Met Office

Coastal Hydrology and Surface Processes linked to
Air/Sea Modelling workshop, Madeira
27 September 2017

UK Environmental Prediction
Towards integrated coupled predictions for the UK at the convective scale

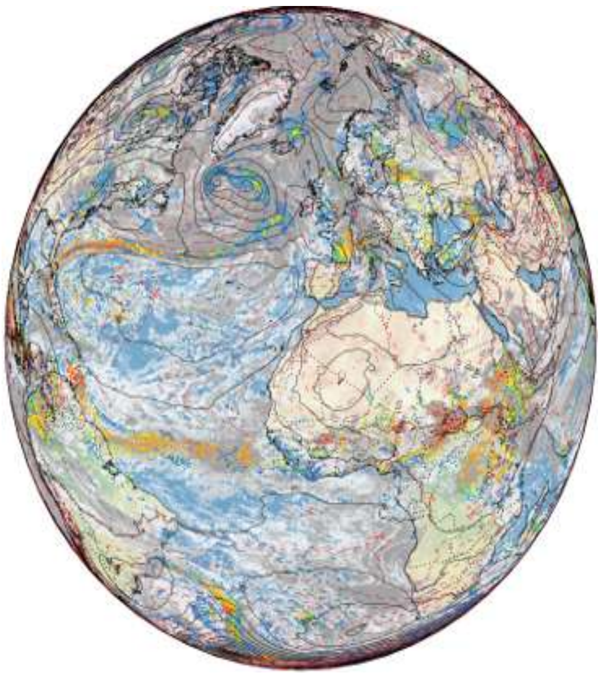
Huw Lewis
huw.lewis@metoffice.gov.uk

With thanks to Joachim Fallmann, Juan Castillo, Alex Arnold, and many other UK and international colleagues…

1. Some motivations
2. The UK coupled prediction system
3. Windy days
4. Warm days
5. Wet days
6. Some challenges and future directions

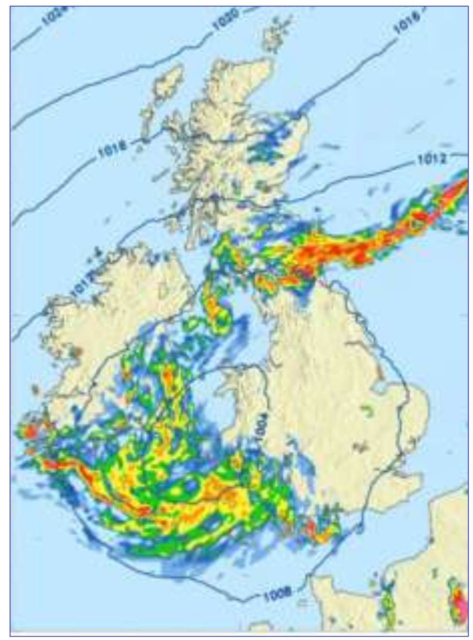
A ‘seamless‘ modelling strategy across scales

Met Office



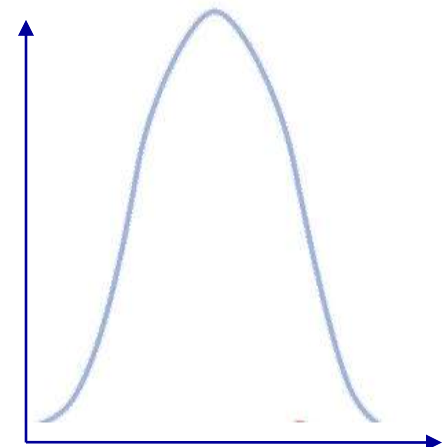
N x **Global coupled model** at ~10km with lead times of days to years:

Synoptic-scale drivers in atmosphere, land and ocean



N x **local coupled model** at ~<=1km :

Local meteorology, surface and sea state



PDF of local hazard:

Impacts

….and for the hour, day, week, month, year, decades ahead

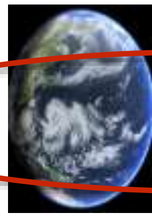
Global Physical Modelling

Unified Prediction across Timescales

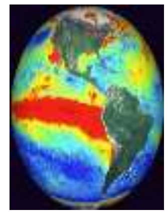
Met Office

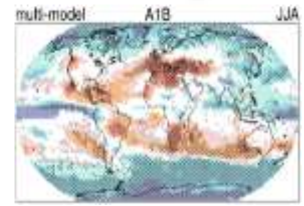
NERC SCIENCE OF THE ENVIRONMENT

Hours Days Weeks Months Seasons Decades Centuries



MOGREPS





NWP - AL, OI, W
Deterministic Atmos & Marine

Atmos Ensemble

GloSea

Decadal

Climate Change & UKESM1

Component Models	Coupled AOIL Model
GA6 , GL6, GO5, GSI6	GC2.0

Australian Government Bureau of Meteorology

CSIRO

KMA

NIWA

NCMRWF

South African Weather Service

Met Office Unified Model™ Global Atmosphere

JULES Global Land

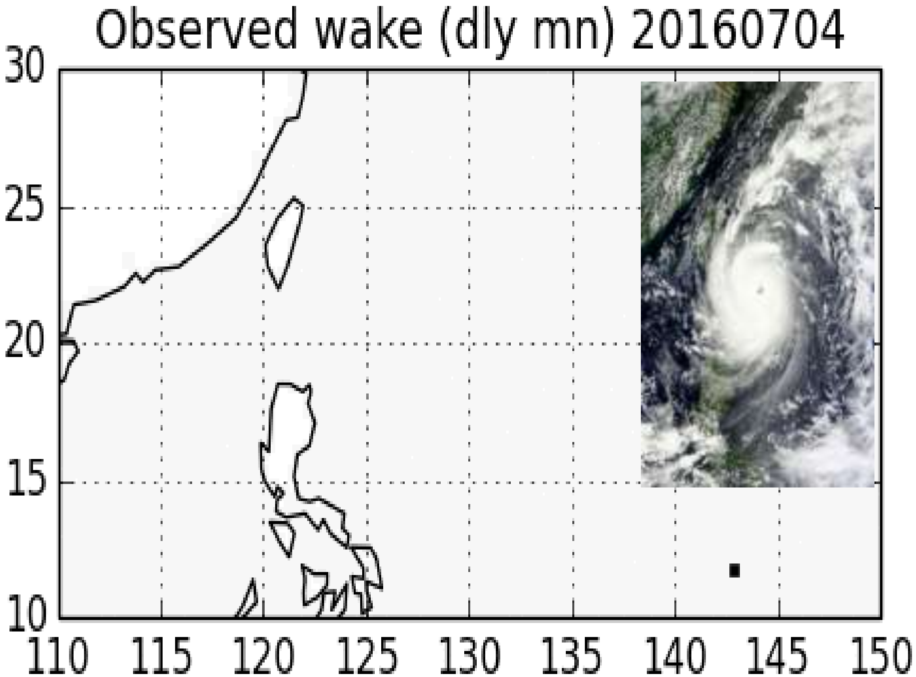
NEMO Global Ocean

CICE Global Sea Ice

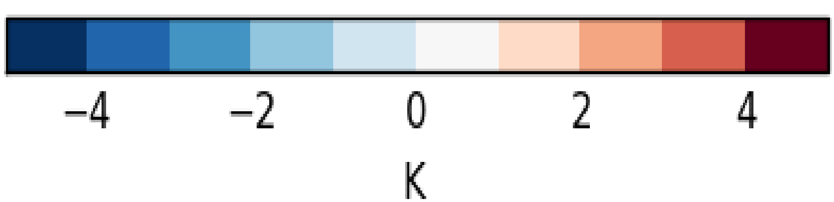
WaveWatch III Global Waves

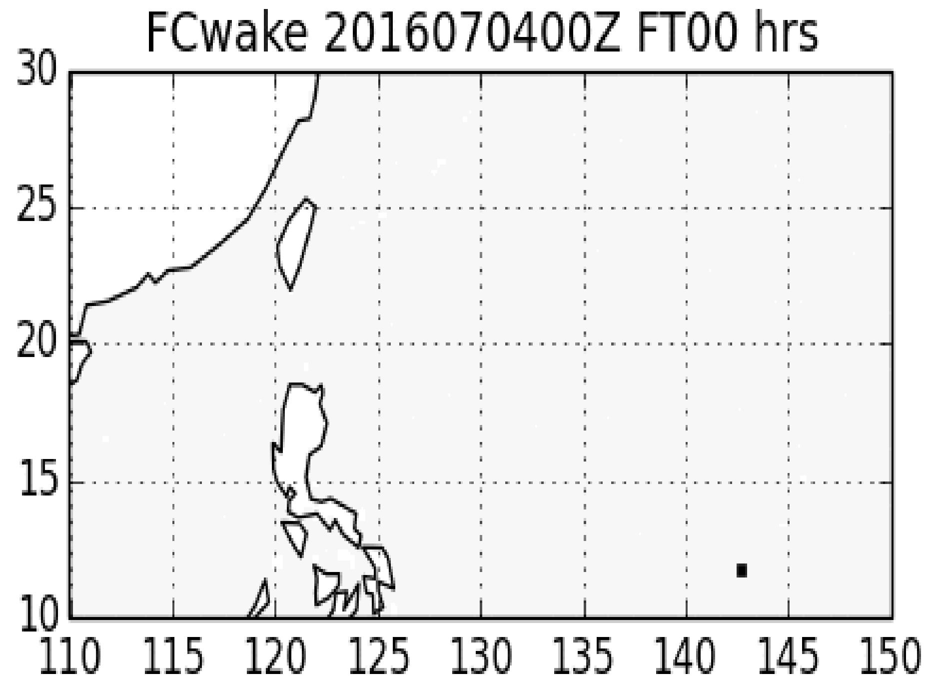
Coupled NWP - Typhoon Nepartak (2016)

A global 10km coupled NWP case study

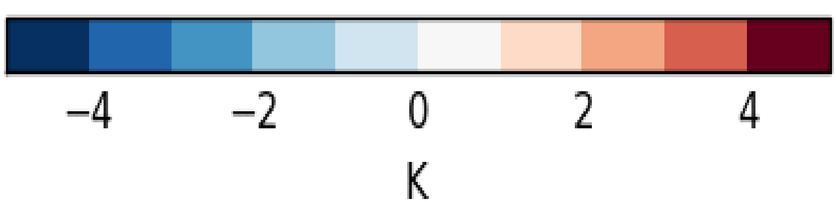


Observed



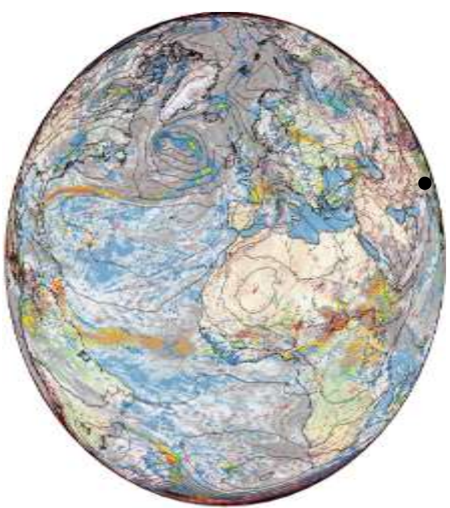


Coupled NWP



Global coupled numerical weather and ocean prediction systems

- From Research 2 Operations phase for ‘NWP scales’
- Already have coupled **climate/seasonal systems**;
- New science at days-weeks timescale, but well-developed infrastructure
- Weakly coupled **data assimilation** developed for NWP (Lea et al, 2015)
- **Transition to operations** Met Office deterministic/ensembles global weather forecasting at 10/20 km atmos coupled to 0.25^{o} Ocean by **2019+**
- Increased resolution deterministic ocean (~10 km) by **2020+**

