Bot river estuary,
W. Cape, S. Africa

Standalone JULES simulation of rivers and inundation

National Oceanography Centre

CHAMFER

Dr Toby Marthews (with huge thanks to many colleagues at UKCEH and the UKMO)

09-SEP-2026

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1. UK Coasts and CHAMFER
2. OWRMS and Sea Surges
3. Inundation in the Boyne and the Spey

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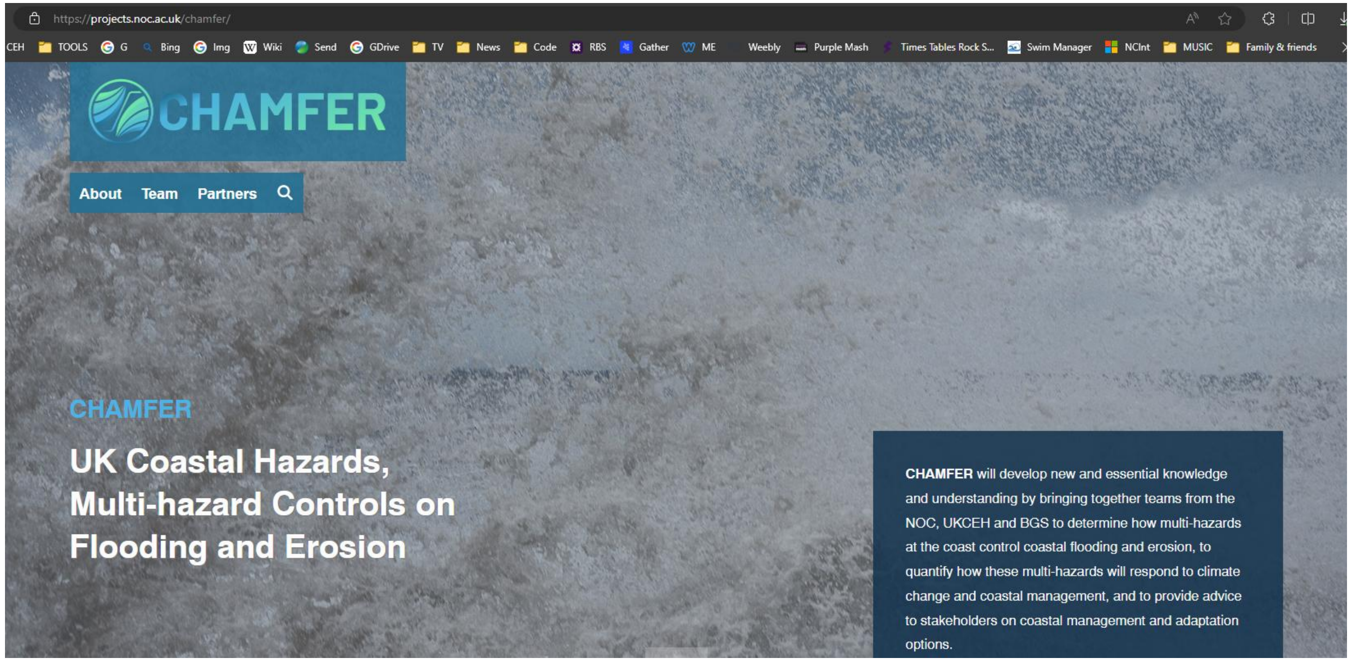
Project CHAMFER

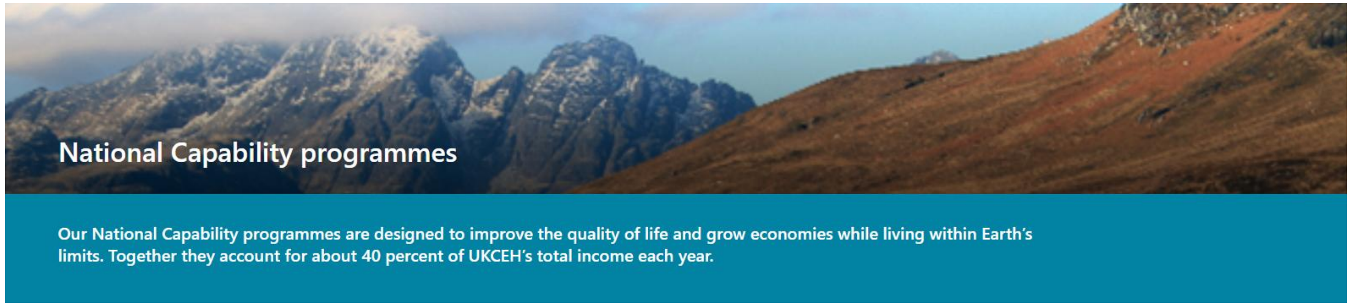
CHAMFER is a UK National Capability project (UK Coastal HAzards - Multi-hazard controls on Flooding and ERosion).
https://projects.noc.ac.uk/chamfer/

Modelling the coastal zone of the UK at 500m resolution.

Project duration: 2022-2027

CHAMFER will develop new and essential knowledge and understanding by bringing together teams from the NOC, UKCEH and BGS to determine how multi-hazards at the coast control coastal flooding and erosion, to quantify how these multi-hazards will respond to climate change and coastal management, and to provide advice to stakeholders on coastal management and adaptation options.



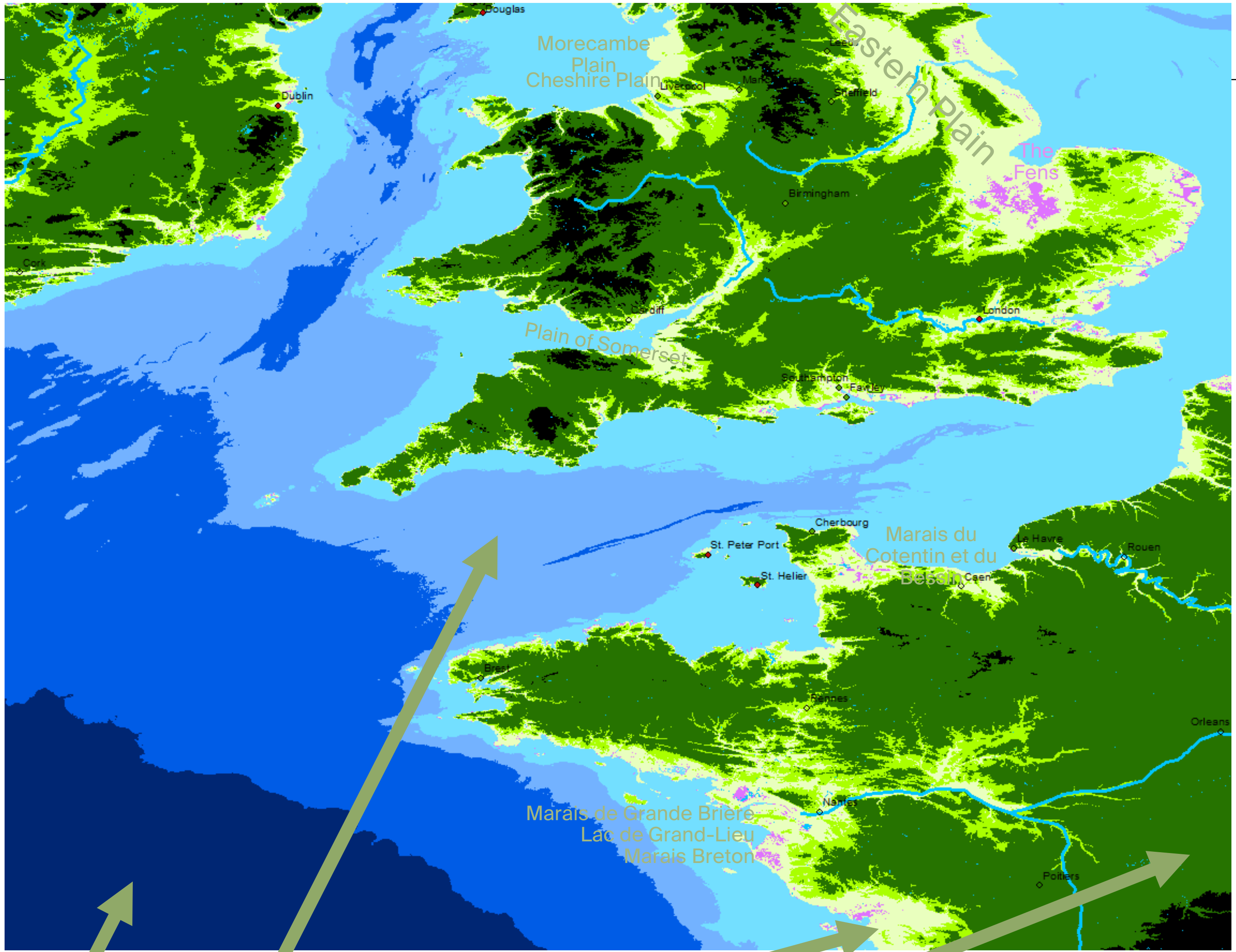


We are concerned with the **COASTAL ZONE**, which we define very broadly to include both coastal land and coastal ocean.

Approximately one third of the UK population lives within 10 km of the coast.

An important zone: 200 million people worldwide live along coastlines less than 5 m above sea level, and it is estimated that this figure could increase to 400 to 500 million by the end of the 21st century.

In the UK, responsibility for coastal zone research is divided between UKCEH and NOC.



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UPLANDS / PIEDMONT (>60 m asl)

COASTAL PLAIN (yellow <30 m asl; light green <60 m asl)

COASTAL OCEAN / SHELF SEAS (light blue <60 m depth; middle <100 m; dark <200 m)

OCEANIC ZONE (>200 m depth)

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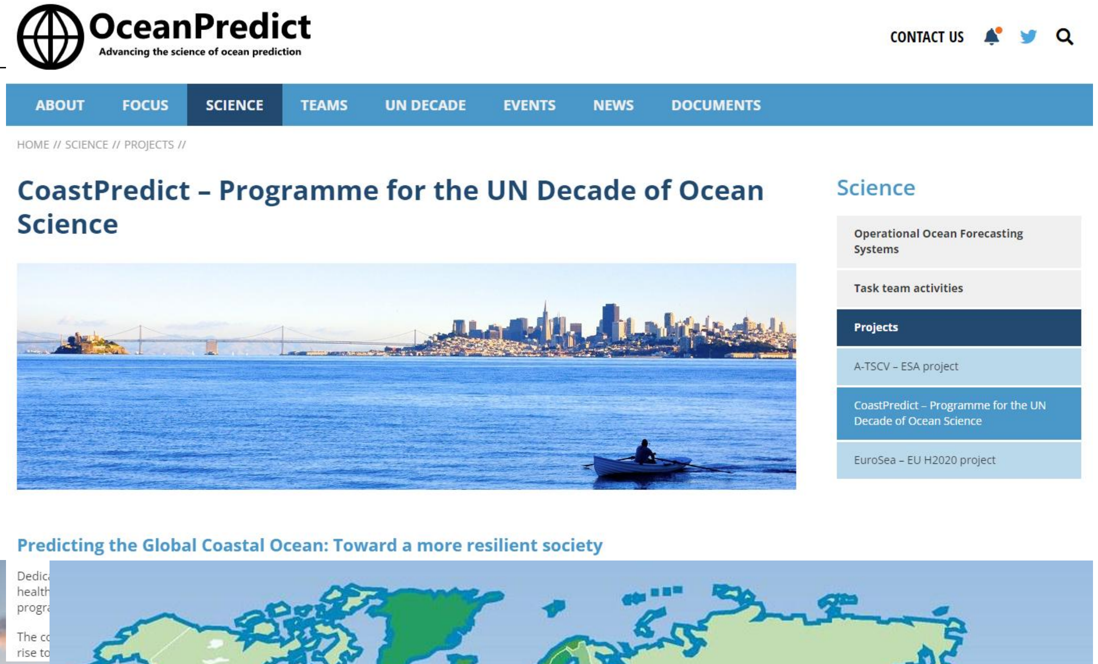
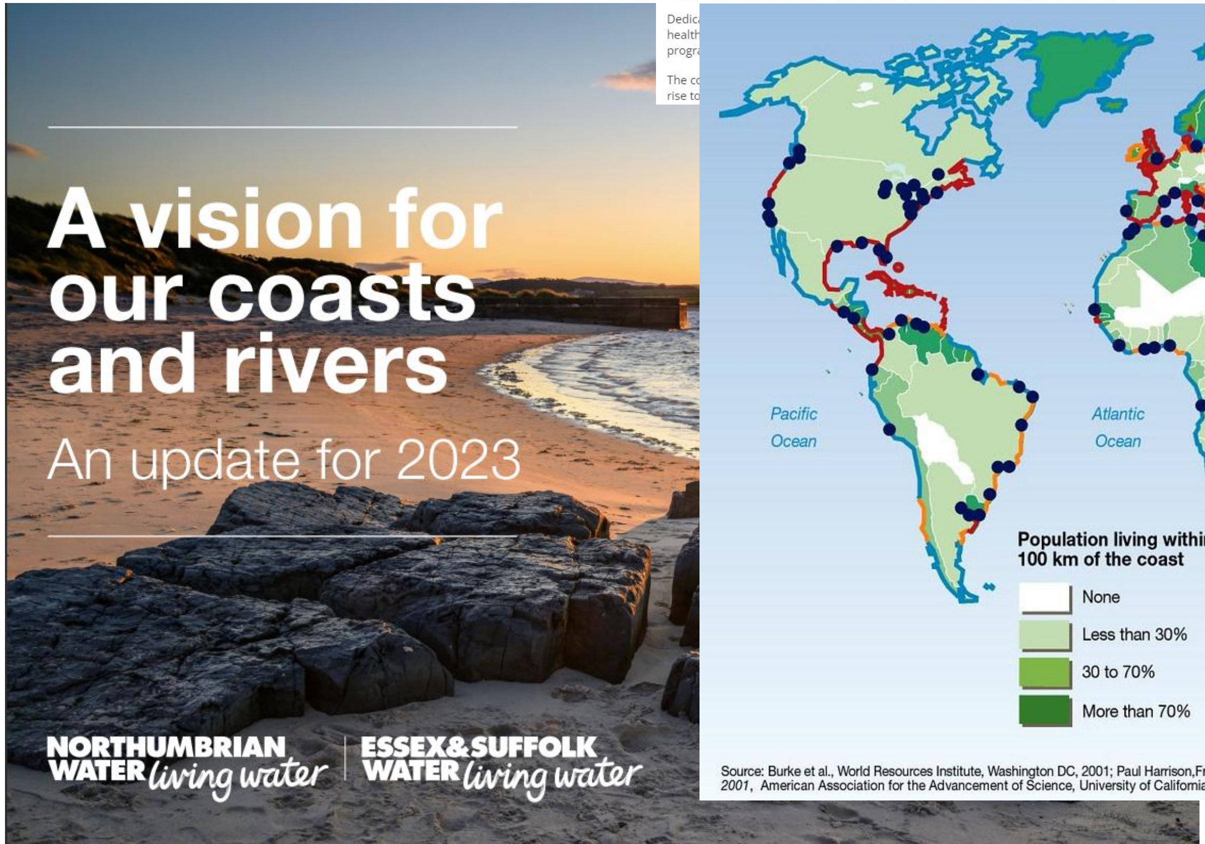
Focus on COASTS

