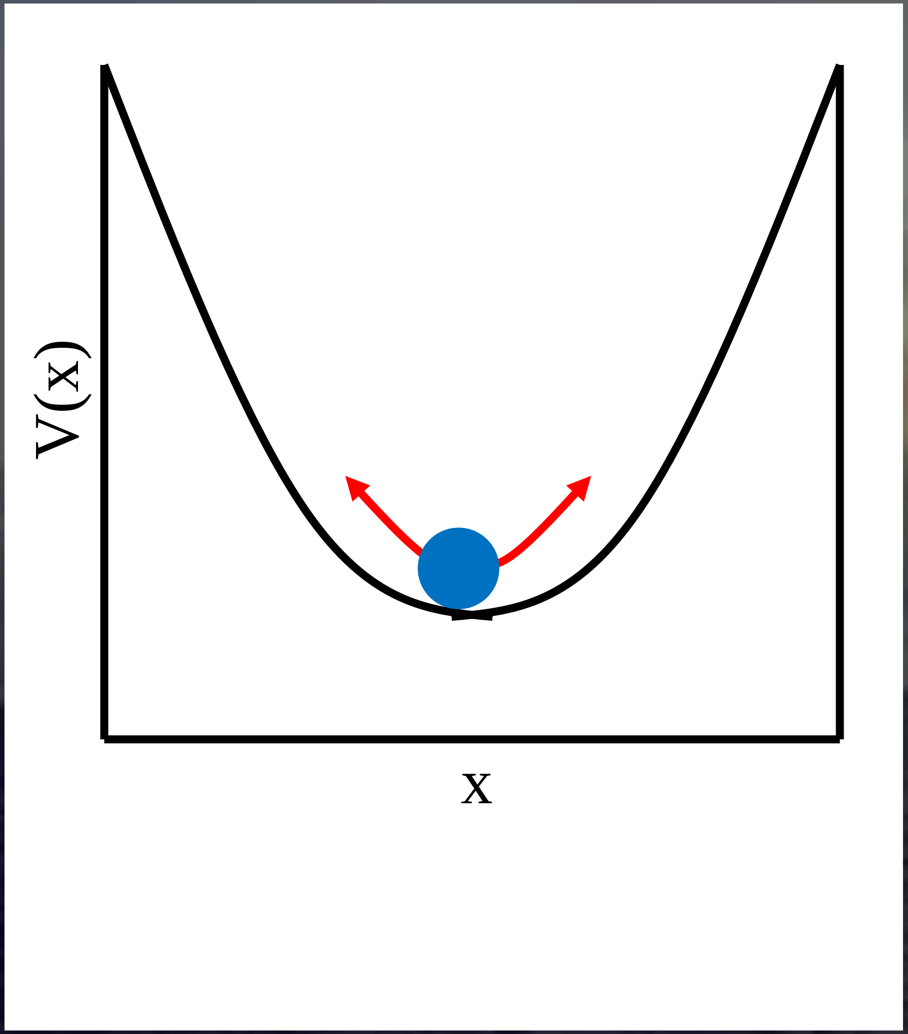
Using Stochastic Parameterisations to Study the Sensitivity of the Global Atmosphere to Near-Gridscale Variability in Physical Processes.

Michael Ball (University of Reading)

Supervisors
Bob Plant (University of Reading)
Neill Bowler (UK Met Office)
Alberto Arribas (UK Met Office)

Thought Experiment – Rolling Ball



Ball rolls around in a potential well V(x), such that $\frac{d^2x}{dt^2} = -\frac{dV(x)}{dx}$

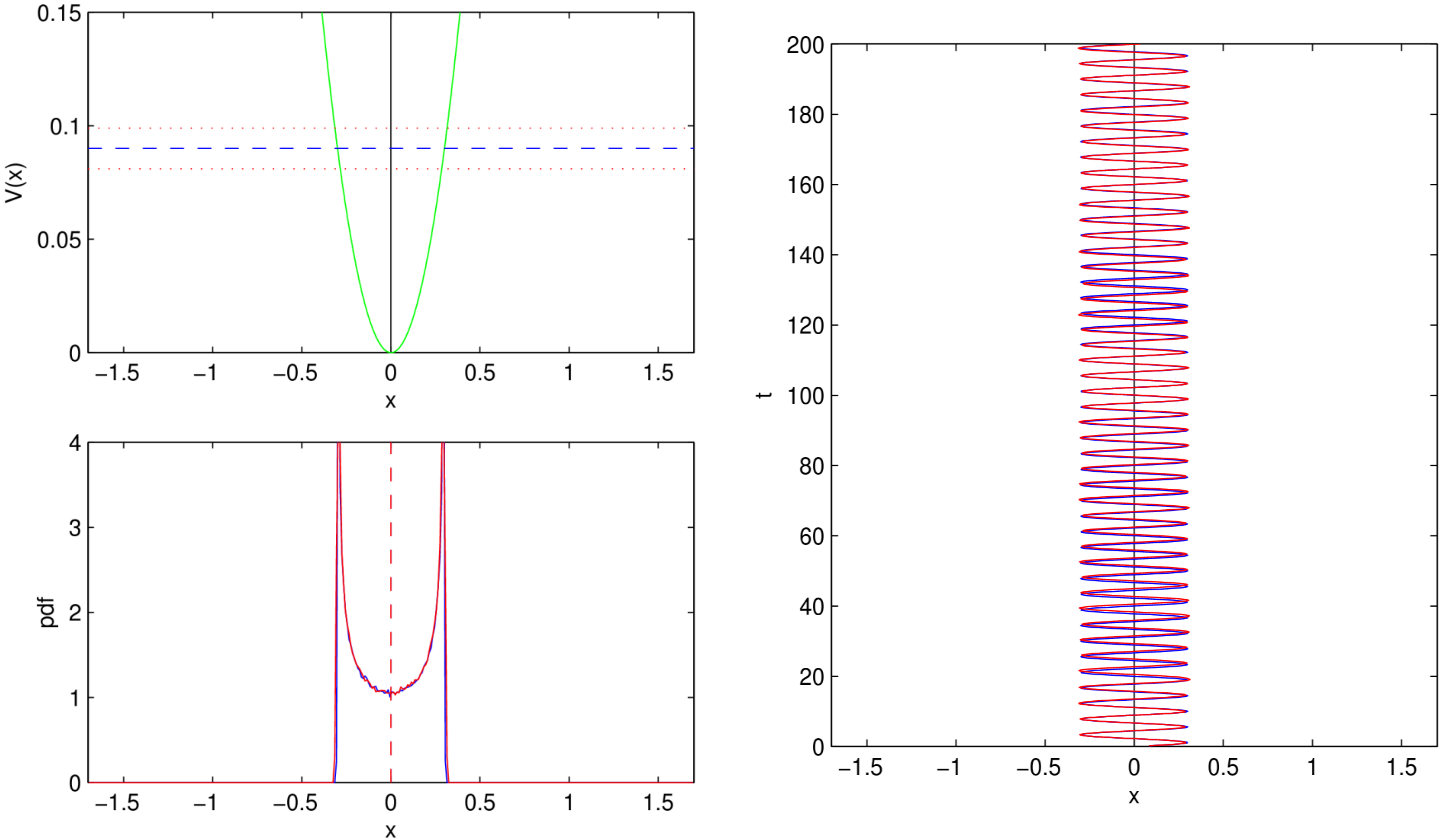
- Trajectory is deterministic and periodic and conserves total energy $E_{tot} = \frac{1}{2}\left(\frac{dx}{dt}\right)^2 + V\ x$

- But suppose there is some unresolved component of the system? $E_{tot} = \frac{1}{2}\left(\frac{dx}{dt}\right)^2 + V\ x + \varepsilon(t)$

- Stochastic component ε(t) varies on timescale of a few model timesteps.

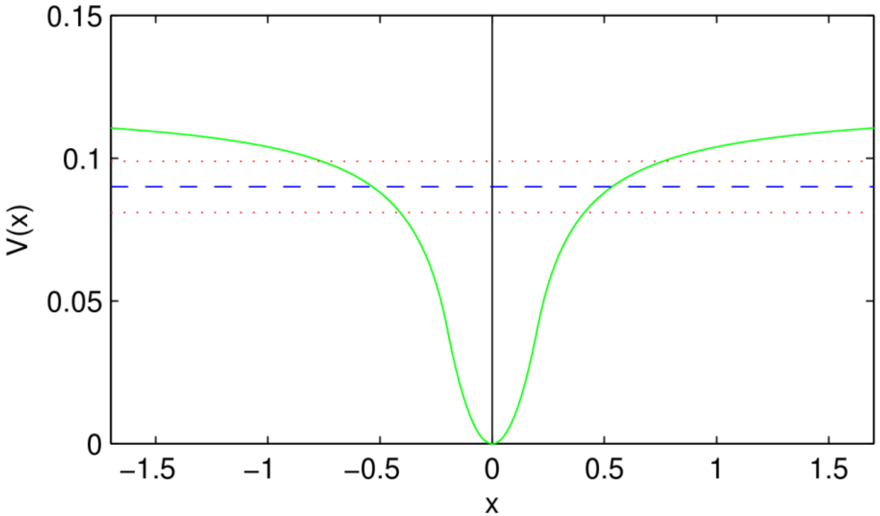
Thought Experiment – Rolling Ball

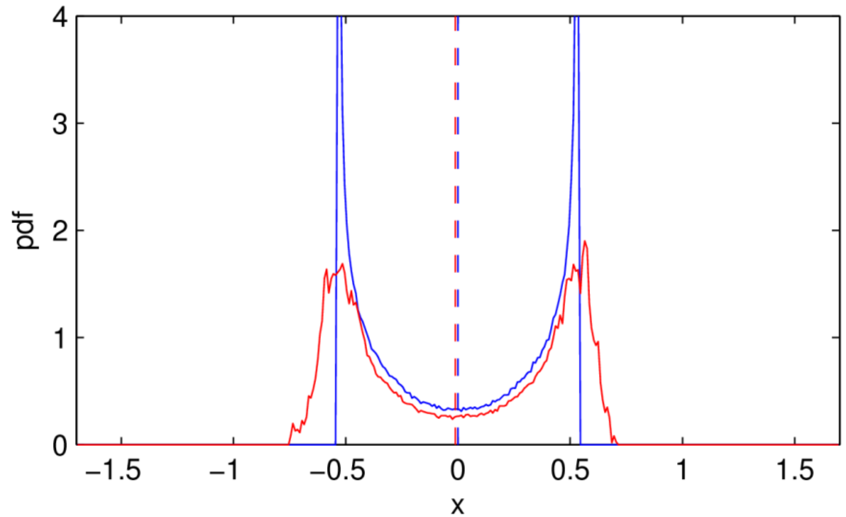
Linear system – quadratic potential well

