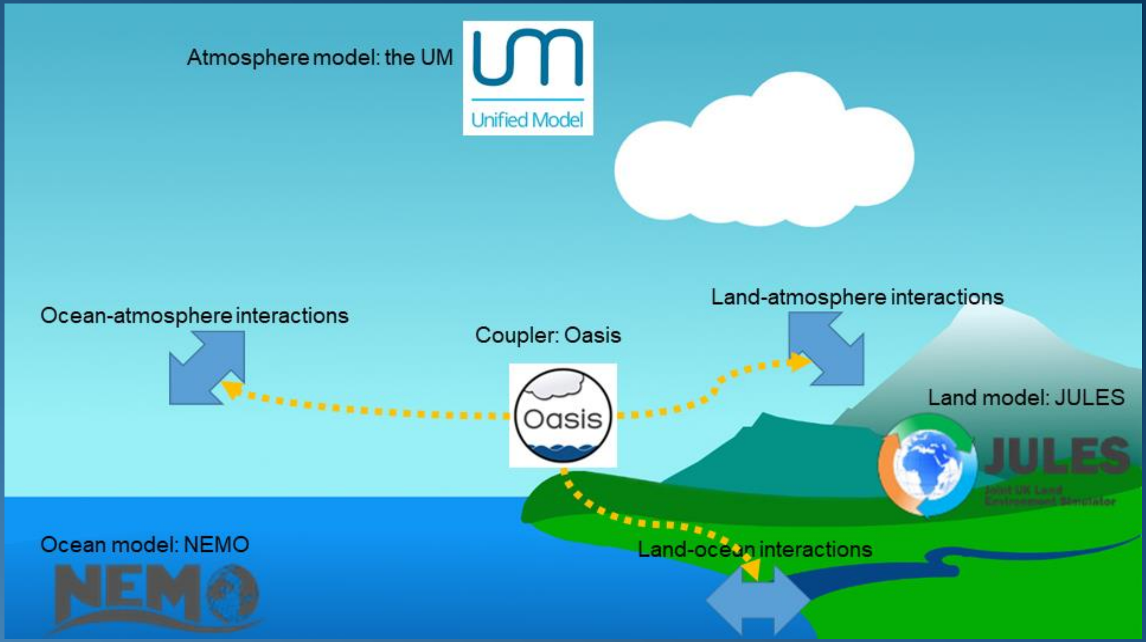
Rivers and inundation in the CHAMFER project

Toby Marthews, UKCEH Wallingford
Douglas Clark, UKCEH Wallingford
Matt Wiggins, UKCEH Wallingford

with huge thanks to colleagues at
NOC Liverpool,
UKCEH Bangor,
the UK Met Office,
BGS
and elsewhere.

14th September 2023



National Oceanography Centre
UK Centre for Ecology & Hydrology
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL
UKRI Natural Environment Research Council
Met Office

Introduction

My name is **Toby Marthews**. I work at the **UK Centre for Ecology & Hydrology (UKCEH)**.

UKCEH is a UK research centre spread across four sites (right). We specialise in research in **terrestrial and freshwater ecosystems** and their interactions with the atmosphere.

The CHAMFER Project:

CHAMFER (UK Coastal HAzards - Multi-hazard controls on Flooding and ERosion) is part of *UKCEH*'s National Capability LTSM portfolio.

Project led by Laurent Amoudry at NOC Liverpool; duration 2022-27.

I'm task leader for ***Task 1.3:*** *River modelling: the river meets the ocean*.

National Oceanography Centre

UK Centre for Ecology & Hydrology

Bangor

Wallingford

Laurent Amoudry

Michela de Dominicis

Angus Garbutt

Joanna Harley

Toby Marthews

Matthew Wiggins

https://projects.noc.ac.uk/chamfer/

The CHAMFER Project:

In *CHAMFER* we're trying to deliver predictive capability in **coastal inundation** for the UK on a 500 m resolution grid.

Currently, we cannot simulate coastal inundation impacts on the land surface. In order to do this, we need:

1. A **coupled model** so that the land and the ocean can exchange information. We are working with Ségolène Berthou to use the *UM_JULES* Coupled model (Marthews *et al*. 2023).

2. ***CaMa-Flood*** river routing so that we can have inundation from the ocean 'back up' onto the land surface.

Met Office

Ségolène Berthou

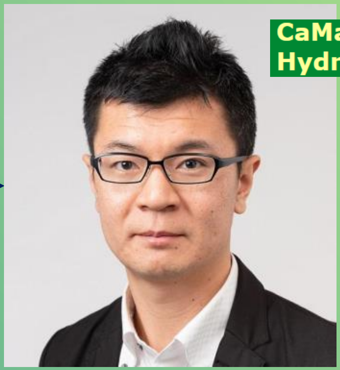
Unified Model

Momentum
The Unified Earth Environment Prediction Framework

東京大学
THE UNIVERSITY OF TOKYO

JAMSTEC 国立研究開発法人 海洋研究開発機構
Japan Agency for Marine-Earth Science and Technology
海洋・地球・生命の総合的理解への挑戦

CaMa-Flood: Global River Hydrodynamics Model



Dai Yamazaki

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

1. Coastal inundation

2. Coupled modelling

3. CaMa-Flood and Coastal Exchange Points (CEPs)

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1. **Coastal inundation**

2. Coupled modelling

3. CaMa-Flood and Coastal Exchange Points (CEPs)

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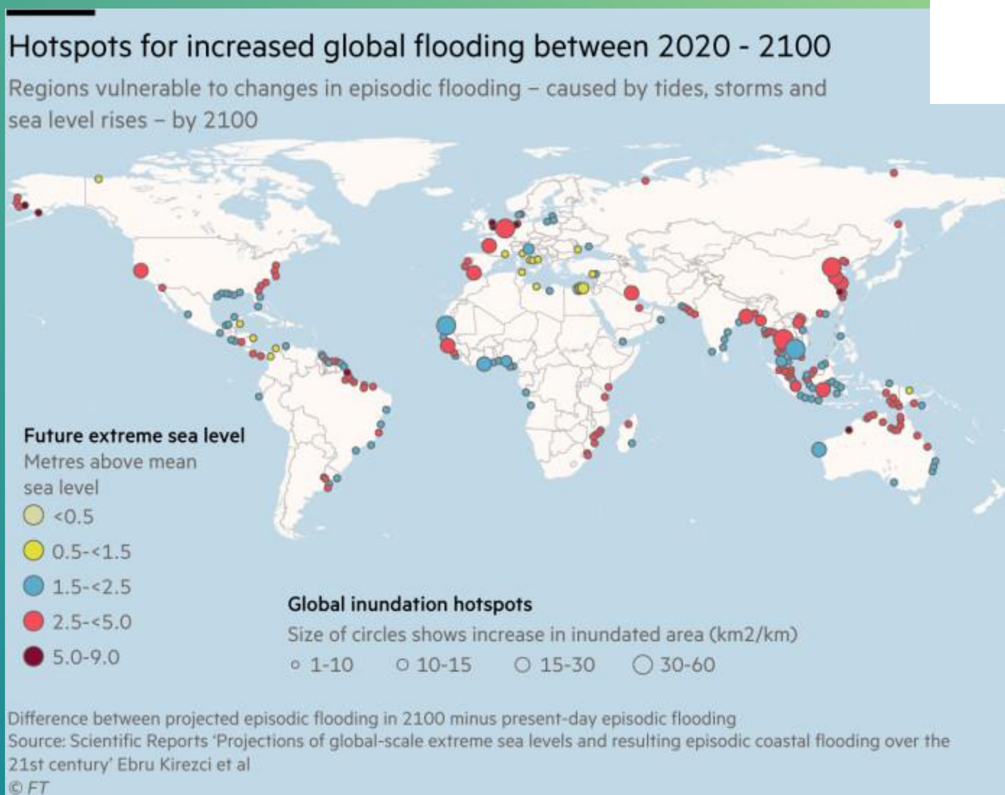
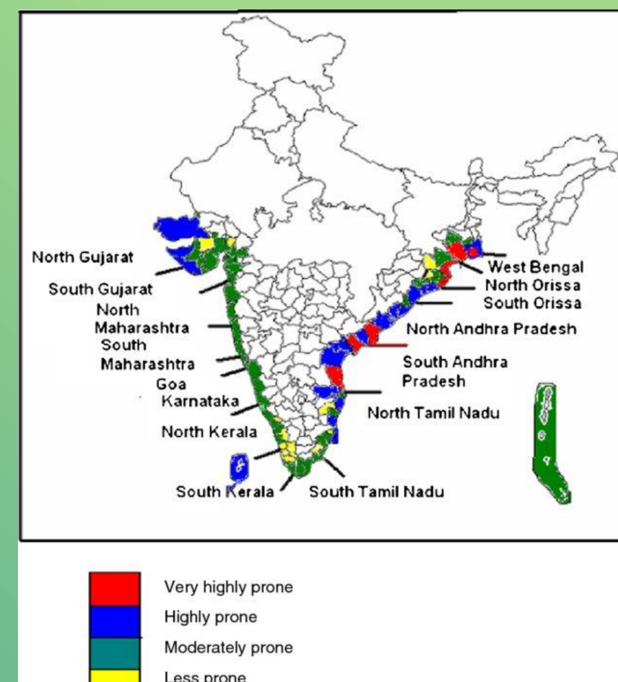
Inundation

It is very clear that flooding and related extreme events are happening with increasing frequency around the world.

Coastal flooding especially is a major global issue.





Mohapatra (2015). Cyclone hazard proneness of districts of India. J Earth Syst Sci 124

Inundation

What can we say about inundation and flooding with a model like JULES?

- 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. Routines have been inserted to improve runoff prediction (PDM/TOPMODEL), represent river routing (TRIP/RFM) and land surface inundation.

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.

However, I believe JULES is not too far away from being really quite a good hydrological model: a lot of work is currently in train to improve the river simulation routines, including new 'rivers-only' options, and efforts to include the CaMa-Flood hydrodynamic model led by UKCEH.