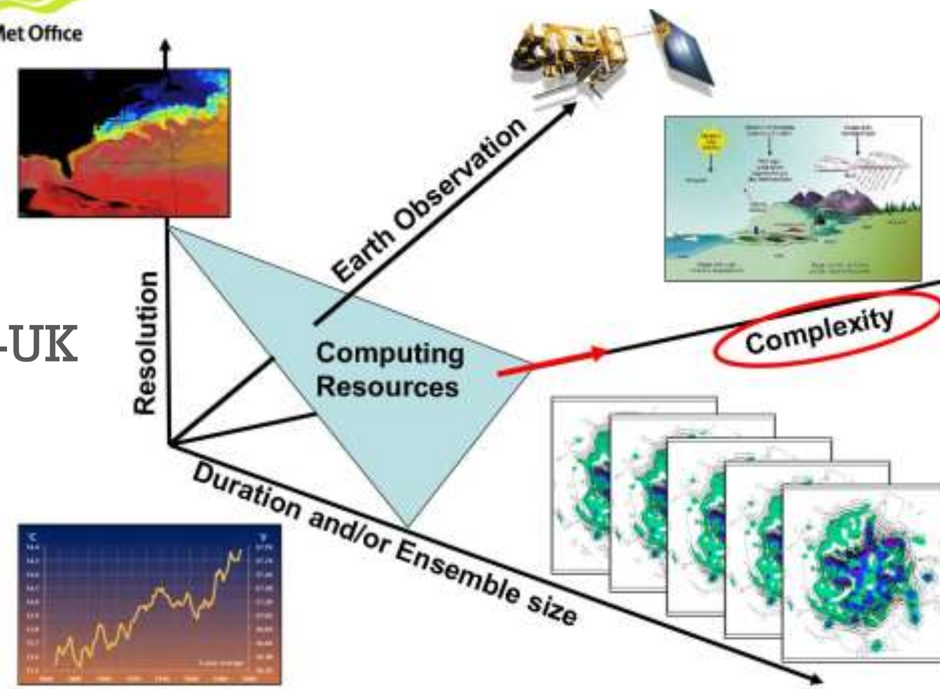


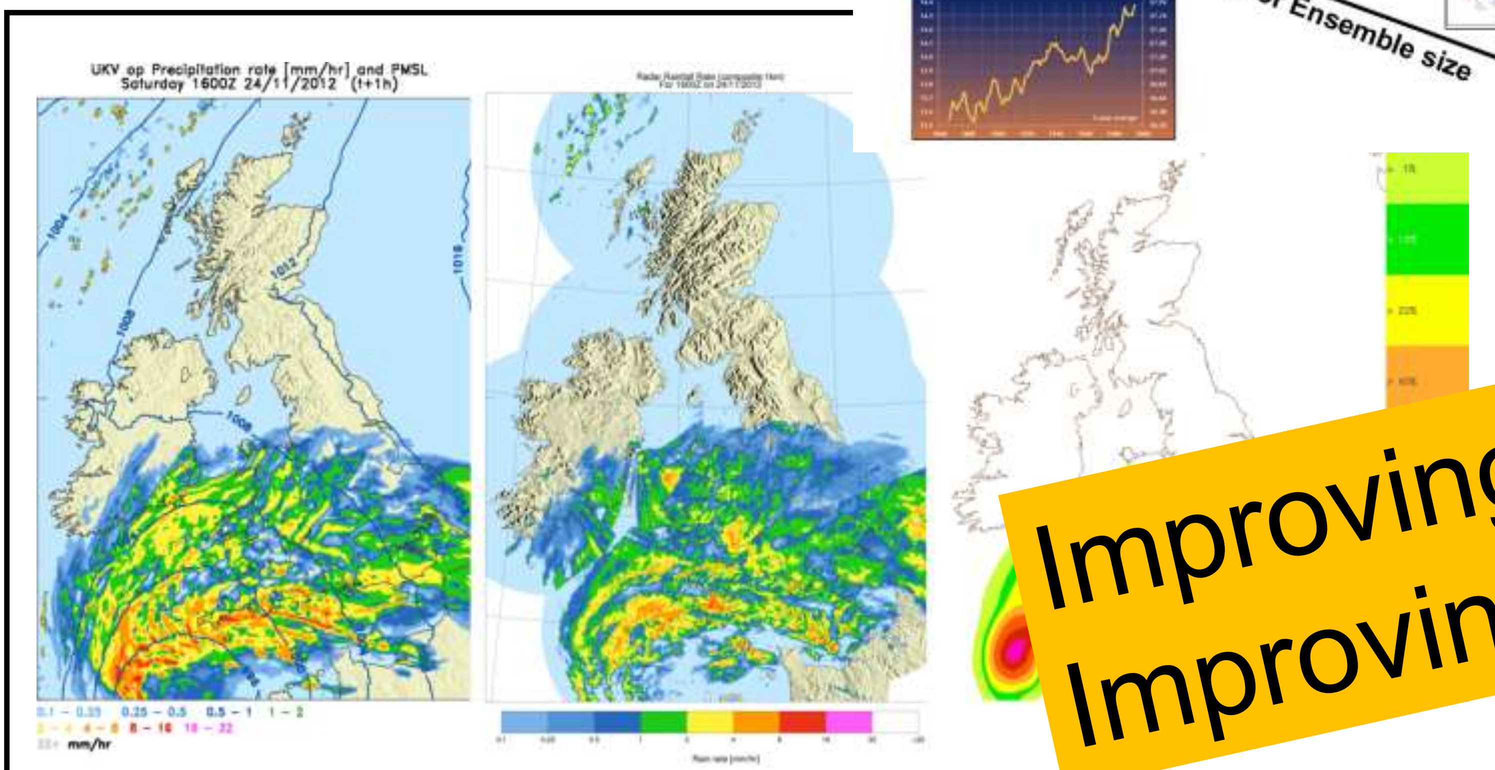
Improving forecast skill and use

Resolution → UKV

Uncertainty → MOGREPS-UK

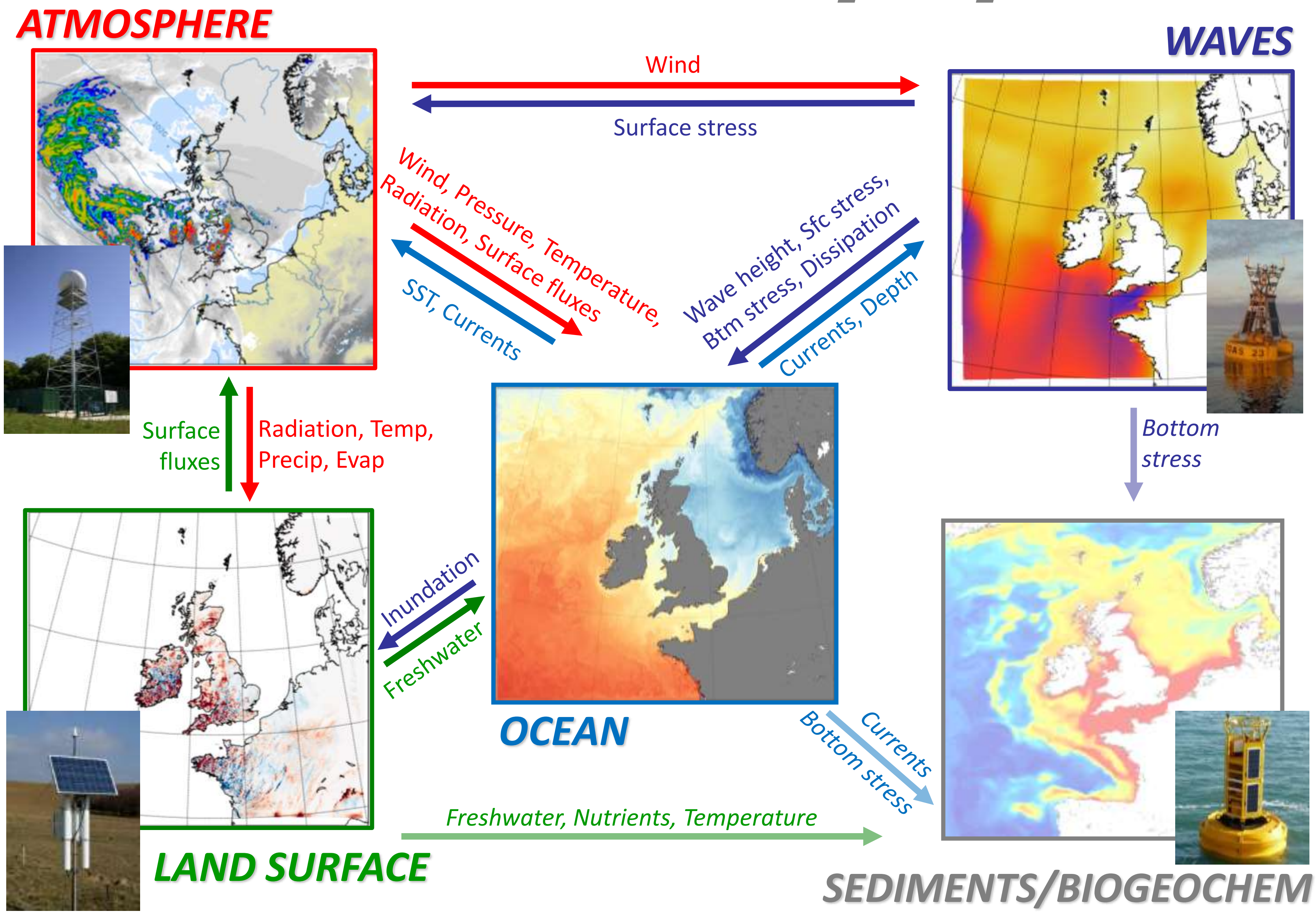
Complexity → …





Improving skill?
Improving use?

Towards coupled prediction?

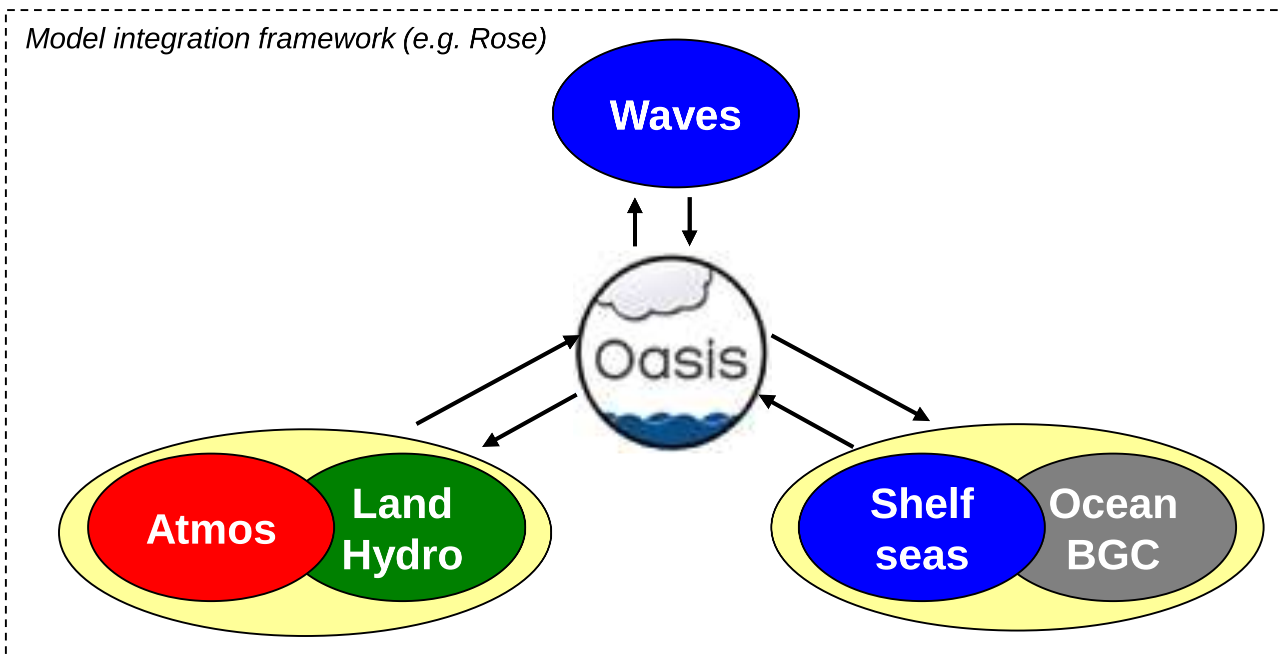


Met Office | Centre for Ecology & Hydrology (CEH) NATURAL ENVIRONMENT RESEARCH COUNCIL | National Oceanography Centre NATURAL ENVIRONMENT RESEARCH COUNCIL | PML Plymouth Marine Laboratory

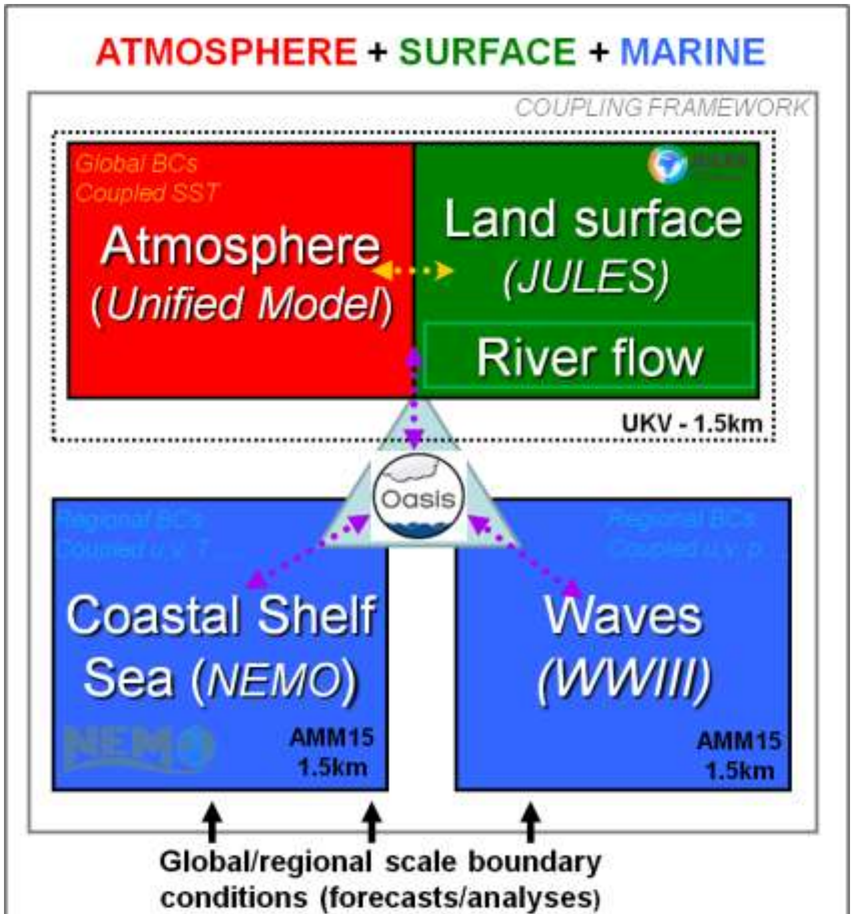
A *Prototype* project (2014-2016)

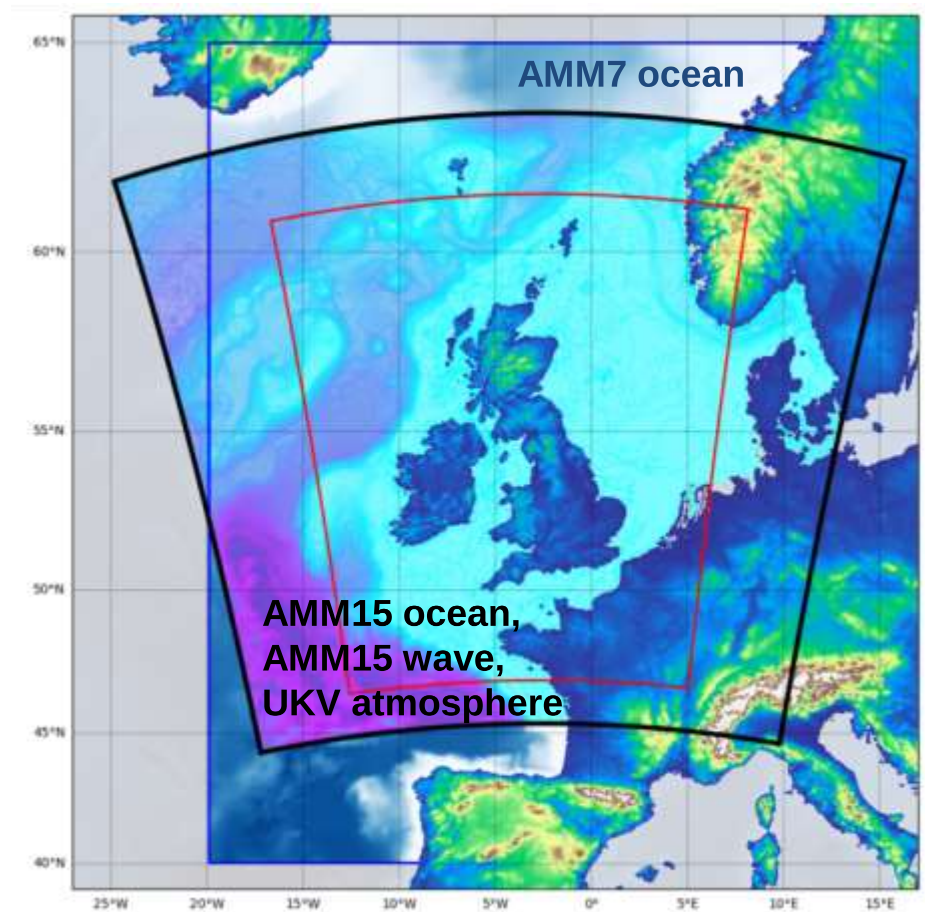
Objectives:

1. To **build and evaluate** a ‘first look’ regional coupled prediction system for the UK at 1km scale.
2. To **identify key scientific and technical issues** to be addressed (within the timescale of the prototype project and for longer term R&D) to enable the UK Environmental Prediction vision to be achieved.
3. To **demonstrate** the UK coupled prediction concept.
4. If suitable, to identify and pick some ‘low hanging fruit’ for improved operational capability and/or societal application using the UK Environmental Prediction prototype system



