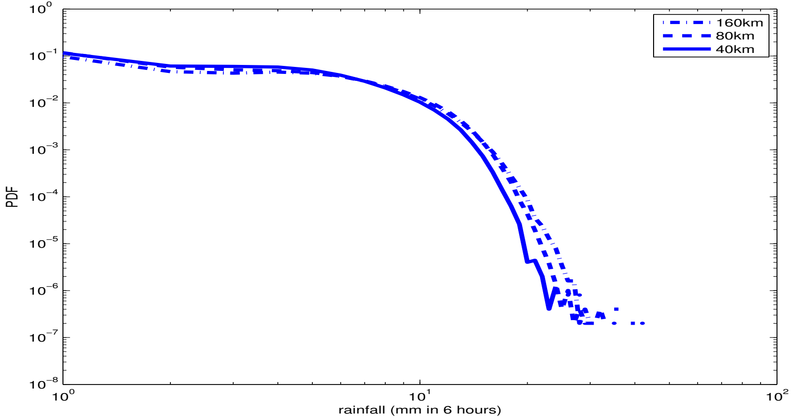
# PDFs of 6-hour rainfall accumulation for the stochastic scheme, at three different resolutions.

- Every 6 hours for 3–6 months, between ±20 degrees latitude.



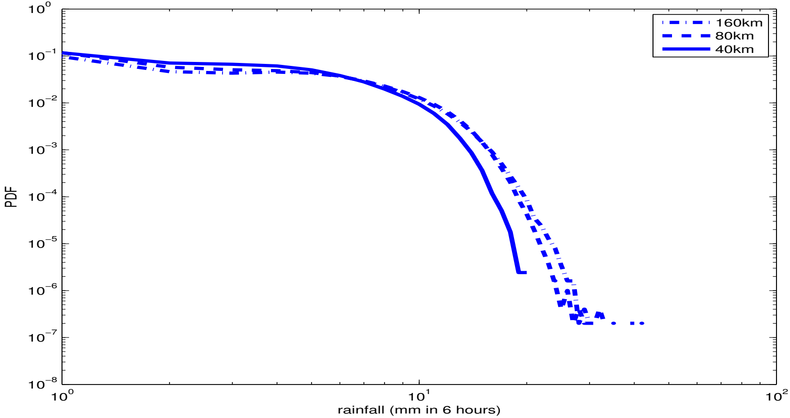
# PDFs of 6-hour rainfall accumulation for the stochastic scheme, upscaled onto the 160 km grid.

- Every 6 hours for 3–6 months, between ±20 degrees latitude.



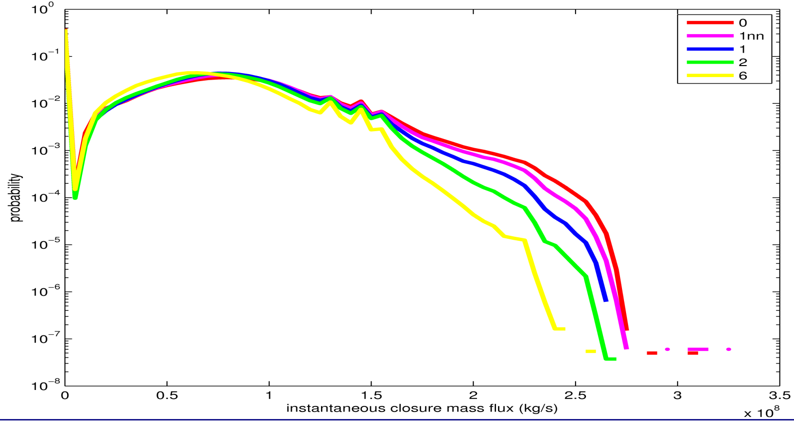
# PDFs of 6-hour rainfall accumulation for the stochastic scheme, upscaled, with no input averaging.

- Every 6 hours for 3–6 months, between ±20 degrees latitude.