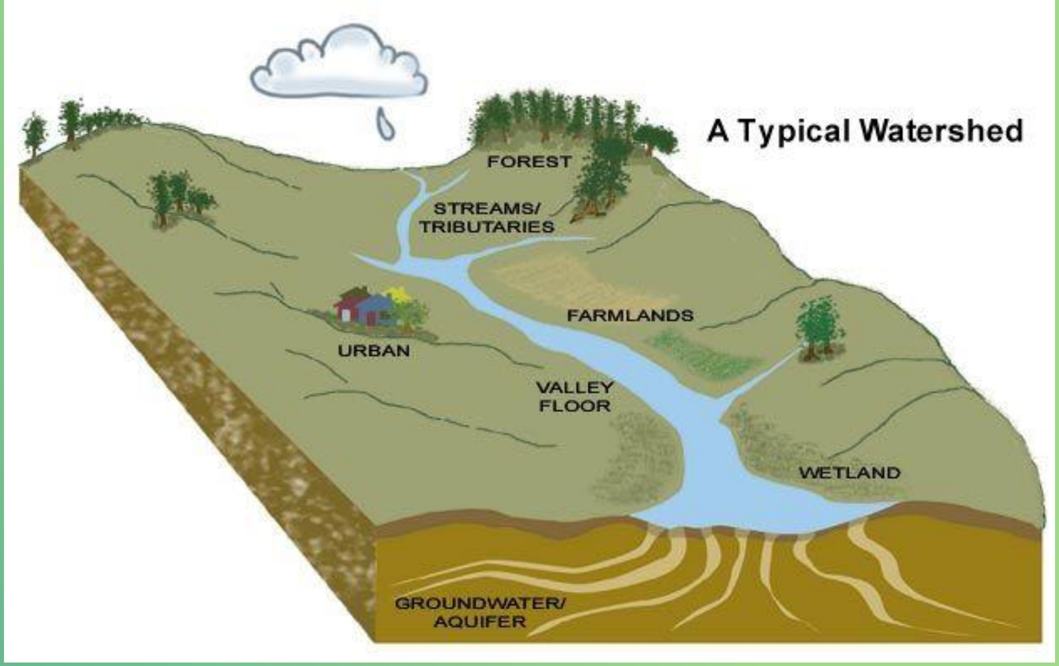
Flooding in Chennai, India

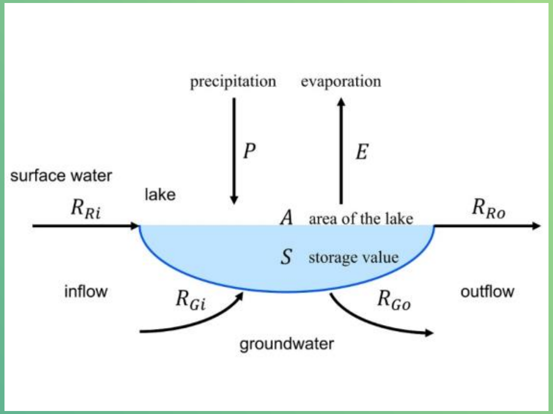
Rivers

On the land surface, the main stores of water are (of course) rivers and lakes.

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.

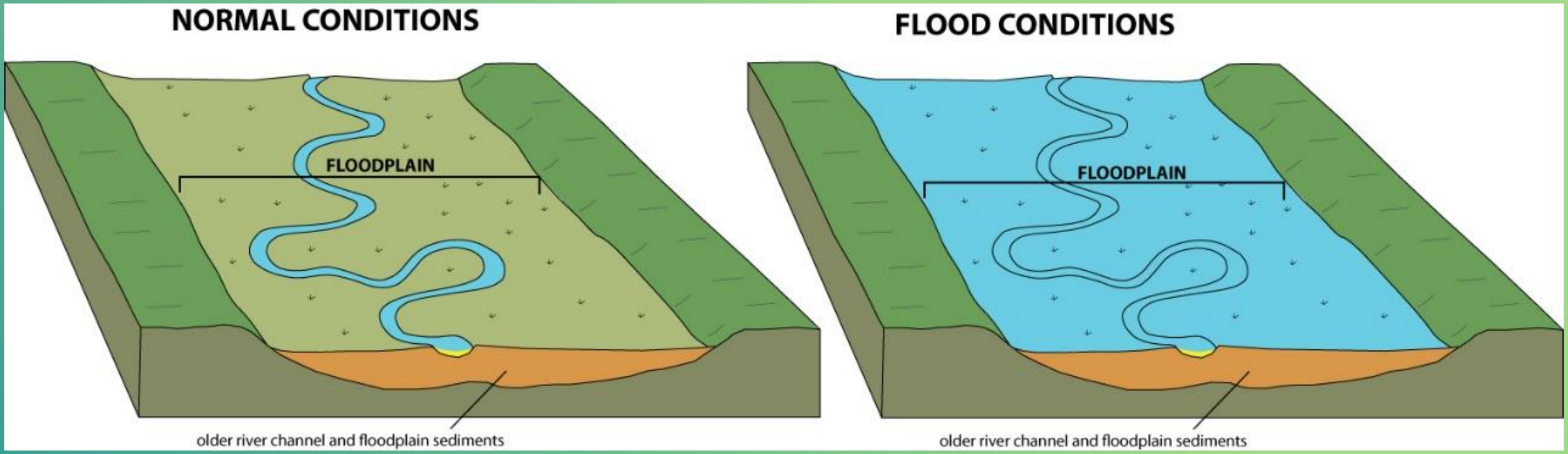
However, water is famously 'badly behaved': it doesn't always stay inside well-defined rivers and lakes.





Hydro-JULES

River overbank inundation



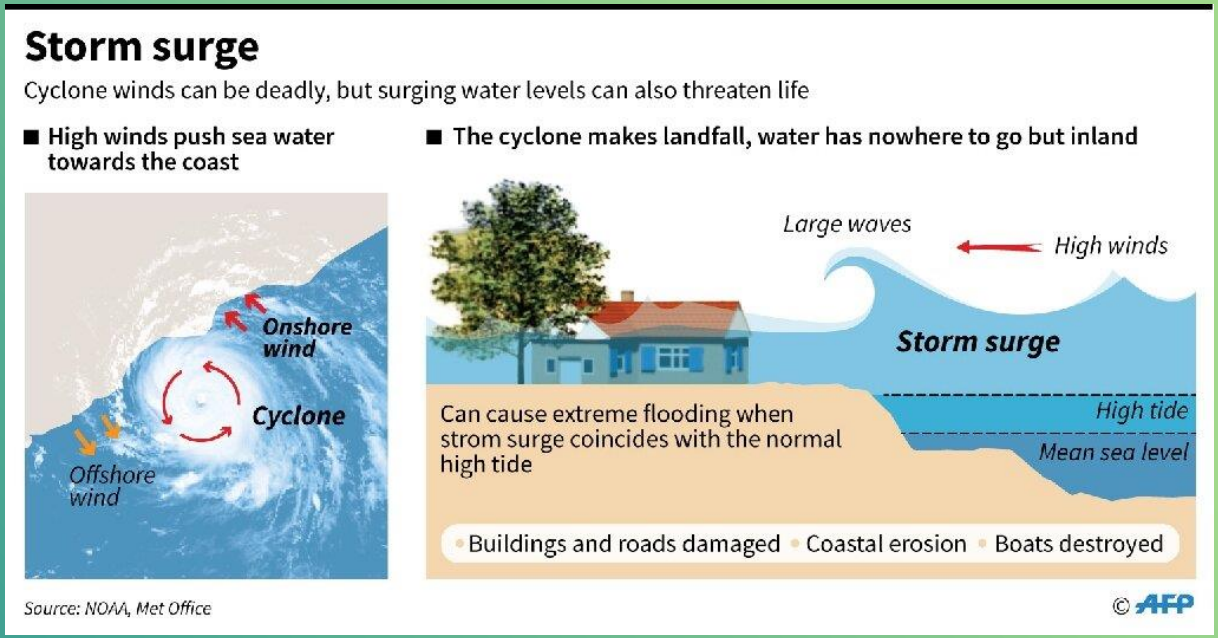
- Inundation can be divided into **three** types
- ***1. Overbank inundation*** is generally the most familiar form of flooding. It is the process by which rivers burst their banks and expand temporarily to inundate part of their floodplain.

Guadalupe River (Tx, USA) during Hurricane Harvey, 2017, from https://www.today.com/video/guadalupe-river-could-reach-32-feet-above-flood-stage-in-harvey-s-wake-1033626179738

Groundwater inundation

- ***2. Groundwater inundation*** occurs when a natural underground drainage system is incapable of sufficiently draining itself, resulting in the emergence of groundwater at the surface. For example, in Rep. Ireland, the most extensive form of groundwater flooding is related to prolonged rainfall causing water table rise in limestone lowland areas (e.g. above, from https://www.gsi.ie/en-ie/programmes-and-projects/groundwater/activities/groundwater-flooding/Pages/default.aspx)

Coastal inundation



Source: https://phys.org/news/2019-05-storm-surge-dangerous.html

3. Coastal inundation is partly a result of river flow and groundwater (e.g. permanent coastal wetlands), but can have large components of tidal surge and storm surge from the ocean. This can only be simulated in the Met Office system if we couple a land surface model to an ocean model.

- ***Coastal inundation*** is a ‘multi-hazard’ resulting from a combination of river flow, groundwater and ocean intrusion ('Multi-hazard' is the "M" of CHAMFER).