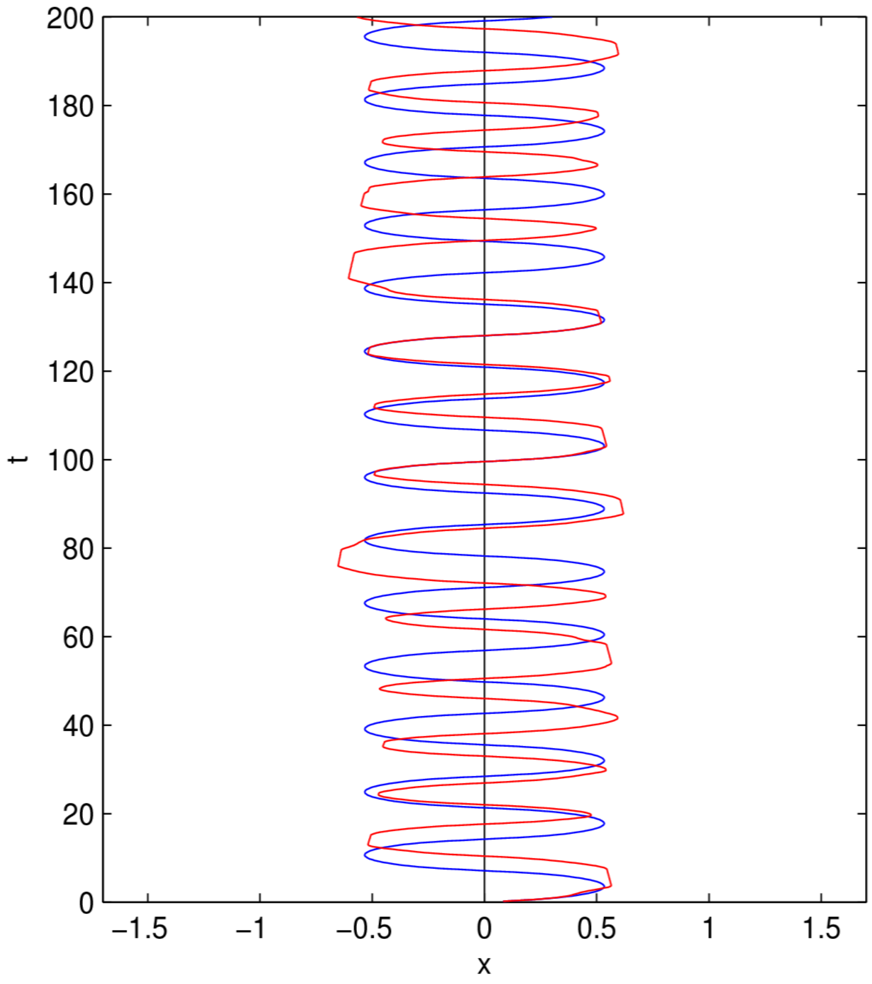


Thought Experiment – Rolling Ball

Non-linear system – gravitational potential well

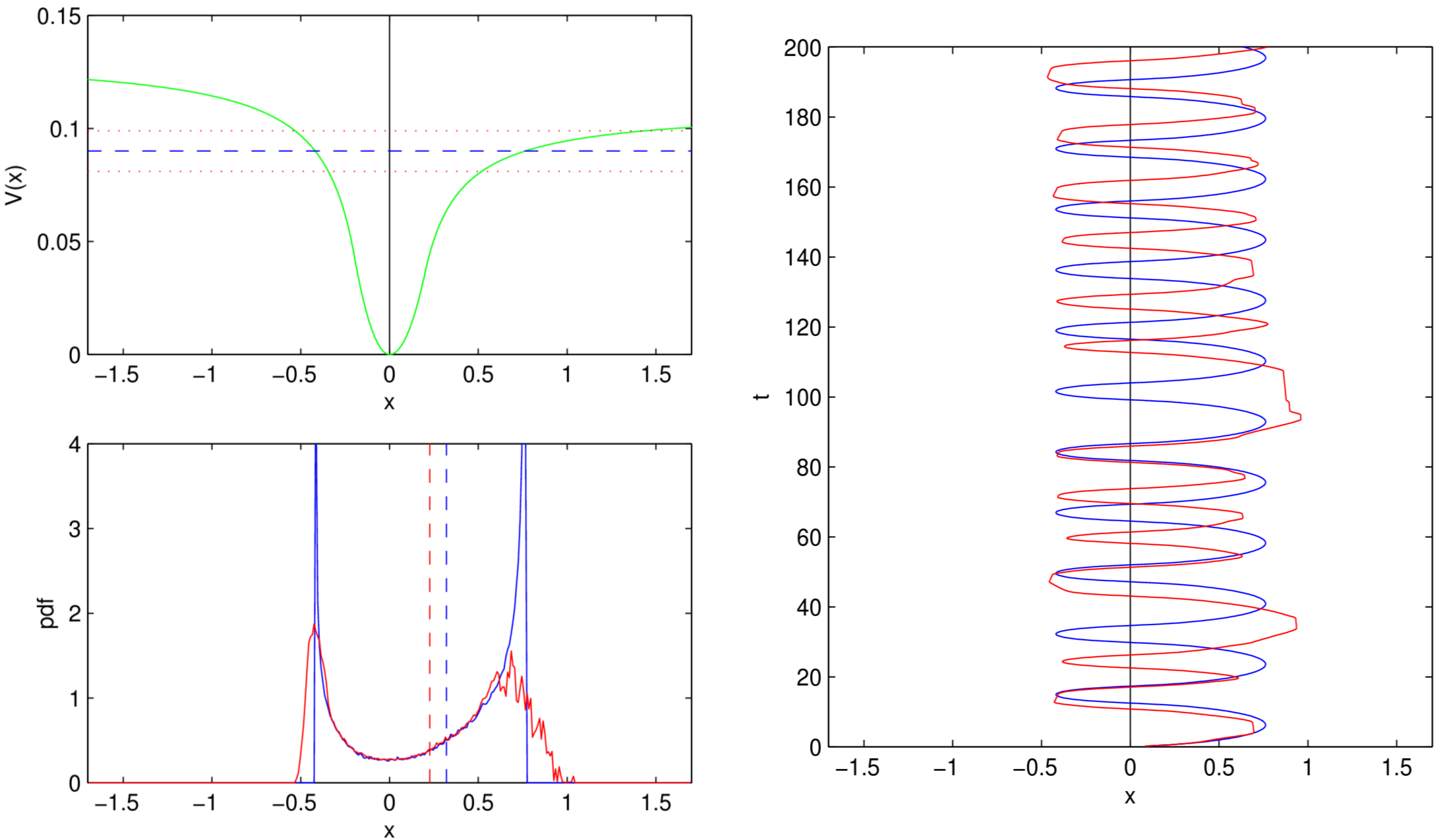






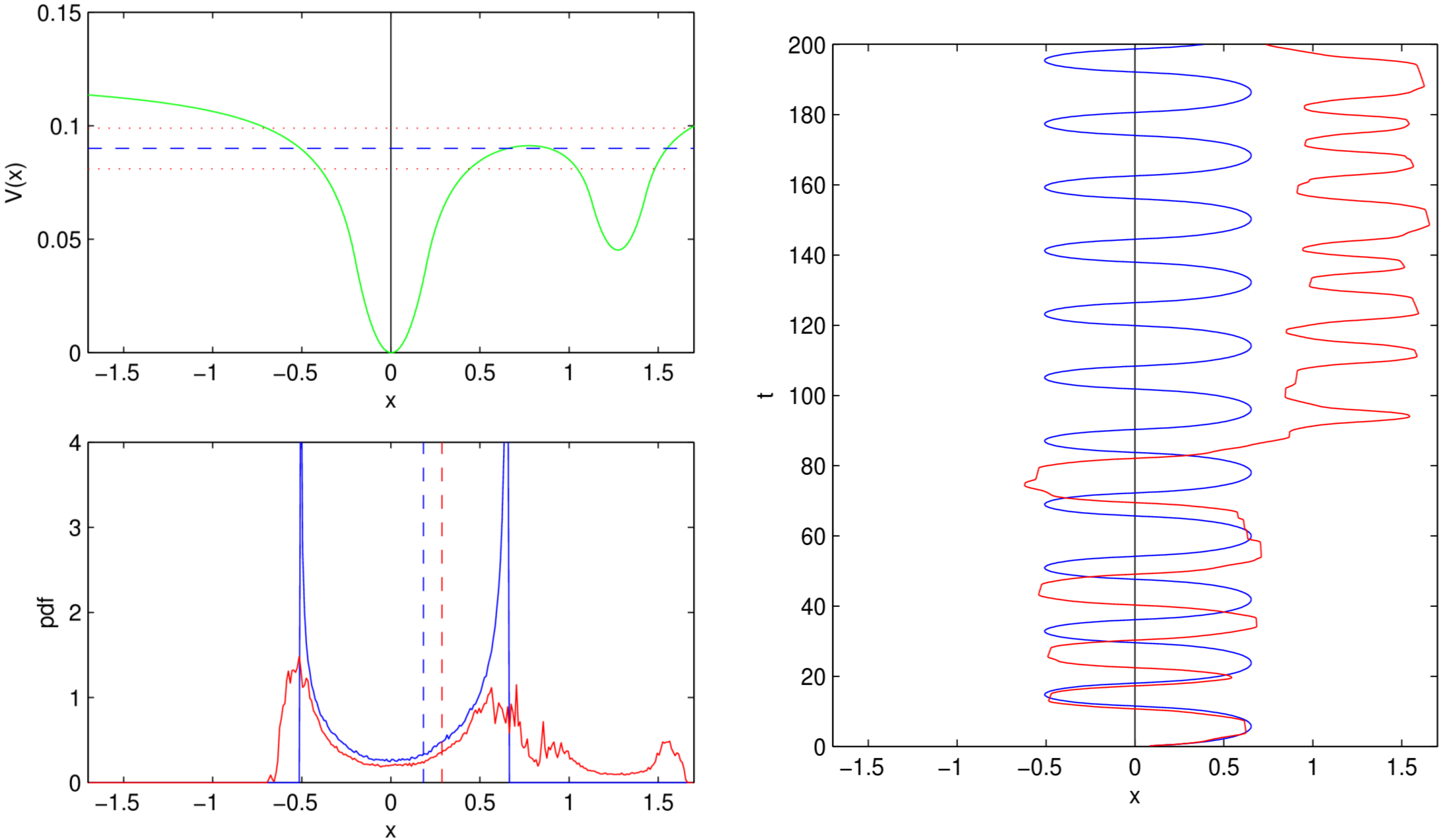
Thought Experiment – Rolling Ball

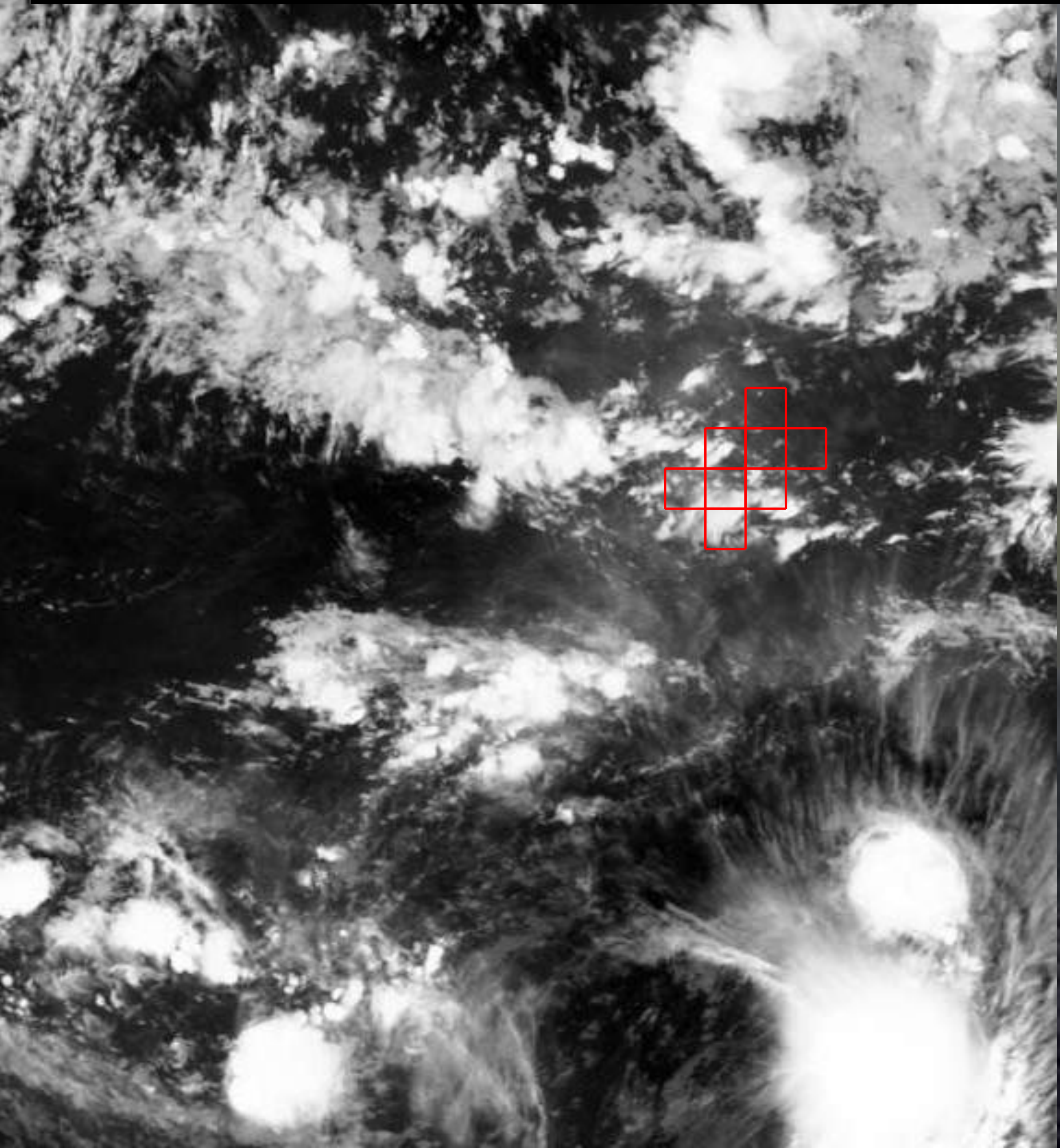
Non-linear system – asymmetric potential well



Thought Experiment – Rolling Ball

Non-linear system – potential well with multiple equilibria





The Atmosphere

- Much higher dimensionality!

- Atmospheric state governed by non-linear “well” of feedbacks.

- Contains many fast processes which are unresolved in models.

Parameterised Atmospheric Physics

Parameterisations attempt to represent unresolved physical and sub-grid processes using bulk formulae.

$$\dot{X} = D(X) + P(p, X)$$

X = model state vector
D(*X*) = model *dynamics* tendency (conserves air parcel PV, q, θ)
P(*X*) = model "*physics*" tendency (parameterisations)
p = set of model *parameters* on which parameterisations depend

The parameterisations *P(X)* are a major source of model error as assumptions required to obtain closure don't always hold. Eg Assumed scale separation between sub-grid processes and resolved dynamics often not true for deep convection.

- Such errors often result in underestimation of the *variability* associated with parameterised processes in GCMs.

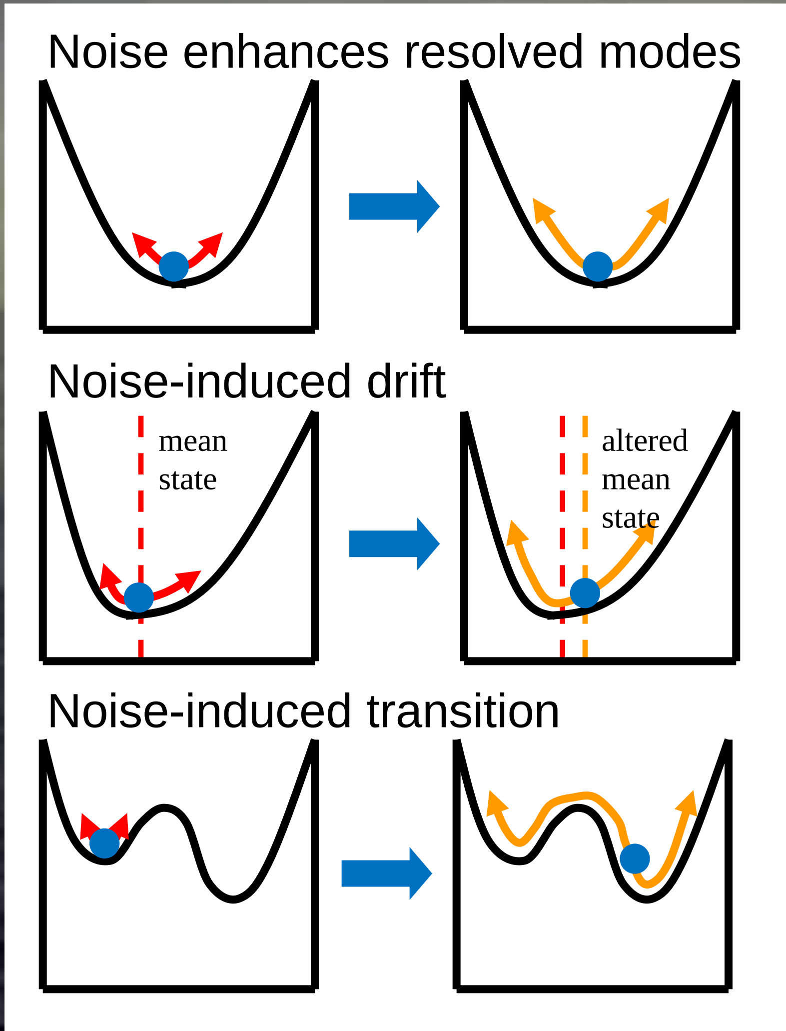
- *Uncertainties* in parameterisations need to be accounted for in Ensemble Prediction Systems to produce appropriate ensemble spread.

Stochastic Parameterisations

Various stochastic schemes have been developed. These introduce a random element to a host model:

- to represent parameterisation *uncertainty* in an Ensemble.

- to simulate the effects of some physical source of *variability* known to be absent in the default deterministic parameterisations.



The latter is important in climate modelling because the atmosphere's large-scale variability and mean state can be sensitive to variability near typical GCM grid-scales.

Stochastic Parameterisations

Even simple stochastic schemes designed to represent parameterisation uncertainty can be used to explore the sensitivity of the atmosphere to fast / small-scale variability. In particular:

- What effect does near-gridscale variability associated with parameterised processes have on the atmosphere's large-scale behaviour?

- How sensitive is this large-scale response to the *nature* of the small-scale variability? (eg to its amplitude, timescales, etc).

The latter is important, because much work has been done in recent years to develop increasingly sophisticated and realistic stochastic schemes.

Experimental Overview

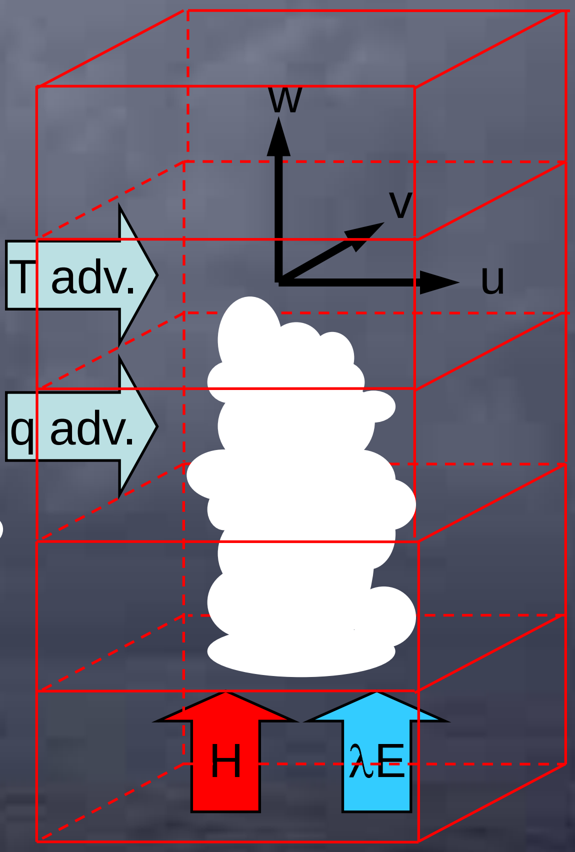
Experiments carried out using the UK Met Office’s Single Column Unified Model.