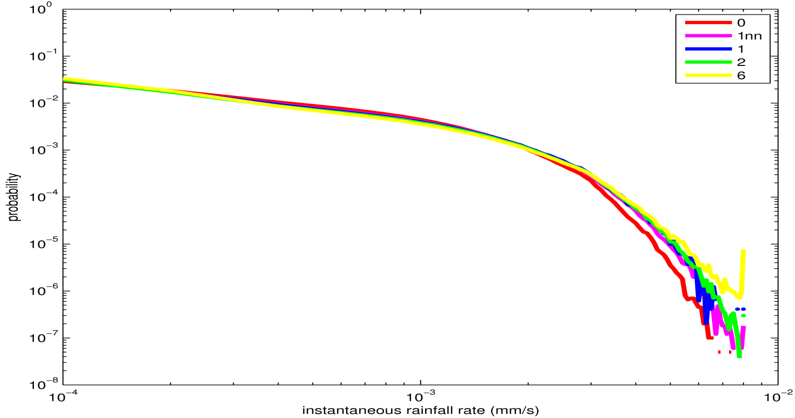
# PDFs of instantaneous mass flux ($\langle M \rangle$ from the CAPE closure) for the stochastic scheme

- Every 6 hours for 10–50 days, between ±20 degrees latitude.
- Results are for 40 km grid spacing.



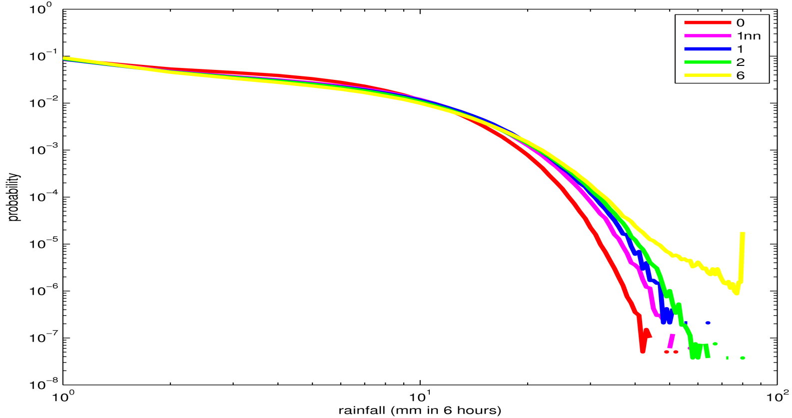
# PDFs of instantaneous rainfall rate for the stochastic scheme, for different amounts of input averaging.

- Every 6 hours for 10–50 days, between ±20 degrees latitude.
- Results are for 40 km grid spacing.

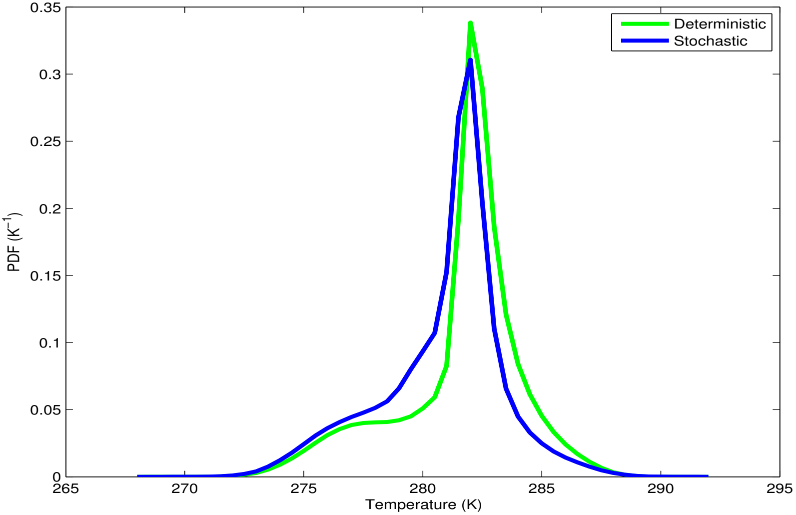


# PDFs of 6-hour rainfall accumulation for the stochastic scheme, for different amounts of input averaging.

- Every 6 hours for 10–50 days, between ±20 degrees latitude.
- Results are for 40 km grid spacing.