1. Coastal inundation

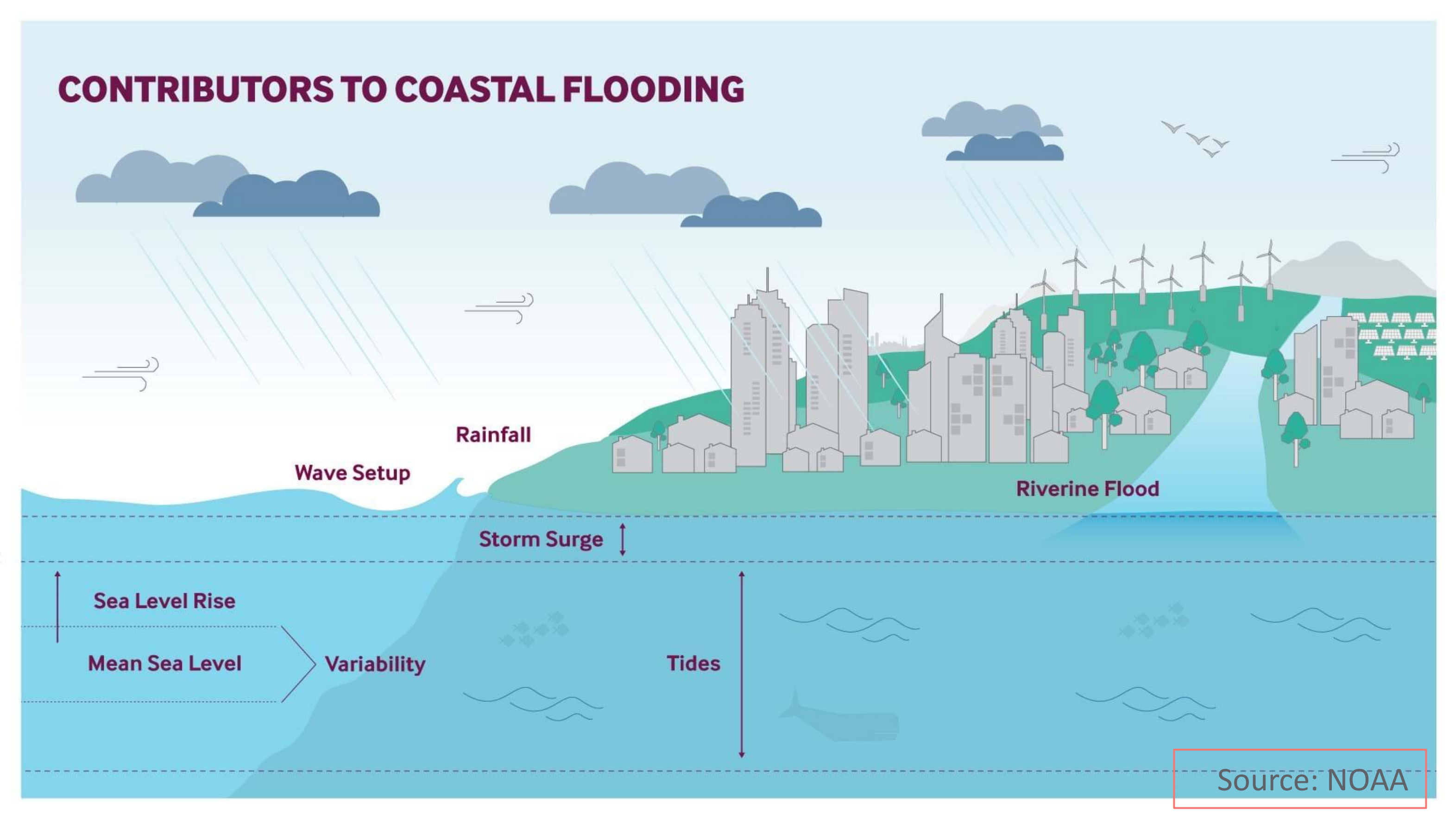
2. Coupled modelling

3. CaMa-Flood and Coastal Exchange Points (CEPs)

UK Centre for Ecology & Hydrology

Coupled Modelling using the UM_JULES framework

Hydrological modelling and coastal ocean modelling typically do not consider two-way interactions between them, leading to erroneous assessments due to backwater effect in the transitional waters (e.g. estuaries and tidal rivers) which host a large proportion of infrastructure (e.g. ports, airports, power stations) and habitats of national and international significance.



Slide many thanks to Michela de Dominicis

Coupled Modelling using the UM_JULES framework

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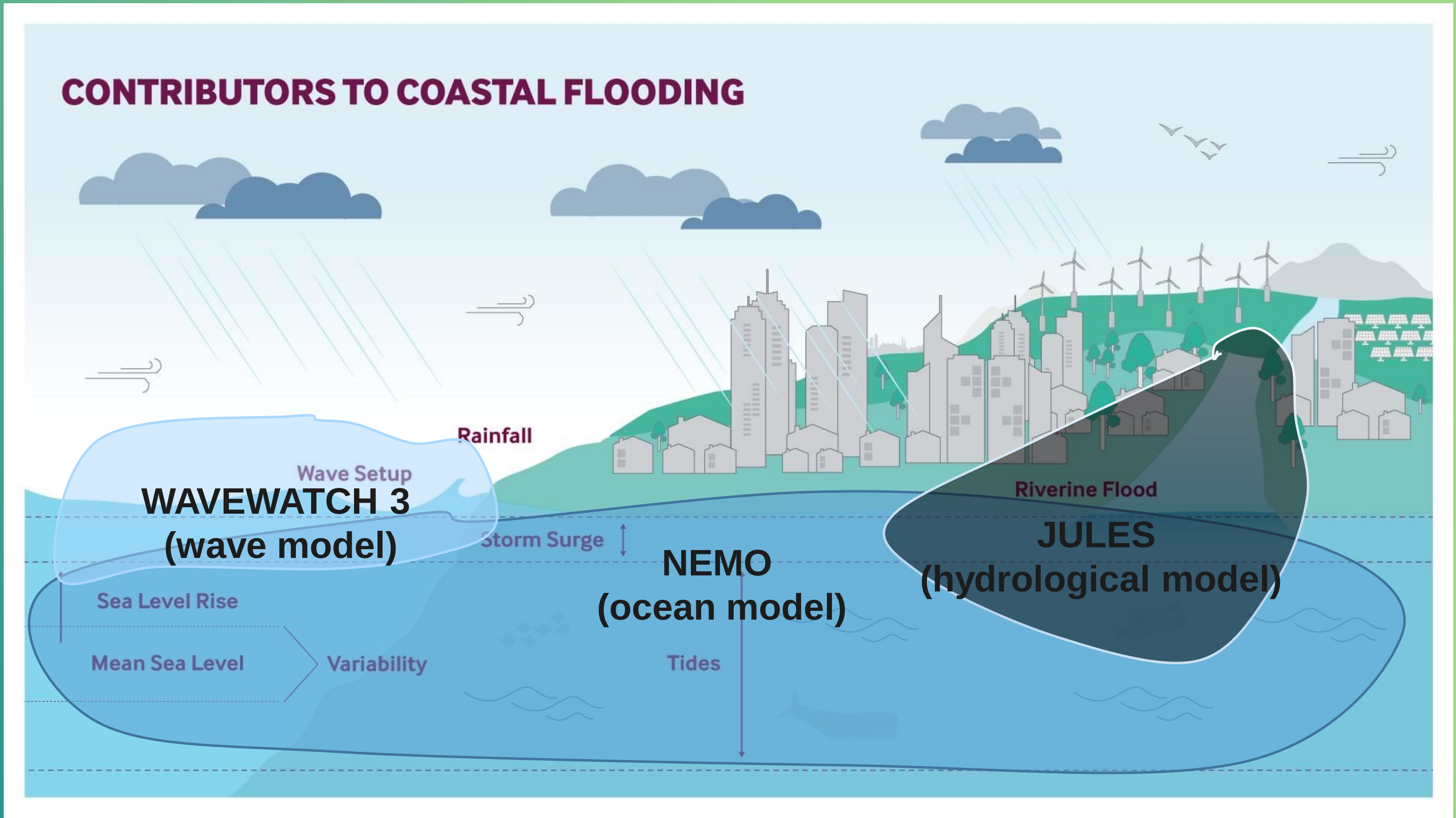


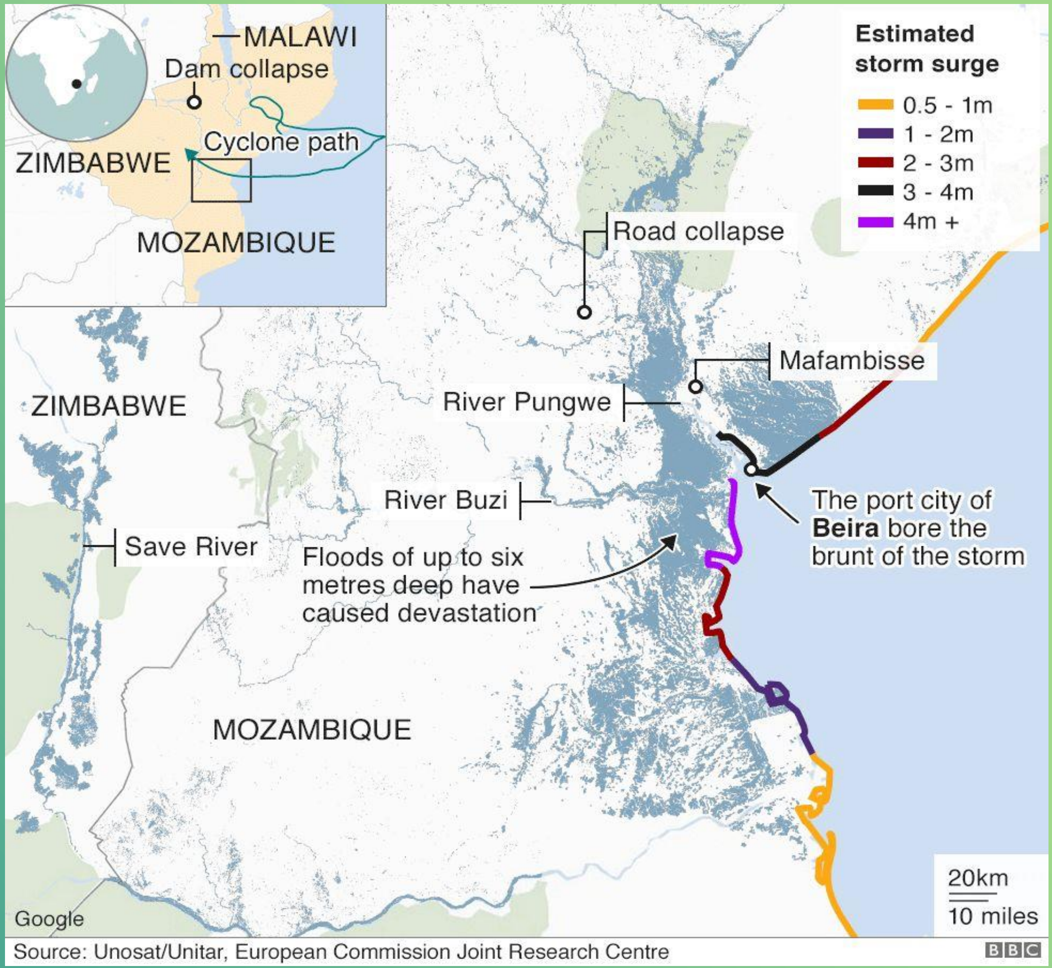
Slide many thanks to Michela de Dominicis

Coupled Modelling using the UM_JULES framework

Here is an illustration from a BBC article about the 2019 Cyclone Idai. Note the light blue shading for coastal inundation and the multi-coloured line at the coast indicating the magnitude of the sea surge.

Although this is not a UK example (CHAMFER's spatial focus is the UK), I find this BBC illustration is the best way to present our modelling approach in CHAMFER.

Essentially, what we want the model to be able to do is to acquire the ability to predict the light blue inundation areas based on the coastal sea surge numbers in the legend.