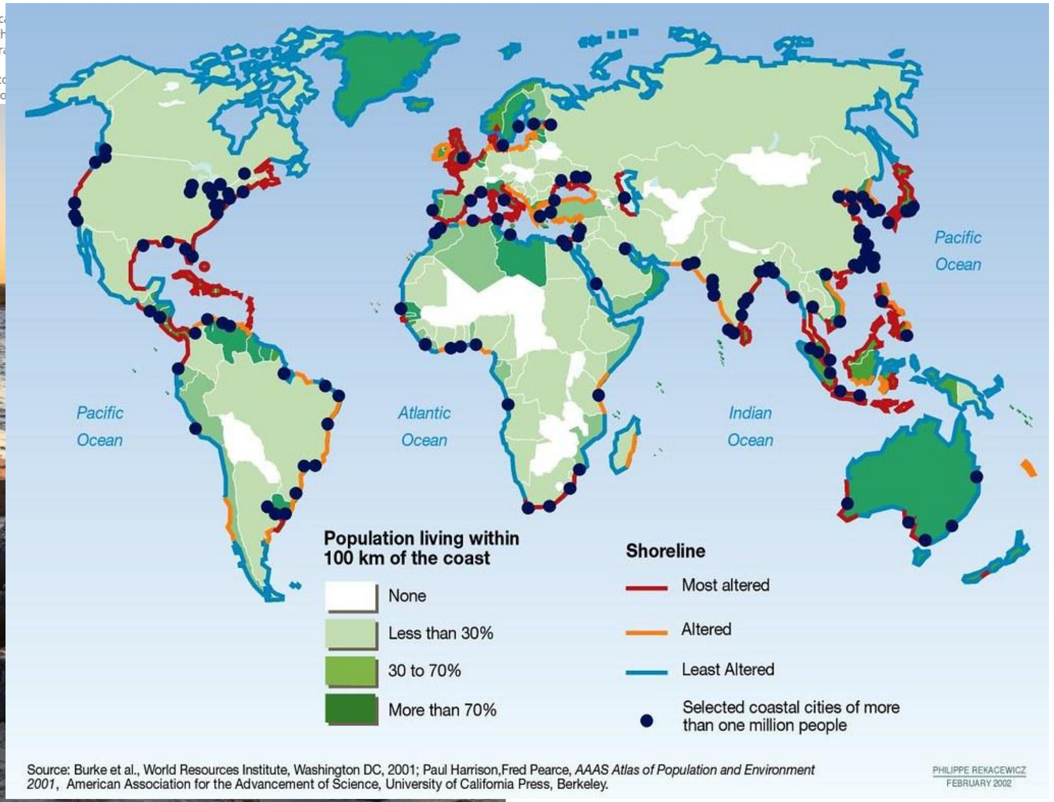
In the last few years, new regional, national and international programmes have highlighted the importance of the coastal zone (both the coastal plain and the coastal ocean).



FLOOD 2023 & COAST
floodandcoast.com

Flood & Coast 24



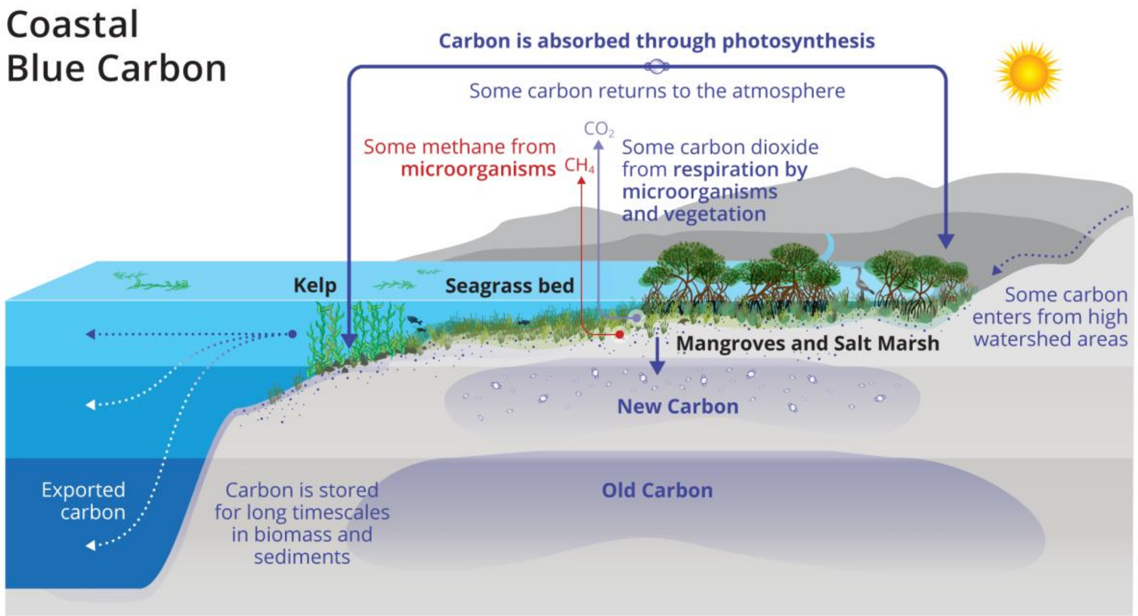


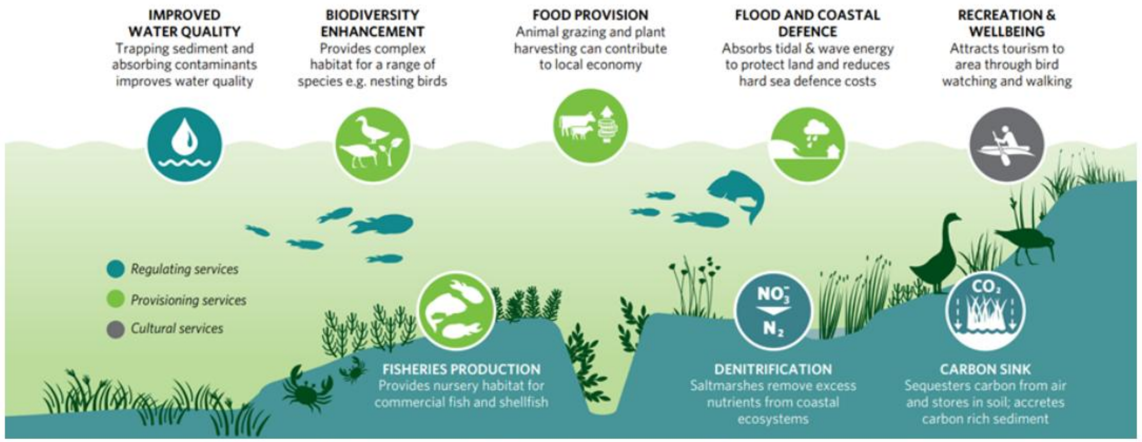
Focus on COASTS

CHAMFER is concerned with quantifying coastal impacts, including flooding, coastal erosion and ecosystem degradation.

In order to do this, we need to improve our understanding of UK coastal ecosystems and exchanges across this 'border zone' between the ocean and the land.

This is broadly part of current attempts to quantify 'blue carbon'.





Saltmarshes provide a range of ecosystem services such as coastal defense improving water quality, enhancing biodiversity, supporting fisheries and grazing, recreation and wellbeing and storage and removal of carbon and excess nutrients. Graphic from: Hudson, R, Kenworthy, J and Best, M (eds) (2021). *Saltmarsh Restoration Handbook: UK and Ireland*. Environment Agency, Bristol, UK.

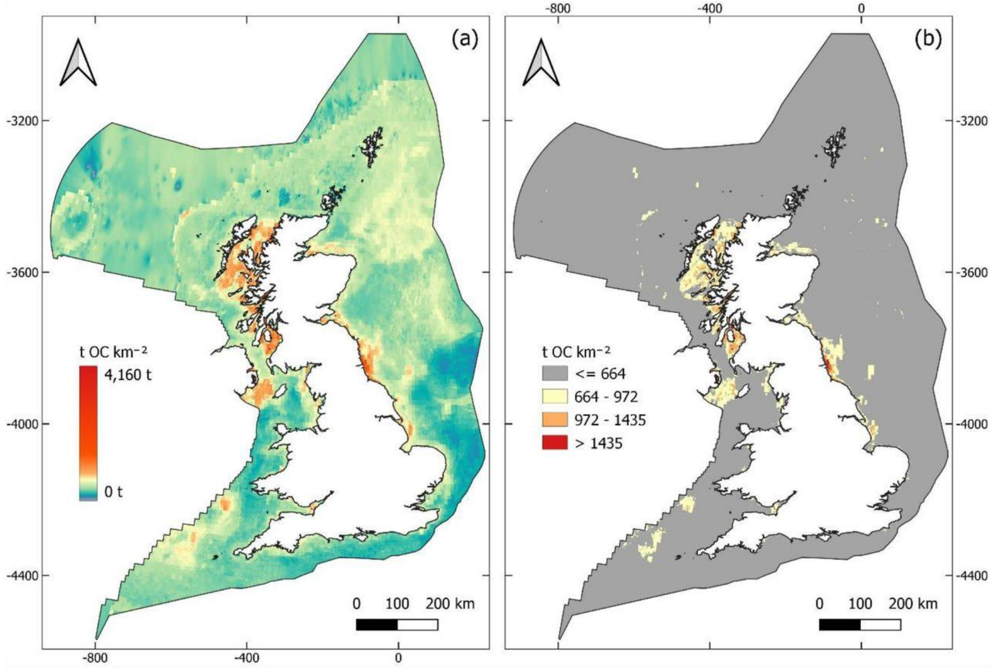
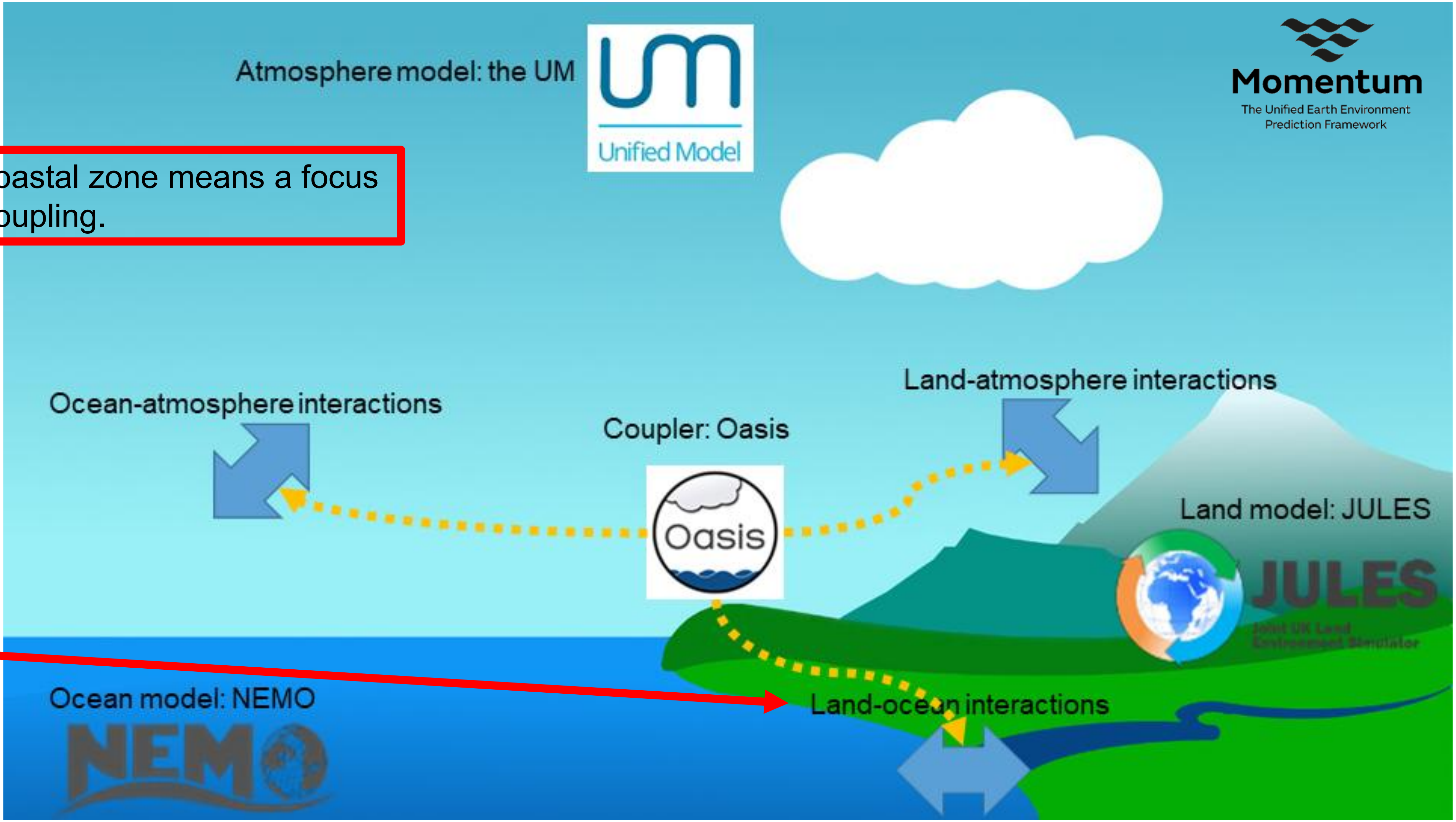