Delivery of a Prototype





GMD, Lewis et al 2017

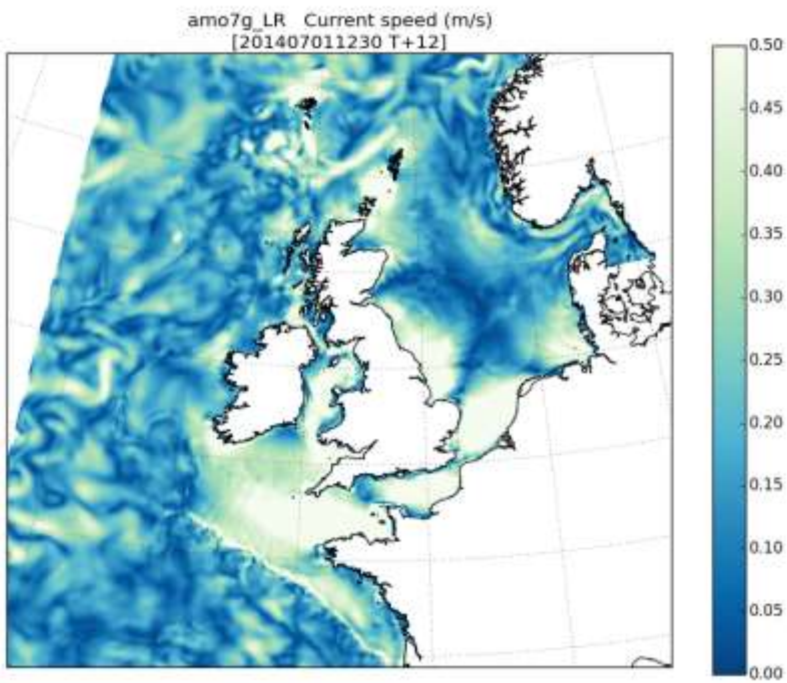
https://www.geosci-model-dev-discuss.net/gmd-2017-110/

…a 2D coupling task

1.5 km ocean model

NEMO vn3.6 @ r6232

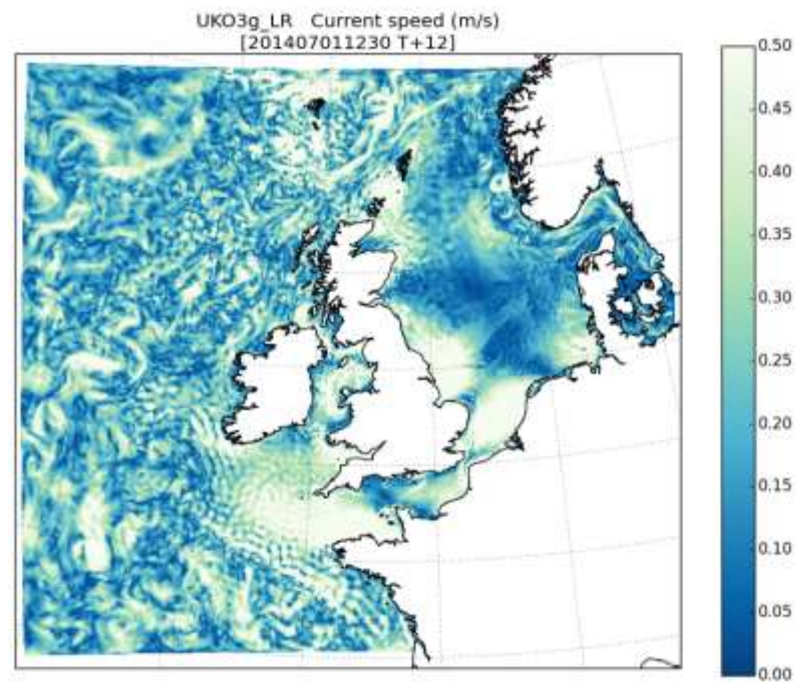
- Atlantic Margin Model AMM7



NOOS-based bathymetry
NATL12 boundary forcing
EHYPE rivers

51 vertical σ-levels
297 x 375 grid points

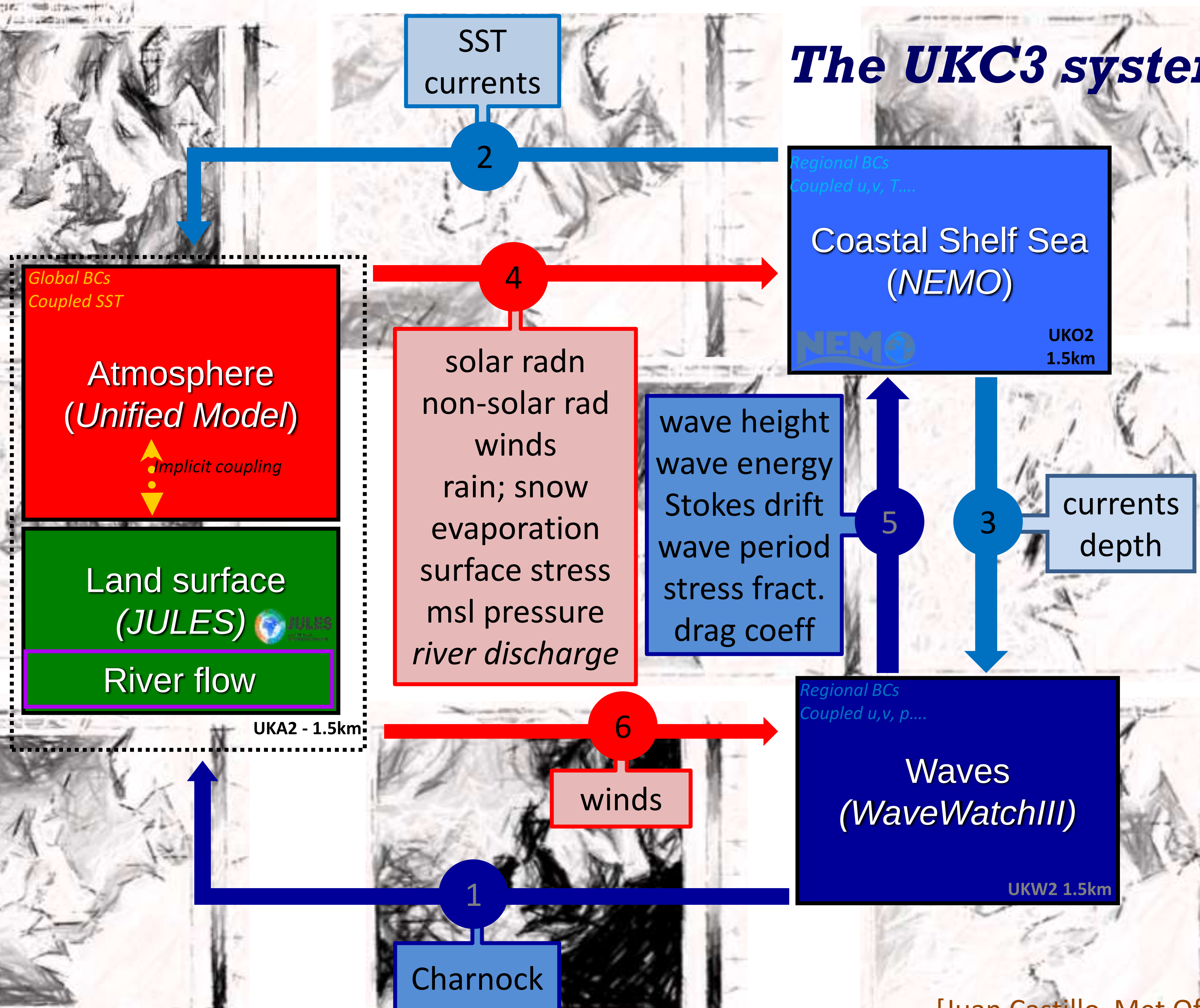
- Atlantic Margin Model AMM15



EMODNet-based bathymetry
NEMO 0.25 global boundary forcing
Climatological rivers

51 vertical σ-levels
1458 x 1345 grid points

The UKC3 system



[Juan Castillo, Met Office]

