

# Lessons learnt from global high resolution modelling

Annelize van Niekerk, Benoit Vanniere, Inna Polichtchouk, Ivan Bastak Durran, Birgit Sützl, Tobias Becker and many others!

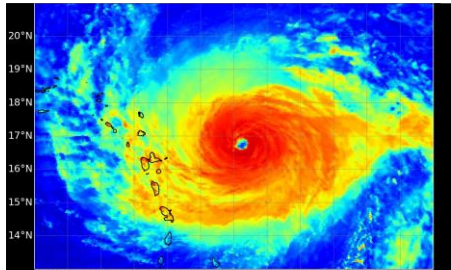
[Annelize.vanNiekerk@ecmwf.int](mailto:Annelize.vanNiekerk@ecmwf.int)

# High resolution modelling activities at ECMWF



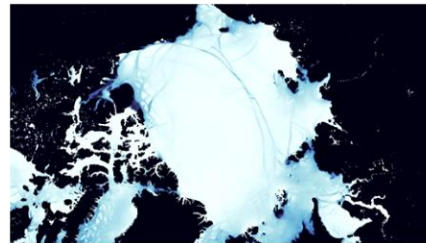
Short forecasts  
pioneering physics for  
global km-scale

Multiple case studies up to  
IFS (2.8km/1.4km) + NEMO12 (9km)



Multidecadal  
coupled simulations

In 2024, 30 years of  
IFS (4.4km) + NEMO025 (25km)  
IFS (4.4km) + FESOM (5km)

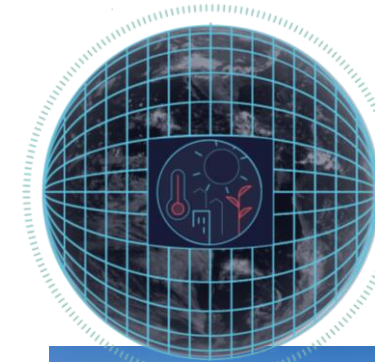


## Destination Earth

Implemented by

Pathway to operational use

Climate  
adaptation DT

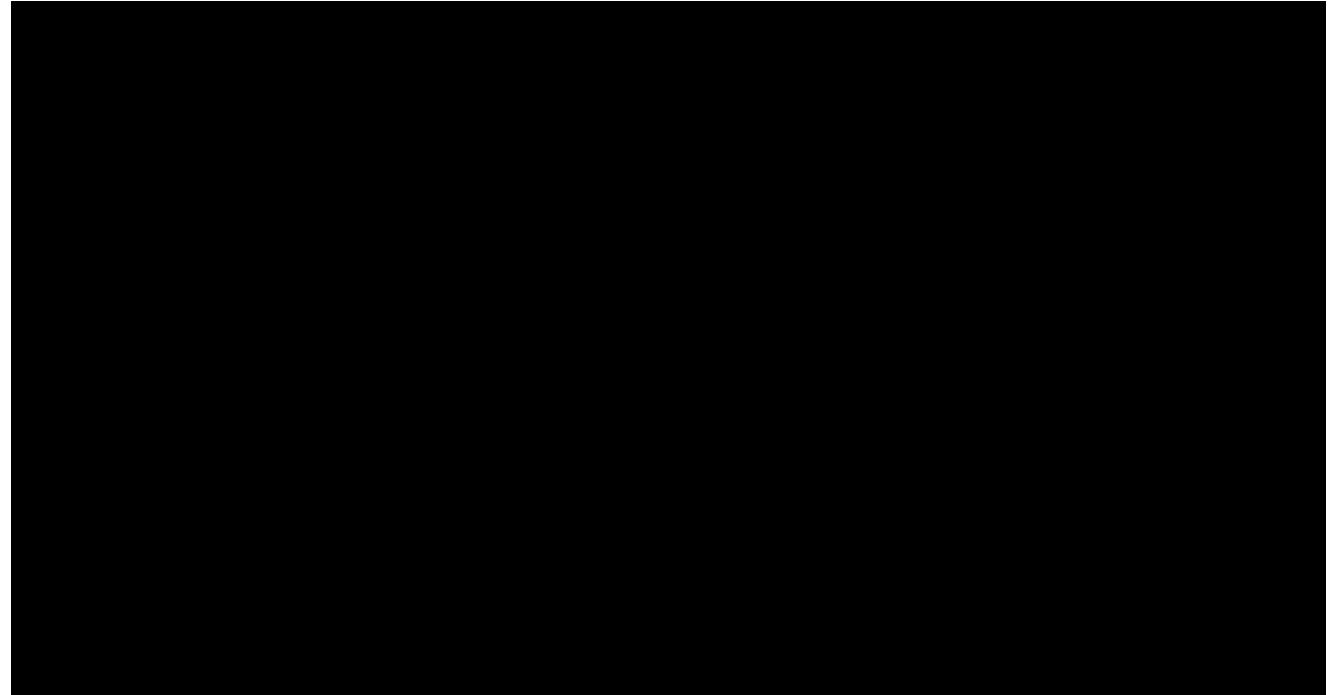


Weather-Induced  
Extremes DT



# What we *hope* is better represented at km-scales

- Orography
- Convection
- Large-scale circulation
- Tropical Cyclones



km-scale 'out of the box'



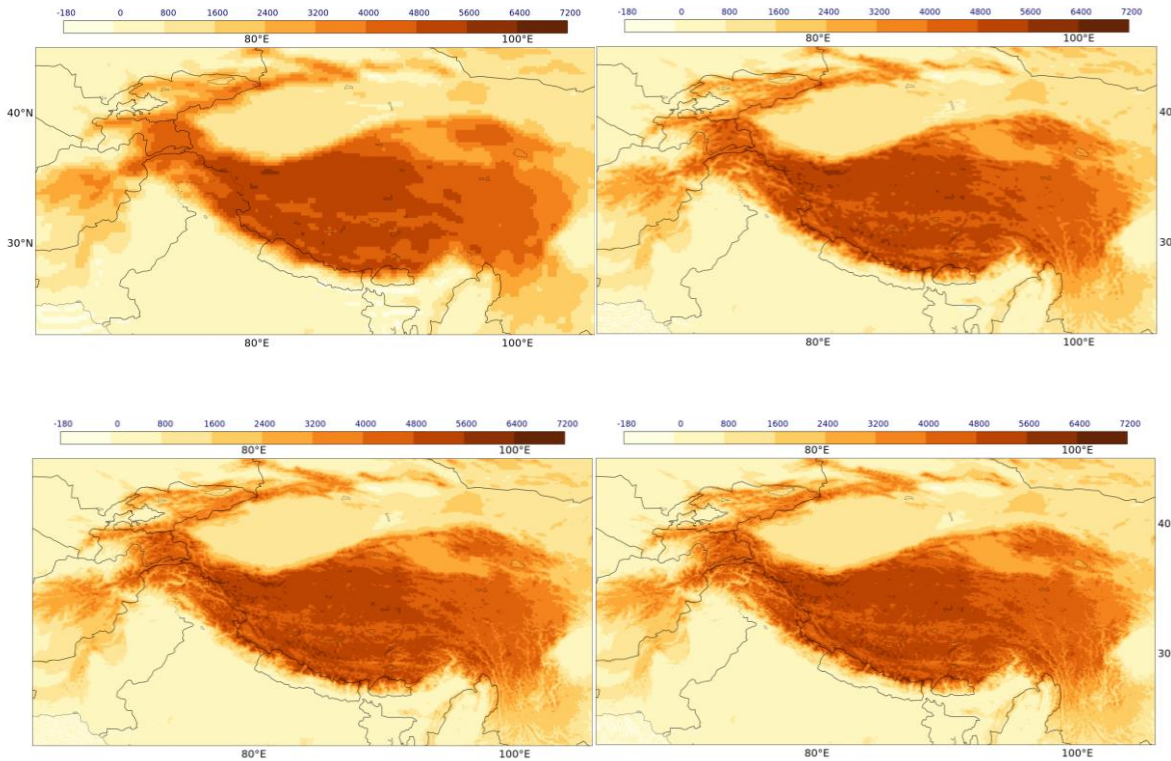


# Orography

# Smaller scales of orography are resolved

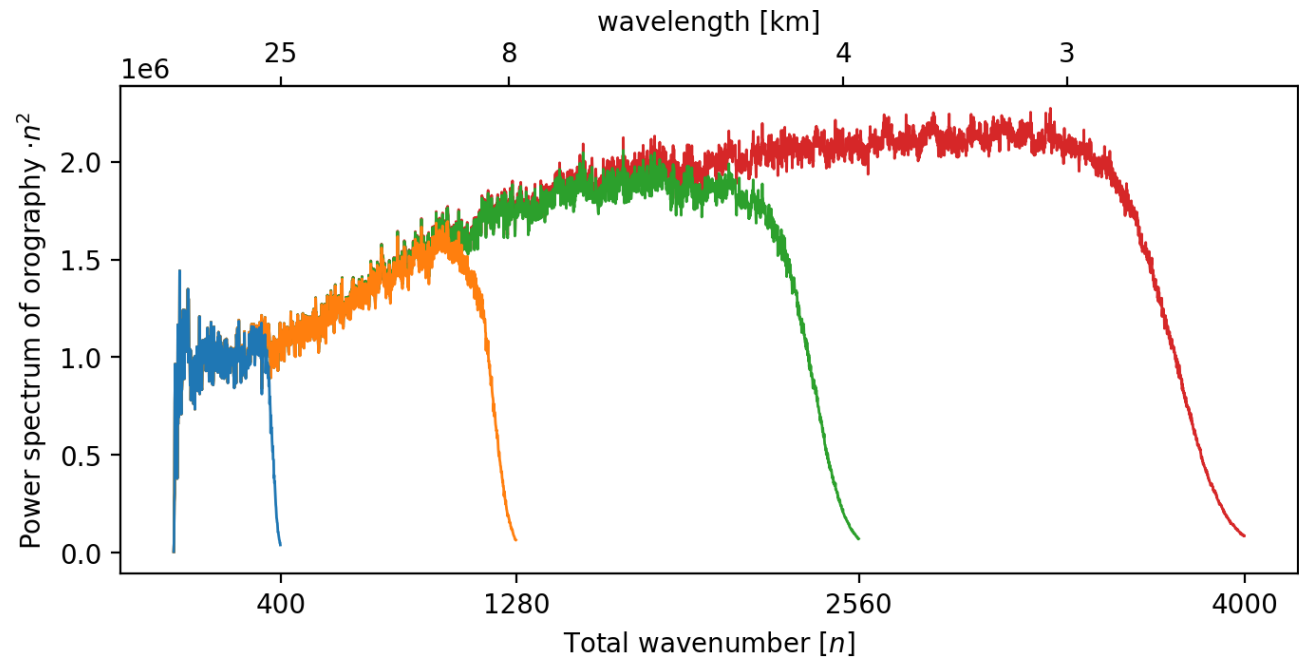
25 km

9 km

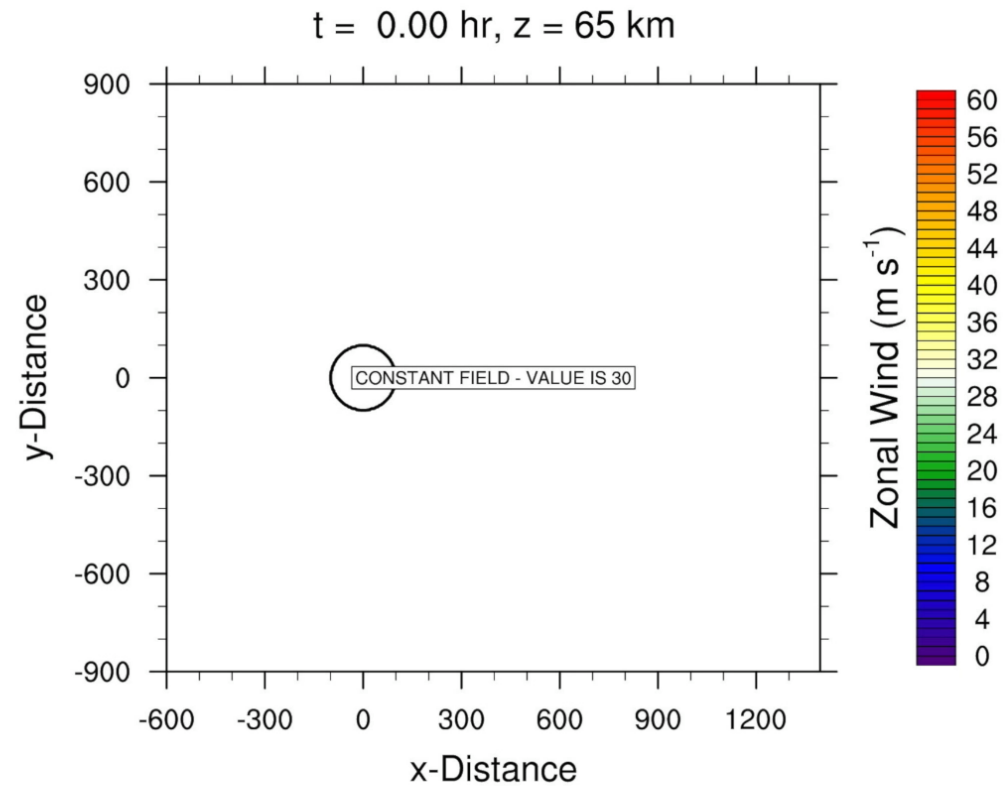
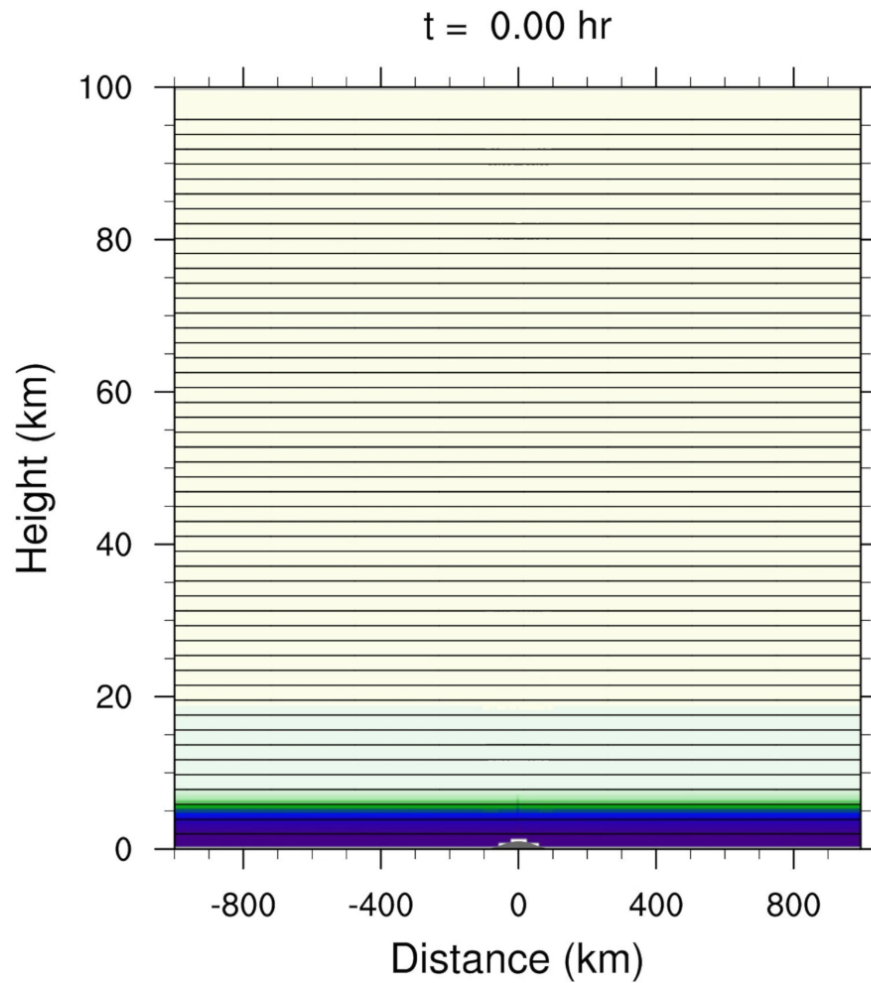


