The effect of including boundary perturbations in ensembles of the North-West European Shelf-Seas

Tom Louden-Cooke and Matthew Martin

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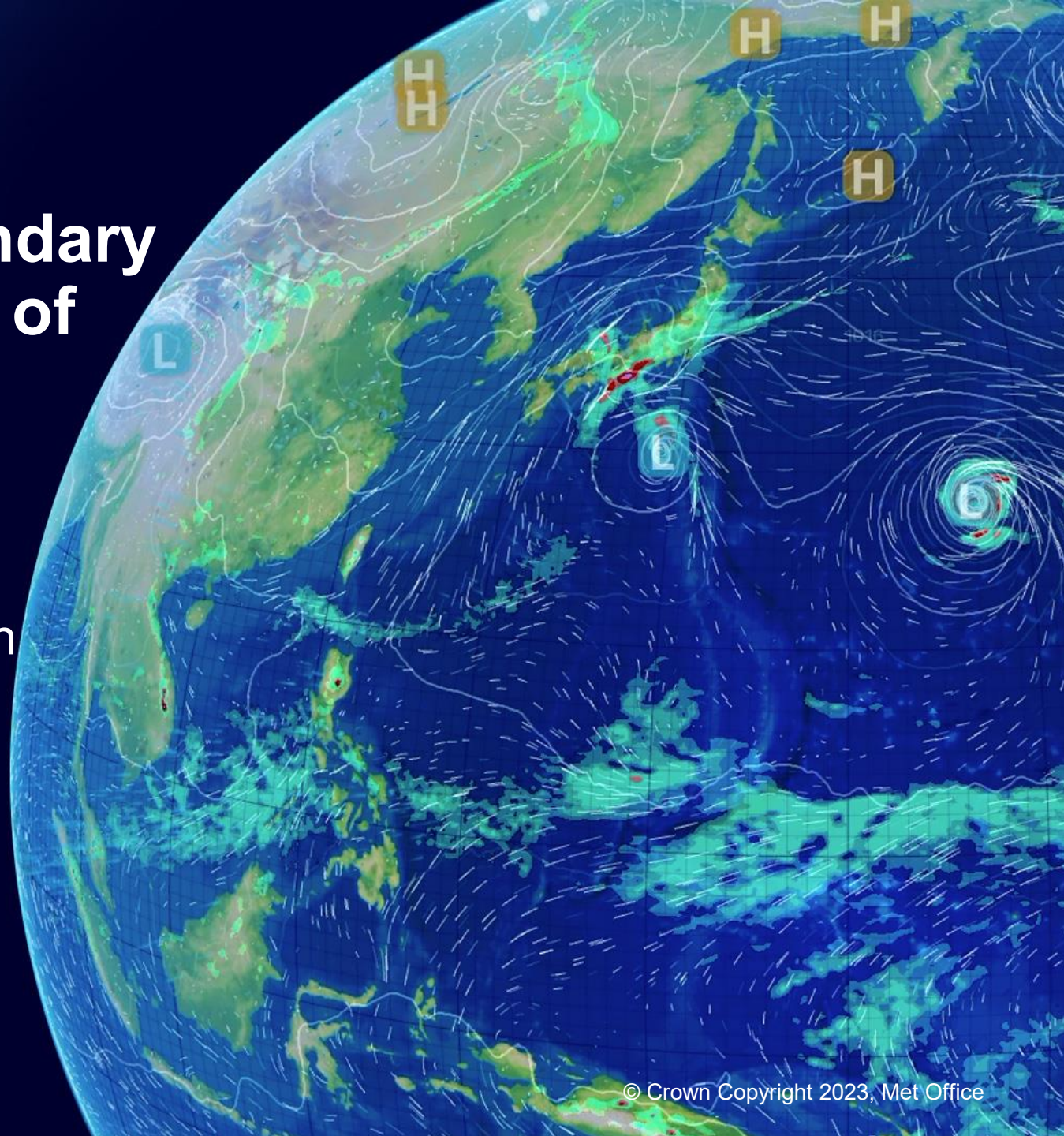
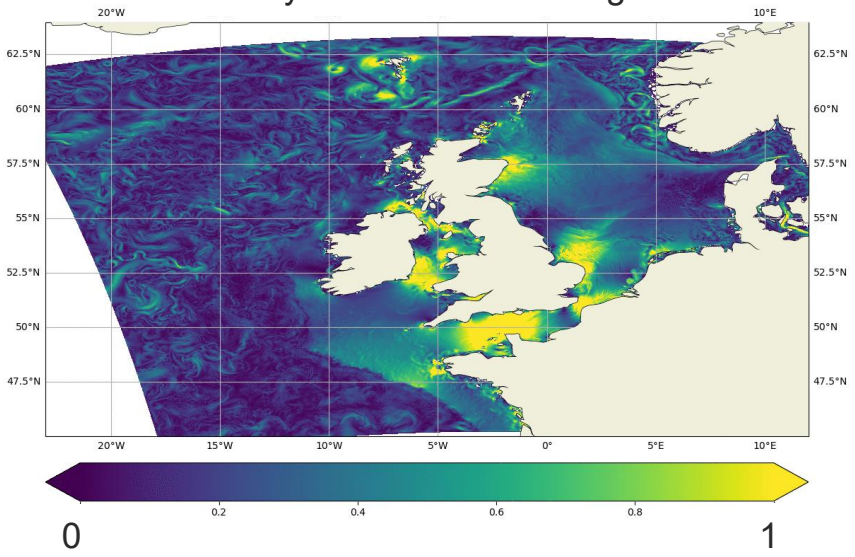


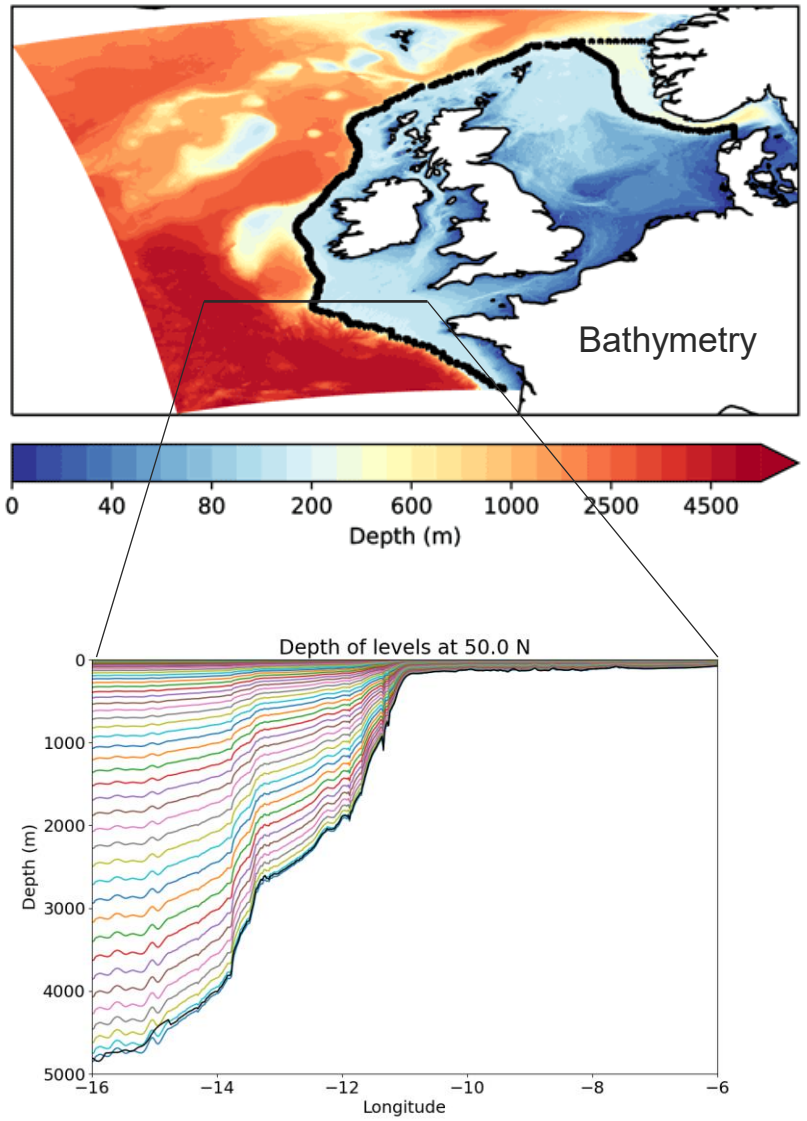
Existing NWS MFC forecasting system
Model

Current operational systems [Tonani et al., 2019]:

- Configuration called CO8 - NEMO model v3.6
- Hybrid s-sigma terrain-following coordinates (51 levels) which vary with time.
- AMM15 (1.5 km) with coupled waves (WWIII)
- AMM7 (6-7 km) with coupled BGC (ERSEM) (not in this ensemble)
- Variability on different spatial and temporal scales.