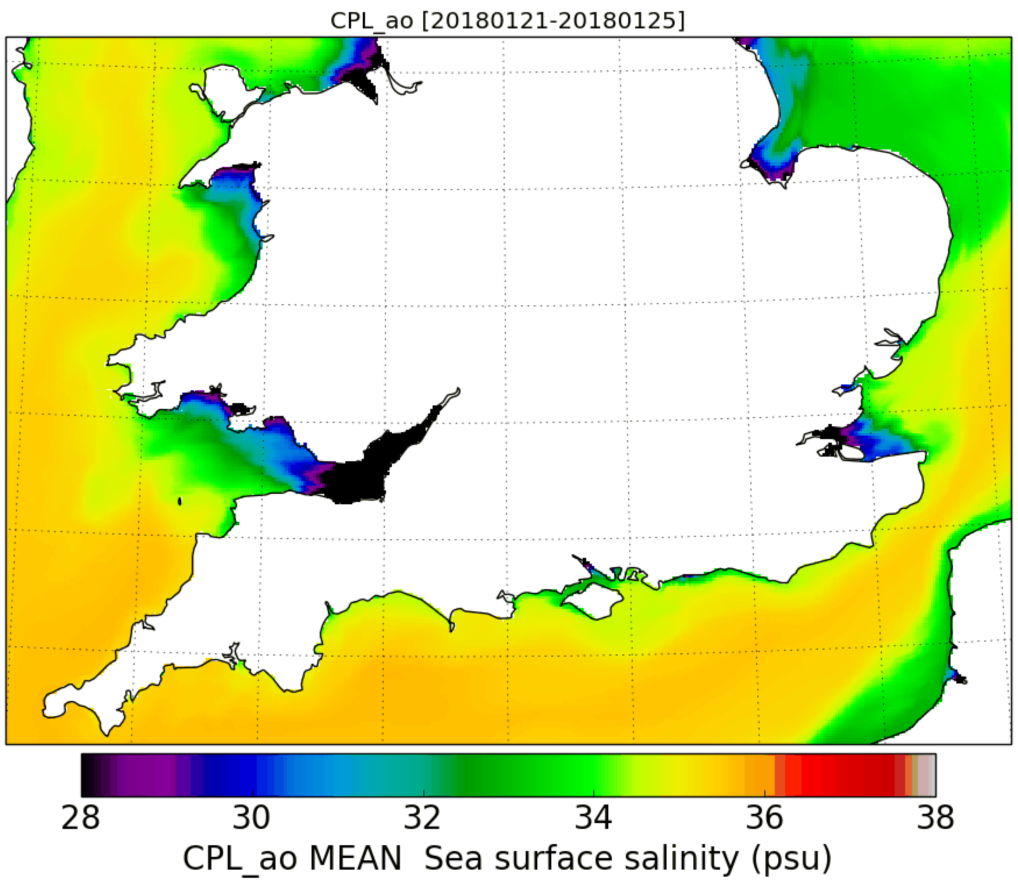
Fig. 1.Seabed organic carbon (OC) stocks in the top 10 cm of sediment across the UK EEZ.(A) Concentration of OC across the study area. Colours follow an exponential scale from low concentrations in blue to high concentrations in red. **(B)** Areas of the study region which contain the highest concentrations of OC. Colours are equivalent to highest 0.1% of values - red, 1% - orange, and 5% - yellow. From Epstein & Roberts (2022) https://doi.org/10.1101/2022.02.10.479679

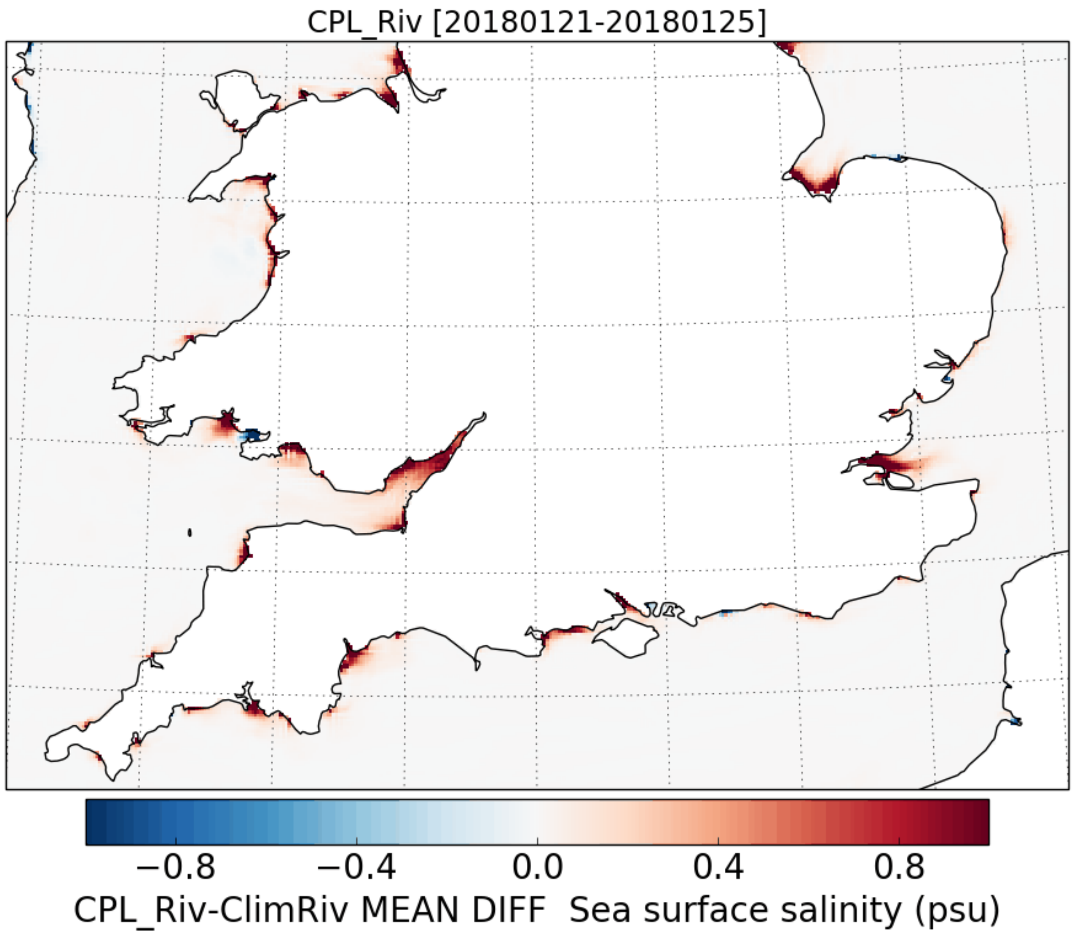
A focus on the coastal zone means a focus on land-ocean coupling.



Marthews TR, Wiggins M & Garbutt A (2023). The land-ocean interface in land surface models. *UKCEH Report*.

Two examples of land-ocean coupling: (1) river outflow has a huge effect on the near ocean.



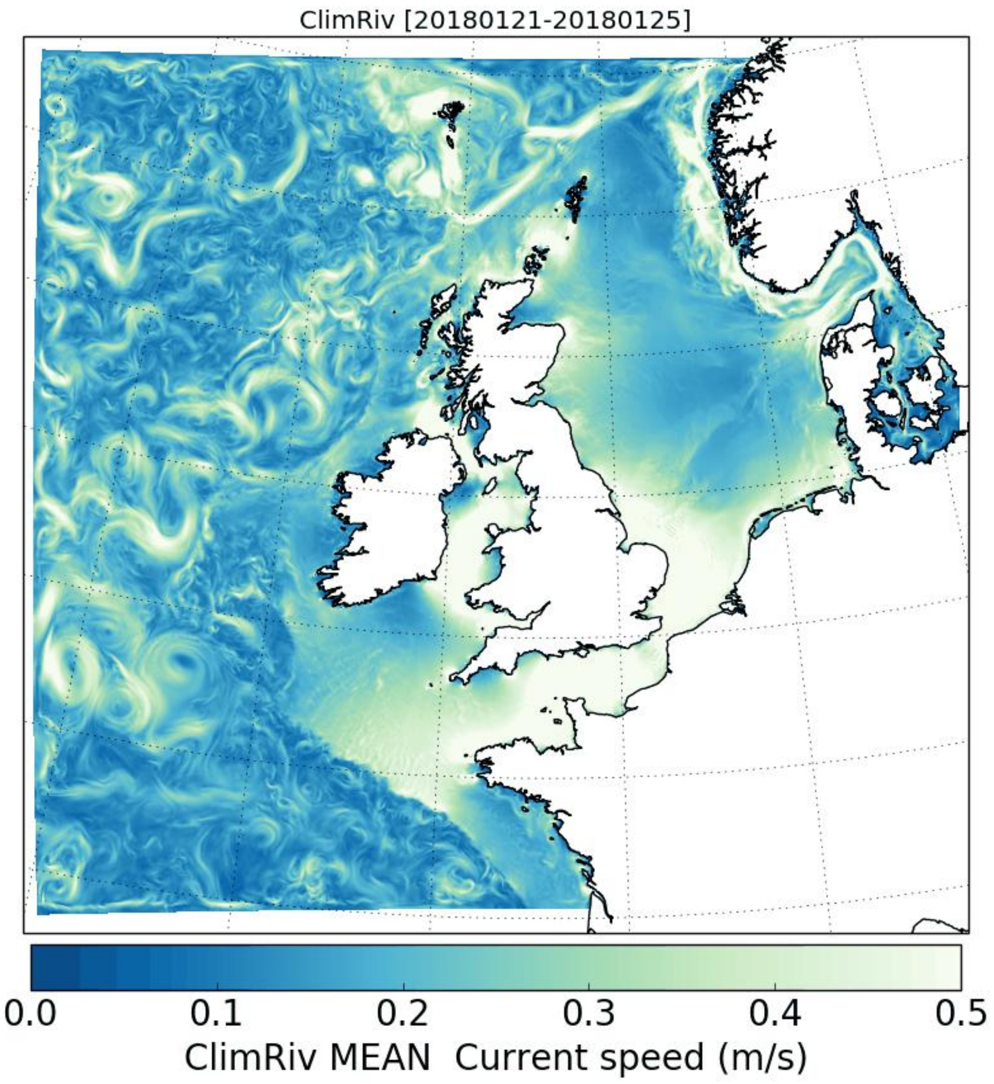


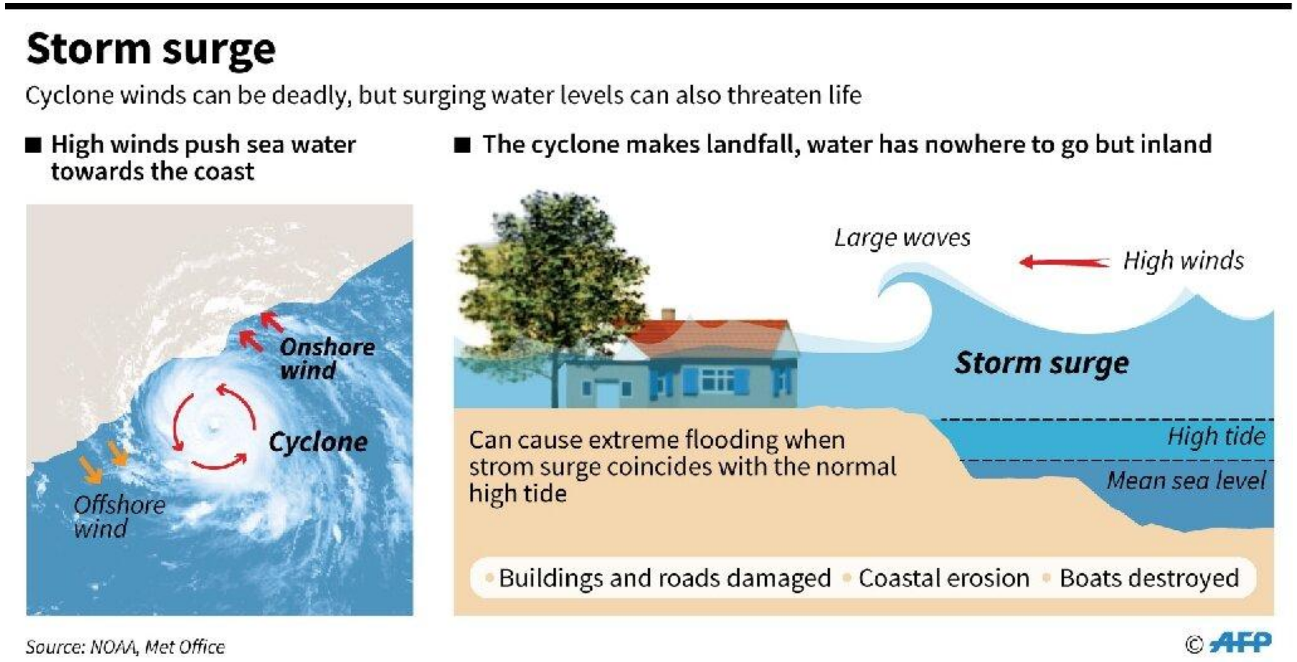
- Surface salinity – climatological river inputs
- *5-day case study runs, January 2018*

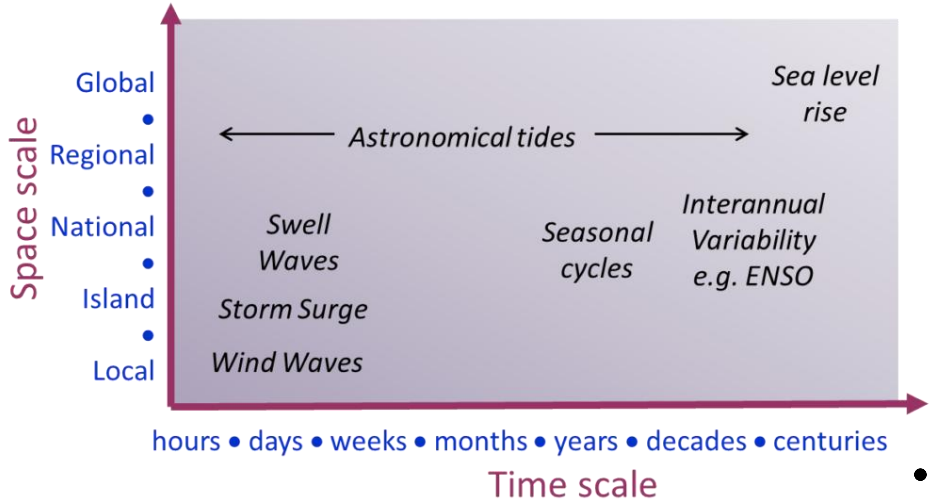
- Impact of coupling on near-coastal salinity

Figures many thanks to Huw Lewis (data from Dan Copsey)

Two examples of land-ocean coupling: (2) sea surges occur when sea water intrudes onto the land surface.







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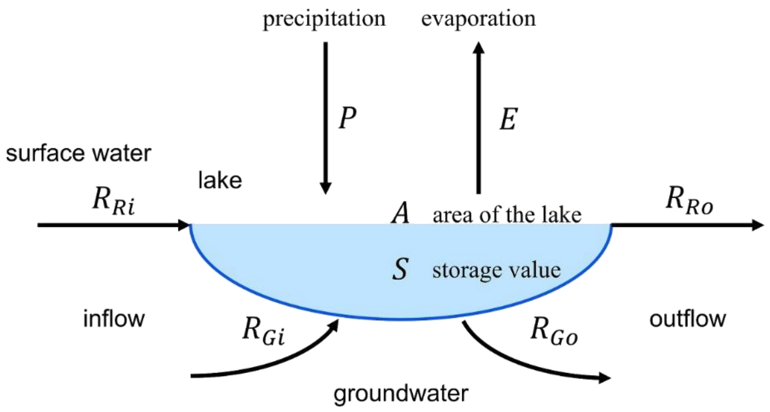
Modelling inundation

Much of my work benefits from **UK National Capability funding**, where the focus is on quantifying impacts as we (try to) move towards a net zero world.

