Improving the SPPT Scheme using High-Resolution Model Simulations

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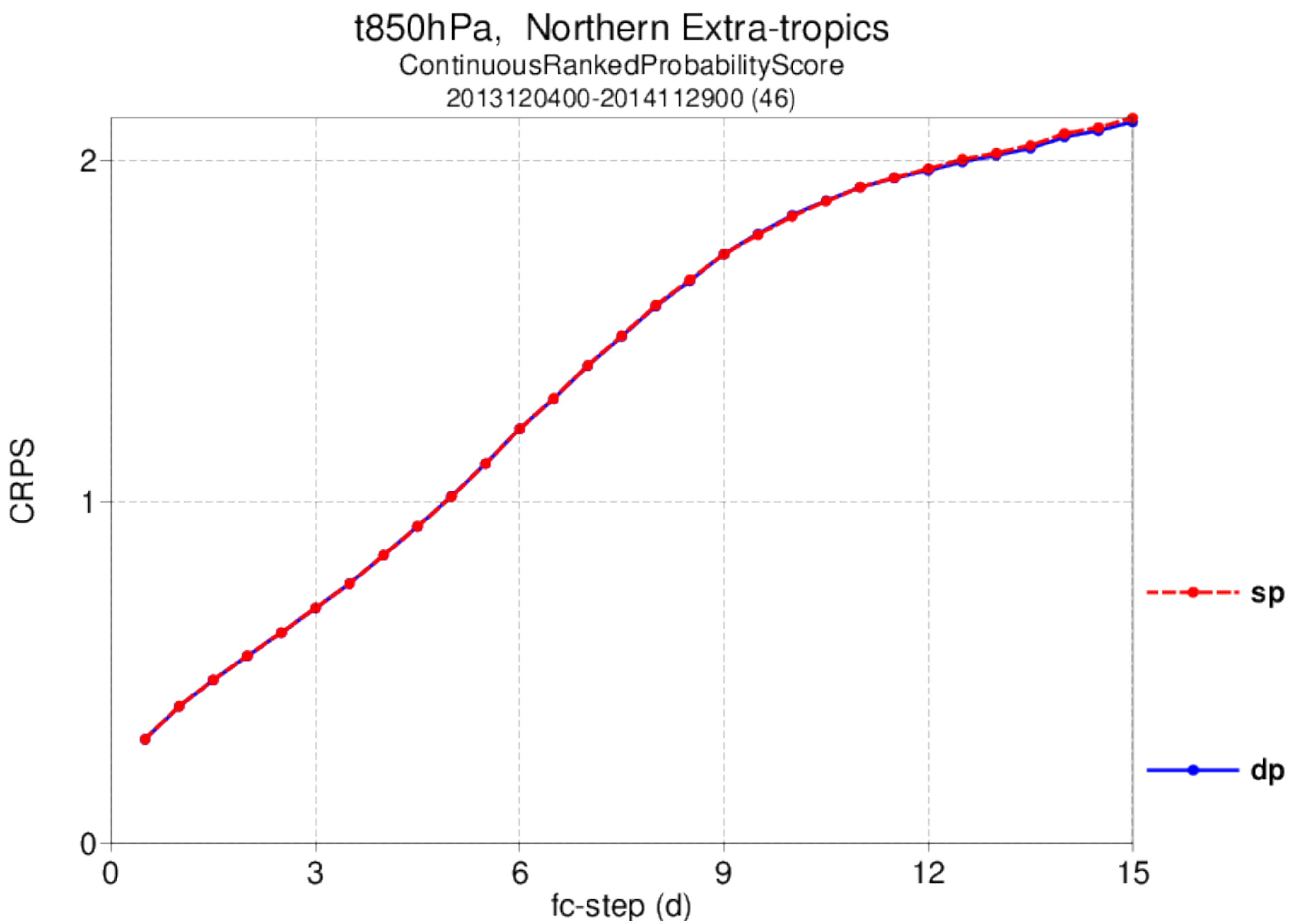
Predictability of Weather and Climate at Oxford

- Development and analysis of stochastic parametrisation schemes in Earth-System models
- Inexact hardware in numerical weather and climate models
  - Double precision as a default is overcautious – whether models are stochastic or deterministic
  - Reducing precision for the small scales can lead to significant energy savings

IFS in Single Precision



- Ensemble forecasts at T 399 are almost identical, but with 40% speed up

Düben et al, MWR 2015. Vana et al, submitted to GRL

A Scale Selective Approach

- Small scale dynamics are inherently uncertain due to parametrisation schemes, viscosity, missing data, initialisation, …
- We can push the small scales harder than the large scales
- The smallest scales are the most expensive ones

- Our vision: a global circulation model which uses just the right level of precision, reducing numerical precision with scales
- e.g. possible approach: a spectral model using single precision for wavenumbers 0-500, and half precision for wavenumbers 500-2000

A Scale Selective Approach

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- e.g. possible approach: a spectral model using single precision for wavenumbers 0-500, and half precision for wavenumbers 500-2000

Please see
Peter Düben's poster
for more details!

Improving the SPPT Scheme using High-Resolution Model Simulations

SPPT is one of the most widely used stochastic parametrisation schemes

- SPPT: 'Stochastically Perturbed Parametrisation Tendencies'
- Holistic approach for representing uncertainty in **all** sub-grid physics parametrisations
- SPPT scheme used in weather, seasonal and climate models

Implemented/tested in:

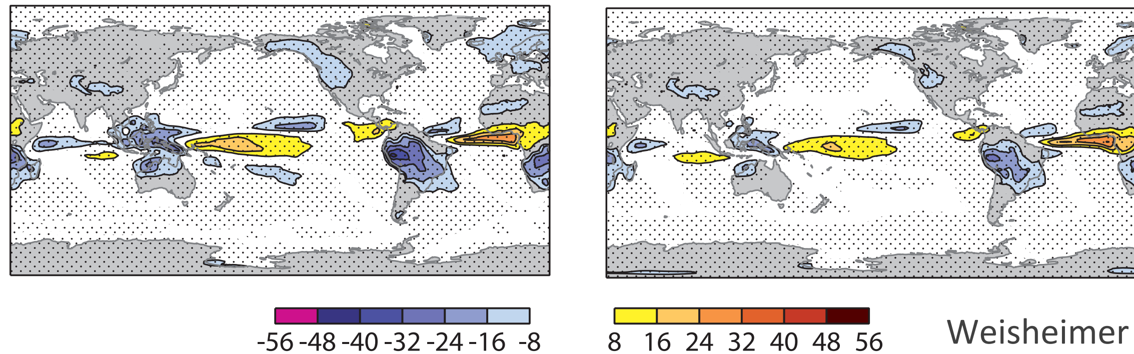
- UK Met Office
- ECMWF IFS (med. range & System 4)
- Japan Meteorological Agency
- AROME
- COSMO
- WRF
- CESM
- EC-Earth

Beneficial impact on reliability of forecasts, mean square error, and climatology of model

Reducing OLR bias in System 4 seasonal forecasts ➔

CTRL – OBS

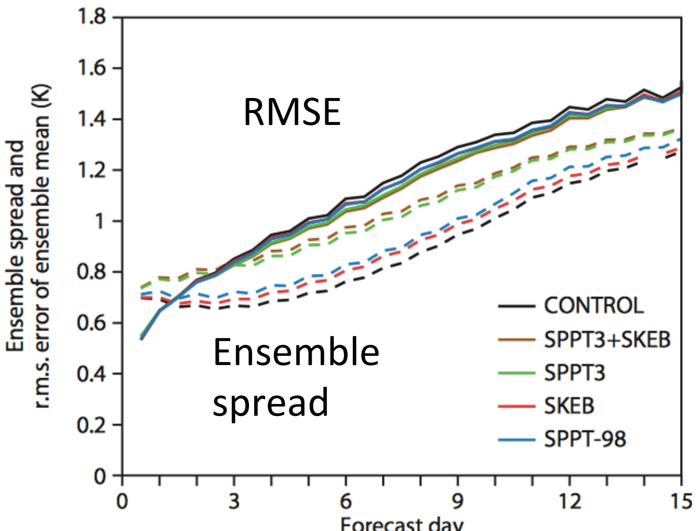
STOCHASTIC (SYS4) – OBS



Weisheimer et al, 2014, Phil Trans

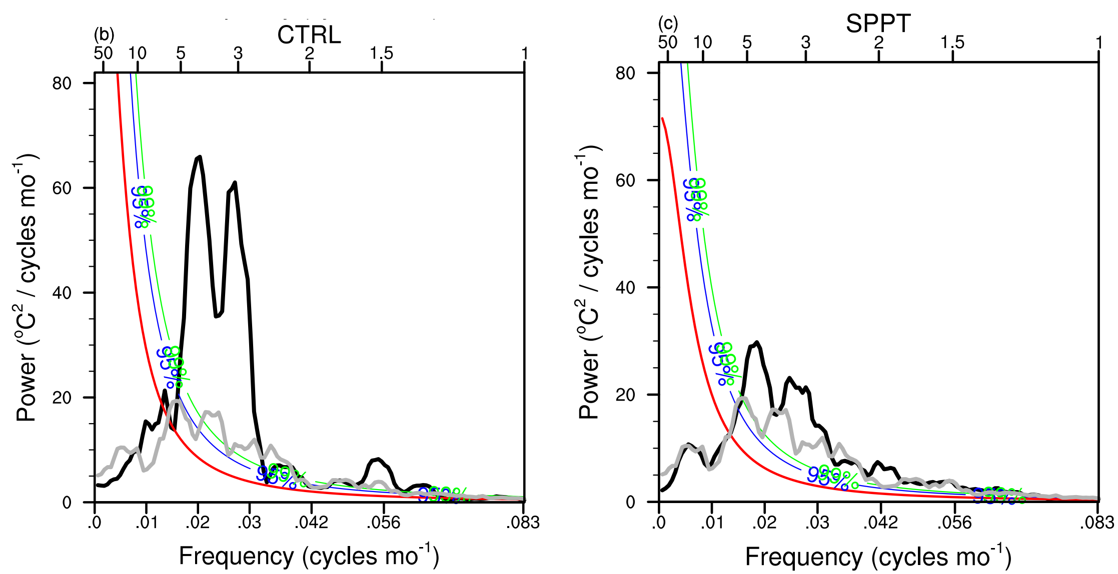
Reliability of T850 in IFS Medium-range forecasts ➔

T850, tropics



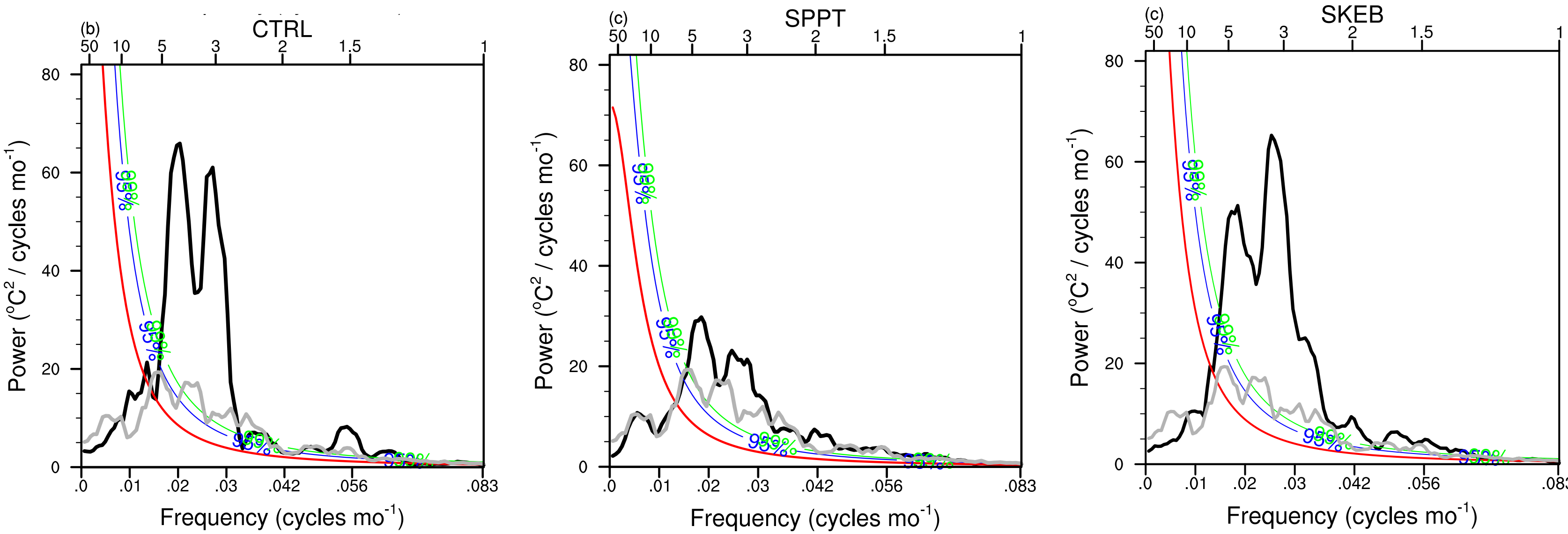
Shutts et al, 2011

Improving ENSO variability in CCSM4 ➔



Christensen, Berner, Coleman and Palmer, submitted to J. Climate, 2016

Improving ENSO variability in CCSM4



- Because of multiplicative nature of SPPT
  - Additive noise scheme (SKEB) does not have the same impact
- Tested additive and multiplicative noise in simple 'Delayed Oscillator' model of ENSO
  - Equivalent result as in CCSM4
  - additive noise amplified ENSO whereas multiplicative noise reduced the amplitude