An evaluation toolkit

ATMOSPHERE-ONLY **UKA2**

g: global (17km) OSTIA SST

h: UKO2 (1.5km) SST

Sensitivity to initial SST

Unified Model

JULES

vn10.1

UKV

OCEAN-ONLY **UKO2**

g: global UM forcing

h: UKA2

6

15

WAVE-ONLY **UKW2**

g: global 17km UM winds

h: UKA2 1.5km UM winds

c: UKA2 1.5km UM winds +

Sensitivity to wind, currents, levels forcing

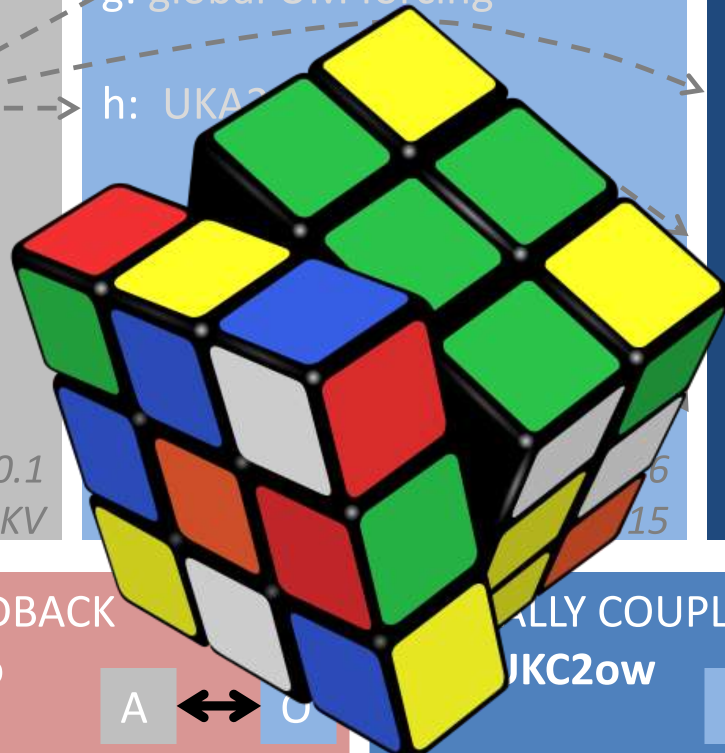
s +

UKO2 currents +

UKO2 water levels

WWIII

vn4.18



OCEAN FEEDBACK

A-O **UKC2ao**

A ⟷ O

LLY COUPLED

UKC2ow

O ⟶ W

FULLY COUPLED

A-O-W **UKC2aow**

A ⟷ O, O ⟶ W, W ⟷ A

N.B. Introduced in UKC3: Wave feedbacks in ocean

Oasis

Hourly *coupling via OASIS3-MCT*

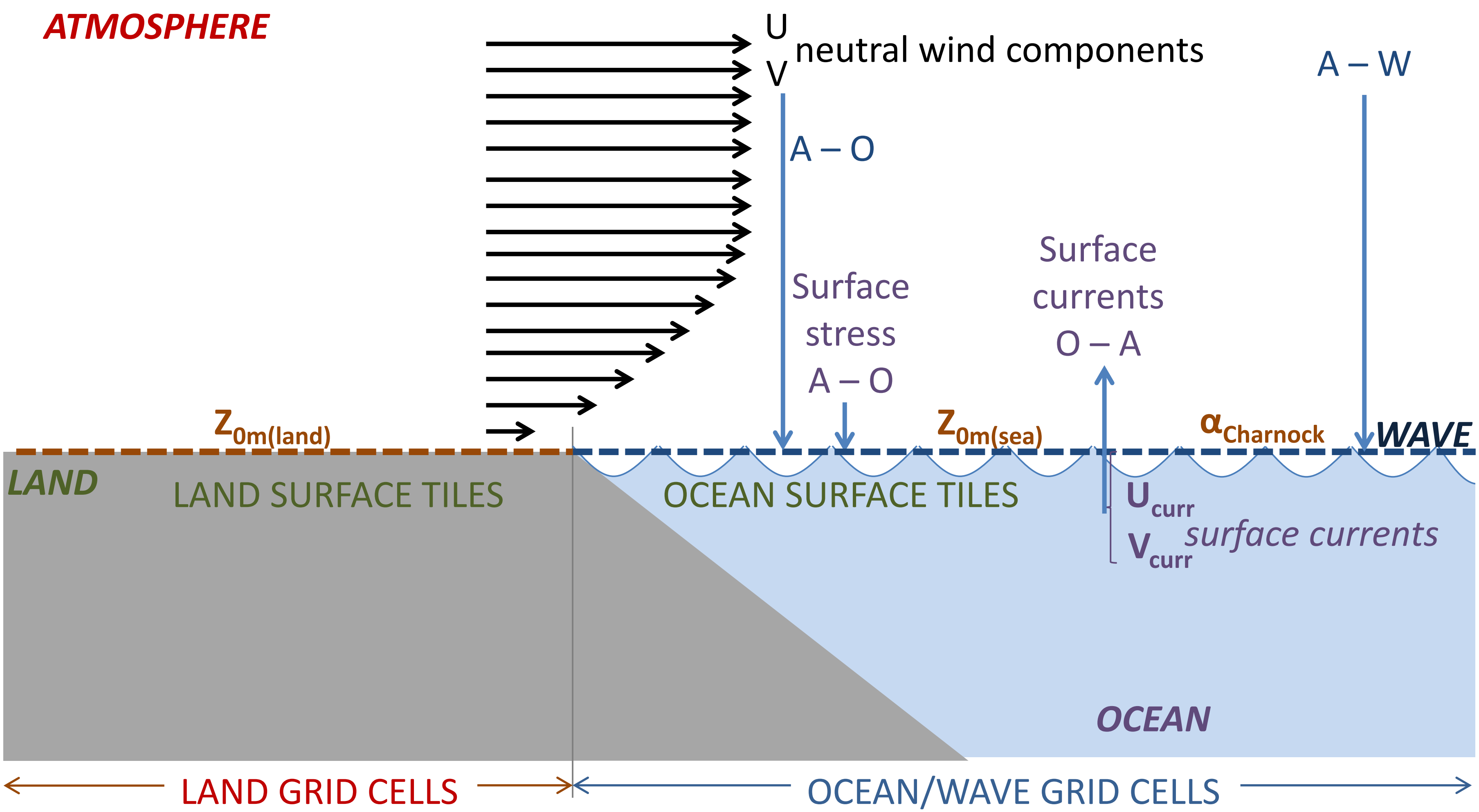
Met Office

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

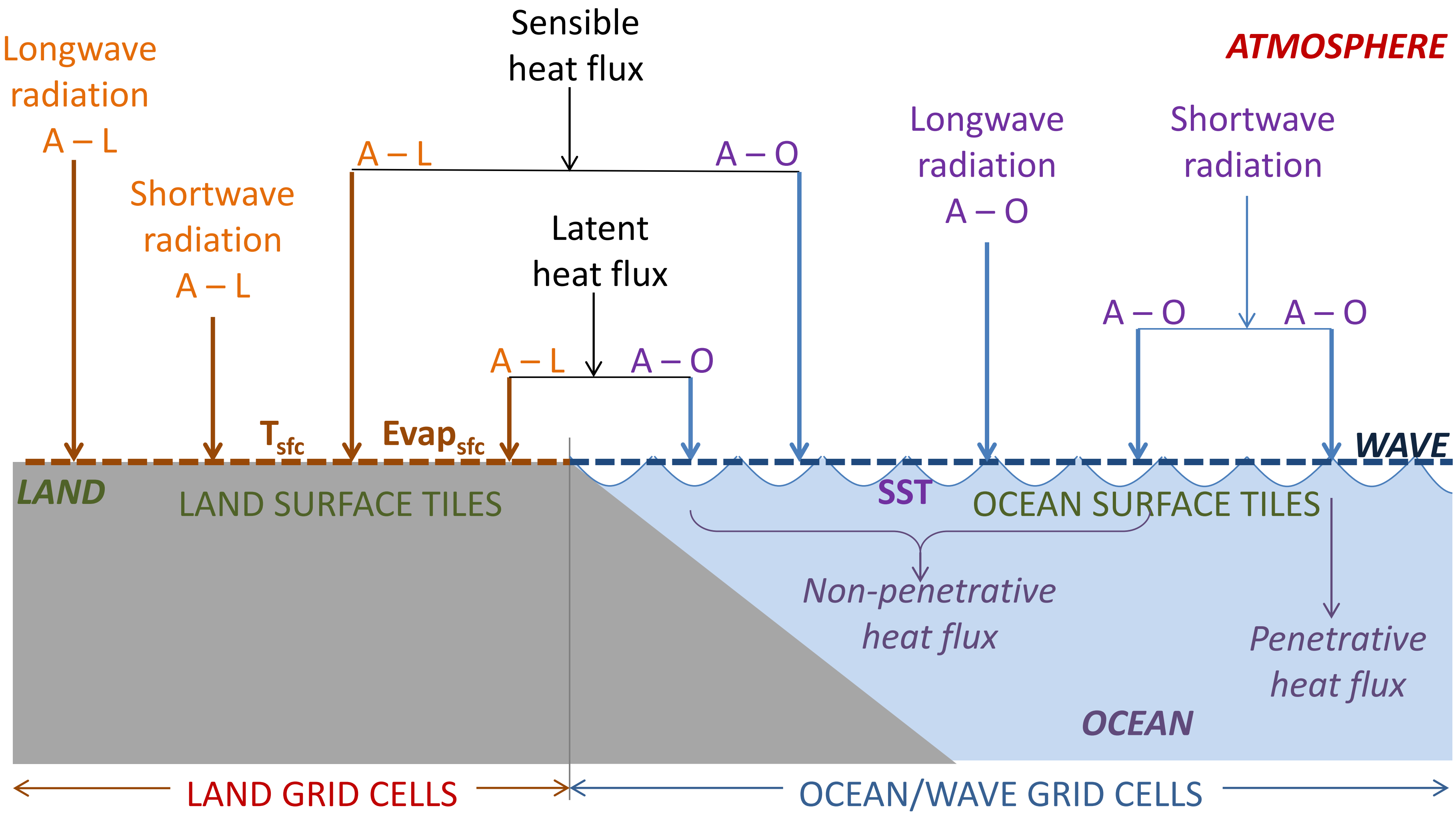
PML Plymouth Marine Laboratory

(a) UKC2 momentum exchanges



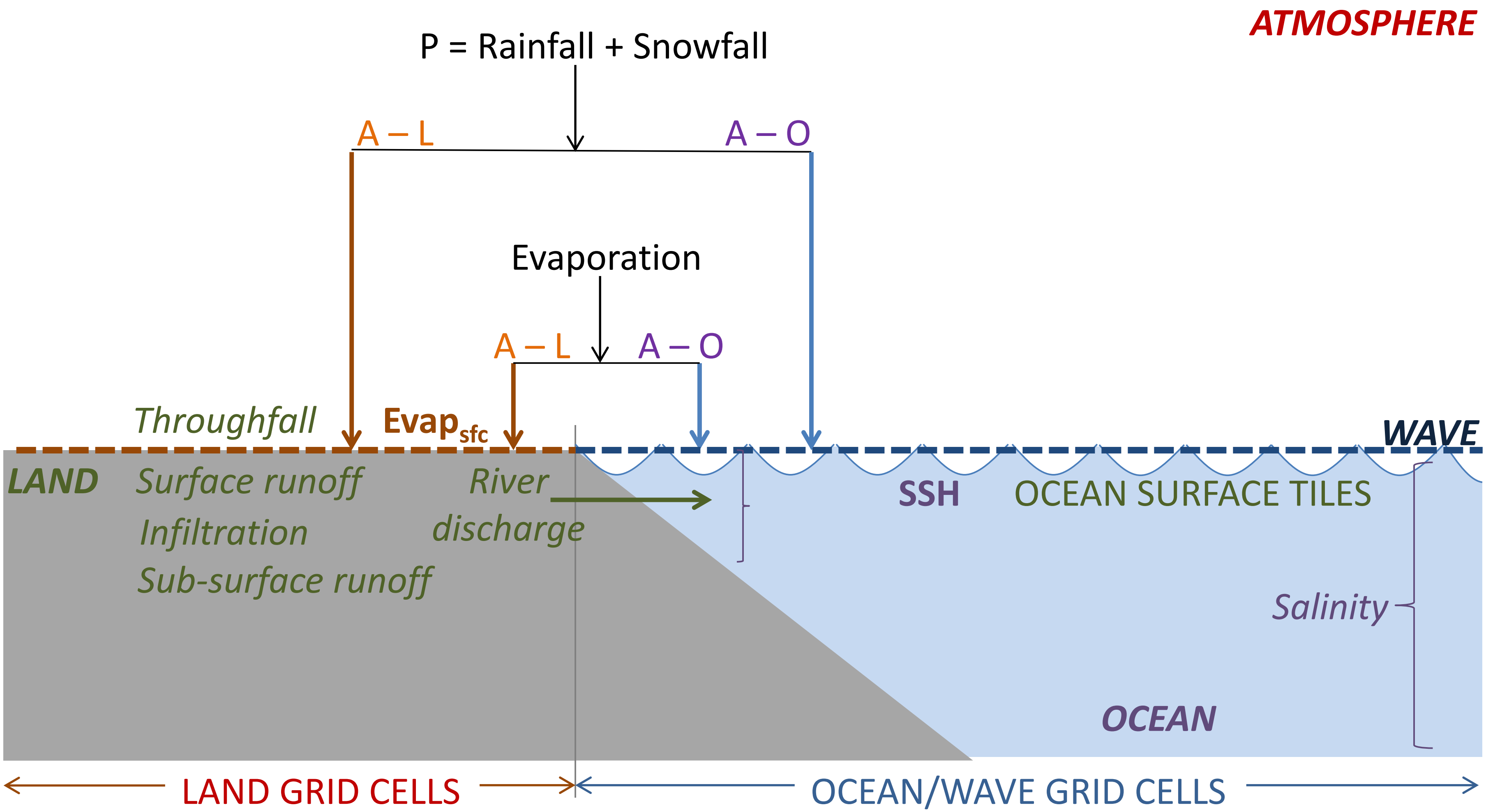
UK Environmental Prediction science

(b) UKC2 heat exchanges



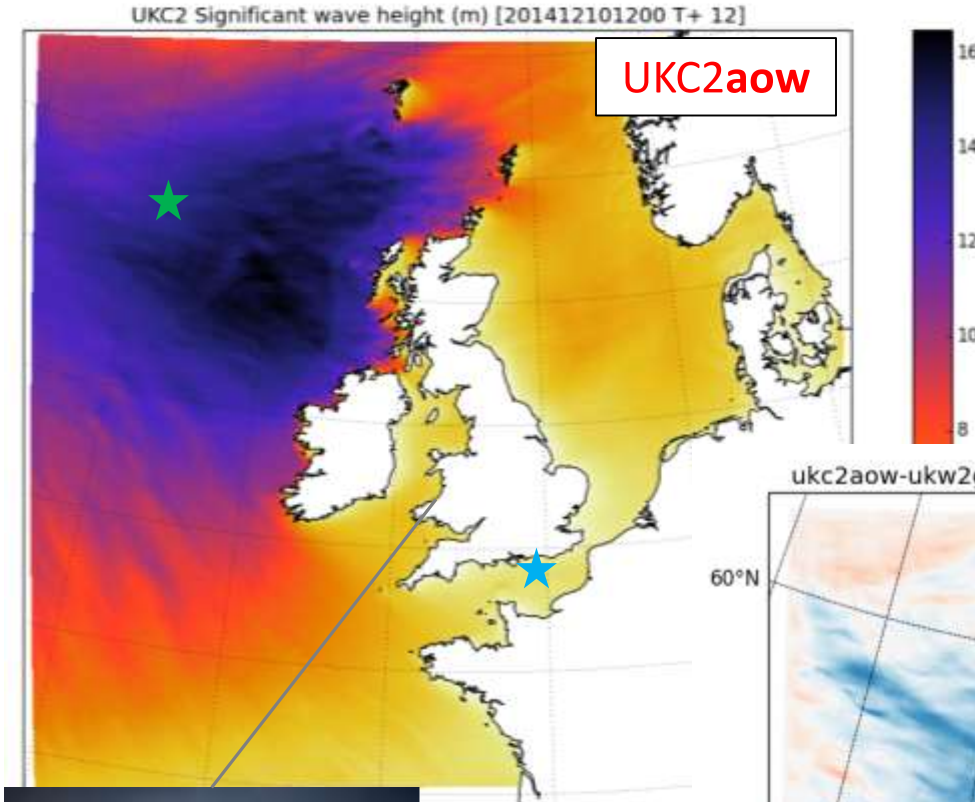
UK Environmental Prediction science

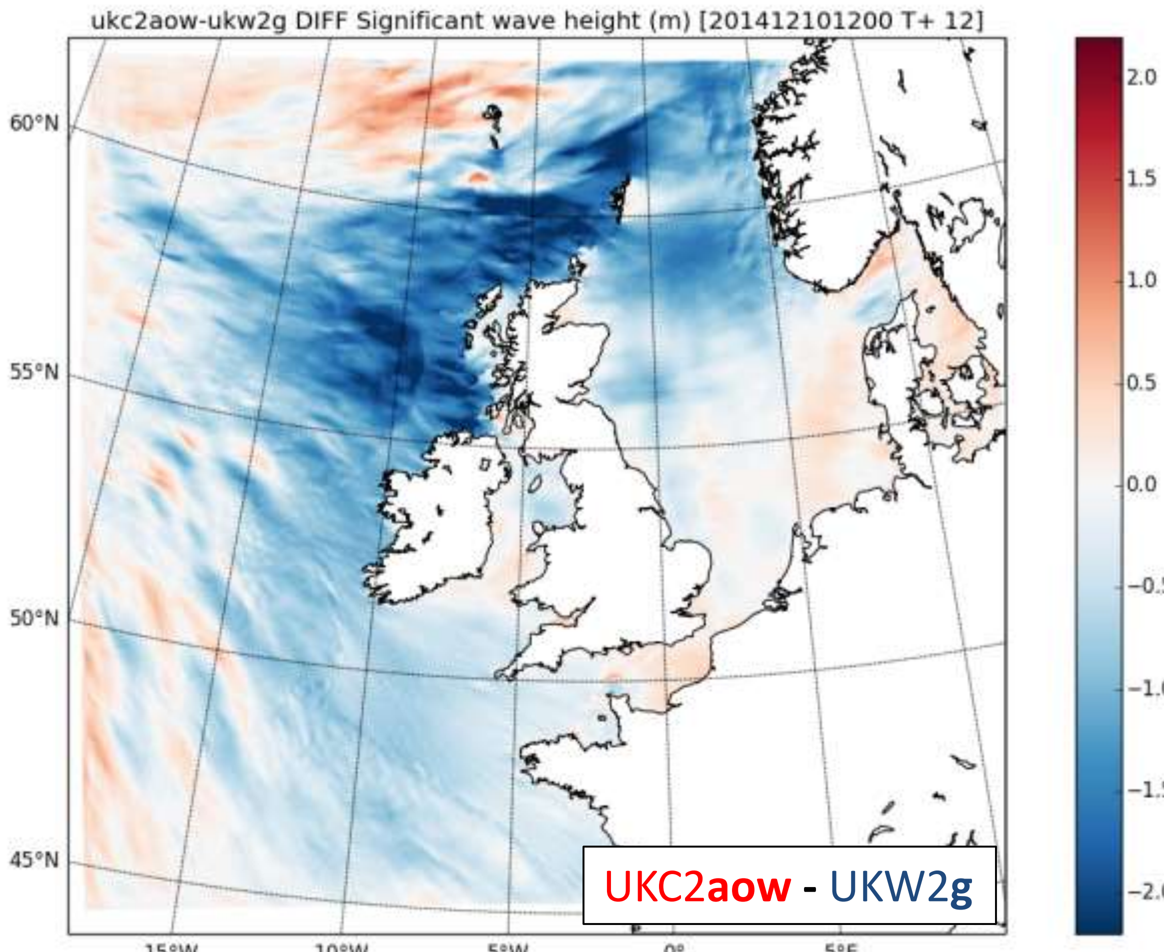
(c) UKC2 freshwater exchanges



PART I: *'momentum'*

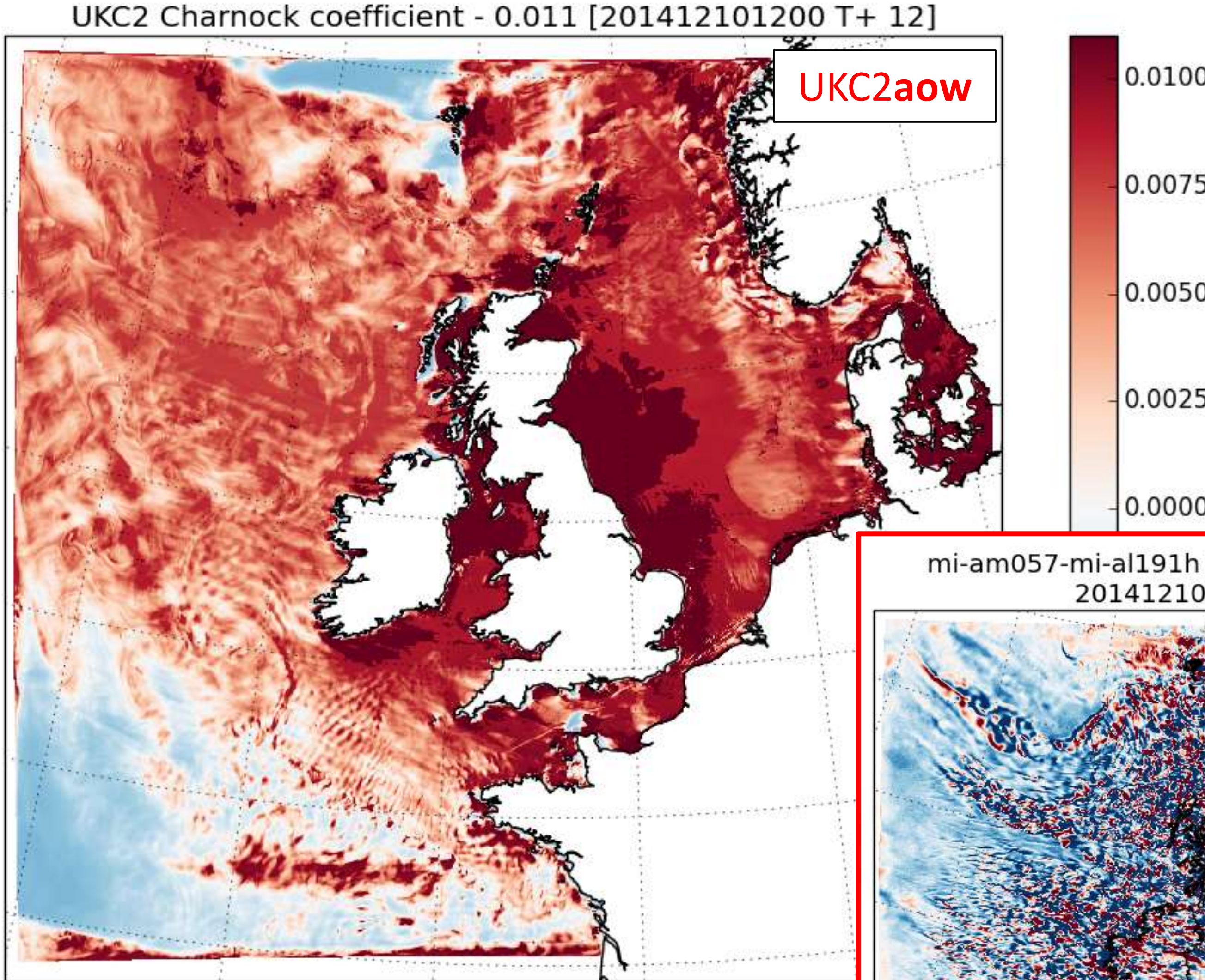
Impact on waves?
A “weather bomb”:
5-day case study Dec 2014