3-hourly surface current magnitude



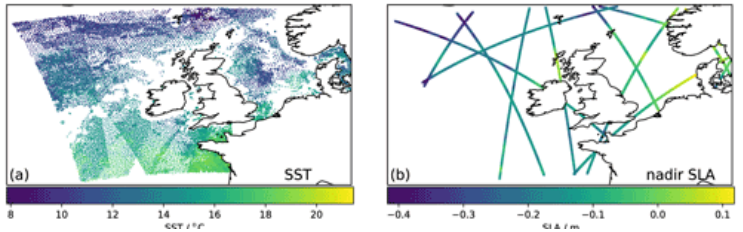


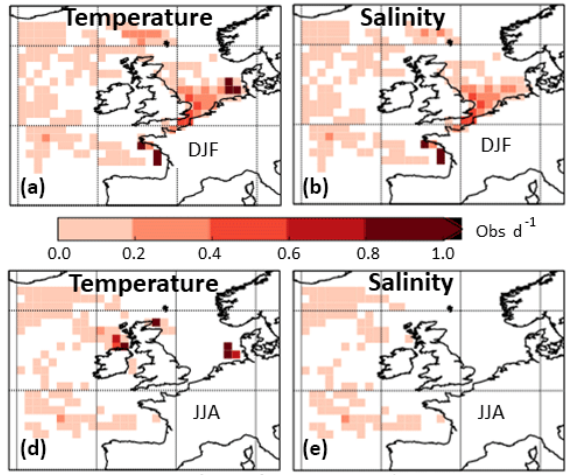
Existing NWS MFC forecasting system
Observations

- Observations assimilated:
  - In situ and swath (L2) satellite SST (SEVIRI, MetOp/AVHRR, S3/SLSTR, VIIRS, AMSR2).
  - Along-track nadir SLA data:
    - Tides removed but we include the signal due to inverse barometer.
    - H(x) calculated using 24 h 50 min average of the model SLA.
    - MDT (CLS18)
  - In situ profiles of T/S.
    - Argo (in deep part), moorings, gliders, marine mammals, XBTs, CTDs, Ferrybox, …
    - Not many profile obs, particularly on the shelf.
  - Ocean colour in AMM7 [Fowler et al., 2023].

- Observation bias correction:
    - SST using variational BC approach [While & Martin, 2019]
    - Bias correction for SSH assimilation to account for errors in MDT [Lea et al., 2008].

Example daily coverage

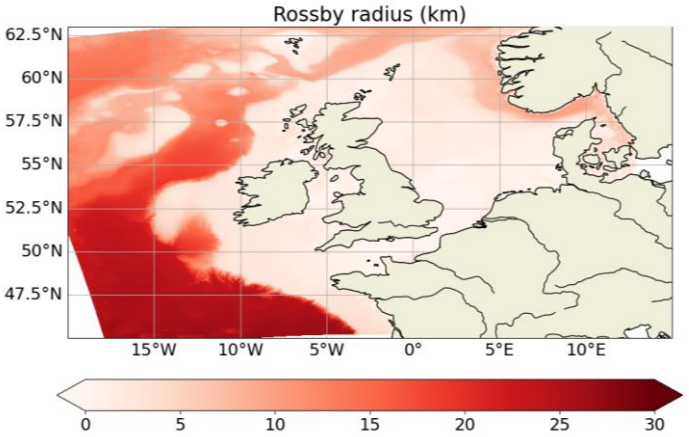




Obs/day in 2° bins

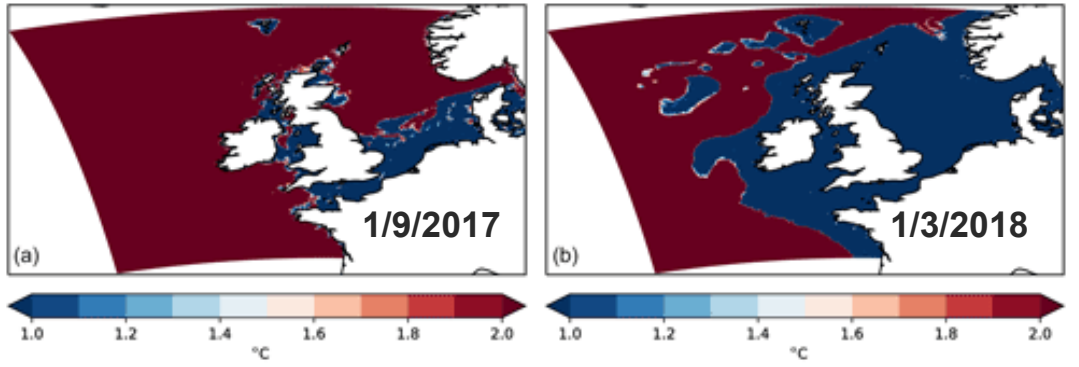
Existing NWS MFC forecasting system
Data assimilation with NEMOVAR

- Multivariate incremental 3DVar-FGAT scheme [King et al., 2018, King & Martin, 2021].
- Observation operator and IAU code in NEMO (obs oper will eventually use JEDI).
- Implicit diffusion operator for modelling spatial correlations in **B** which spreads information along the model levels (not horizontal).
- Two horizontal length-scales in **B**:
  - 100 km for the long length-scale
  - Rossby radius of deformation for the short length-scale (limited to a minimum of 3 times the grid scale).
  - Each background error scale component has an associated set of spatially and seasonally varying error variances.
- Vertical length-scales depend on the background mixed layer depth



- Multivariate balances:
  - T/S relationship, dynamic height, geostrophy.
  - Baroclinic SSH balance with subsurface T/S only applied fully when ΔT > 2°C, and not at all when ΔT < 1°C.
  - SLA data produce mainly barotropic corrections on the shelf during the unstratified periods.

$$\Delta T = T_{z=0} - T_{z=bottom}$$



Ongoing development work – ensemble capability *Operational implementation over the next 2-3 years*

Ensemble AMM15 development (currently being tested in AMM7)

- Forced at the surface by an atmospheric ensemble (currently ERA5 but moving to MOGREPS-G)
- Each member runs its own data assimilation with perturbed H(x) in an EDA approach:
  - perturbations to H(X) should have the characteristics of R (Van Leeuwen, 2020).
  - We add measurement errors and mimic representation error by perturbing the location at which H(X) is calculated.
- Each member has stochastic model perturbations in NEMO using the code developed by Andrea Storto called STOPACK which includes SPP, SPPT and SKEB methods.
- Capability was developed in collaboration with NOC to perturb the river inputs (Zedler et al 2023)

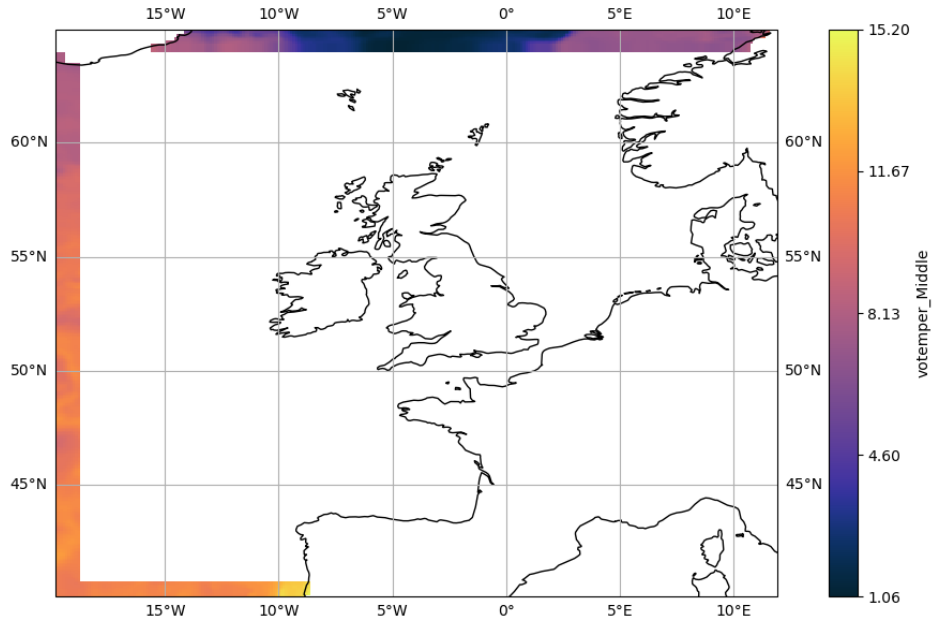
An early version of the AMM7 version of this system was used in collaboration with PML to run coupled physics/BGC ensemble experiments to understand uncertainty of ecosystem indicators (Skakala et al 2024)