4.4 km

2.8 km

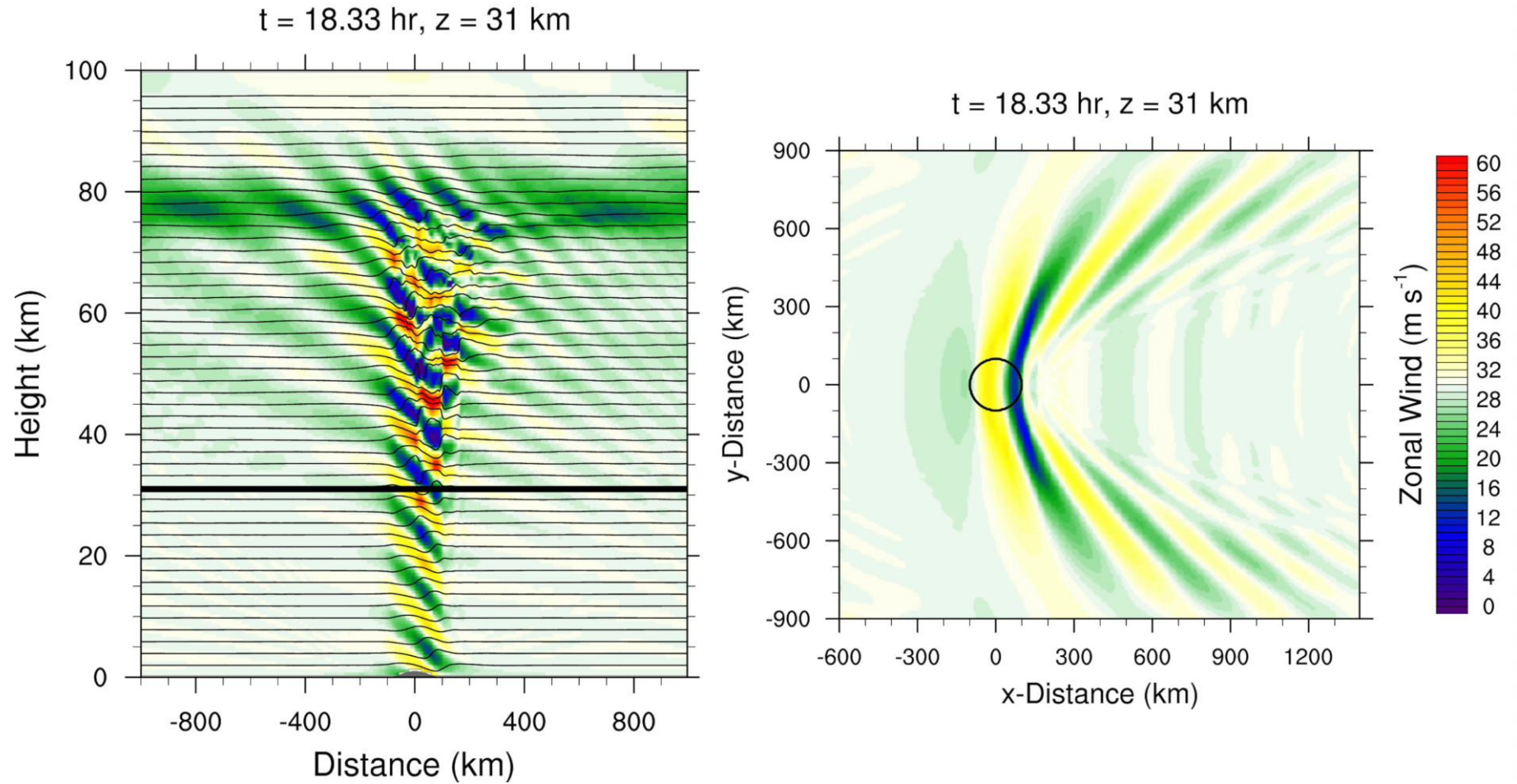


# Gravity waves generated by mountains

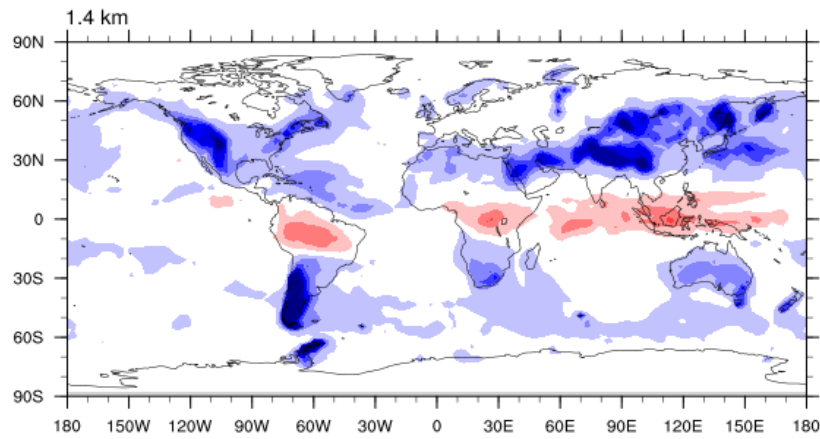


Judwiga Richter, Chris Kruse

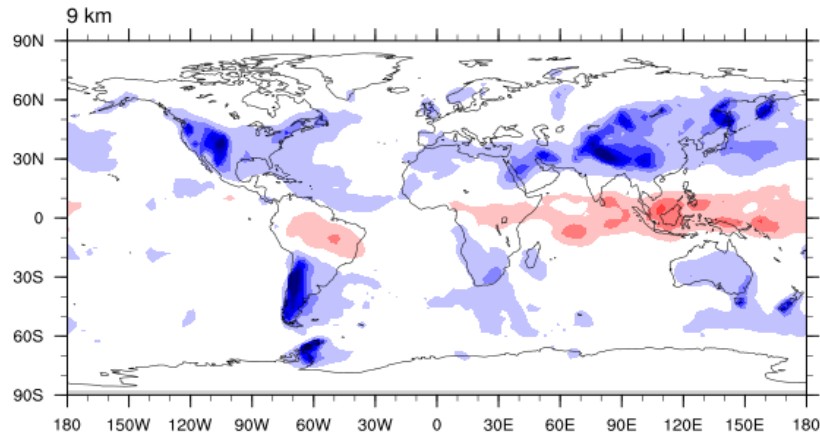
# Gravity waves generated by mountains



1.4 km



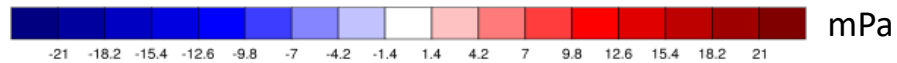
9 km



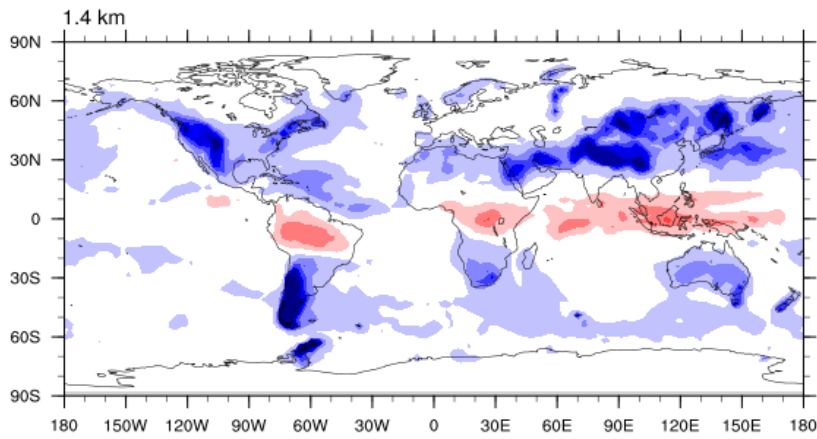
Plot shows gravity wave  
zonal momentum flux

$$\overline{\rho u'w'}$$

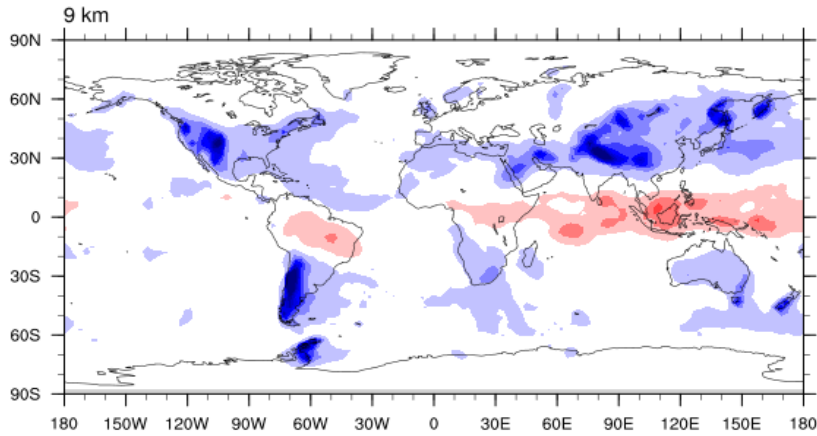
at 80 hPa



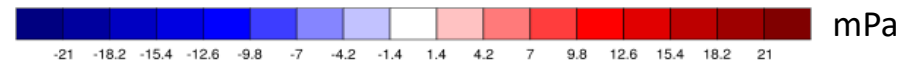
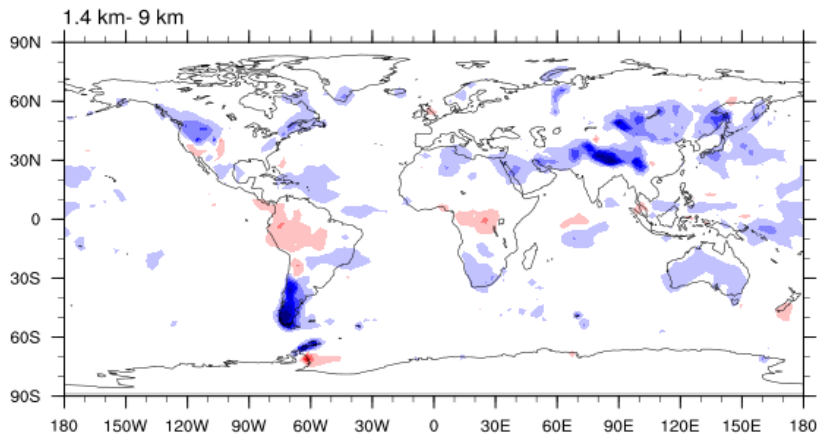
1.4 km



9 km



1.4 km - 9 km



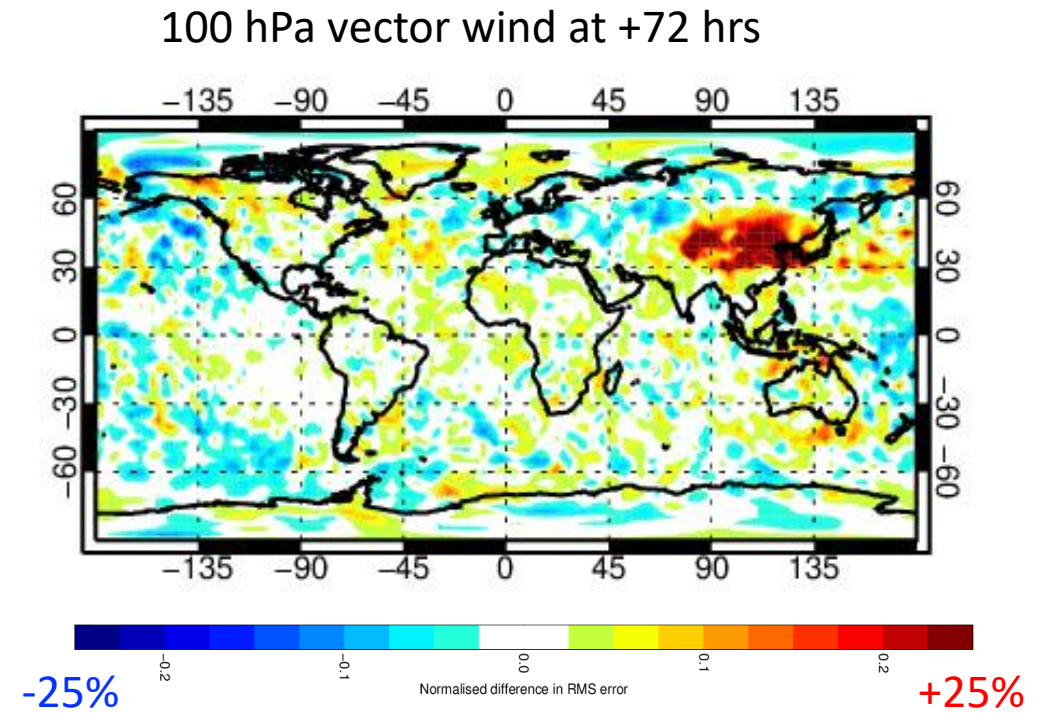
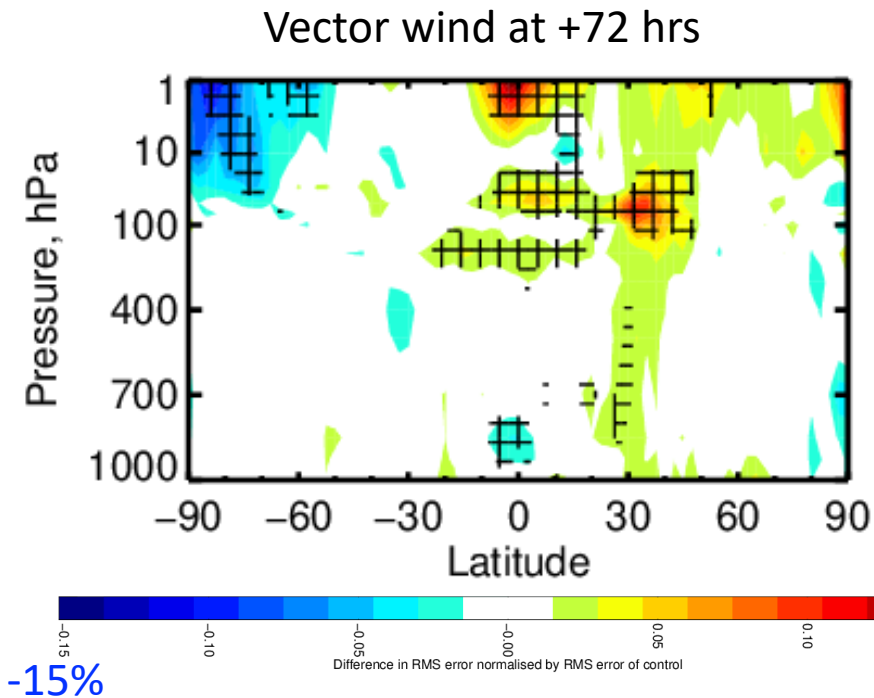
Plot shows gravity wave zonal momentum flux

$$\overline{\rho u'w'}$$
 at 80 hPa

Large increase in momentum fluxes over orography with increased resolution

# Increased orographic gravity wave drag over Himalayas decelerates winds in stratosphere

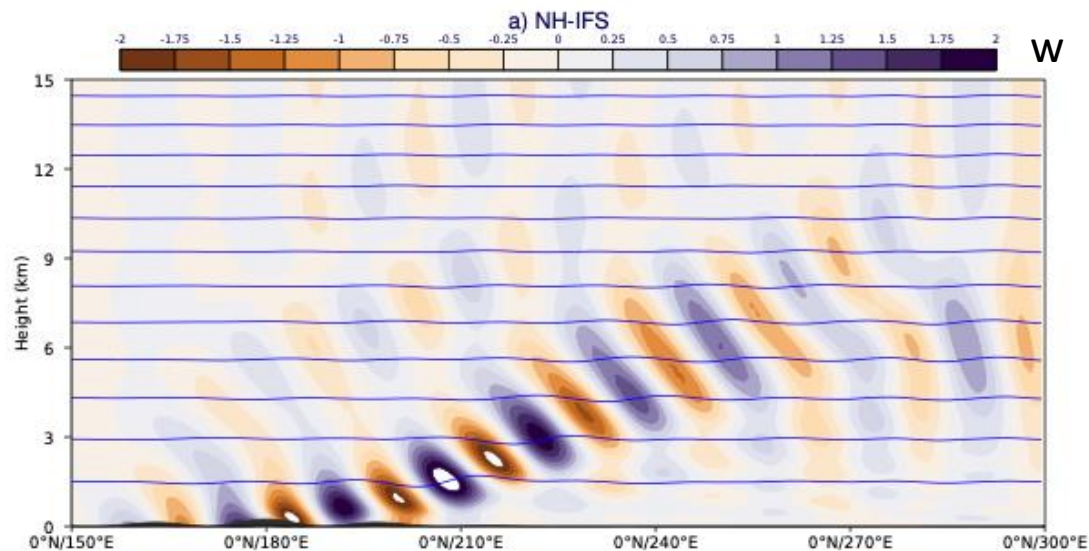
**$\Delta$ RMSE of 4.4 km – 9 km**



# Accounting for non-hydrostatic effects in dynamics

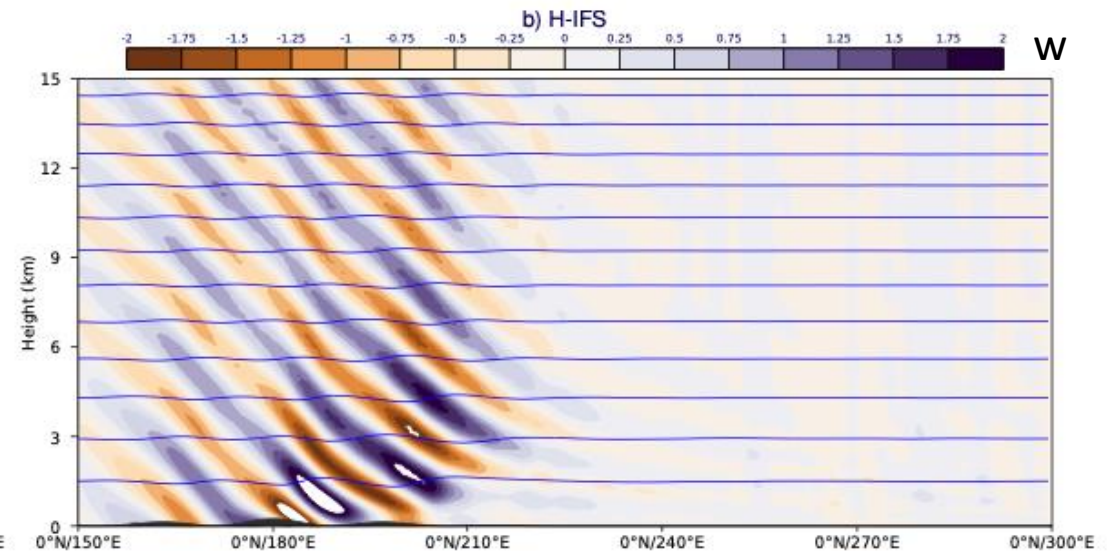
# Idealised simulations over a small mountain

## Non-hydrostatic IFS



Non-hydrostatic waves propagate horizontally (more dispersive)

## Hydrostatic IFS



Hydrostatic waves propagate more vertically

# Impact of non-hydrostatic dynamics on resolved gravity wave drag

Jan 2022

Gravity wave zonal wind drag

$$\frac{1}{\rho} \frac{\partial}{\partial z} \overline{\rho u' w'}$$

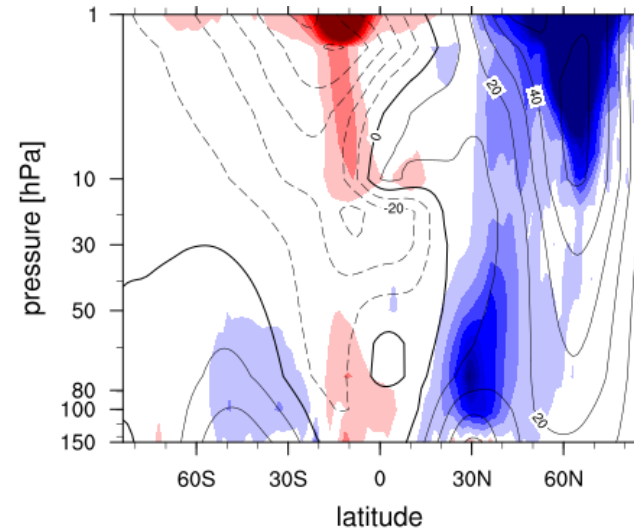
above 150hPa

Gravity wave zonal momentum flux

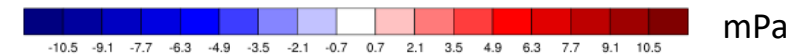
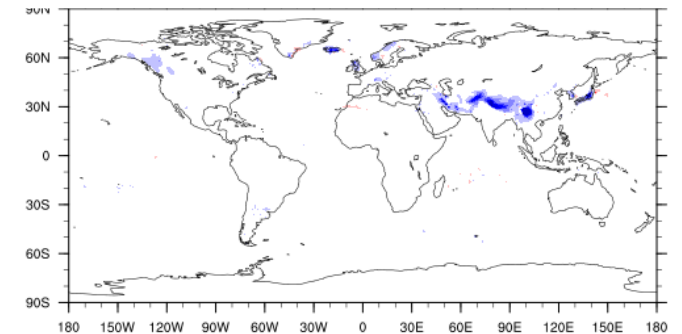
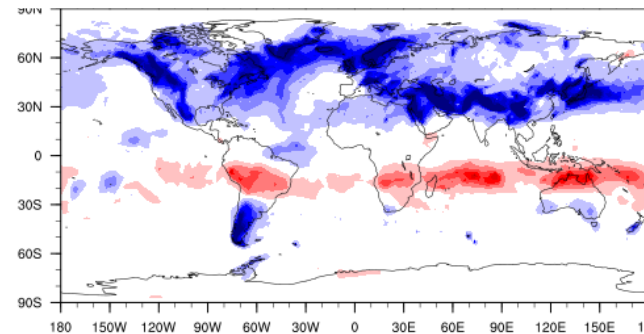
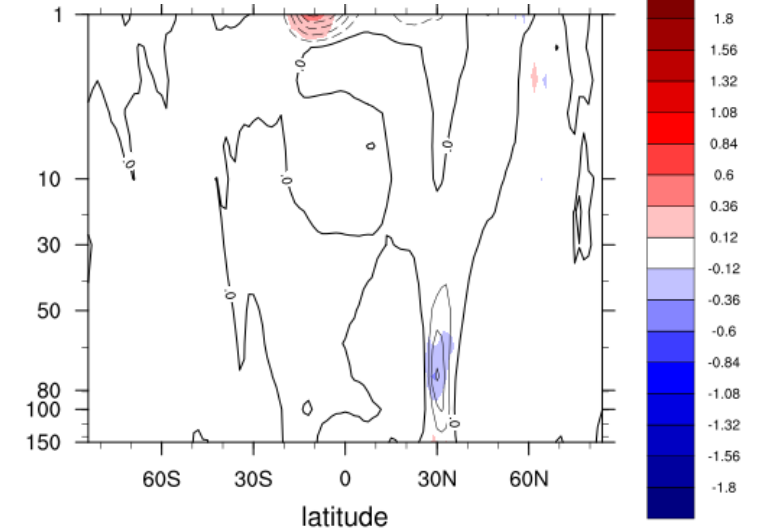
$$\overline{\rho u' w'}$$