# Effect on distribution of temperature at 2.67 km



# Met Office (Global and) Regional Ensemble Prediction System

- The setup described here is what was used in this study.
- 24 members, 24 km grid length.
- Domain over Europe and the North Atlantic.
- 2 forecasts per day, 10–31 July 2009 (34 forecasts in total); 54 hour lead time.
- MOGREPS forecasts with the Plant-Craig scheme ("EXP") are verified in comparison with the Gregory-Rowntree scheme ("CTL").
- Rainfall over the UK is investigated in detail using NIMROD data.

# Met Office (Global and) Regional Ensemble Prediction System

- The setup described here is what was used in this study.
- 24 members, 24 km grid length.
- Domain over Europe and the North Atlantic.
- 2 forecasts per day, 10–31 July 2009 (34 forecasts in total); 54 hour lead time.
- MOGREPS forecasts with the Plant-Craig scheme ("EXP") are verified in comparison with the Gregory-Rowntree scheme ("CTL").
- Rainfall over the UK is investigated in detail using NIMROD data.

# Met Office (Global and) Regional Ensemble Prediction System

- The setup described here is what was used in this study.
- 24 members, 24 km grid length.
- Domain over Europe and the North Atlantic.
- 2 forecasts per day, 10–31 July 2009 (34 forecasts in total); 54 hour lead time.
- MOGREPS forecasts with the Plant-Craig scheme (“EXP”) are verified in comparison with the Gregory-Rowntree scheme (“CTL”).
- Rainfall over the UK is investigated in detail using NIMROD data.

# Met Office (Global and) Regional Ensemble Prediction System

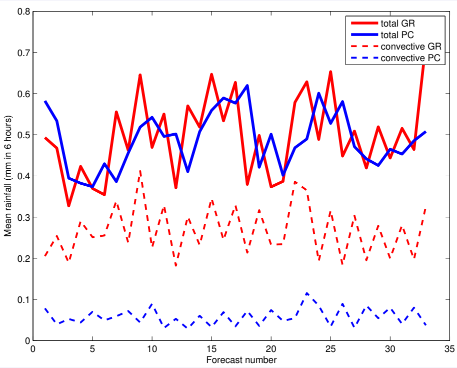
- The setup described here is what was used in this study.
- 24 members, 24 km grid length.
- Domain over Europe and the North Atlantic.
- 2 forecasts per day, 10–31 July 2009 (34 forecasts in total); 54 hour lead time.
- MOGREPS forecasts with the Plant-Craig scheme ("EXP") are verified in comparison with the Gregory-Rowntree scheme ("CTL").
- Rainfall over the UK is investigated in detail using NIMROD data.

# Met Office (Global and) Regional Ensemble Prediction System

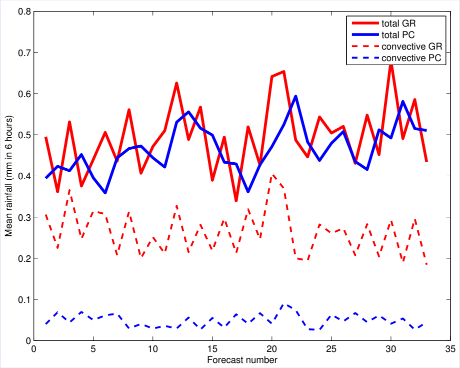
- The setup described here is what was used in this study.
- 24 members, 24 km grid length.
- Domain over Europe and the North Atlantic.
- 2 forecasts per day, 10–31 July 2009 (34 forecasts in total); 54 hour lead time.
- MOGREPS forecasts with the Plant-Craig scheme ("EXP") are verified in comparison with the Gregory-Rowntree scheme ("CTL").
- Rainfall over the UK is investigated in detail using NIMROD data.