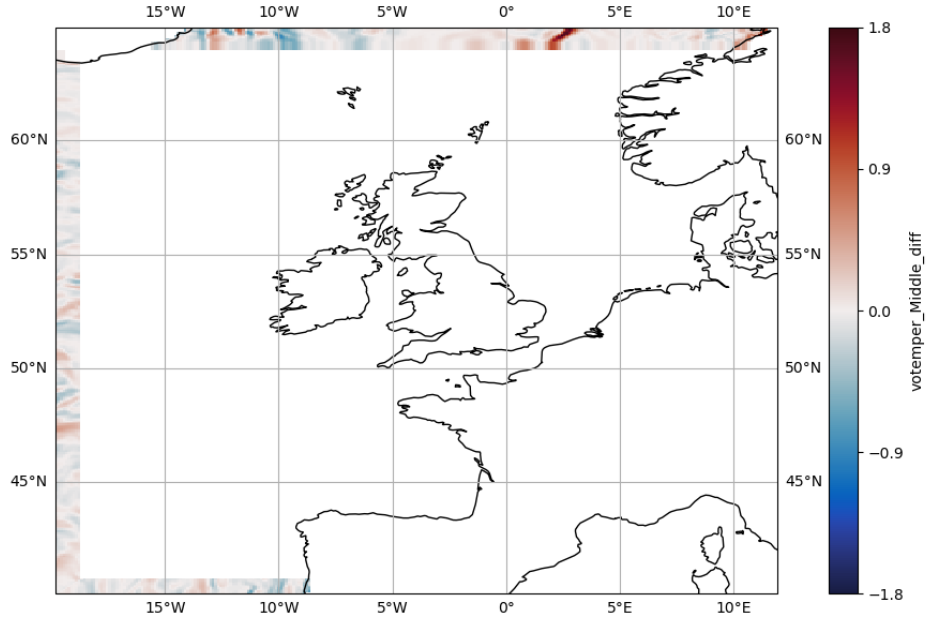
Boundary perturbations in the AMM7 ensemble – motivation

- The boundaries of the domain are currently identical between all ensemble members
- This fails to capture a key piece of uncertainty, contributing to the general under
- Appropriate boundary ensembles are not available in the operational system in this time
- What is needed is a simple perturbation system that can be implemented operationally
- Enables a thorough study of the effects of boundary perturbations on the domain

Boundary perturbation method

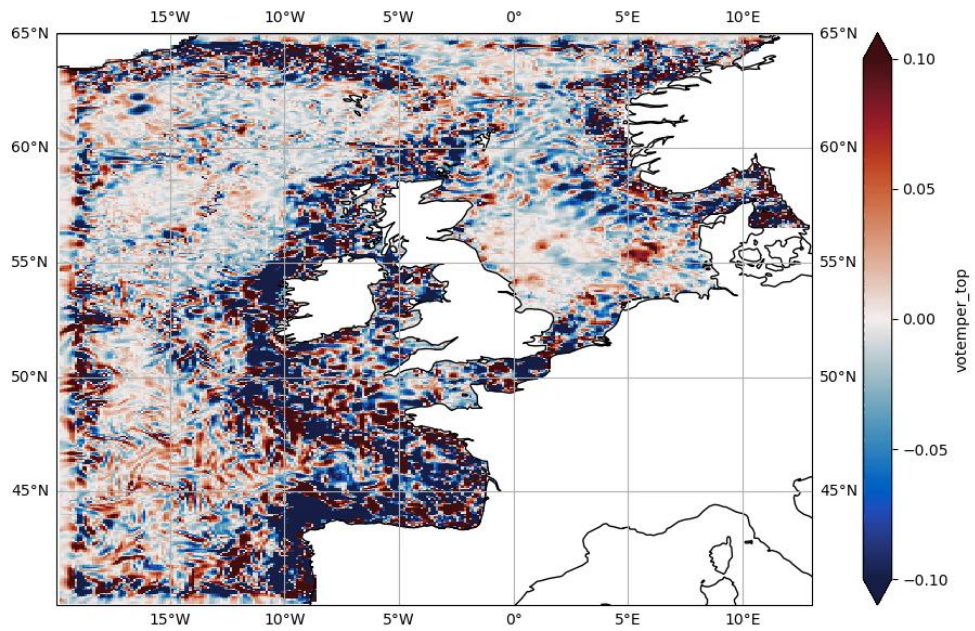
- Lateral and temporal perturbation
- Lateral and temporal perturbations chosen so the scale is similar to what is observed in global ensembles
- Fixed seed based on ensemble number and date
- Magnitude of the perturbation is a gaussian variable
- Linear interpolation in both directions
- Requires the previous and subsequent data files to be available