at 80 hPa

NH 2.5 km



H - NH 2.5 km  $ms^{-1}day^{-1}$



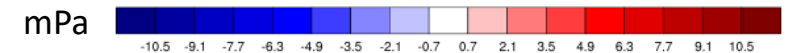
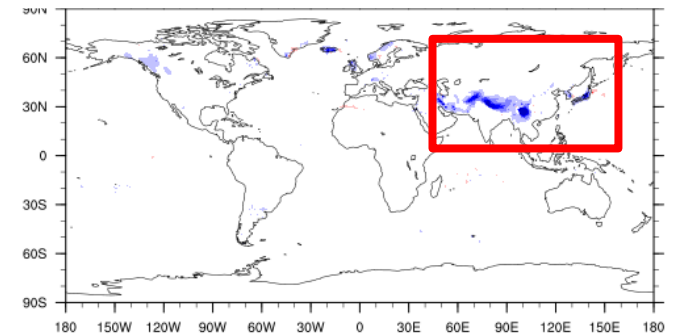
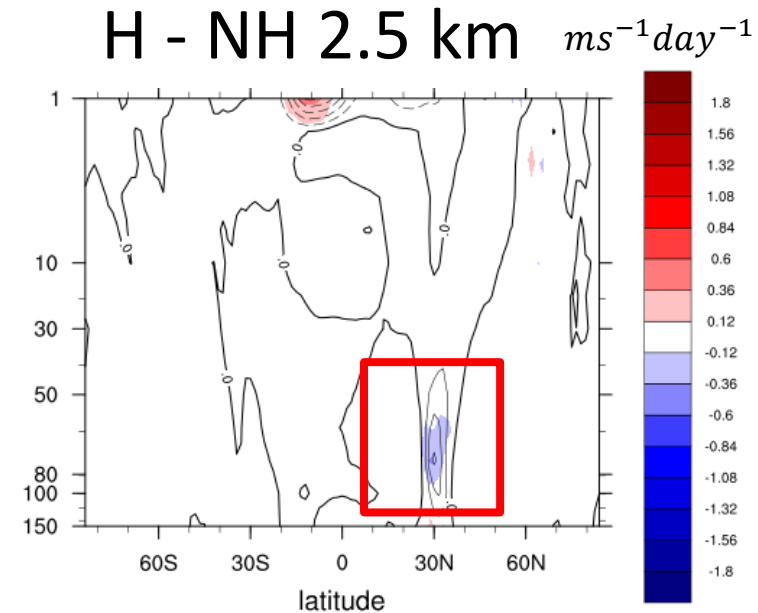
# Impact of non-hydrostatic dynamics on resolved gravity wave drag

Jan 2022

Hydrostatic model has more resolved gravity wave drag in the stratosphere above the Himalayas

$$\frac{1}{\bar{\rho}} \frac{\partial}{\partial z} \overline{\rho u' w'}$$

$$\overline{\rho u' w'}$$

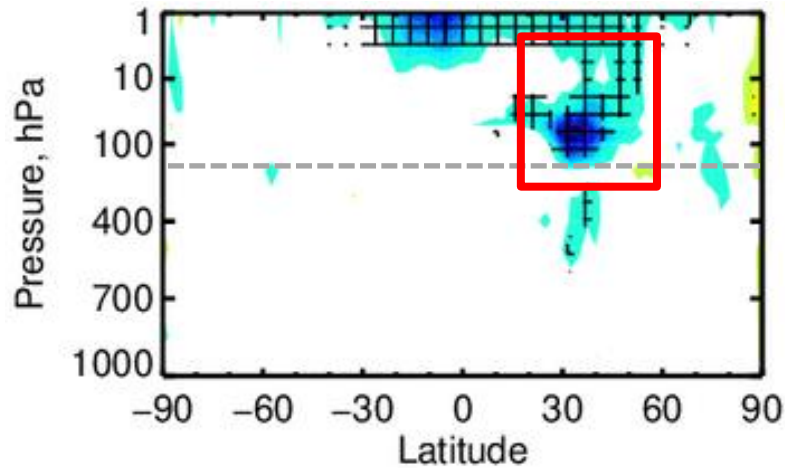


# Impact of non-hydrostatic dynamics on resolved gravity wave drag

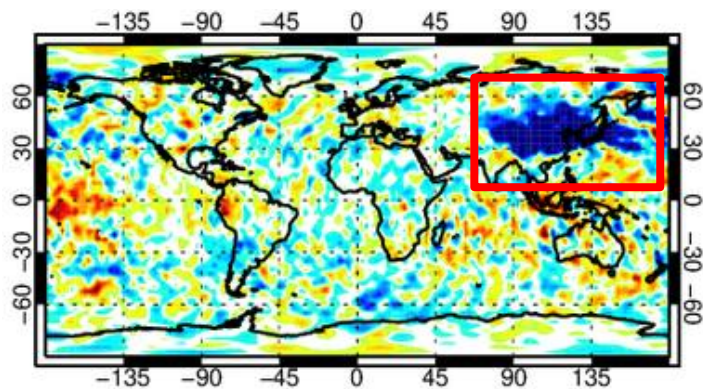
$\Delta$ RMSE NH – H (4.4 km)

Jan 2022

Vector wind at +72 hrs



100 hPa vector wind at +72 hrs



-10%

Hydrostatic model has more resolved gravity wave drag in the stratosphere above the Himalayas

$$\frac{1}{\bar{\rho}} \frac{\partial}{\partial z} \overline{\rho u' w'}$$

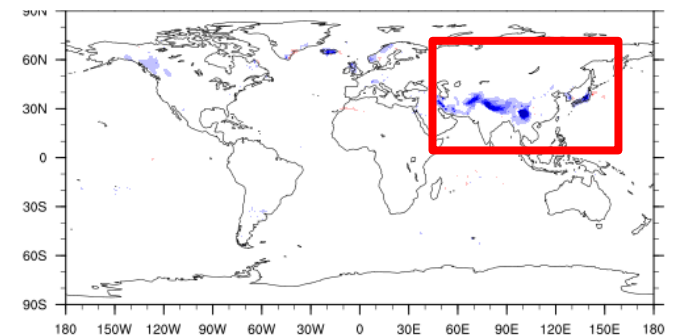
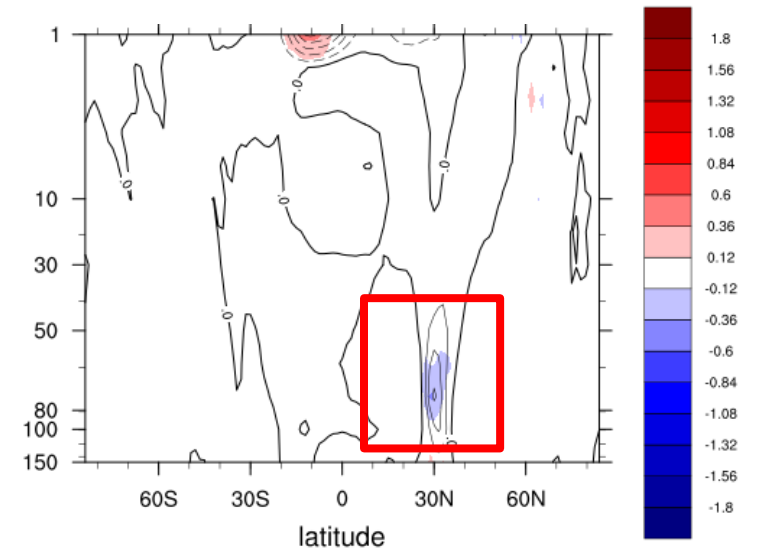
Using non-hydrostatic dynamics leads to reduced RMSE of winds in stratosphere

$$\overline{\rho u' w'}$$

+10%

Jan 2022

H - NH 2.5 km  $ms^{-1}day^{-1}$



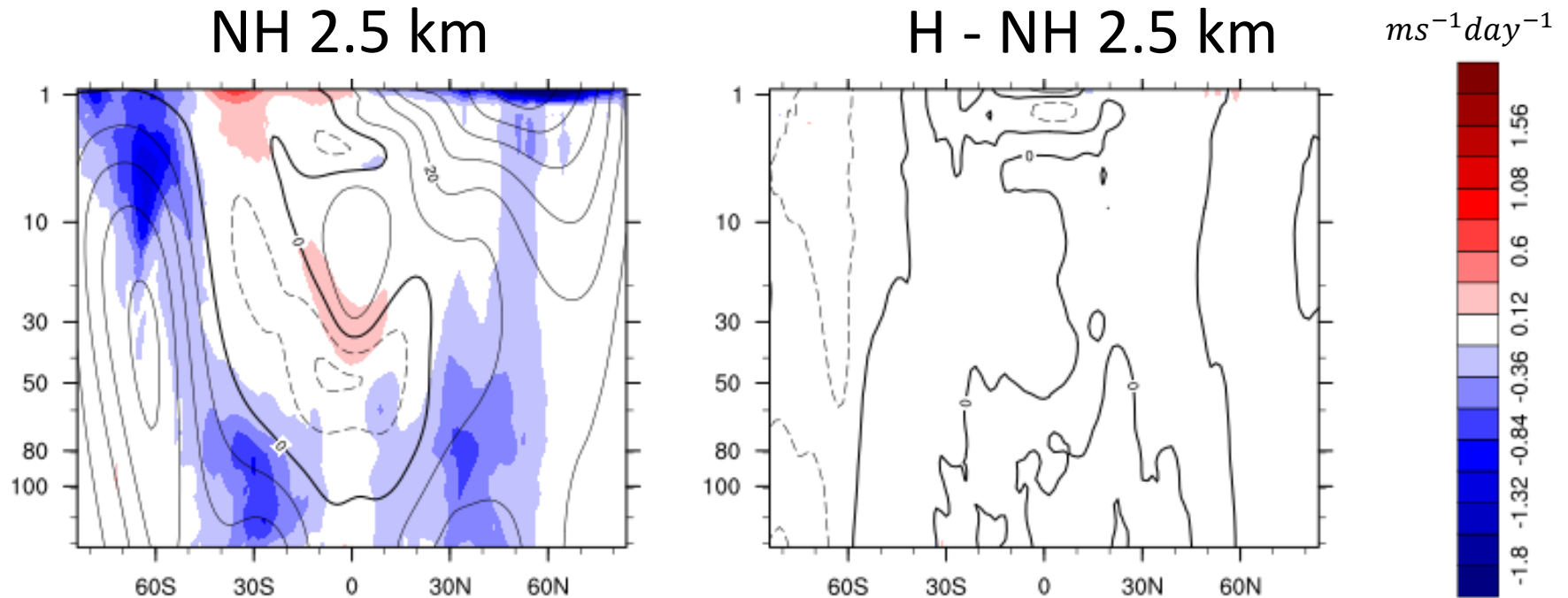
mPa

# Non-hydrostatic effects are flow dependent

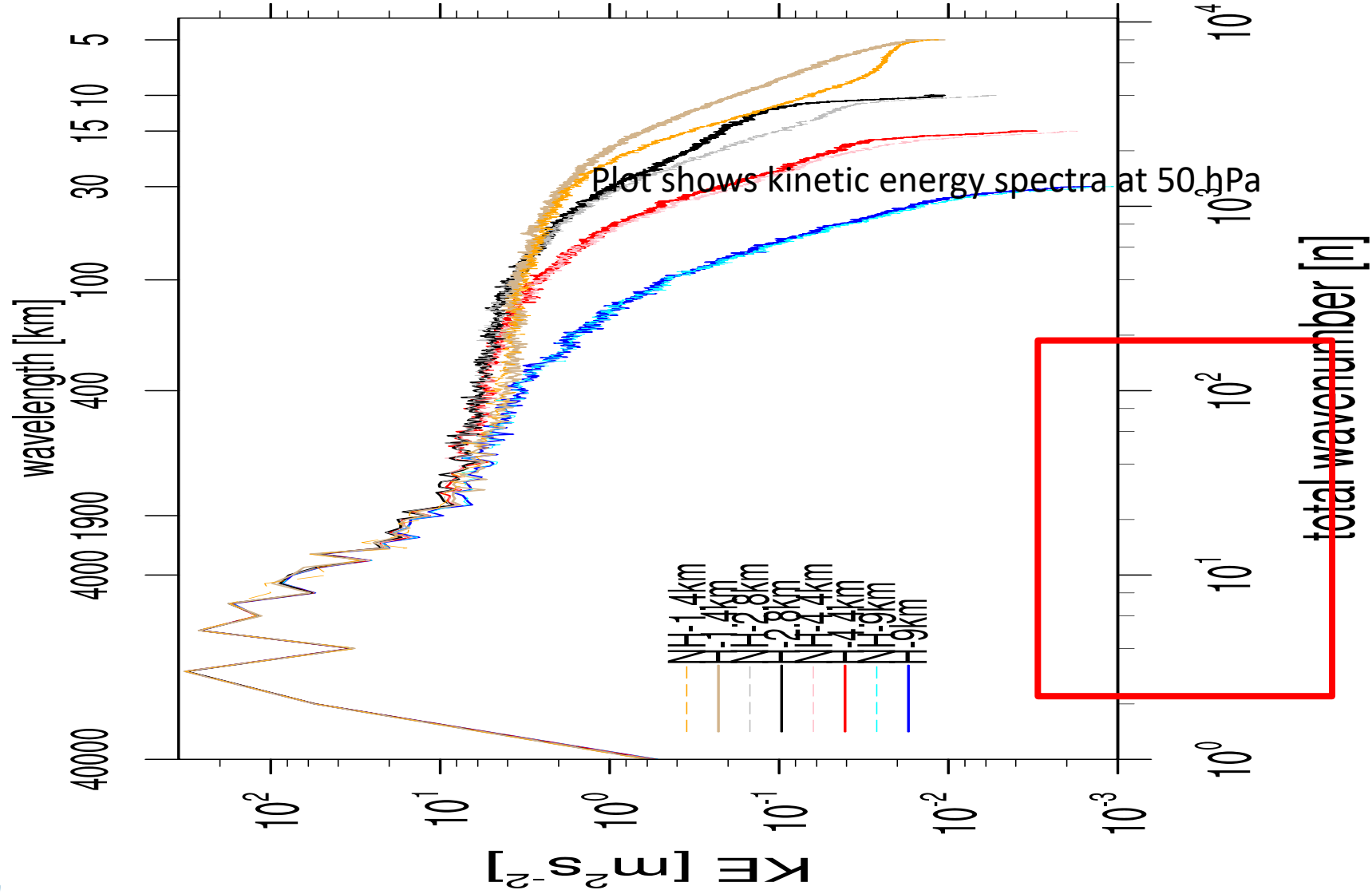
Relaxing hydrostatic approximation makes little difference to resolved GW drag or fluxes at 2.8km.

Nov 2018

$$\frac{1}{\bar{\rho}} \frac{\partial}{\partial z} \overline{\rho u' w'}$$



# Global Kinetic Energy - Jan 2022

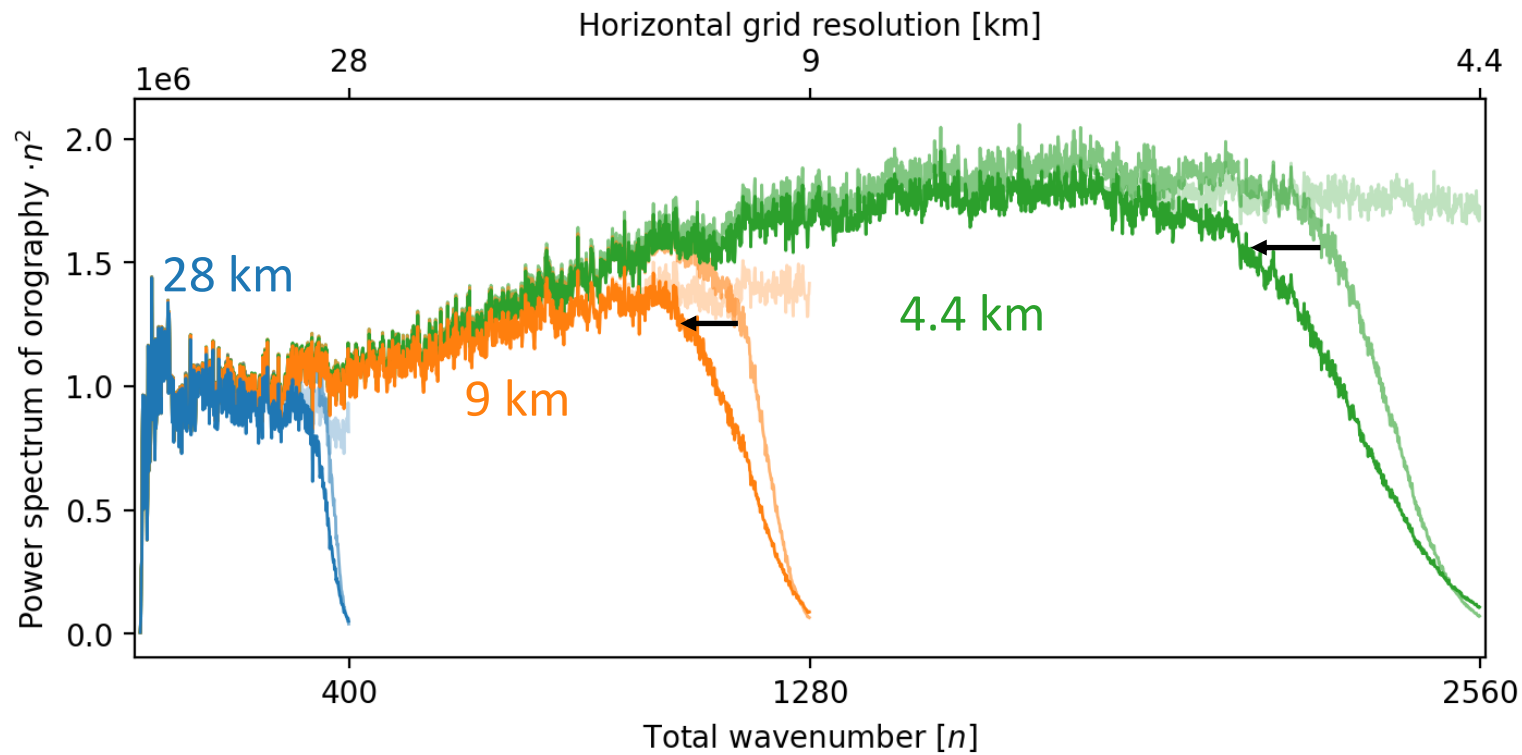


Can we treat these small scales in some other way?