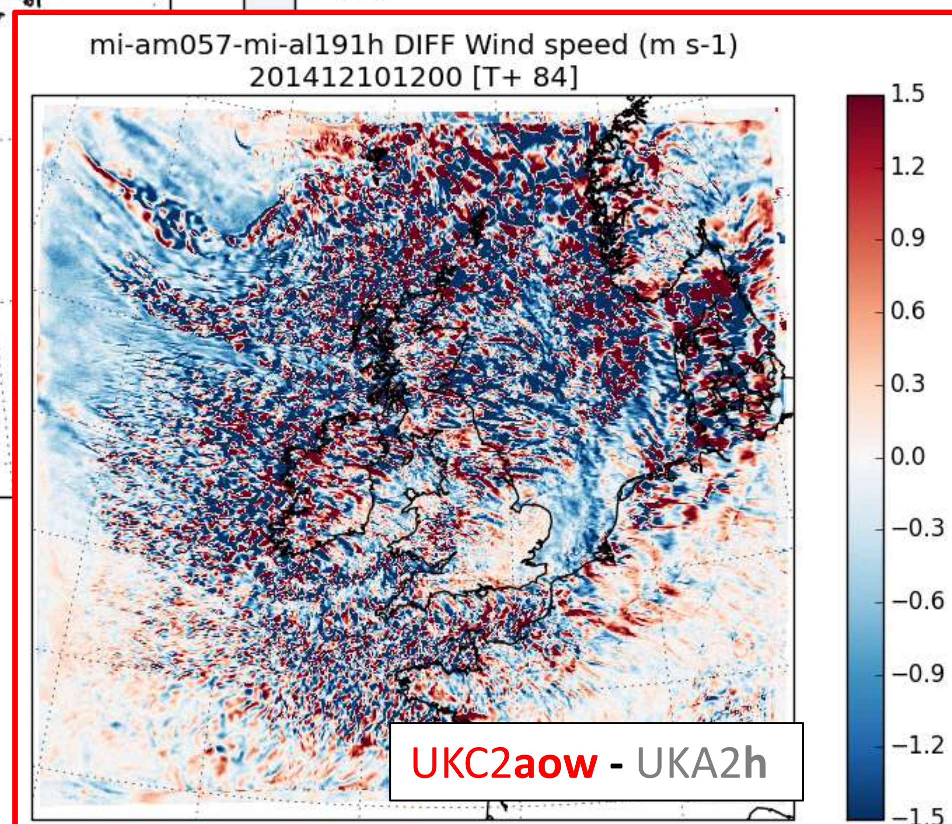




Impact of atm-wave coupling on winds

5-day case study
Dec 2014

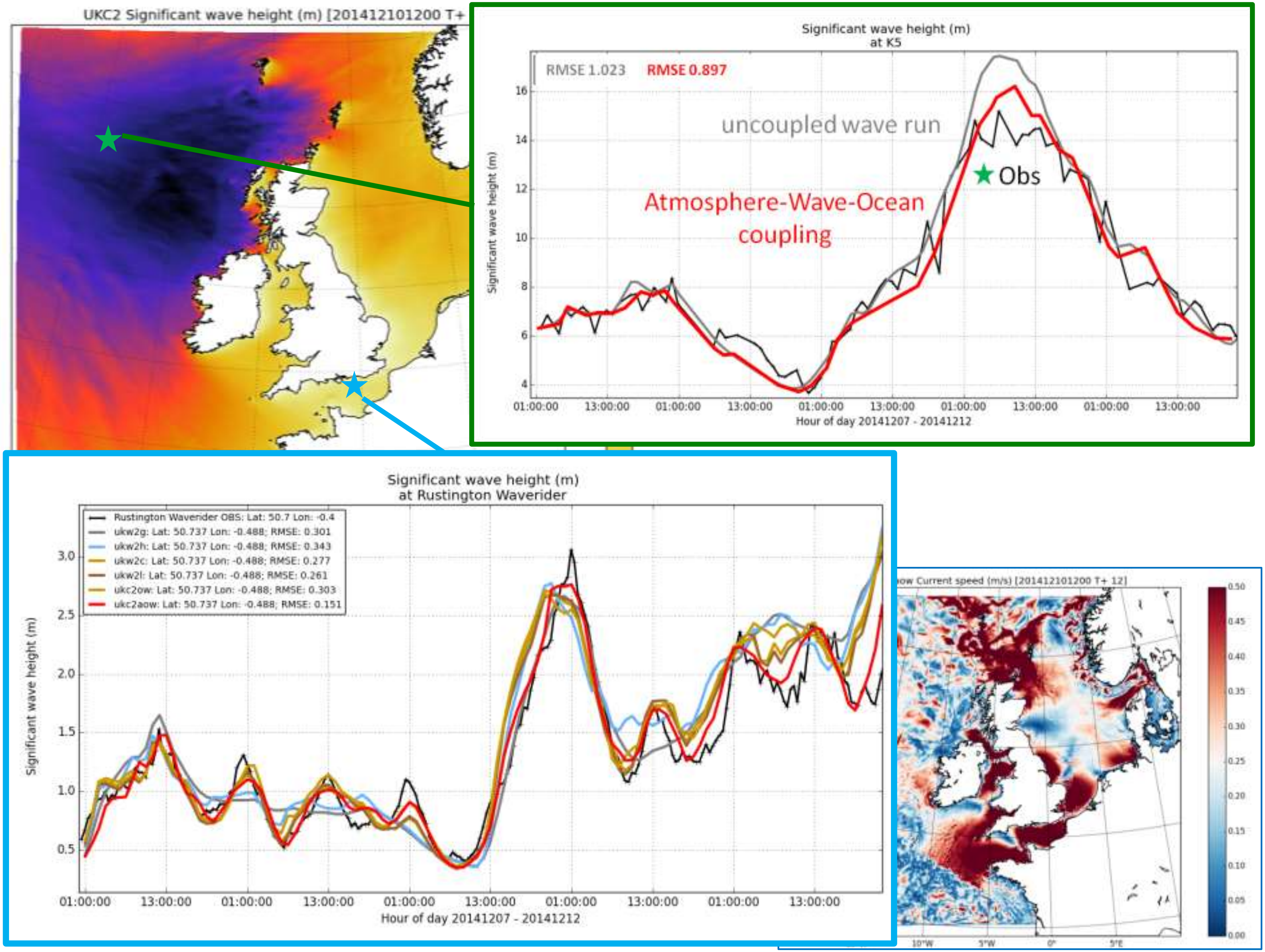




'Rougher' surface than control constant

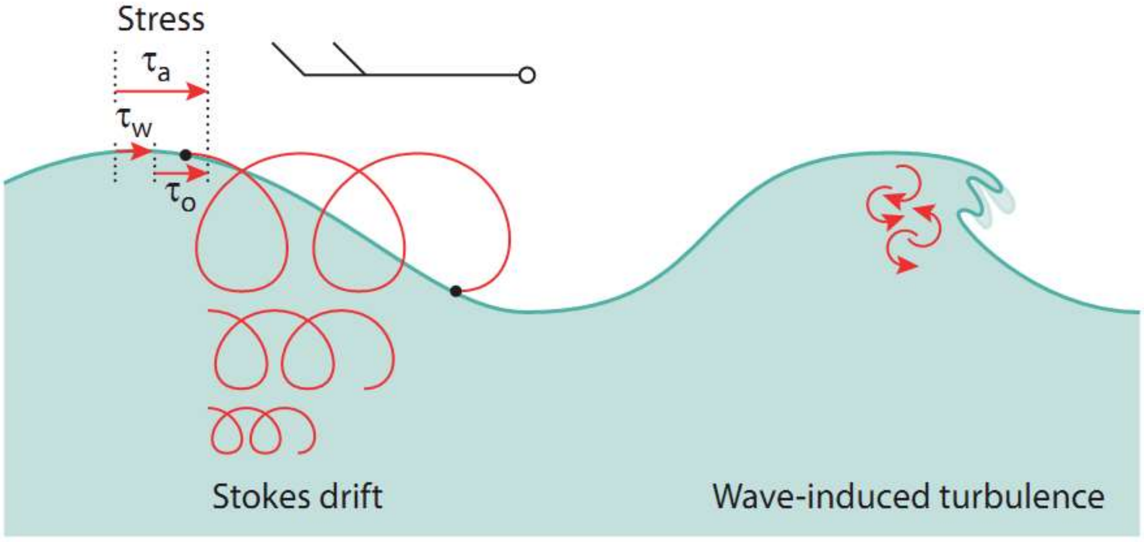
'Smoother' surface than control constant

$$z_{0m(sea)} = \frac{1.54\times10^{-6}}{u_*} + \frac{\alpha}{g}u_*^2$$


UKC2 Significant wave height (m) [201412101200 T+
Significant wave height (m)
at K5
RMSE 1.023
RMSE 0.897
uncoupled wave run
Obs
Atmosphere-Wave-Ocean
coupling
Significant wave height (m)
Hour of day 20141207 - 20141212
Significant wave height (m)
at Rustington Waverider
Rustington Waverider OBS: Lat: 50.7 Lon: -0.4
ukw2g: Lat: 50.737 Lon: -0.488; RMSE: 0.301
ukw2h: Lat: 50.737 Lon: -0.488; RMSE: 0.343
ukw2c: Lat: 50.737 Lon: -0.488; RMSE: 0.277
ukw2l: Lat: 50.737 Lon: -0.488; RMSE: 0.261
ukc2ow: Lat: 50.737 Lon: -0.488; RMSE: 0.303
ukc2aow: Lat: 50.737 Lon: -0.488; RMSE: 0.151
Significant wave height (m)
Hour of day 20141207 - 20141212
ow Current speed (m/s) [201412101200 T+ 12]
10°W
5°W
0°
5°E

Wave effects in NEMO [UKC3]

- **Stress:** As waves grow under the influence of the wind, the waves absorb momentum (τ_w) which otherwise would have gone directly into the ocean (τ_0) .
- **Stokes-Coriolis forcing:** The Stokes drift sets up a current in the along-wave direction. Near the surface it can be substantial (~1m/s). The Coriolis effect works on the Stokes drift and adds a new term to the momentum equations.
- **Mixing:** Mixing: As waves break , turbulent kinetic energy is injected into the ocean mixed layer, significantly enhancing the mixing.



[Slide courtesy Jean Bidlot, ECMWF]

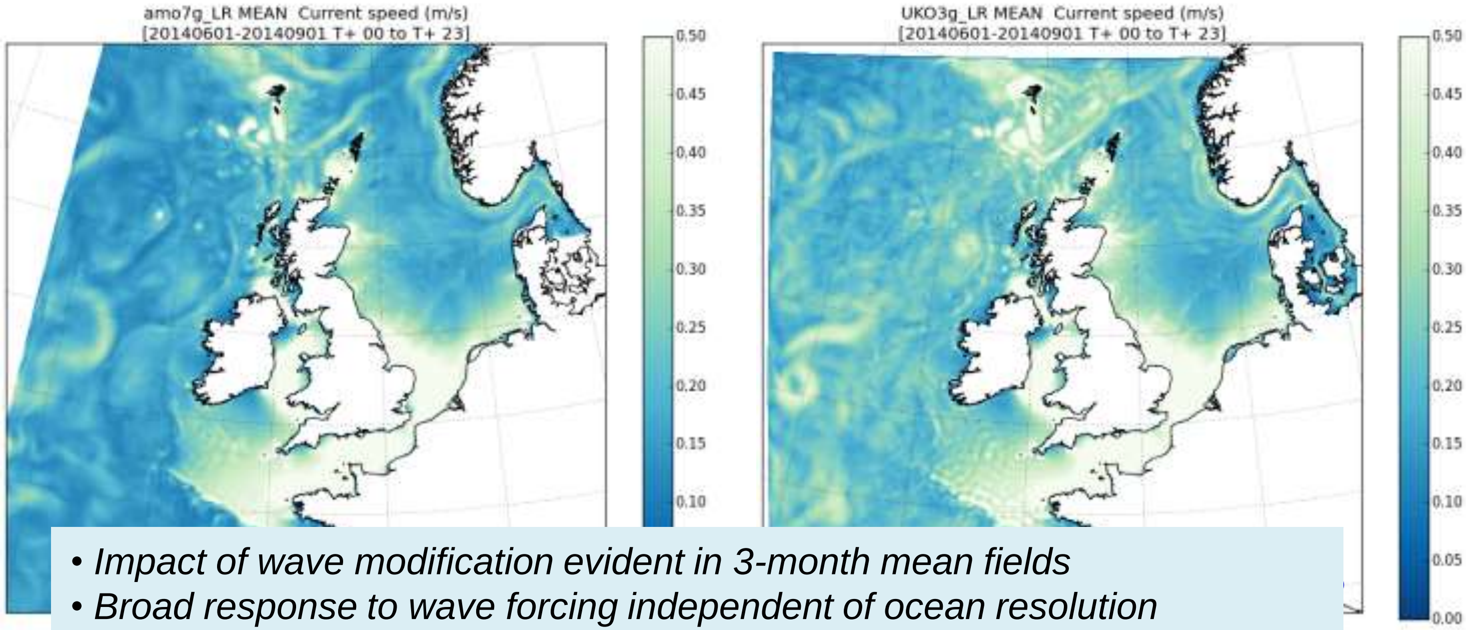
2-year UKC3ow runs

Summer 2014 [JJA]