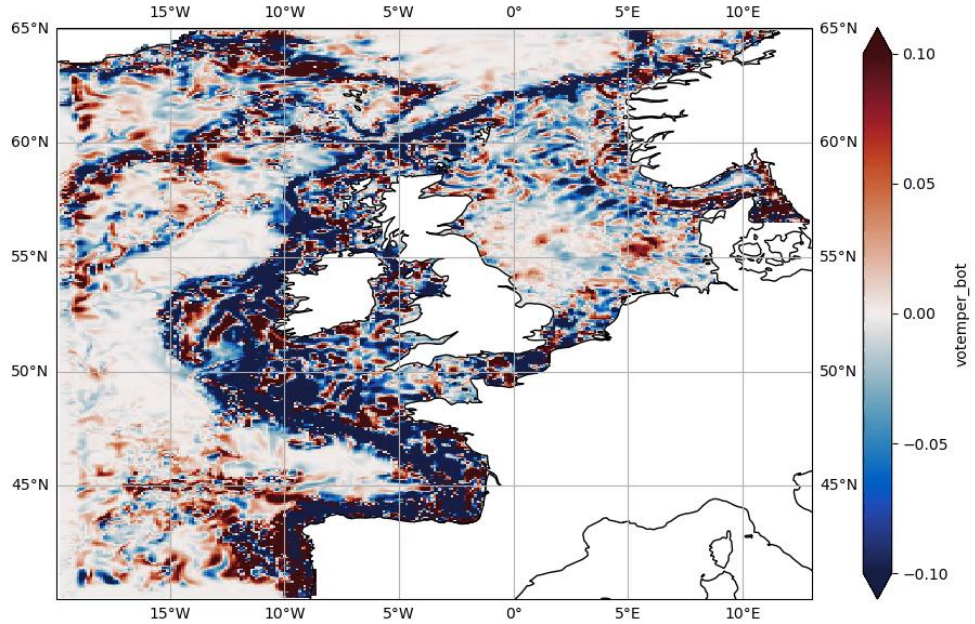




Test run

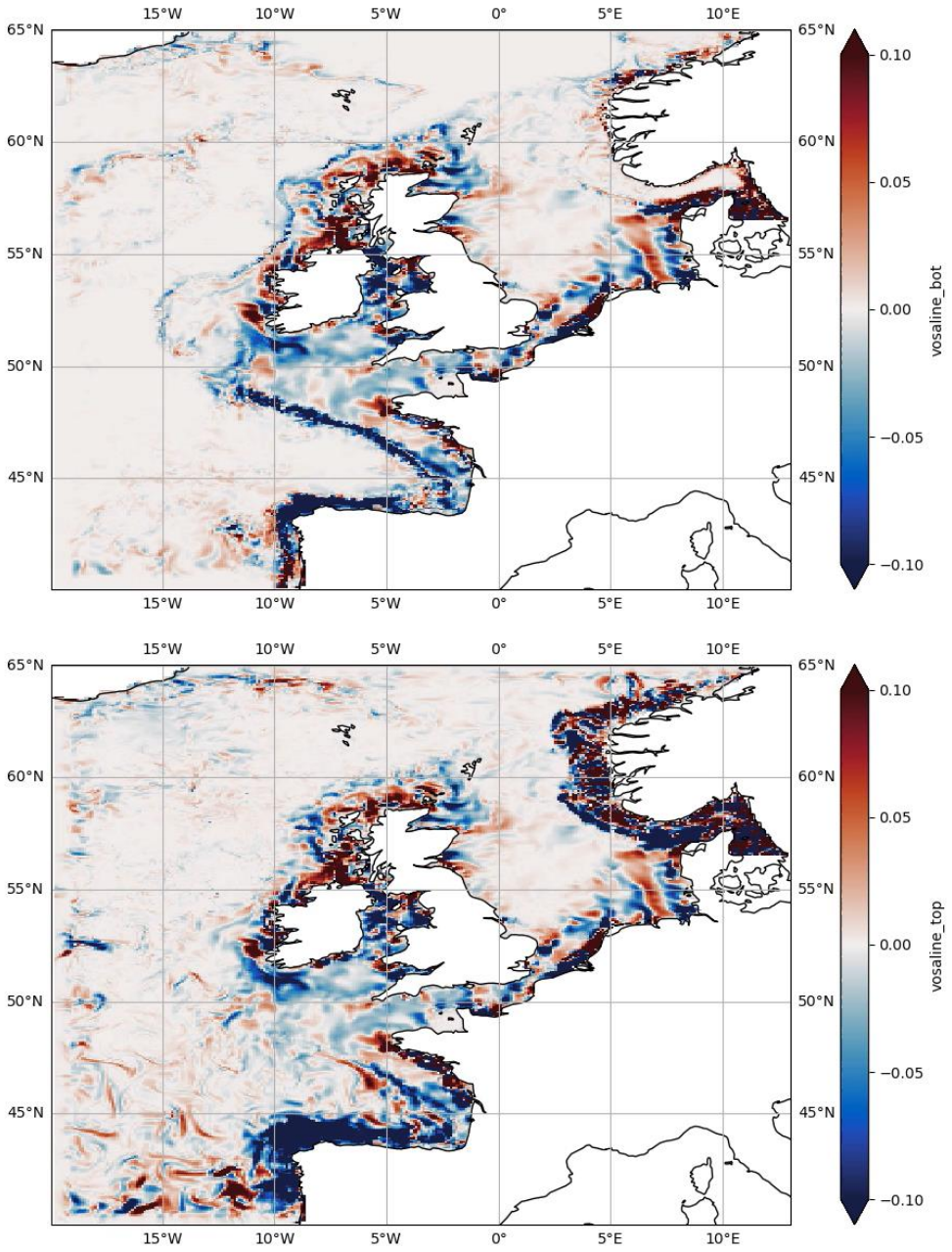
- The AMM7 ensemble was run in reanalysis mode for a period of 4 months in 2019
- The ensemble was fully burned in for a period of 6 months in 2018 before any further experiments took place
- The lateral and temporal boundary perturbations were applied to the domain
- After four months, the differences between this run and a regular run with our existing perturbations applied
- (note, the other perturbations are seeded, so will be identical between the two runs so will not show up in these difference plots)





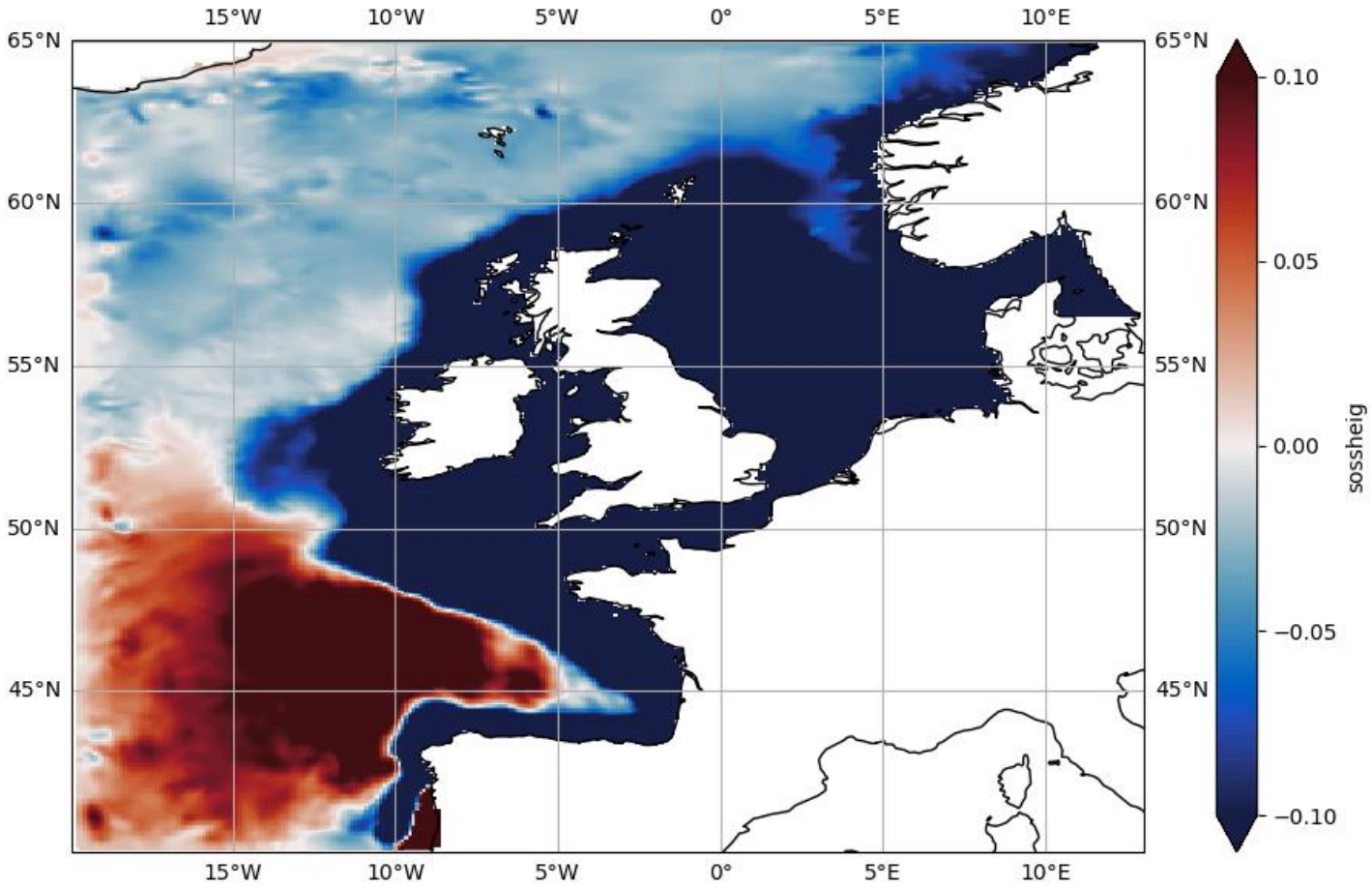
Gradient problems

- Problem – due to the way the grid system is defined, at some depths the lateral shifts in regions of high bathymetry gradient are unrealistic
- Causes very strong perturbation effects, particularly apparent on the southern region border near the shelf break
- These perturbations travel rapidly through the domain via the shelf break
- The propagation is expected and in line with theoretical results – the large scale of the perturbations is not!



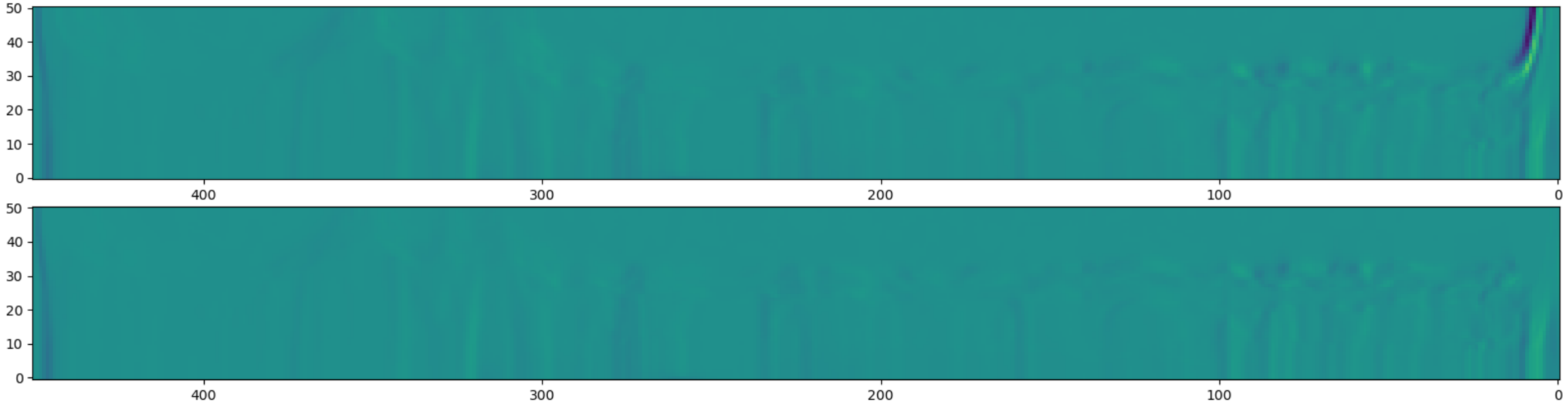
Boundary differences

- Worse still, this effects the sea surface height in an unphysical way
- Even worse still, the effect builds up over time!
- This behaviour is unsatisfactory…