- Simulations for 9th-28th January at location 2 S, 156 E, in the Tropical West Pacific warm pool region.

- Default UM control run, plus runs using a few different stochastic parameterisation schemes.

- Only studying the response of parameterised physics schemes to their own / each-others’ variability; there are no dynamics in the Single-Column Model (SCM).

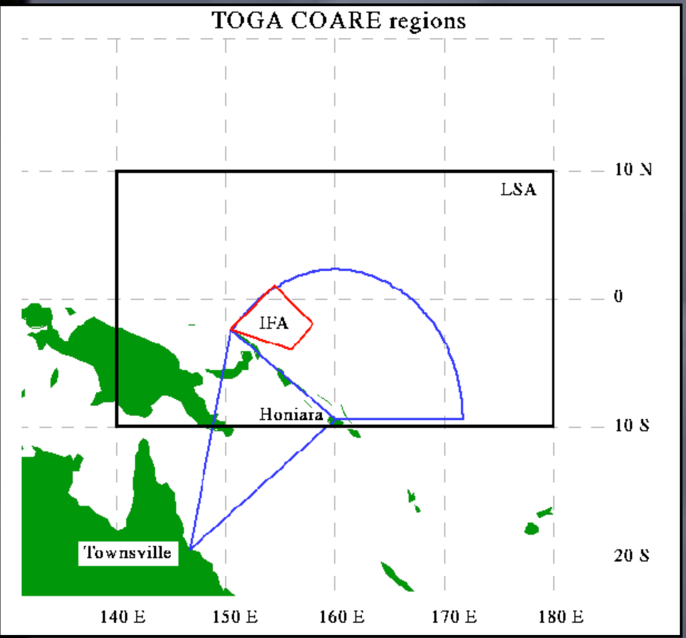
- Dynamical tendencies prescribed using forcing data derived from TOGA-COARE observation campaign.



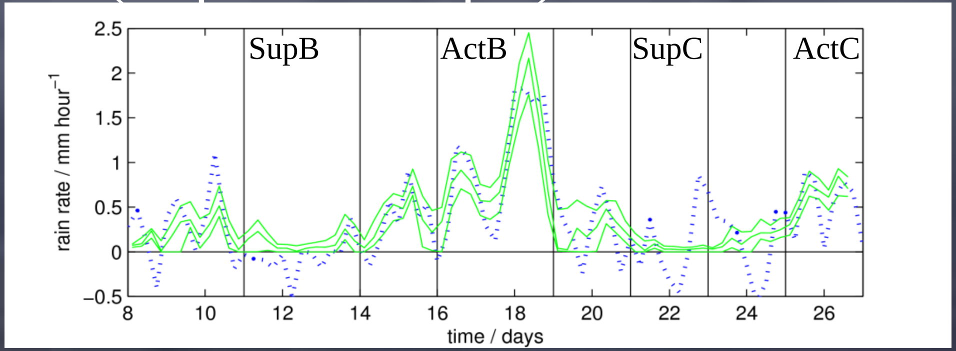
Meteorological Overview

- Region characterised by vigorous deep tropical convection over the warm ocean.

- Model runs include convectively active periods with heavy rains (ActB and ActC) as well as periods in which the (prescribed) large-scale dynamics act to suppress convection (SupB and SupC).

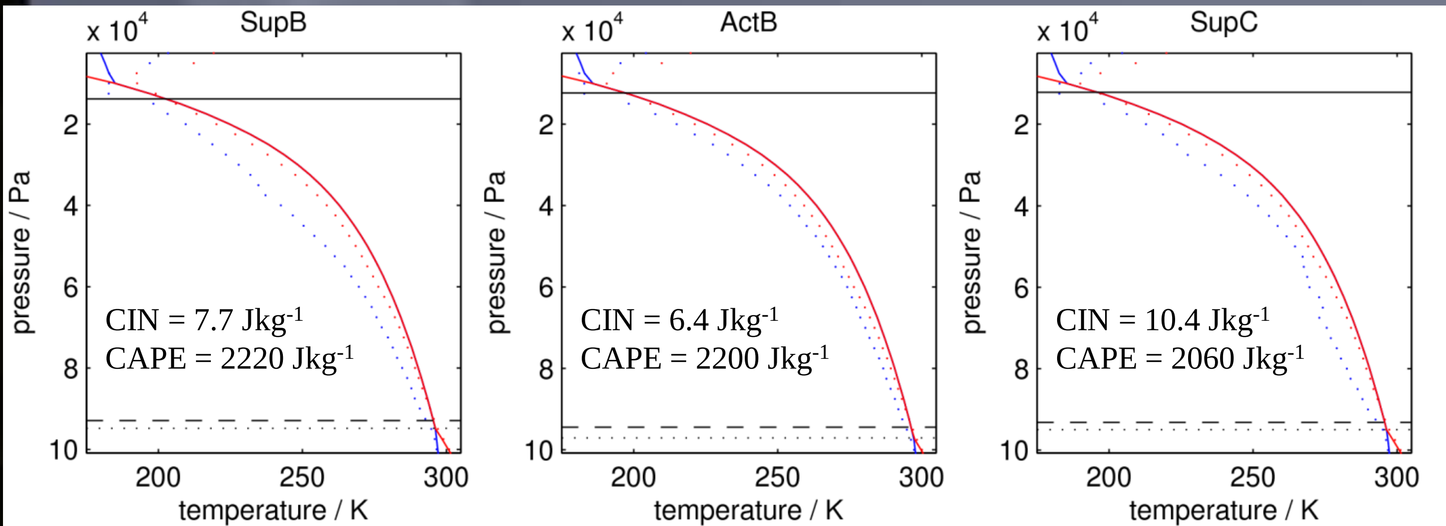


Map showing the location of TOGA-COARE measurements. The SCM simulates a column in the IFA (Intensive Flux Area).



6-hourly mean rainfall rates; 10th, 50th and 90th percentiles from the default UM ensemble (green) and a budget-derived estimate from TOGA-COARE data (dotted blue).

Meteorological Overview

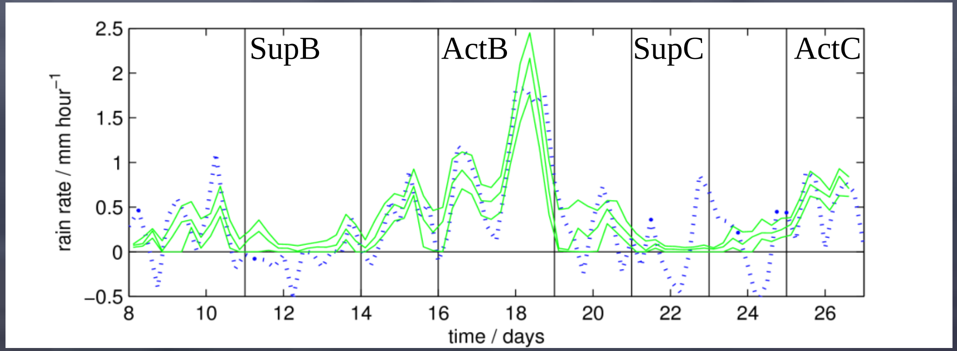


Mean observed environment (dotted) and moist nondilute parcel ascent (solid) profiles of T_{dry} (red) and T_{dew} (blue) over three sub-periods.

- CAPE changes little between suppressed and active phases.

- Heat and moisture content of Boundary Layer fairly constant.

- But free-troposphere moisture varies considerably...

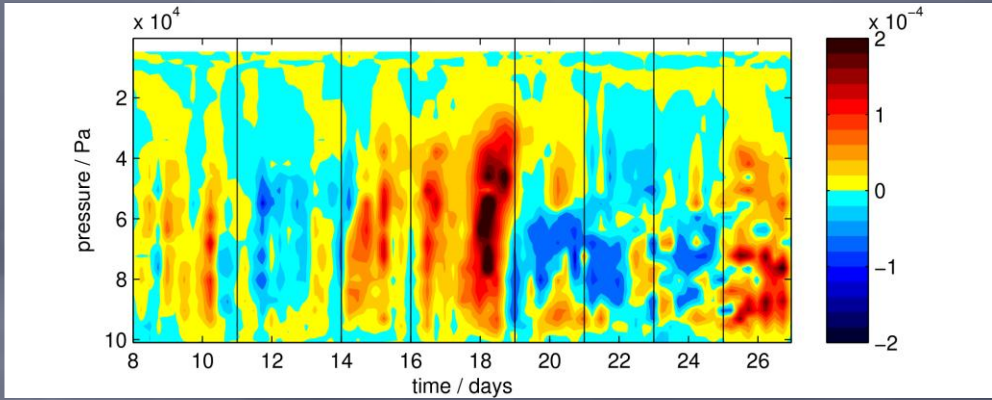


6-hourly mean rainfall rates; 10th, 50th and 90th percentiles from the default UM ensemble (green) and a budget-derived estimate from TOGA-COARE data (dotted blue).

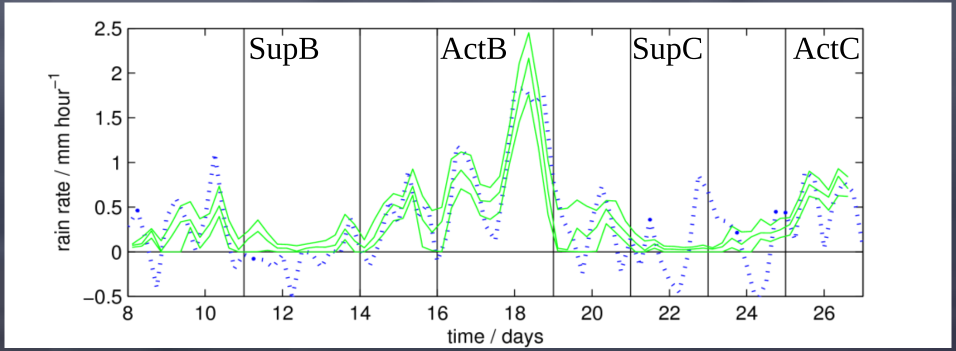
Meteorological Overview

- Rainfall rate correlates well with moistening of the free-troposphere by the prescribed large-scale dynamical forcings.

- Moisture content of air entrained by convective plumes is the dominant control on convective rainfall.



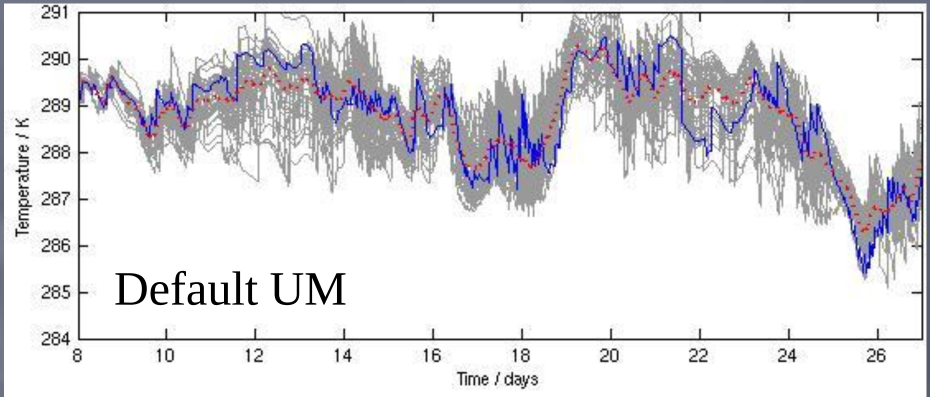
Prescribed dynamical tendencies in specific humidity / kg kg^{-1} per timestep (30 minutes)



6-hourly mean rainfall rates; 10th, 50th and 90th percentiles from the default UM ensemble (green) and a budget-derived estimate from TOGA-COARE data (dotted blue).

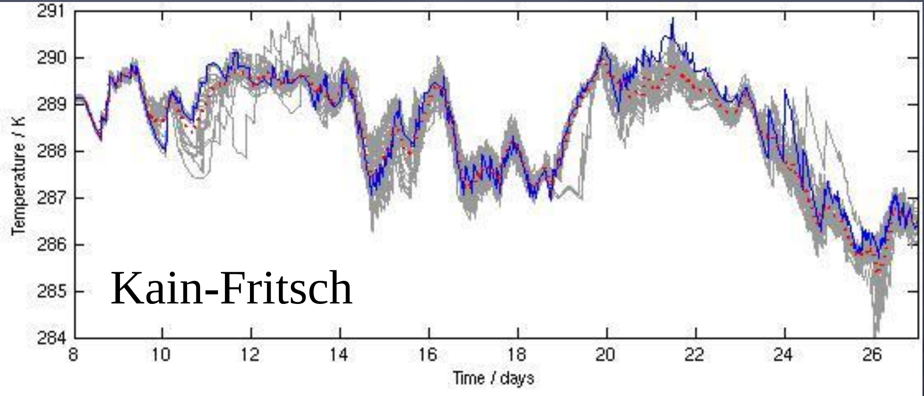
SCM Ensembles

- 39-member ensembles generated using small initial condition perturbations to Temperature in the Boundary Layer, and using a different random number seed for the stochastic scheme in each run.



Ensemble plume of T / K at 850 hPa with default Gregory & Rowntree convection scheme.

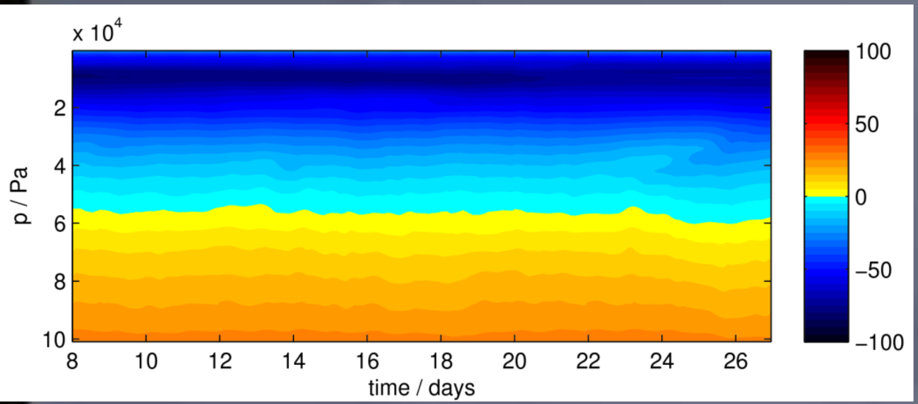
- Deterministic control ensemble exhibits considerable fast variability by itself!



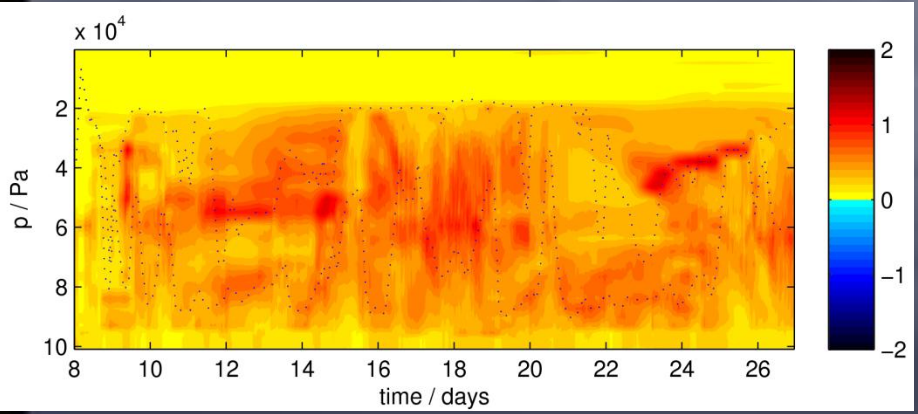
Ensemble plume of T / K at 850 hPa with Kain-Fritsch convection scheme.