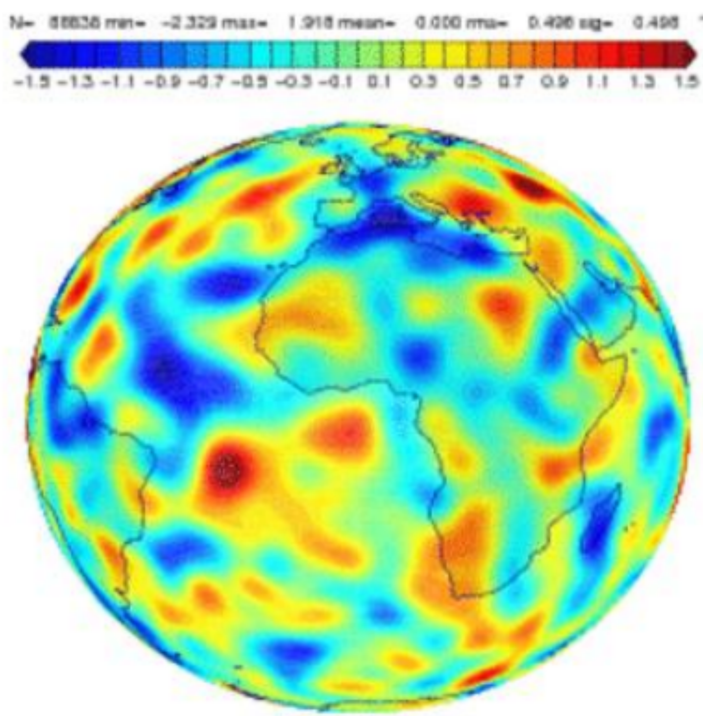
Christensen, Berner, Coleman and Palmer, submitted to J. Climate, 2016

SPPT: Stochastically Perturbed Parametrisation Tendencies

SPPT

$$T = D + (1+e)\sum_{i=1}^{6} P_i$$

T – Total tendency
D – Dynamics tendency
P – Parametrisation tendency



All IFS physics schemes are perturbed using same pattern:

1. Radiation
2. Turbulence & Gravity Wave Drag
3. Convection
4. Cloud
5. Non-Orographic Grav. Wave Drag
6. Methane Oxidation

Four variables perturbed: T, U, V, q

Perturbation constant vertically, tapered in BL and stratosphere

Palmer et al, 2009. ECMWF Tech Memo 598

Testing "Independent SPPT" in IFS

SPPT

$$T = D + (1+e)\sum_{i=1}^{6} P_i$$

iSPPT

$$T = D + \sum_{i=1}^{6} (1+e_i) P_i$$

T – Total tendency
D – Dynamics tendency
P – Parametrisation tendency

- Perturb IFS physics schemes with independent random fields
  - Assumes errors from different schemes are uncorrelated
  - Set noise magnitude and correlations separately for each scheme
  - Able to only taper certain schemes if desired
  - Start with same σ, ϕ as operational SPPT

Testing "Independent SPPT" in IFS

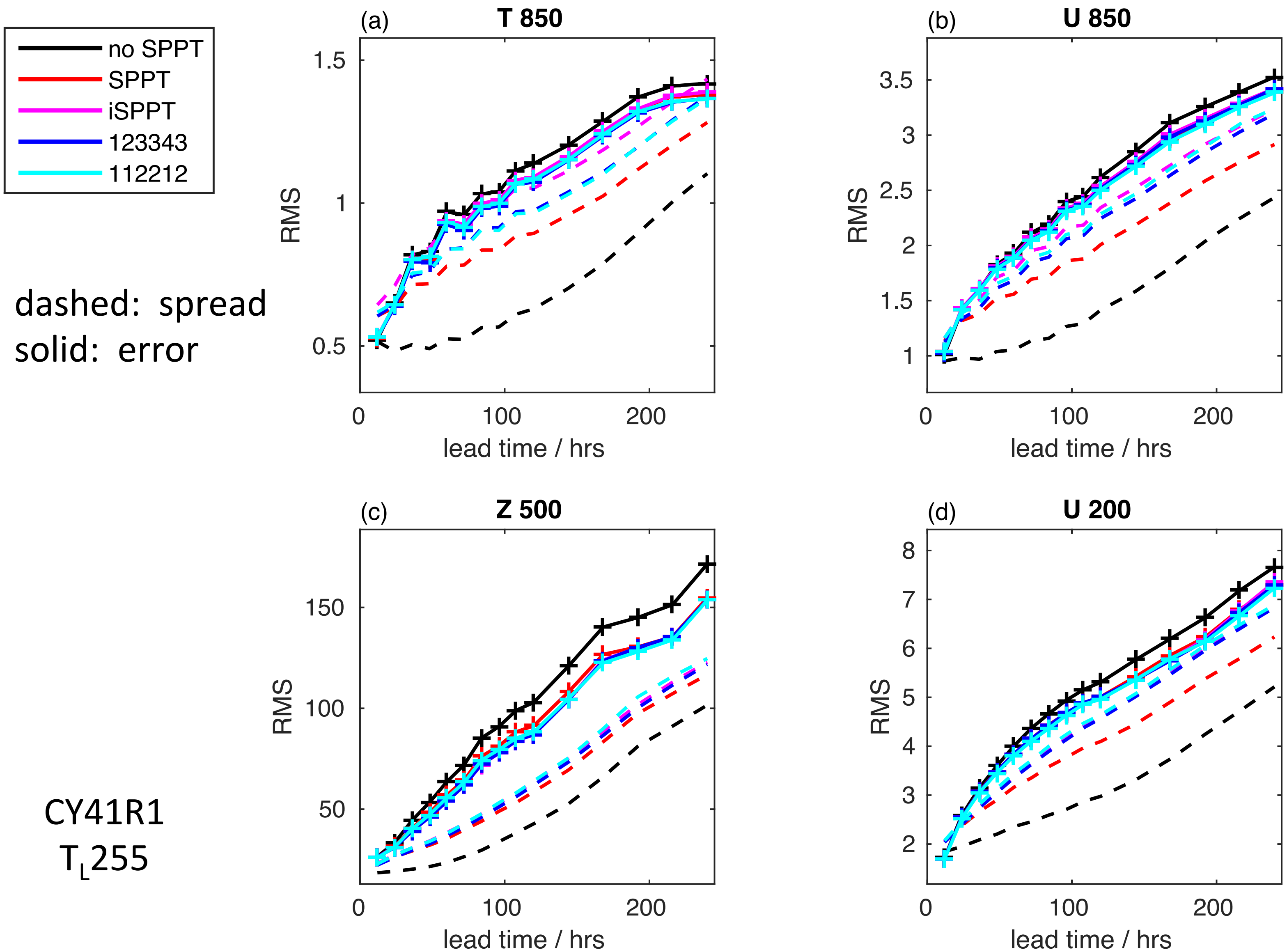
- Series of experiments
  - CY41R1 at T_L255 (12 start dates)
  - CY42R1 at $T_{CO}255$ (48 start dates)
- 21 ensemble members
- Antje Weisheimer's global moisture fix on

1. Radiation
2. Turbulence & Grav. Wave Drag
3. Convection
4. Cloud
5. Non-Orog Grav. Wave Drag
6. Methane Oxidation

- Standard SPPT: (111111)
- Independent SPPT: (123456)
- Partially independent SPPT: (123343)
  (112212)

nomenclature: assign each independent pattern a number

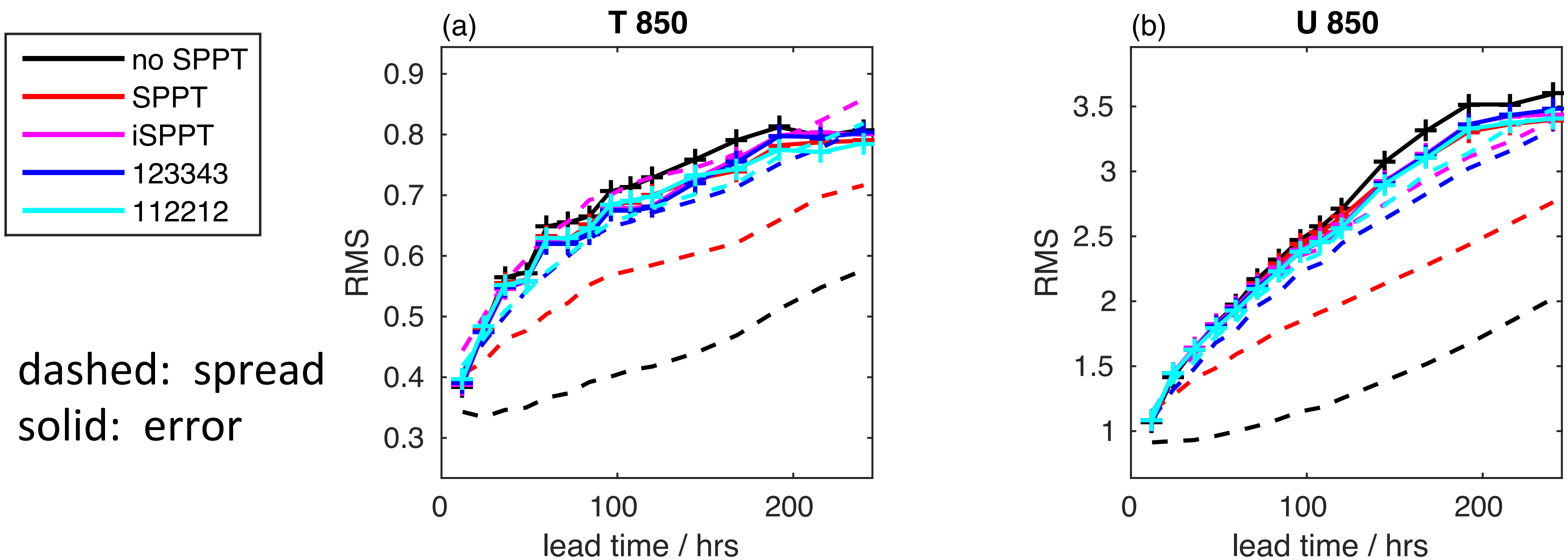
iSPPT: significant improvement in the Tropics



dashed: spread
solid: error

CY41R1
T_L255

Impact is in regions with significant convection



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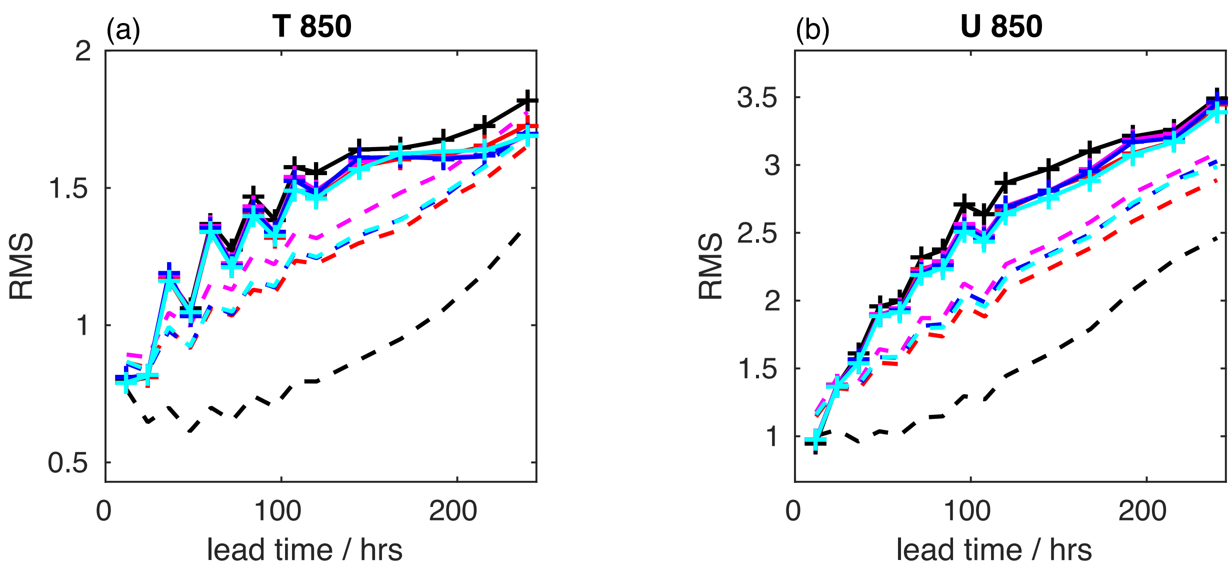
Tropical regions with significant convection