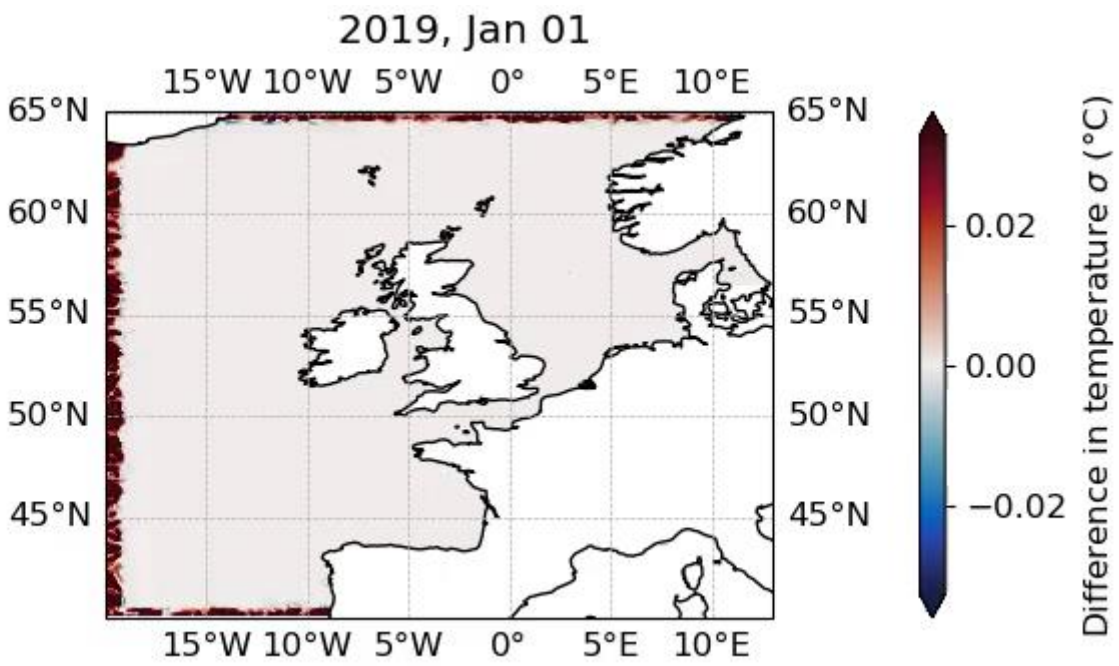


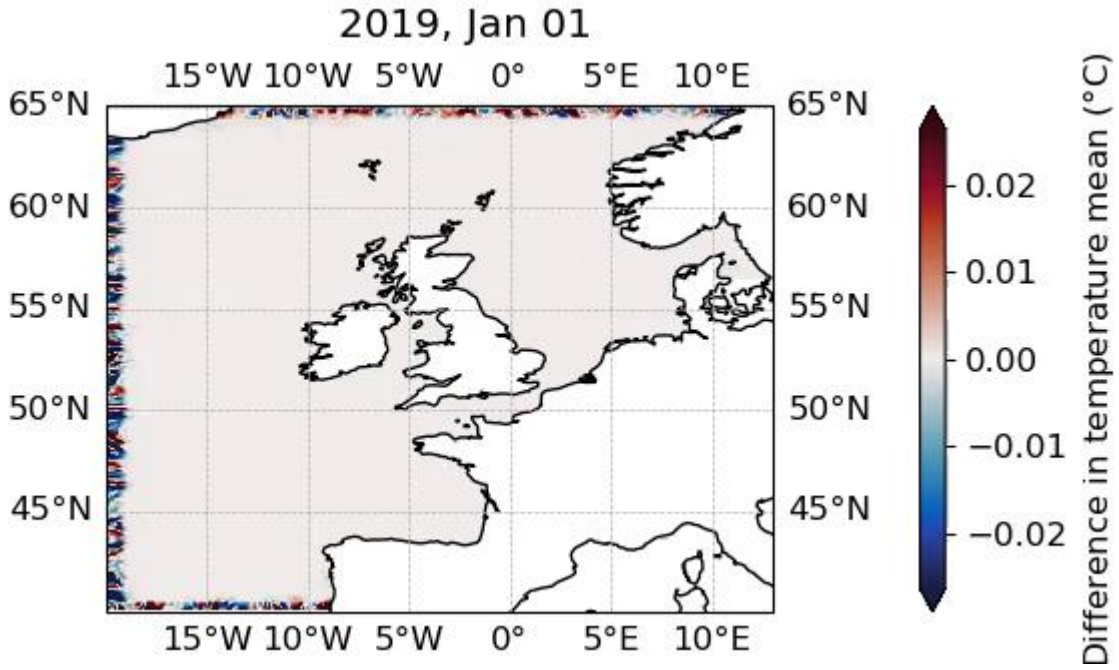
Solution

- Region of high cell-to-cell depth coordinate difference found corresponding to the shelf break
- The assumptions of the lateral perturbation scheme break down in these regions – it becomes a vertical perturbation, not what we want!
- A simple weighted roll-off smoothly de-activates the pertubations in regions of high gradient

