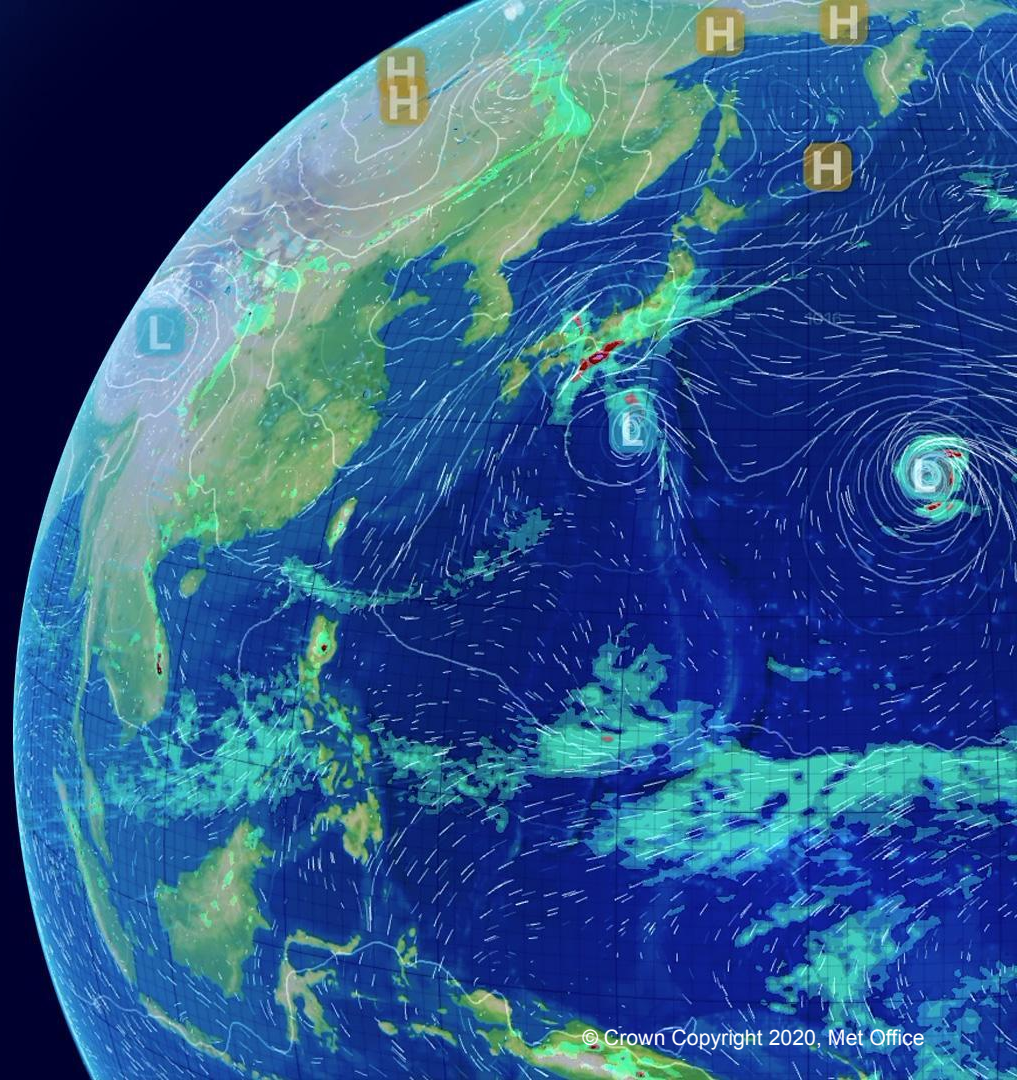


# The Long View of Model Development

Martin Willett

Seamless Global Modelling Workshop,  
3<sup>rd</sup> June 2025



- Background and Motivation
- AMIP
- NWP
- Summary and conclusions
- Questions?

# Background and Motivation

- At the Met Office we have been developing a seamless model since 2010.
- First configuration, GA3, was frozen in 2010/11.
- The most recent configuration, GAL9/GC5, was released in 2023.
- Aims of development process:
  - Include new science to improve representation of physical processes
  - Not make anything significant worse in climate and NWP
  - Deliver a configuration that is as good or better overall than the previous configuration at all timescales
- **What progress has been made by 10+ years of model development?**
- **Has the seamless model development strategy been successful?**

# GA configurations

Config	Date	NWP	Climate	Notable developments*
GA4GL4	2012	-	-	<ul style="list-style-type: none"> <li>• Rain particle size distribution</li> <li>• Revised entrainment</li> </ul>
GA6GL6	2013	GA6.1GL6.1 (2013)	-	<ul style="list-style-type: none"> <li>• ENDGame dynamics</li> <li>• Sea ice roughness</li> <li>• Increase entrainment</li> </ul>
GA7GL7	2016	GA7.2GL8.1 (2019)	CMIP6 UKESM1[.1]	<ul style="list-style-type: none"> <li>• 6a Convection</li> <li>• Multilayer snow</li> <li>• UKCA glomap mode</li> </ul>
GA8GL9	2020/21	GC4 (2022)	-	<ul style="list-style-type: none"> <li>• Prognostic based entrainment</li> <li>• Time smoothed conv increments</li> <li>• Drag package</li> <li>• Multigrid solver</li> </ul>
GAL9	2022/23	GC5.1 (end 2025)	CMIP7 UKESM2	<ul style="list-style-type: none"> <li>• No deep convection</li> <li>• Surface tile albedo improvements</li> <li>• Bimodal cloud</li> <li>• Fountain buster</li> </ul>

\* There are many more changes at each configuration. For full details of all changes see papers linked from [GMD – Special issue](#)

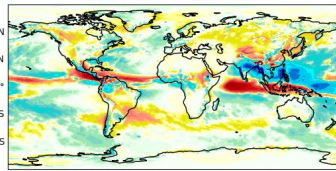
# AMIP

- The format of AMIP tests have not changed over many years; this allows comparisons between tests run many years apart.
- Here we compare GAL9 (2022) with GA8GL8 (2020), GA7GL7 (2016), GA6GL6 (2013) and GA4 (2012) all at N216 (60 km)
- Results shown are from N216 (60 km) unless stated otherwise