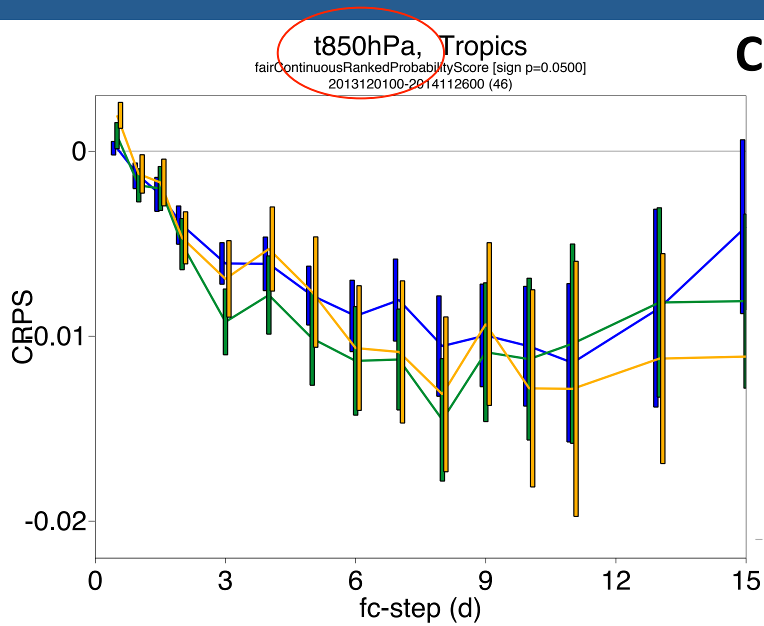


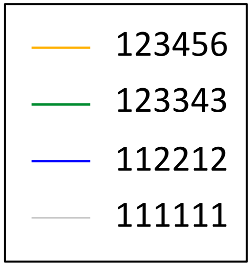
Tropical regions with little convection

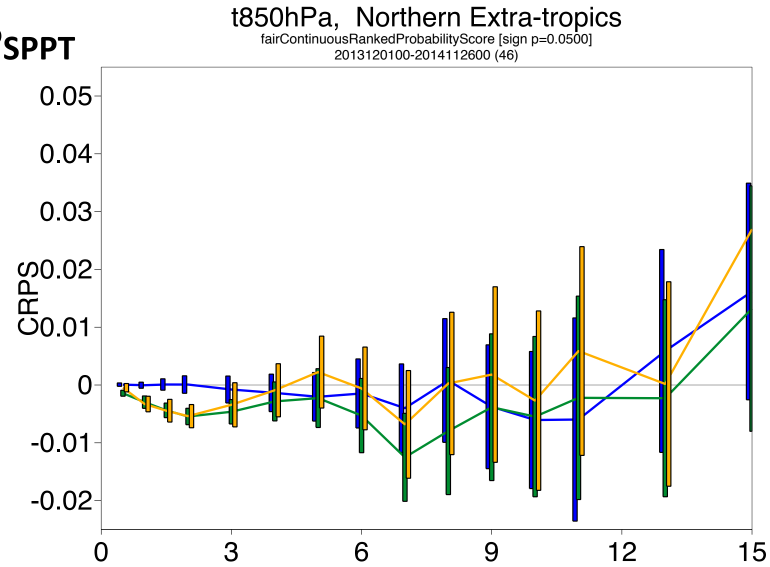
CY41R1
T_L255

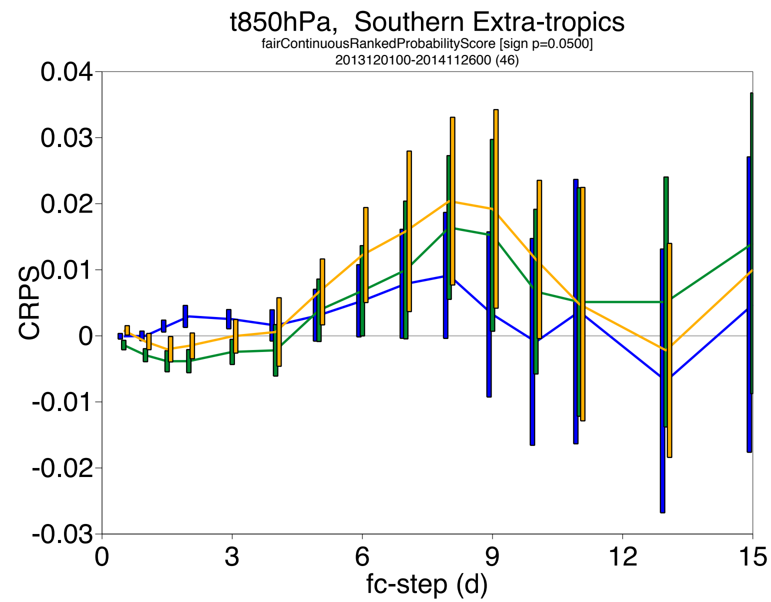
Two-pattern scheme improves over SPPT & iSPPT

$CRPS_{iSPPT}$ - $CRPS_{SPPT}$









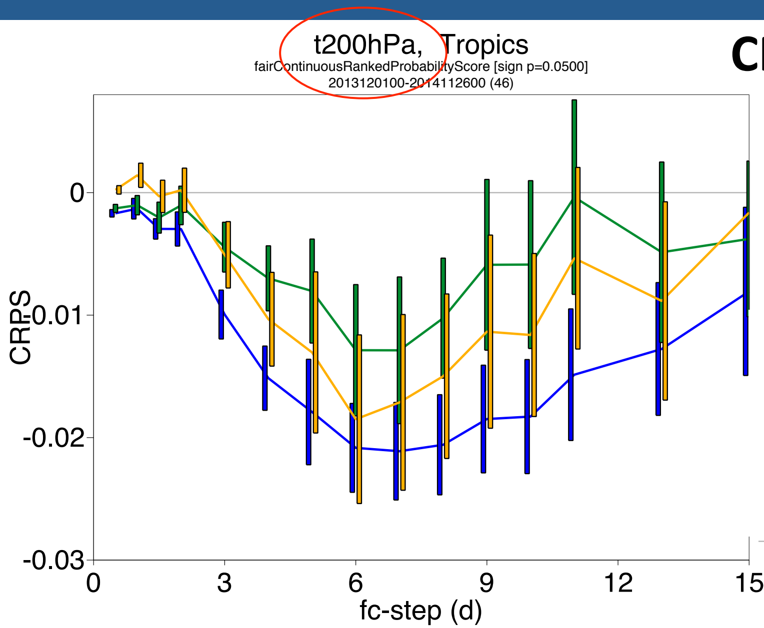
CRPS (iSPPT) – CRPS (SPPT3)

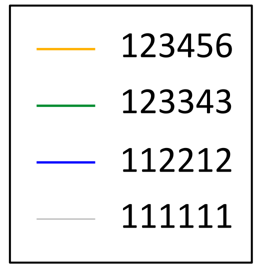
- better than operational SPPT and full iSPPT
- large **spread** increase in tropics, smaller increase in extra tropics
- **error** reduction in tropics, neutral in NET, small increase in SET

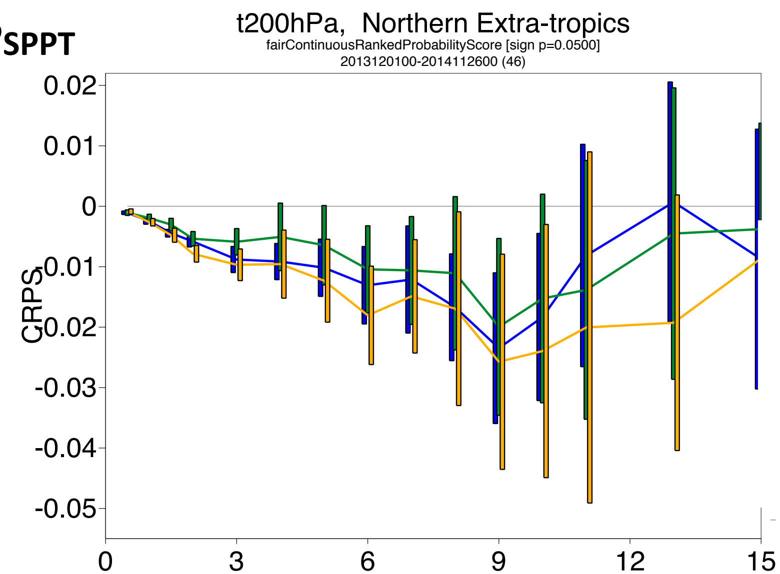
CY42R1
$T_{CO}255$

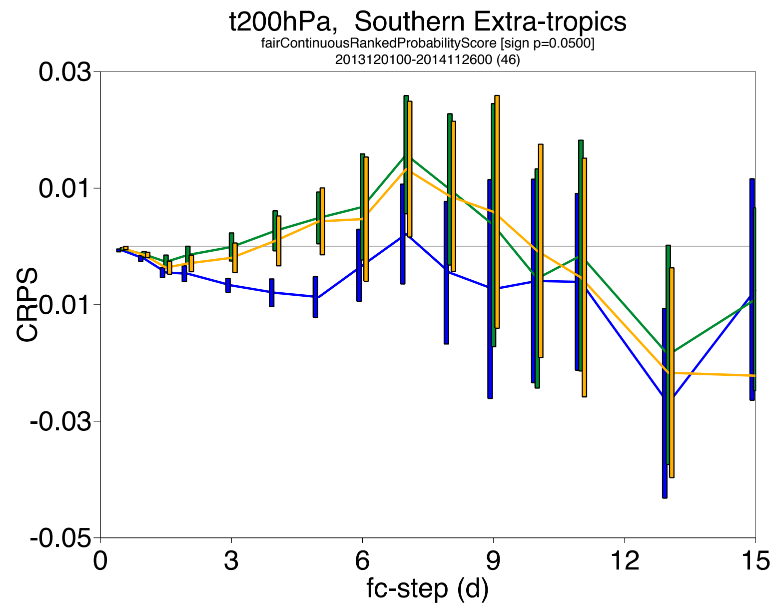
Two-pattern scheme improves over SPPT & iSPPT

$CRPS_{iSPPT}$ - $CRPS_{SPPT}$







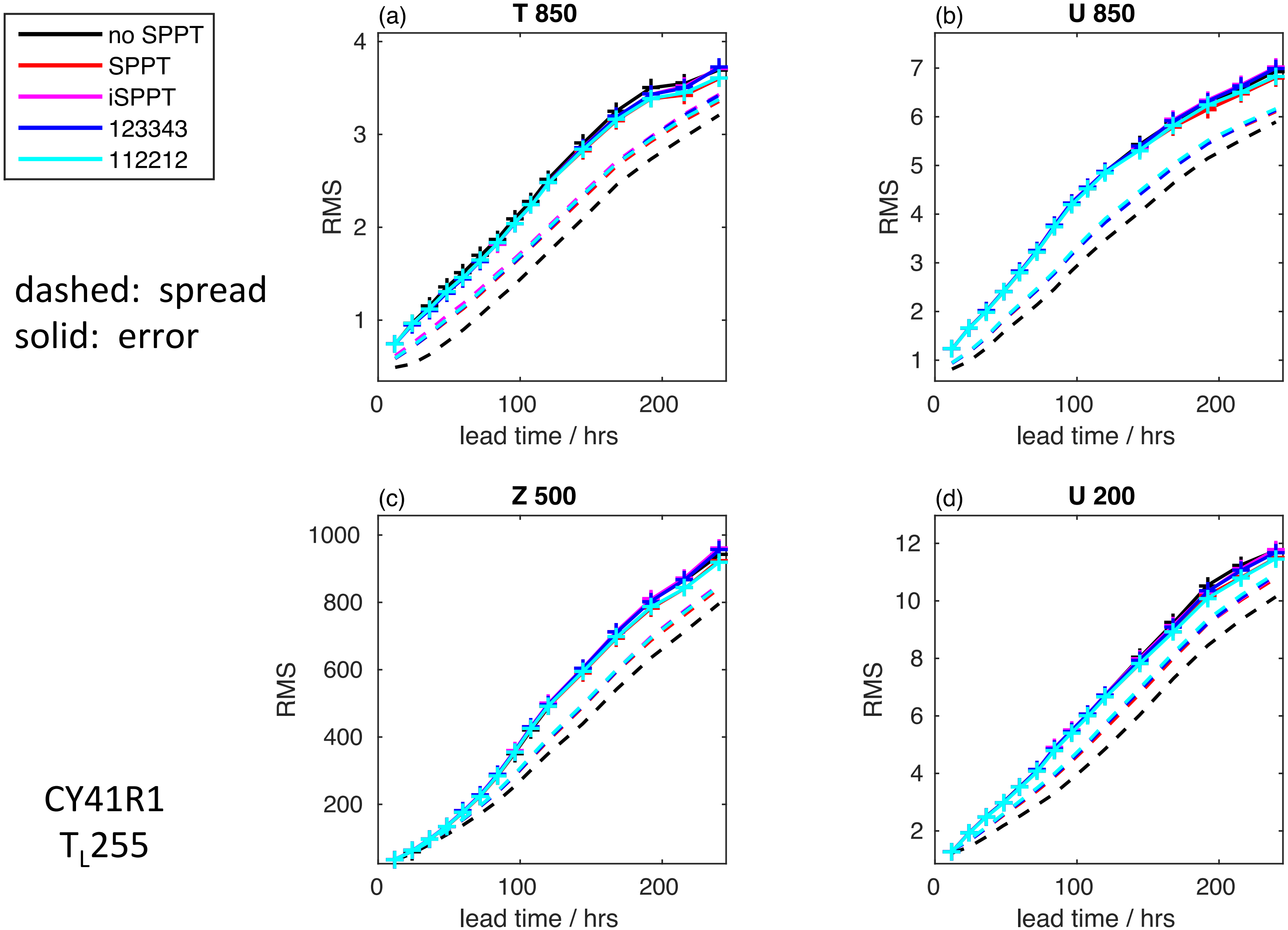


- better than operational SPPT and full iSPPT
- large **spread** increase in tropics, smaller increase in extra tropics
- **error** reduction in tropics, neutral/slight reduction in NET and SET

CY42R1

$T_{CO}255$

iSPPT: only small degradation in S. Extra Tropics



dashed: spread
solid: error

CY41R1
T_L255

iSPPT seems a promising approach

- **BUT** can we improve SPPT more systematically?
- Can we justify SPPT? Can we explain why it does such a good job?
- Can we identify where it doesn't do a good job and why?