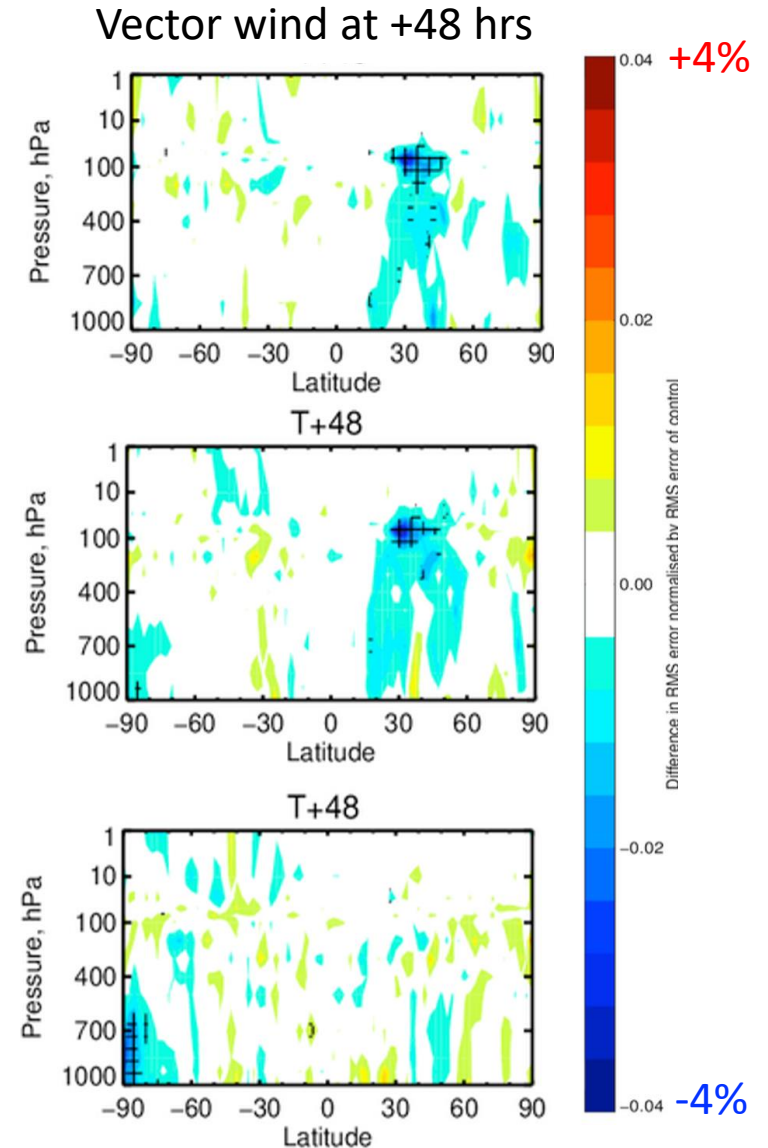
# Filtering small scale orography

# Filtering small-scale orography

## $\Delta$ RMSE of filtered - unfiltered



Compromise must be made between removing small scales that are not accurately represented by the model grid/discretization/ formulation and preserving mountain detail

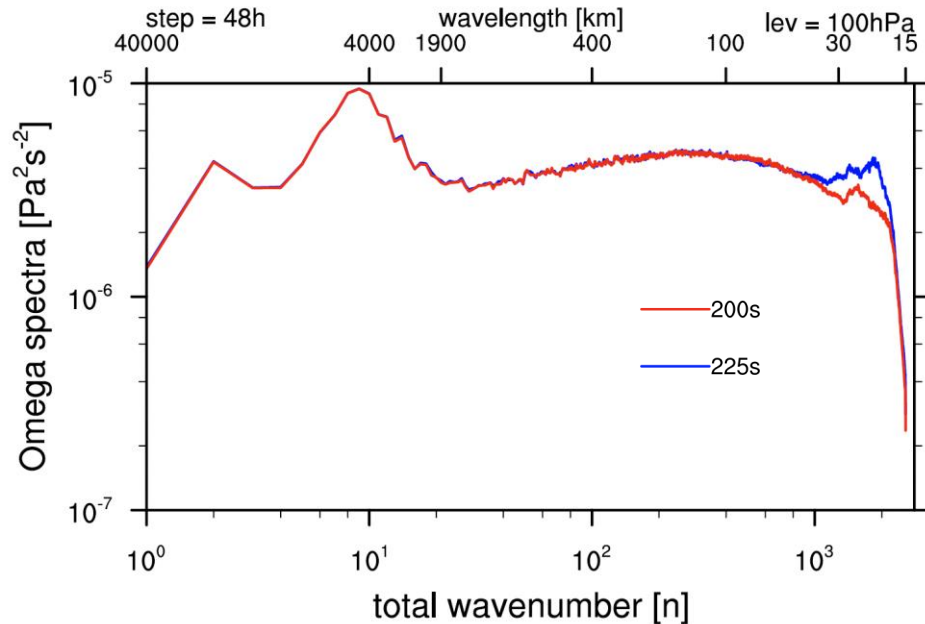


# Model timestep sensitivity

# Reducing timestep also acts to “damp” waves

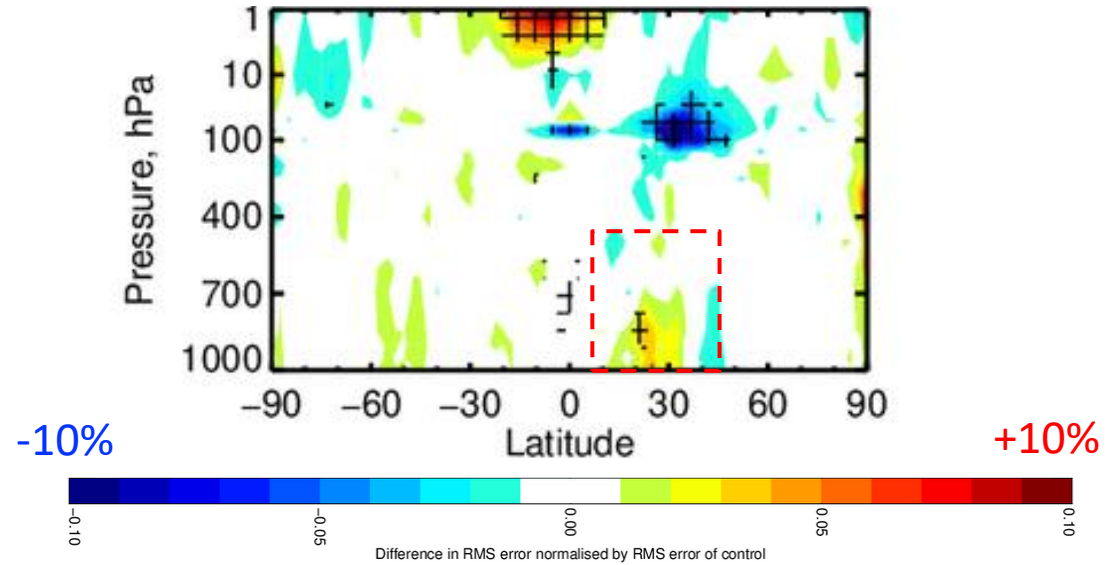
$\Delta RMSE$  of  $\Delta t = 180s$  -  $\Delta t = 225s$

Power spectrum of  $\omega$  (vertical velocity)  
at 100hPa

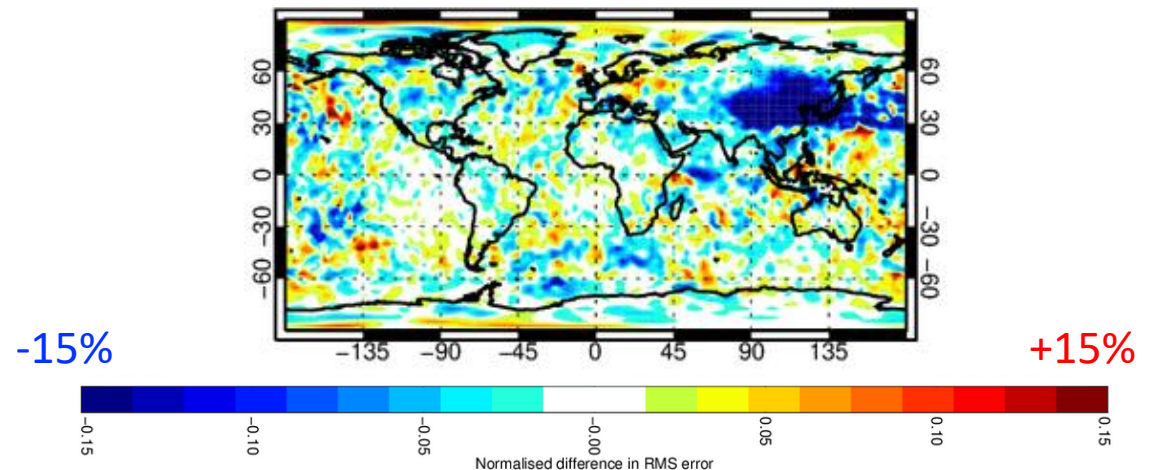


The stratospheric winds get much better with smaller timestep – possibly due to increased semi-Lagrangian interpolations

Vector wind at +72 hrs

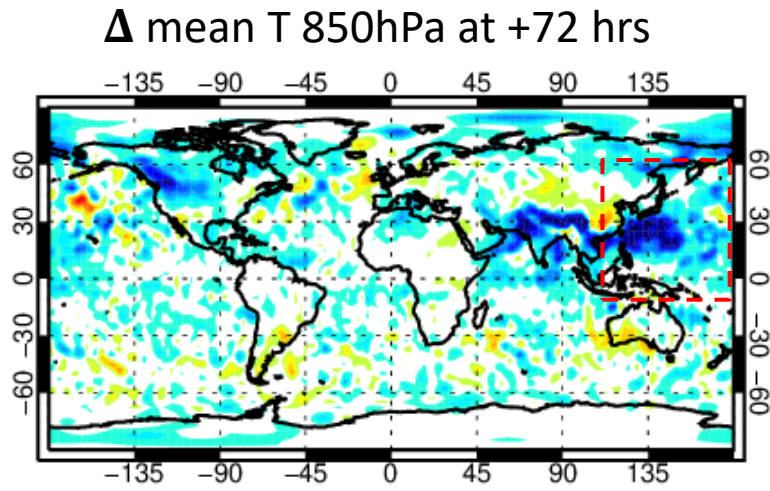


100 hPa vector wind at +72 hrs

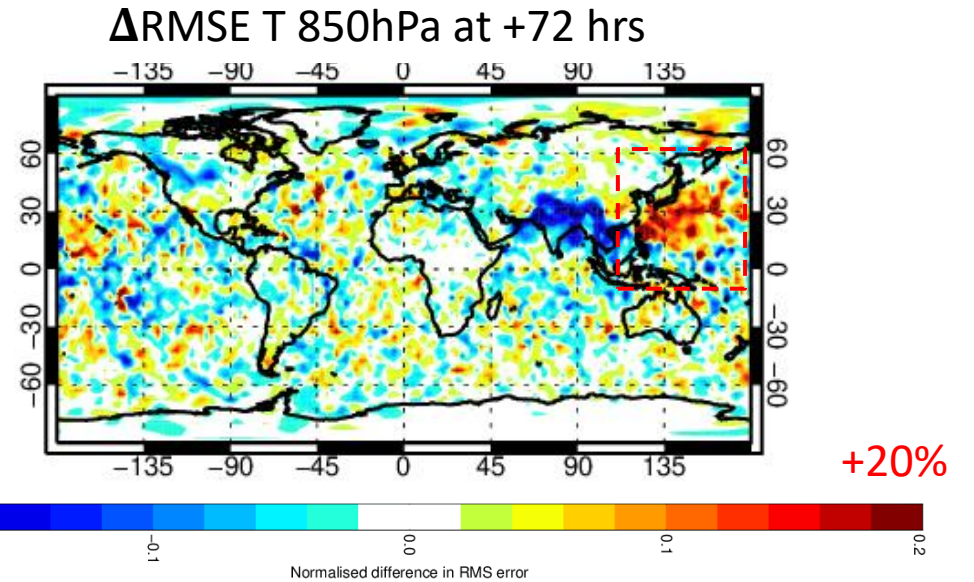


# ...but there is a strong near-surface timestep sensitivity

$$\Delta t = 180s - \Delta t = 225s$$



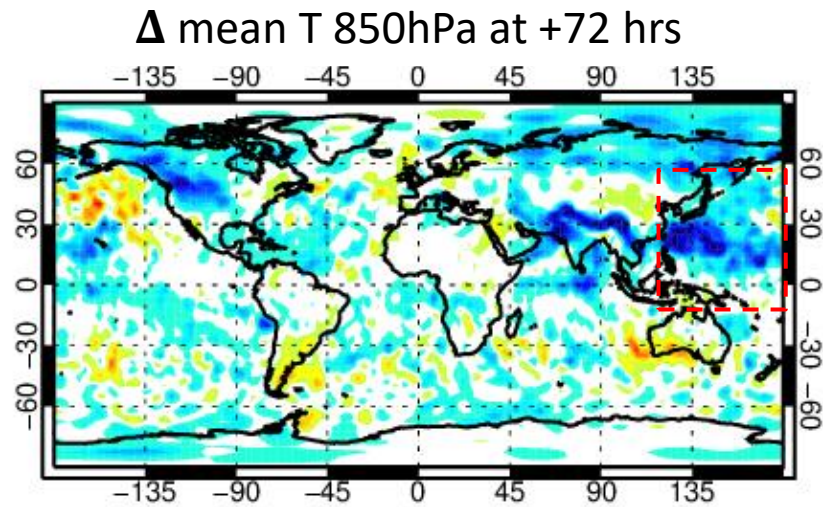
Cooling at 850hPa over the west pacific with reduced timestep



Increase in RMSE of T 850hPa

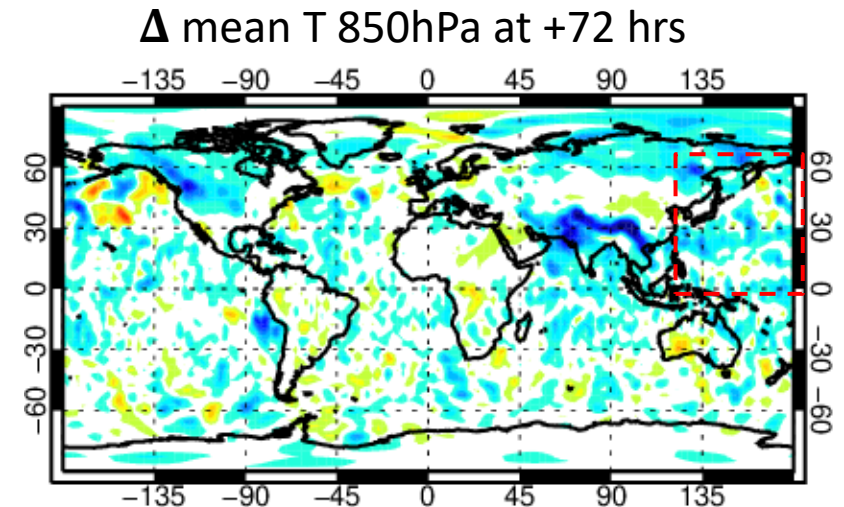
# ...from convection

$\Delta t = 225s$  –  $\Delta t = 450s$



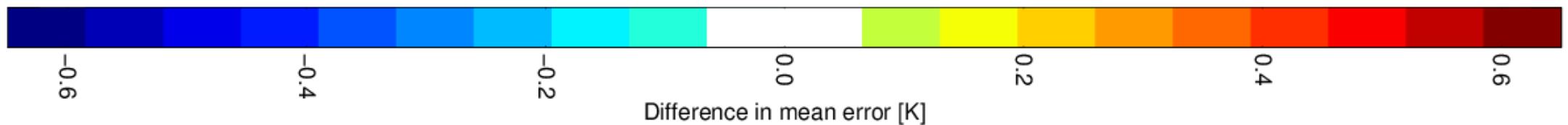
$\Delta t = 225s$  –  $\Delta t = 450s$

**No convection**



-0.6K

+0.6K



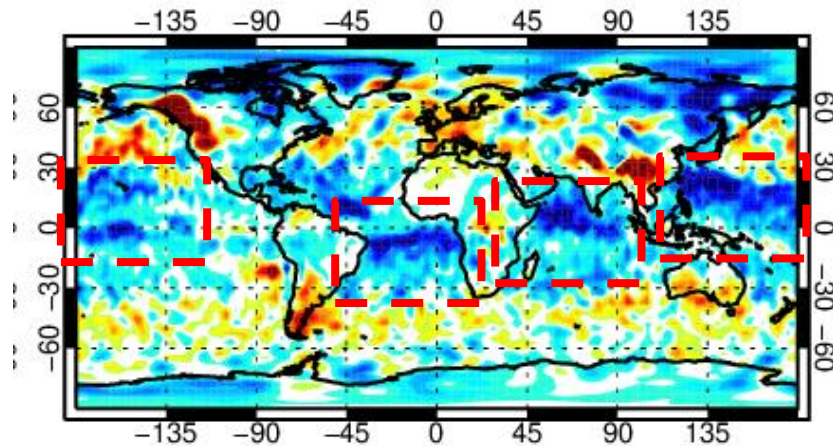
# Reducing timestep sensitivity of convection scheme