Coupled Modelling using the UM_JULES framework

To make this work, we need a COUPLED MODEL.

Three ***top-level divisions***: atmosphere, land and ocean. At the UK Met Office, the coupling arrangements of the *UM* family of models reflect this: the family is composed of an atmosphere model (the UM), an ocean model (NEMO) and a land model (JULES), with exchange of information between these three main models synchronised by a coupler (OASIS). In the US, the Community Earth System Model (CESM) follows a similar approach with different component models.

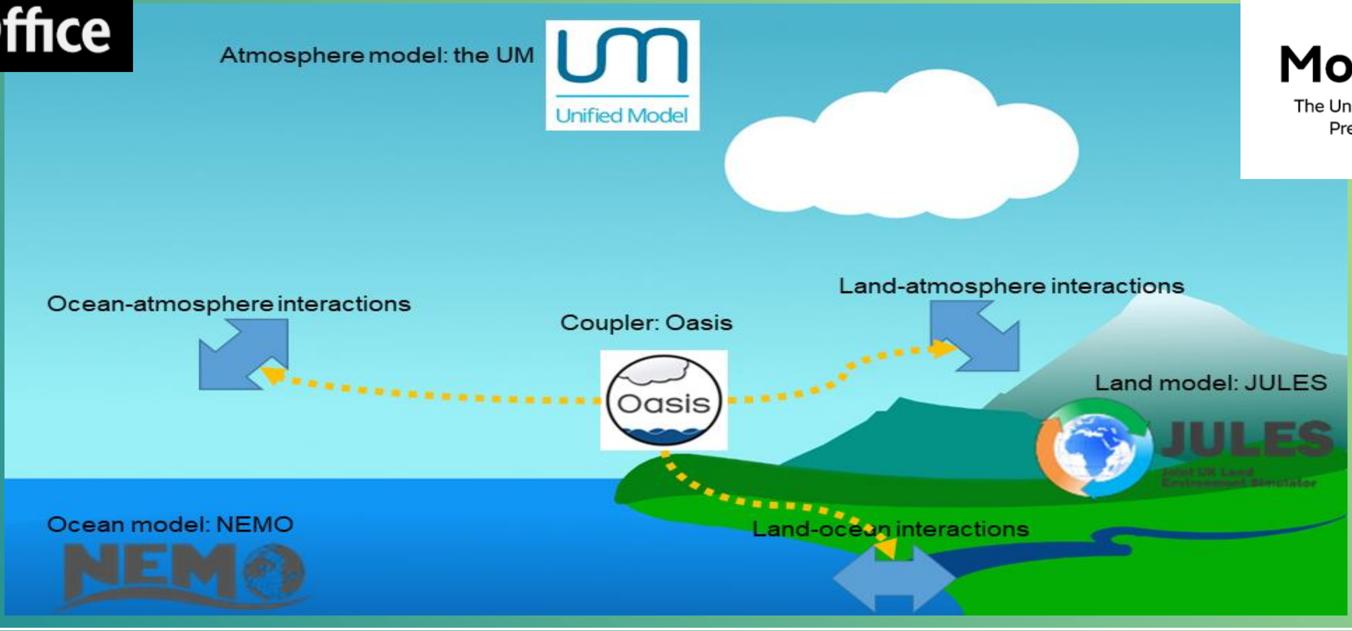
Within each division there are also what we could call ***second-level divisions*** that are less globally standardised: dividing the ocean into shelf seas, deep ocean and sea ice (e.g. Lewis et al. (2018)) or dividing the land surface into surface soil, susurface soil and open water (e.g. Hallouin et al. (2022)).

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

Met Office

Momentum

The Unified Earth Environment Prediction Framework



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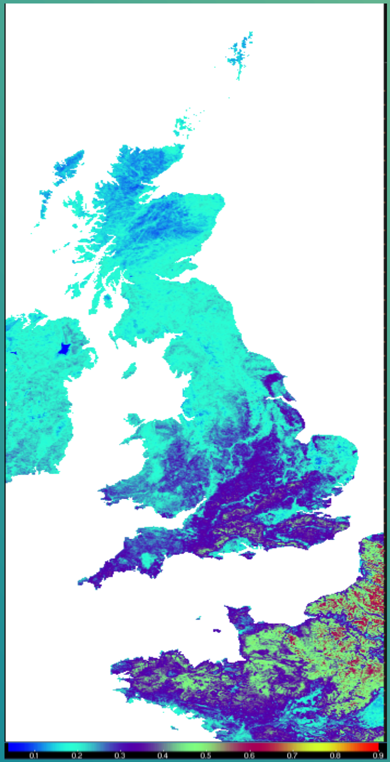
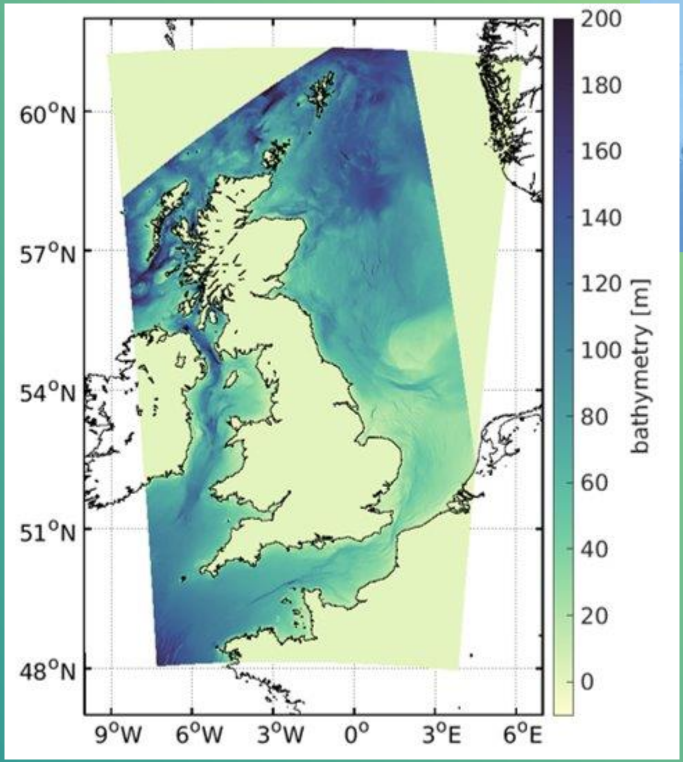
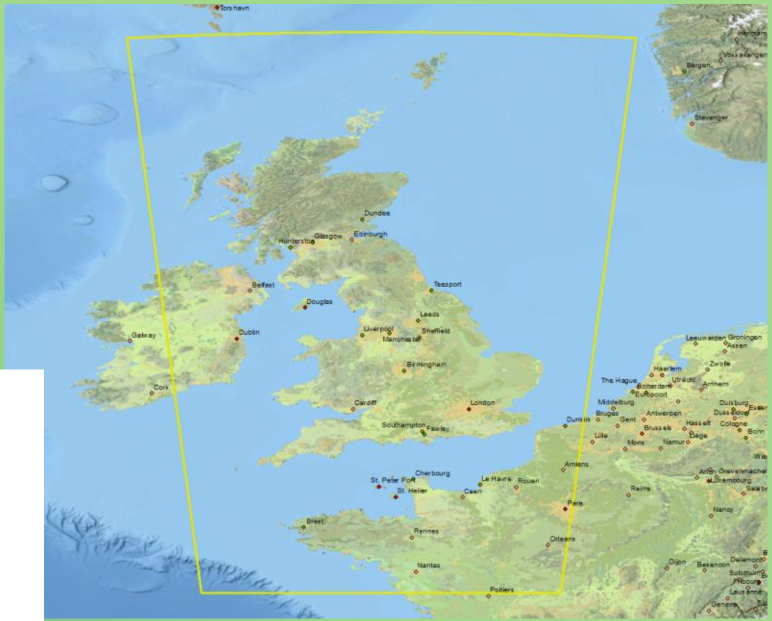
Coupled Modelling using the UM_JULES framework

Doing any of this requires ancillary files, so my first job has been to agree the grid we will use with NOC and BGS, then generate ancillaries. NOC will be using ancillaries with irregular boundaries (deeper areas >250m masked out).

e.g. Soil matric suction at saturation (SATHH) (left); Bathymetry from EMODNET (2020) (right).







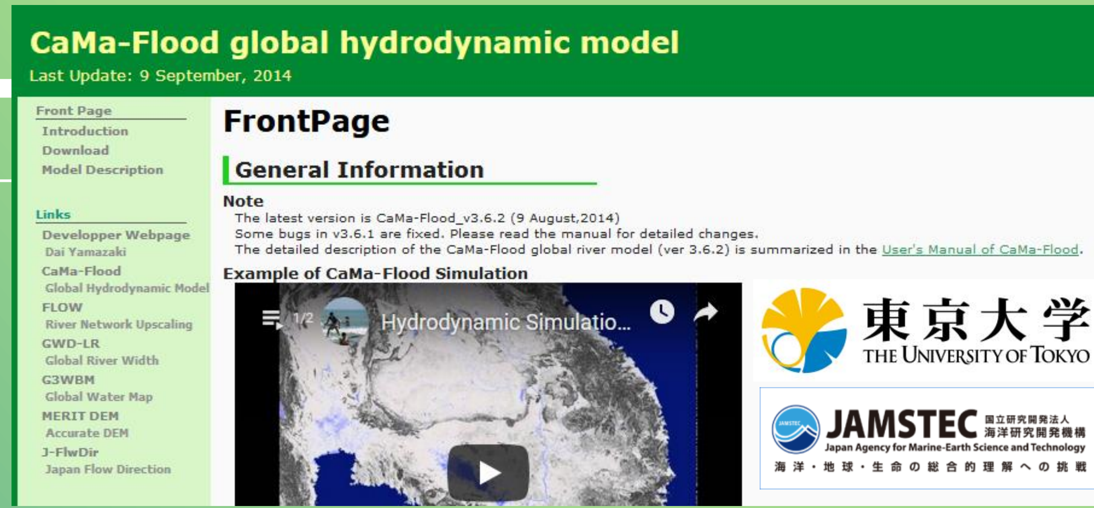
1. Coastal inundation
2. Coupled modelling
3. **CaMa-Flood and Coastal Exchange Points (CEPs)**

UK Centre for Ecology & Hydrology

CaMa-Flood

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 (more or less equivalent to the diffusion wave approx.).