- SPPT scheme includes several assumptions
  - Multiplicative noise
  - All schemes treated the same: uncertainty in tendency proportional to total tendency (cf. **iSPPT:** errors from schemes uncorrelated)
  - Specifies standard deviations, temporal and spatial correlations with no physical reason for choices

- **Q: Can we constrain some of the characteristics of the stochastic term using high-resolution model output?**

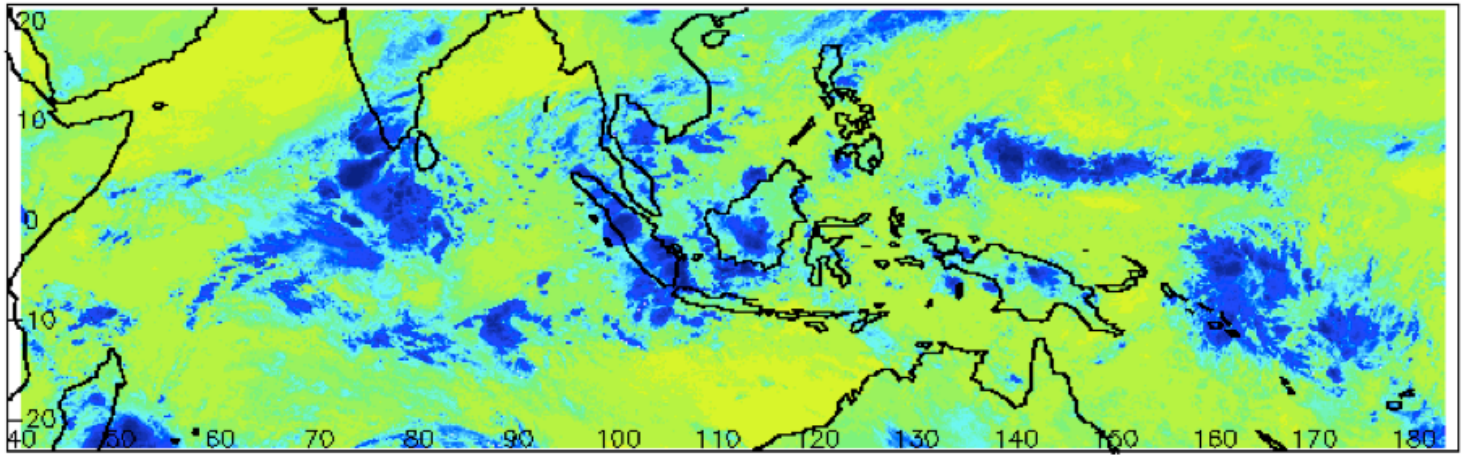
  - Following in the footsteps of Shutts and Palmer 2007 (J. Clim.), Shutts and Callado Pallares 2014 (Phil Trans R. Soc. A) …

Use the CASCADE dataset as 'truth'

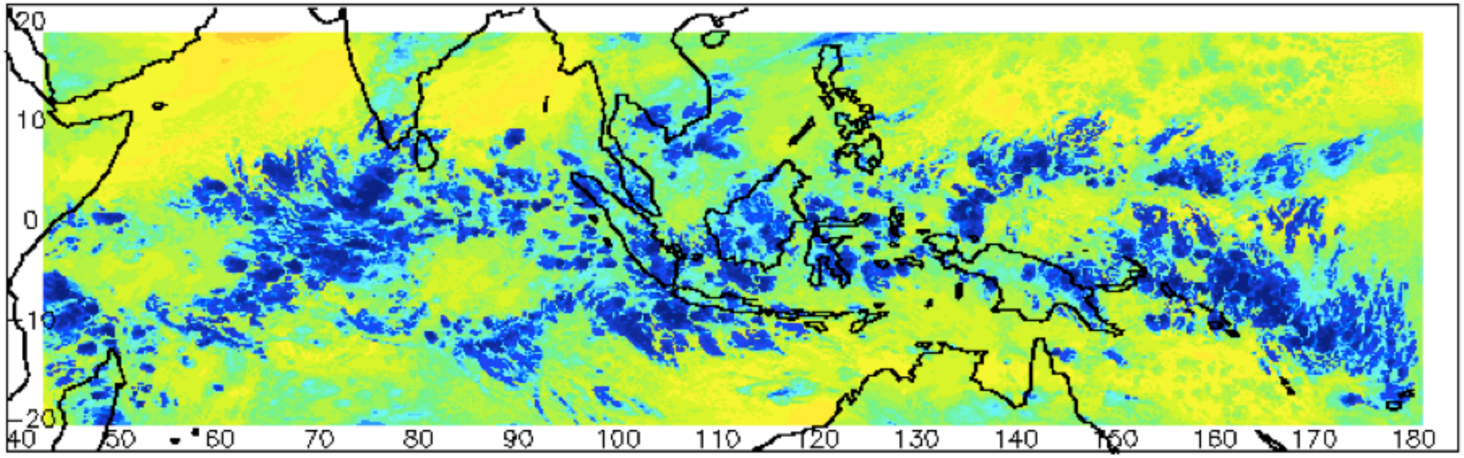
Compare IFS SCM to this truth

thanks to **Chris Holloway, U. Reading**

TRMM

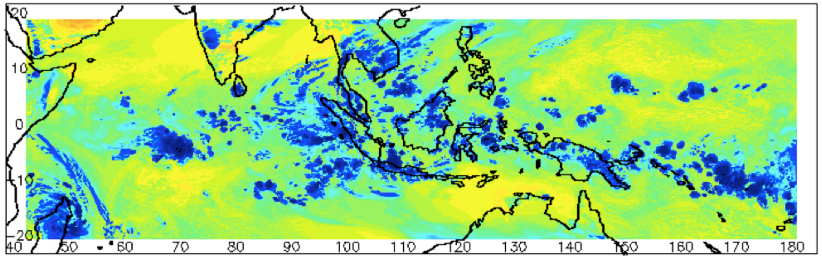


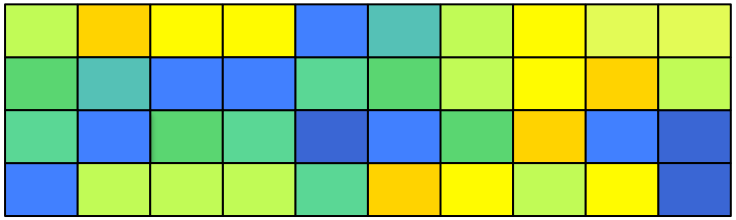
CASCADE 4km 3DSmag OLR



Coarse graining experiments

1. Coarse grain CASCADE to model grid to provide ICs and forcing data for IFS SCM at T639 = 30km

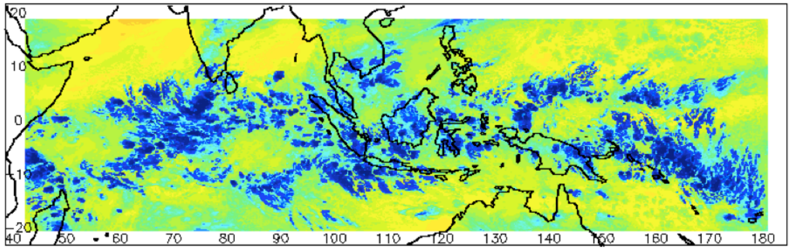


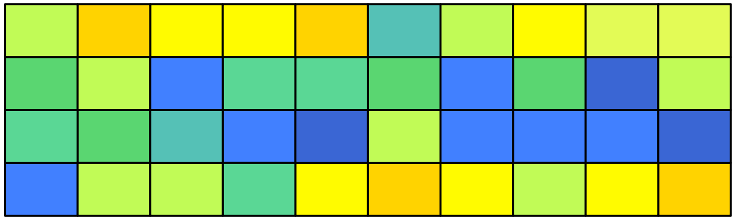


CASCADE

2. Evolve in time: SCM dt = 15 min

SCM





3. Compare SCM to CASCADE at later time

Analysing the data: multiplicative noise?

SPPT:

$$T = D + (1+e)\sum_{i=1}^{5} P_i$$

Calculate 'true' total tendency from CASCADE

Assume SCM dynamics tendency is 'correct'

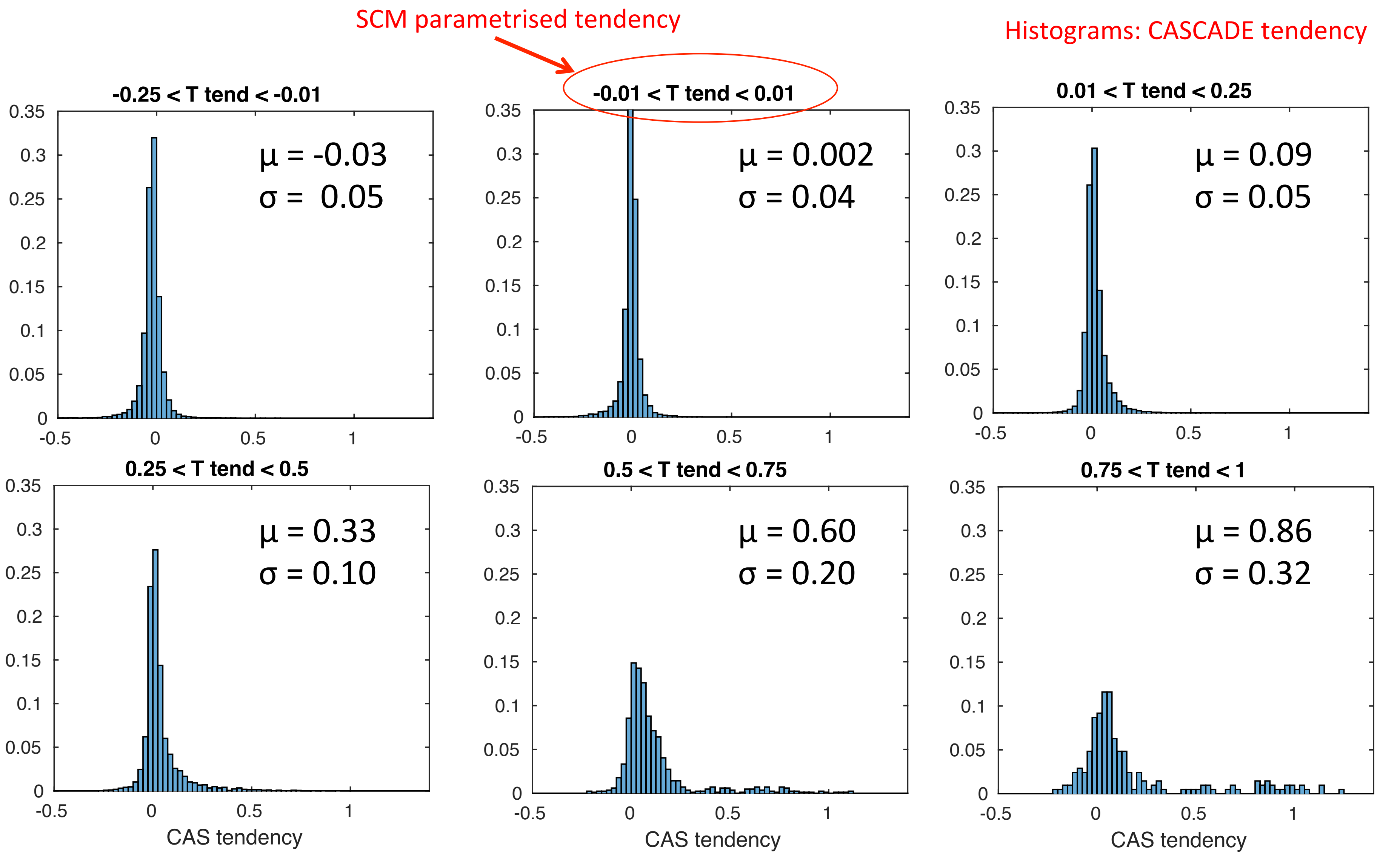
Consider error in SCM physics tendencies

$$\underbrace{T - D}_{\text{Compare 'true' physics tendency ...}} = (1+e)\underbrace{\sum_{i=1}^{5} P_i}_{\text{... to parametrised physics tendency}}$$

Compare 'true' physics tendency …

… to parametrised physics tendency

Consider T tendency at 850hPa



Analysing the data: characteristics of *e*

SPPT:

$$T = D + (1+e)\sum_{i=1}^{5} P_i$$

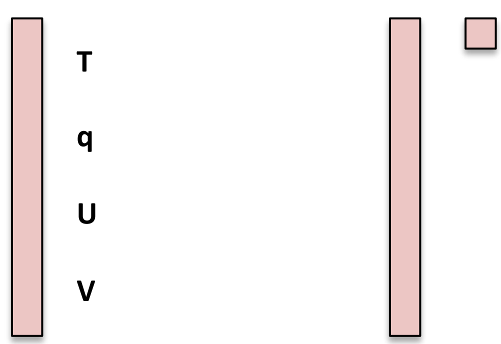
Calculate 'true' total tendency from CASCADE

Assume SCM dynamics tendency is 'correct'

Consider error in SCM physics tendencies

SOLVE

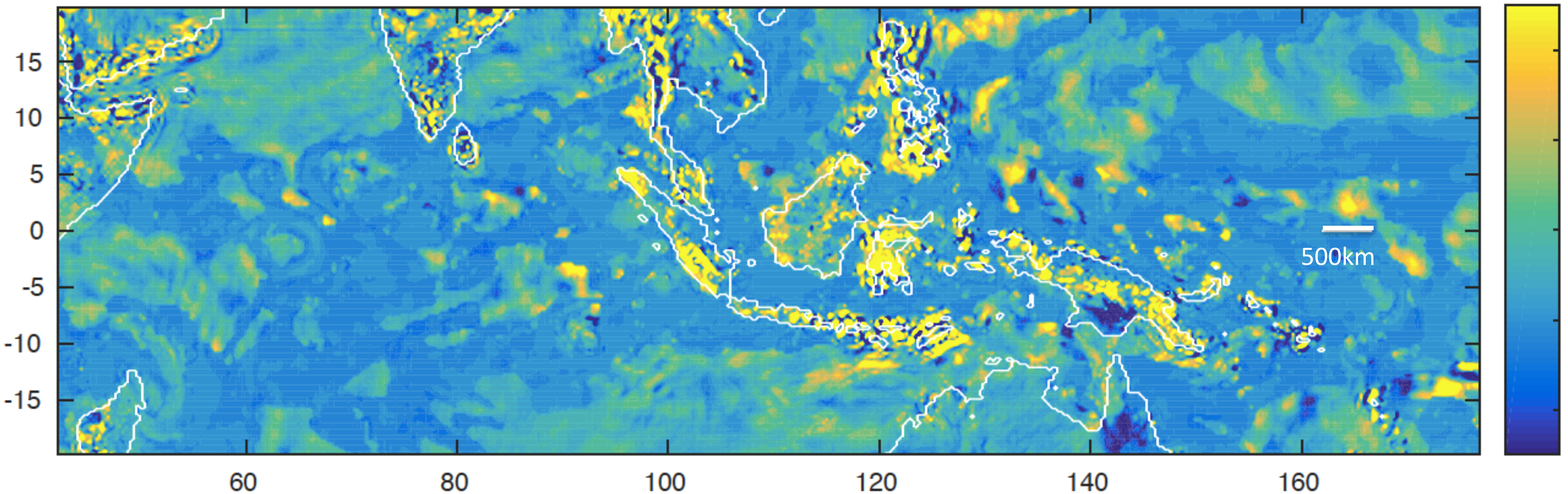
$$T - D - \sum_{i=1}^{5} P_i = e\sum_{i=1}^{5} P_i$$



i.e.
Following the assumptions of SPPT, can we measure the statistical characteristics of the perturbation ***e***