As with all land surface models, JULES calculates a water balance at each of its gridcells, which includes all the main movements of water into and out of that location. Inundation then happens as a consequence of these flow variables.



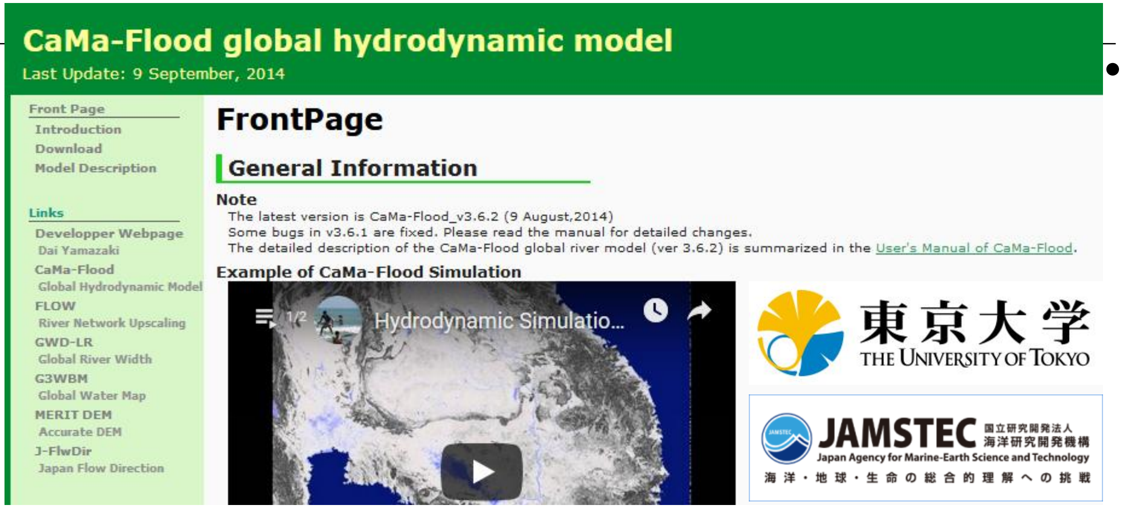
River flow

River flow is predicted using the Saint Venant equations, which are derived from water balance considerations.

Our approach is to use the well-tested global hydrodynamic model *CaMa-Flood*. This is a substantial 'upgrade' from the current river models in *JULES* (*TRIP* and *River Flow Model*).

A key part of this upgrade is moving from a kinematic wave model (used by *RFM*) to a local inertial approximation where only the convective acceleration term is neglected (de Almeida & Bates 2013).

de Almeida GAM & Bates P (2013). Applicability of the local inertial approximation of the shallow water equations to flood modelling. *Water Resources Research* 49:4833-4844.



CaMa-Flood is a Global Hydrodynamic model developed by Dai Yamazaki at Univ. Tokyo. It is the only open-source global river routing model based on the local inertial approximation of the Saint Venant equations.

Crucially, this version of the Saint Venant equations includes *backwater effects*, i.e. temporary reversals of flow in river branches.

This is something we need to be able to model coastal inundation: NEMO communicates the height of the sea wall to JULES (via Oasis), but then the river routing scheme in JULES must be able to allow that water to travel upstream to produce inundation. This is not possible with RFM because it follows the kinematic wave equation that assumes no flow reversals.

Various Forms of the Momentum Equation

$$\frac{1}{A}\frac{\partial Q}{\partial t}+\frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+g\frac{\partial y}{\partial x}-g(S_o-S_f)=0$$

Local acceleration term | Convective acceleration term | Pressure force term | Gravity force term | Friction force term

RFM $$\cancel{\frac{\partial V}{\partial t}}+\cancel{V\frac{\partial V}{\partial x}}+\cancel{g\frac{\partial y}{\partial x}}-g(S_o-S_f)=0$$

Kinematic Wave

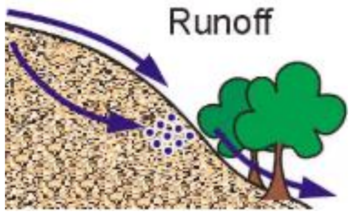
Diffusion Wave

Dynamic Wave

During CHAMFER, between myself and NOC, we have developed the following workflow:

JULES
Joint UK Land Environment Simulator

Precipitation (regridded from ISIMIP3b meteorology)

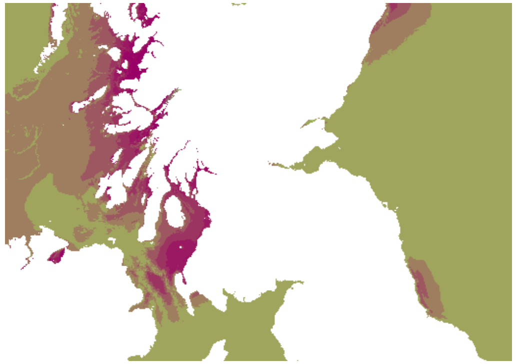


Run **JULES** for time period with standard (not CMF) river flow (no coastal exchange). Produces file of river outflows at all Coastal Exchange Points (CEPs) (runoff calculated by JULES internally)

Runs carried out by UKCEH

Use river outflows to run ocean model **NEMO**

NEMO produces sea wall heights at all CEPs as output.



Runs carried out by NOC

Rerun **JULES** with JULES-Camaflood* routing, with sea wall heights as boundary condition at all estuaries.

CaMa-Flood

Output of inundation predictions and other impact variables

*A recoded Fortran module based on v3.95a CaMa-Flood with no flow bifurcations

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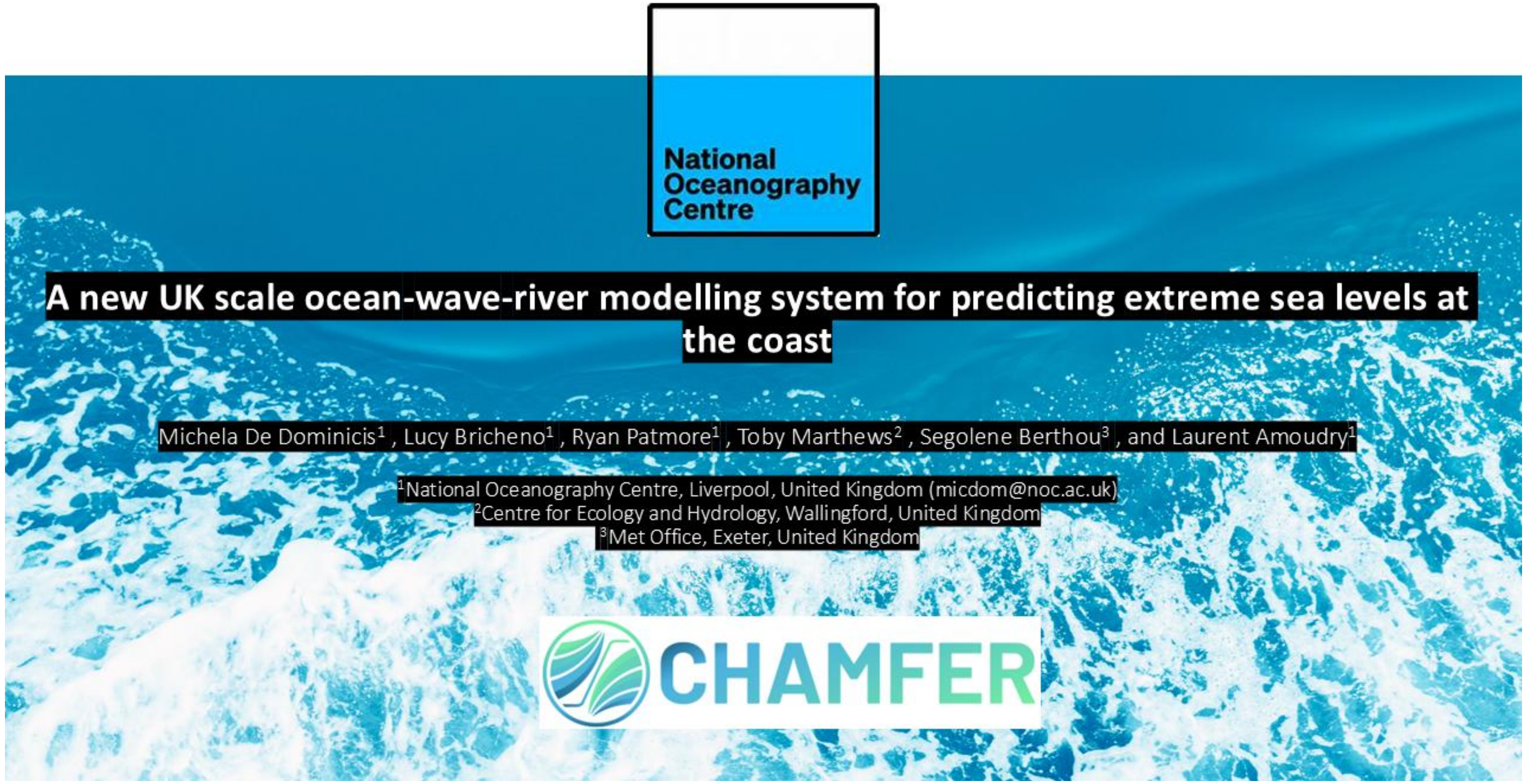
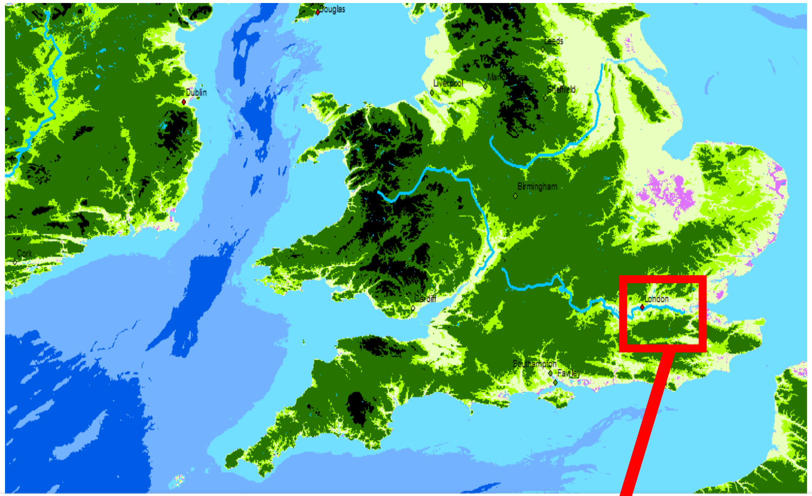
JULES Joint UK Land Environment Simulator | Met Office | National Oceanography Centre | UK CEH

Project CHAMFER

This system is what I mean by OWRMS, producing predictions at 500 m resolution all around the coastline of the UK. This system will then be used to underpin management advice about coastal hazards and impacts.





UKCEH

Poole harbour catchment

I have been using the 820km^2 Poole Harbour Catchment as a test case, because it is large enough to show all the river dynamics I am trying to simulate, but still small enough to run acceptably quickly (it is much smaller than the Thames 12935km^2 or Mersey, 4680km^2).

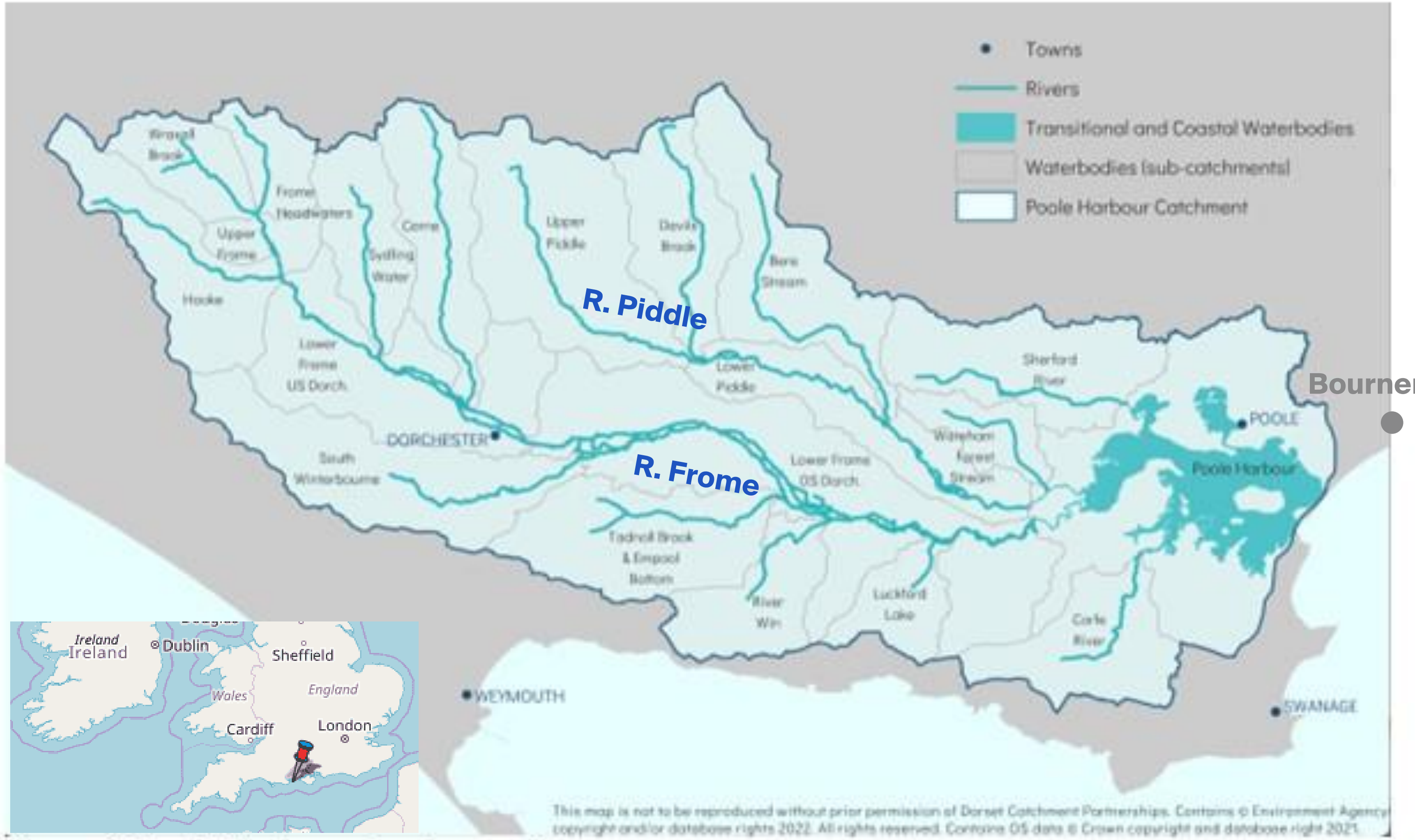


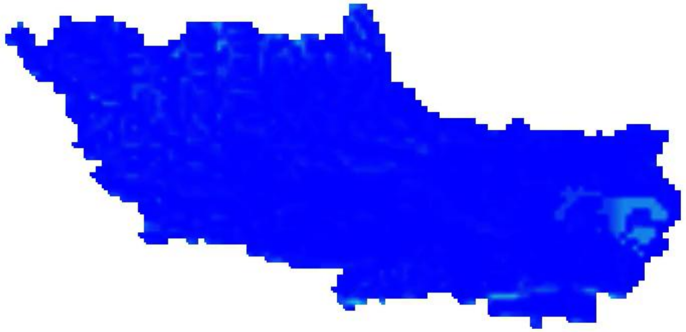
Figure 1: Poole Harbour Catchment Area

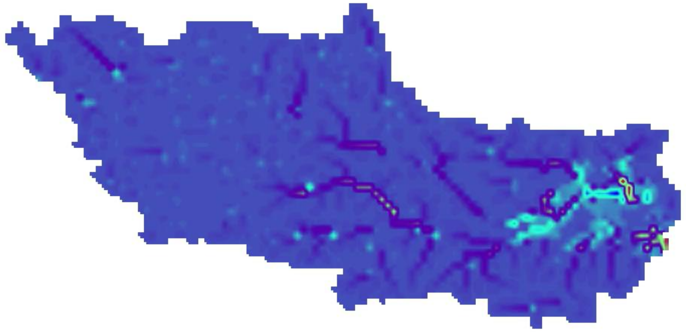
Note where the ‘handover’ is between the land model and the ocean model here: Poole harbour is mostly saline, but this estuary is on the DEM for the land model and therefore it is simulated as a lake on the land surface (by JULES), not as an arm of the sea (which would be handled by NEMO). For most estuaries there is no choice about this: the DEM (land-sea mask) specifies where the boundary is between land and sea.