$\Delta$ Mean of T 850hPa 4.4 km – 9 km

$$M_{up} + M_{down} < \frac{\Delta p}{g\Delta t}$$

Control

T+72; 850hPa



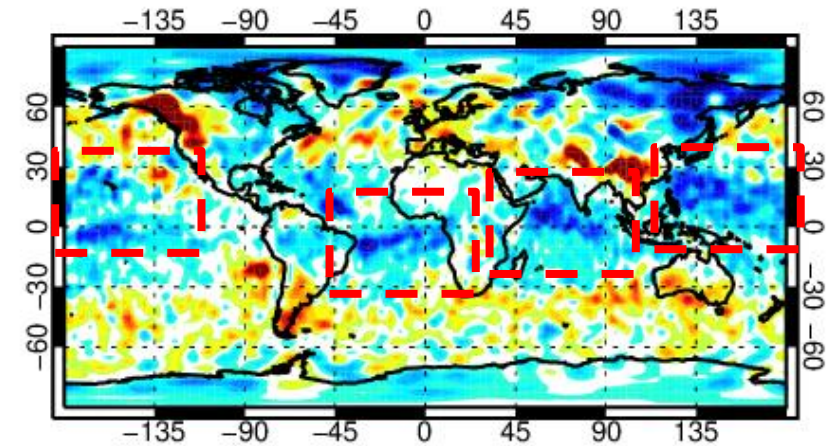
-0.35K

$$M_{up} + M_{down} < \frac{\Delta p}{g \text{ MAX}(\Delta t, 450s)}$$

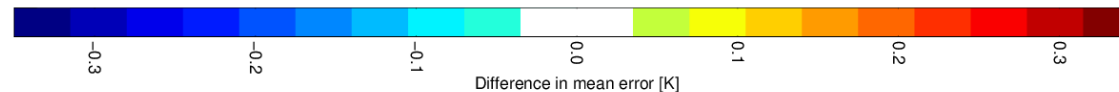
Capped CFL criterion

T+72; 850hPa

Less cooling over tropics



+0.35K



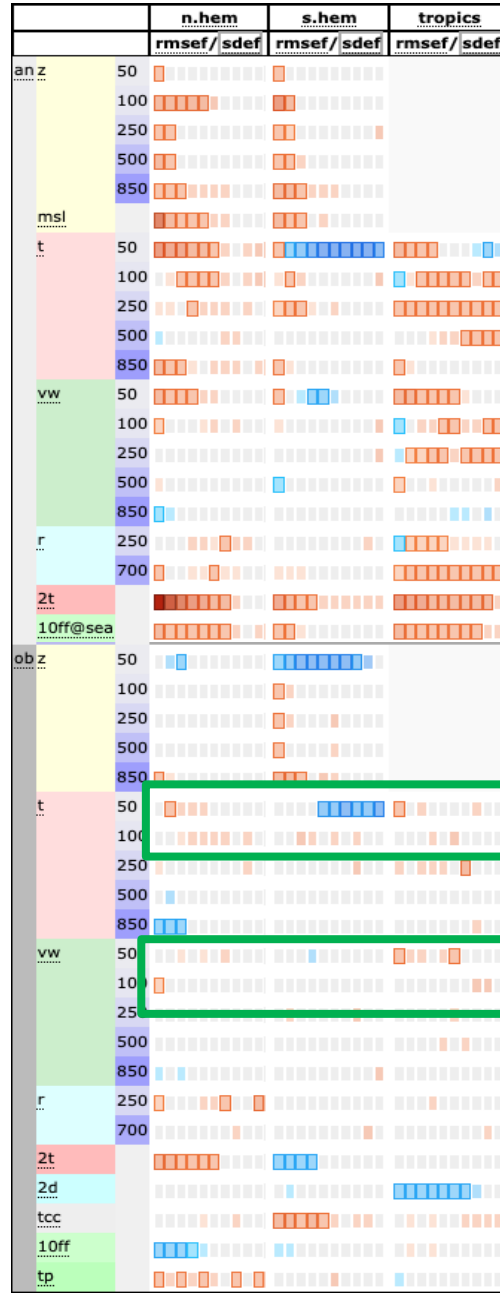
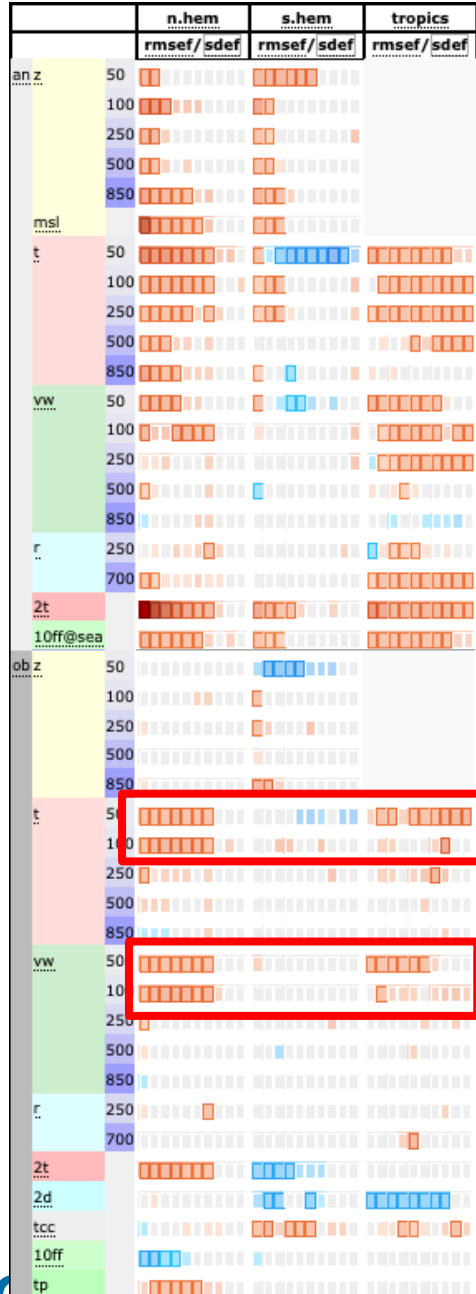
Where are we at now?

DJF : Previous 4.4 km – 9km

New 4.4 km – 9km

vs 9 km operational analysis

vs observations



## Physics changes include:

- Filtered mean orography
- New 30m orography dataset
- Reduced timestep
- Change in CFL criterion of deep convective mass flux

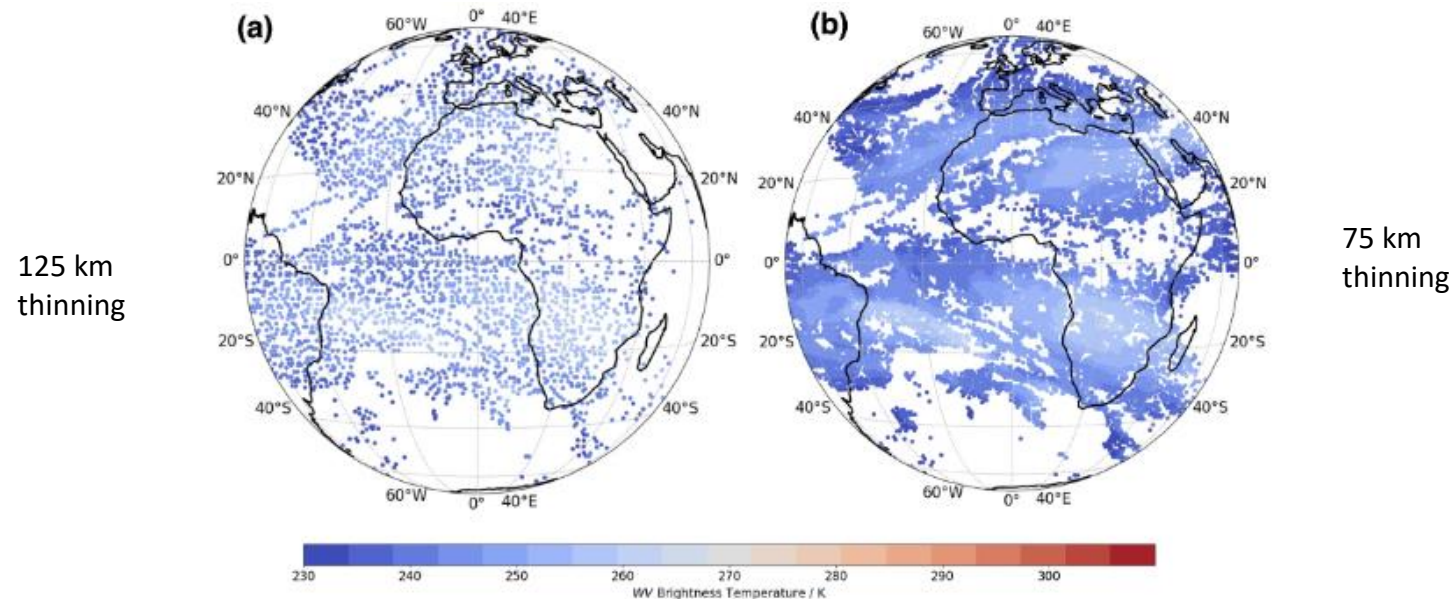
Neutral against observations with physics changes

Still degraded against 9km analysis

# High resolution data assimilation

## Setup of the high-resolution DestinE analyses:

- TCo2559 (4.4 km) trajectory using latest 49r1 DestinE forecast (new orog, time-step)
- Increased resolution of minimisation (TL319/TL399/TCo399/TCo511)
- Observation time-slots reduced from 1800s to 400s
- High-resolution geostationary satellite data :



# High resolution data assimilation

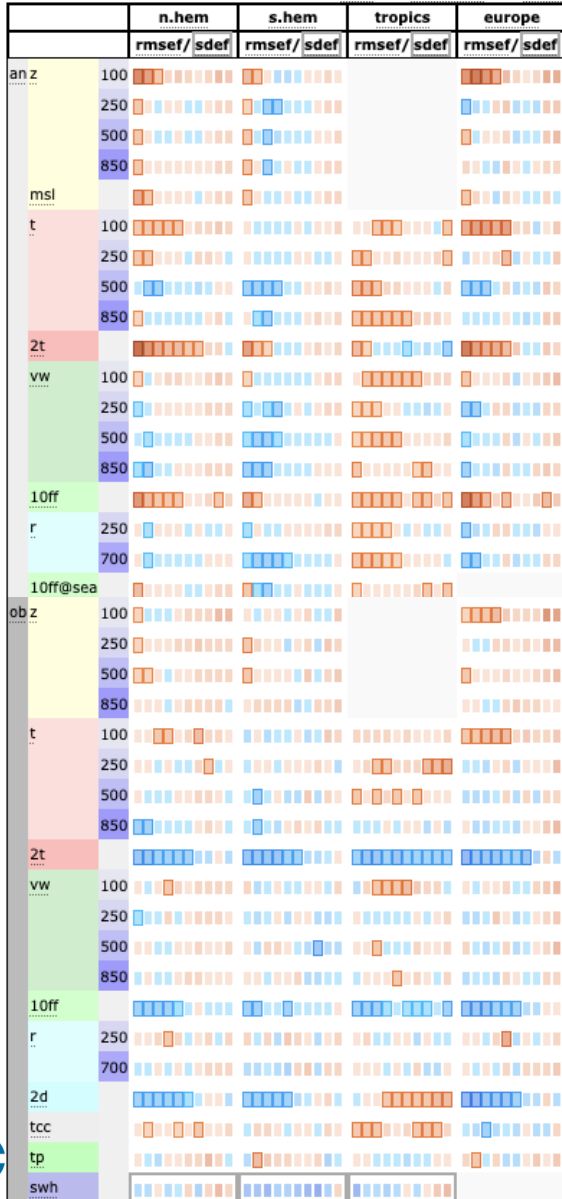
JJA

New  
4.4 km – 9km

New + analysis  
4.4 km – 9km

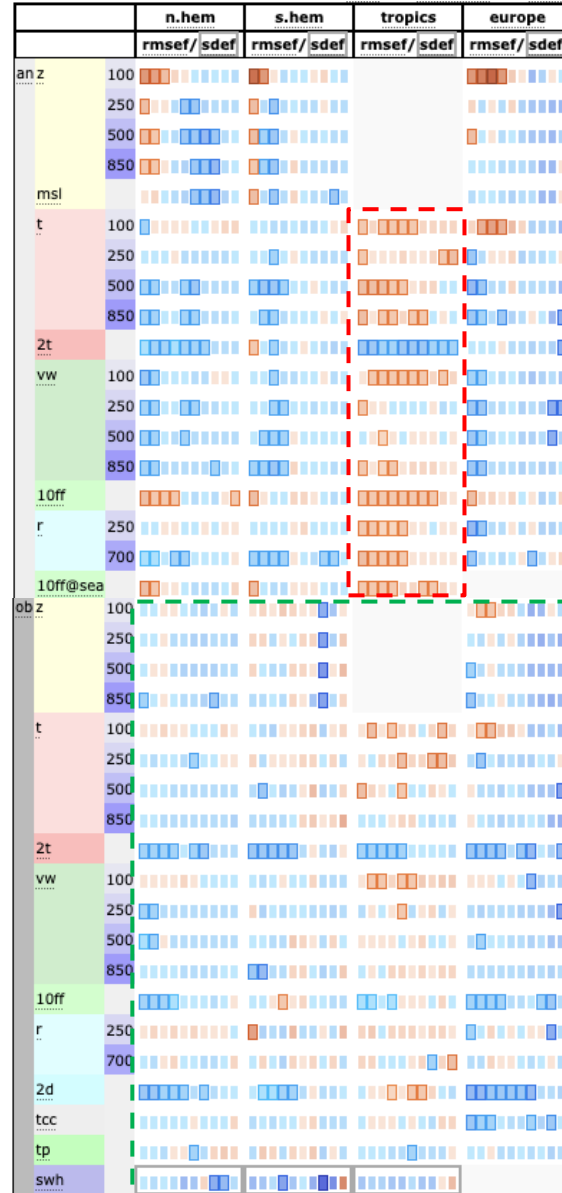
vs 9 km operational analysis

vs observations



vs 4.4 km analysis

vs observations



4.4 km improved against observations

Still some degradation in the tropics



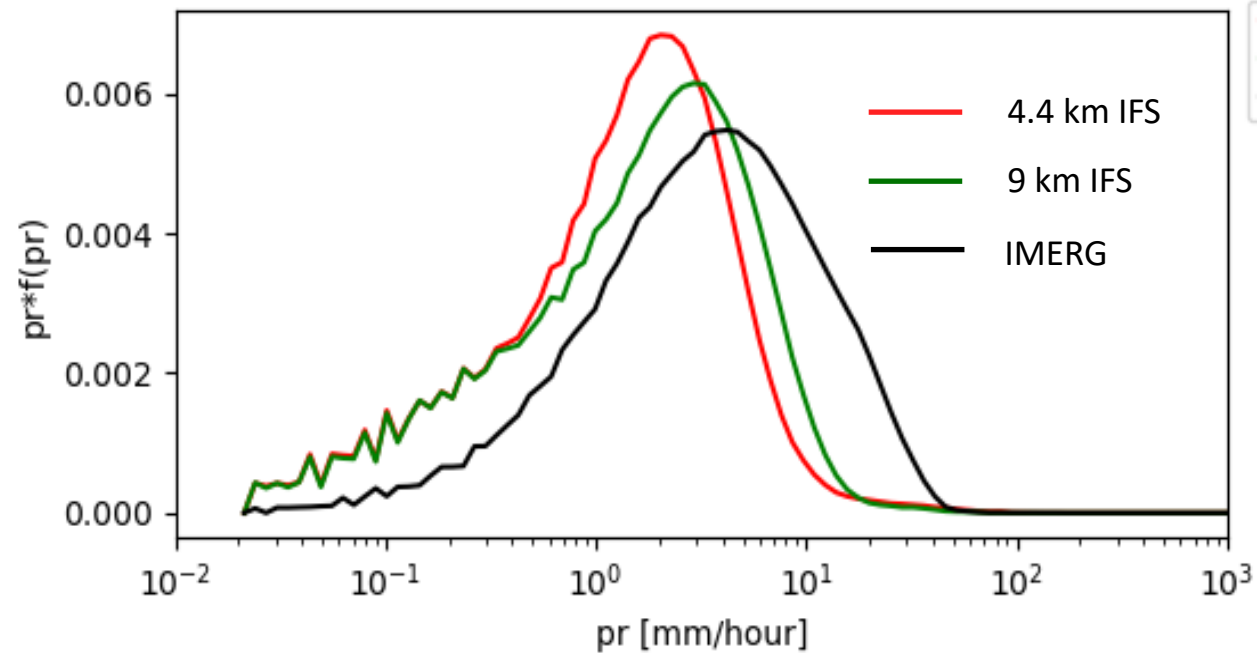
Z. Zaplotnik, J. Schröttele,  
E. Orlandi and J. Bandejas

A more detailed look...

# Convection

# Too much light precipitation

PDF of hourly precipitation over the tropics



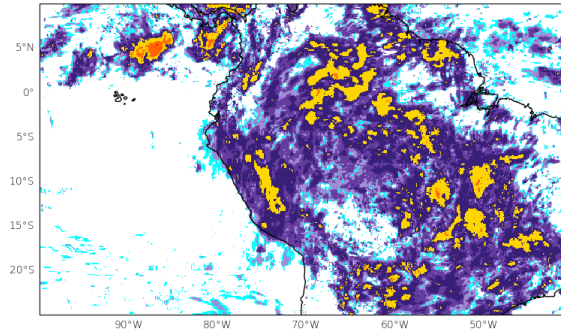
Precipitation weighted frequency – integral gives total precipitation

‘Out of the box’ the 4.4 km simulations have even more light precipitation compared with the 9km

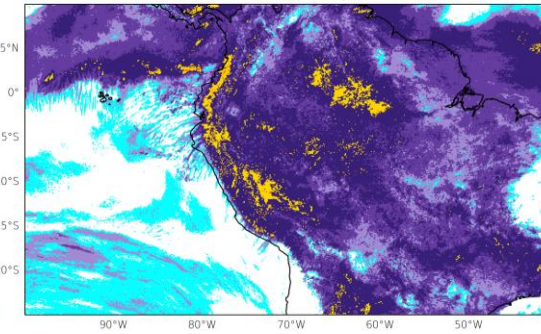
# Too much light precipitation and spurious waves

Amazon Basin

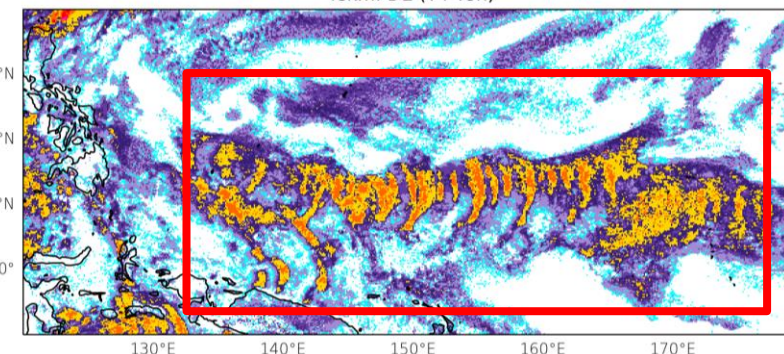
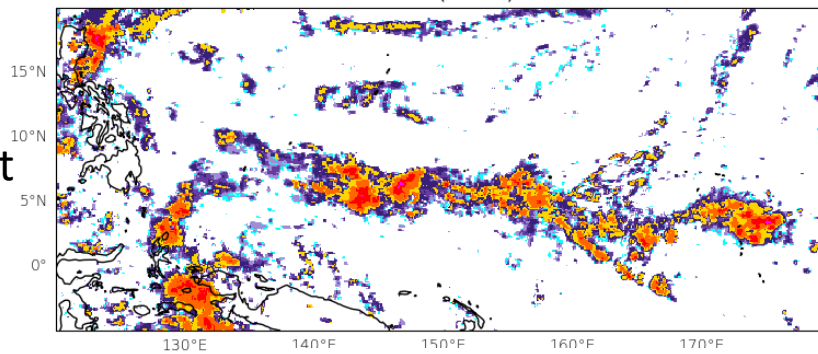
IMERG



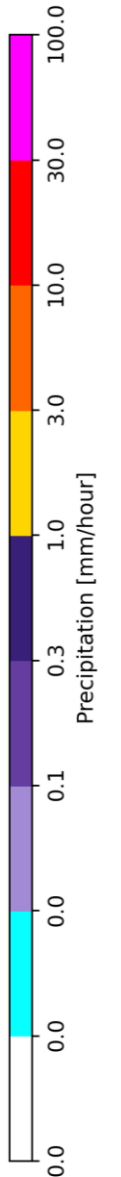
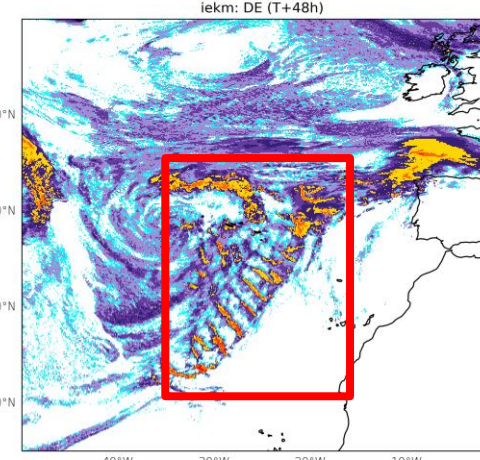
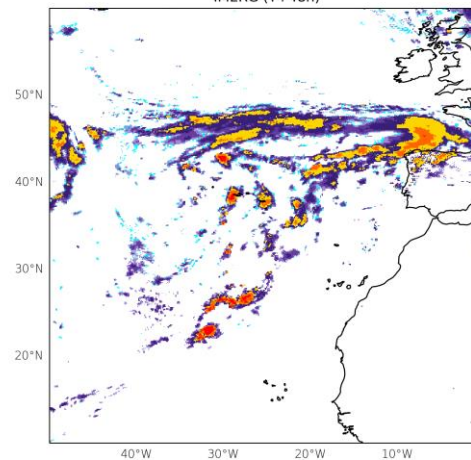
DestinE (4.4 km)



Maritime Continent



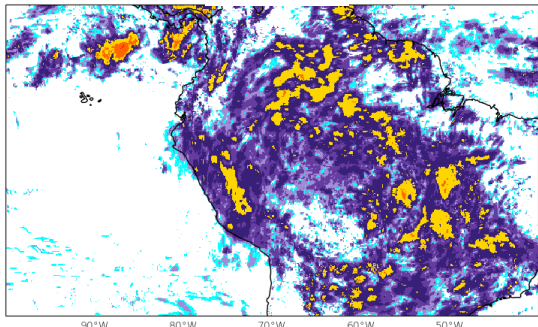
North Atlantic



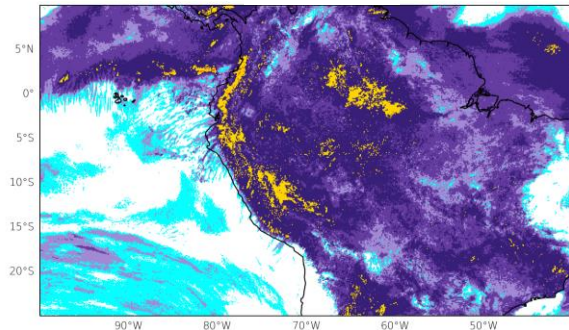
Pick your favourite configuration...