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



St Venant Equations / Shallow-Water equations of open channel flow

Continuity Equation

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

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

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

Kinematic Wave

Diffusion Wave

Dynamic Wave

This is something we need for modelling coastal inundation: the ocean model NEMO communicates the height of the sea wall to JULES (via Oasis), but then the river routing scheme in JULES must allow that water to travel upstream to produce inundation.

This is not possible with RFM because it follows the kinematic wave equation that cannot allow temporary flow reversals.

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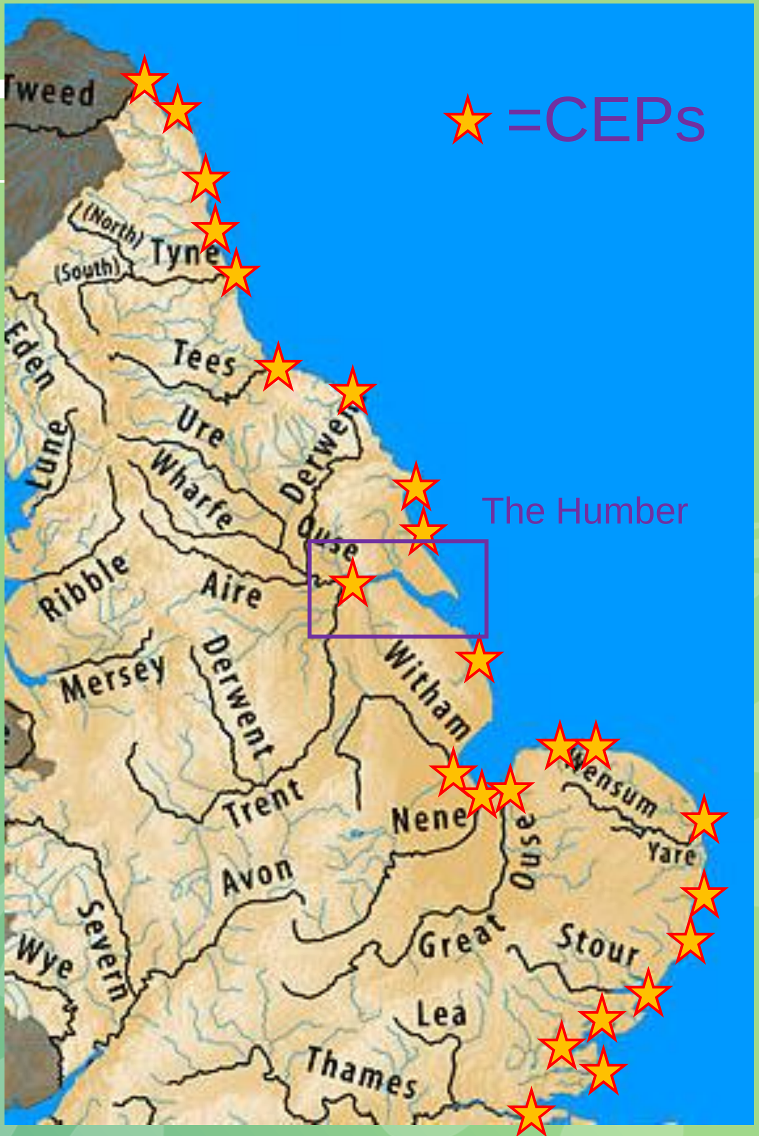
Coastal Exchange Points (CEPs)

I have added a routine to the CaMa-Flood code that parses the input river directions ancillary and identifies the river estuary points (see output below).

Over the globe I get 18,481 estuary points with the CaMa-Flood ancillary file (though that number changes if I use different files).



[INFO] init_rivers_props: RIVMAP_INIT: calculate river sequence
[INFO] init_rivers_props: Longest river on grid is 259 gridcells long (source to mouth).
[INFO] init_rivers_props: Over the river domain: 4646 inland_drainage points found
[INFO] init_rivers_props: Over the river domain: no. labelled river_mouth points is 18481
[INFO] init_rivers_props: Over valid river domain: no. river routing points = 252383
Over valid river domain: 73564 gridcells are either inland_drainage points or river source points (headwaters)
[INFO] init_rivers_props: Over the river domain, we have 247737 points that are real flowpath points headwater to mouth (exc. inland_drainage and river_mouth points)

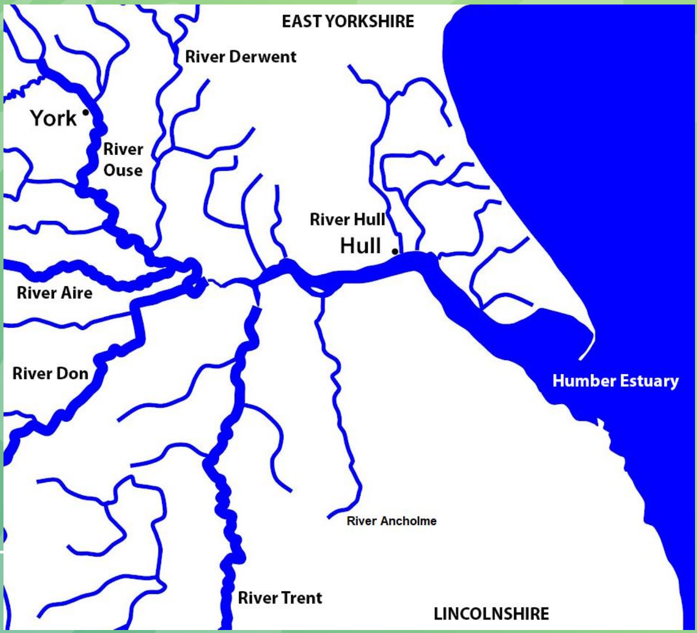
Coastal Exchange Points (CEPs)

The Humber Estuary (right) is very dynamic with a tidal range of up to six metres near the mouth at Spurn Head. Severe storms can raise water levels by up to 1.5 metres above normal and result in waves up to four metres high near the mouth (Boukalova et al. 2011).

Fig. from Boukalova et al. (2011). Blue = saline sediments, indicating flood-risk areas.

Modelling this with a CEP approach, we only allow exchange of water between the land and ocean at the CEP:

- Inundation upstream from the CEP is handled by JULES (overbank inundation code)
- Inundation adjacent to the rest of the Humber is not modelled.
- Remembering the three types of inundation above, inundation will have contributions from (i) groundwater, (ii) upstream flow causing overbank inundation and (ii) sea/tidal surge. The current code can handle (i) and (ii) left of the line, but we need the sea wall height numbers from NEMO in order to add the effects of (iii).



1. Coastal inundation
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UK Centre for Ecology & Hydrology

Summary

All of this is a lot to put together and it is taking a long time (!). Here's a summary of what we're intending for CHAMFER:

- We need to get CaMa-Flood into JULES so that we can have temporary reversals of flow in rivers in the model.
- Then we need a version of the UM_JULES coupled framework that allows two-way coupling between land and sea (i.e. not just river outflow, but also ocean intrusion).
- Then we need all of this running at 500 m resolution over the UK (new ancillaries, etc.)
- Then we need data from UK estuaries (collected by CHAMFER colleagues) to validate all of this.

At the end of it all, we will have a top-flight set of hydrodynamic routines within the coupled UM_JULES framework (i.e. Momentum) that will allow us to simulate all forms of inundation.

THANK YOU

CHAMFER: **https://projects.noc.ac.uk/chamfer/**

For more about me and my research, see:
https://www.tobymarthews.com/

What is MOMENTUM?

Momentum
The Unified Earth Environment Prediction Framework

Press release from 28th June 2023 at https://cehacuk.sharepoint.com/sites/hub-news/SitePages/Met-Off

For the many of you across UKCEH who collaborate with the Met Office, there is a renaming of their weather / climate numerical simulation methods, as well as related products. Please see an outline message below. For more details please contact George Pankiewicz at the Met Office.

Momentum is the new name for the Unified Earth Environment Prediction Framework from the Met Office, successor to the Unified Model (UM).

The Met Office, a major partner with UKCEH in global modelling and environmental prediction, has developed its Unified Model (UM) over 30 years used in collaboration with institutions around the world for weather forecasting and climate modelling.

Now it is developing its Next Generation Modelling Systems (NGMS) to make best use of continually-evolving supercomputing architectures and in particular their own Generation 2 supercomputer.

The modelling framework delivered by NGMS will be given a new name, Momentum, the Unified Earth Environment Prediction Framework. This includes the software code and infrastructure used to model the components of the Earth system, as well as the model configurations. The Met Office and its Partners will use these elements of Momentum to build prediction systems, which are not part of Momentum.

Scientists across UKCEH use the outputs of the UM for such things as hydrological forecasting, impacts modelling and understanding land-atmosphere interactions. Hydro-Climate Research (HCR) scientists are involved in running and evaluating the UM, including as partners in the UK Earth System Model. UKCEH are key partners in the land surface model JULES, which is a component of the UM and which HCR scientists are developing to become part of Momentum.

I like this illustration from Ward et al. (2020).

Essentially, by putting in the inundation code a few years ago we managed to (mostly) sort out these arrows:

Through CHAMFER we hope to sort out these arrows too:

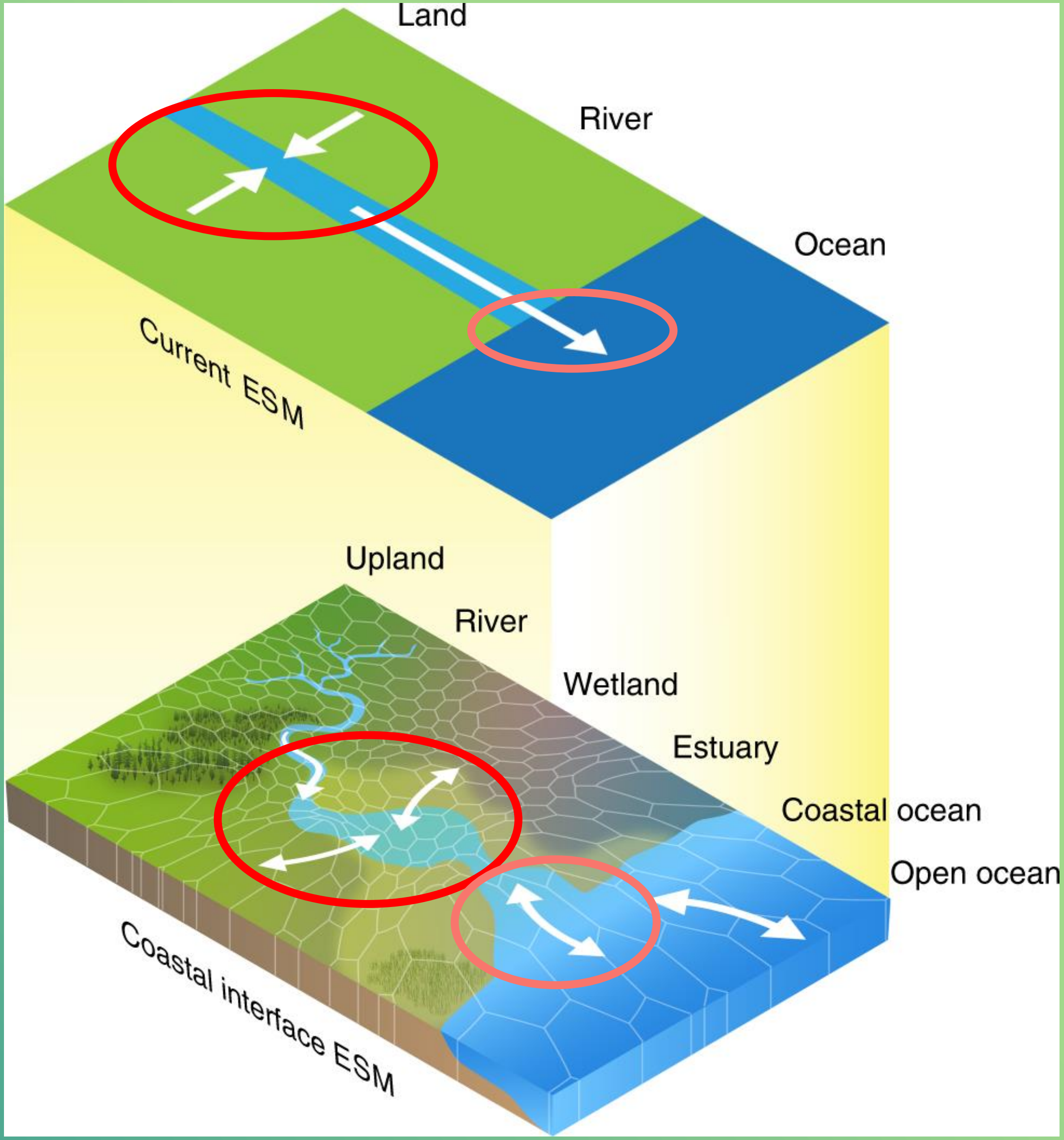


Fig. 1 from Ward *et al.* (2020): Current Earth system models (ESMs) represent the land and ocean as disconnected systems, with freshwater discharge being the only meaningful connection. Next-generation models should represent land–sea connections by incorporating coastal features such as the tidal rivers, wetlands, estuaries, the continental shelf, and tidal exchange across the coastal terrestrial–aquatic interface. This likely necessitates coupling different models to produce details at the sub-grid scale.

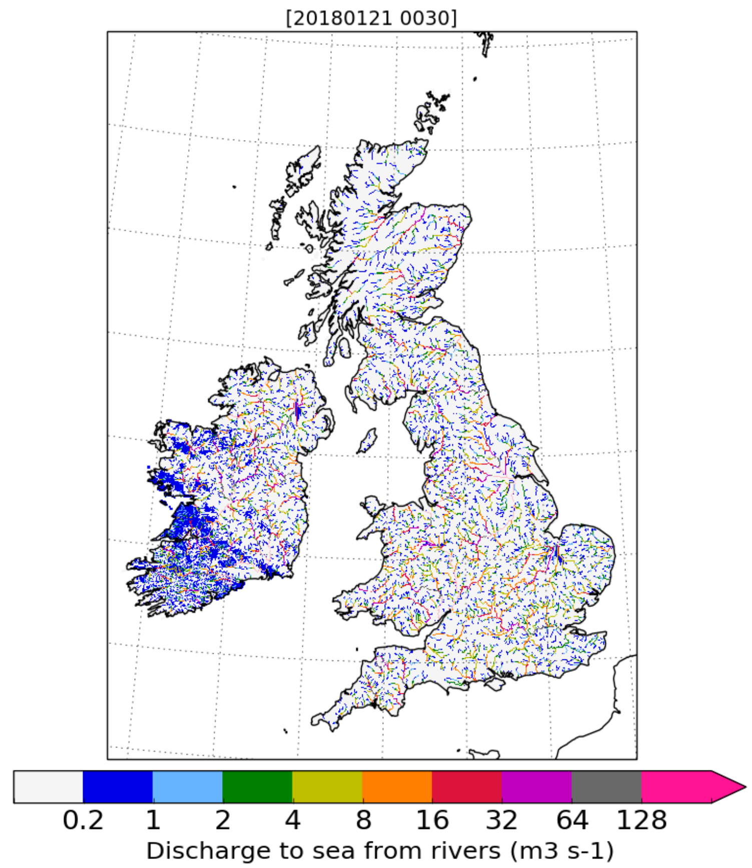
Ward *et al.* (2020). Representing the function and sensitivity of coastal interfaces in Earth system models. *Nature*. https://www.nature.com/articles/s41467-020-16236-2

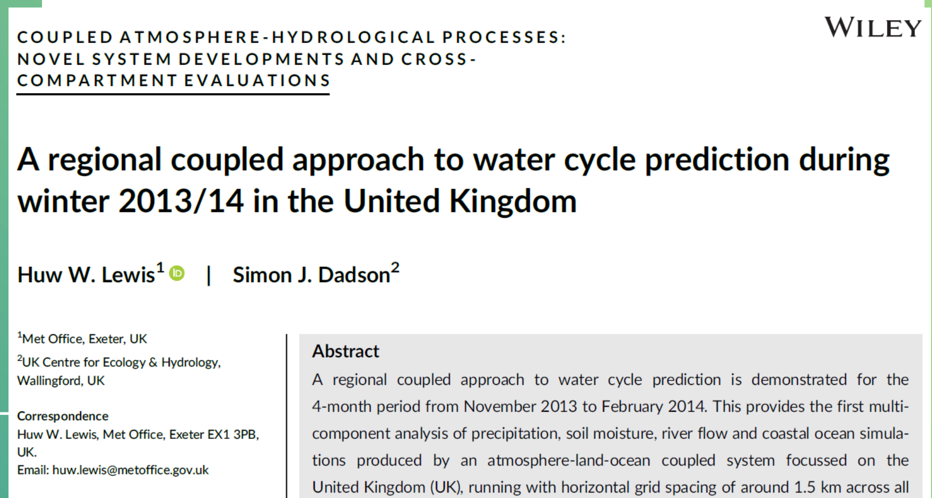
UK Environmental Prediction (UKEP)

- In the *UKEP* project (2016-20) the capability was developed to do some kinds of coupled runs (Lewis *et al*. 2018, *GMD,* Lewis & Dadson 2021).

- This animation looks (I feel) very impressive. However, in *CHAMFER* we want to do better in two ways:

1. We want a finer spatial scale than this (0.5km rather than 1.5km or 2.2km) and
2. We want interchange with the ocean.





COUPLED ATMOSPHERE-HYDROLOGICAL PROCESSES: NOVEL SYSTEM DEVELOPMENTS AND CROSS-COMPARTMENT EVALUATIONS

WILEY

A regional coupled approach to water cycle prediction during winter 2013/14 in the United Kingdom

Huw W. Lewis[1] | Simon J. Dadson[2]

[1]Met Office, Exeter, UK
[2]UK Centre for Ecology & Hydrology, Wallingford, UK

Correspondence
Huw W. Lewis, Met Office, Exeter EX1 3PB, UK.
Email: huw.lewis@metoffice.gov.uk

Abstract
A regional coupled approach to water cycle prediction is demonstrated for the 4-month period from November 2013 to February 2014. This provides the first multi-component analysis of precipitation, soil moisture, river flow and coastal ocean simulations produced by an atmosphere-land-ocean coupled system focussed on the United Kingdom (UK), running with horizontal grid spacing of around 1.5 km across all

Met Office
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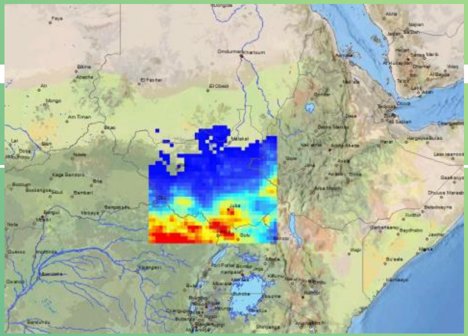
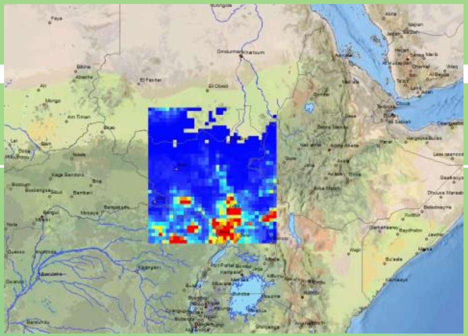
PML Plymouth Marine Laboratory

Simulated water cycle elements of the Sudd wetland, South Sudan, during 2009-2015.