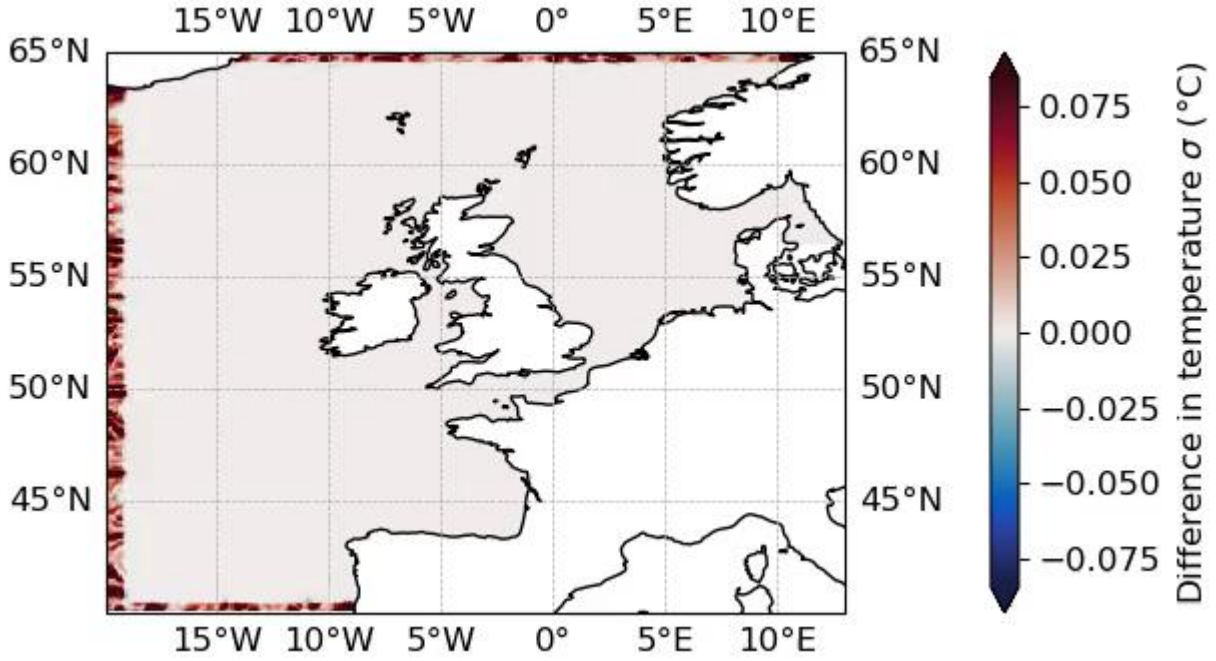


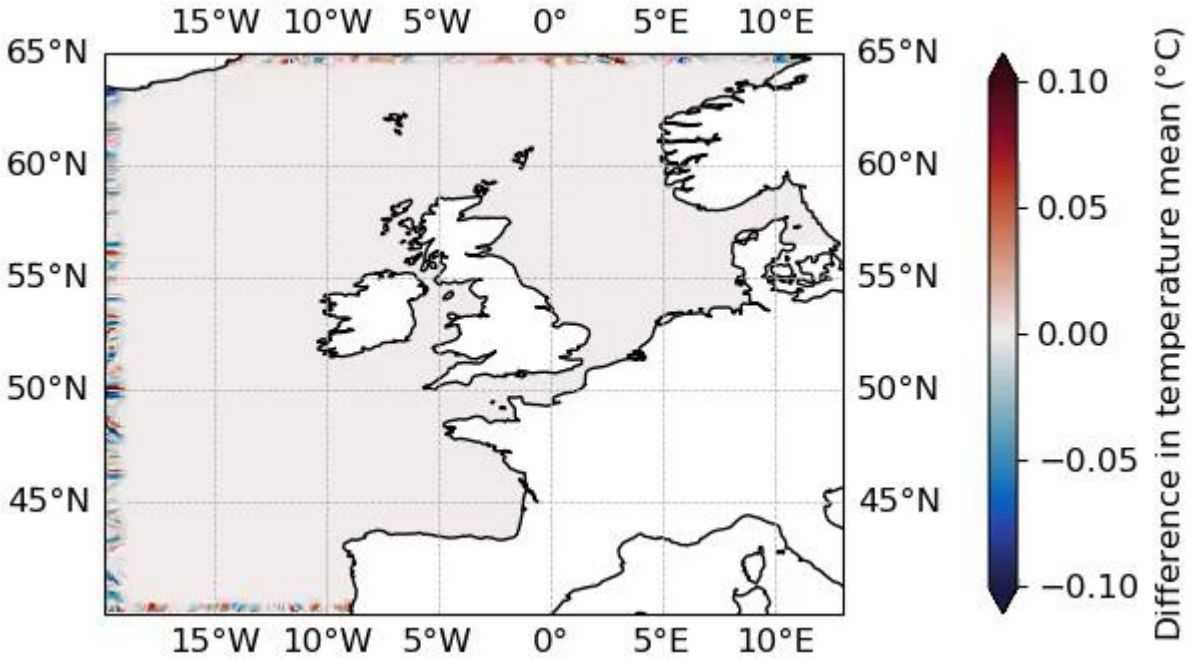
Differences in the ensemble std and mean after 3 months



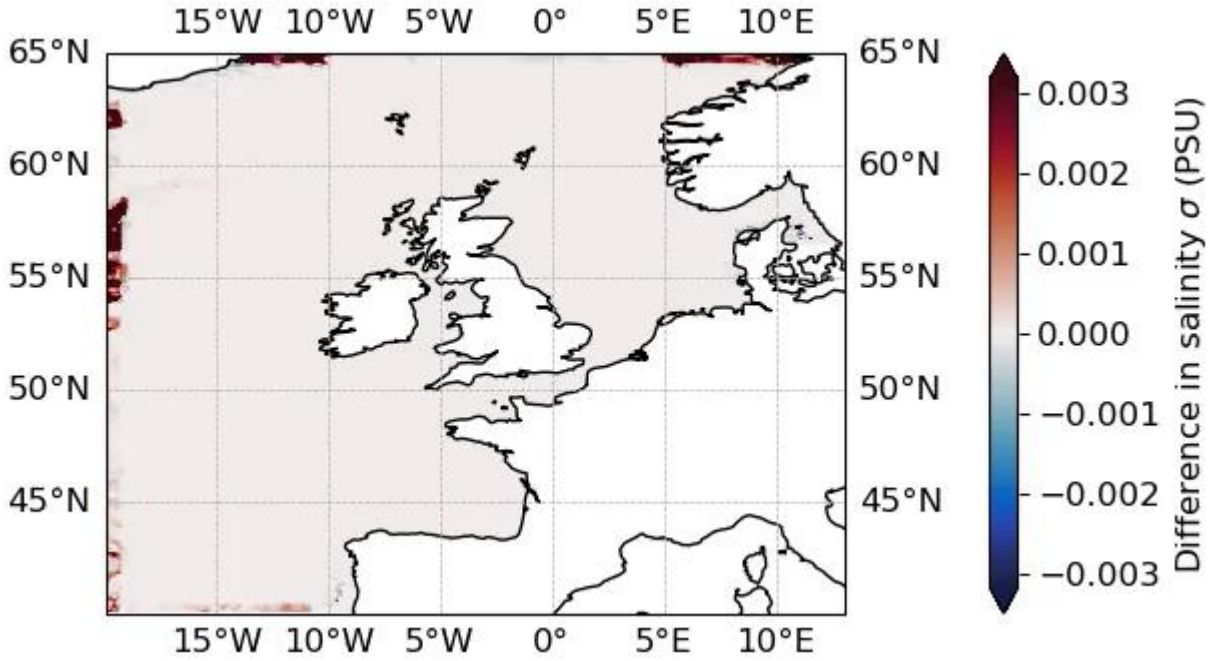


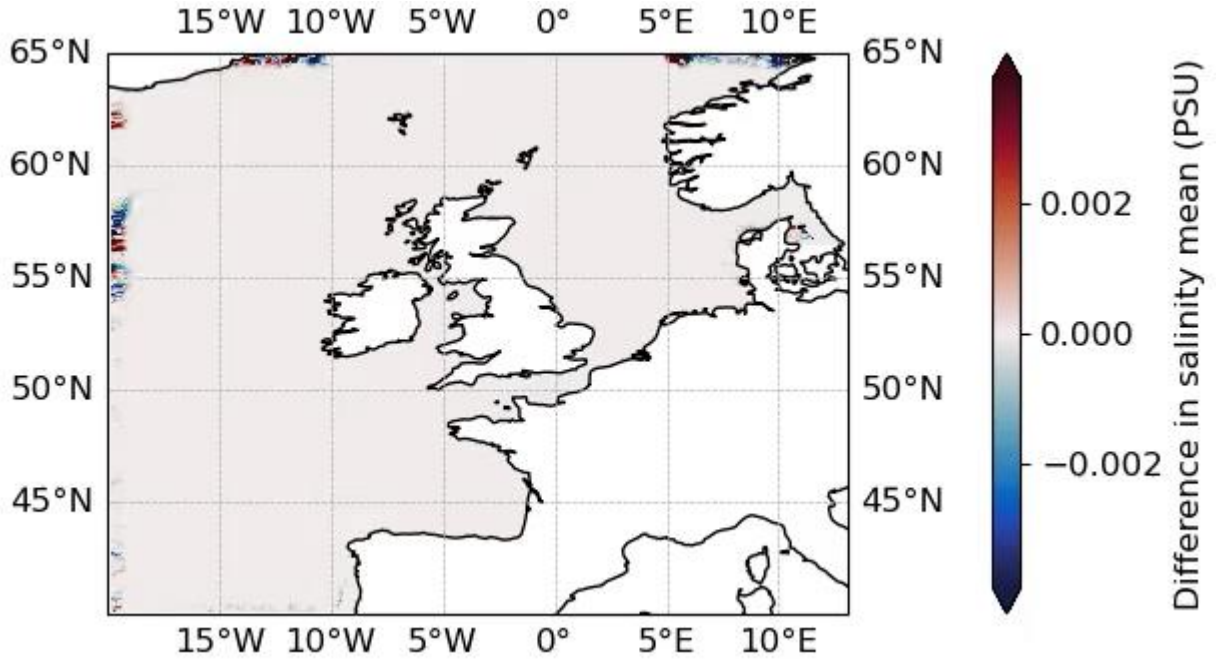
Free run- SST Ensemble evolution over one year