- Ensemble spread sensitive to convective parameterisation.

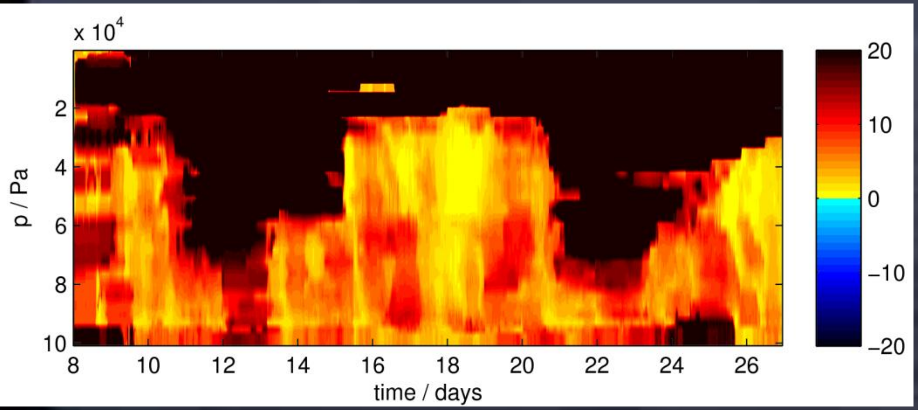
SCM Ensembles



Ensemble mean T / C in the default UM.



Ensemble spread (standard deviation) in T / C in the default UM.

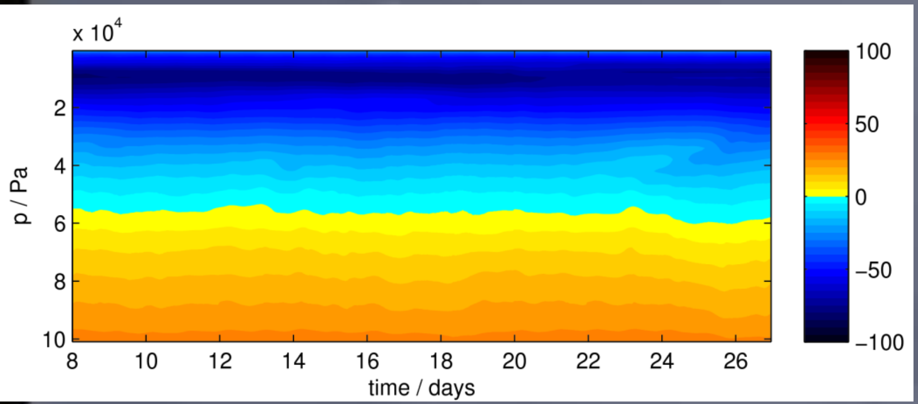


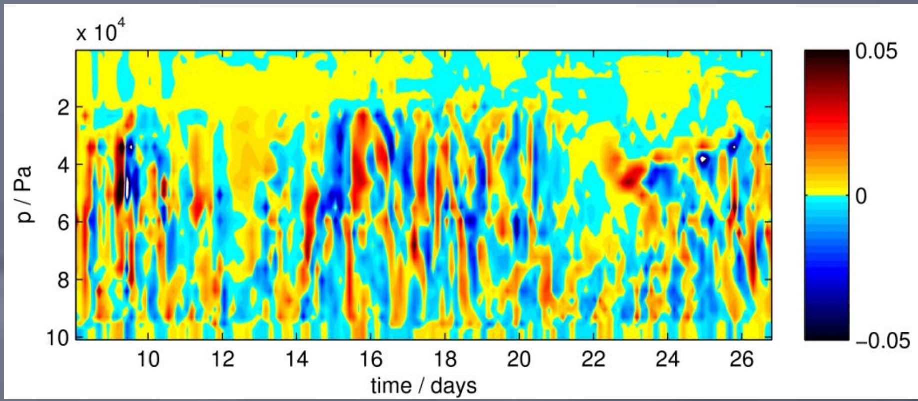
Ensemble correlation timescale / hours

-Ensemble spread saturates after ~5 days; “forgets” initial conditions and responds to model’s variability.

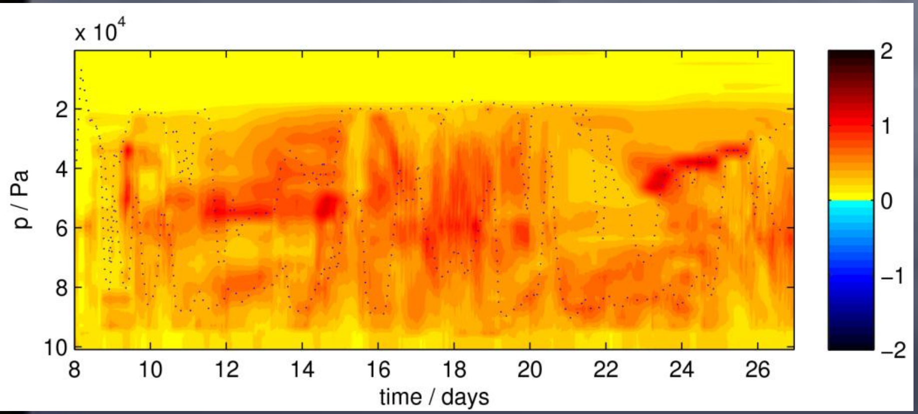
-Complex pattern relates to atmospheric physics.

-Short timescales associated with noisy “on-off” deep convection scheme.

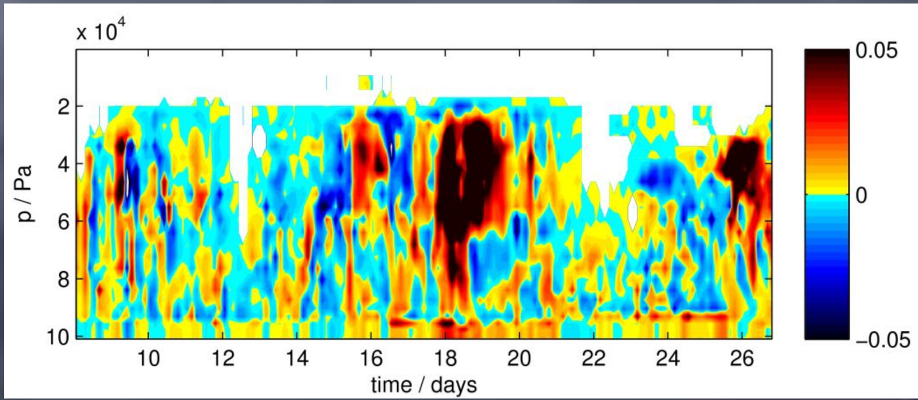




Tendency in ensemble spread / K per timestep.

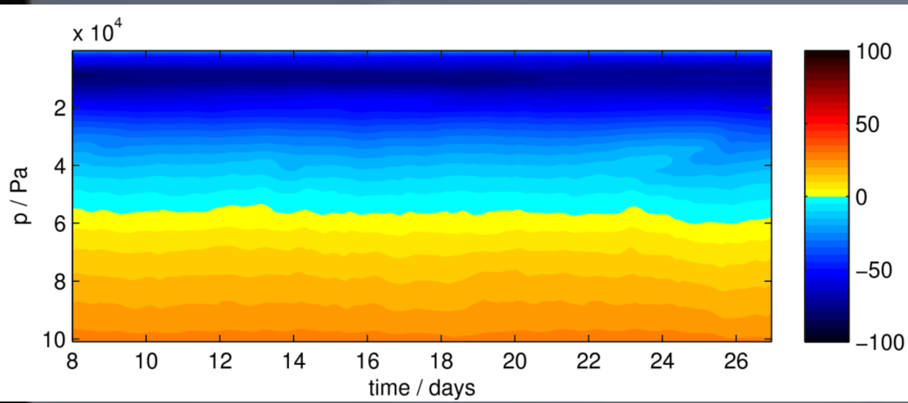


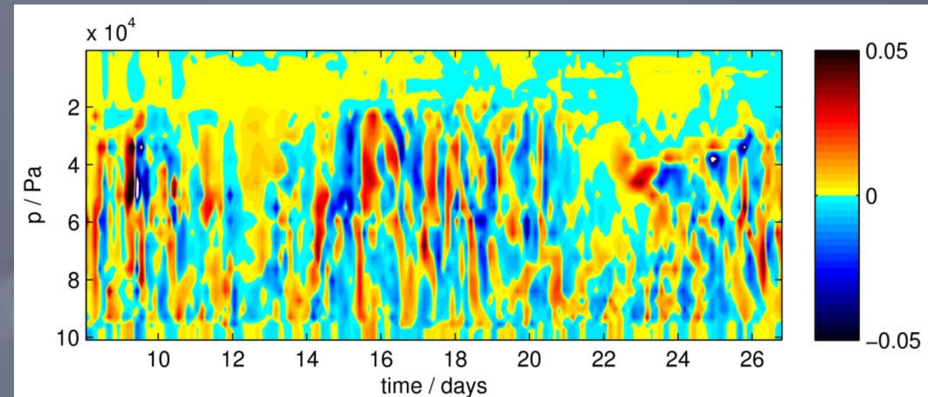
-Convection explains many features in the ensemble spread pattern (but with convection alone the spread would be much larger!)



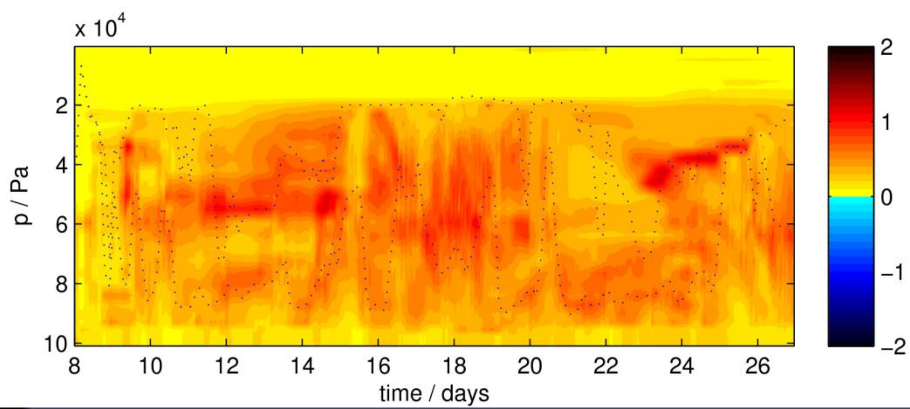
Spread tendency (in T) computed from convection scheme increments only.

Convection tries to redistribute excess heat & moisture, but often over-does it.

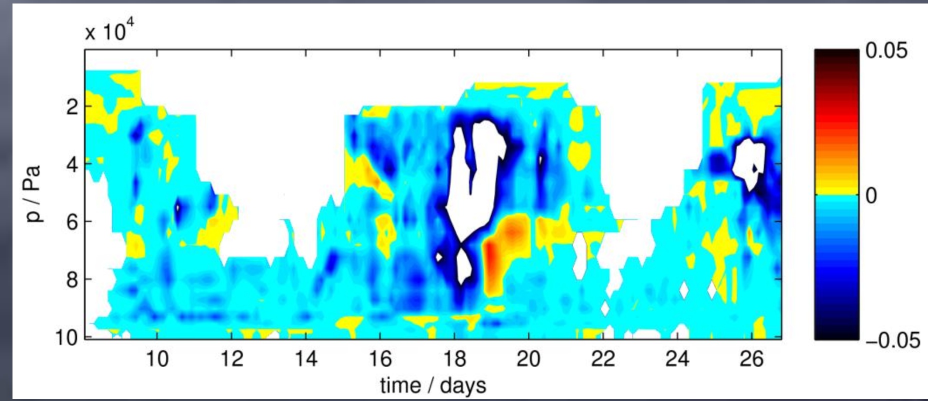




Tendency in ensemble spread / K per timestep.



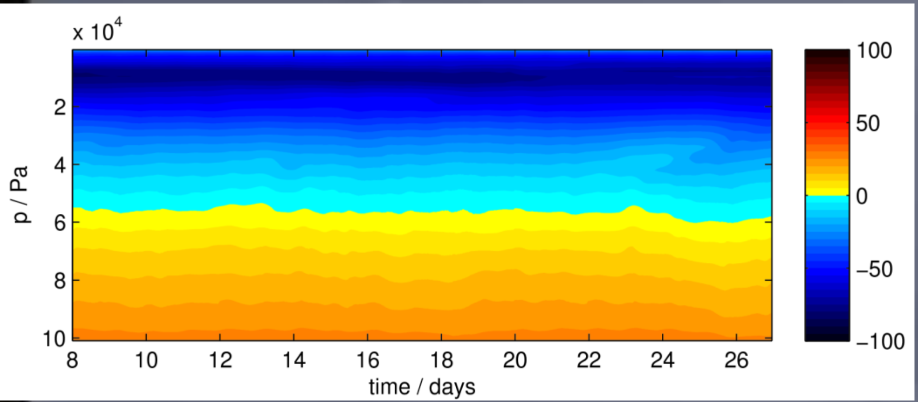
-Layer cloud changes offset spread from “on-off” strong deep convective events.

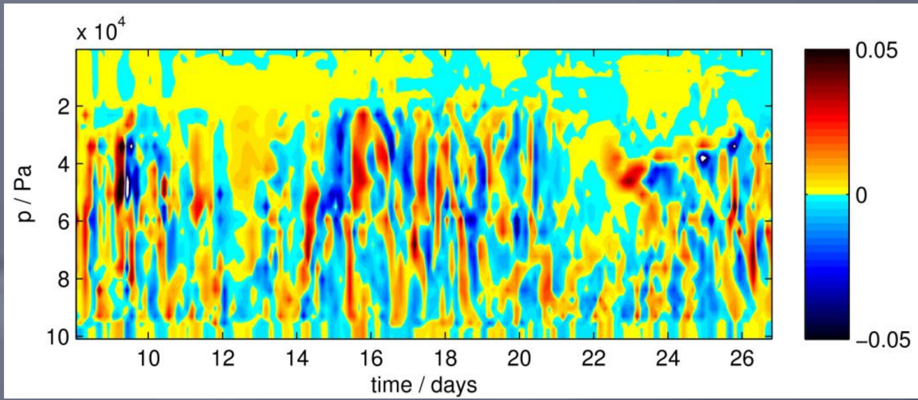


Spread tendency (in T) computed from cloud scheme increments only.