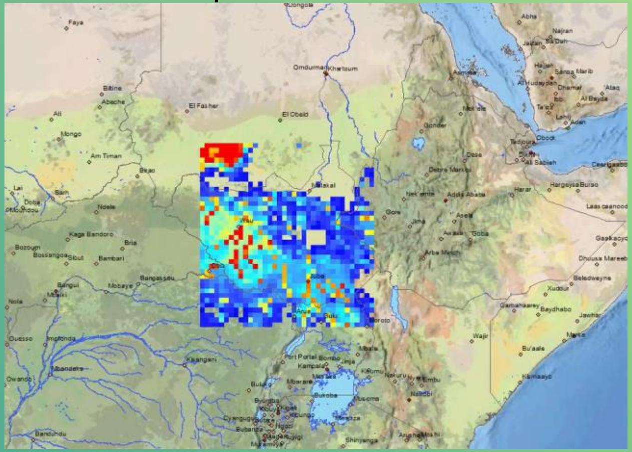


Precipitation

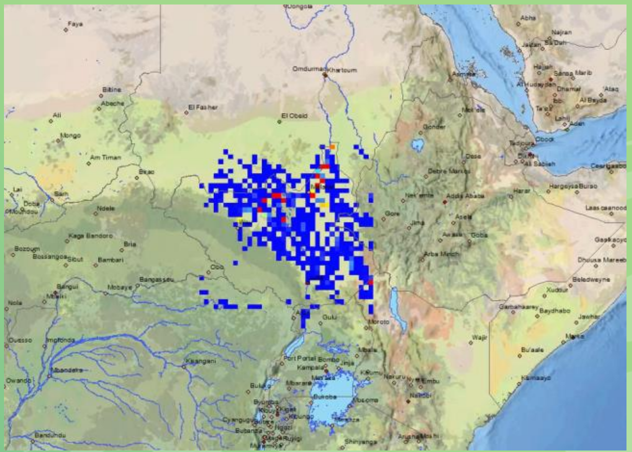


Runoff

River flow



Area of shallow inundation (*fwetl*)

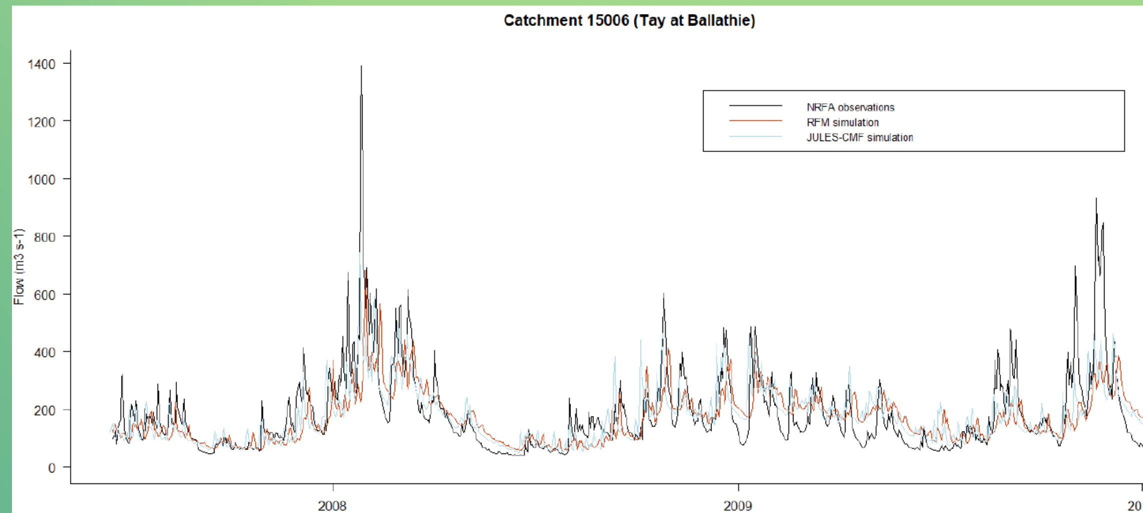


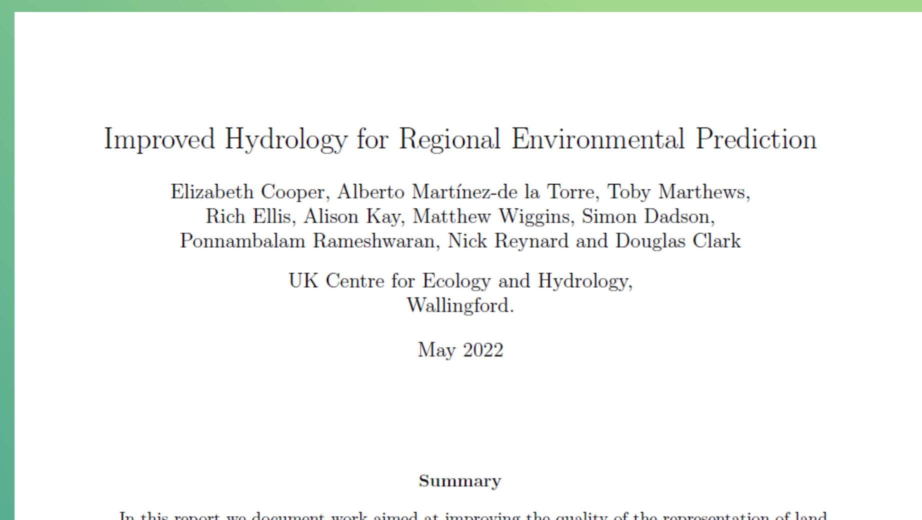
Overbank inundation (*frac_fplain*)

- You can see the ‘path of the water’ moving from precipitation to land surface runoff to river flow, and eventually to inundation.
- Movies are from a gridded JULES run using TOPMODEL for runoff and RFM for rivers + overbank inundation.
- Apologies: equivalent movies for CaMaFlood not shown: runs only finished last night (!).

Regional Environmental Prediction (REP)

- The *REP* project extended the work of *UKEP* (Castillo *et al.* 2022, *GMD*).
- As part of the UKCEH contribution to *REP*, Douglas Clark started the process of putting *CaMa-Flood* into *JULES* (Cooper *et al*. 2022).
- Basically, *JULES-Camaflood* does better than *JULES-RFM* over UK catchments, though it has taken a lot of work in 2022-23 for me to get this working at a global level.





Improved Hydrology for Regional Environmental Prediction

Elizabeth Cooper, Alberto Martínez-de la Torre, Toby Marthews, Rich Ellis, Alison Kay, Matthew Wiggins, Simon Dadson, Ponnambalam Rameshwaran, Nick Reynard and Douglas Clark

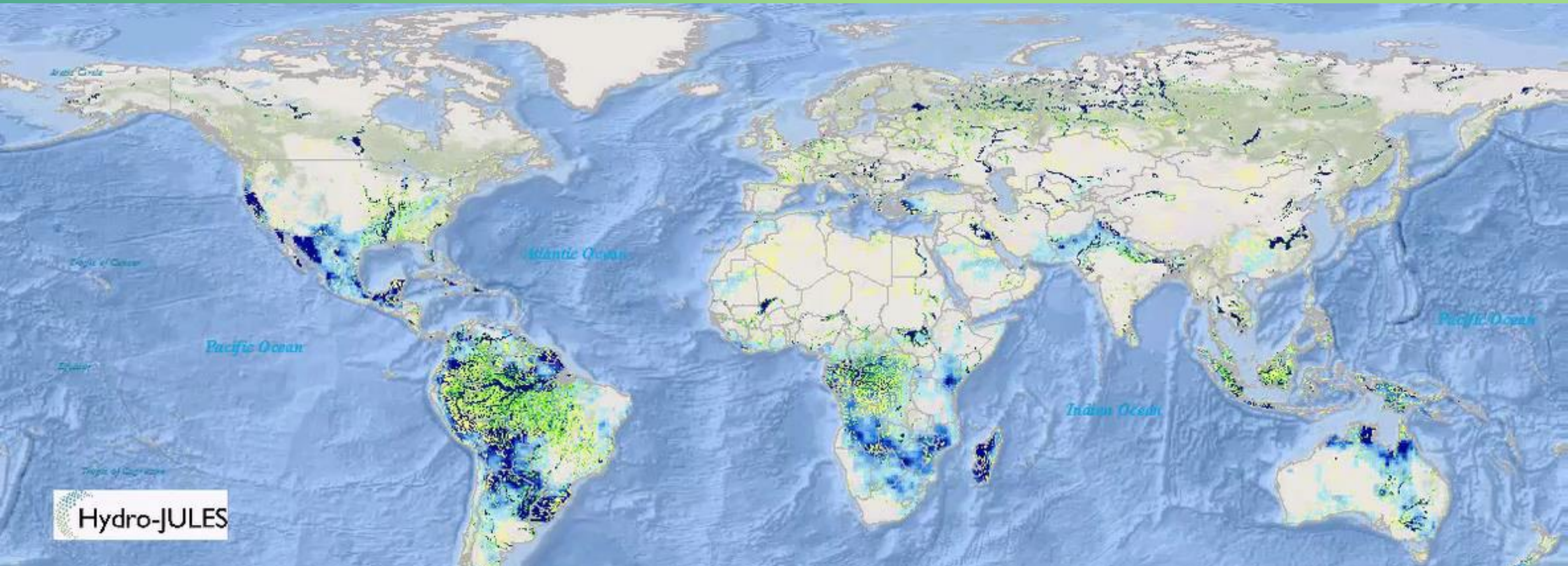
UK Centre for Ecology and Hydrology, Wallingford.

May 2022

Summary

In this report we document work aimed at improving the quality of the representation of land

Global precipitation and river inundation fraction (Jan-Dec 1993)



- *CaMa-Flood* does better than *RFM* at global scale too.
- Even without coupling to the ocean, we can capture the majority of large-scale effects, including the broad annual sweep of inundation between the N and S hemispheres.
- After *CHAMFER*, this will be better at finer scale too.

Simulation created by taking MSWEP precipitation at 0.25° resolution (*eartH2Observe* project; shades of blue, background), using JULES to generate surface runoff (not shown) and then using CaMa-Flood to generate river inundation from the simulated runoff *(Hydro-JULES* project; yellow to dark blue, foreground).

JULES-Coast

TRAC plan for developing **JULES-Coast** is at https://code.metoffice.gov.uk/trac/jules/wiki/OceanRiverInterface :

JULES
Joint UK Land Environment Simulator

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wiki: OceanRiverInterface

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Progress towards JULES-Coast

Development of a new version of JULES (Coupled) that represents coastal processes, provisionally called JULES-Coast.

Work started with the start of the CHAMFER project in late 2022 https://projects.noc.ac.uk/chamfer/ .

Treatment of the interface between ocean and river has previously proved a challenge owing to the need for consistent physical treatment of the dynamical equations representing flow on either side of the boundary. Overall, our aim is to improve the representation of the joint effects of coastal and terrestrial processes on coupled coastal flooding.

Processes to be considered:

RIVER ROUTING:

We need to use the new CaMa?-Flood river routing option (not TRIP or RFM). As part of CHAMFER, a code branch has been put together containing all the required changes (based on JULESvn6.2): https://code.metoffice.gov.uk/trac/jules/browser/main/branches/dev/tobymarthews/vn6.3_cmf. This will be split up into a hopefully small number of tickets for submission to the trunk. (we will NOT looking at: unrelated issues related to river grid options)

RIVER OVERBANK INUNDATION:

(but NOT looking at: unrelated issues related to artificial inundation (for which see Irrigation plan) or non-fluvial inundation (there is no representation of ponding or detention storage / depression storage in JULES yet) or issues related to the impacts of inundated water (as of March 2023, inundation extent is still only a 'diagnostic' that does not affect e.g. gridcell infiltration or evaporation rates)

WATER TRANSFER RIVER -> OCEAN:

This has already been coded (see https://code.metoffice.gov.uk/trac/gmed/ticket/381 and Activity 3.2.5 below). (we will NOT be looking at anything being carried by the water, e.g. nutrients or DOC river plumes: we need to get the water sorted out first)

Modelling inundation: current situation in UM/JULES/etc.