Do not use data from BL or stratosphere (tapered)

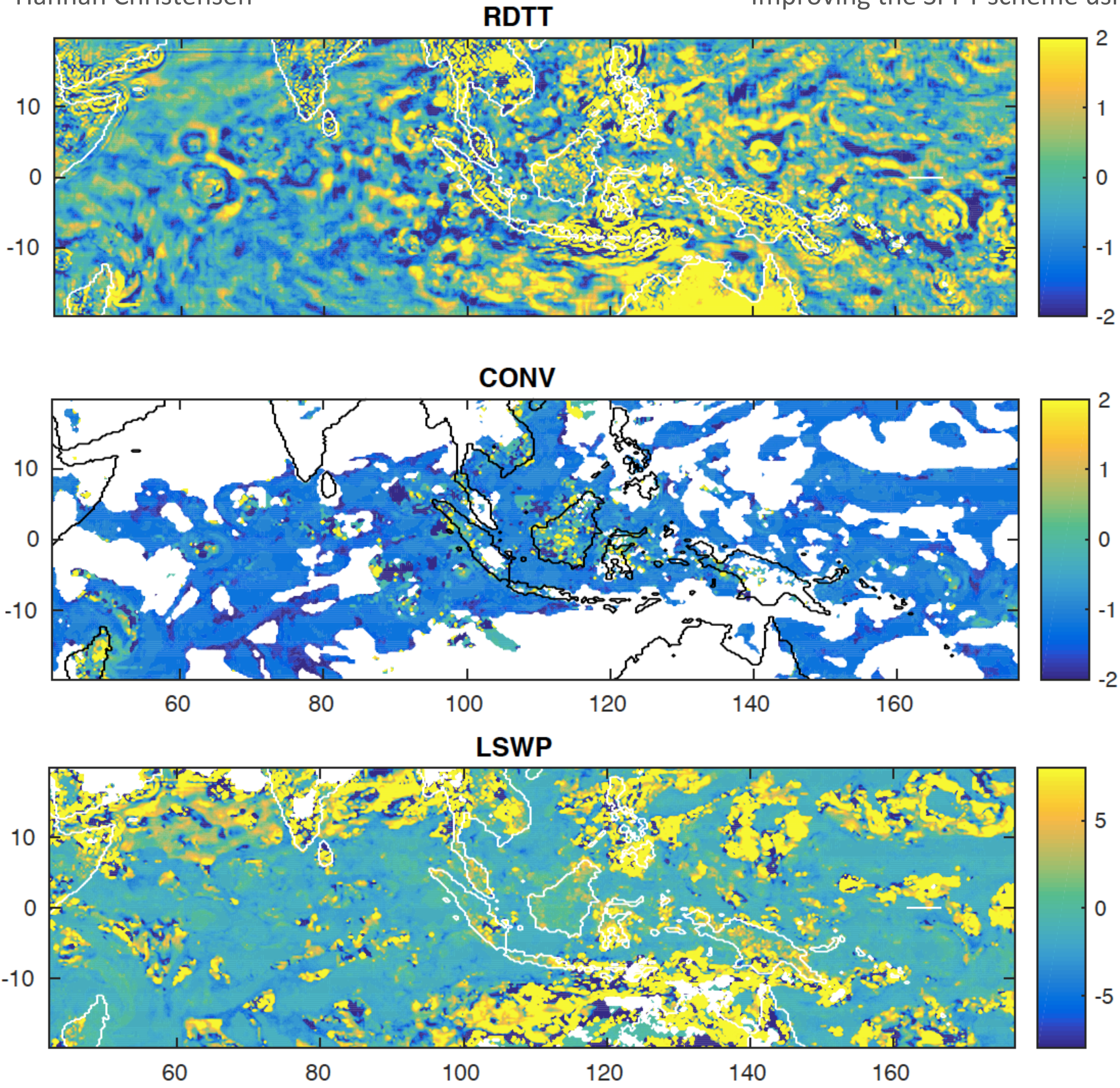
e.g. *e* for a single time step



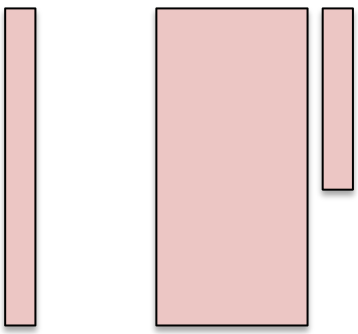
$$T - D - \sum_{i=1}^{5} P_i = e \sum_{i=1}^{5} P_i$$

Calculate ***e*** as a function of position for a single time step

Consider different schemes



$$T - D - \sum_{i=1}^{5} P_i = \sum_{i=1}^{5} e_i P_i$$



Conclusions

- SPPT is a skilful approach for representing uncertainty in weather and climate models
- iSPPT improves tropical reliability of SPPT in medium range
  - Two pattern iSPPT appears particularly skilful in tropics and extra tropics

- Use coarse-graining to measure error characteristics of different schemes
  - Multiplicative noise appears a reasonable model for uncertainty in tendencies
  - BUT different error characteristics for different schemes motivates treating the parametrisation schemes separately
  - If convection is not triggered, the error characteristics of the other schemes change

These are early results! Future work: refine techniques used to calculate error, calculate statistical properties of error term

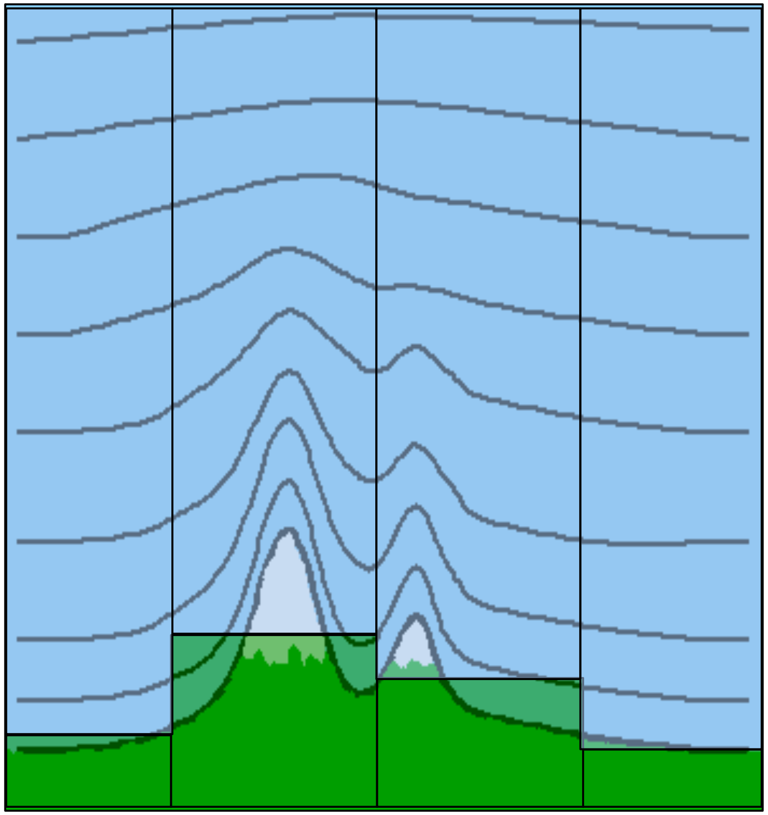
Thanks for listening!

CASCADE: model set up

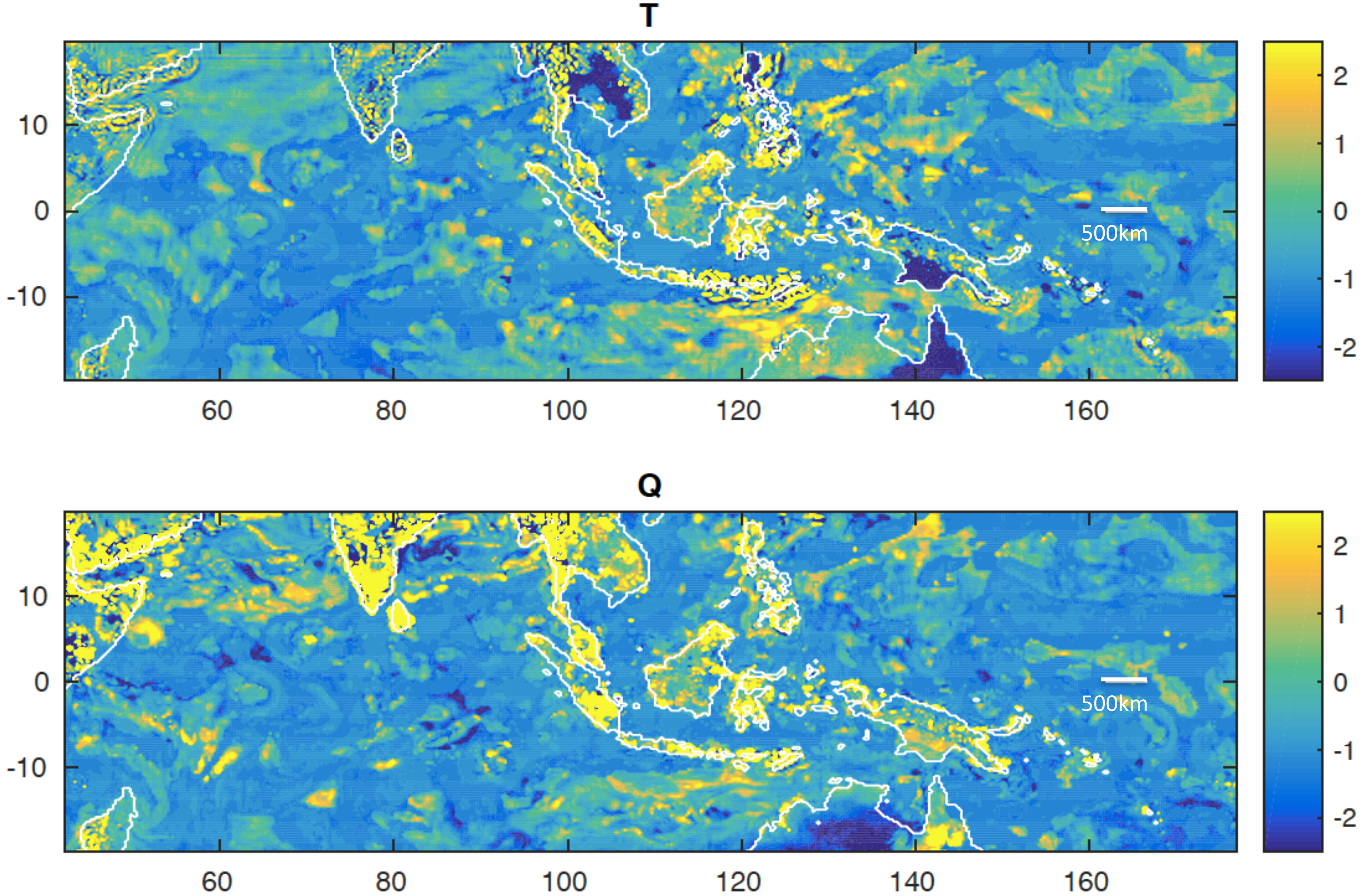
- UK Met Office atmospheric model setup
- Semi-Lagrangian, non-hydrostatic dynamics
- Cloud-system resolving (4 km, 70 levels) one-way nested grid
- Large tropical domain (15,500 km x 4,500 km)
- Prescribed constant SST and updated lateral boundary conditions from ECMWF 25 km forecast analyses for the Year of Tropical Convection (YOTC)
- 3D Smagorinsky mixing
- Convection scheme switched on but closure such that convection scheme is only active in low CAPE environments (tends to produce shallow/congestus)

Some technical details

- Coarsen using a simple ‘top hat’ function
- Spatially average first, before interpolating from CASCADE to SCM levels
- CASCADE data only every 1hr, so linearly interpolating between
- SCM has higher top than CASCADE data: fill in using ERA reanalysis
- Use standard IFS boundary files (orography, land cover etc)
- Automate running 75,000 SCMs per time step