Currents

3-month MEANS

OCEAN ONLY



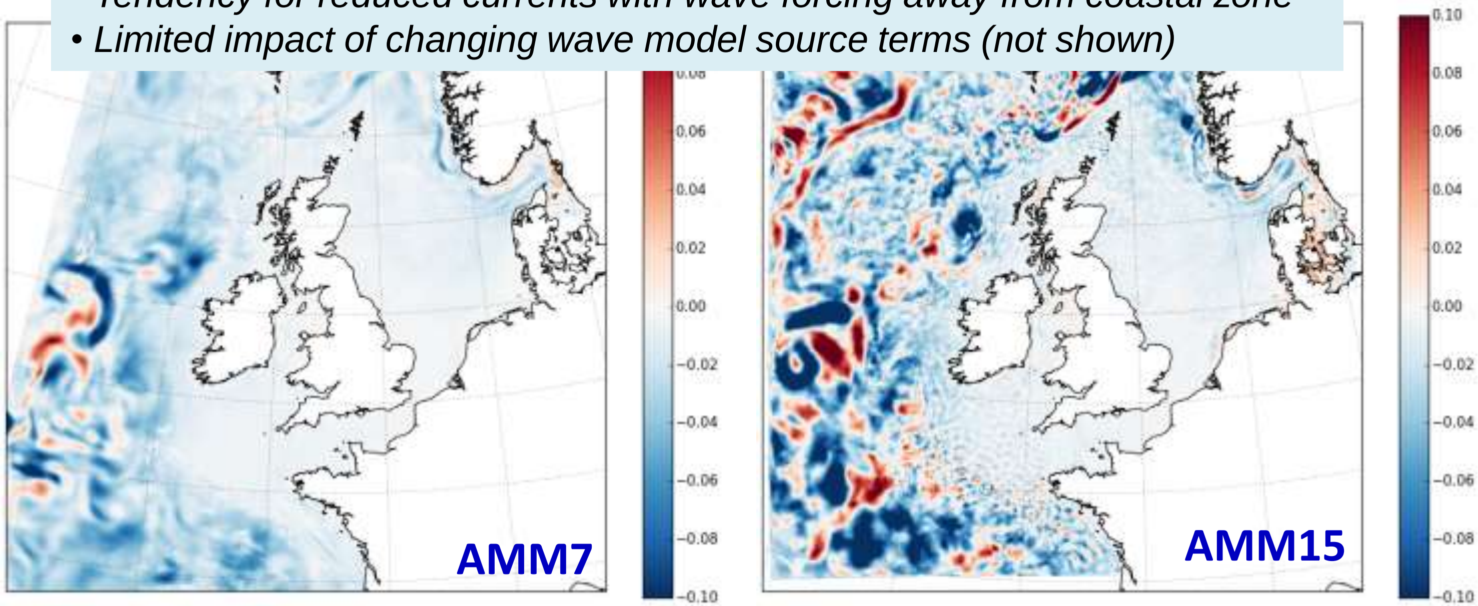
- *Impact of wave modification evident in 3-month mean fields*
- *Broad response to wave forcing independent of ocean resolution*
- *Greater sensitivity in AMM15 than AMM7*
- *Tendency for reduced currents with wave forcing away from coastal zone*
- *Limited impact of changing wave model source terms (not shown)*

3-month DIFFERENCE

WAVE FORCED

-

OCEAN ONLY



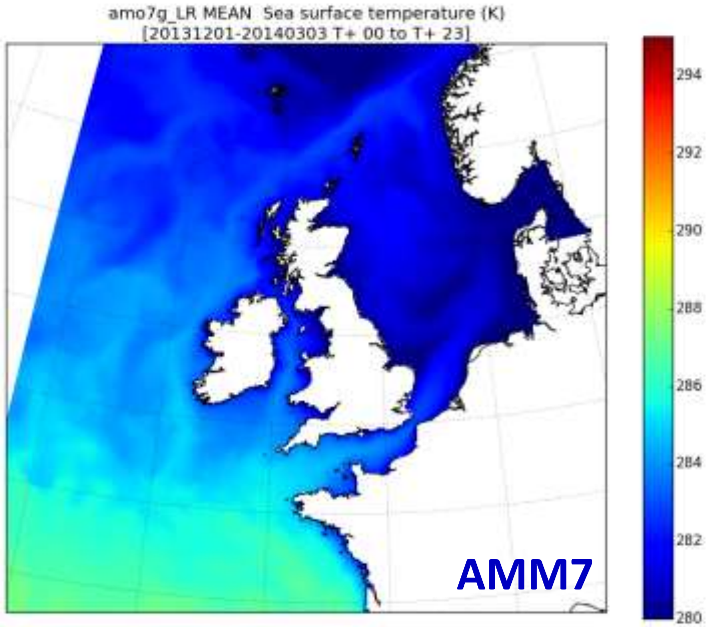
2-year UKC3ow runs

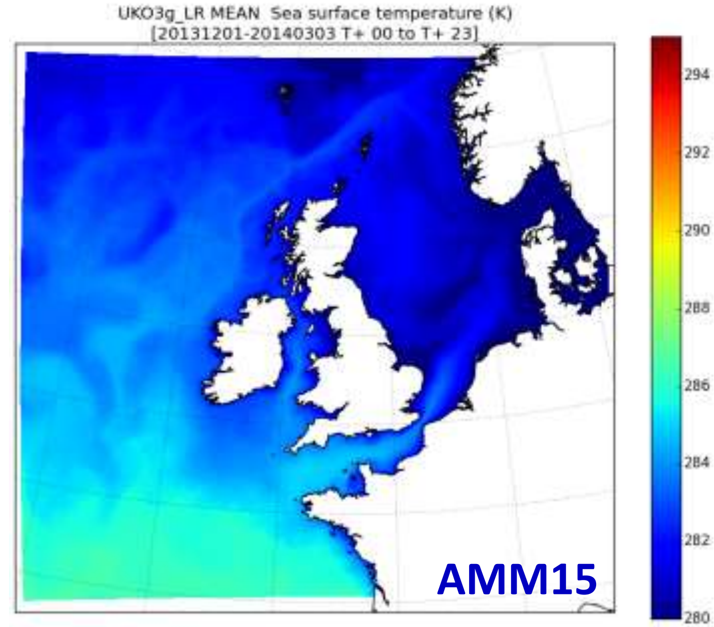
Winter 2013/14 [DJF]

SST

3-month MEANS

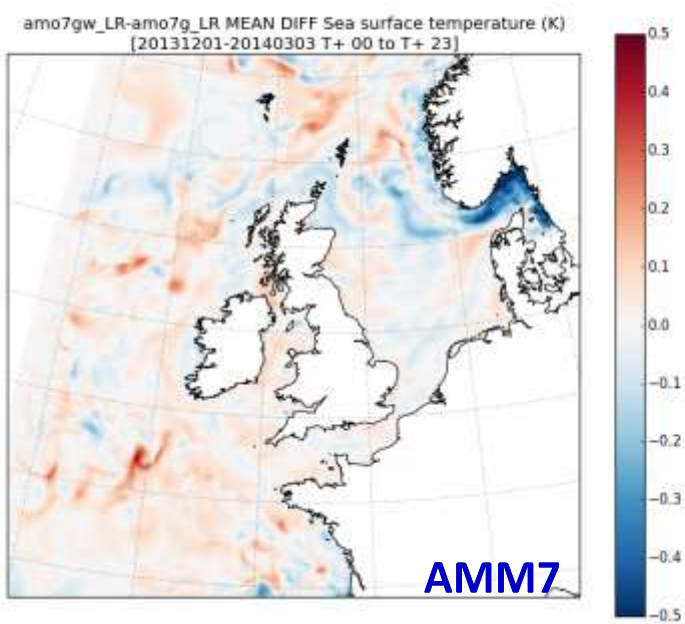
OCEAN ONLY

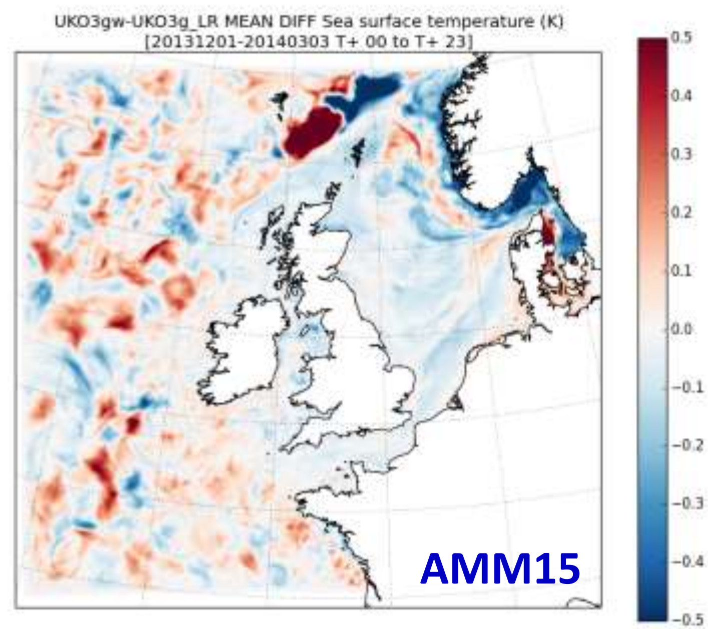




3-month DIFFERENCE

WAVE FORCED
-
OCEAN ONLY





2-year UKC3ow runs

Summer 2014 [JJA]

SST

3-month MEANS

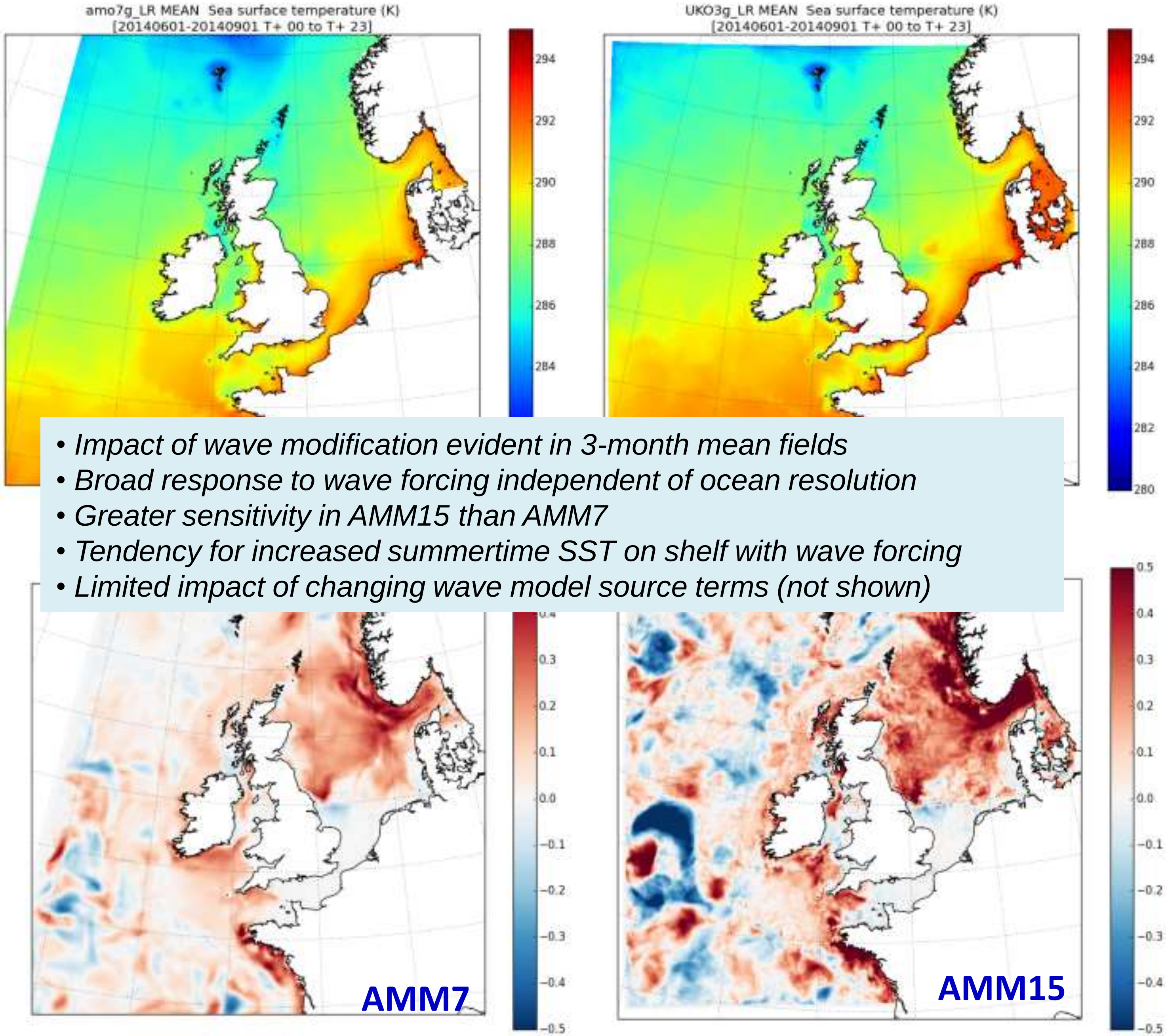
OCEAN ONLY

3-month DIFFERENCE

WAVE FORCED

-

OCEAN ONLY

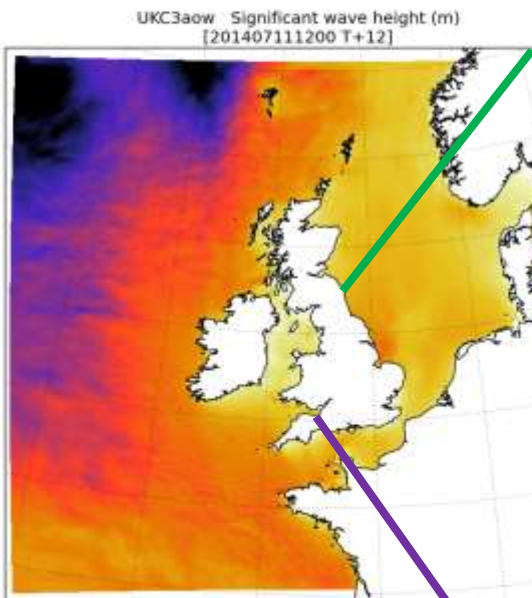


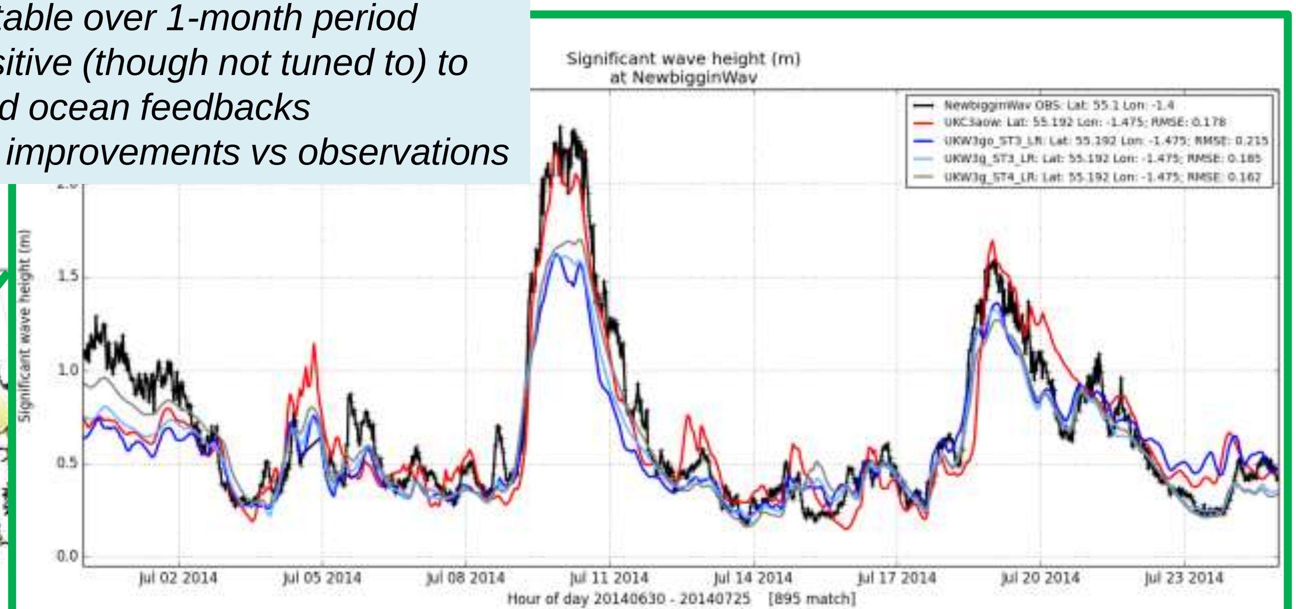
- *Impact of wave modification evident in 3-month mean fields*
- *Broad response to wave forcing independent of ocean resolution*
- *Greater sensitivity in AMM15 than AMM7*
- *Tendency for increased summertime SST on shelf with wave forcing*
- *Limited impact of changing wave model source terms (not shown)*