# Mean rainfall accumulation

## 12–18 hour forecast



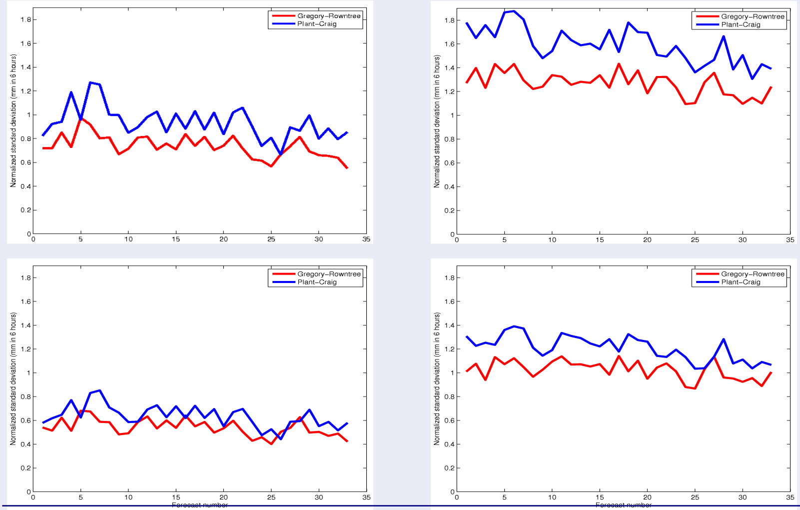
## 48–54 hour forecast



# Rainfall accumulation variability

## 12–18 hour forecast

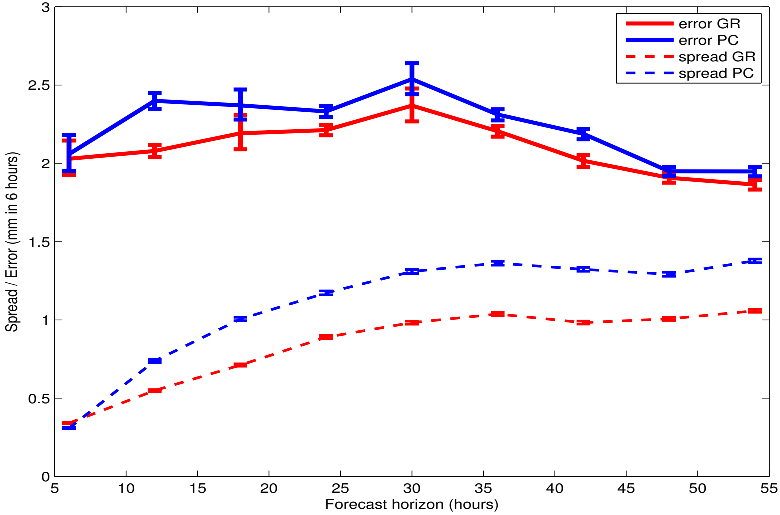
## 48–54 hour forecast



24 km

120 km

# Model spread and error



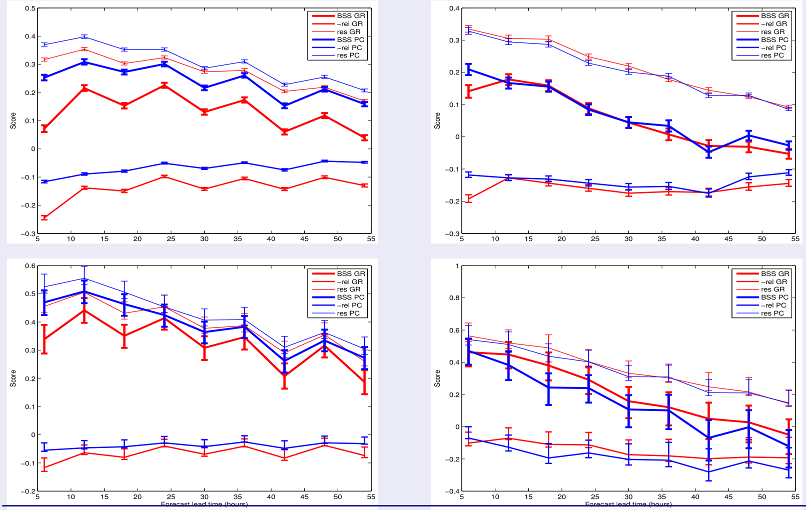
# Brier Skill Scores

Threshold: 0.3 mm

Threshold: 3.0 mm

24 km

120 km



# Convective equilibrium experiment

- UK Met Office UM used in idealised mode.
- Square domain, with bicyclic boundary conditions.
- 32km grid length, 512km total domain size.
- Constant sea-surface temperature applied; the surface heat transfer is allowed to vary.
- The atmosphere is forced by a uniform imposed cooling profile.
- The ensemble mean total mass flux $\langle M \rangle$ is constant.