YES

- River routing and flow regime. We do get river flows approx. correct in comparison to gauge data (*UKEP* and *REP* projects).
- Groundwater inundation is also well-validated, i.e. topography ('pinch points').
- Overbank inundation has been in the code since 2015. It could do with some more validation (see Marthews *et al.* 2022) and there are caveats (e.g. receding of floodwater), but we have this too.

PARTIALLY

- CaMa-Flood (and the necessary *backwater effects* it simulates) has been put into a temporary branch of *JULES* in collaboration with JAMSTEC. However, it is not yet in the code base of JULES.

CaMa-Flood: Global River Hydrodynamics Model

JAMSTEC 国立研究開発法人 海洋研究開発機構
Japan Agency for Marine-Earth Science and Technology
海洋・地球・生命の総合的理解への挑戦

NOT YET (TO DO IN CHAMFER)

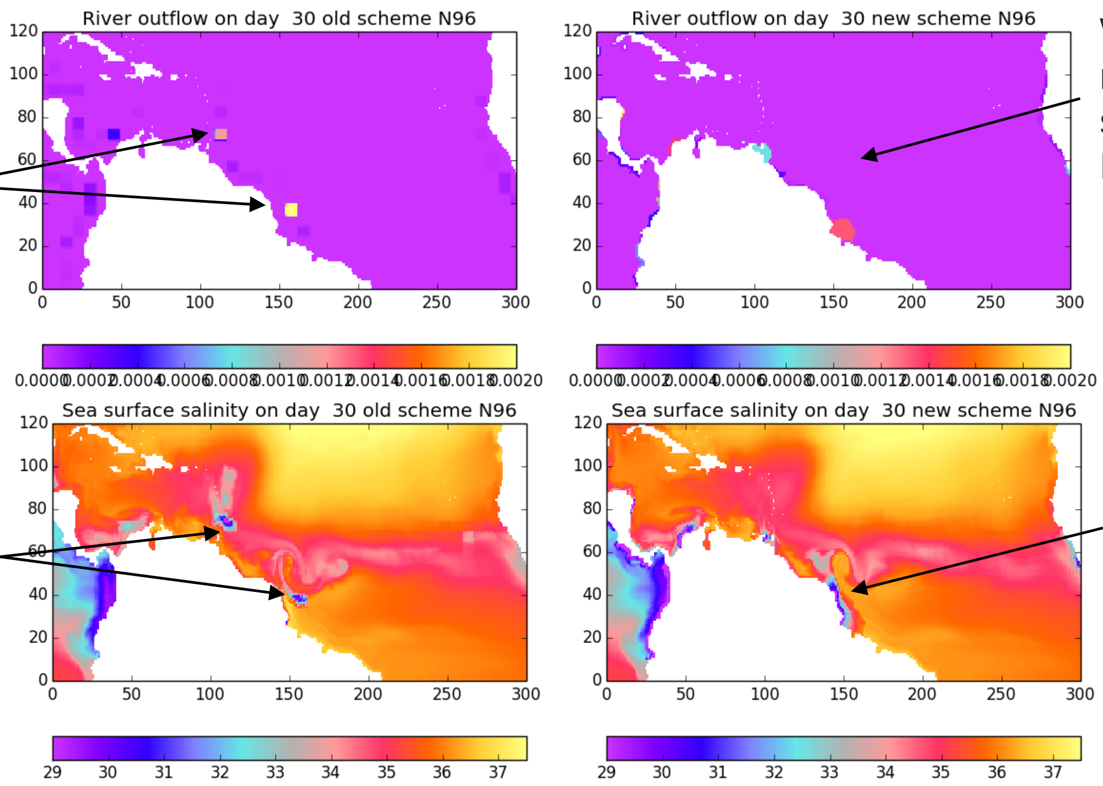
- Where rivers meet the ocean, we need to look at model coupling (https://code.metoffice.gov.uk/trac/jules/wiki/OceanRiverInterface):
  - Water transfer river -> ocean (i.e. river outflow)
  - Water transfer ocean -> river (storm and tidal surges)
- This has been partly implemented by Met Office colleagues.

The positioning of CEPs is important

Slide with thanks from Dan Copsey, MetO

River outflow appears 100s of km out to sea in N96 squares

With this change runoff appears in the same locations as NEMO ocean only.



Fresh water is also out to sea and flows further away from the coast (it should hug the coast)

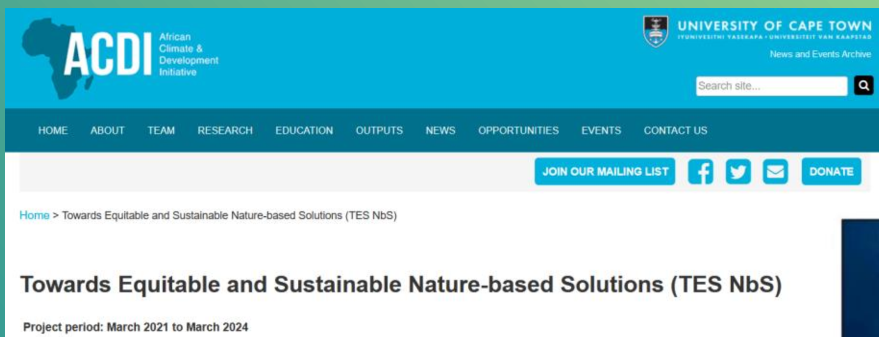
With this change freshwater hugs the coastline.

- Dan Copsey's river outflow points are 1568 of the 1875 NEMO climatological runoff points (see the Ticket details of UM ticket #3405), i.e. more rivers than the 151 of *COSCAT*.
- Note that these are not calculationally linked to the river directions layer used by JULES and therefore cannot be assumed to be consistent with it in general.

Met Office

TES-NbS:

Project at Univ Cape Town, SA, with Prof. Mark New, Petra Holden and Assumpta Onyeagoziri http://www.acdi.uct.ac.za/towards-equitable-and-sustainable-nature-based-solutions-tes-nbs . This project is looking at nature-based solutions across the Southern African region



TES NbS
Towards Equitable & Sustainable Nature-based Solutions in Southern Africa's Water Towers

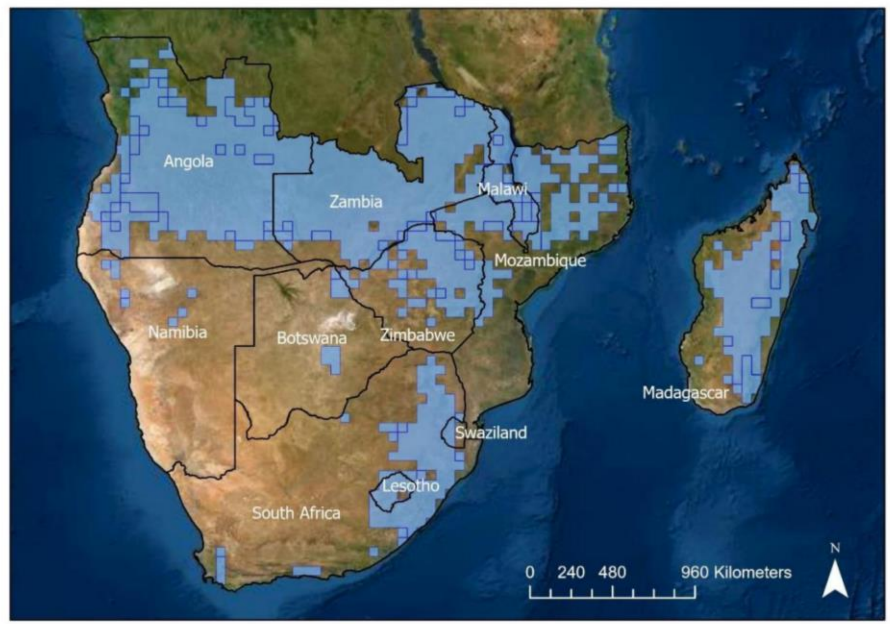


Figure 1 Rough boundaries for Water Towers in Southern Africa (Sources: Viviroli et al 2007; Esri, Maxar, GeoEye, Earthstart Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN and the GIS User Community)

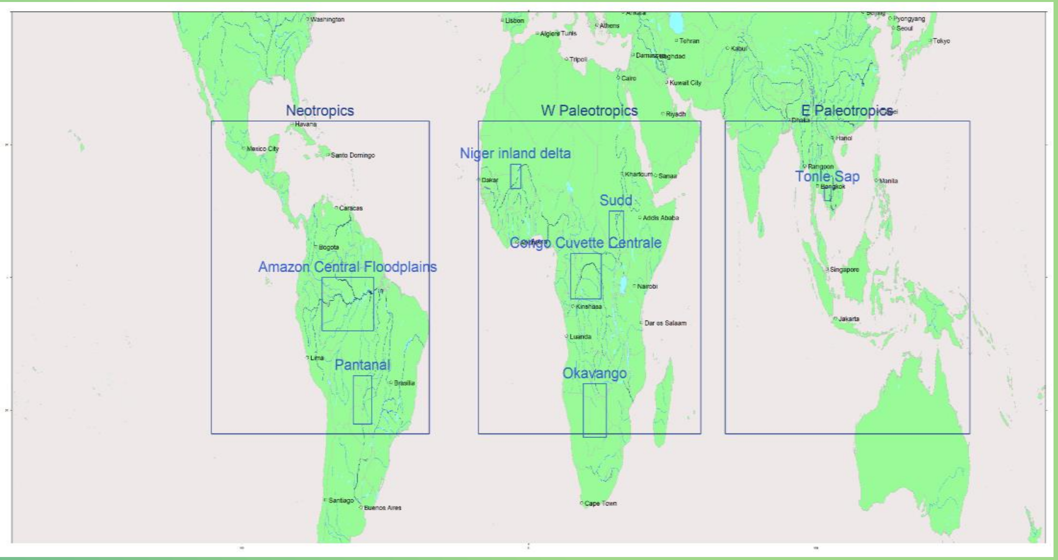
CHAMFER

In addition to producing new data, CHAMFER is an opportunity to bring together several strands of recent work at UKCEH:

- *Hydro-JULES*, where I have been working on wetland model predictions (see Marthews *et al.* 2022).

and two Met Office projects:

- The UKEP project up to 2021
- The REP project 2021-22



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Inundation prediction in tropical wetlands from JULES-CaMa-Flood global land surface simulations

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