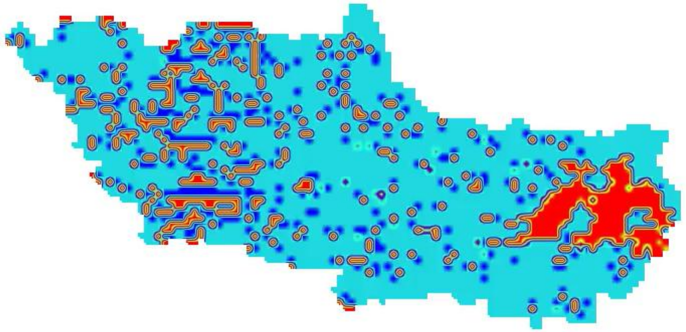
Poole harbour catchment

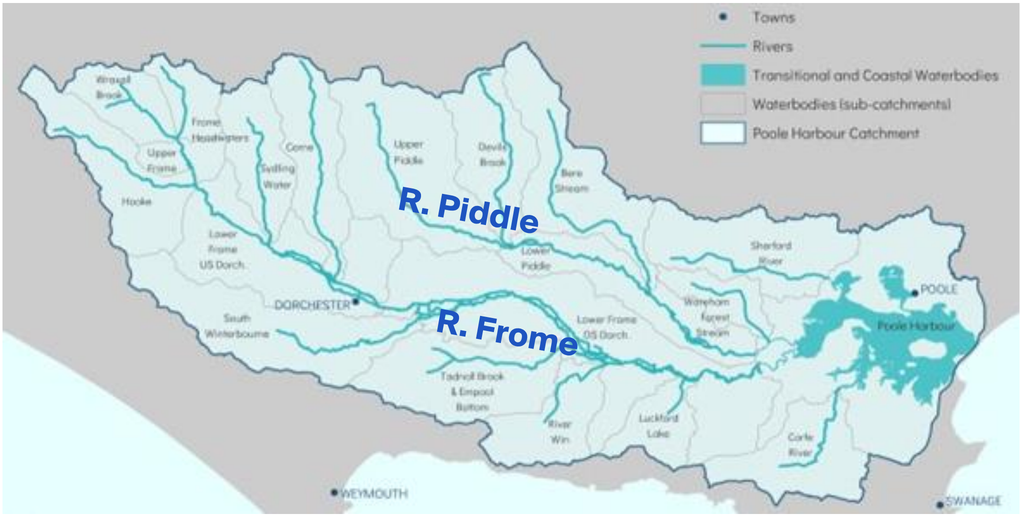
Here we can see runoff (top), river flow (middle) and inundation extent (bottom) for 1993, as simulated by JULES using Camaflood river routing:

(in updated runs, I have also included river depth as an output)









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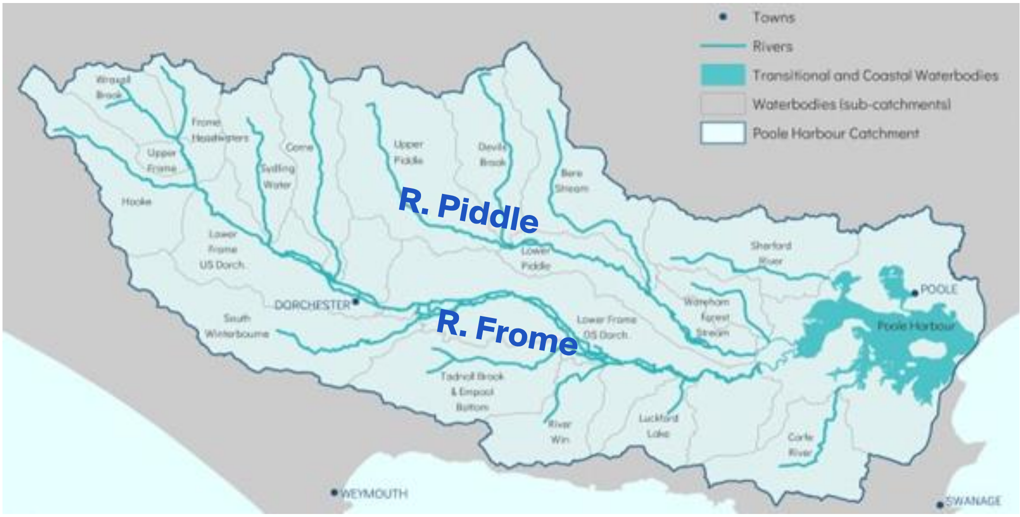
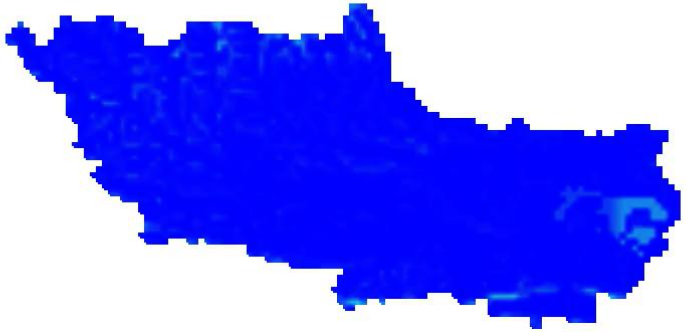
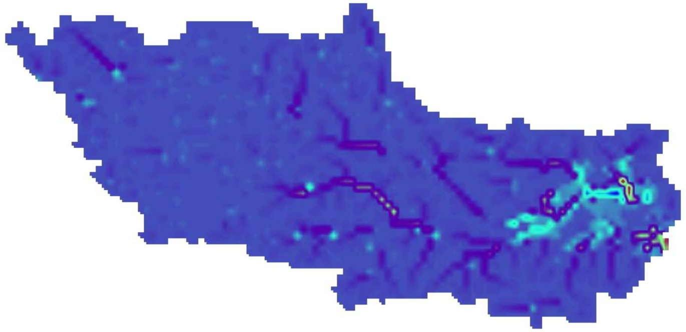
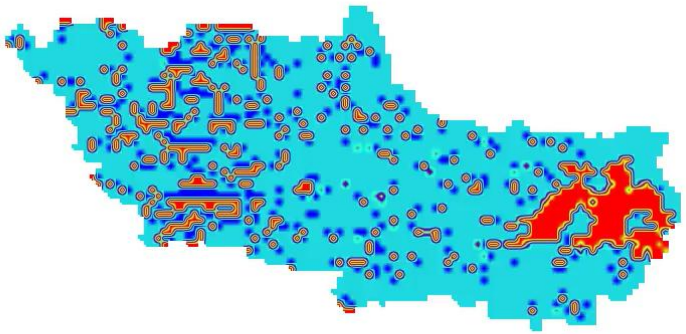


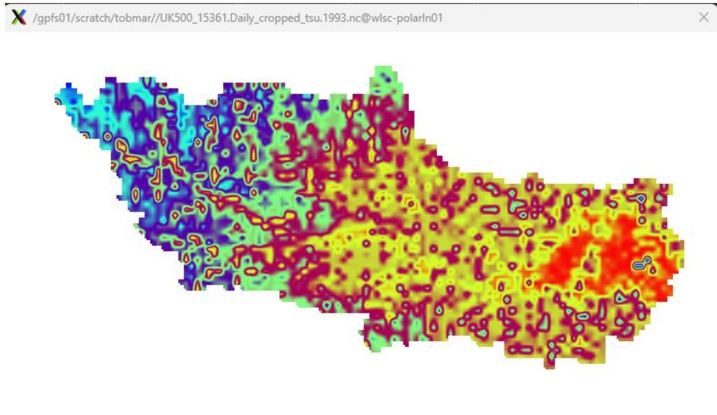






JULES gets a lot of things right here:

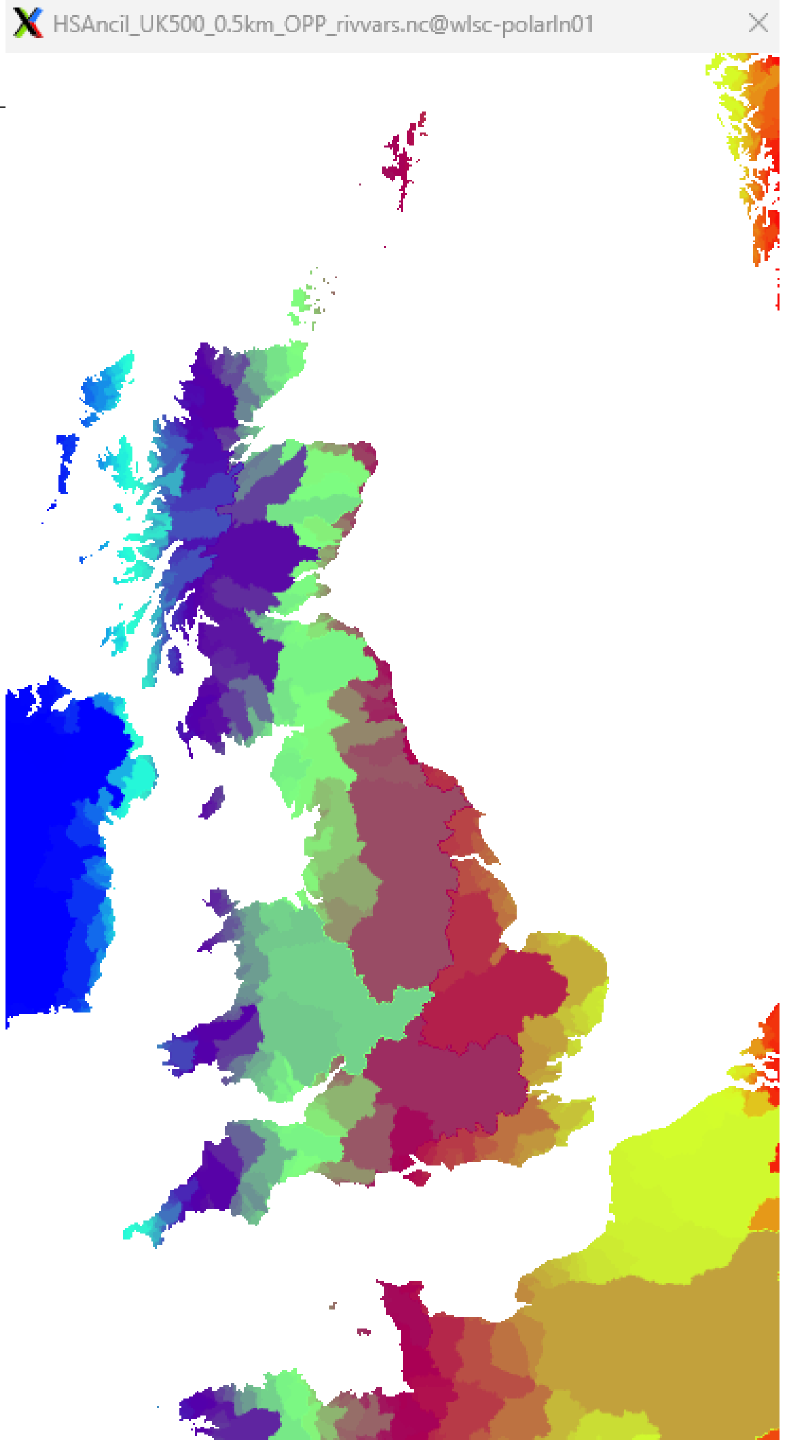
- The rivers Frome and Piddle are in the right places and flow rates are approx. correct
- The estuary is a permanently-inundated lake, as you would expect.
- You can see the flashes of runoff directly come through as flashes of river flow (each frame is 1 day, so each flash is a rainy day).
- Also, I can apply a 2.5 m “tidal wave” at the estuary and inundation spreads further inland, as it should.



Simulating UK500

Doing the same for all of UK500 is much more challenging.

- First step: split the UK500 domain into all its separate catchments. I did this with a bespoke script and got 9674 catchments (most of these are very small catchments).
- Next, I need to setup a **job array**. This is a way of sending 9674 jobs to the HPC at the same time (a special kind of slurm job).
- This approach is very heavy on **filespace**: each year of each catchment generates an output file, which means 30*9674= 290,000 files plus spin-up and dumps. Luckily, >50% of these catchments are really tiny (some only 1 pixel).
- All these catchments are running right now. The largest catchments are taking ~50 days to run all 30 years, so it is still a nontrivial set of JULES runs.
- Side point: I have calculated the catchments directly from my ancillary file of 500 m river directions using a script (rather than downloading any separate set of river districts), so I know that the catchments and river directions agree with each other 100%.