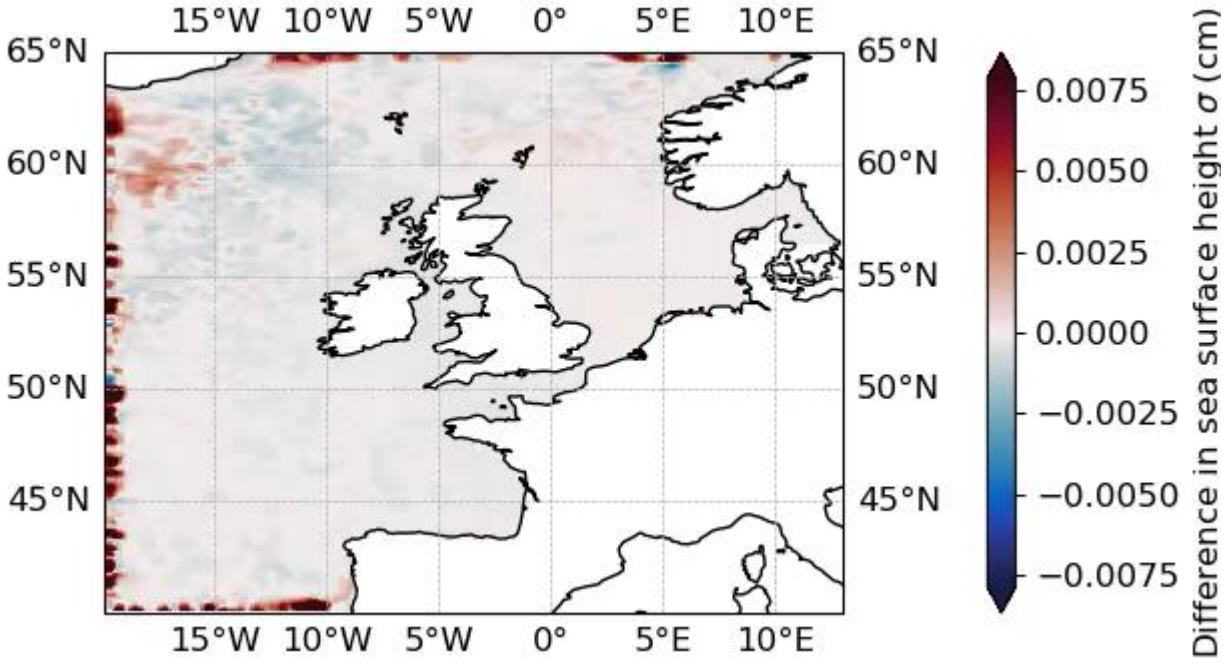


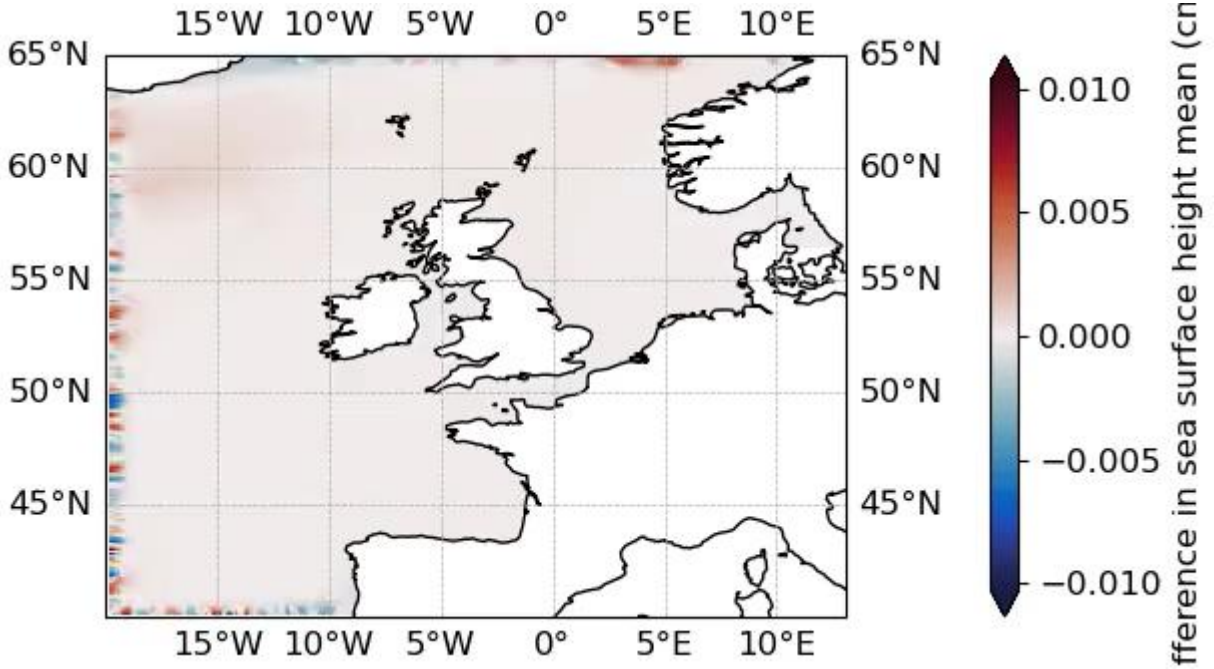
Free run- Bottom salinity Ensemble evolution over one year





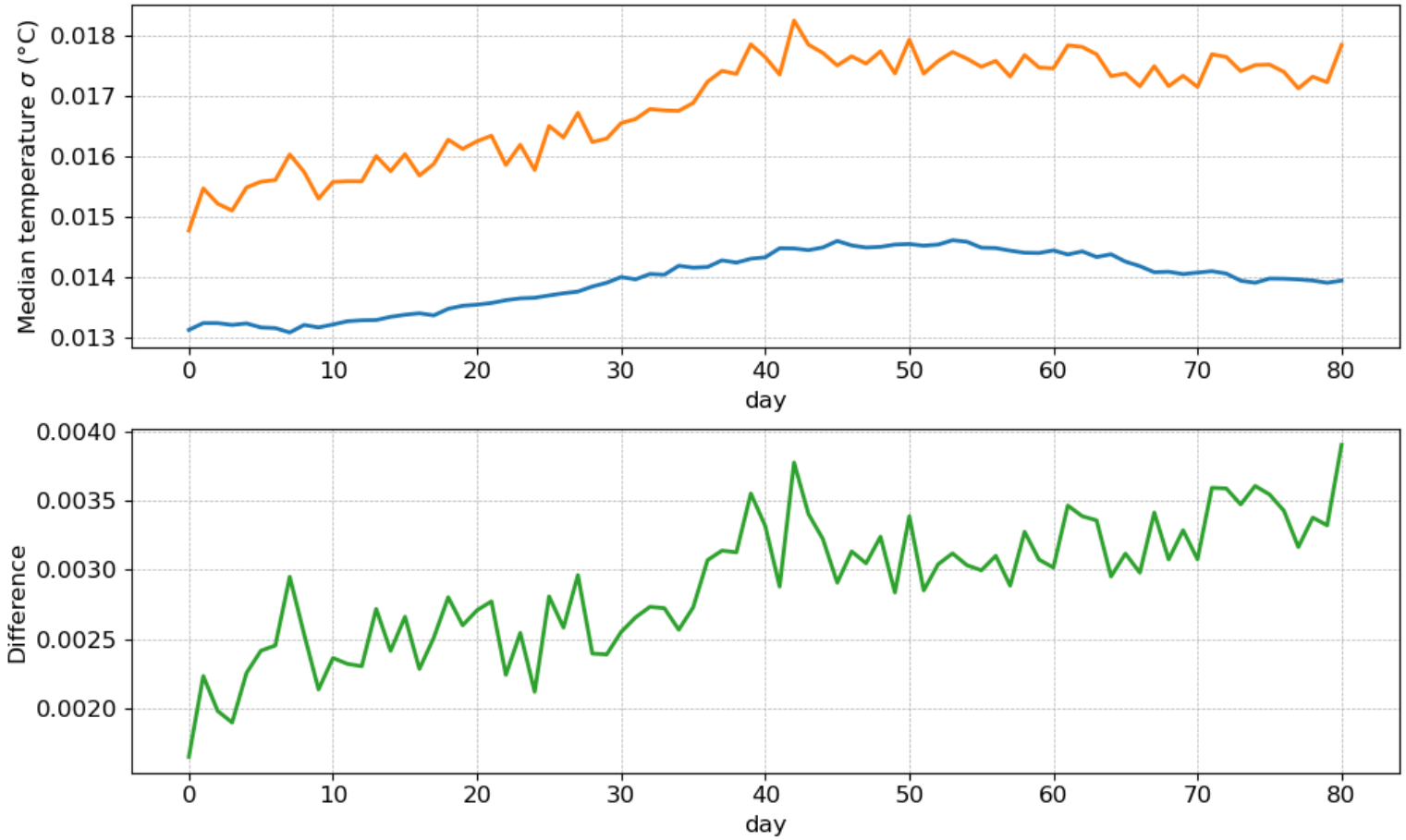
Free run – SSH evolution over one year (success)!