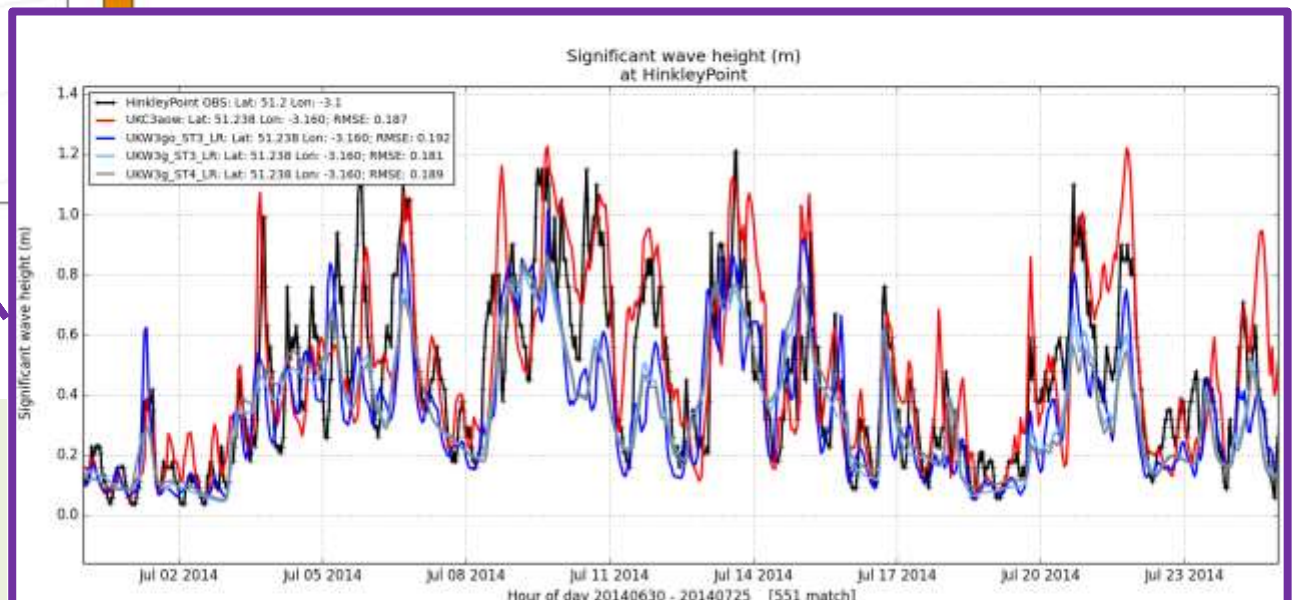
Impacts on wave prediction: Hs

1 month fully-coupled ocn-wave-atm run

- *UKC3aow wave predictions stable over 1-month period*
- *Near-coast wave heights sensitive (though not tuned to) to high-resolution met forcing and ocean feedbacks*
- *Challenge to validate process improvements vs observations*



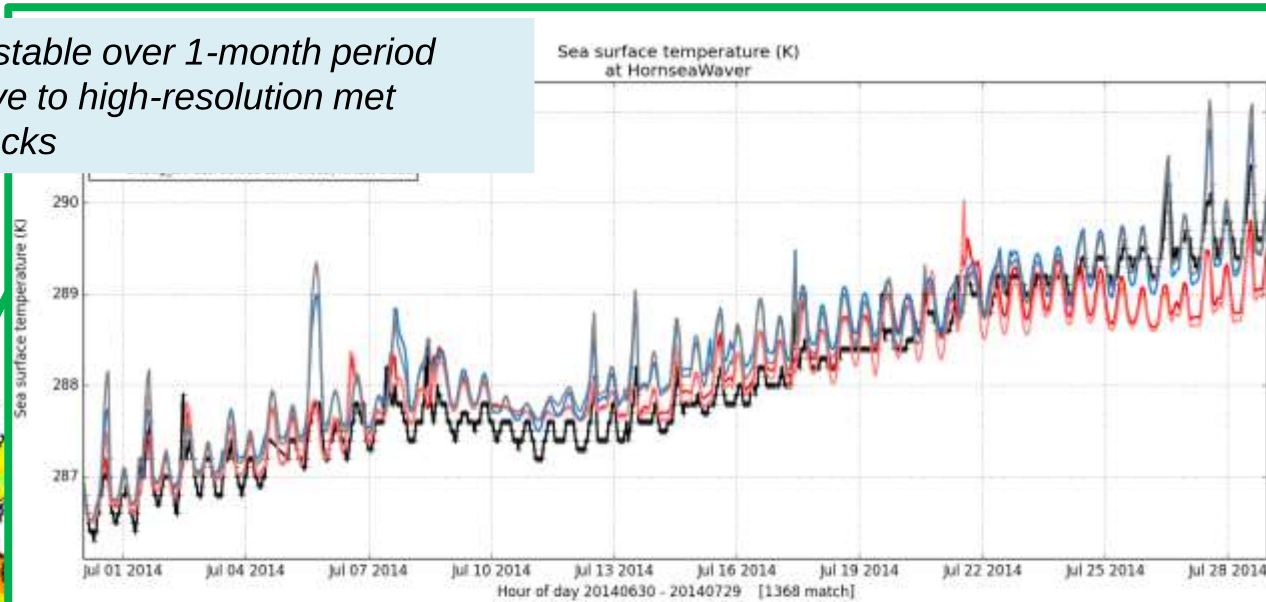


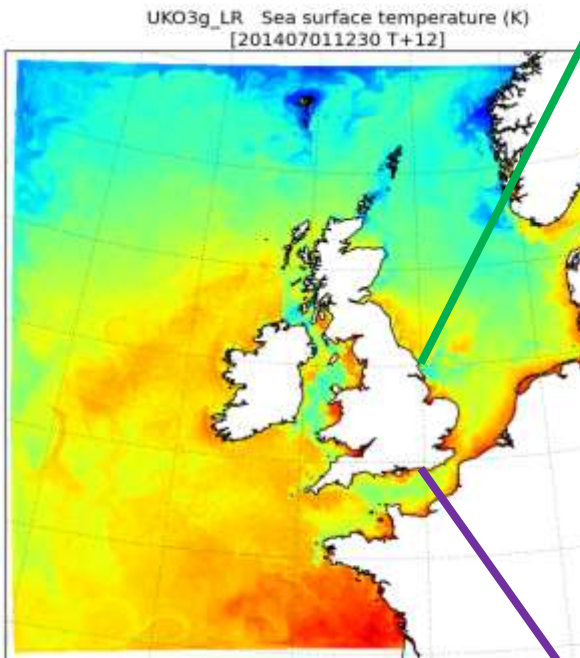


Observations
Fully coupled
Ocean-forced, global met.
Wave only, global met.

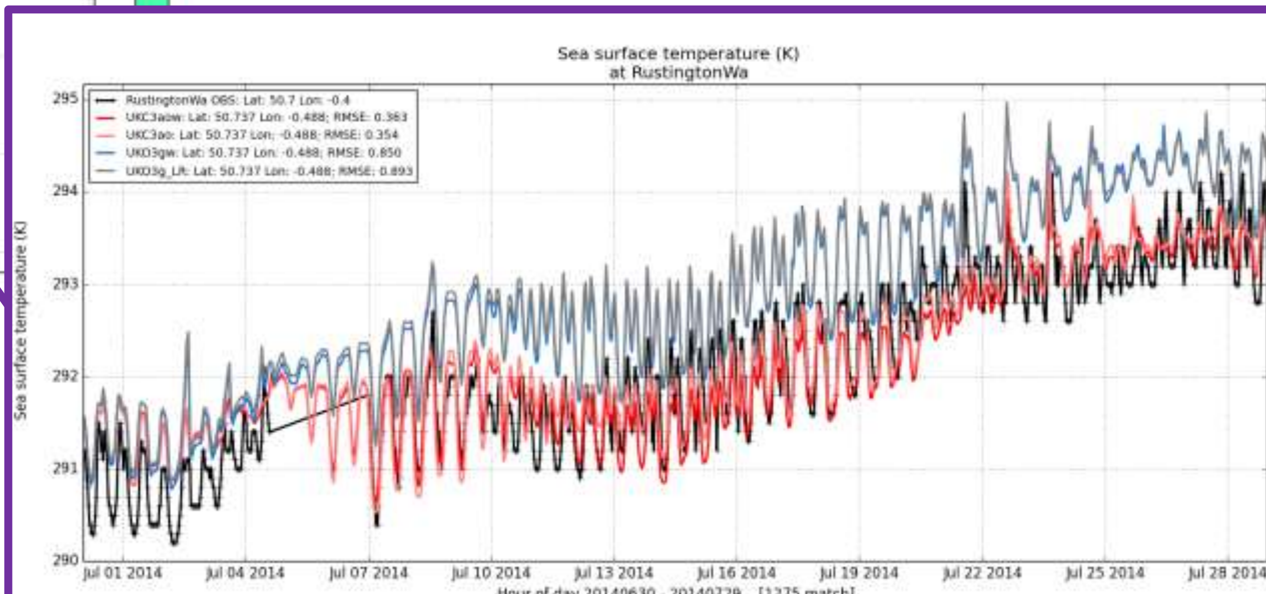
Representing air-sea interaction: UKC3aow

- *UKC3aow ocean predictions stable over 1-month period*
- *Near-coast SST more sensitive to high-resolution met information than wave feedbacks*



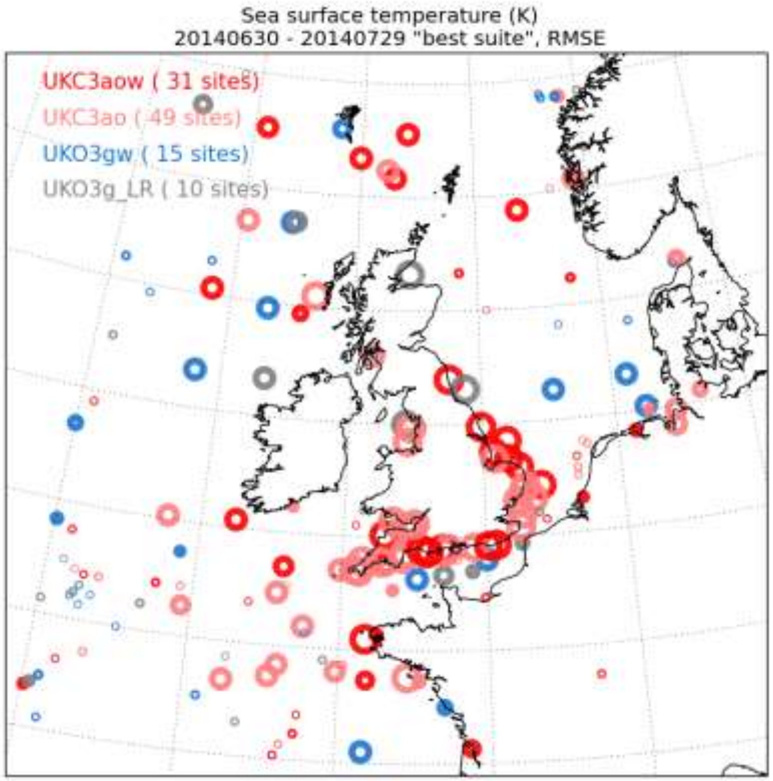


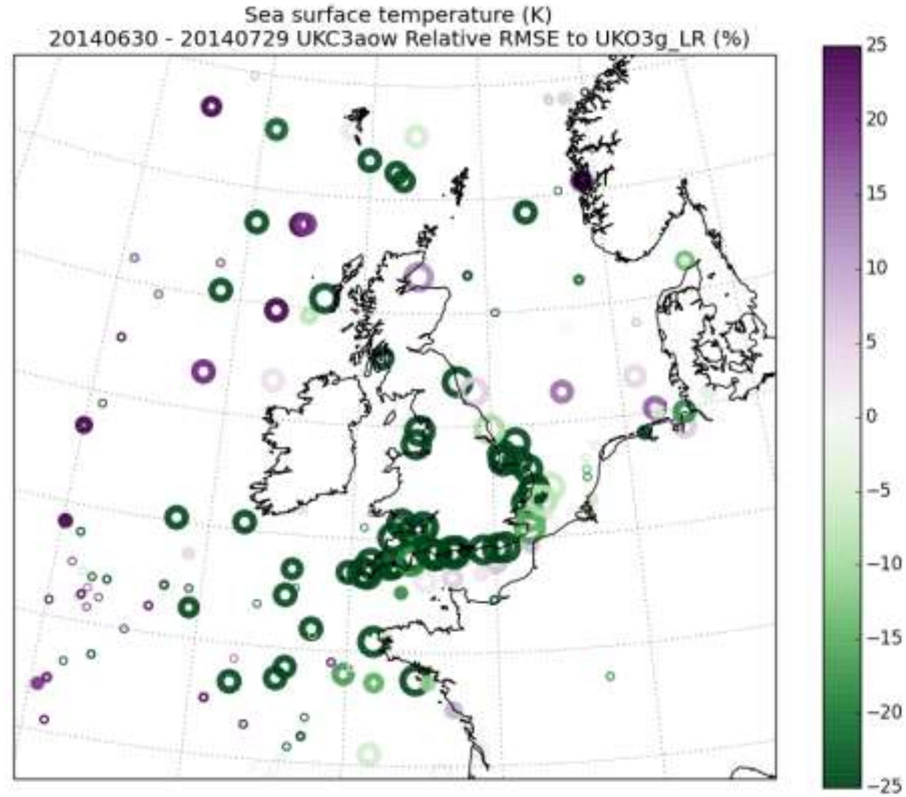
1 month fully-coupled ocn-wave-atm run



Observations
Fully coupled
Wave-forced, global met.
Ocean only, global met.