# Sensitivity to various physics configurations

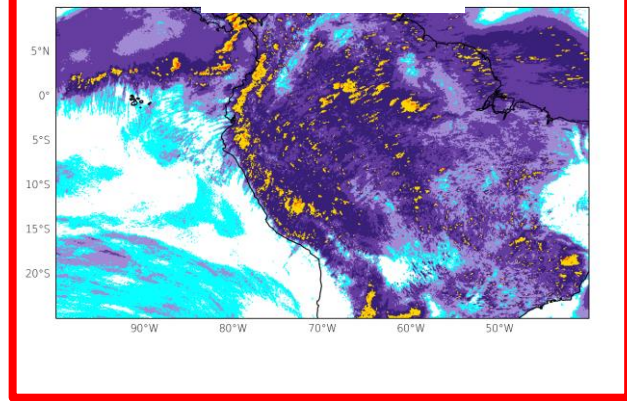
IMERG



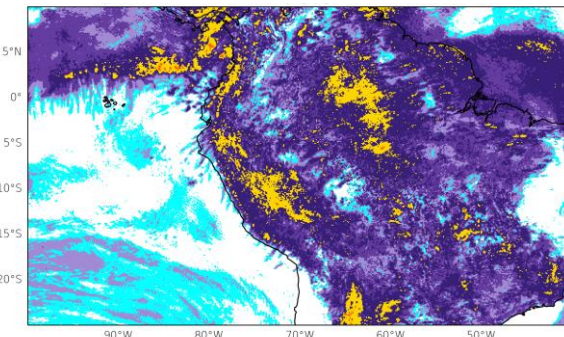
DestinE



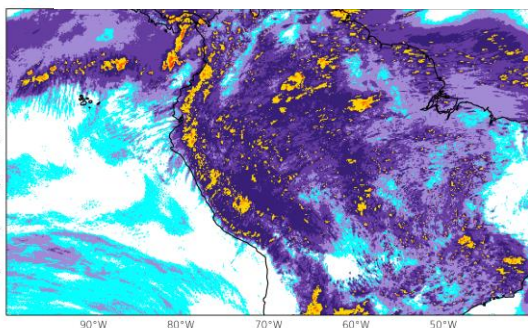
RCBMF



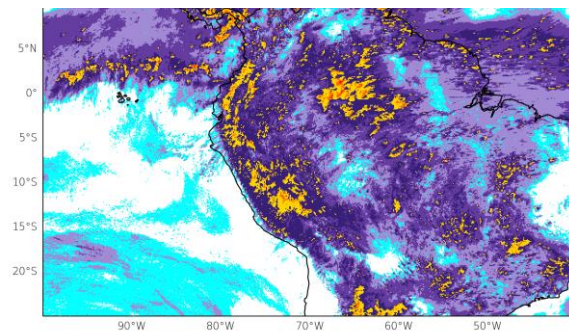
RCMBF (/5) + conv Q (\*5) + phys-dyn coupling



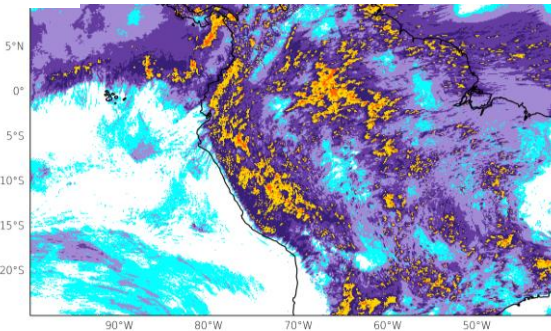
RCBMF + no conv Q



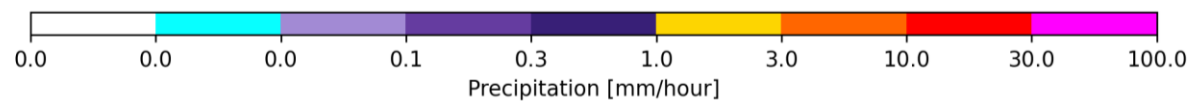
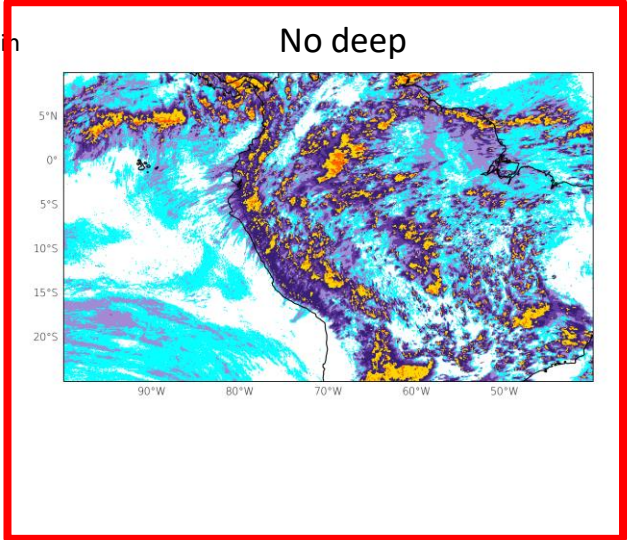
RCBMF + no conv Q + DM rain evap



RCBMF + no conv Q + DM rain evap + TKE + CP detrain

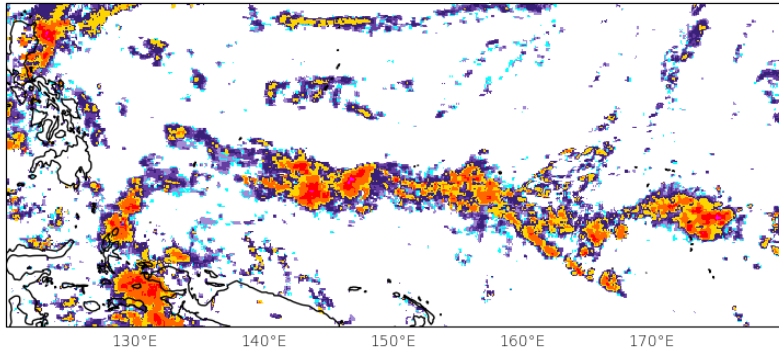


No deep

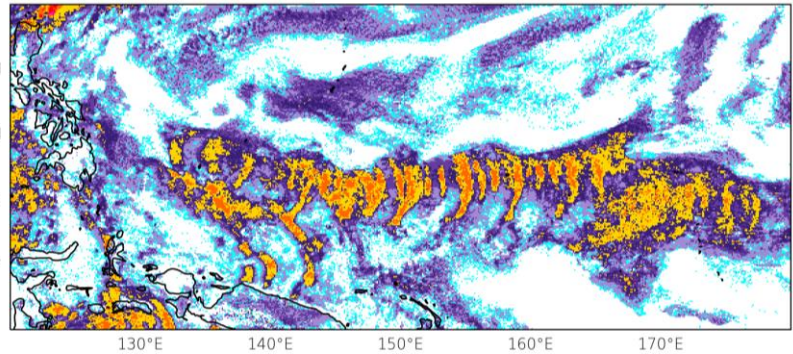


Amazon Basin

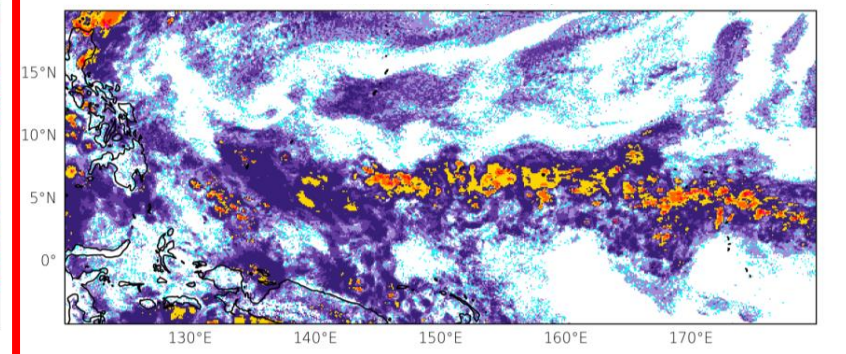
IMERG



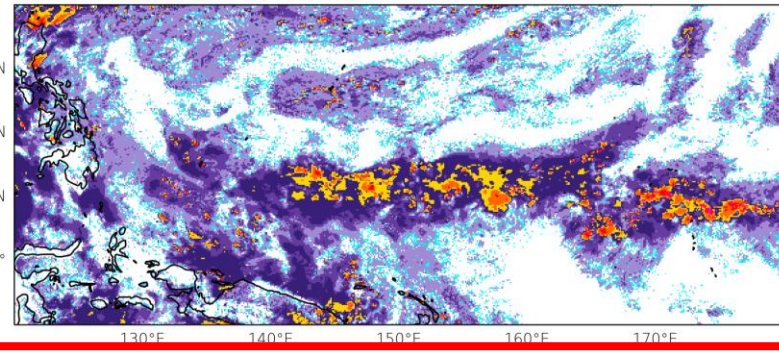
DestinE )



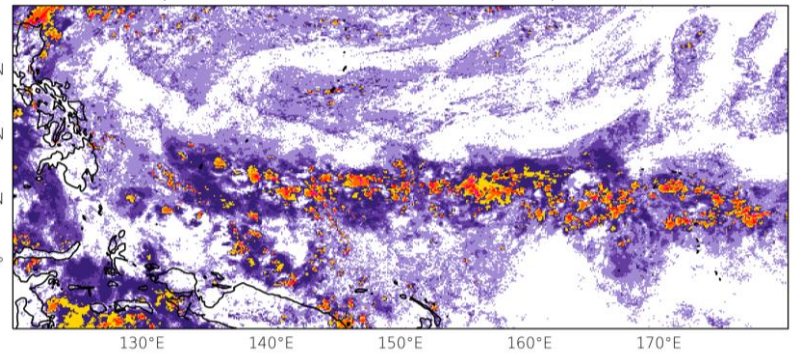
RCBMF



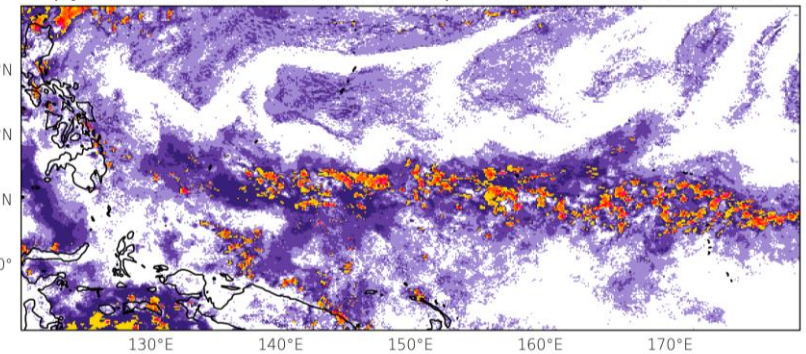
RCBMF + no conv Q



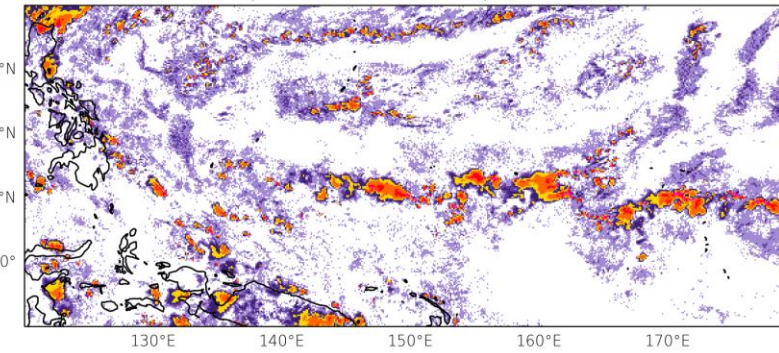
RCBMF + no conv Q + DM rain evap



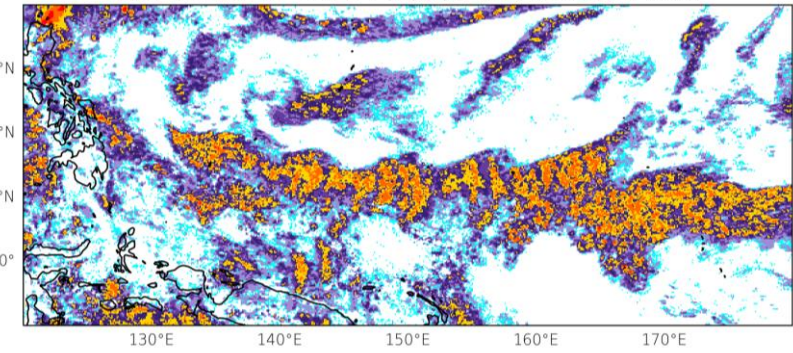
RCBMF + no conv Q + DM rain evap + TKE + CP detrain



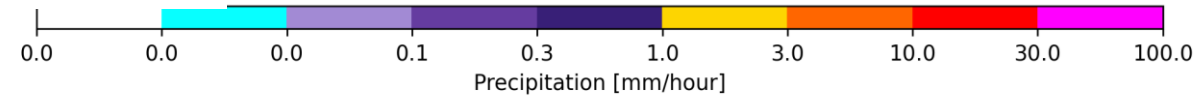
No deep



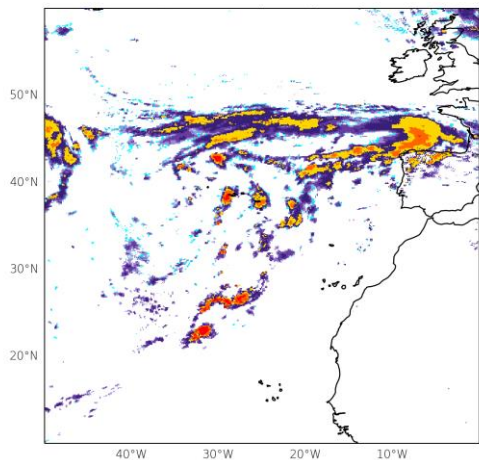
RCMBF (/5) + conv Q (\*5) + phys-dyn coupling



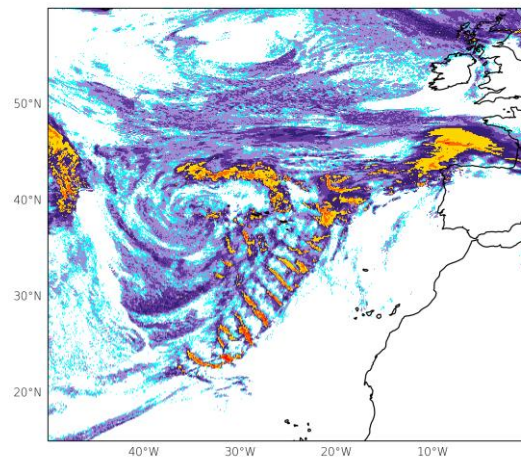
Maritime  
Continent



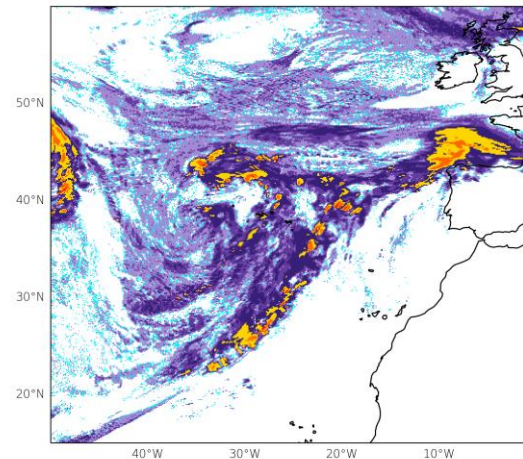
IMERG



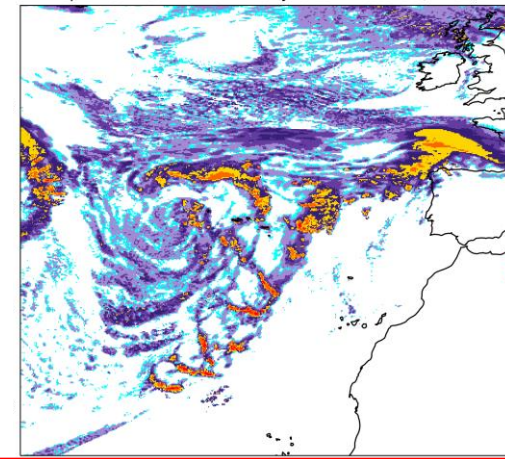
DestinE



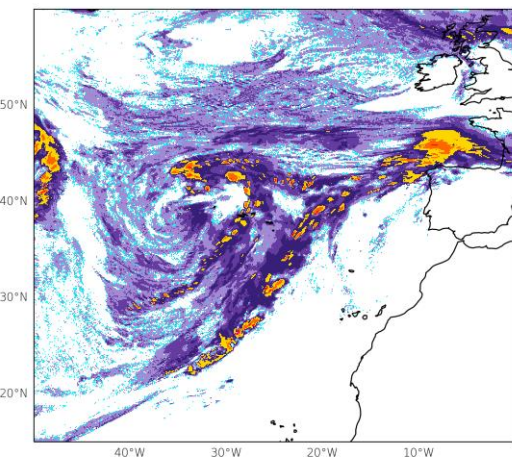
RCBMF



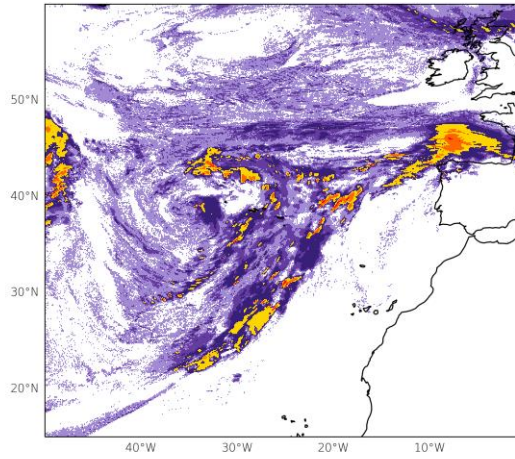
RCBMF for CAPE only (/3)