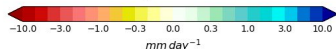
# JJA precipitation vs GPCPv2

## GAL9 - GA4

b) Precipitation for jja  
U-CO766: GAL9 minus XHCEA: GA4

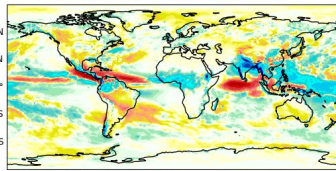


Area-weighted rms diff = 1.83

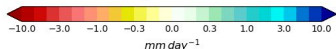


## GAL9 - GA6

b) Precipitation for jja  
U-CO766: GAL9 minus U-AB069: GA6GL6

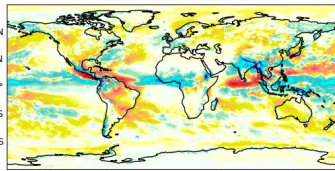


Area-weighted rms diff = 1.41



## GAL9 - GA7

b) Precipitation for jja  
U-CO766: GAL9 minus U-B5279: GA7GL7

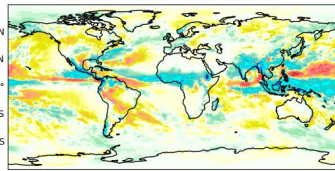


Area-weighted rms diff = 1.17

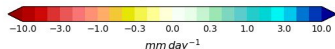


## GAL9 - GA8

b) Precipitation for jja  
U-CO766: GA9.0 minus U-CO760: GA8.0

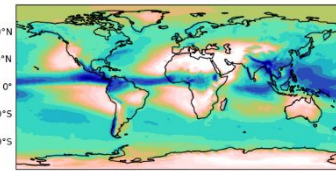


Area-weighted rms diff = 0.842

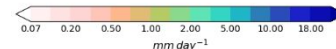


## GAL9

a) Precipitation for jja  
U-CO766: GA9.0

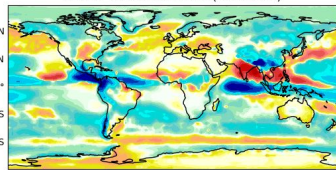


Area-weighted rms diff = 0.07

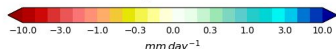


## GA4 - GPCP2

c) Precipitation for jja  
XHCEA: GA4 minus GPCP2 (1979-1998)



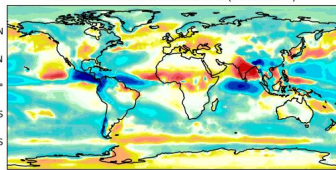
Area-weighted rms diff = 2.23



**RMS=2.23**

## GA6 - GPCP2

c) Precipitation for jja  
U-AB069: GA6GL6 minus GPCP2 (1979-1998)



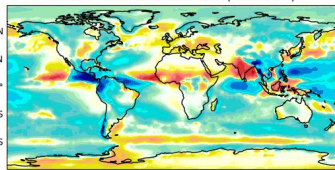
Area-weighted rms diff = 1.87



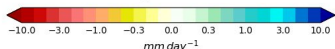
**RMS=1.87**

## GA7 - GPCP2

c) Precipitation for jja  
U-B5279: GA7GL7 minus GPCP2 (1979-1998)



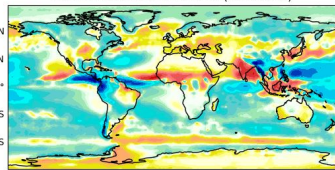
Area-weighted rms diff = 1.75



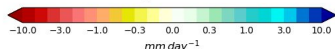
**RMS=1.75**

## GA8 - GPCP2

c) Precipitation for jja  
U-CO760: GA8.0 minus GPCP2 (1979-1998)



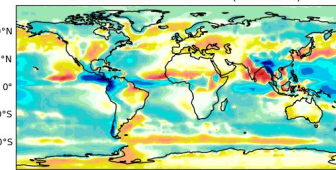
Area-weighted rms diff = 1.65



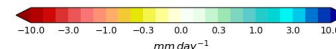
**RMS=1.65**

## GAL9 - GPCP2

d) Precipitation for jja  
U-CO766: GA9.0 minus GPCP2 (1979-1998)



Area-weighted rms diff = 1.58



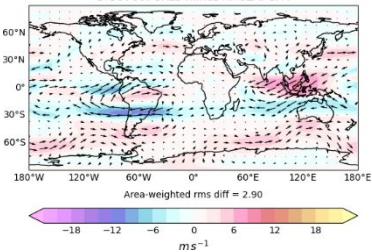
**RMS=1.58**

- Continuous improvement in JJA precipitation (and other seasons)
- Indian monsoon in GAL9 far, far better than in GA4
- Some of the long term “biases” are actually in the obs. Model will look better if we update obs.

# JJA 200hPa wind vs ERAI

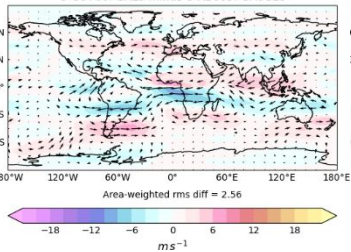
## GAL9 - GA4

b) U wind at 200 mb for jja  
U-CO766: GAL9 minus XHCEA: GA4



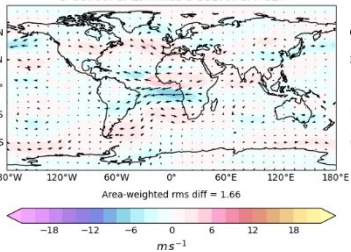
## GAL9 - GA6

b) U wind at 200 mb for jja  
U-CO766: GAL9 minus U-AB069: GA6GL6



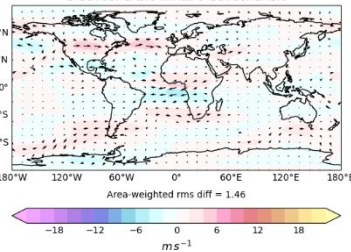
## GAL9 - GA7

b) U wind at 200 mb for jja  
U-CO766: GAL9 minus U-BS279: GA7GL7



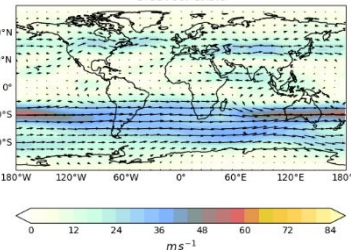
## GAL9 - GA8

b) U wind at 200 mb for jja  
U-CO766: GA9.0 minus U-CO766: GA8.0



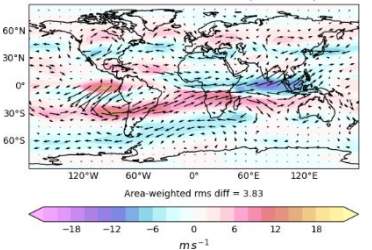
## GAL9

a) U wind at 200 mb for jja  
U-CO766: GA9.0



## GA4 - ERAI

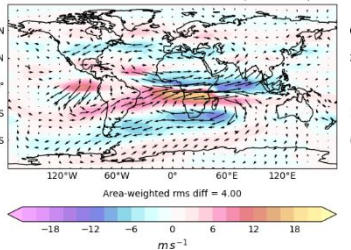
c) U wind at 200 mb for jja  
XHCEA: GA4 minus ERA-Interim (1989-2008)