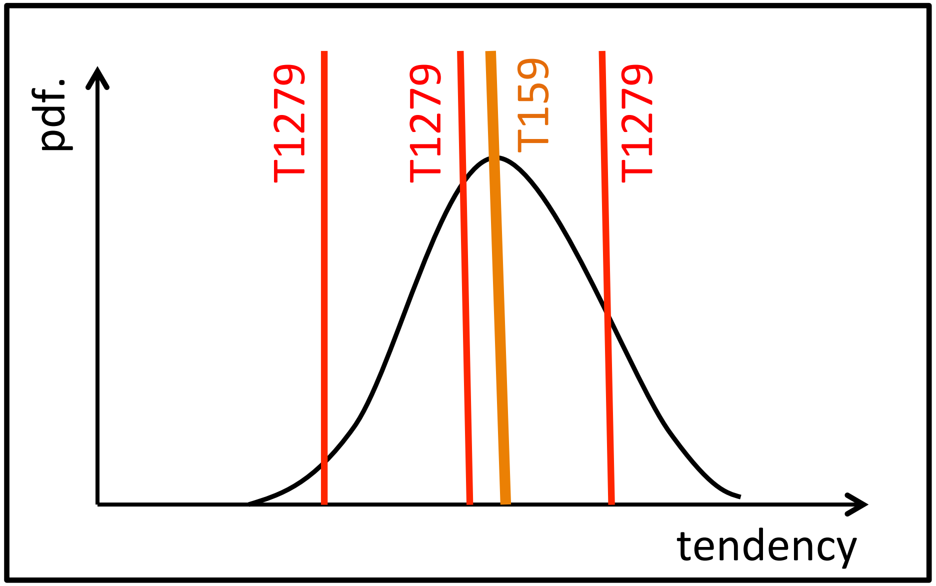


Calculate *e* separately for different variables



Coarse graining experiments

- Performed by Alfons Callado Pallares and Glenn Shutts
  - Define tendencies from IFS @ T1279 (16km) to be "truth"
  - Compare to tendencies from forecast: IFS @ T159 (130km)
  - Use 24 x 12-hour forecasts from identical initial conditions
  - Coarse grain both resolutions in time (12hr triangular filter) and space (to 500km grid)
  - Calculate mean and standard deviation of T1279 tendencies conditioned on the T159 tendencies



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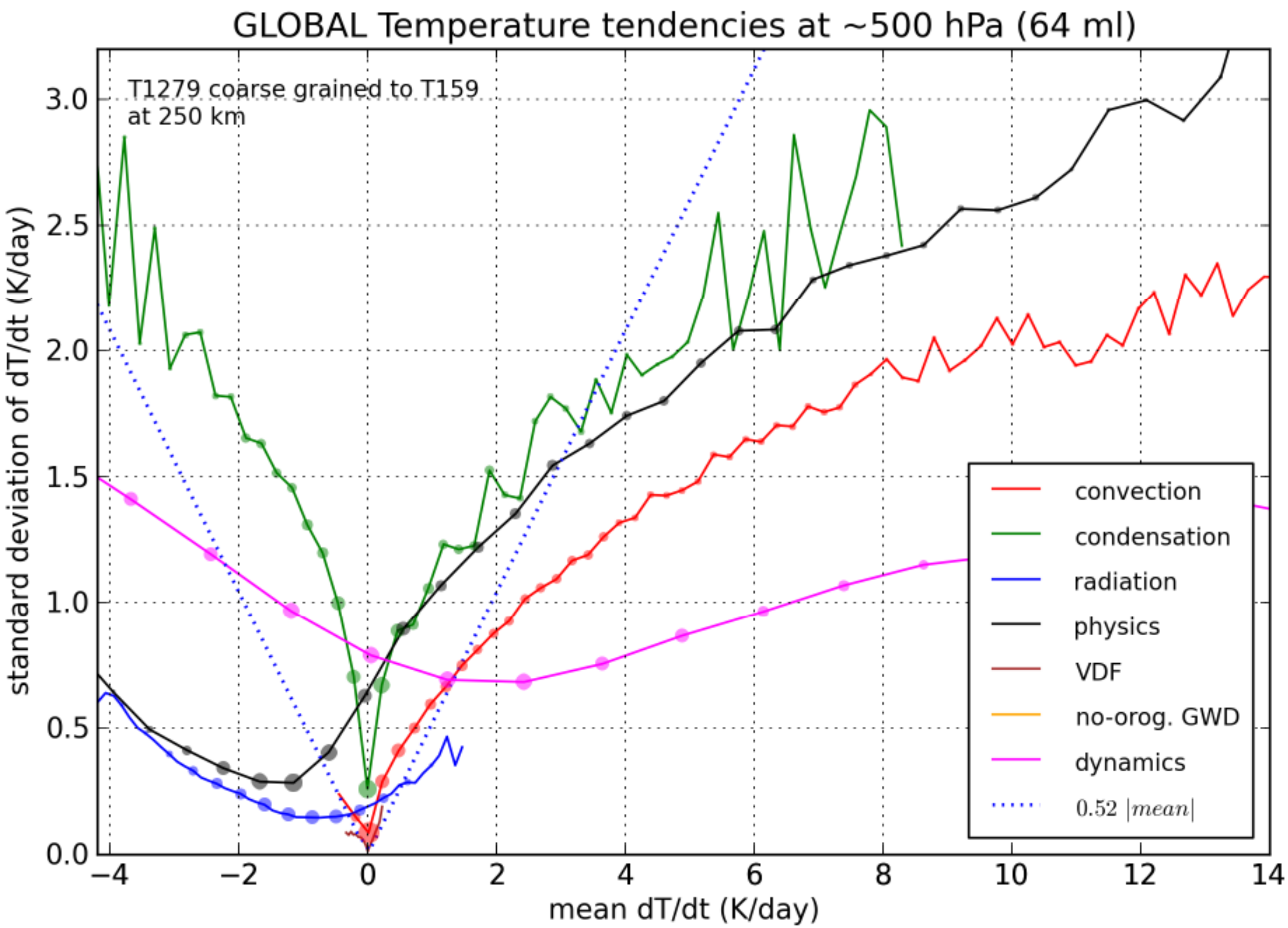
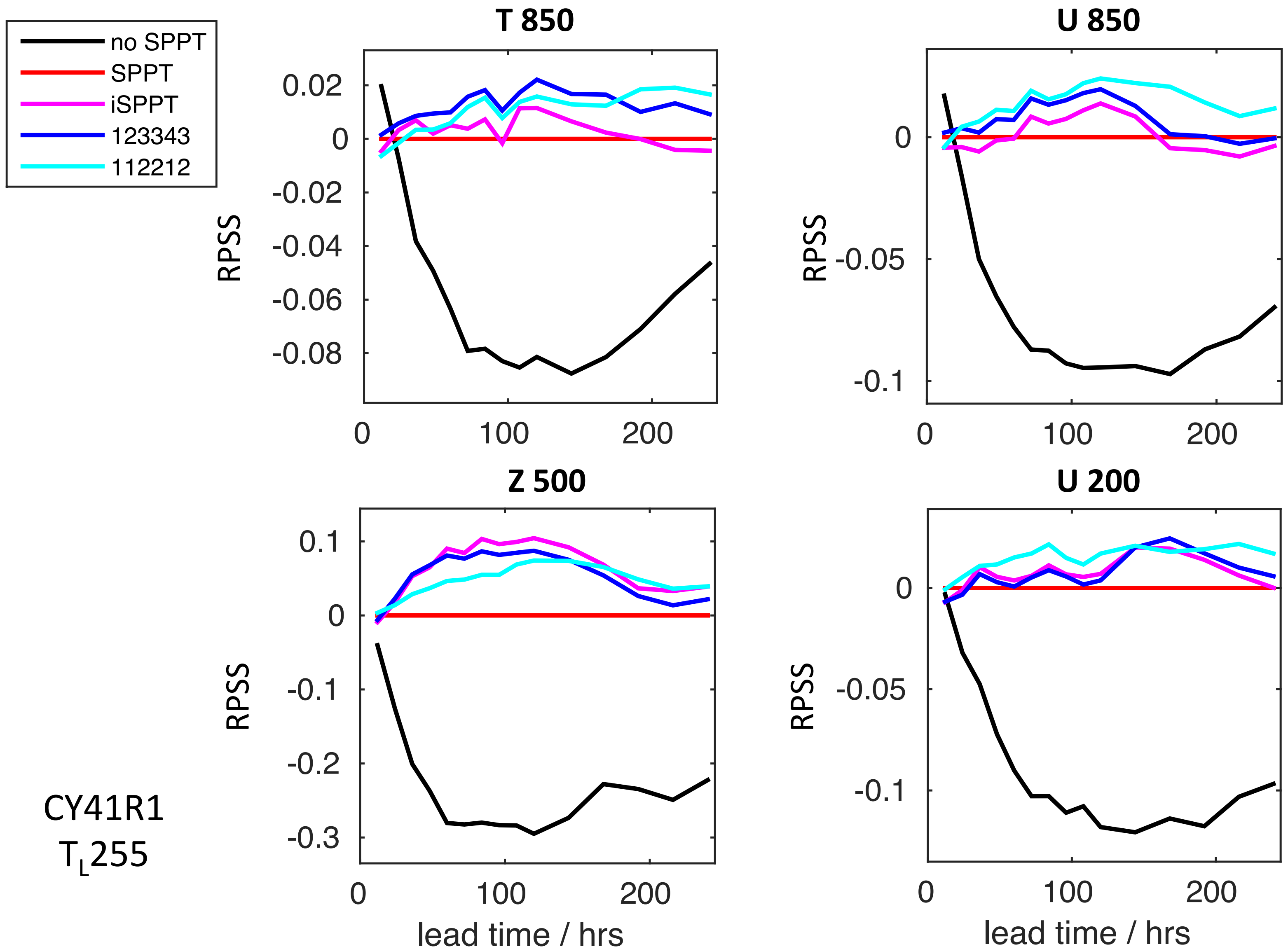


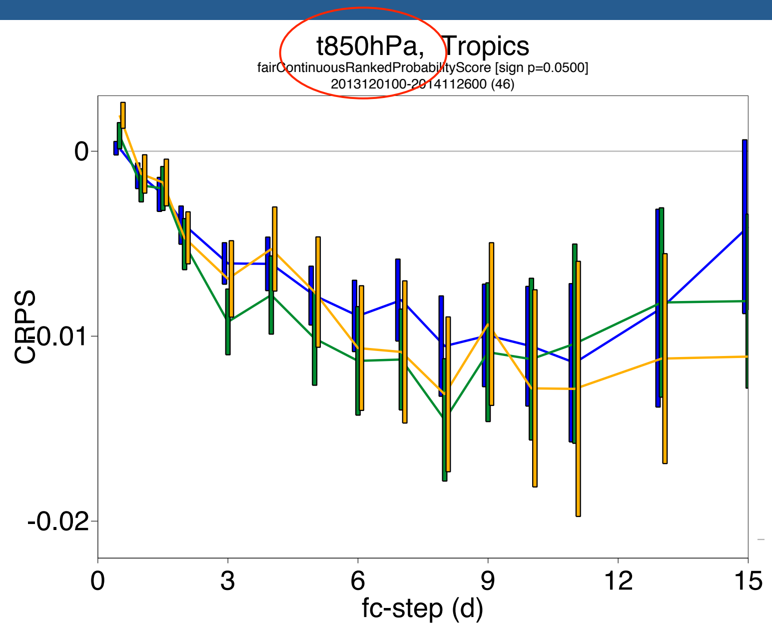
fig from A. Callado-Pallares and G. Shutts