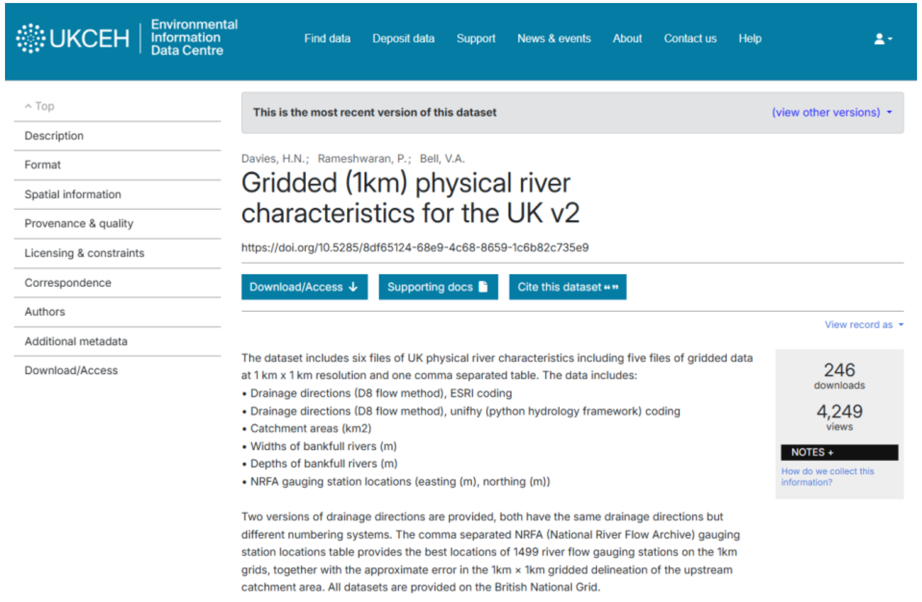


UKCEH

New ancils on channel depths and widths

We are using the ancillaries of channel depths and widths assembled by Helen Davies at UKCEH in 2022.

Note: channel depths here go up to only 3 m for the UK because these are an average across the channel. Data do not exist for the deepest point of each channel and arguably this leads to a slight underestimation of flow in CaMa-Flood.



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- Format
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This is the most recent version of this dataset (view other versions)

Davies, H.N.; Rameshwaran, P.; Bell, V.A.

Gridded (1km) physical river characteristics for the UK v2

https://doi.org/10.5285/8df65124-68e9-4c68-8659-1c6b82c735e9

Download/Access | Supporting docs | Cite this dataset

View record as

The dataset includes six files of UK physical river characteristics including five files of gridded data at 1 km x 1 km resolution and one comma separated table. The data includes:
- Drainage directions (D8 flow method), ESRI coding
- Drainage directions (D8 flow method), unifhy (python hydrology framework) coding
- Catchment areas (km2)
- Widths of bankfull rivers (m)
- Depths of bankfull rivers (m)
- NRFA gauging station locations (easting (m), northing (m))

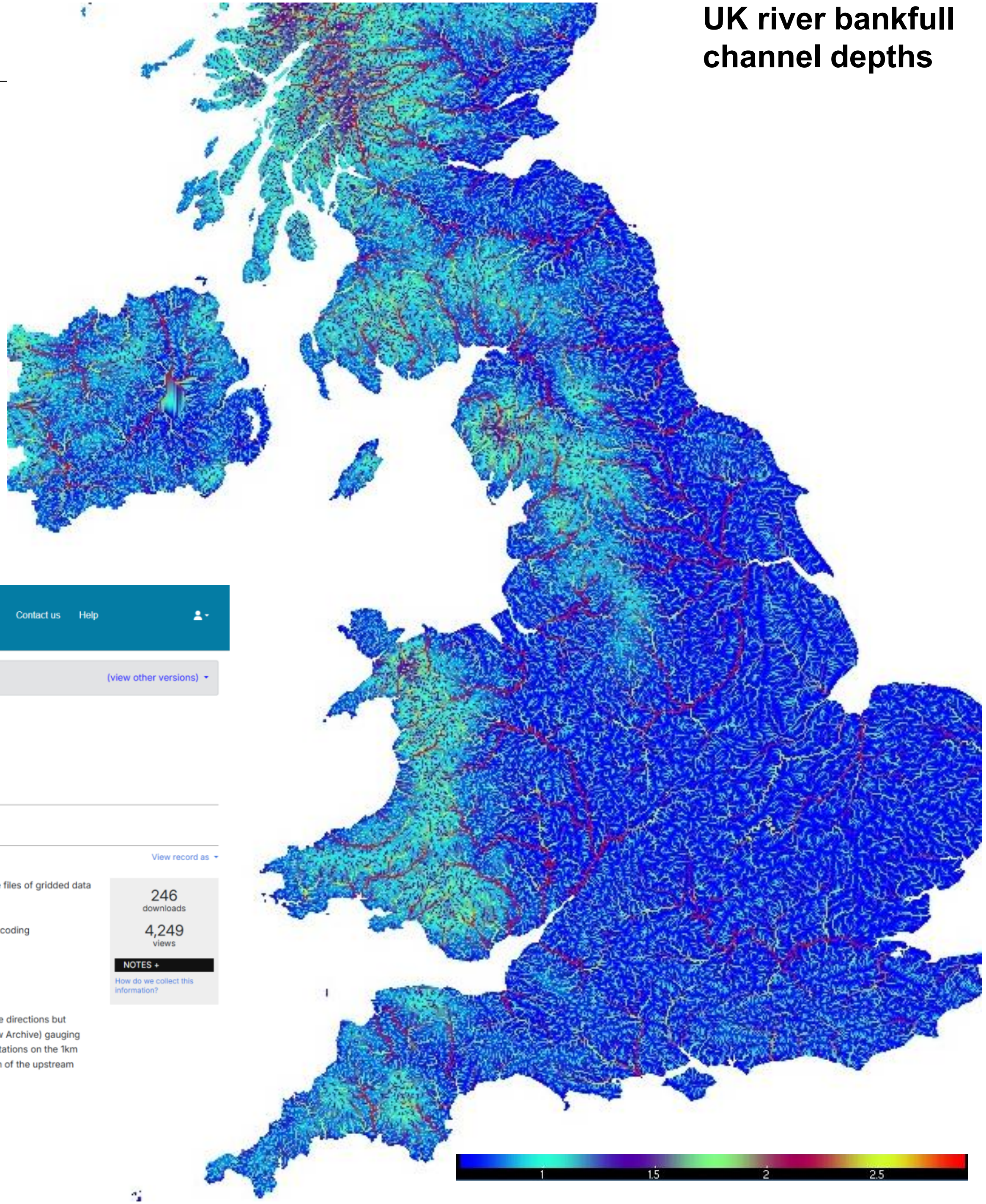
Two versions of drainage directions are provided, both have the same drainage directions but different numbering systems. The comma separated NRFA (National River Flow Archive) gauging station locations table provides the best locations of 1499 river flow gauging stations on the 1km grids, together with the approximate error in the 1km x 1km gridded delineation of the upstream catchment area. All datasets are provided on the British National Grid.

246 downloads

4,249 views

NOTES +

How do we collect this information?



UK river bankfull channel depths

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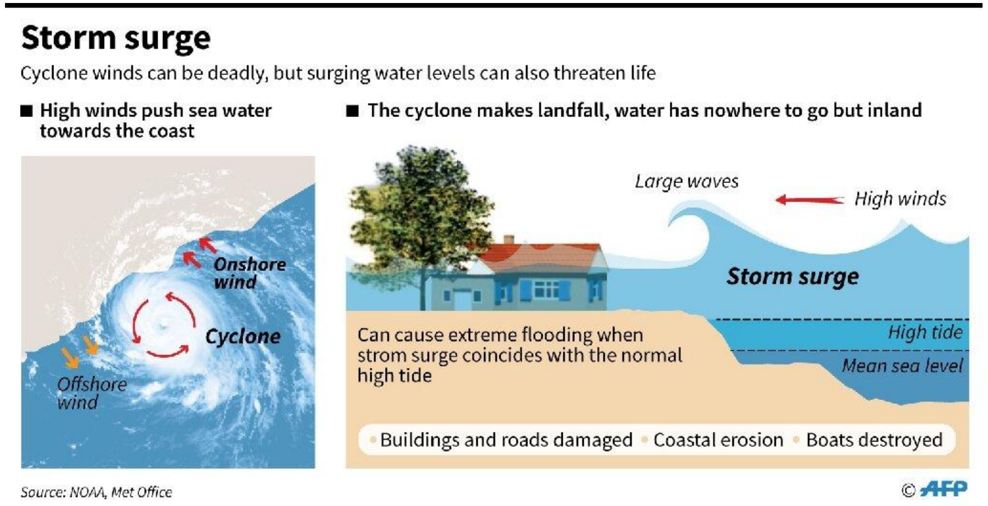
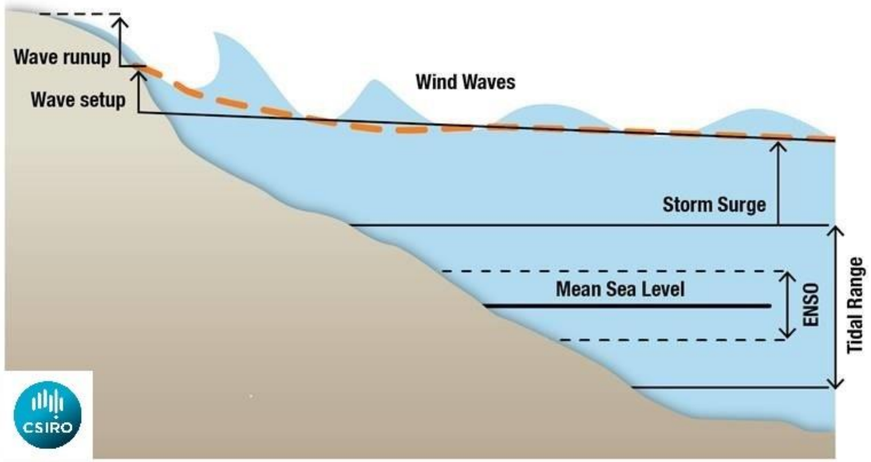
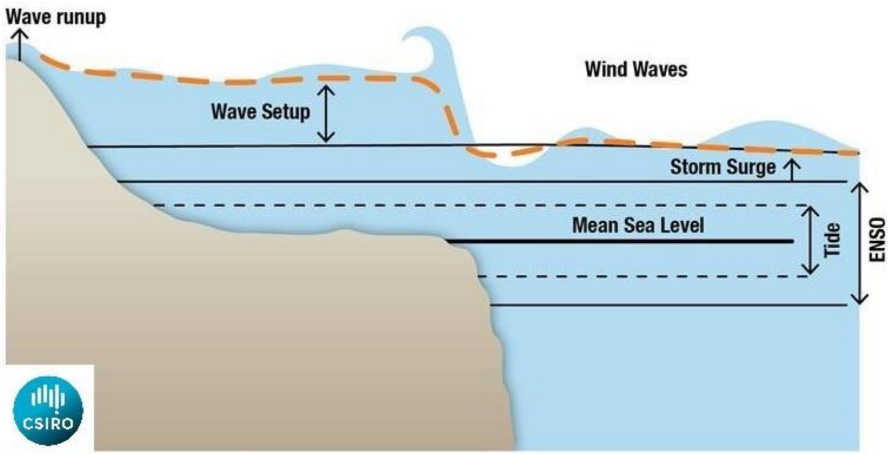
Sea surges

Being able to simulate sea surges is a fundamental aim of the CHAMFER project.

Sea surges are caused by various factors (including storms). The inundation and damage they cause depends on many factors, including timing (e.g., whether they occur at high tide and are reinforced by the tides) and coastal geometry (e.g., see below).







Graphics with thanks to https://research.csiro.au/slrwavescoast/extremes/causes-extreme-sea-levels/ and https://phys.org/news/2019-05-storm-surge-dangerous.html

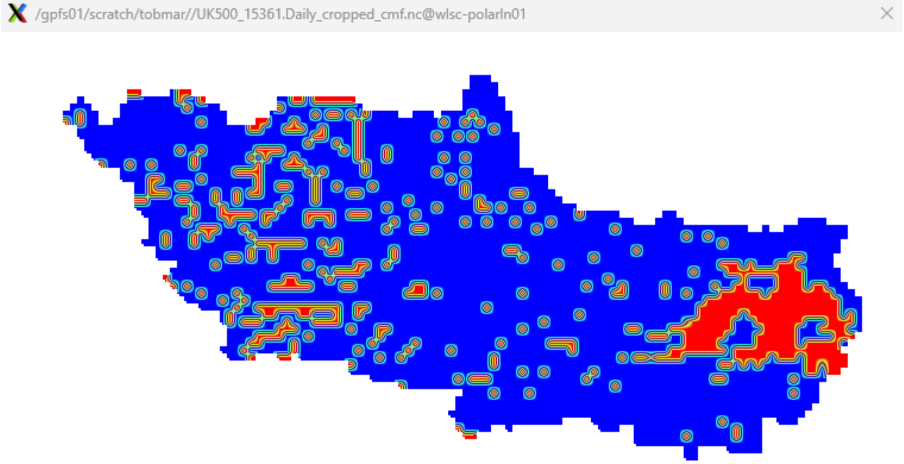
UKCEH

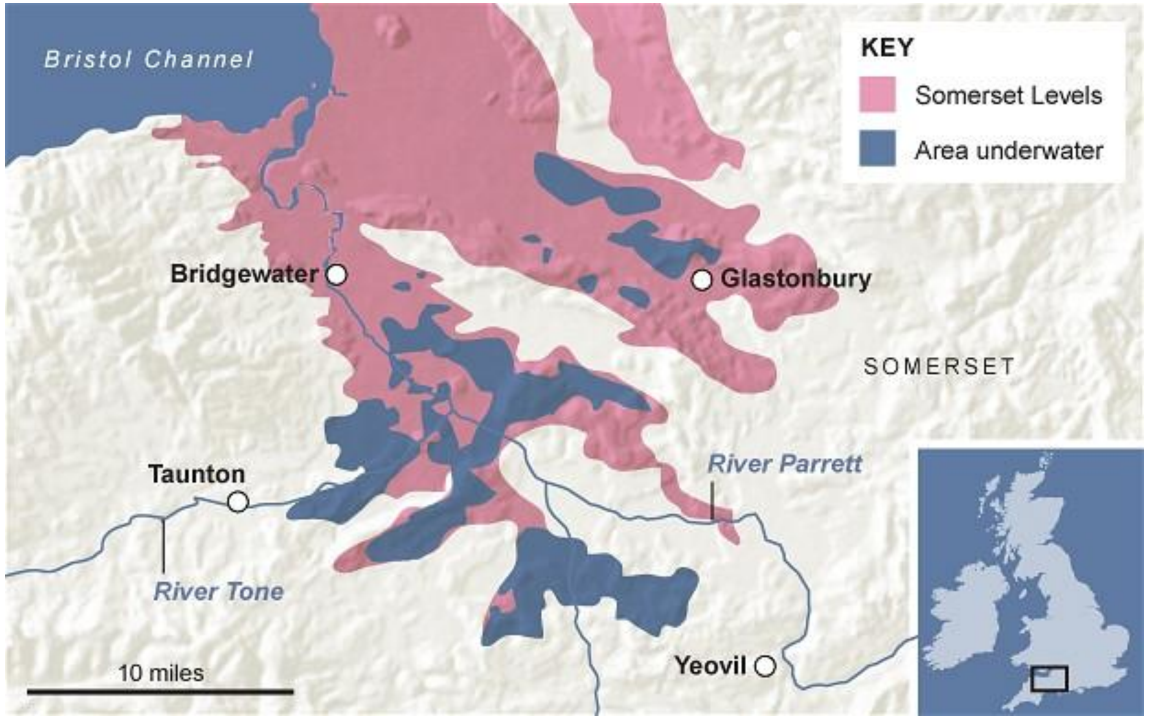
Sea surges

Take the example of the Somerset Levels in 2014 (map from https://www.telegraph.co.uk/news/earth/earthnews/10601978/Why-do-the-Somerset-Levels-flood.html):

If you try to predict where flooding occurs based simply on filling up the topography, then you would get the whole area (red+blue) in this map. However, this 'bathtub' approach is incorrect: the area underwater was further inland, and much of the Levels does not actually flood as much as you might think. Essentially, this is why you need a river routing model like CaMa-Flood.