RMS=3.83

## GA6 - ERAI

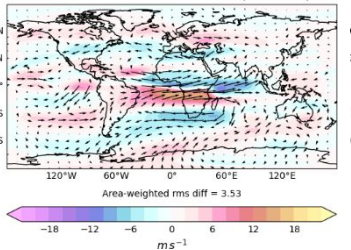
c) U wind at 200 mb for jja  
U-AB069: GA6GL6 minus ERA-Interim (1989-2008)



RMS=4.00

## GA7 - ERAI

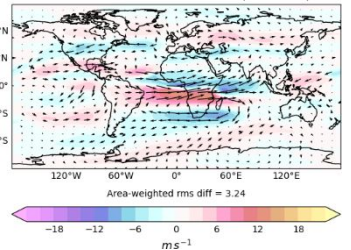
c) U wind at 200 mb for jja  
U-BS279: GA7GL7 minus ERA-Interim (1989-2008)



RMS=3.53

## GA8 - ERAI

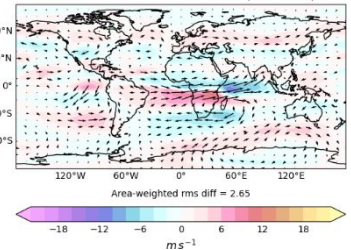
c) U wind at 200 mb for jja  
U-CO766: GA8.0 minus ERA-Interim (1989-2008)



RMS=3.24

## GAL9 - ERAI

d) U wind at 200 mb for jja  
U-CO766: GA9.0 minus ERA-Interim (1989-2008)



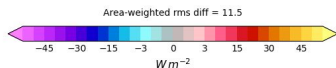
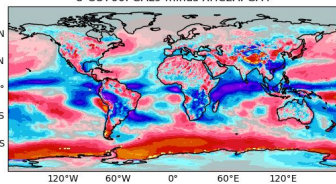
RMS=2.65

- Near continuous improvement in 200hPa winds
- GAL9 far better than GA4

# DJF Outgoing SW vs CERES-EBAF4.1

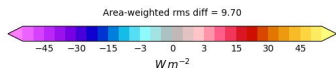
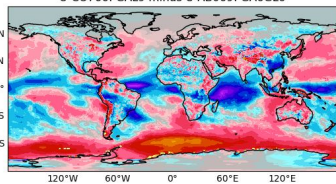
## GAL9 - GA4

b) Outgoing shortwave (TOA) for djf  
U-CO766: GAL9 minus XHCEA: GA4



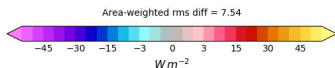
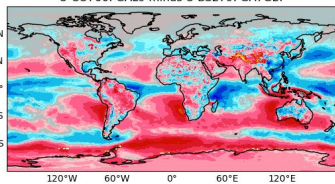
## GAL9 - GA6

b) Outgoing shortwave (TOA) for djf  
U-CO766: GAL9 minus U-AB069: GA6GL6



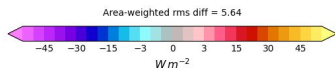
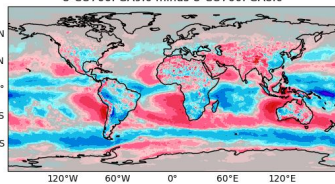
## GAL9 - GA7

b) Outgoing shortwave (TOA) for djf  
U-CO766: GAL9 minus U-BS279: GA7GL7



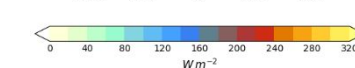
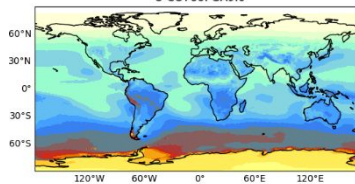
## GAL9 - GA8

b) Outgoing shortwave (TOA) for djf  
U-CO766: GA9.0 minus U-CO760: GA8.0



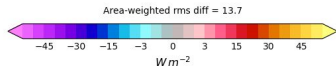
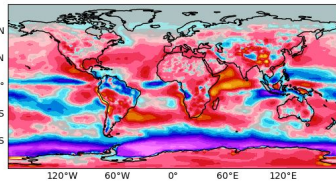
## GAL9

a) Outgoing shortwave (TOA) for djf  
U-CO766: GA9.0



## GA4 - CE4

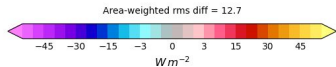
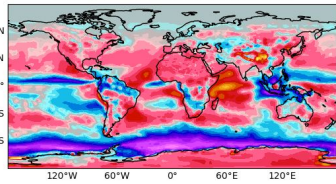
c) Outgoing shortwave (TOA) for djf  
XHCEA: GA4 minus CERES-EBAF Ed4.1



RMS=13.7

## GA6 - CE4

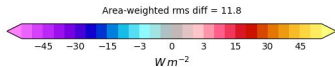
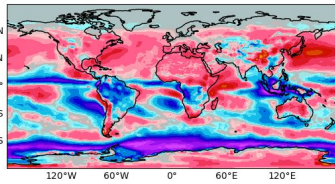
c) Outgoing shortwave (TOA) for djf  
U-AB069: GA6GL6 minus CERES-EBAF Ed4.1



RMS=12.7

## GA7 - CE4

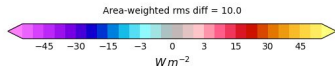
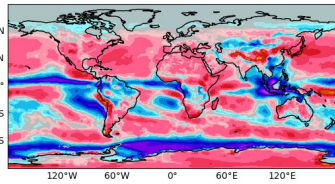
c) Outgoing shortwave (TOA) for djf  
U-BS279: GA7GL7 minus CERES-EBAF Ed4.1