iSPPT: significant improvement in the Tropics

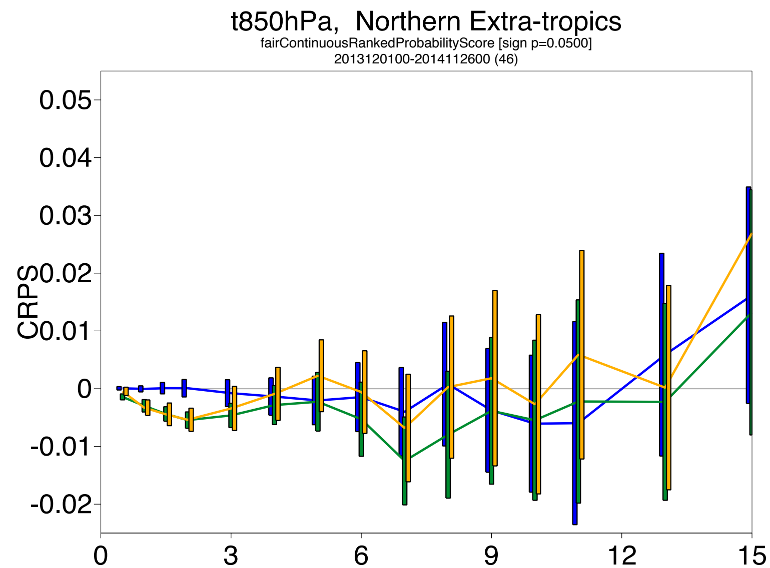


CY41R1
T_L255

T850 CRPS

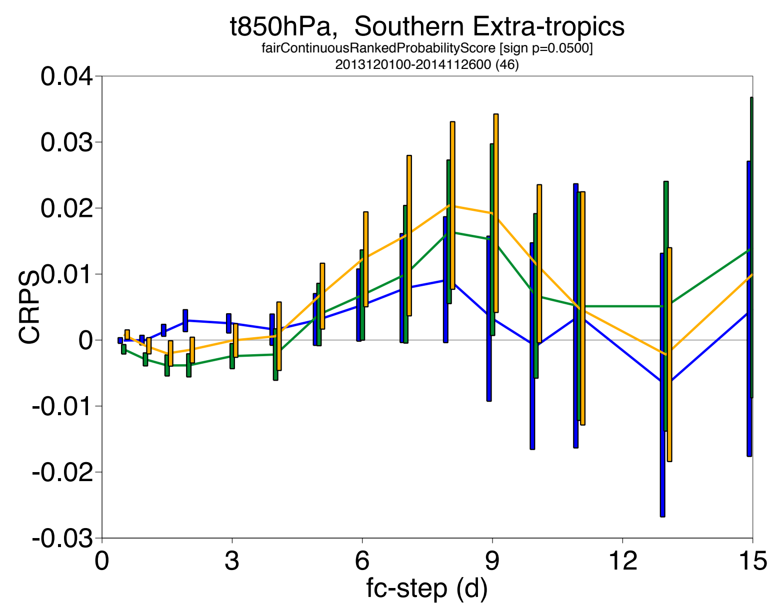


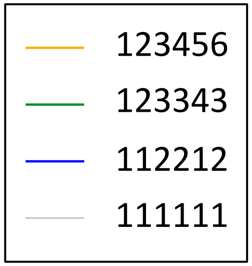
CRPS



… but (112212) scheme

- reasonably good in extra-tropics,
- large improvement in the tropics

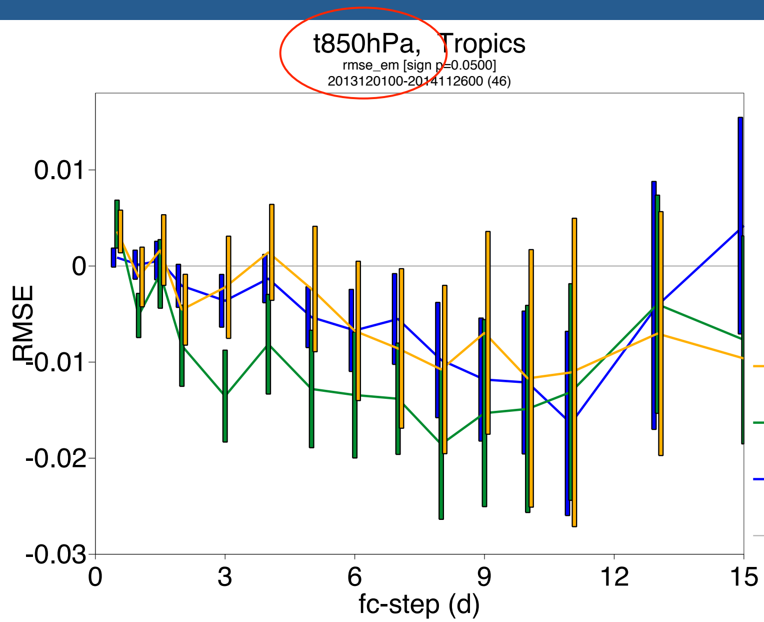




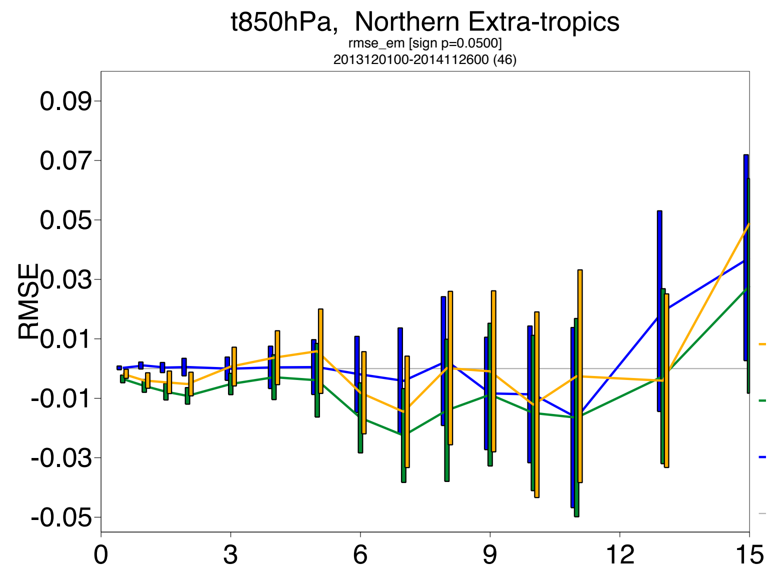
CY42R1

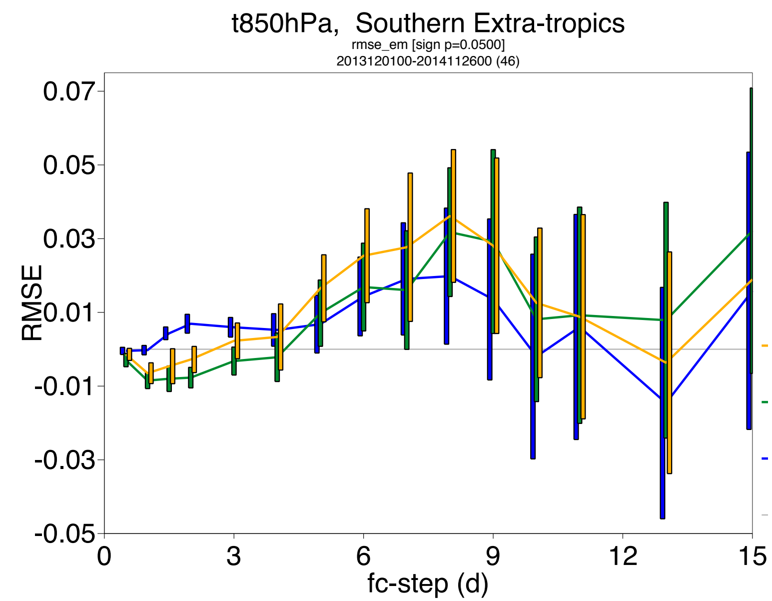
$T_{CO}255$

T850 RMSE in ensemble mean



RMSE





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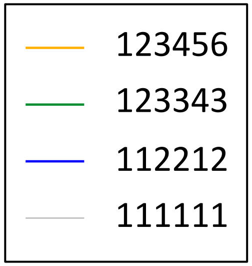
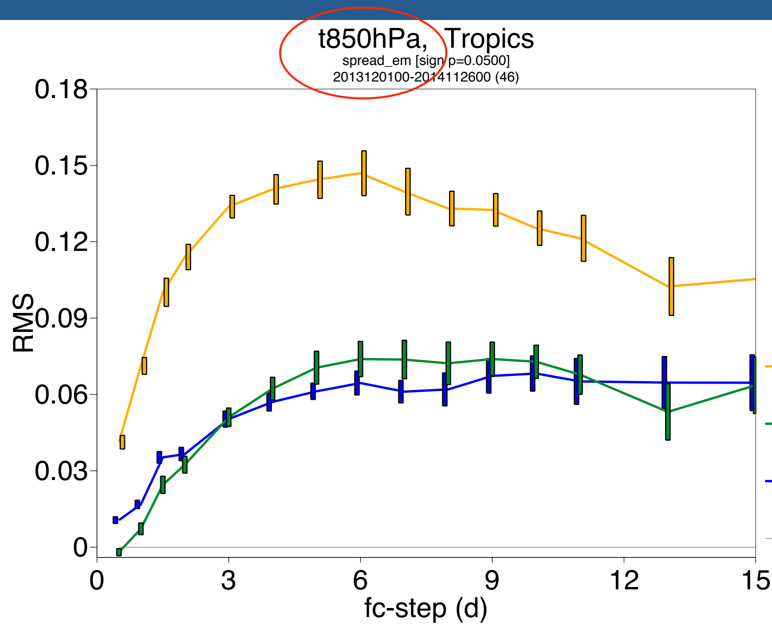


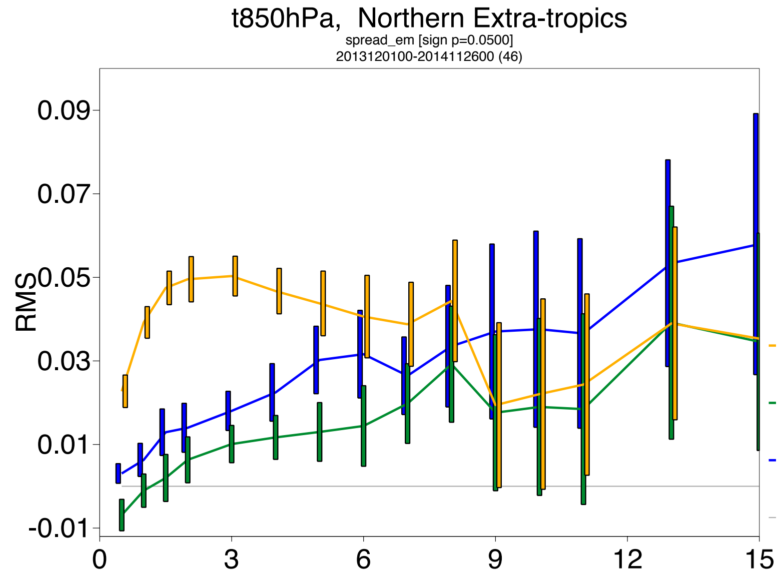
CY42R1

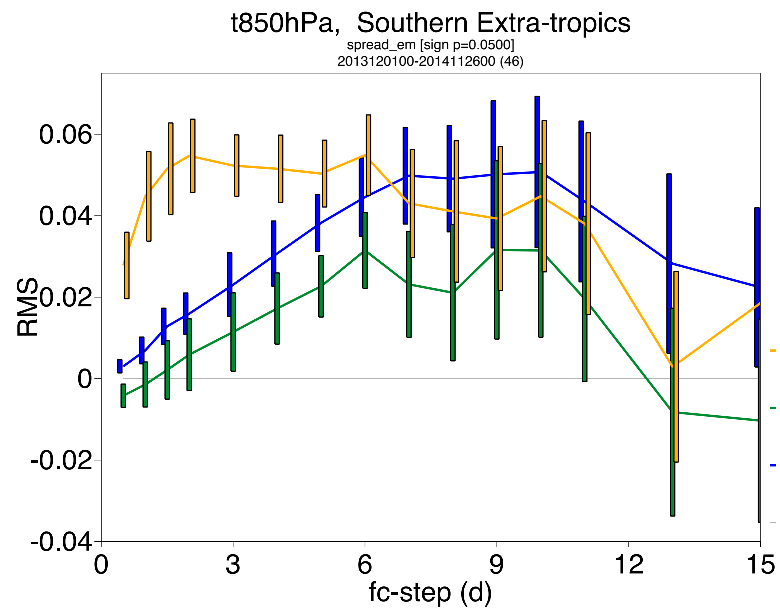
$T_{CO}255$

T850 RMS ensemble spread



RMSS





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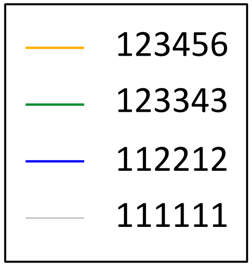

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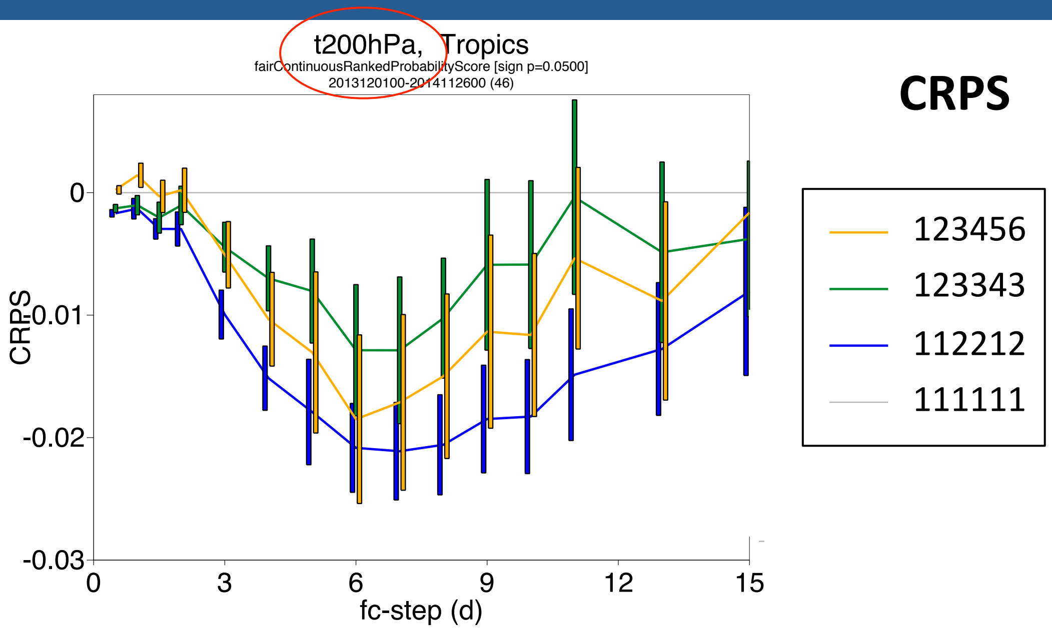
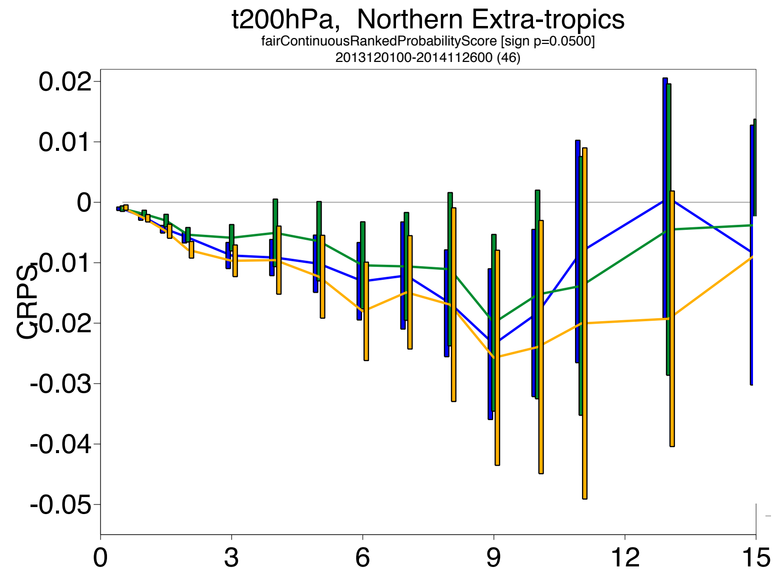
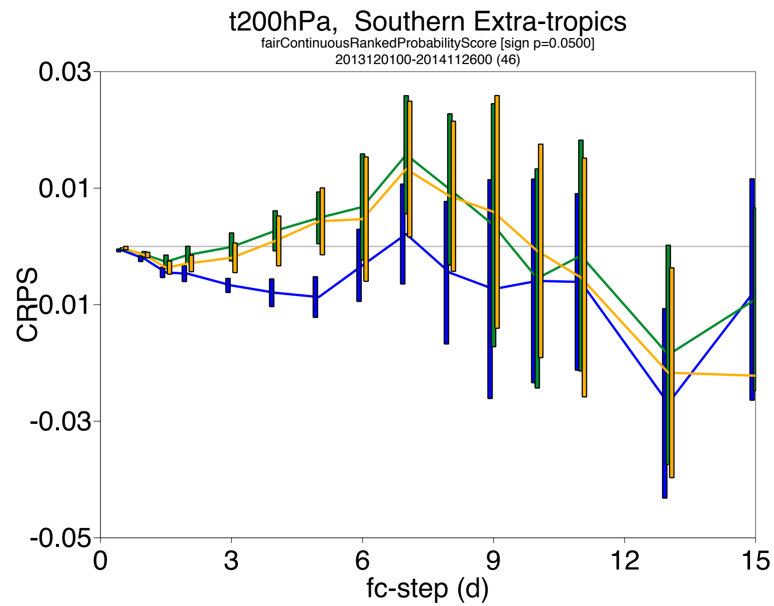
Two-pattern scheme improves over SPPT & iSPPT