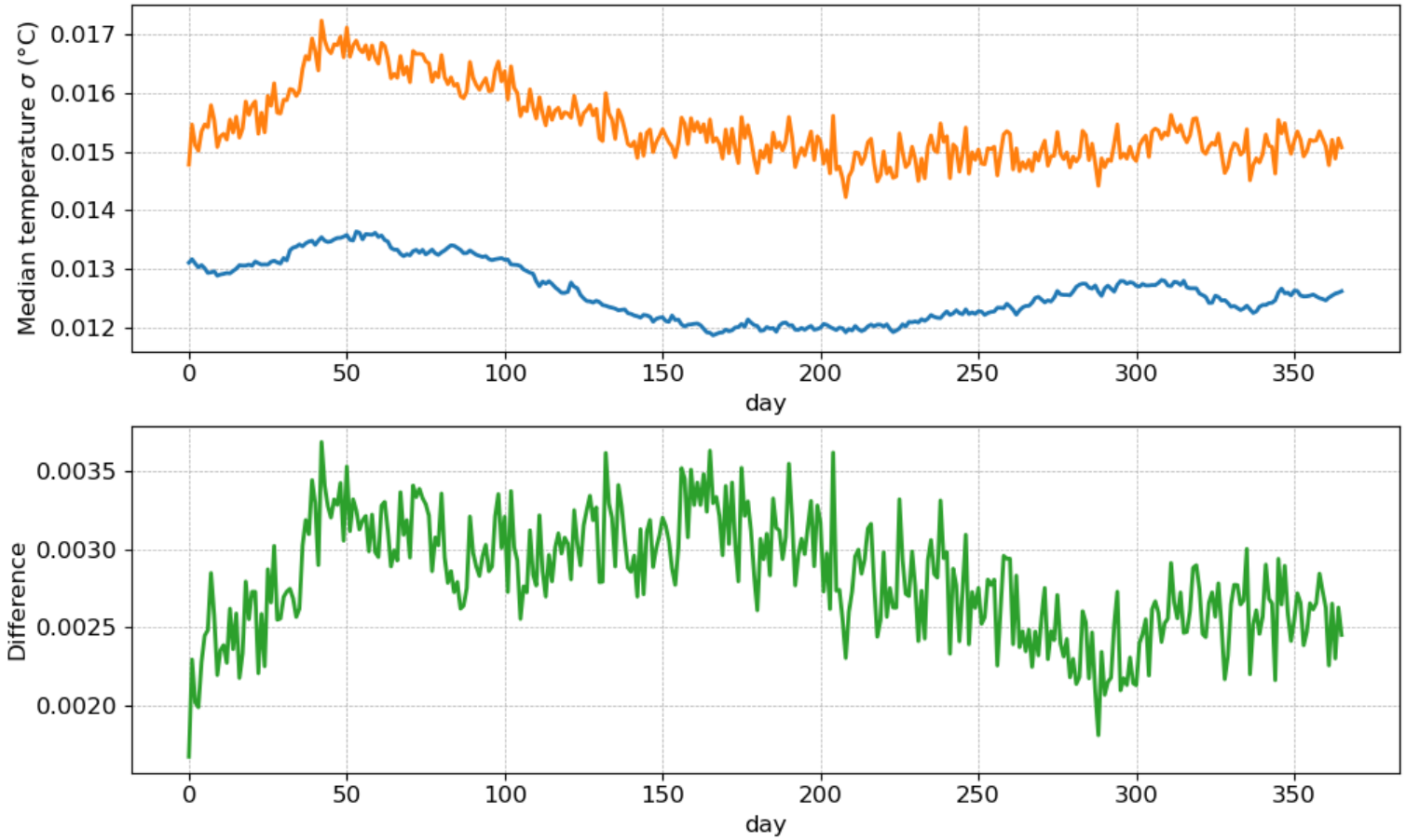
Met Office

Time Series



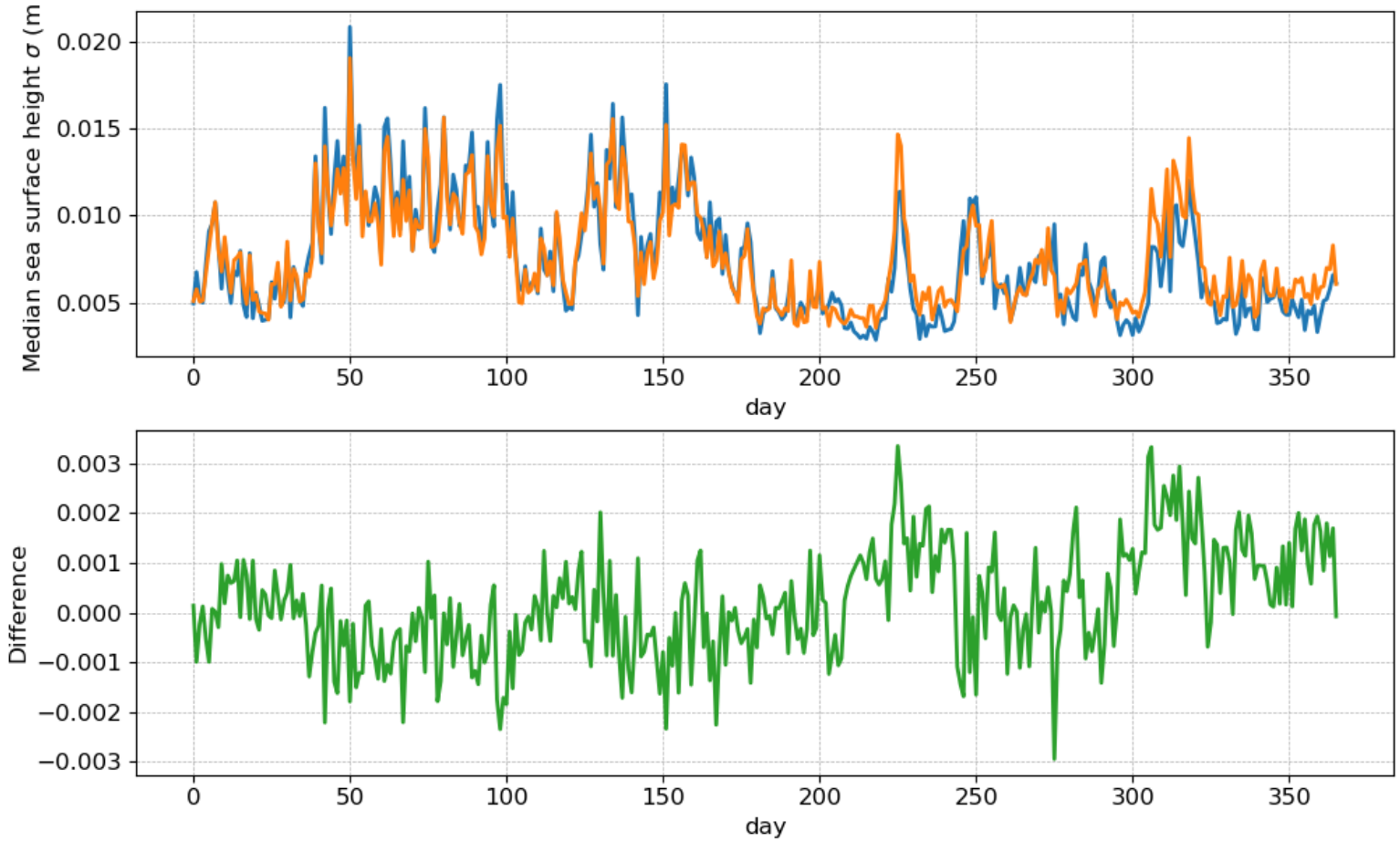
Met Office

Time Series – Free



Met Office

Time series – Free



Conclusions

Summary

- Lateral and temporal boundary perturbations were applied to the AMM7 ensemble
- The perturbations travel rapidly along the shelf break, but generally struggle to propagate onto the shelf
- Errors in the lateral boundary can have domain wide, unintuitive effects
- After corrections, long duration testing demonstrates the stability of this approach

Ongoing work

- Quantifying the change in the forecasts between perturbed and unperturbed
- Quantifying the relationship between the perturbation parameters and the spread
- Update to CO9 configuration – based on NEMO 4.04
- Ensemble AMM15 operational within 2 years

Thank you

Any questions please contact

Tom.louden-cooke@metoffice.gov.uk