In 2014, there was a very large amount of rain on the Mendips as well as a storm surge that arrived at high tide. The storm surge made the river back up and that was (partly) why the flooding occurred inland. In our simulations **we *do* get backwater effects** like this when we use the Camaflood option.





Sea surges

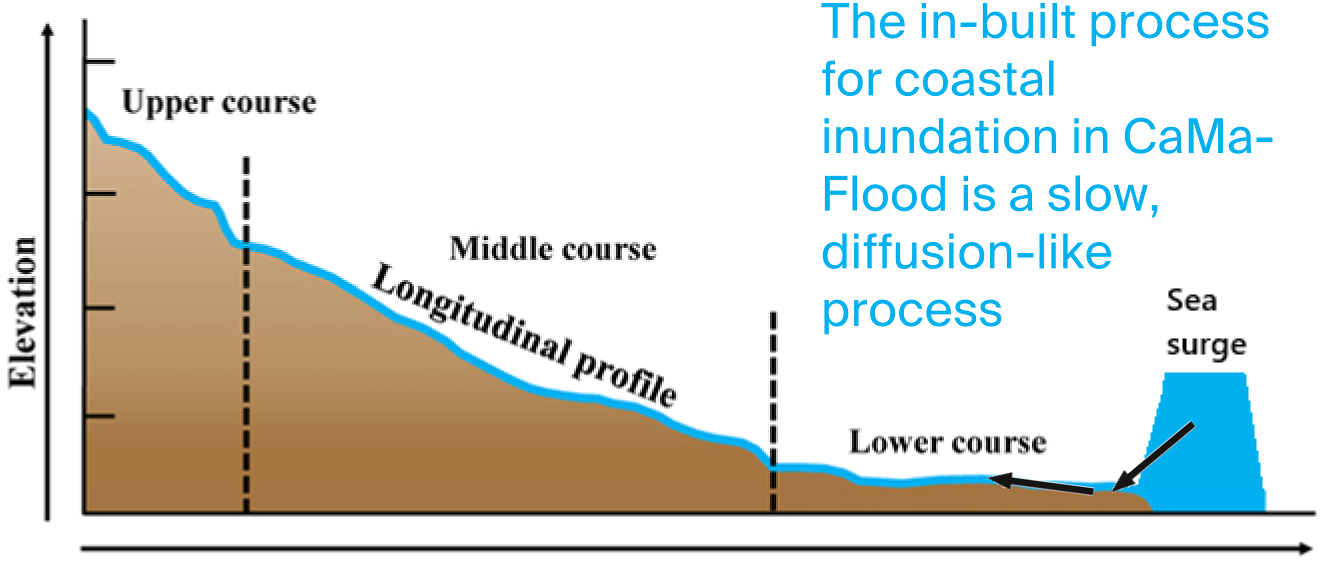
CaMa-Flood has a facility to allow sea surge inundation onto the land surface already (at v3.9.5) (here called **Slow coastal inundation**). This was investigated in the CASPER project a few years ago at UKCEH (Clark *et al.* 2021).

However, I found this to be a very slow process and did not capture the faster dynamics of a storm-induced sea surge. Therefore, I have modified CaMa-Flood to implement a faster process of coastal flooding (here called **Fast coastal inundation**).

In terms of ODEs, one can think of the slow inundation as an equilibrium solution and the fast inundation as a transient solution. CaMa-Flood appears to have been coded for equilibrium solutions only (conserving differentiability of the water surface along all flowpaths and limiting water slopes to 0.005 m/m). This is appropriate for long-term sea level rise, but not for storm surges which are, of course, a transient phenomenon.

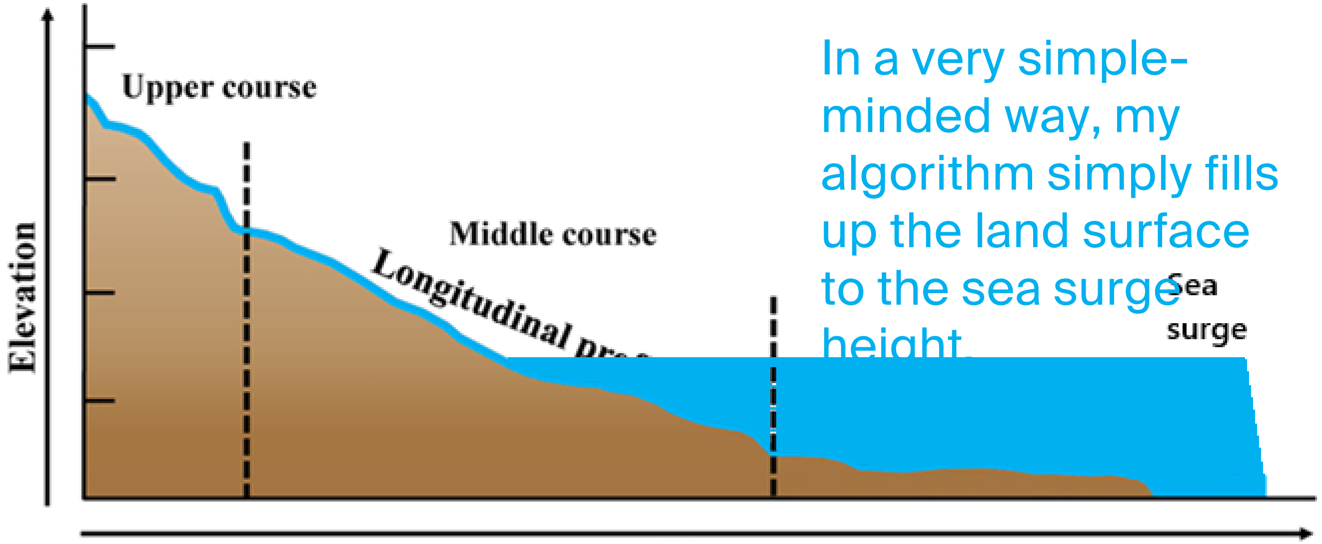
Clark D, Wiggins W & Feng X (2021). Land-ocean coupling. *Report for WCSSP India Project CASPER*.

Slow coastal inundation



The in-built process for coastal inundation in CaMa-Flood is a slow, diffusion-like process

Fast coastal inundation

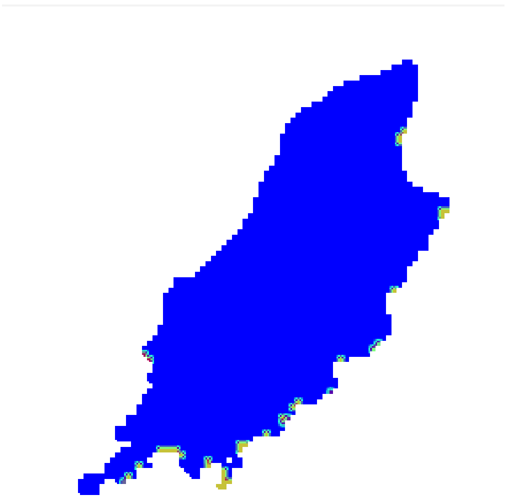
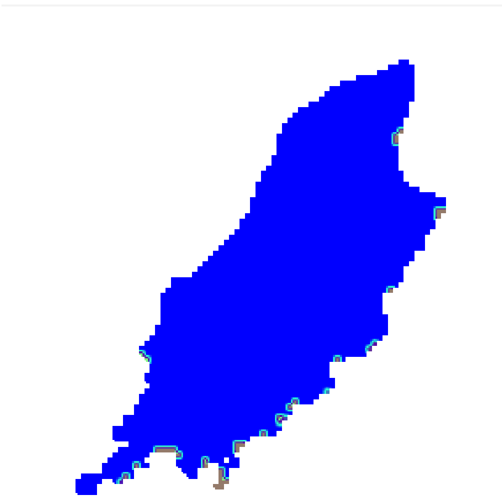
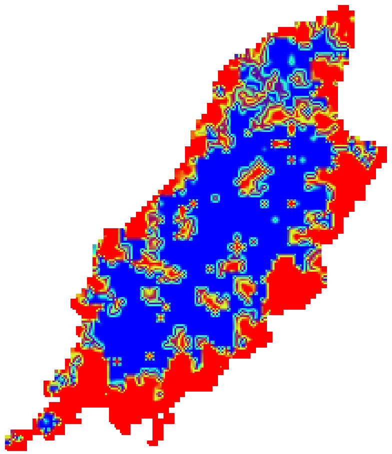
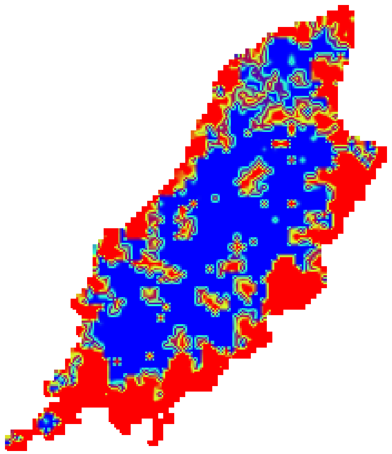


In a very simple-minded way, my algorithm simply fills up the land surface to the sea surge height

Sea surges

Plots right use hypsometric overbank inundation.

I simulated a 50 m high sea surge around the Isle of Man (i.e. a tsunami) and allowed this **sea surge** to inundate the land surface either using CMF's in-house coastal inundation scheme (slow) and a new code addition by me to simulate storm surge inundation (fast). Plot is a screenshot after 10 days of tsunami.

JULES-CaMa-Flood river routing	Without slow coastal inundation	With 'slow' coastal inundation (CMF's method for coastal inundation)
Without fast coastal inundation		
With fast coastal inundation (i.e., Toby's addition to the CMF code)		

Fraction of gridcell

Standalone JULES simulation of rivers and inundation

1. UK Coasts and CHAMFER
2. **OWRMS and Sea Surges**
3. Inundation in the Boyne and the Spey

Standalone JULES simulation of rivers and inundation

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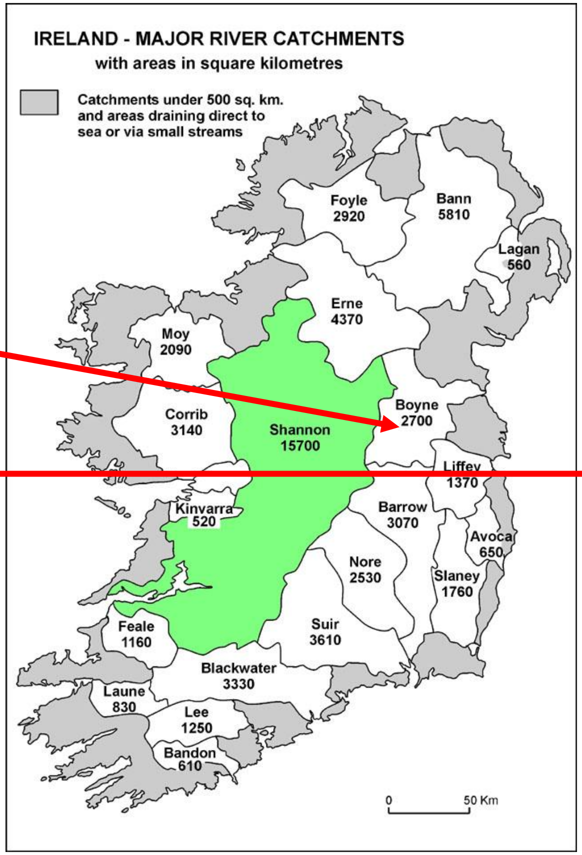
Inundation in the Boyne and the Spey

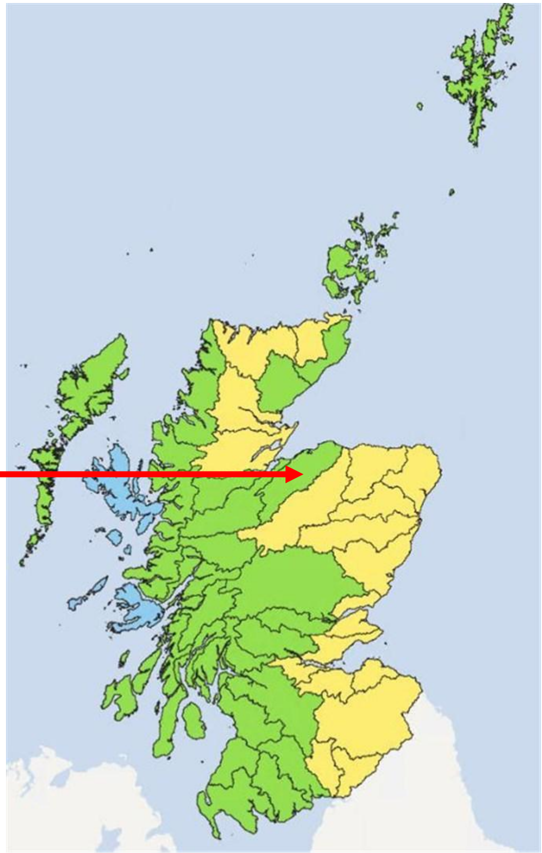
Focus on two similar-sized catchments:

The Boyne (2700 km2)

and

The Spey (3000 km2)





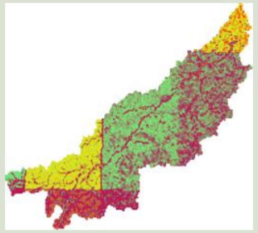
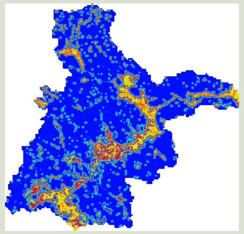
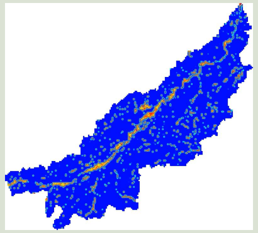
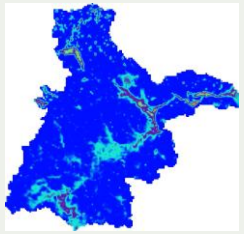
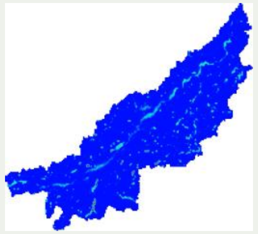
UKCEH

Inundation in the Boyne and the Spey

Simulation shown for the year 2000 (each frame = 1 day). Runs carried out on the UKCEH local cluster POLAR.