RMS=11.8

## GA8 - CE4

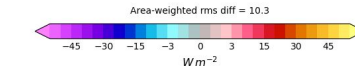
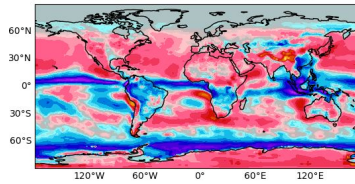
c) Outgoing shortwave (TOA) for djf  
U-CO760: GA8.0 minus CERES-EBAF Ed4.1



RMS=10.0

## GAL9 - CE4

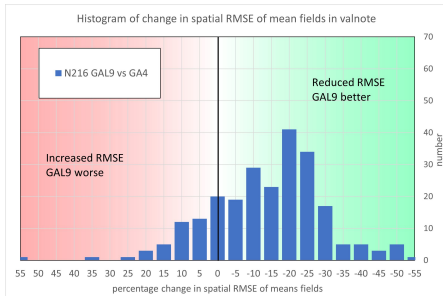
d) Outgoing shortwave (TOA) for djf  
U-CO766: GA9.0 minus CERES-EBAF Ed4.1



RMS=10.3

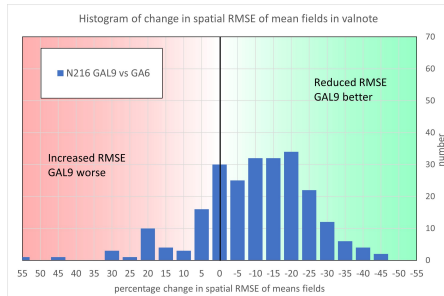
- Near continuous improvement in DJF OSW
- GAL9 far better than GA4 especially in southern ocean

## GAL9 vs GA4



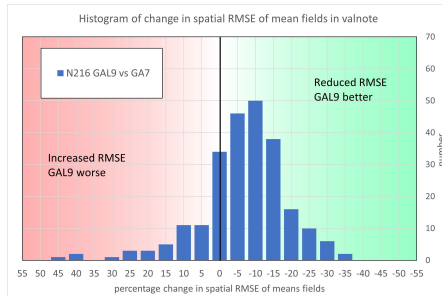
192 of 239 fields improved  
Median  $\Delta$ RMSE = -16.7%

## GAL9 vs GA6



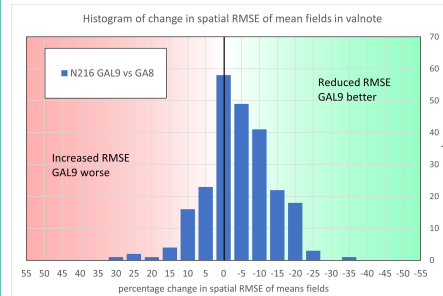
186 of 239 fields improved  
Median  $\Delta$ RMSE = -11.3%  
(N96: 182, -14.0%)

## GAL9 vs GA7



193 of 239 fields improved  
Median  $\Delta$ RMSE = -7.8%  
(N96: 196, -10.9%)

## GAL9 vs GA8



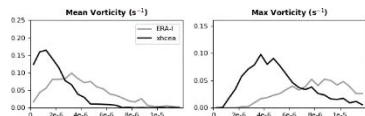
167 of 239 fields improved  
Median  $\Delta$ RMSE = -3.8%  
(N96: 183, -5.8%)

- Histograms of percentage change in spatial RMSE of all mean fields\* in valnote summary.
- Some fields will always be improved and some degraded. Overall, there is continuous improvement with each consecutive configuration with that rate of improvement greater at N96 than at N216.
- The improvement over two science upgrades at N216 is comparable to (or at N96 larger than) the improvement seen between N96 and N216. cf. N216 vs N96 median  $\Delta$ RMSE=-6.8% (GAL9), -7.3% (GA8).
- In these metrics N96 GAL9 would be better than N216 GA7!

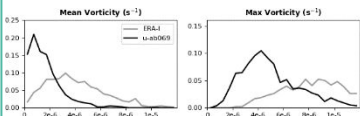
\* Fields include TOA and surface radiative fluxes, winds, temperatures, GPH, PMSL, humidity, precipitation, etc and are compared to obs and reanalyses.