# Convective equilibrium experiment

- UK Met Office UM used in idealised mode.
- Square domain, with bicyclic boundary conditions.
- 32km grid length, 512km total domain size.
- Constant sea-surface temperature applied; the surface heat transfer is allowed to vary.
- The atmosphere is forced by a uniform imposed cooling profile.
- The ensemble mean total mass flux $\langle M \rangle$ is constant.

# Convective equilibrium experiment

- UK Met Office UM used in idealised mode.
- Square domain, with bicyclic boundary conditions.
- 32km grid length, 512km total domain size.
- Constant sea-surface temperature applied; the surface heat transfer is allowed to vary.
- The atmosphere is forced by a uniform imposed cooling profile.
- The ensemble mean total mass flux $\langle M \rangle$ is constant.

# Convective equilibrium experiment – Cohen-Craig theory

Given an average number of clouds $\langle N\rangle$, the actual number of clouds $N$ follows a Poisson distribution:

$$p_{\langle N\rangle}(N) = \frac{\langle N\rangle^N \mathrm{e}^{-\langle N\rangle}}{N!}.$$

Combining this with the probability that the mass flux is $M$, given $N$:

$$p_N(M) = \int_0^M p_{N-1}(M-u)p(u)\mathrm{d}u$$

leads to a PDF of total mass flux:

$$\begin{aligned} p(M,\langle m\rangle,\langle M\rangle) =& \delta(M)\mathrm{e}^{-\frac{\langle M\rangle}{\langle m\rangle}} + \\ & \frac{1}{\langle m\rangle}\sqrt{\frac{\langle M\rangle}{M}}\mathrm{e}^{-\frac{M+\langle M\rangle}{\langle m\rangle}} I_1\left(\frac{2}{\langle m\rangle}\sqrt{M\langle M\rangle}\right). \end{aligned}$$

# Convective equilibrium experiment – Cohen-Craig theory

Given an average number of clouds $\langle N\rangle$, the actual number of clouds $N$ follows a Poisson distribution:

$$p_{\langle N\rangle}(N) = \frac{\langle N\rangle^N \mathrm{e}^{-\langle N\rangle}}{N!}.$$

Combining this with the probability that the mass flux is $M$, given $N$:

$$p_N(M) = \int_0^M p_{N-1}(M-u)p(u)\mathrm{d}u$$

leads to a PDF of total mass flux:

$$\begin{aligned} p(M,\langle m\rangle,\langle M\rangle) =& \delta(M)\mathrm{e}^{-\frac{\langle M\rangle}{\langle m\rangle}} + \\ & \frac{1}{\langle m\rangle}\sqrt{\frac{\langle M\rangle}{M}}\mathrm{e}^{-\frac{M+\langle M\rangle}{\langle m\rangle}} I_1\left(\frac{2}{\langle m\rangle}\sqrt{M\langle M\rangle}\right). \end{aligned}$$

# Convective equilibrium experiment – Cohen-Craig theory

Given an average number of clouds $\langle N\rangle$, the actual number of clouds $N$ follows a Poisson distribution:

$$p_{\langle N\rangle}(N) = \frac{\langle N\rangle^N \mathrm{e}^{-\langle N\rangle}}{N!}.$$

Combining this with the probability that the mass flux is $M$, given $N$:

$$p_N(M) = \int_0^M p_{N-1}(M-u)p(u)\mathrm{d}u$$

leads to a PDF of total mass flux:

$$\begin{aligned} p(M,\langle m\rangle,\langle M\rangle) = & \delta(M)\mathrm{e}^{-\frac{\langle M\rangle}{\langle m\rangle}} + \\ & \frac{1}{\langle m\rangle}\sqrt{\frac{\langle M\rangle}{M}}\mathrm{e}^{-\frac{M+\langle M\rangle}{\langle m\rangle}} I_1\left(\frac{2}{\langle m\rangle}\sqrt{M\langle M\rangle}\right). \end{aligned}$$

# Comparing rainfall PDFs

- Assume that convective rainfall $C$ is a linear function of mass flux $M$.
- Then a PDF of rainfall $p(C, \langle c\rangle, \langle C\rangle)$ can be derived, with the same shape as $p(M, \langle m\rangle, \langle M\rangle)$.
- This allows a comparison of PDFs from different schemes.
- This can be done for different scales, by looking at the rainfall over different numbers of grid boxes.
- Because $\langle c\rangle$ is not known, it is fitted to give the best agreement, for *one* scale.
  - This *same* value is then used for *all* scales.
  - In this way, the scale adaptivity of each scheme can be assessed.