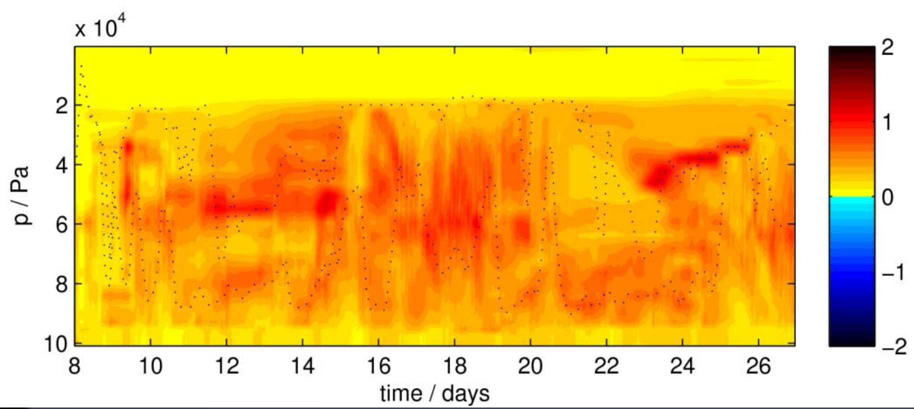
Convection “on” → subsidence & rainout → warming & drying → evaporate cloud

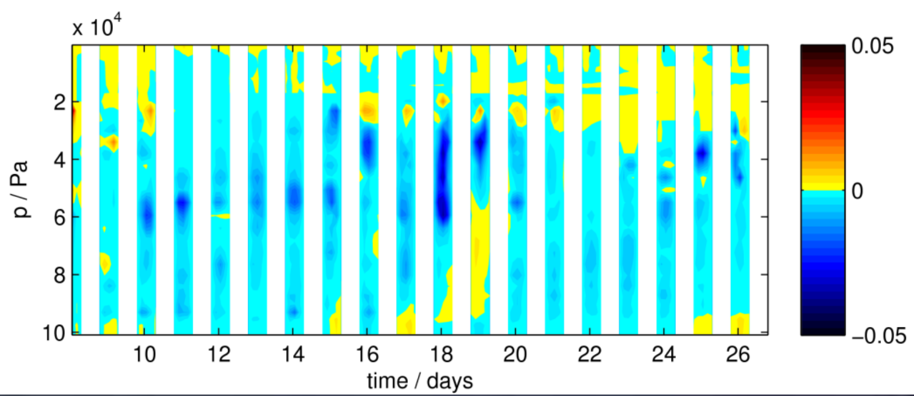
Convection “off” → LW cooling & prescribed moisture forcing → form cloud





Tendency in ensemble spread / K per timestep.

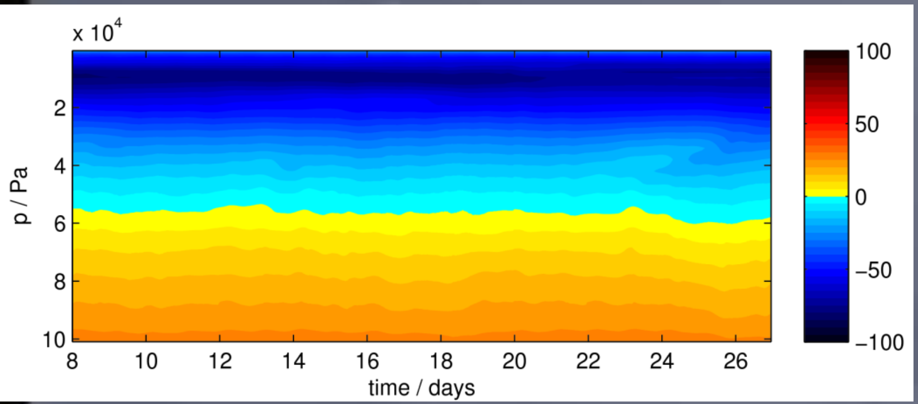


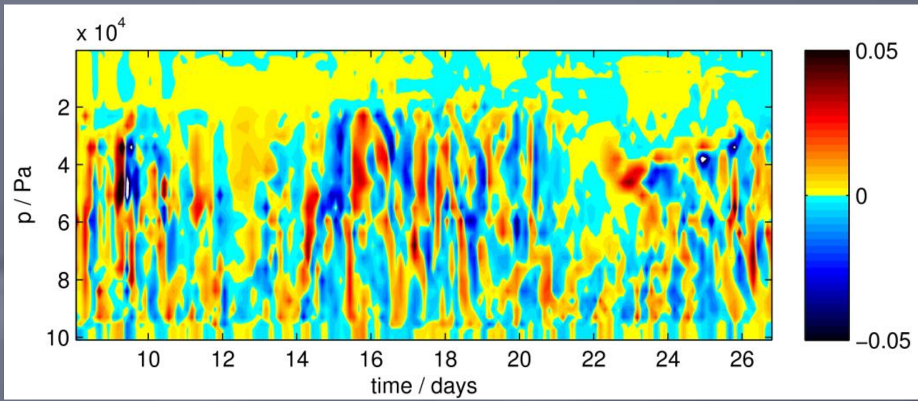


Spread tendency (in T) computed from SW radiation increments only.

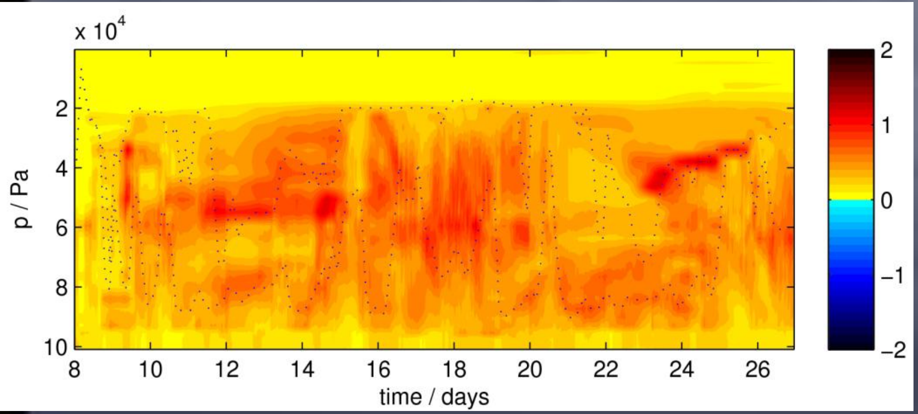
-Solar radiation acts to reduce ensemble spread (most strongly where layer cloud is abundant).

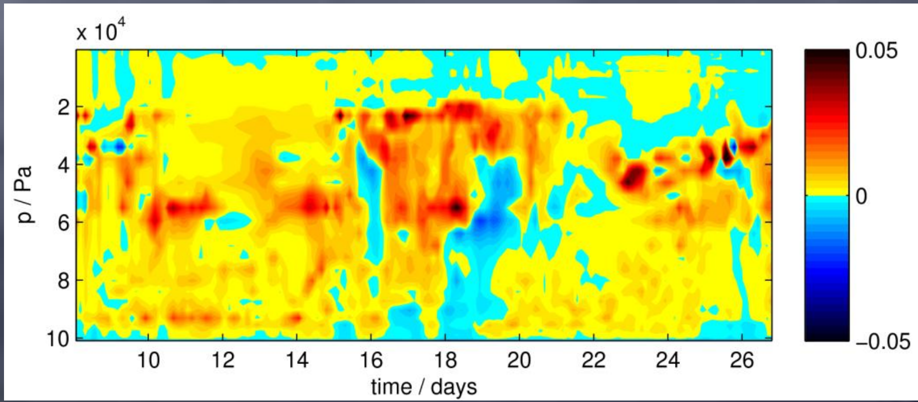
Warmer air → lower RH → less layer cloud → less warming from absorption of SW
Cooler air → higher RH → more layer cloud → more warming from absorption of SW





Tendency in ensemble spread / K per timestep.





Spread tendency (in T) computed from LW radiation increments only.

-LW radiation acts to increase spread in T wherever there is broad spread in cloud or upper troposphere water vapour.

Warmer air → lower RH → less cloud → less cooling from emission of LW

Cooler air → higher RH → more cloud → more cooling from emission of LW

Multiplicative Noise

$$\dot{X} = D(X) + (1+\beta\varepsilon)P(p,X)$$

ε is a random number drawn from a uniform distribution between 1, and the parameter β controls the amplitude of stochastic perturbations.

The first stochastic parameterisation in a GCM: Buizza et al (1999) implemented a *multiplicative noise* scheme in the ECMWF Ensemble Prediction System to account for parameterisation uncertainty.

Tendencies in T, q, u and v from all model parameterisations multiplied by a randomly varying scaling.

Scaling held constant for lengths of time τ to apply temporal correlation.

Q. J. R. Meteorol. Soc. (1999), **125**, pp. 2887–2908

Stochastic representation of model uncertainties in the ECMWF Ensemble Prediction System

By R. BUIZZA*, M. MILLER and T. N. PALMER

European Centre for Medium-Range Weather Forecasts, UK

(Received 18 August 1998; revised 19 March 1999)

SUMMARY

A stochastic representation of random error associated with parametrized physical processes ('stochastic physics') is described, and its impact in the European Centre for Medium-Range Weather Forecasts Ensemble Prediction System (ECMWF EPS) is discussed. Model random errors associated with physical parametrizations are simulated by multiplying the total parametrized tendencies by a random number sampled from a uniform distribution between 0.5 and 1.5. A number of diagnostics are described and a choice of parameters is made. It is shown how the scheme increases the spread of the ensemble, and improves the skill of the probabilistic prediction of weather parameters such as precipitation. A choice of stochastic parameters is made for operational implementation. The scheme was implemented successfully in the operational ECMWF EPS on 21 October 1998.

KEYWORDS: Ensemble forecasting Model errors Numerical weather prediction Parametrization

Multiplicative Noise

$$\dot{X} = D(X) + (1 + \beta\varepsilon)P(p, X)$$

ε is a random number drawn from a uniform distribution between 1, and the parameter β controls the amplitude of stochastic perturbations.

Even this very simple stochastic scheme has several tuneable features:

- perturbation amplitude β

- perturbation correlation timescale τ

- are the parameterisations for different physical processes perturbed equally, or should we perturb some more than others?

- are the perturbations to different model variables independent, or should they be correlated with one-another?

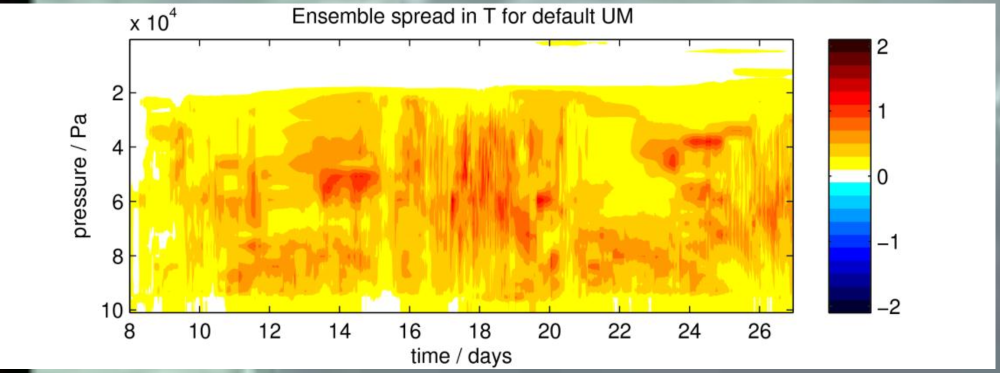
- are the perturbations to different model variables independent or correlated?

Introduction of Multiplicative Noise

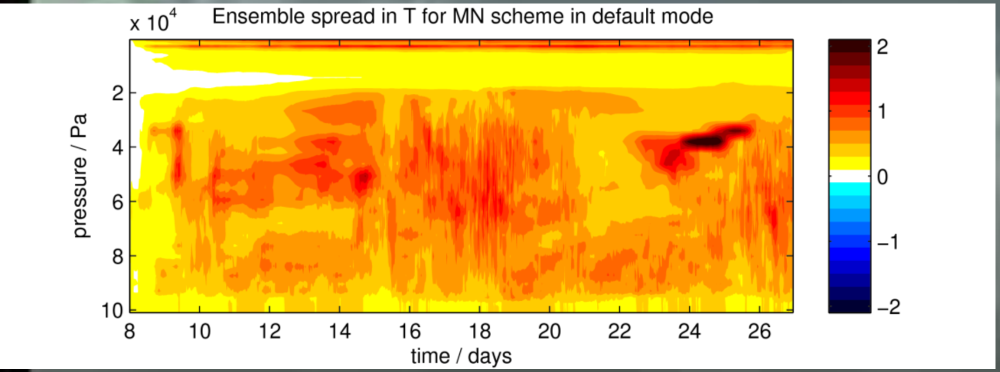
A standard configuration of the Multiplicative Noise scheme is defined as per the configuration implemented in the ECMWF system:

- amplitude $\beta = 0.5$
- update timescale $\tau = 6$ hours
- all physics schemes perturbed with equal scaling amplitude.
- the same random number is drawn for all the schemes to ensure perturbations to each are correlated.
- similarly, the same random number is drawn to perturb both temperature and specific humidity.

Effects of Multiplicative Noise on the Ensemble



Ensemble spread in temperature / K for the default deterministic UM ensemble



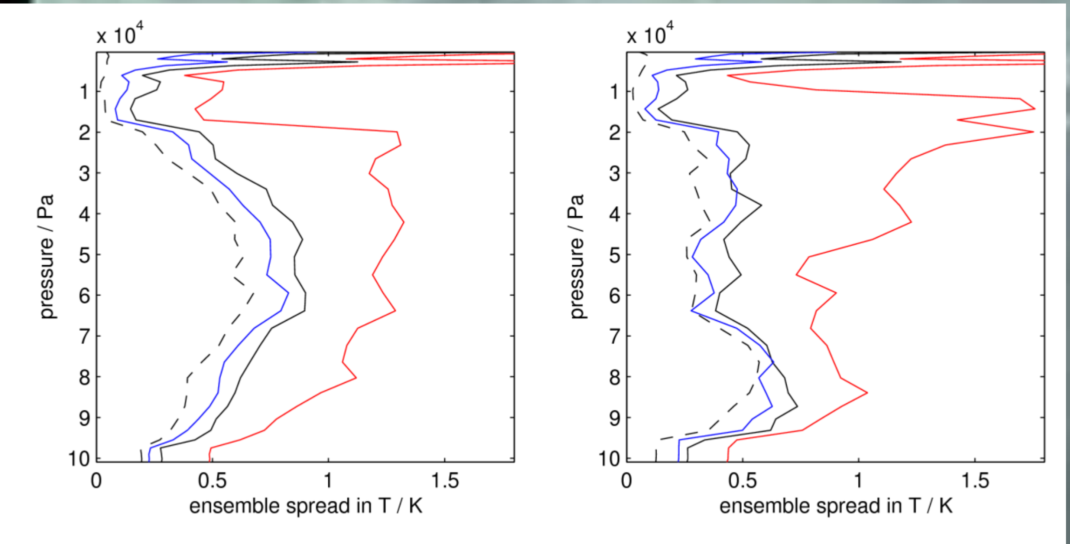
Ensemble spread in temperature / K for the UM with the Multiplicative Noise scheme in standard configuration.

- General increase in ensemble spread.

- Ensemble spread dramatically increased in the stratosphere, where there was very little spread in the Default UM ensemble.

- Noise has been introduced to the strong radiative tendencies there; not very realistic as the radiative fluxes in the stratosphere are quite well defined in models and quite steady in reality.