# African Easterly Waves

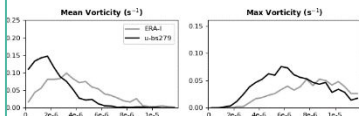
## GA4



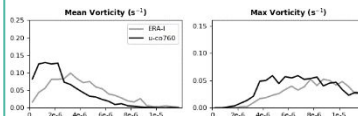
## GA6



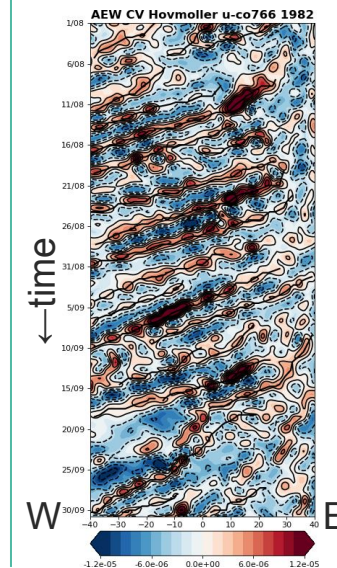
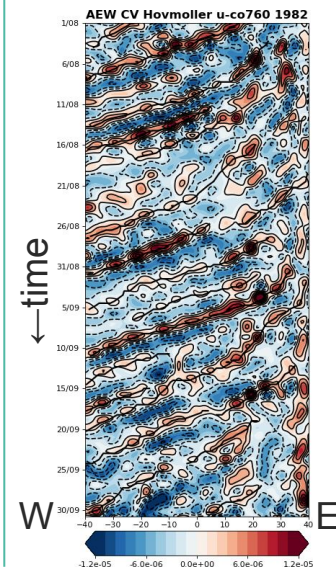
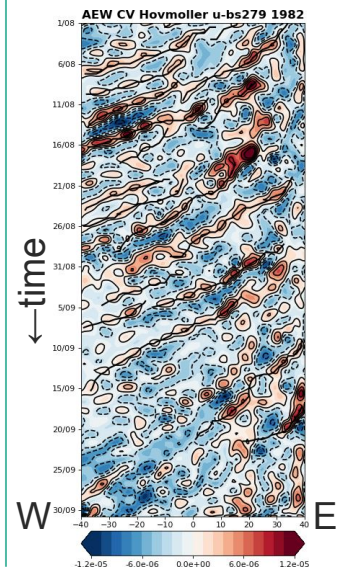
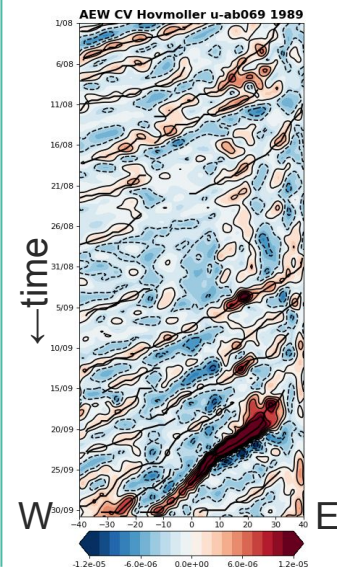
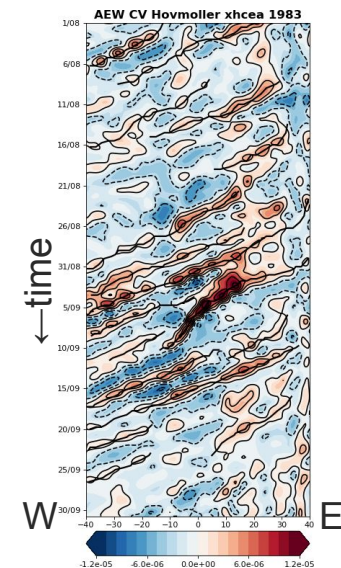
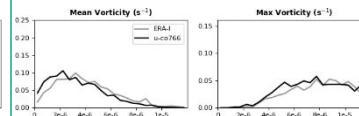
## GA7



## GA8



## GAL9



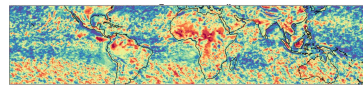
- Mean/max vorticity and number increases with each GA version
- GAL9 has very good mean/max vorticity when compared to ERAI

# Diurnal cycle vs GPM (JJA)

## GA4

Med(land)=5.6 hrs

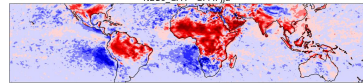
Correlation with GPM



-1.0 -0.8 -0.4 0.0 0.4 0.8 +1.0

amp err

Error in normalised diurnal cycle amplitude  
N216\_GA4 - GPM: jja

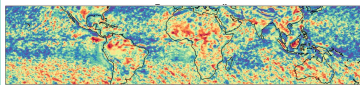


-1.2 -0.8 -0.4 0.0 0.4 0.8 1.2

## GA6

Med(land)=5.1 hrs

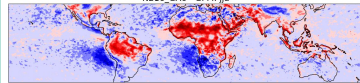
Correlation with GPM



-1.0 -0.8 -0.4 0.0 0.4 0.8 +1.0

amp err

Error in normalised diurnal cycle amplitude  
N216\_GA6 - GPM: jja

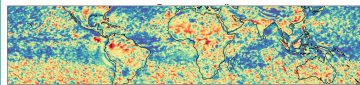


-1.2 -0.8 -0.4 0.0 0.4 0.8 1.2

## GA7

Med(land)=4.9 hrs

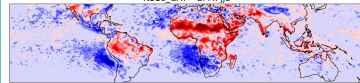
Correlation with GPM



-1.0 -0.8 -0.4 0.0 0.4 0.8 +1.0

amp err

Error in normalised diurnal cycle amplitude  
N216\_GA7 - GPM: jja

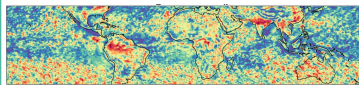


-1.2 -0.8 -0.4 0.0 0.4 0.8 1.2

## GA8

Med(land)=4.6 hrs

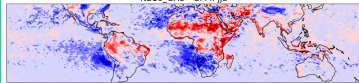
Correlation with GPM



-1.0 -0.8 -0.4 0.0 0.4 0.8 +1.0

amp err

Error in normalised diurnal cycle amplitude  
N216\_GA8 - GPM: jja

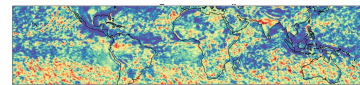


-1.2 -0.8 -0.4 0.0 0.4 0.8 1.2

## GAL9

Med(land)=3.2 hrs

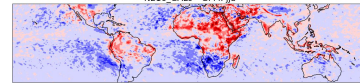
Correlation with GPM



-1.0 -0.8 -0.4 0.0 0.4 0.8 +1.0

amp err

Error in normalised diurnal cycle amplitude  
N216\_GAL9 - GPM: jja



-1.2 -0.8 -0.4 0.0 0.4 0.8 1.2

- Modest improvement in diurnal cycle correlation (and median diurnal harmonic error) between GA4 and GA8. Big improvement between GA8 and GAL9
- Consistent improvement in amplitude. Excessively large amplitude seen in GA4 mostly gone by GAL9
- JJA shown but improvement in other seasons is very similar
- Improvements mostly due to prognostic based entrainment (from GA8) and switching off deep convection (GAL9)