… but (112212) scheme

- ➢ reasonably good in extra-tropics,
- ➢ large improvement in the tropics

CY42R1

$T_{CO}255$

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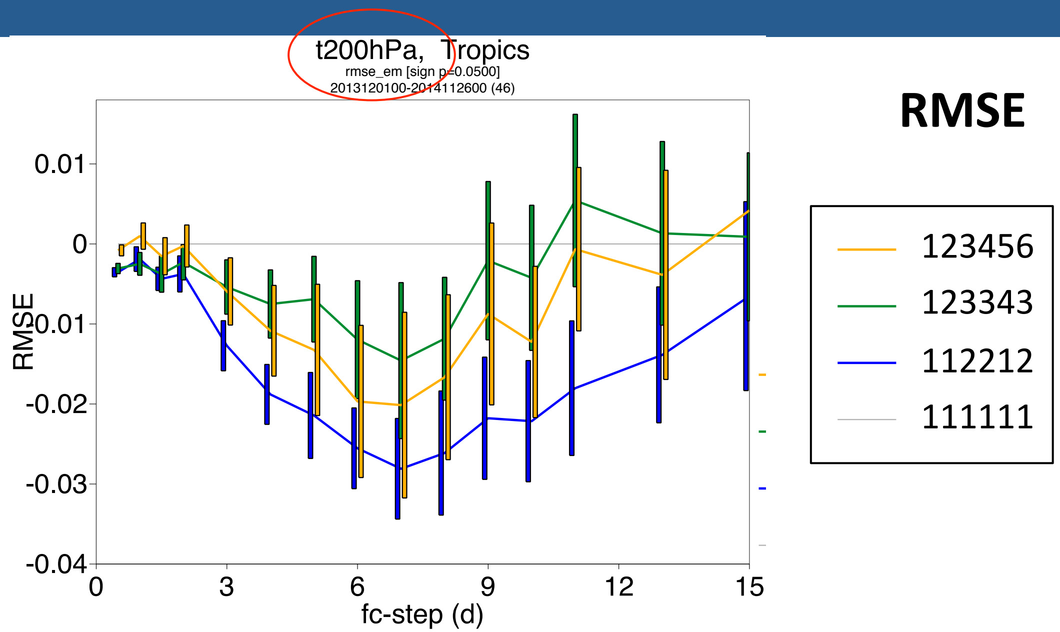

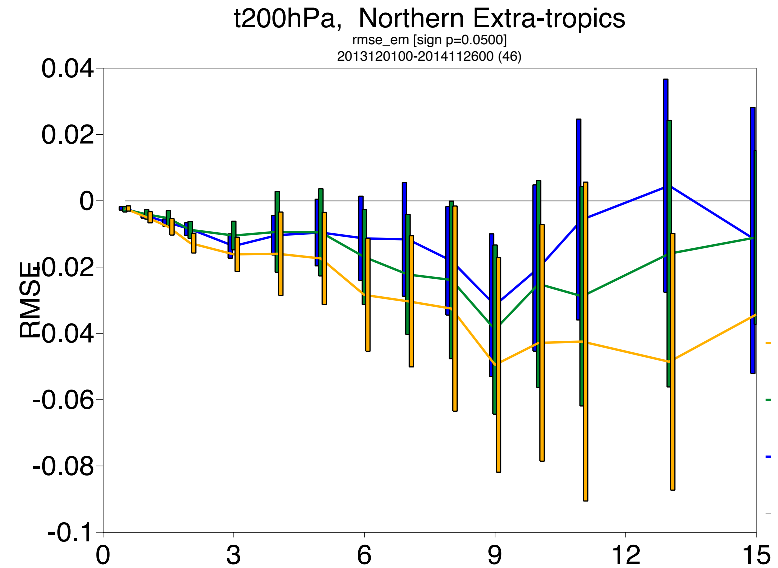

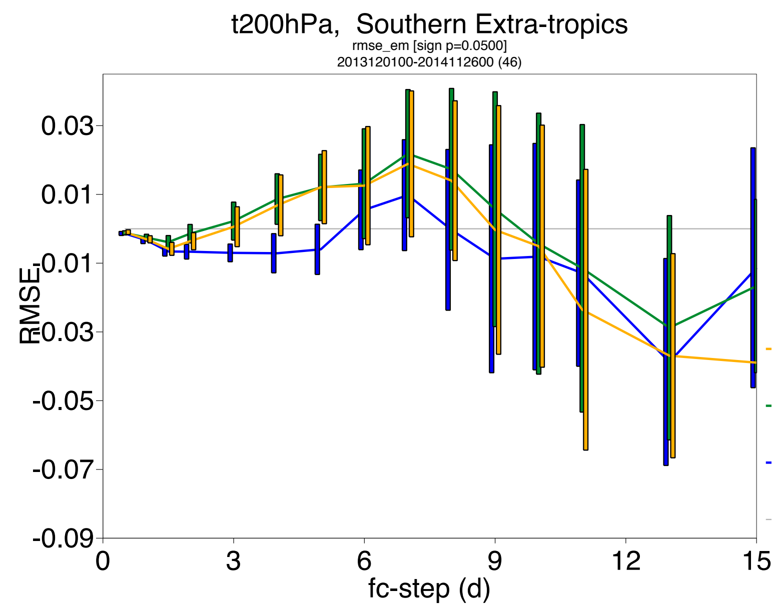

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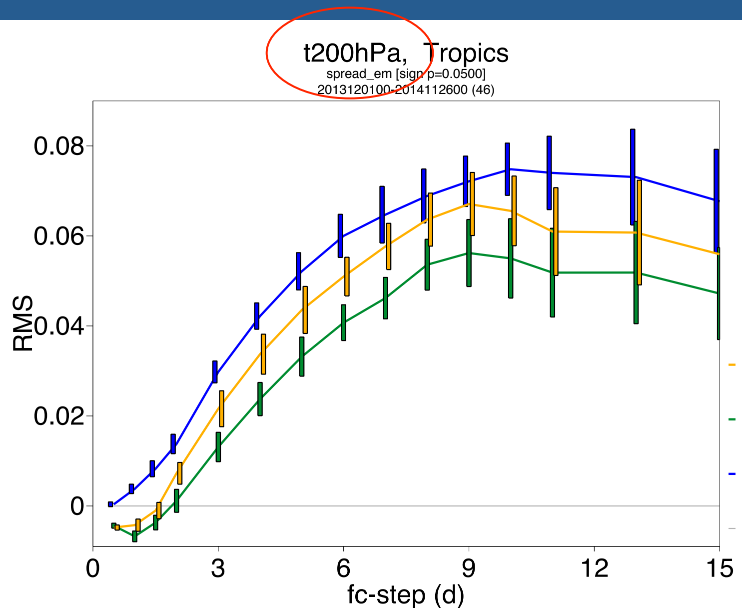
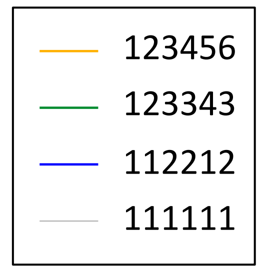
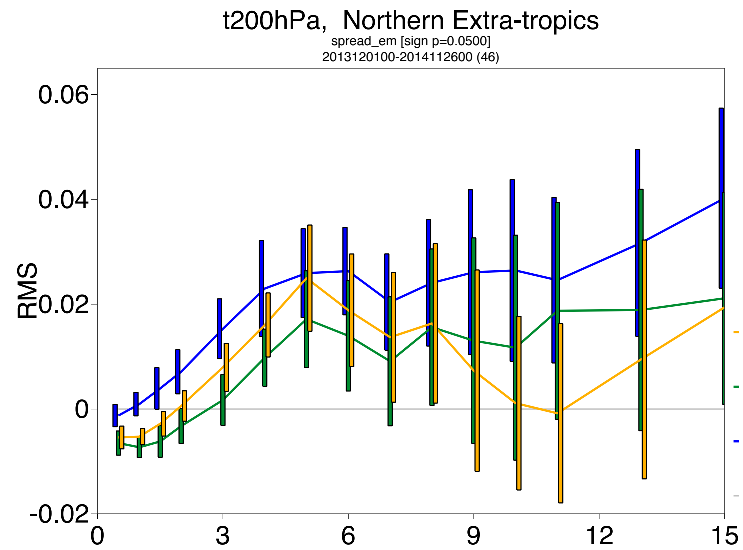
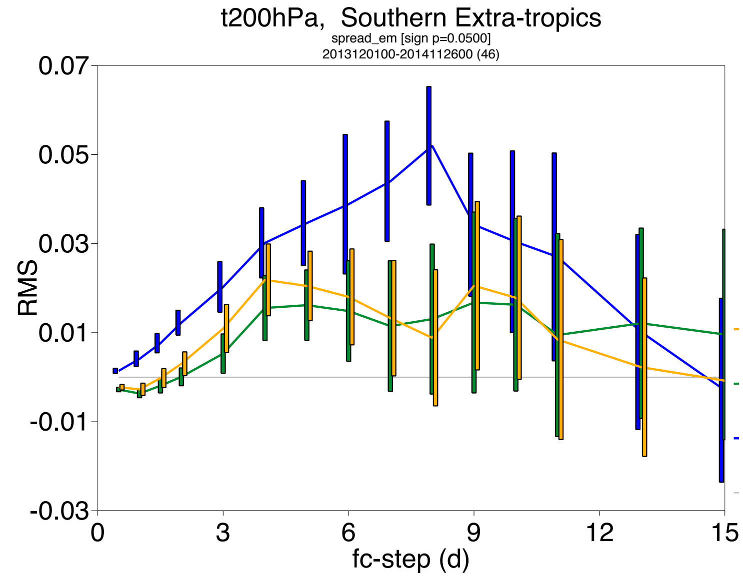


RMSS







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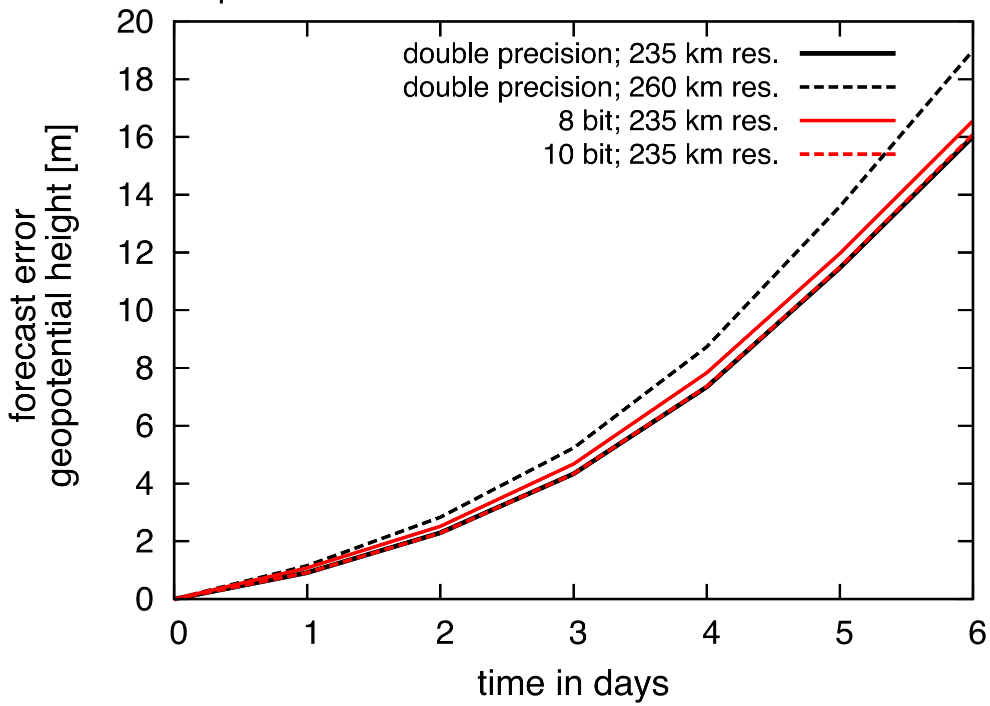
Inexact hardware in numerical weather and climate models

P. Dueben

- Double precision as a default is overcautious – whether models are stochastic or deterministic
- Reducing precision for the small scales can lead to significant energy savings

Experiments with IGCM



Model Run	Normalized Energy Demand	Normalized operations per virtual Joule
235 km, 64 bits	1	1.00
260 km, 64 bits	0.82	1.01
315 km, 64 bits	0.47	1.02
235 km, 24 bits	0.35	2.83
235 km, 22 bits	0.32	3.09
235 km, 20 bits	0.29	3.41

22 bits = 1 sign, 11 exponent, 10 significand
20 bits = 1 sign, 11 exponent, 8 significand