Sensitivity to perturbation Amplitude

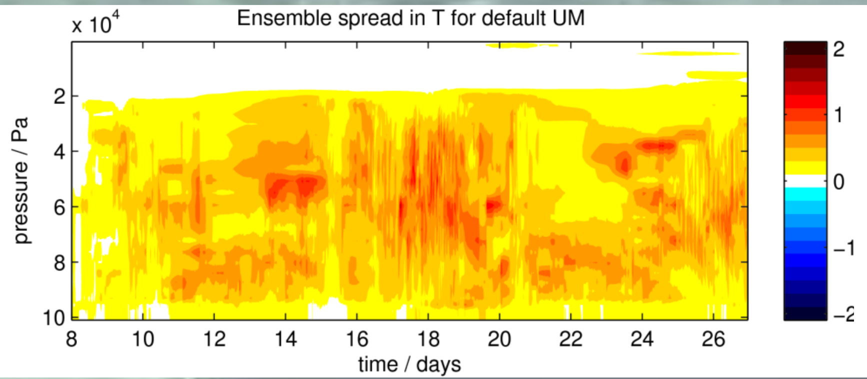


Ensemble spread in temperature for (left) the period ActB, and (right) the period SupC, for (dashed) the default UM, and (solid) the multiplicative noise scheme with amplitude β = (blue) 0.25, (black) 0.5 and (red) 1.0.

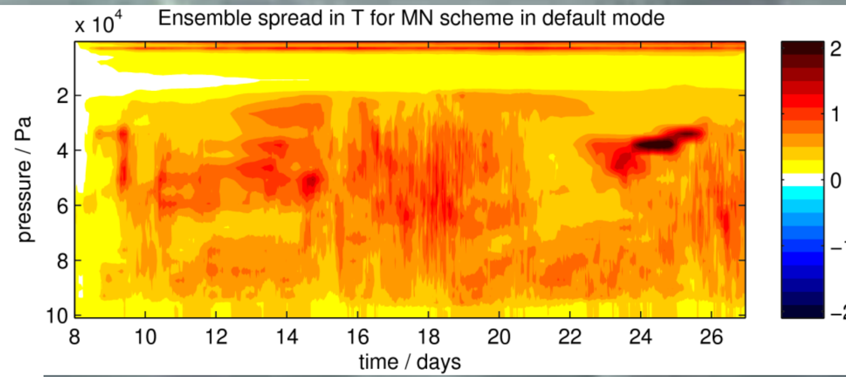
- During the active phase, ensemble spread change relative to the default UM increases roughly linearly with perturbation amplitude.

- But this relation breaks down during the suppressed phase.

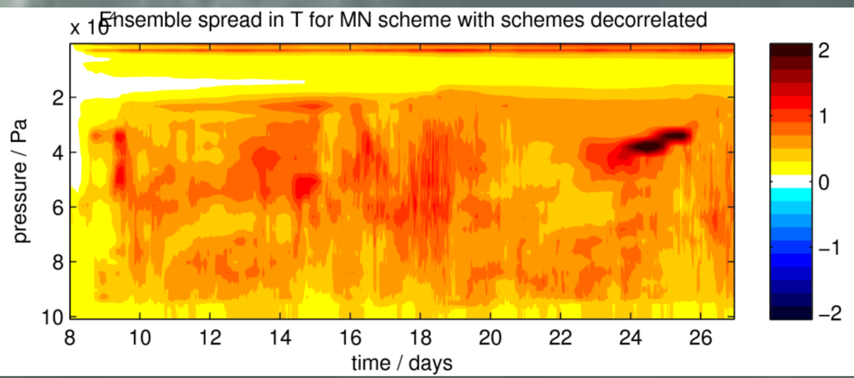
Sensitivity to Correlations



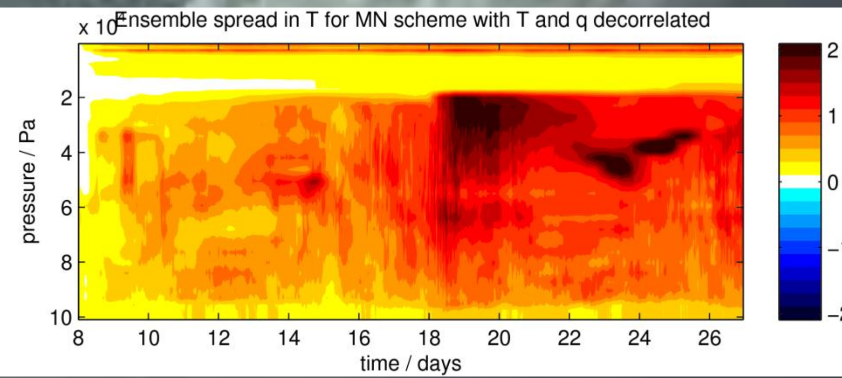
Ensemble spread in temperature for the Default UM SCM ensemble.



Ensemble spread in temperature for the Multiplicative Noise scheme; default full correlations.

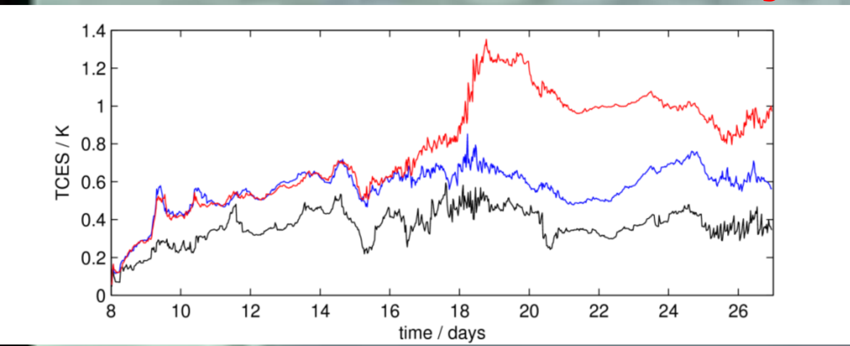


Ensemble spread in temperature for the Multiplicative Noise scheme; perturbations to different routines decorrelated.

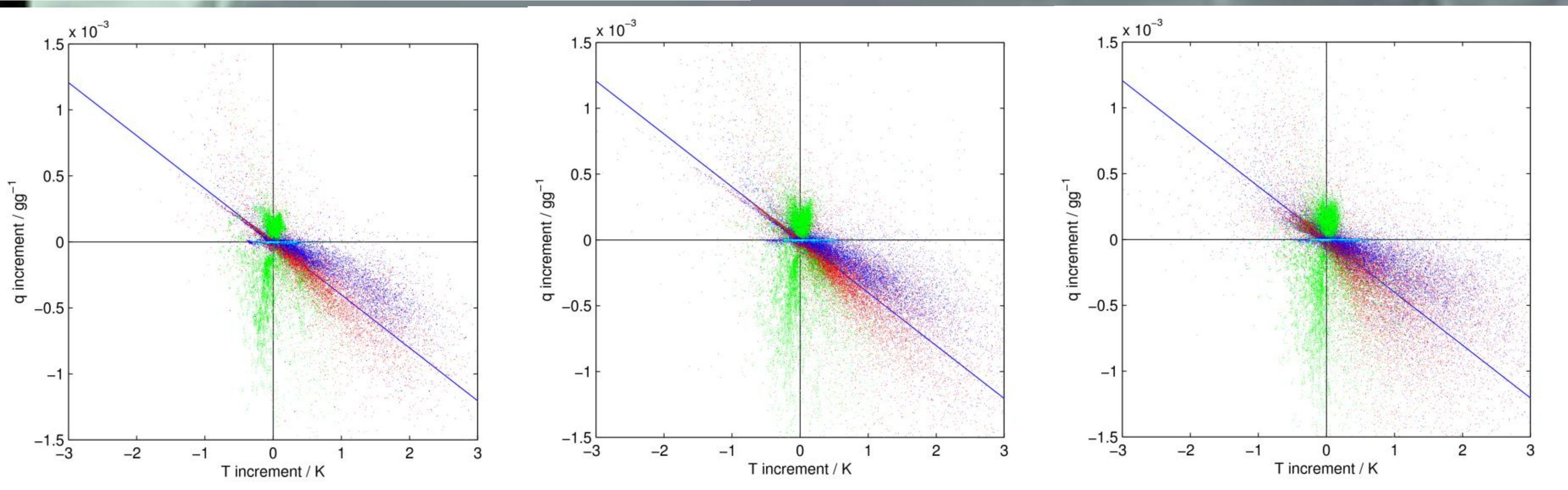


Ensemble spread in temperature for the Multiplicative Noise scheme; perturbations to T and q decorrelated.

Sensitivity to T / q perturbation correlation

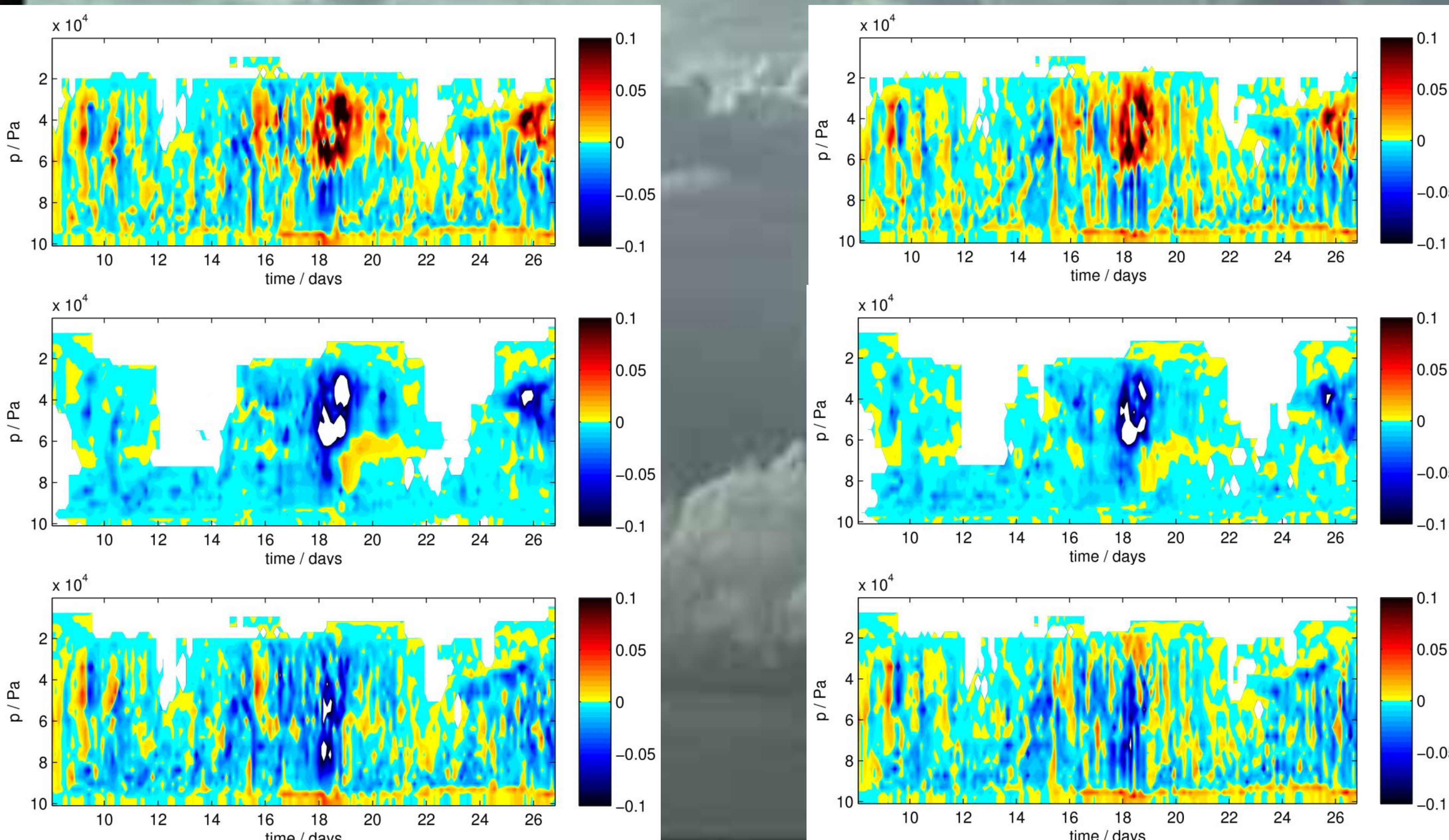


- Sudden massive growth in spread during convectively active phase.



Total physics increments; scatter plot of q inc against T inc for (left) Default UM, (middle) MN scheme in default mode, and (right) MN scheme with perturbation scalings for T and q decorrelated. Colours denote altitude; (green) boundary layer, (red) lower free-troposphere, (blue) upper free troposphere, and (cycan) stratosphere.

Sensitivity to T / q perturbation correlation



Random Parameters

$$\dot{X} = D(X) + P((1+\beta\varepsilon)p, X)$$

Parameterisations contain free parameters which don’t have theoretically defined values. This stochastic scheme accounts for parameterisation uncertainty by allowing these to vary in time within their bounds of uncertainty. The following parameters are varied:

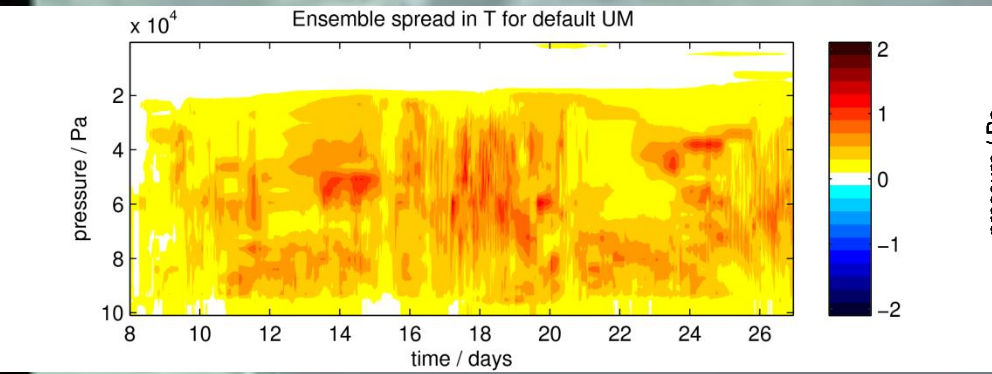
- Entrainment rate coefficient (convection scheme).
- CAPE timescale (convection scheme).
- Neutral mixing-length parameter (boundary layer scheme)
- Stability function parameter (boundary layer scheme)

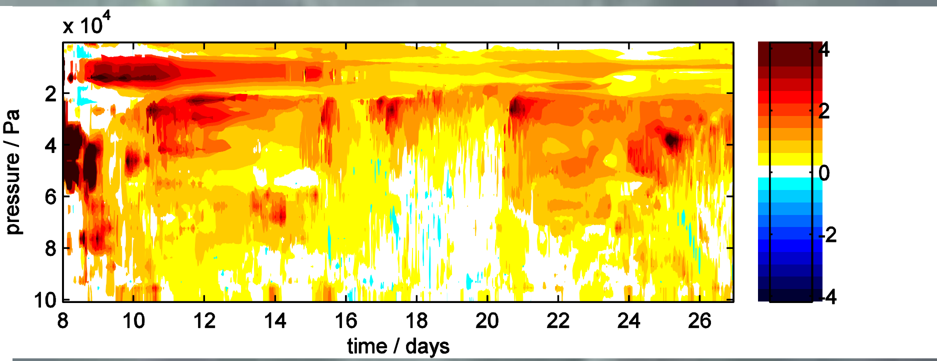
Random Parameters

$$\dot{X} = D(X) + P((1+\beta\varepsilon)p, X)$$

- Critical Relative Humidity for cloud formation (large-scale cloud scheme).
- Threshold liquid water content for drizzle-formation (microphysics scheme).
- Ice-particle fall-speed coefficient (microphysics scheme).
- Surface stress constant (Gravity-Wave Drag scheme).
- Critical Froude number (Gravity-Wave Drag scheme).