# NWP

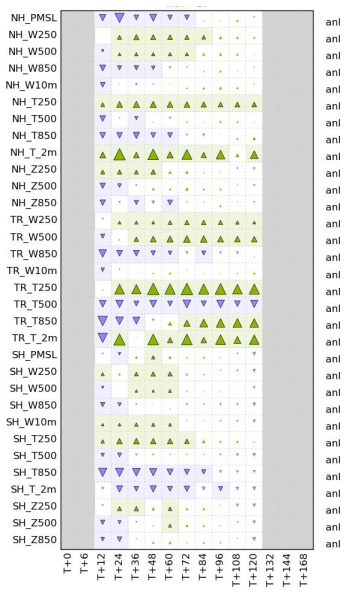
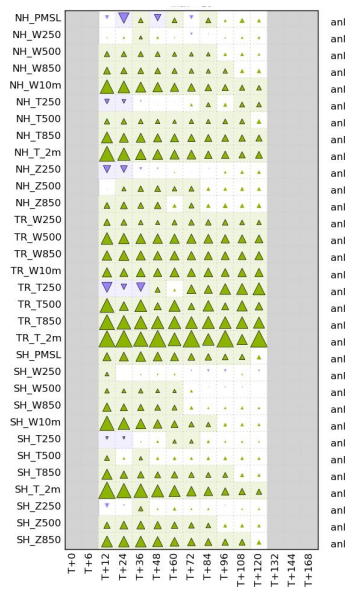
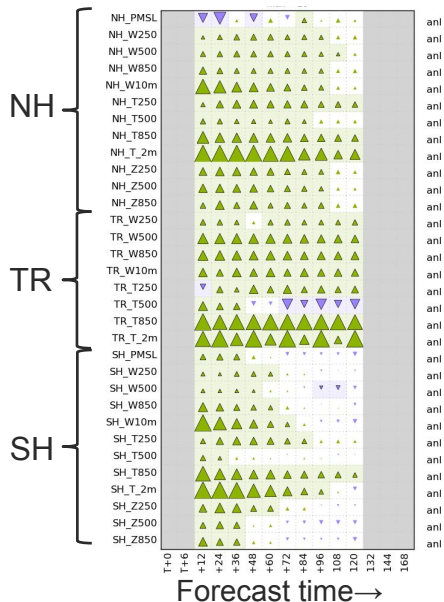
- Case studies using the latest UM version and latest case study setup
- Testing GA6GL6, GA7GL7, GA8GL9 and GAL9.
  - Not testing branch configurations
  - Unable to test GA4 because New Dynamics code unavailable
- N320 resolution – 40km in mid-latitudes
- 59 cases from 2023 spread throughout the year
- Initialised from and verified against operational GC4 (GA8) analyses.
  - This will favour GA8 in verification scores
- Case studies and therefore no interaction with DA
  - Signal possibly stronger in DA trials: better fc → better anl → better fc

# RMSE against analysis: 2023

GAL9 vs GA6:  
+4.3% (+3.0%)\*

GAL9 vs GA7:  
+3.7% (+2.8%)\*

GAL9 vs GA8:  
+0.4% (+0.2%)\*



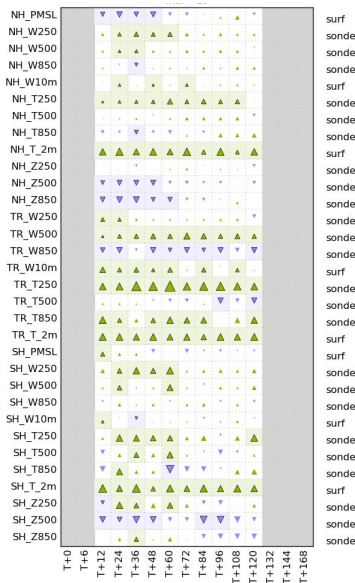
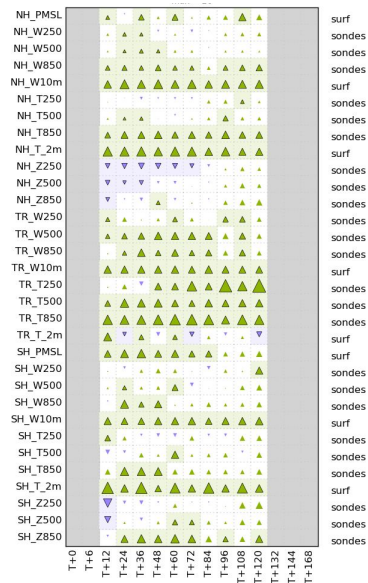
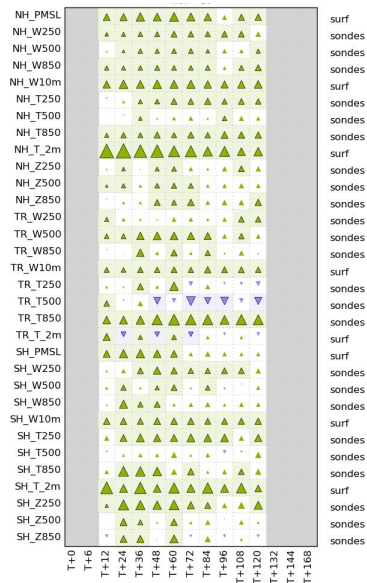
- GAL9 is substantially better than GA6 or GA7, but only a little better than GA8 (NB GA8 Anl).
- For context, N1280 (10 km) gives ~4% improvement over N320 (40 km) in DA trials.

# RMSE against obs: 2023

GAL9 vs GA6:  
+2.5% (+2.2%)\*

GAL9 vs GA7:  
+2.2% (+2.0%)\*

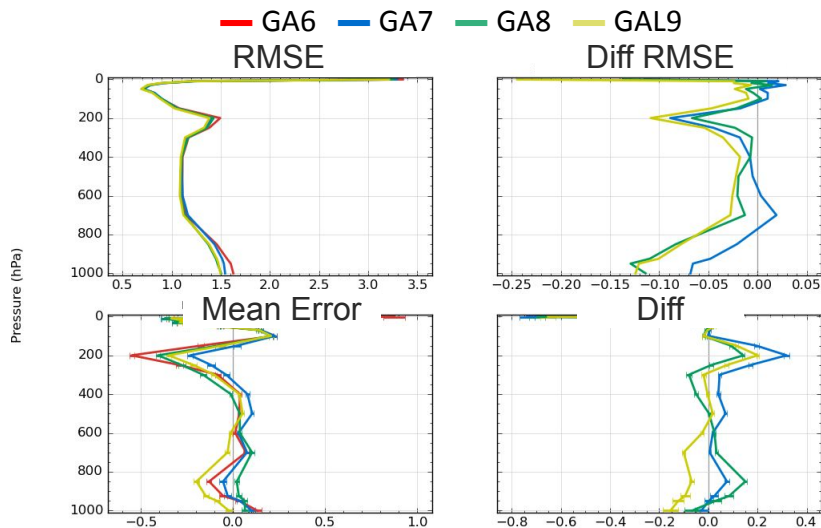
GAL9 vs GA8:  
+0.6% (+0.4%)\*



- GAL9 is substantially better than GA6 or GA7, but only a little better than GA8 (NB GA8 Anl).
- For context, N1280 (10km) gives ~2% improvement over N320 (40 km) in DA trials.