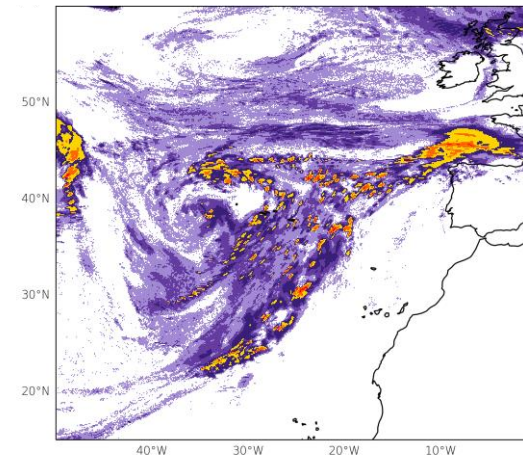
RCBMF + no conv Q



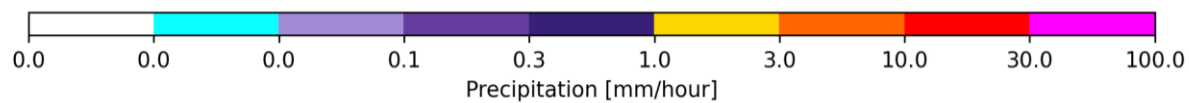
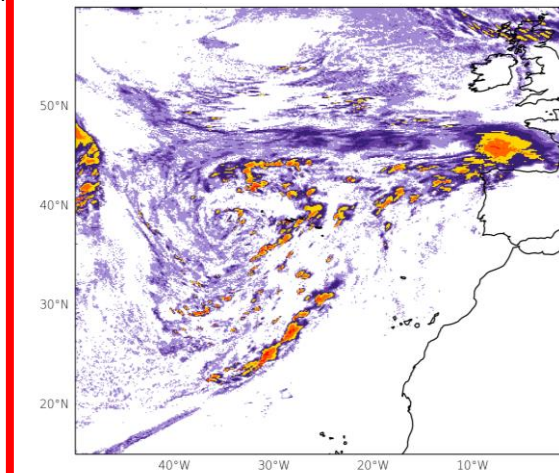
RCBMF + no conv Q + DM rain evap



RCBMF + no conv Q + DM rain evap + TKE + CP detrain



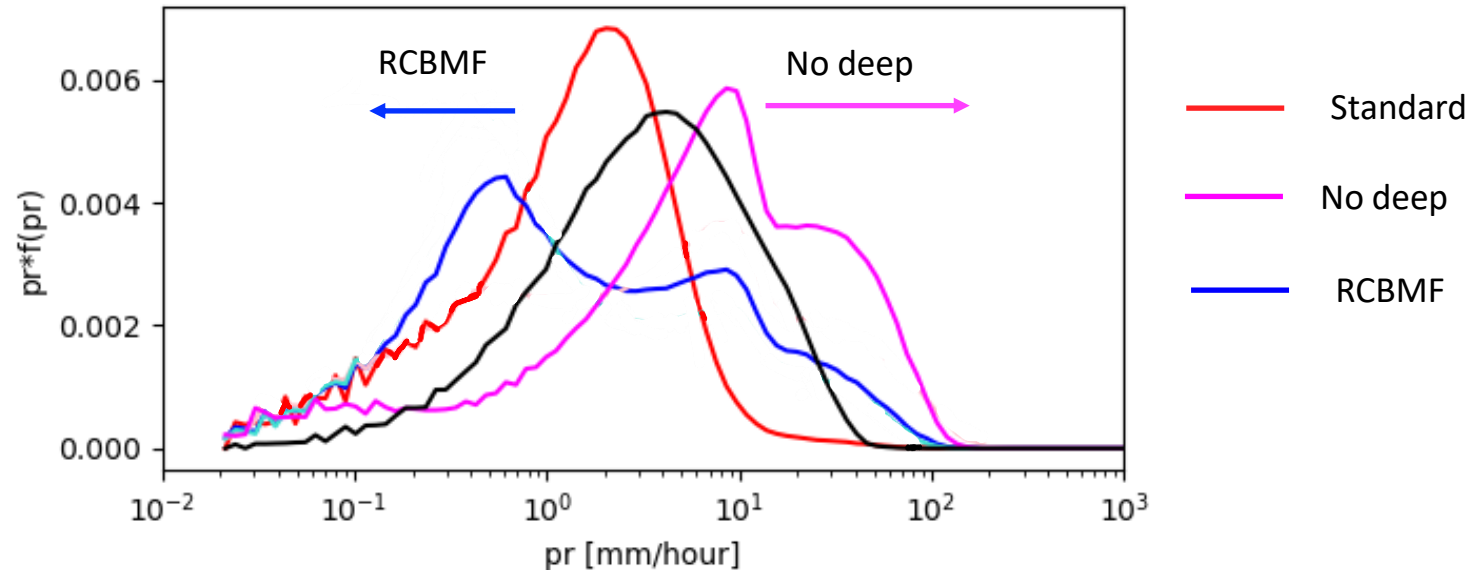
No deep



North Atlantic

# Popular choices

PDF of hourly precipitation over the tropics



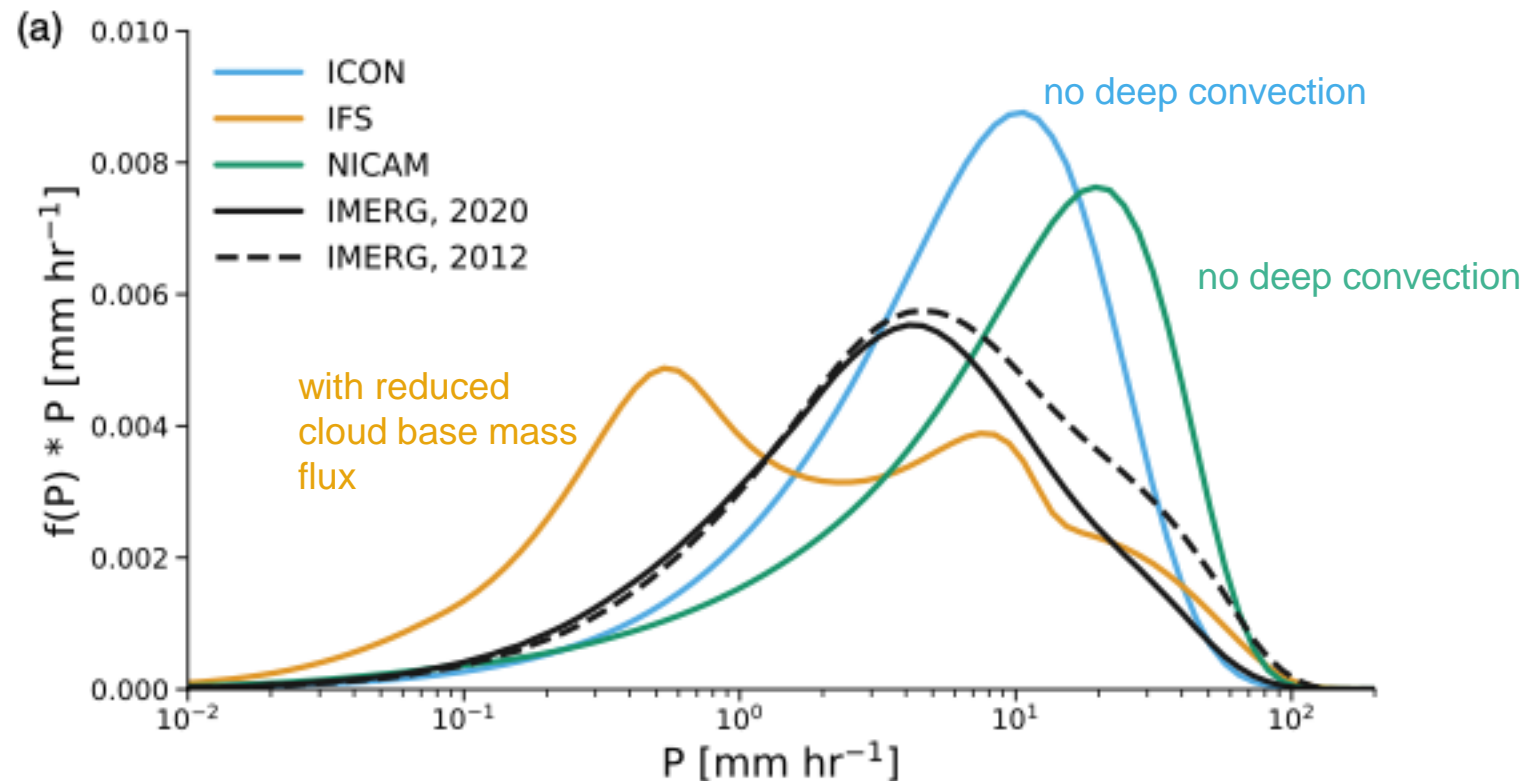
Reducing cloud base mass flux leads to a bimodal PDF

Switching off deep convection entirely leads to too large precipitation rates

Do we need something in-between?

# Other models also have too high precipitation rates with explicit convection

PDF of hourly precipitation over the tropics



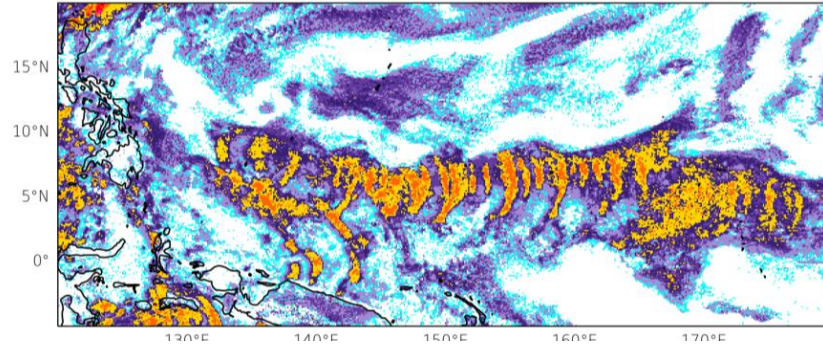
Daisuke Takasuka, Tobias Becker, Jiawei Bao (in prep)

Using the IFS Idealised ‘small-planet channel flow’ to understand physics-dynamics coupling

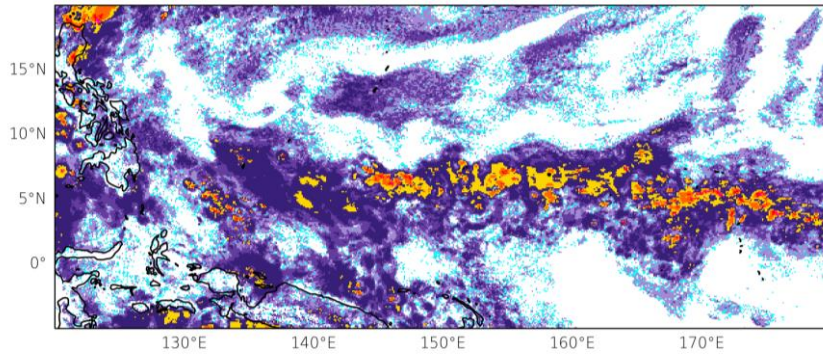
# Idealised simulations reproduce sensitivity to physics seen in the full model

## 4.4 km model

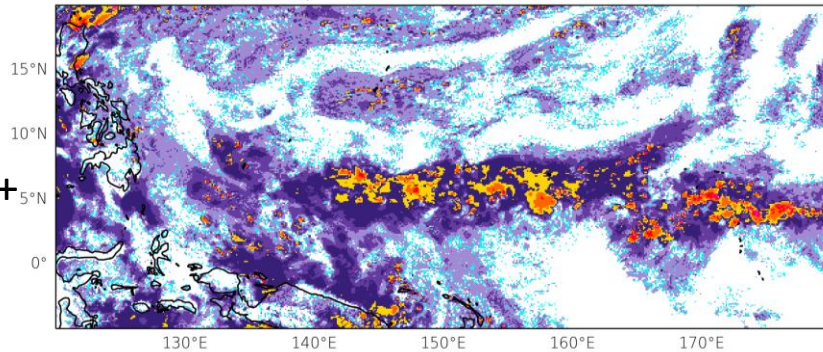
iekm: DE (T+48h)



inīs: DE + RCBMF (T+48h)



insq: DE + RCBMF + no QCV (T+48h)

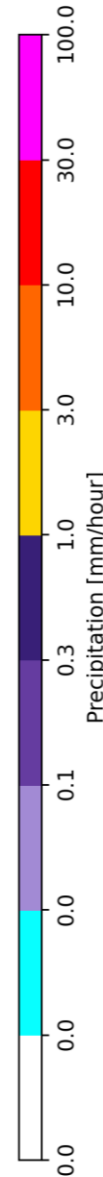
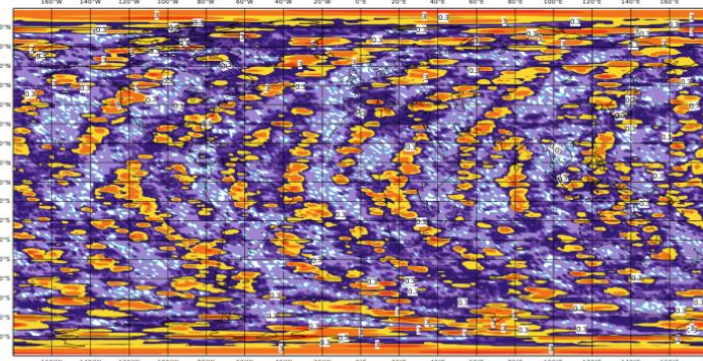
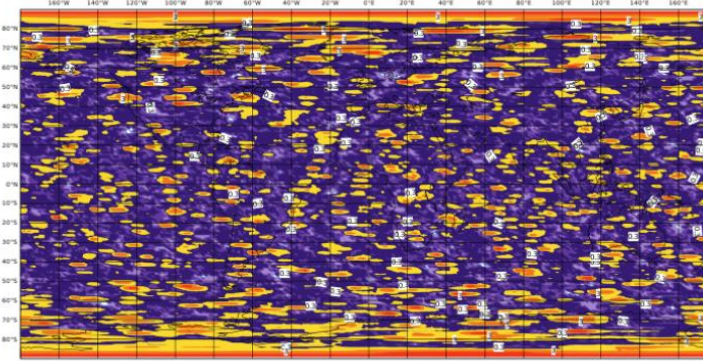
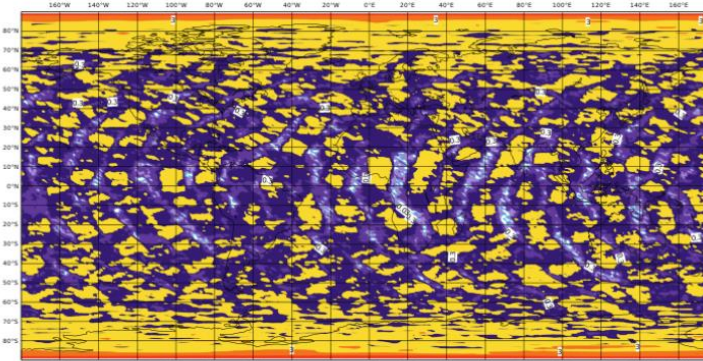


Standard

Reduced cloud base mass flux

Reduced cloud base mass flux + TKE diffusion + no moisture convergence

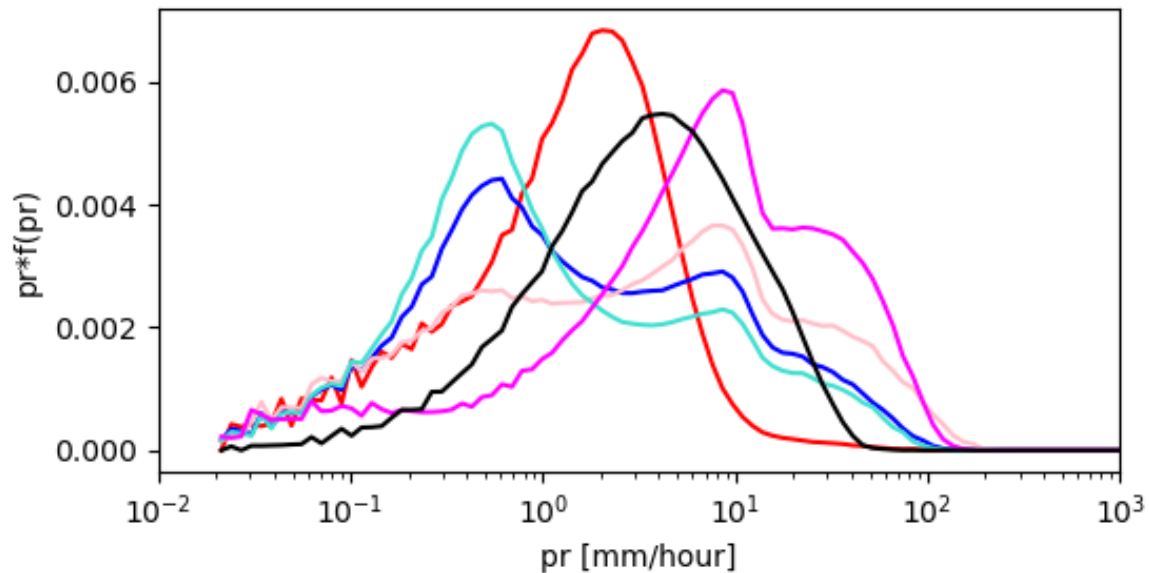
## 3 km idealised IFS (TWPICE)