# Comparing rainfall PDFs

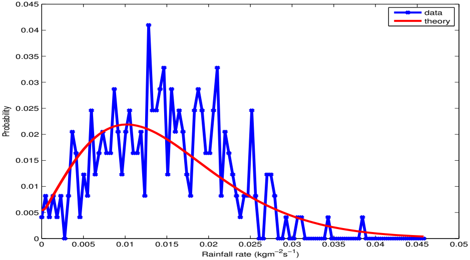
- Assume that convective rainfall $C$ is a linear function of mass flux $M$.
- Then a PDF of rainfall $p(C, \langle c \rangle, \langle C \rangle)$ can be derived, with the same shape as $p(M, \langle m \rangle, \langle M \rangle)$.
- This allows a comparison of PDFs from different schemes.
- This can be done for different scales, by looking at the rainfall over different numbers of grid boxes.
- Because $\langle c \rangle$ is not known, it is fitted to give the best agreement, for *one* scale.
    - This *same* value is then used for *all* scales.
    - In this way, the scale adaptivity of each scheme can be assessed.

# Comparing rainfall PDFs

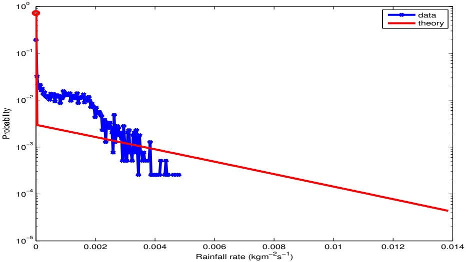
- Assume that convective rainfall $C$ is a linear function of mass flux $M$.
- Then a PDF of rainfall $p(C, \langle c \rangle, \langle C \rangle)$ can be derived, with the same shape as $p(M, \langle m \rangle, \langle M \rangle)$.
- This allows a comparison of PDFs from different schemes.
- This can be done for different scales, by looking at the rainfall over different numbers of grid boxes.
- Because $\langle c \rangle$ is not known, it is fitted to give the best agreement, for *one* scale.
    - This *same* value is then used for *all* scales.
    - In this way, the scale adaptivity of each scheme can be assessed.