## Temperature: T+72

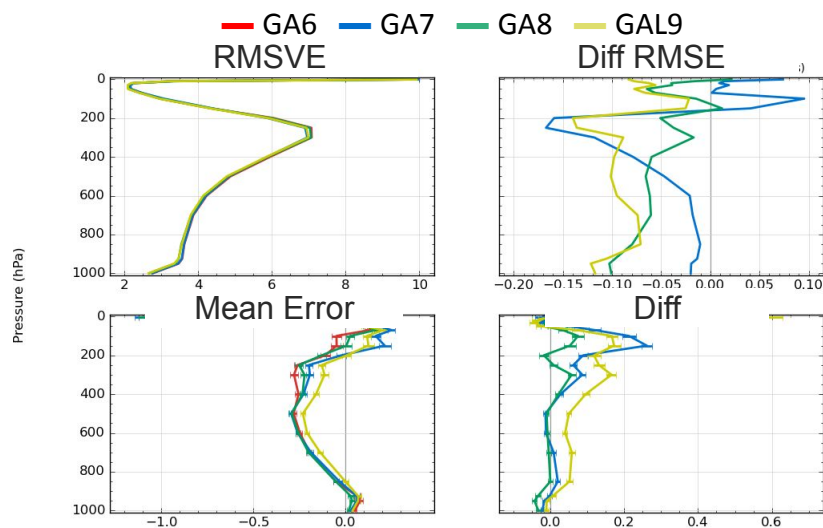
Temperature (K), Northern Hemisphere (CBS area 90N-18.75N), T+72.  
Equalized and Meaned between 20230101 00:00 and 20231231 12:00, Own\_Analysis, 2.5deg grid



± 1 standard error bars calculated assuming independent observations

## Winds: T+72

Wind (m/s), Northern Hemisphere (CBS area 90N-18.75N), T+72.  
Equalized and Meaned between 20230101 00:00 and 20231231 12:00, Own\_Analysis, 2.5deg grid

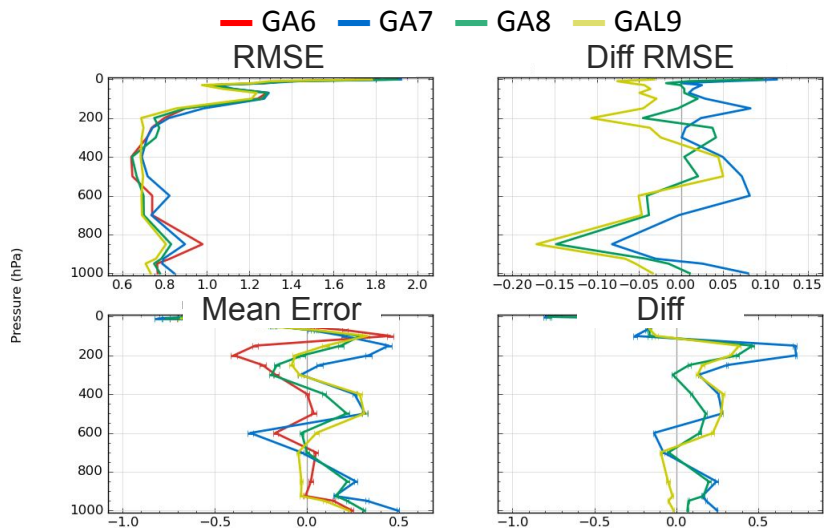


± 1 standard error bars calculated assuming independent observations

- Improved temperature RMSE. GAL9 has a known small (0.2 K) cold bias at 850hPa.
- Reduced wind RMSVEs with reduced slow bias (bias improves further at higher resolutions).

## Temperature: T+72

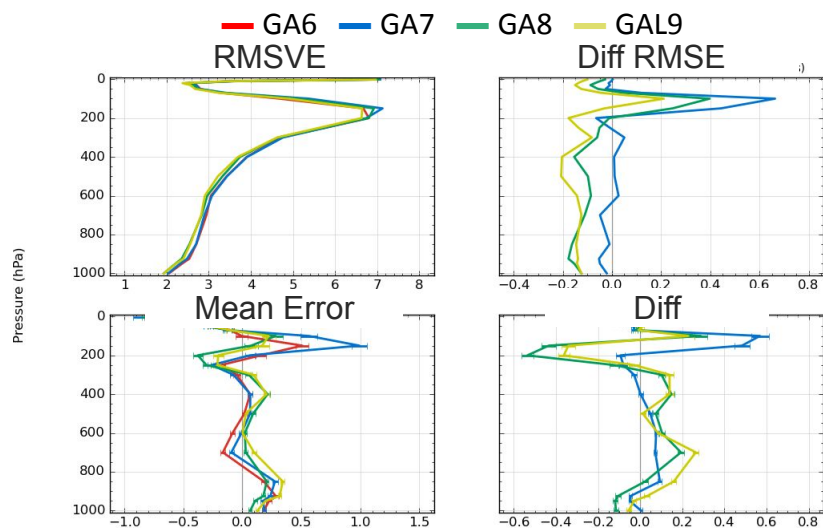
Temperature (K), Tropics (CBS area 18.75N-18.75S), T+72,  
Equalized and Meaned between 20230101 00:00 and 20231231 12:00, Own\_Analysis, 2.5deg grid