Note how flashy the runoff is, but the river flow predicted from it by JULES is comparatively stable. Overall, the Spey has a much more stable flow than the Boyne.

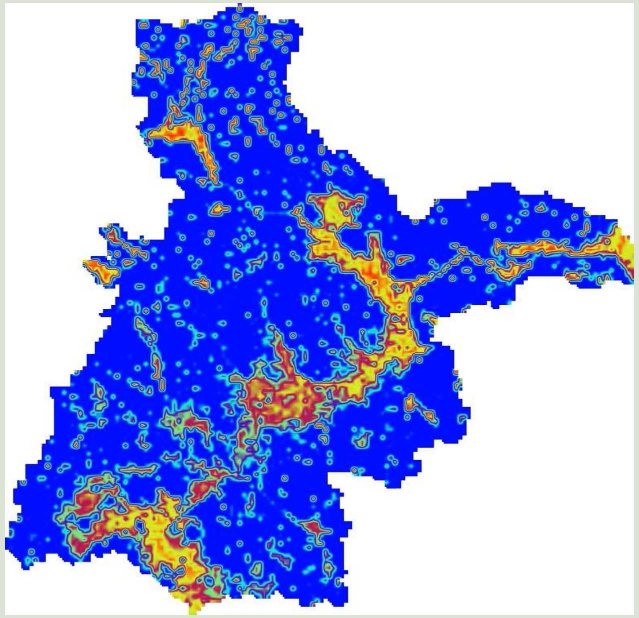
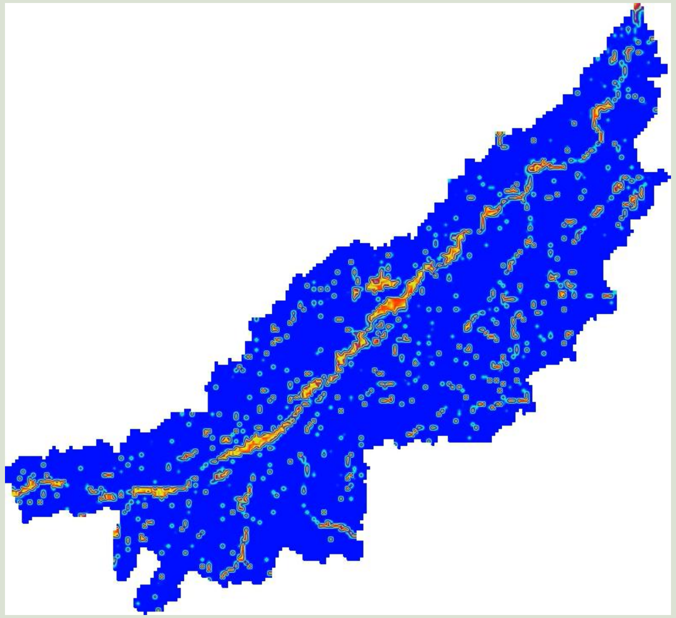
* River depth is not a standard JULES output: I added it to the code in my branch

	Boyne	Spey
Runoff (runoff) (n.b. you can see the imprint of the ISIMIP gridcells from my driving data)		
River flow (rflow)		
Overbank inundation (frac_fplain)		
River depth *		

Inundation in the Boyne and the Spey

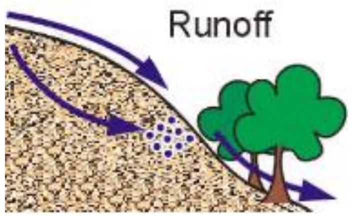
It's difficult to see the detail, so here is a zoom in on the inundation sims. It's been a real challenge to run these at 500 m spatial resolution (and the time resolution is hourly, then integrated to daily for output).

These results also do not yet include coastal inundation: the code is set up to do this, but we are waiting on more data from NOC.

	Boyne	Spey
Overbank inundation (frac_fplain)		

As of Sep 2026, the NEMO step is causing some delay (related to ARCHER2 being taken down).

Precipitation (regridded from ISIMIP3b meteorology)

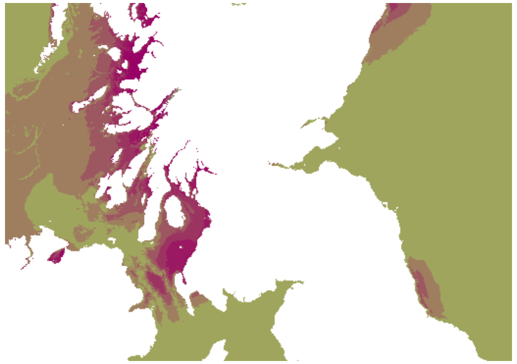


Run **JULES** for time period with standard (not CMF) river flow (no coastal exchange). Produces file of river outflows at all CEPs (runoff calculated by JULES internally)

Runs carried out by UKCEH

Use river outflows to run ocean model **NEMO**

NEMO produces sea wall heights at all CEPs as output.



Runs carried out by NOC

Rerun **JULES** with JULES-Camaflood* routing, with sea wall heights as boundary condition at all estuaries.

CaMa-Flood

Output of inundation predictions and other impact variables

* A recoded Fortran module based on v3.95a CaMa-Flood with no flow bifurcations

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A final thought

JULES

Joint UK Land Environment Simulator

Met Office

I think it's fair to say that *JULES* was not originally conceived as a hydrological / flood prediction model, but over the last ~10 years it has by necessity been moving in that direction as flooding has become a regular part of all our lives worldwide.

Flooding in Venice, Italy (left), and Chennai, India

UKCEH

A final thought

Arguably, JULES is not yet a ‘good’ hydrological model: it is still missing fundamental hydrological processes and we are therefore currently restricted in the kinds of wetlands and inundated areas that we can simulate (not ones with major permafrost or ice flows like the Ob, for example, see discussion in Marthews *et al.* 2022).

However, I believe JULES is not too far away from being really quite a good hydrological model. In addition to what I am working on, a lot of work is currently in train to improve the river simulation routines (including the relatively new **rivers-only** options and a massive effort to clean up the river initialisation subroutines).

Perhaps we should advertise this a little more? Not just ***JULES* the land-surface model**, but ***JULES* the hydrological simulator**?

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Hydrology and Earth System Sciences
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Inundation prediction in tropical wetlands from JULES-CaMa-Flood global land surface simulations

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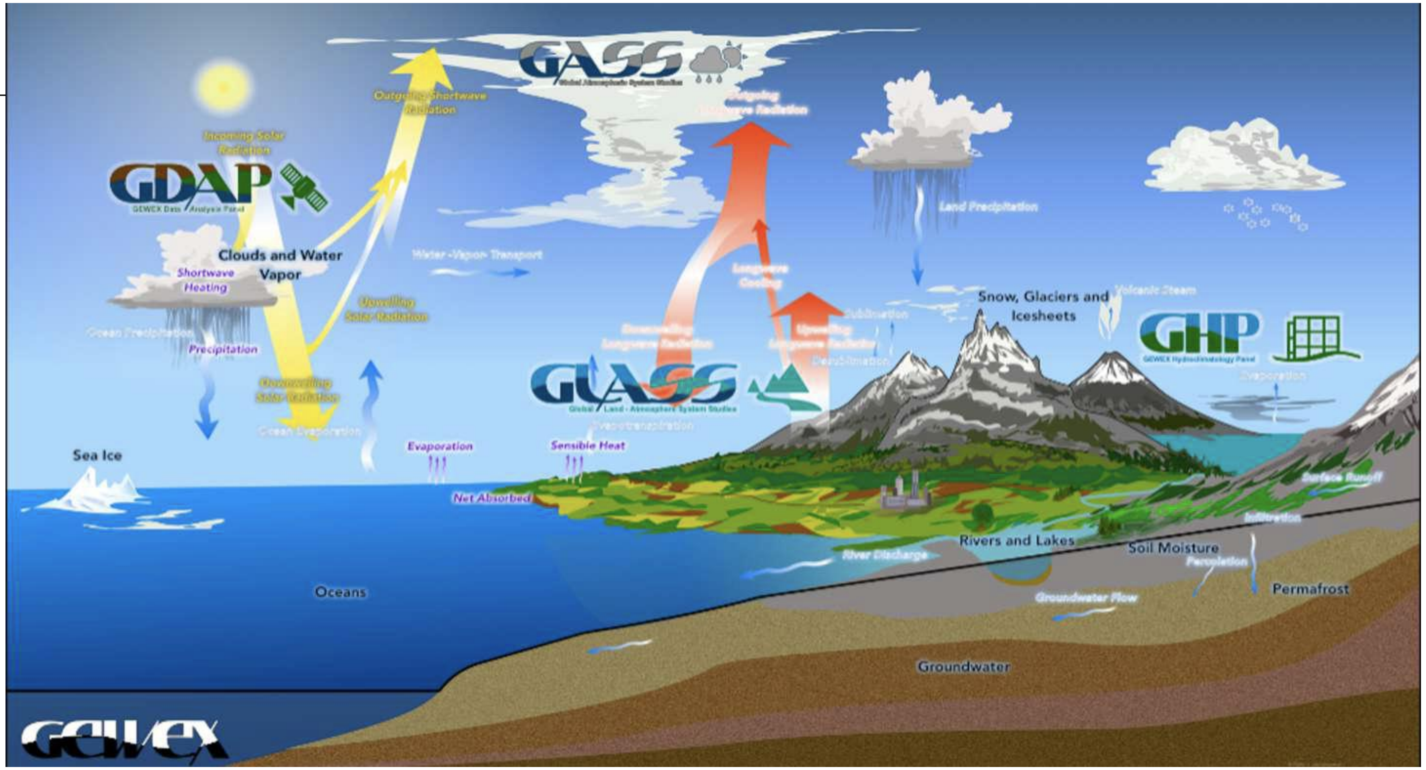
Flooding in Magdeburg, Germany, in 2013



....and by "advertise", I mean we should engage a lot more with the GHP part of GEWEX, perhaps?

I know that we do engage with these bodies already, e.g. Anne Verhoef's *SoilWat* initiative (GEWEX/GLASS), but I get the feeling that we approach GEWEX from the direction of GLASS only, when actually I think we have a lot to offer the GHP as well.

The GEWEX Hydroclimatology Panel (GHP) aims to understand and predict continental to local-scale hydroclimates for hydrologic applications.

GHP concentrates on improving our understanding of environmental water and energy exchanges at the regional scale and from an integrated perspective. Addressing the water cycle at the regional scale allows us

Thank you.

For more information please contact:

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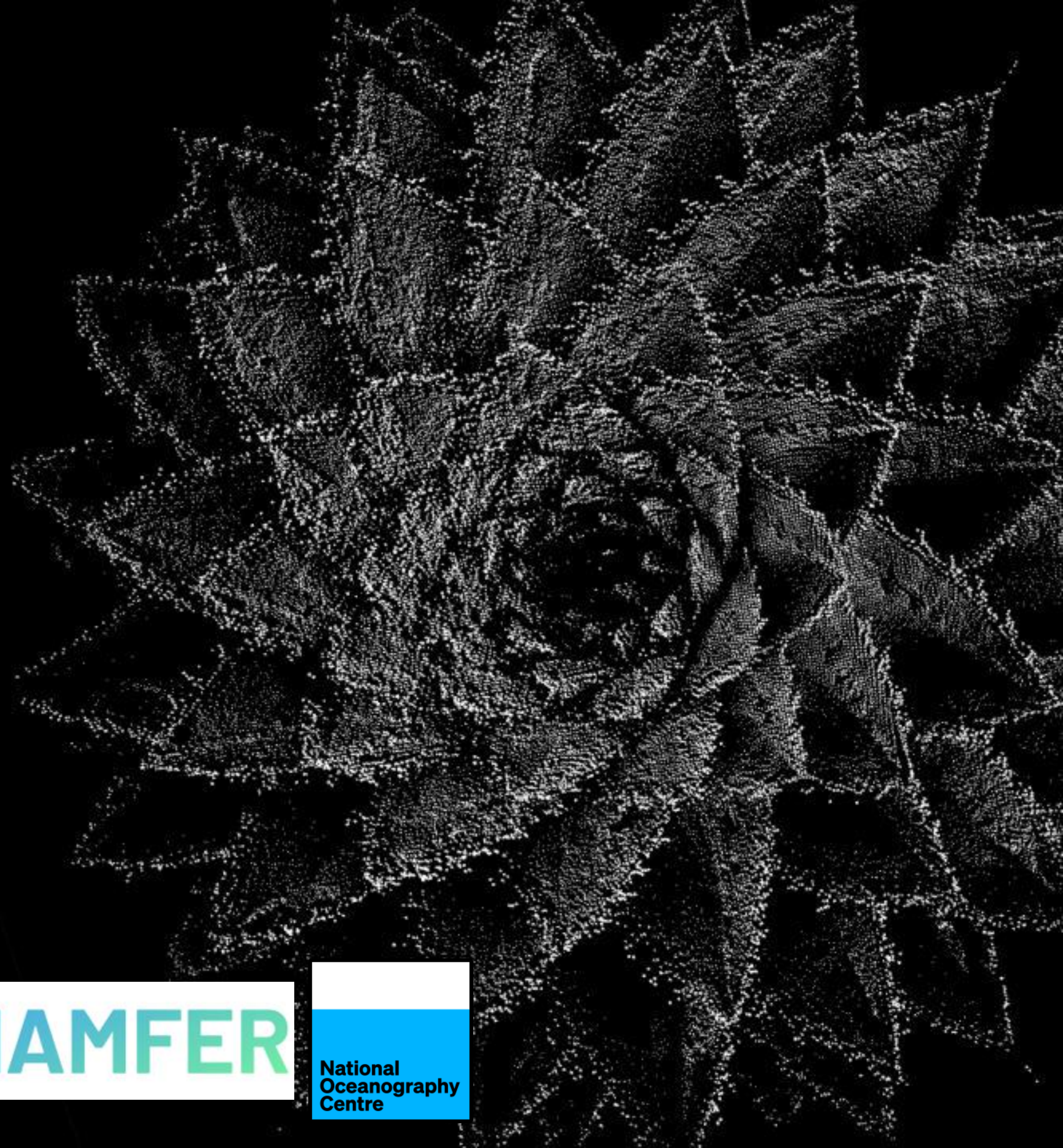

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CHAMFER

National Oceanography Centre