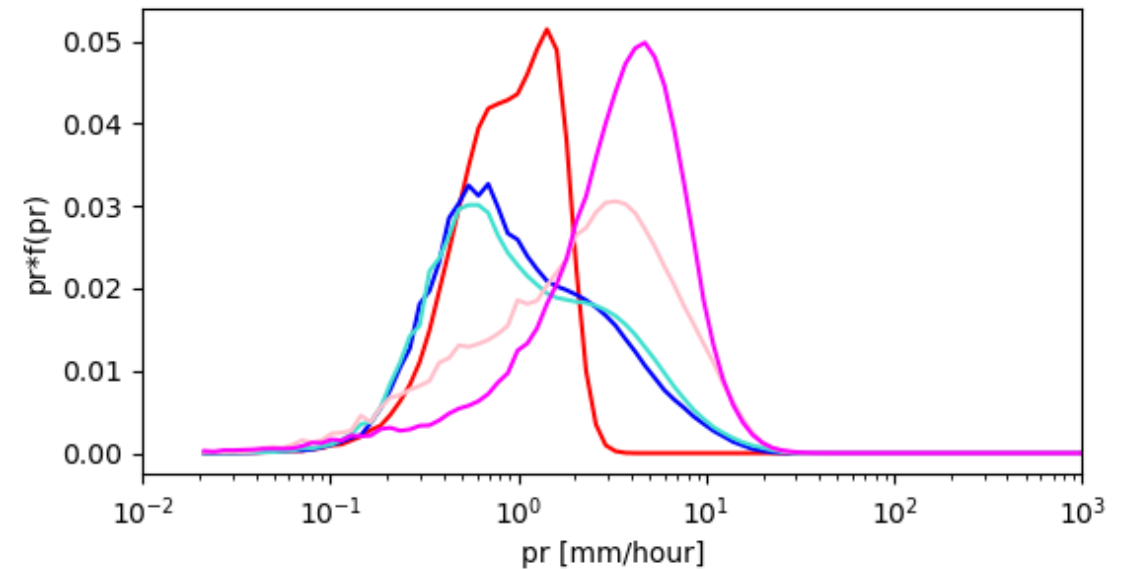
Circulation response to convection is dependent on the resolution and so cannot use low resolution simulations for sensitivity

# Can we use this to test and develop global high resolution model?

4.4 km model



Channel flow (TWPICE)



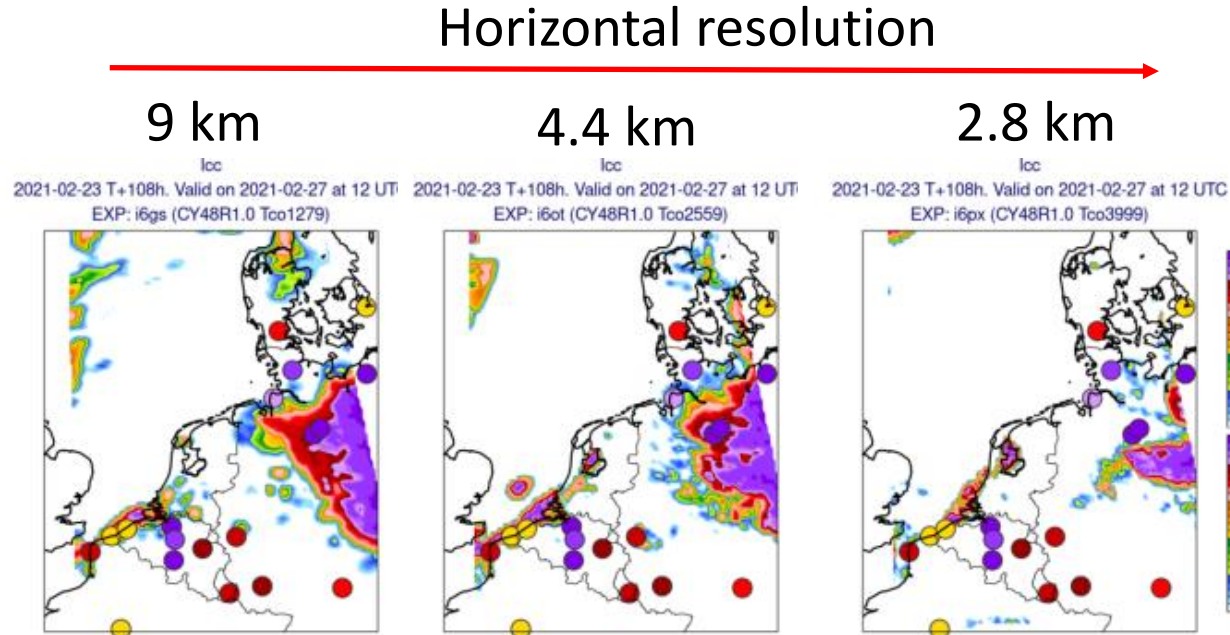
- Standard
- RCBMF
- RCBMF + TKE
- RCBMF + no MFC
- No deep

# Low cloud and fog

# Impact of TKE on low level clouds

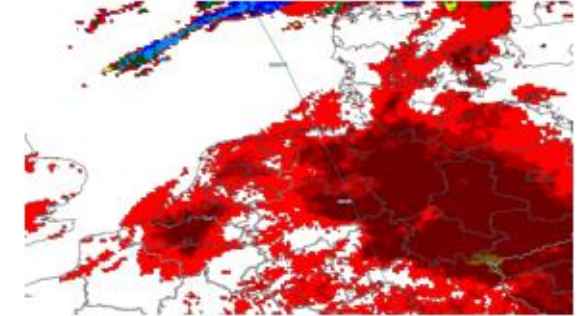
Current turbulence scheme underestimates **low cloud cover**, and more mixing occurs at high resolution

CY48R1.0

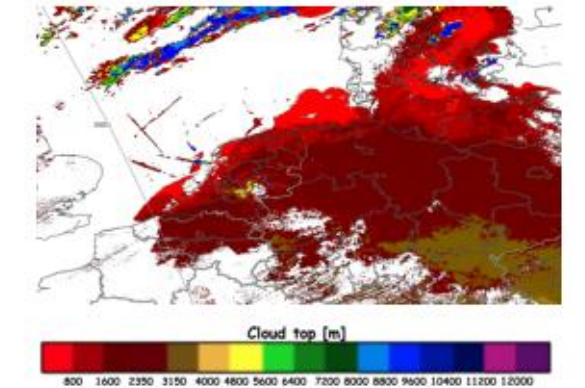


Observation of cloud top height

CI Top Aqua 2021-02-27T12



CI Top NOAA 2021-02-27T12



Figures c/o Ivan Bastak-Duran

# Impact of TKE on low level clouds

Horizontal resolution

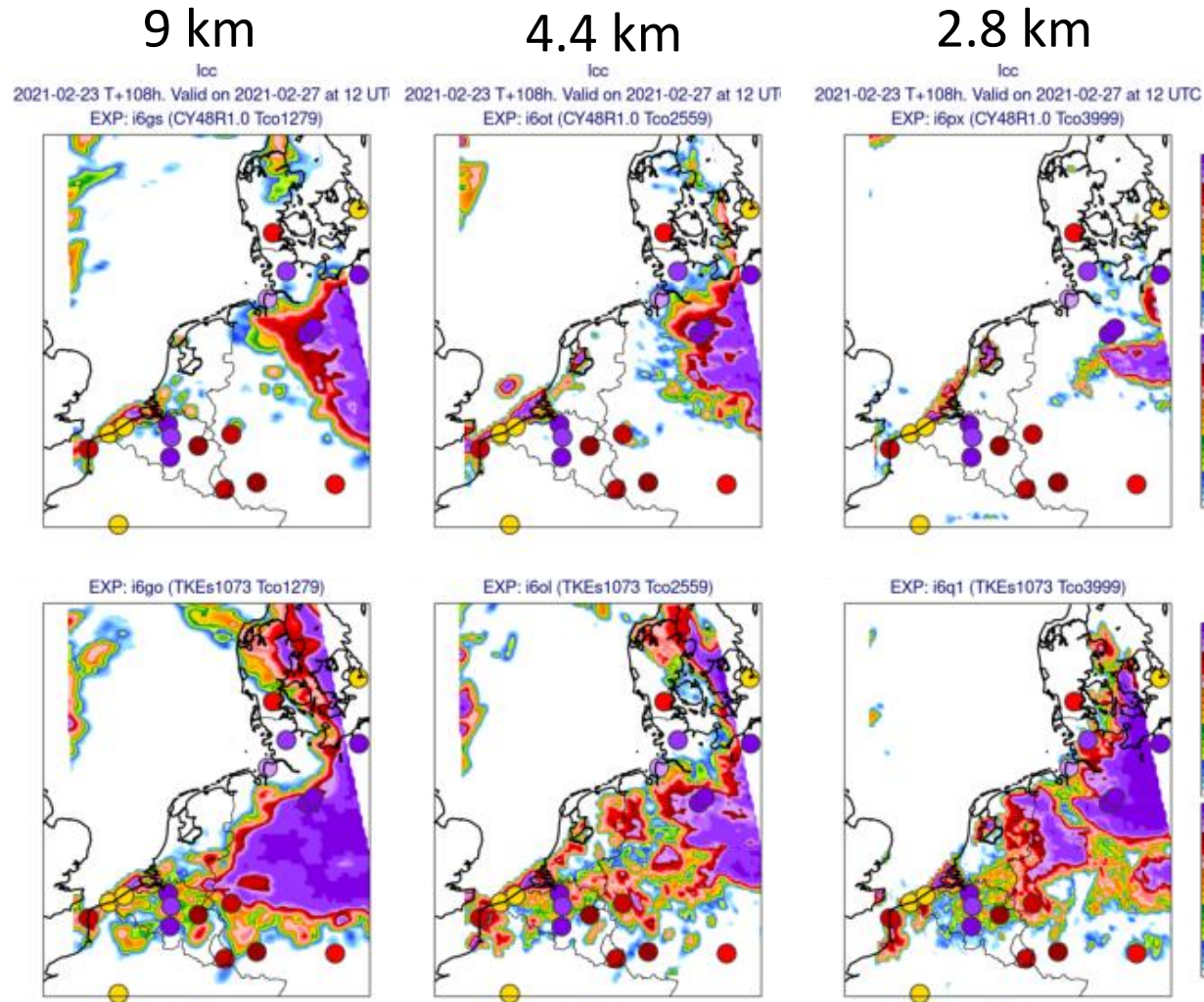


Current turbulence scheme underestimates **low cloud cover**, and more mixing occurs at high resolution

TKE scheme tends to have less mixing in these cases, and so can maintain low cloud

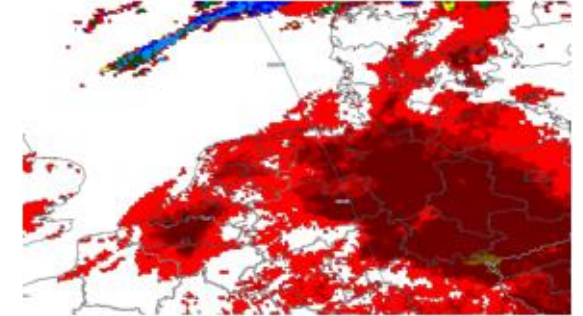
CY48R1.0

TKEs1073

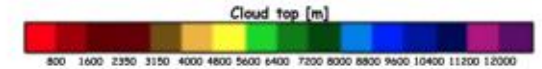
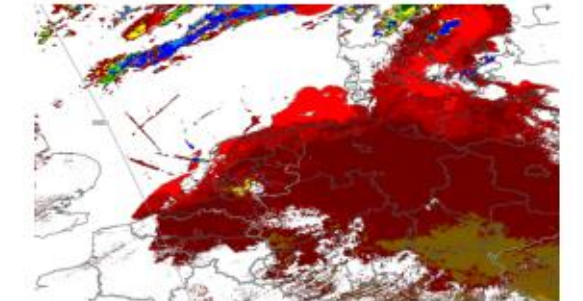


Observation of cloud top height

CI Top Aqua 2021-02-27T12

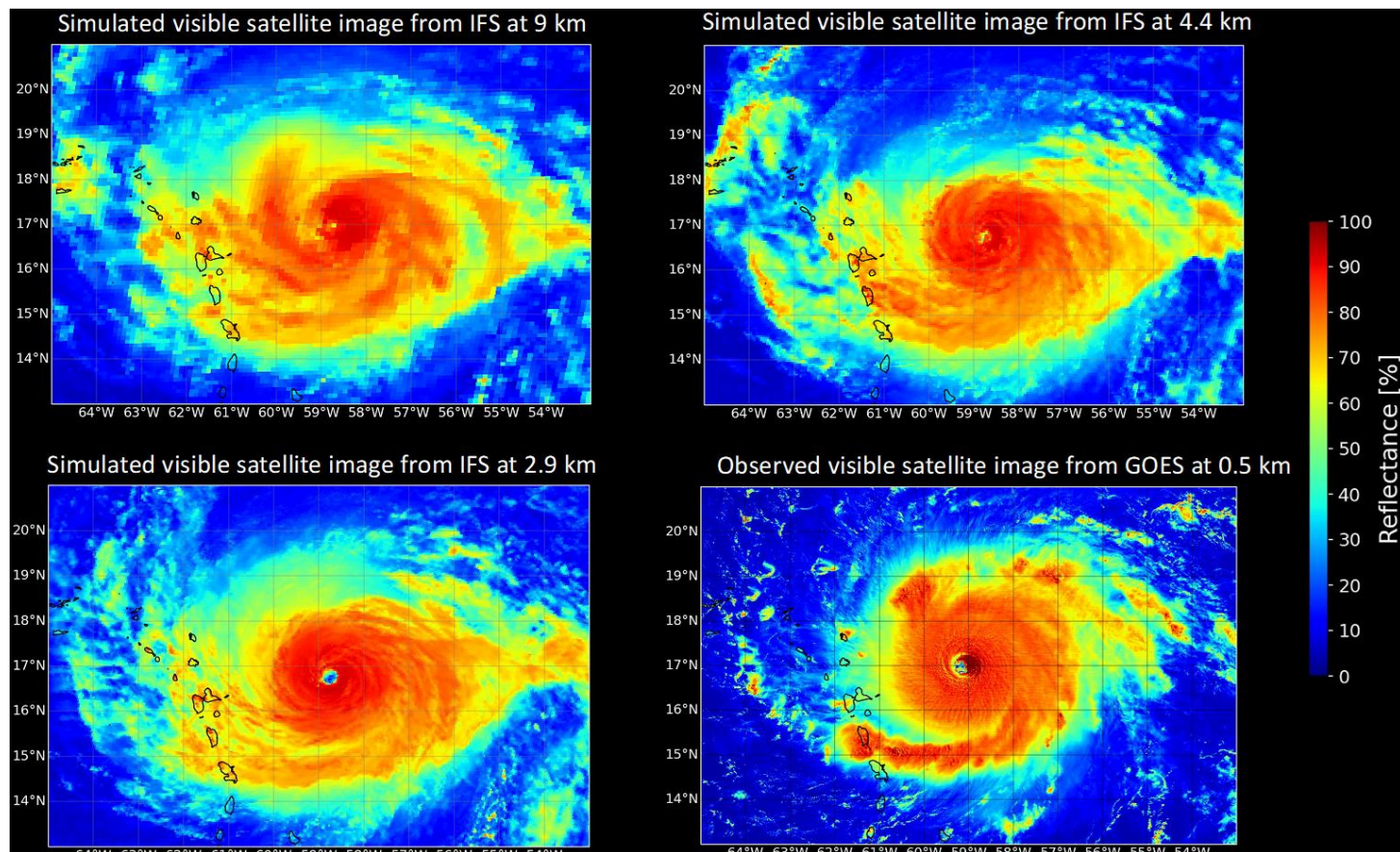


CI Top NOAA 2021-02-27T12



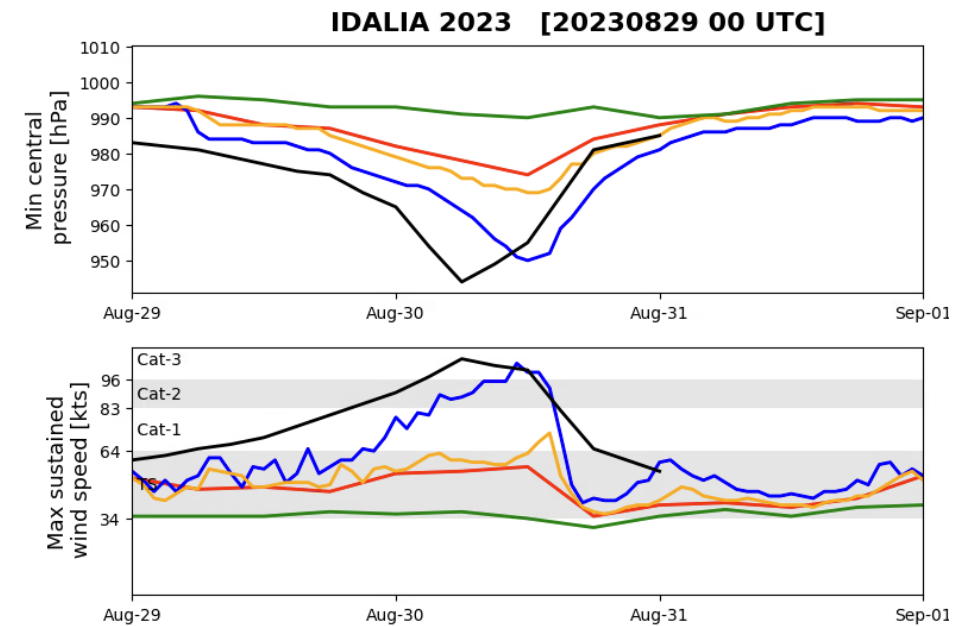
# Tropical cyclones

# Tropical cyclones at km-scale

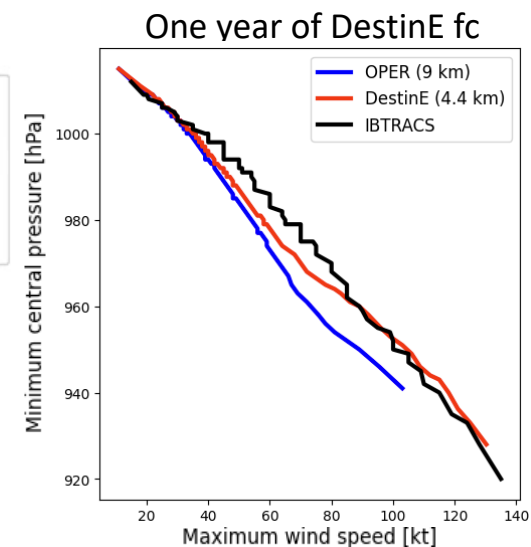


Hurricane Irma (2017-09-05 00 UTC T+18)

... improved mesoscale features & intensity but lingering slow propagation bias



- HRES (9 km)
- DestinE (4.4 km)
- CY49R1 v11 (9 km)
- Pangu (0.25 deg)
- IBTrACS (provisional)



# What have we learnt?

- **Orography**
  - Degradation in NH wintertime with increasing resolution is predominantly from orographic gravity waves over Himalayas
  - Non-hydrostatic effects become important at  $dx < 4.4$  km, but only over the Himalayas and for particularly strong winds
  - Small-scale orography is filtered and timestep is reduced to damp spurious waves
- **Convection**
  - Convection has a timestep sensitivity, likely that other schemes do too?
  - Increasing resolution leads to too much light precipitation over tropics, and spurious waves
  - We do not have an optimal configuration for high resolution, idealized simulations may help us reduce cost of testing physics-dynamics coupling
  - Increasing resolution causes underestimation of low cloud and fog, TKE scheme helps in this
- **Tropical cyclones**
  - The good news is that we do see improvements in tropical cyclone intensity
- **Not shown** but improved extremes, e.g. surface parameters over orography

# Key lessons from **global** high resolution modelling

- Increasing horizontal resolution does not lead to improved forecasts 'out-of-the-box': physical model developments and understanding is required
- Validation methods and observations really matter for high resolutions
- There is **a lot more** potential for the high resolution simulations, with further development e.g. hybrid-AI, tropics, seasonal?