± 1 standard error bars calculated assuming independent observations

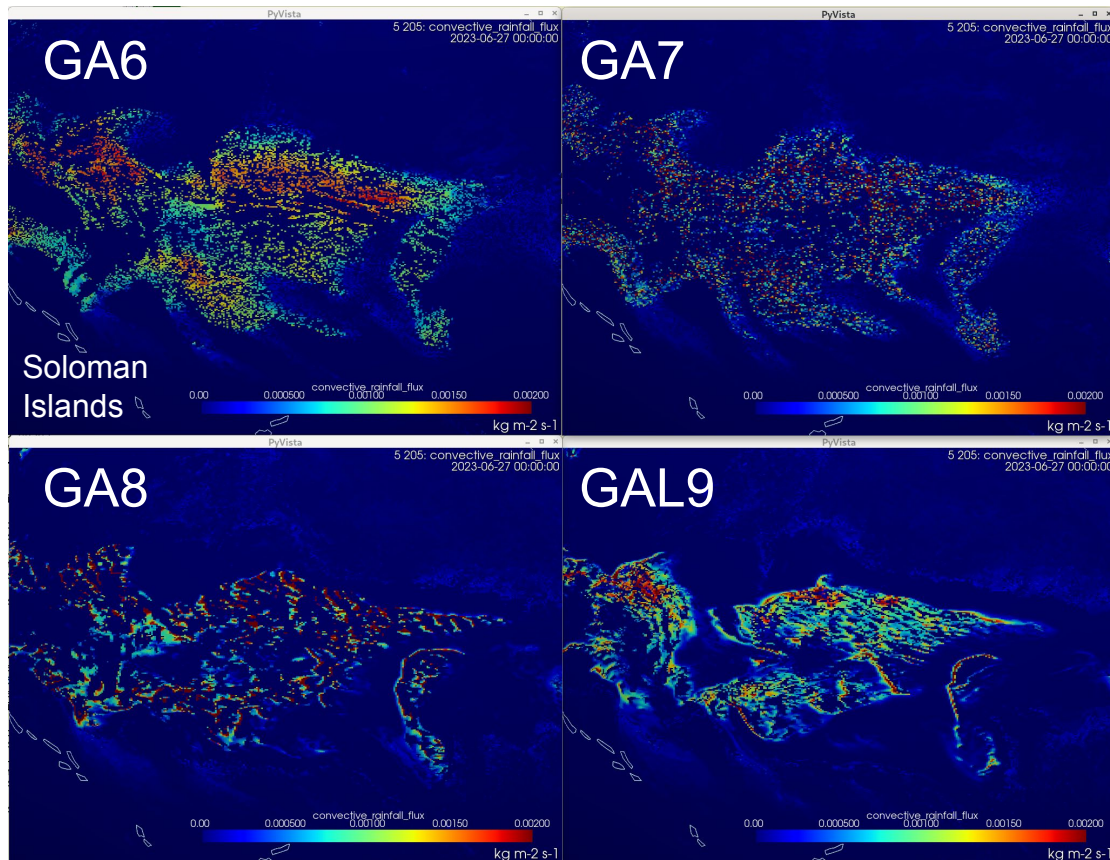
## Winds: T+72

Wind (m/s), Tropics (CBS area 18.75N-18.75S), T+72,  
Equalized and Meaned between 20230101 00:00 and 20231231 12:00, Own\_Analysis, 2.5deg grid



± 1 standard error bars calculated assuming independent observations

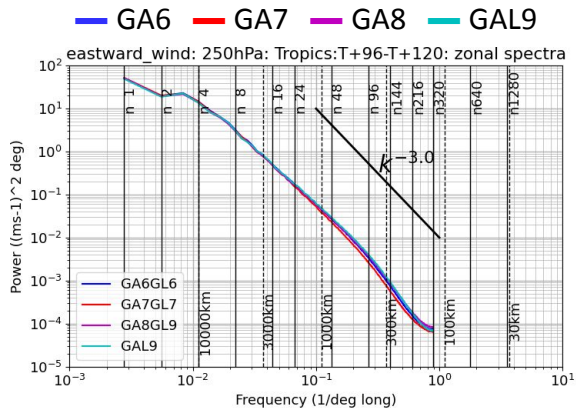
- Improved temperature biases and RMSE apart from around 500hPa
- Reduced wind RMSVEs without slowing winds



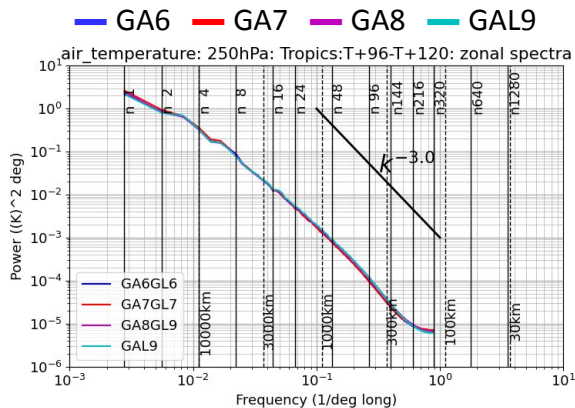
- N1280 Case study
- **Instantaneous** T+48 convective rainfall
- GA6 and GA7 are noisier and more diffuse
- GA8 and GAL9 have more coherent spatial structure
- Changes primarily due to modifications to CAPE closure, prognostic entrainment and switching off deep conv

# Tropics: N320 U & T zonal spectra

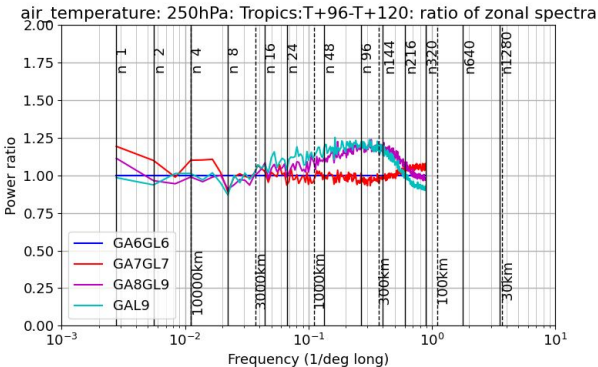
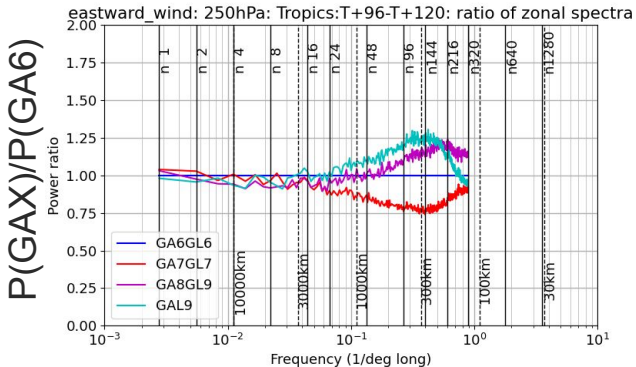
## U-wind spectra: day 5



## T spectra: day 5



- Zonal spectra for N320 cases
- GA8 and GAL9 have more power at mesoscales than GA7 or GA8
- Due to more coherent spatial structure in diabatic forcing from convection
- Improved RMSEs despite increased variability



# Summary and conclusions

# Summary and conclusion

- Some very large improvements between GA4/GA6 and GAL9 in climate and NWP.
- Differences between consecutive versions not always large and sometimes little or no change or even some small degradations in some quantities ...
- ... but a steady improvement over the long-term.
- The GC seamless development process has delivered some substantial improvements at all timescales and can be considered a success.
- Impossible to know for sure if a non-seamless strategy would have been more successful (no control), ...
- ...but, **in my opinion**, it is unlikely to have been as successful.

# Questions