Effects of Random Parameters on Ensemble Spread

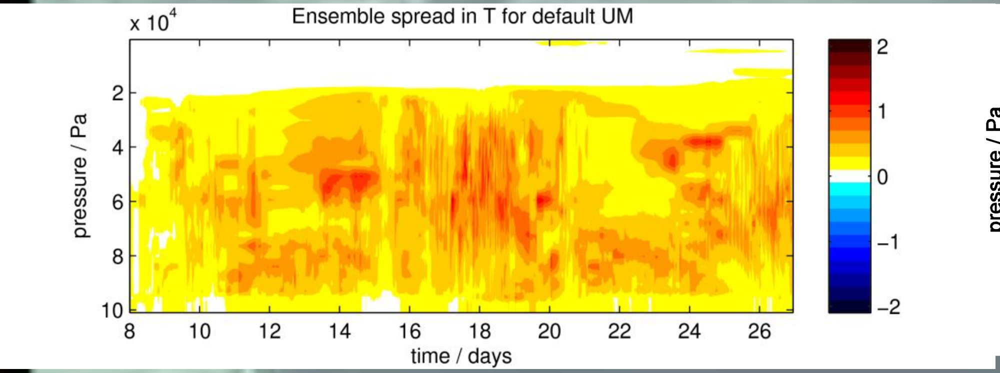




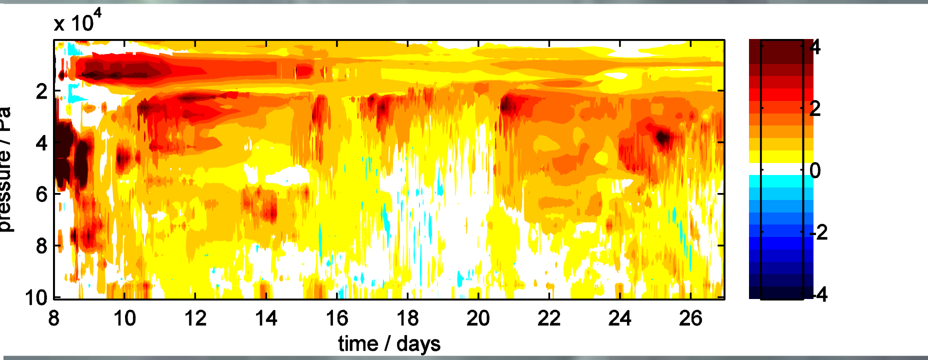
Ensemble spread in temperature / K for the default deterministic UM ensemble

Fractional increase in ensemble spread when all the parameters are randomly varied.

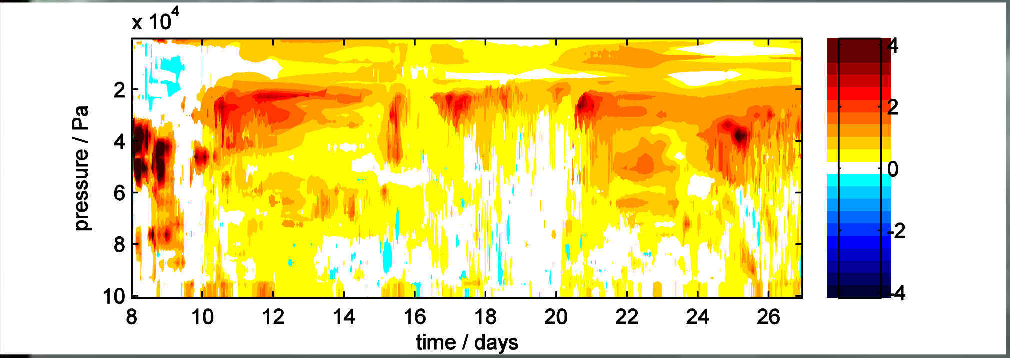
Effects of Random Parameters on Ensemble Spread



Ensemble spread in temperature / K for the default deterministic UM ensemble

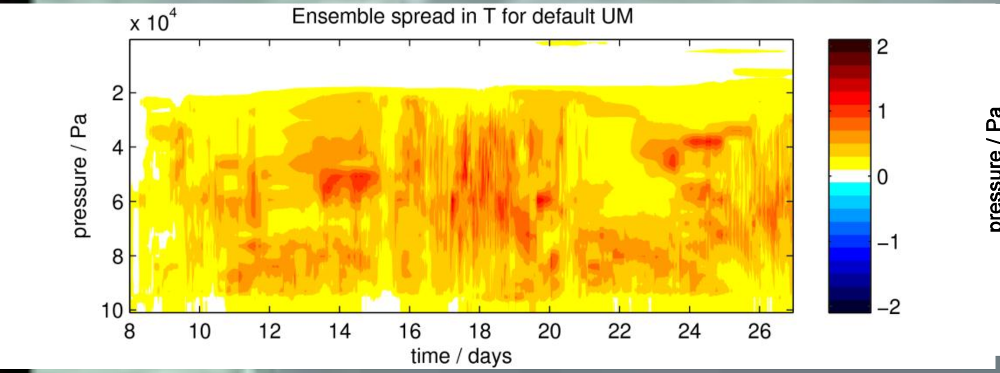


Fractional increase in ensemble spread when all the parameters are randomly varied.

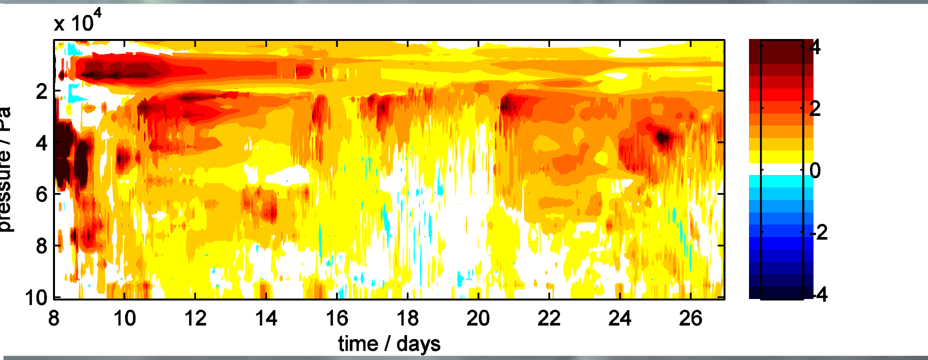


Fractional increase in ensemble spread when only the *entrainment rate coefficient* is randomly varied.

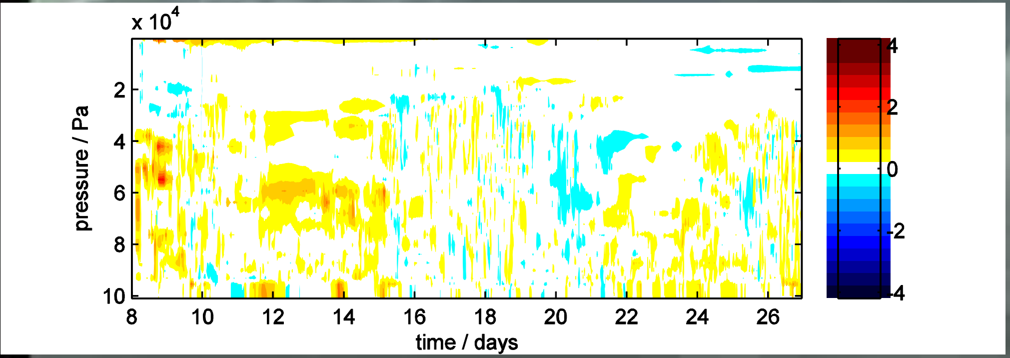
Effects of Random Parameters on Ensemble Spread



Ensemble spread in temperature / K for the default deterministic UM ensemble

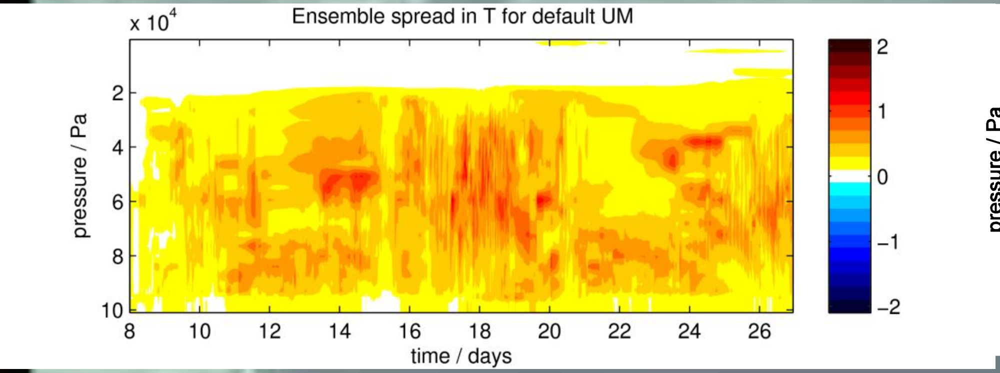


Fractional increase in ensemble spread when all the parameters are randomly varied.

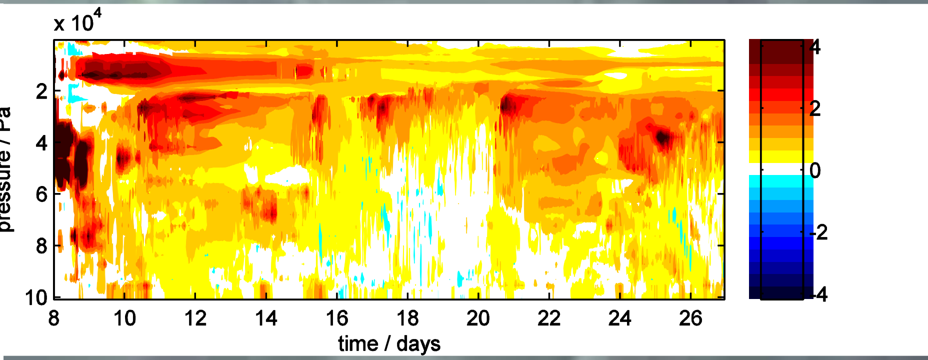


Fractional increase in ensemble spread when only the *CAPE timescale* is randomly varied.

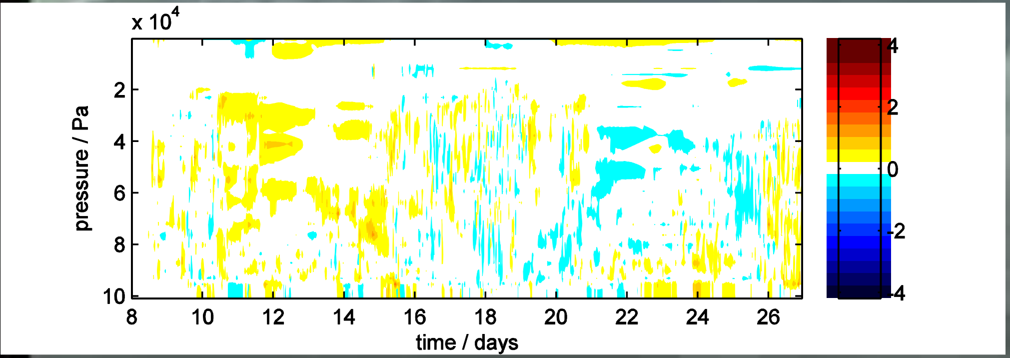
Effects of Random Parameters on Ensemble Spread



Ensemble spread in temperature / K for the default deterministic UM ensemble

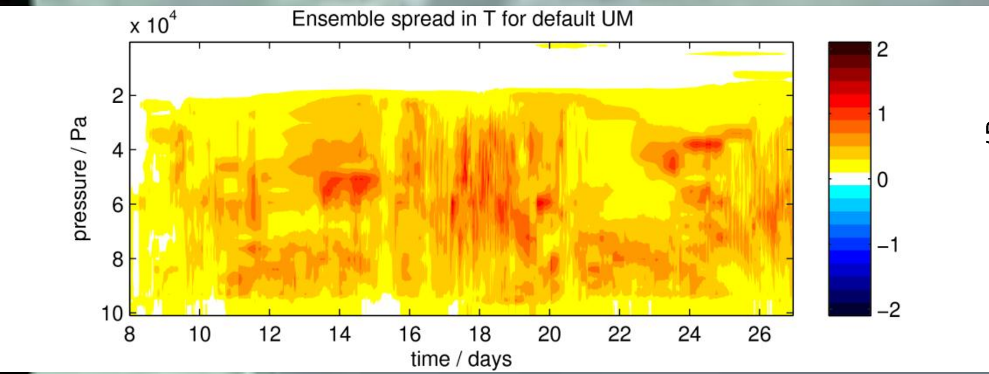


Fractional increase in ensemble spread when all the parameters are randomly varied.

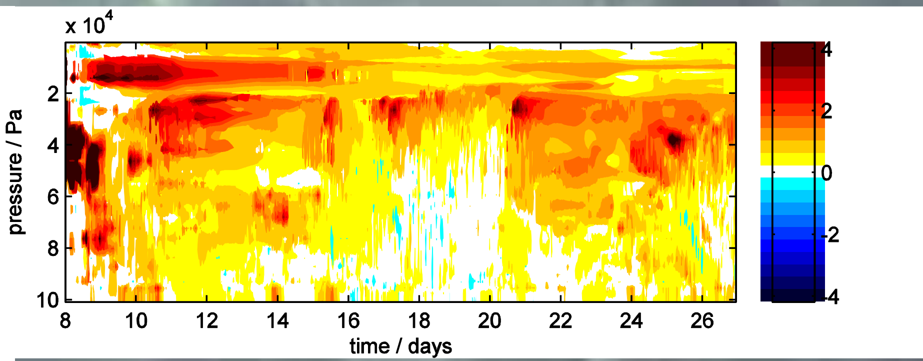


Fractional increase in ensemble spread when only the *neutral mixing-length parameter* is randomly varied.

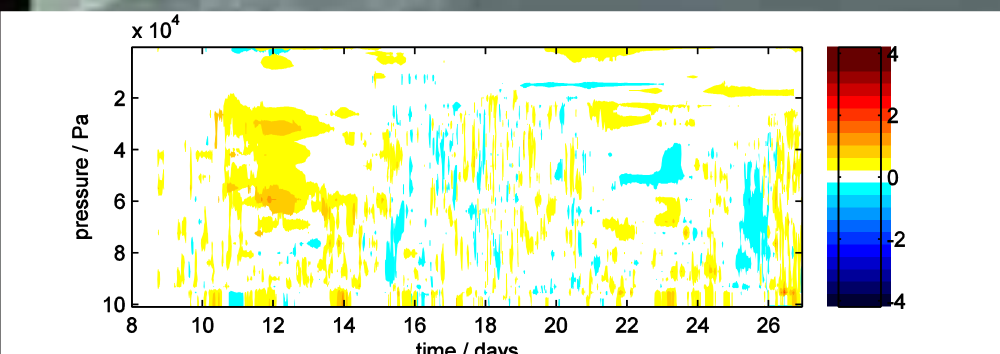
Effects of Random Parameters on Ensemble Spread



Ensemble spread in temperature / K for the default deterministic UM ensemble

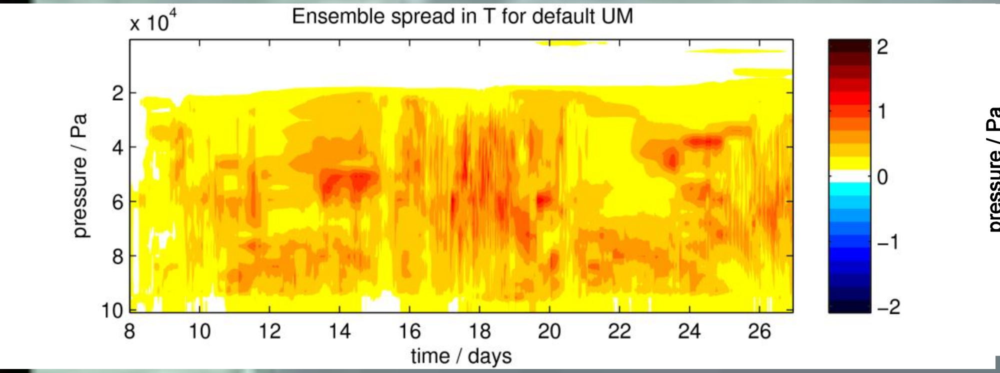


Fractional increase in ensemble spread when all the parameters are randomly varied.