# Rainfall PDFs for Gregory-Rowntree scheme

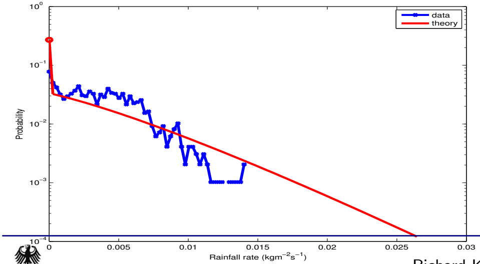
256 km



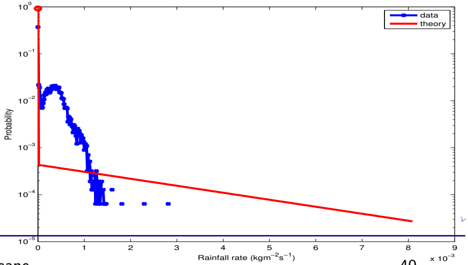
64 km



128 km



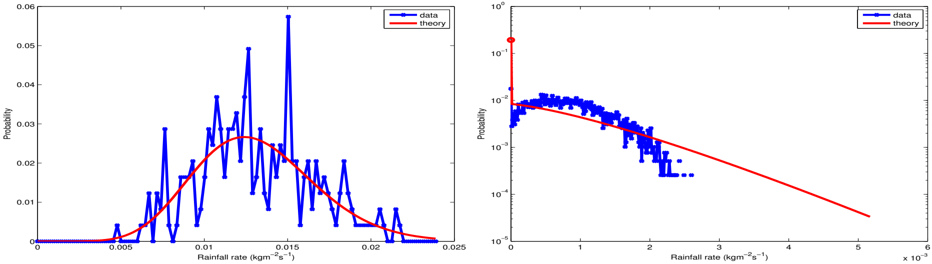
32 km



# Rainfall PDFs for Kain-Fritsch scheme

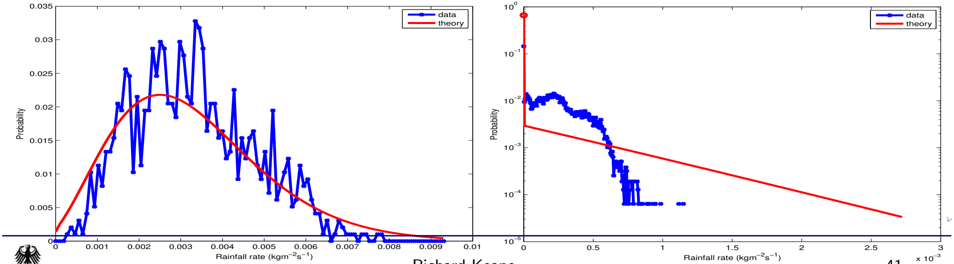
256 km

64 km



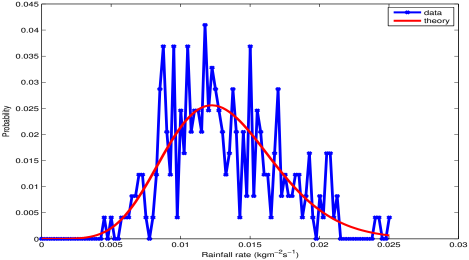
128 km

32 km

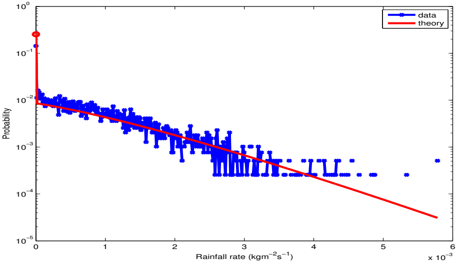


# Rainfall PDFs for Plant-Craig scheme

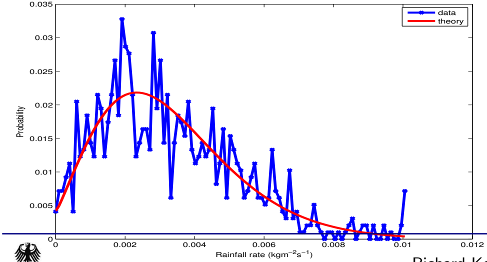
256 km



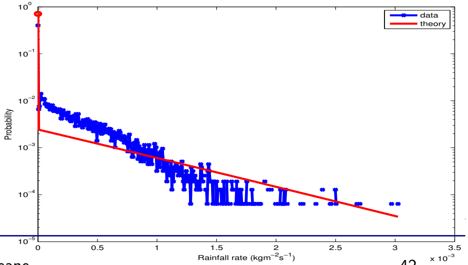
64 km



128 km



32 km



# References

- Keane RJ, Plant RS, Tennant WJ. The Plant-Craig stochastic convection scheme in MOGREPS. In preparation.
- Keane RJ, Craig GC, Zängl G, Keil C, 2013. The Plant-Craig stochastic convection scheme in ICON and its scale-adaptivity. Submitted to J. Atmos. Sci.
- Keane RJ, Plant RS. 2012. Large-scale length and time-scales for use with stochastic convective parametrization. Q. J. R. Meteorological Soc. DOI:10.1002/qj.992
- Craig GC, Cohen BG. 2006. Fluctuations in an equilibrium convective ensemble. Part I: Theoretical formulation. J. Atmos. Sci. 63:1996-2004
- Plant RS, Craig GC. 2008. A stochastic parameterization for deep convection based on equilibrium statistics. J. Atmos. Sci. DOI:10.1175/2007JAS2263.1