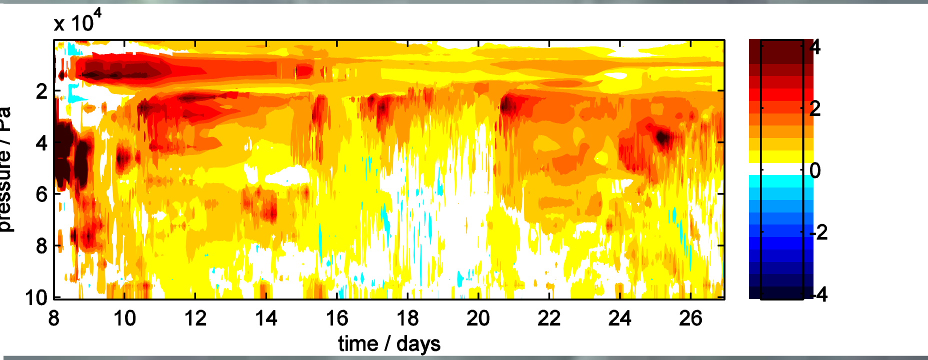


Fractional increase in ensemble spread when only the *stability function parameter* is randomly varied.

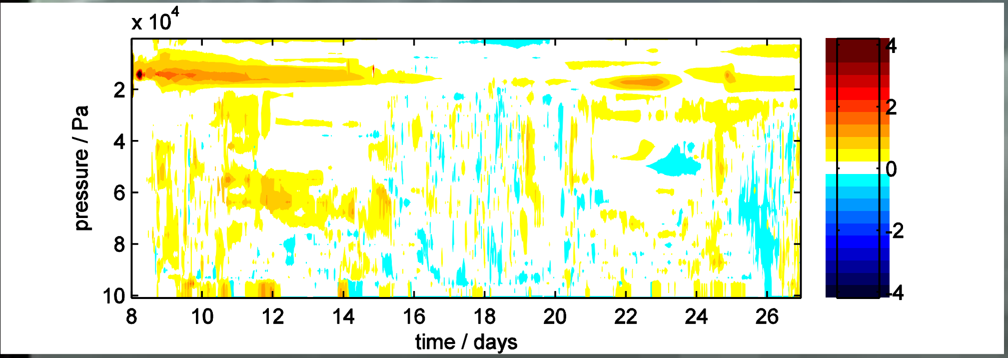
Effects of Random Parameters on Ensemble Spread



Ensemble spread in temperature / K for the default deterministic UM ensemble

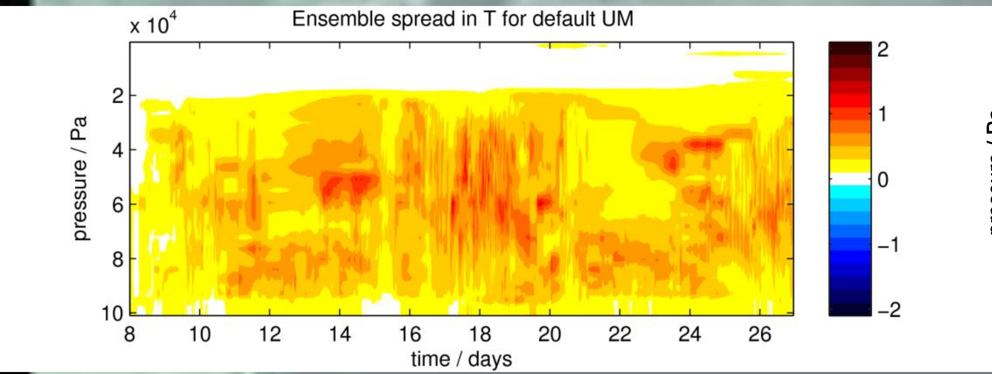


Fractional increase in ensemble spread when all the parameters are randomly varied.

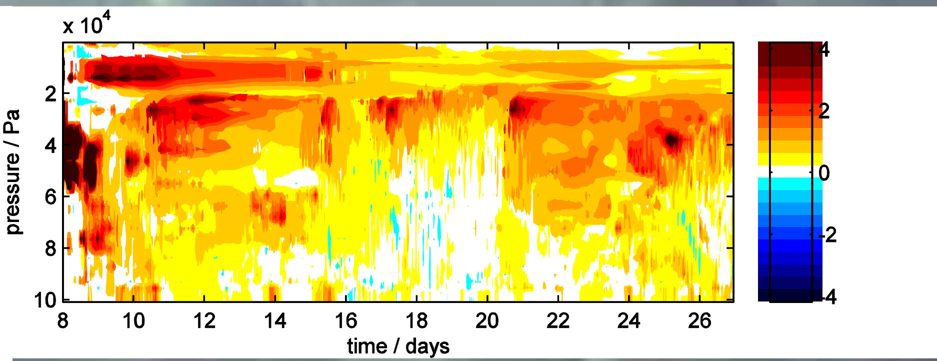


Fractional increase in ensemble spread when only the *critical relative humidity* is randomly varied.

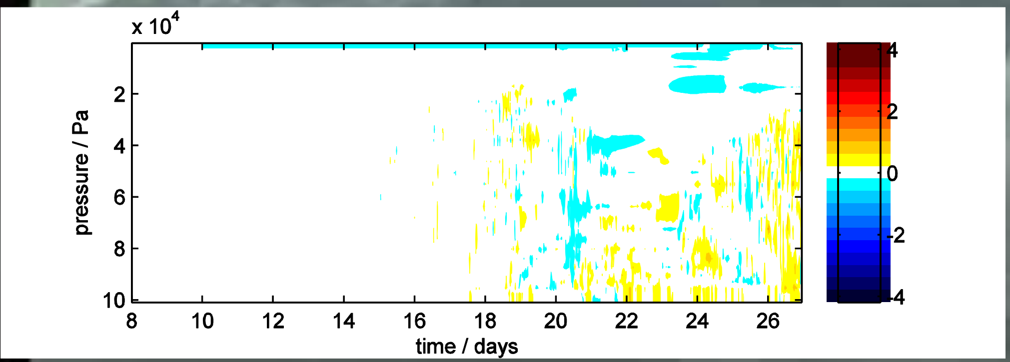
Effects of Random Parameters on Ensemble Spread



Ensemble spread in temperature / K for the default deterministic UM ensemble

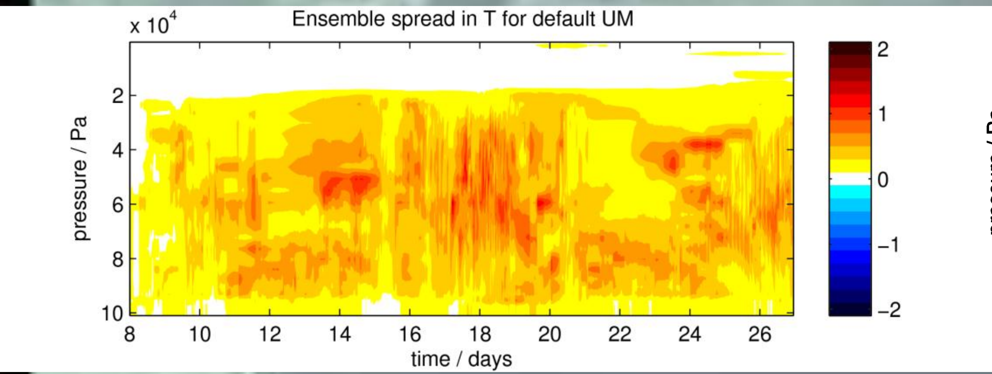


Fractional increase in ensemble spread when all the parameters are randomly varied.

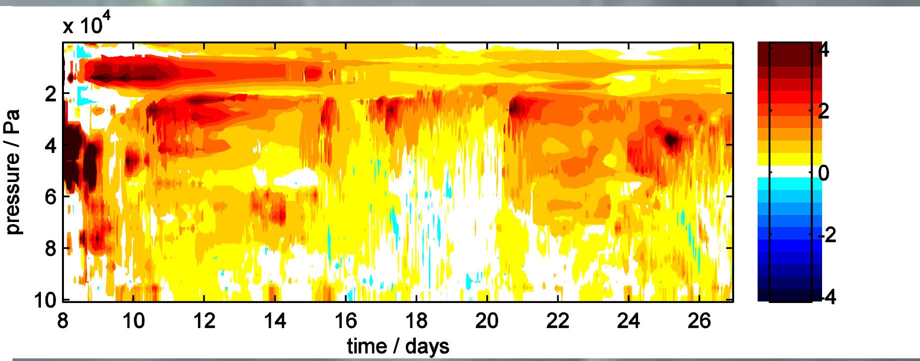


Fractional increase in ensemble spread when only the *threshold liquid water content* is randomly varied.

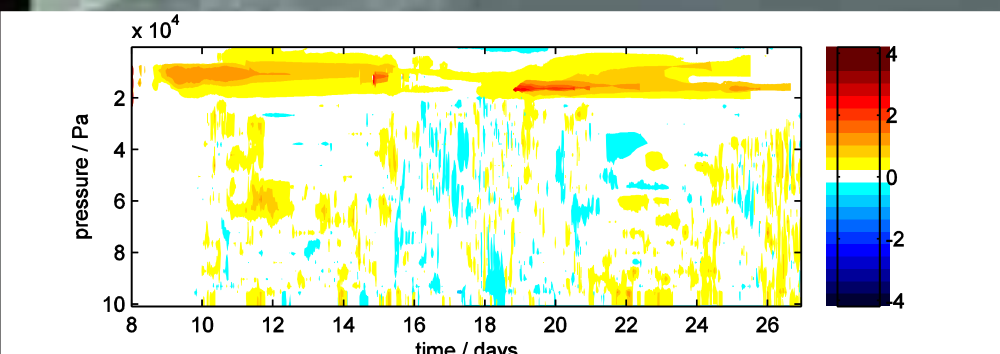
Effects of Random Parameters on Ensemble Spread



Ensemble spread in temperature / K for the default deterministic UM ensemble



Fractional increase in ensemble spread when all the parameters are randomly varied.



Fractional increase in ensemble spread when only the *ice-particle fall speed coefficient* is randomly varied.

Conclusions

- Both of the simple stochastic parameterisations increase ensemble spread (and cause noise-induced drift in the SCM's mean-state).

- Response to Multiplicative Noise perturbations:

  - Scales linearly with perturbation amplitude as long as perturbations are small.

  - Is insensitive to correlations between perturbations applied to different physical processes.

  - Is very sensitive to correlations between perturbations applied to temperature and moisture.

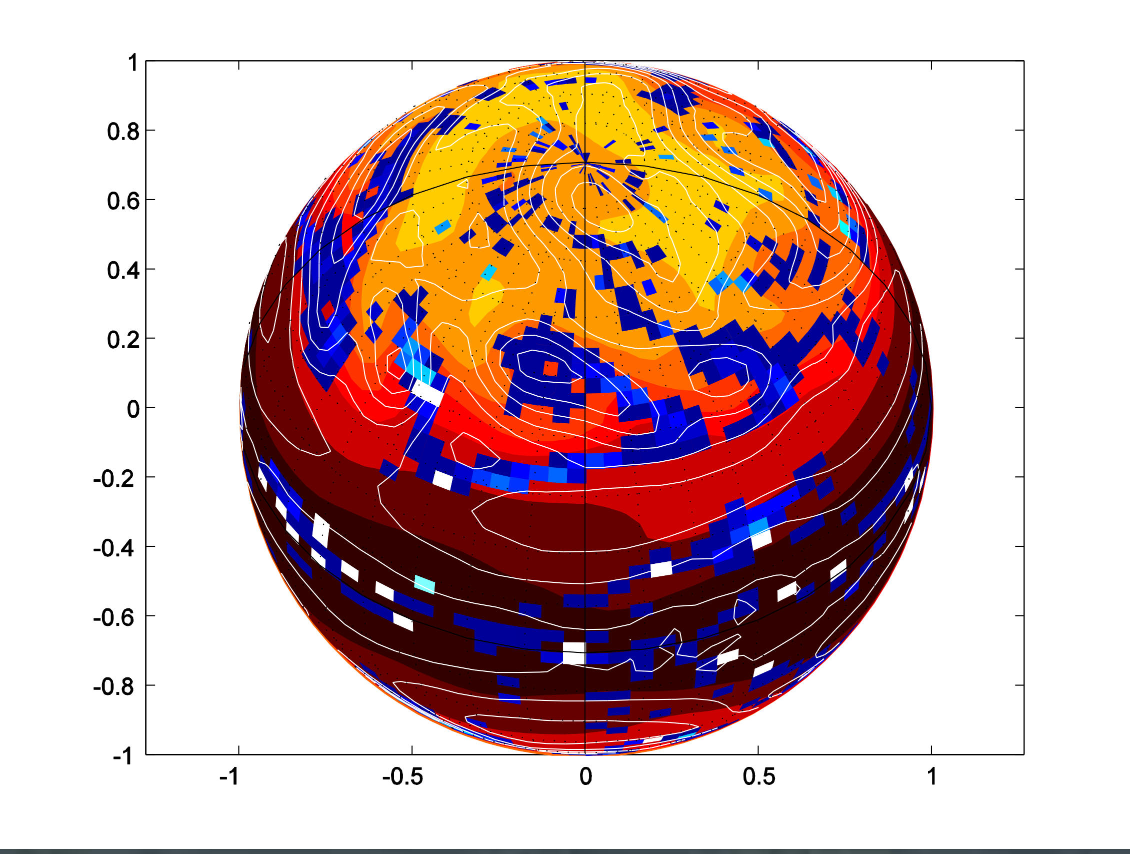
Conclusions

- Multiplicative noise perturbations can cause unphysical behaviour:
  - Noise in the stratosphere when applied to radiation scheme.
  - Breakdown of moist static energy conservation if T and q perturbed independently.
- Variation in the entrainment rate coefficient dominates the ensemble spread caused by the Random Parameters scheme (in this Tropical Convection case study).
- Variation in large-scale cloud and microphysics parameters increases ensemble spread in the stratosphere (radiative response).

Future Work

Aqua-Planet experiments to investigate sensitivity of global atmospheric behaviour to fast / small-scale physical variability.

- Compare climate of default run to one with the Random Parameters scheme using N48 resolution.
- Use N144 resolution runs to compare Plant & Craig scheme to default run with deterministic Kain-Fritsch convection scheme.



Any Questions?