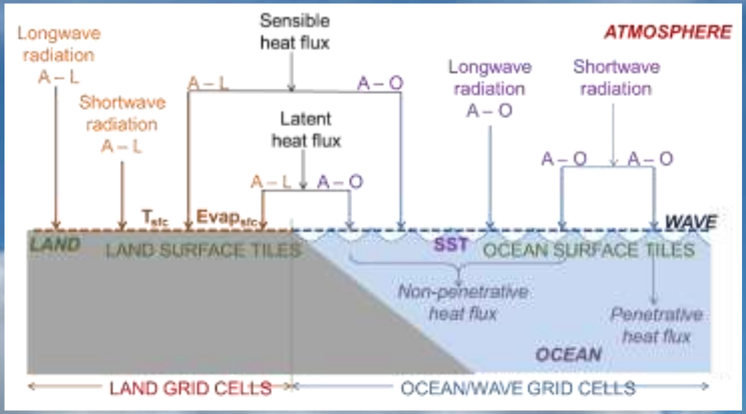
Representing air-sea interaction: UKC3aow





Systematic improvement to ocean SST validation – July 2014

- *High-resolution meteorological information + wave feedbacks in coupled runs provide improvements at near coastal sites*

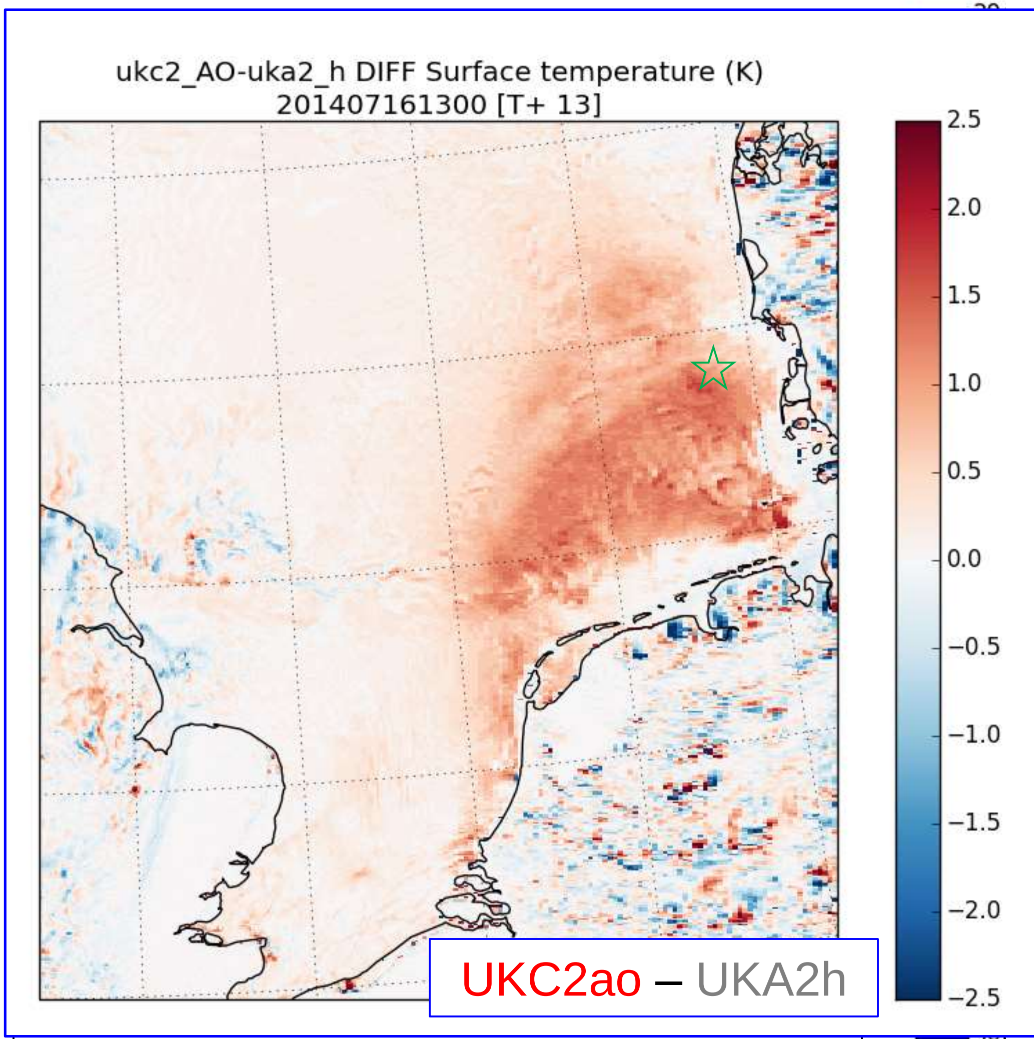


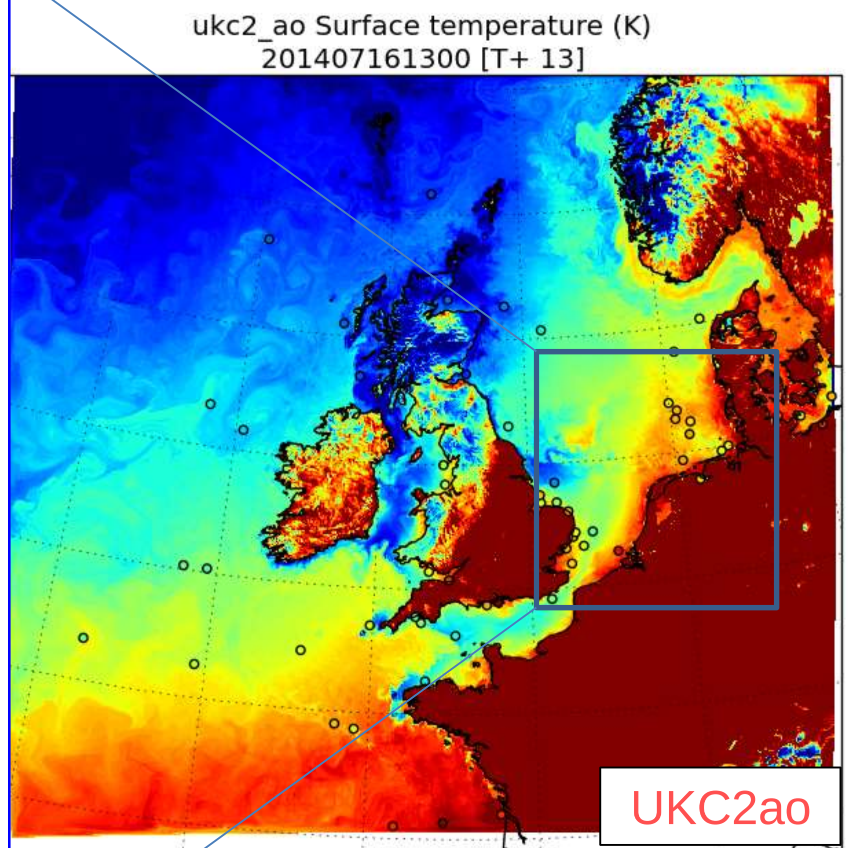
ATMOSPHERE
Sensible heat flux
Longwave radiation A – L
Shortwave radiation A – L
A – L
A – O
Latent heat flux
A – L
A – O
Longwave radiation A – O
Shortwave radiation
A – O
A – O
Tsfc
Evapsfc
WAVE
LAND
LAND SURFACE TILES
SST
OCEAN SURFACE TILES
Non-penetrative heat flux
Penetrative heat flux
OCEAN
LAND GRID CELLS
OCEAN/WAVE GRID CELLS

PART II: *'heat'*

Ocean – atmosphere interaction

A summer's day: July 2014

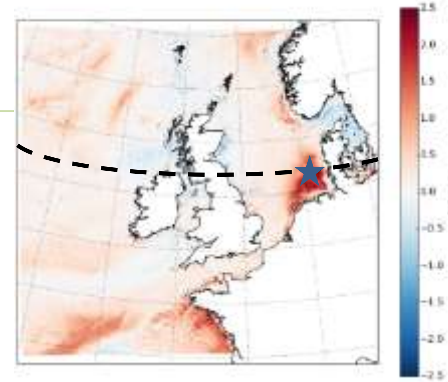


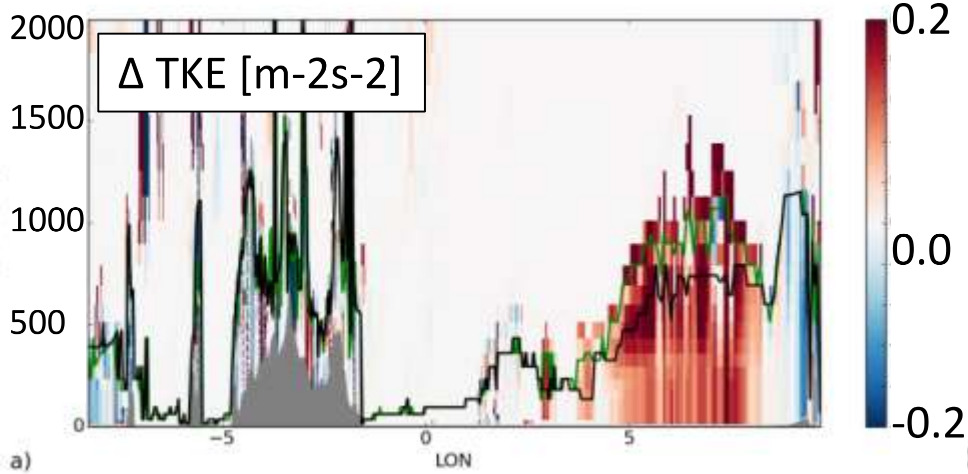


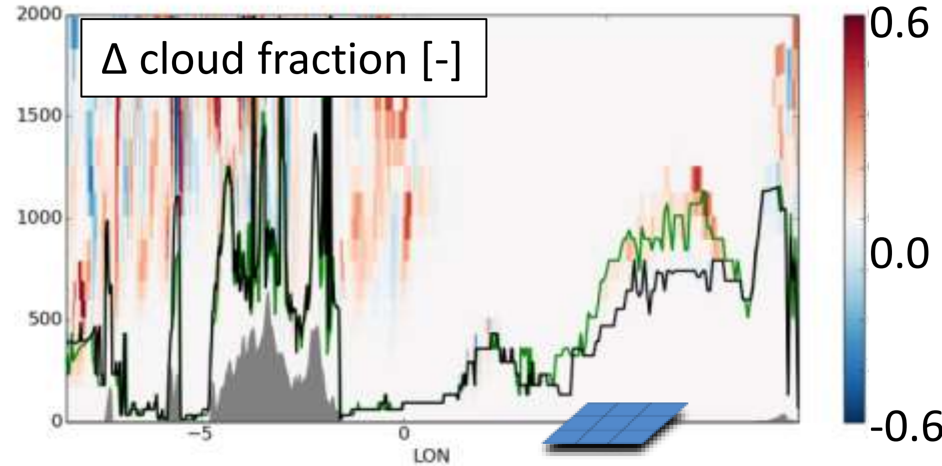
Lower boundary SST evolving through *coupling* to high-res ocean component

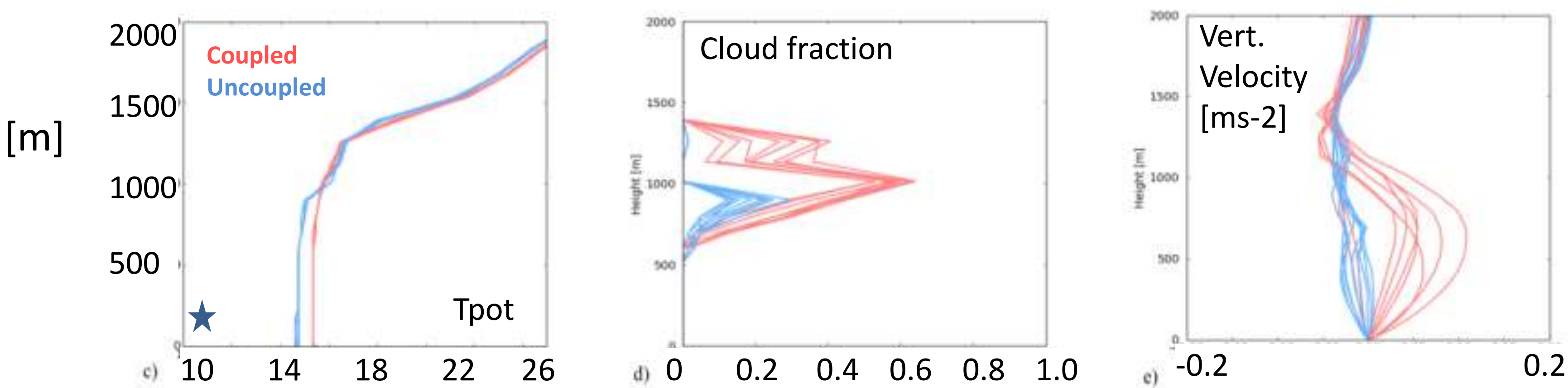
Impacts on atmospheric boundary layer

- Atmospheric boundary layer characteristics through horizontal and vertical profiles
- cloud to boundary layer coupling

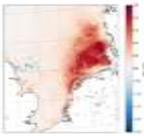






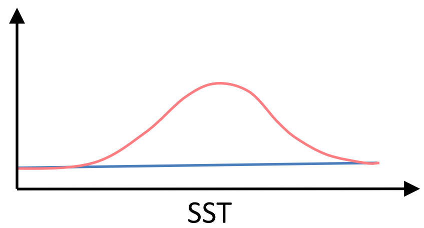


Evaluating feedbacks



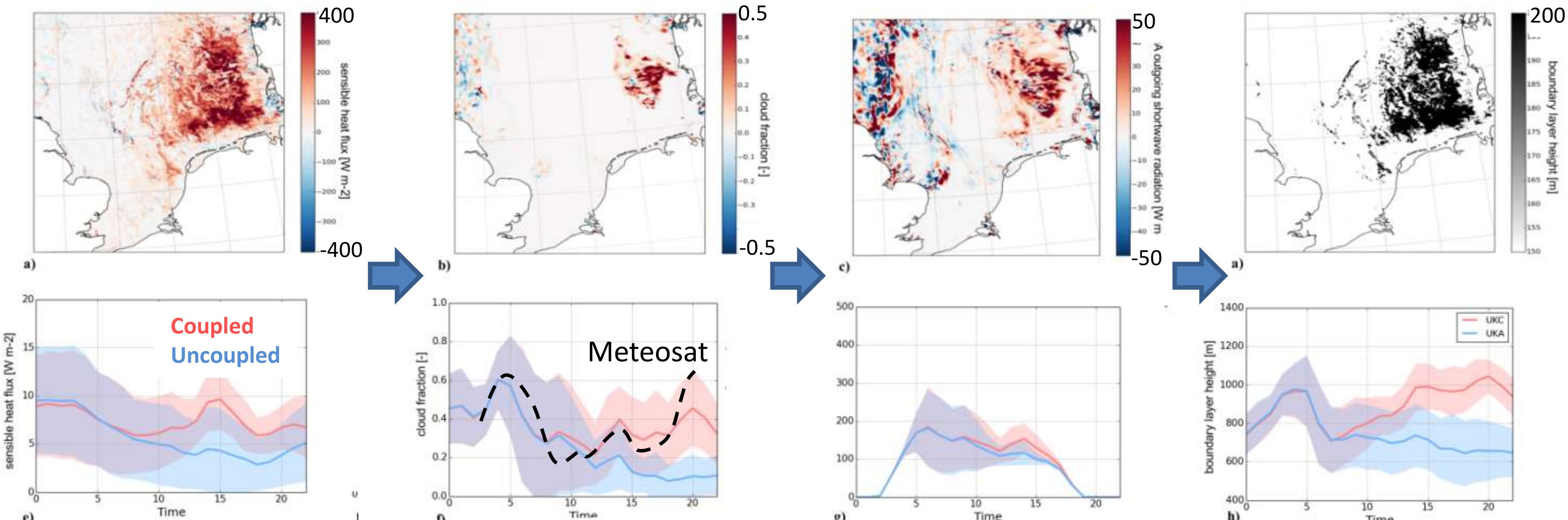
Δ SST → Δ Atmosphere

Coupling:



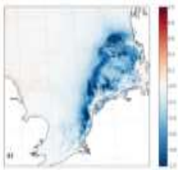
Coupled - Uncoupled

Sensible heat flux | Cloud cover | Shortwave radiation | PBL height



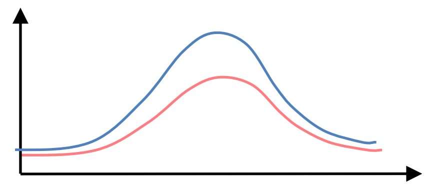
Fallmann et al. 2017 (GRL)

Evaluating feedbacks on the ocean



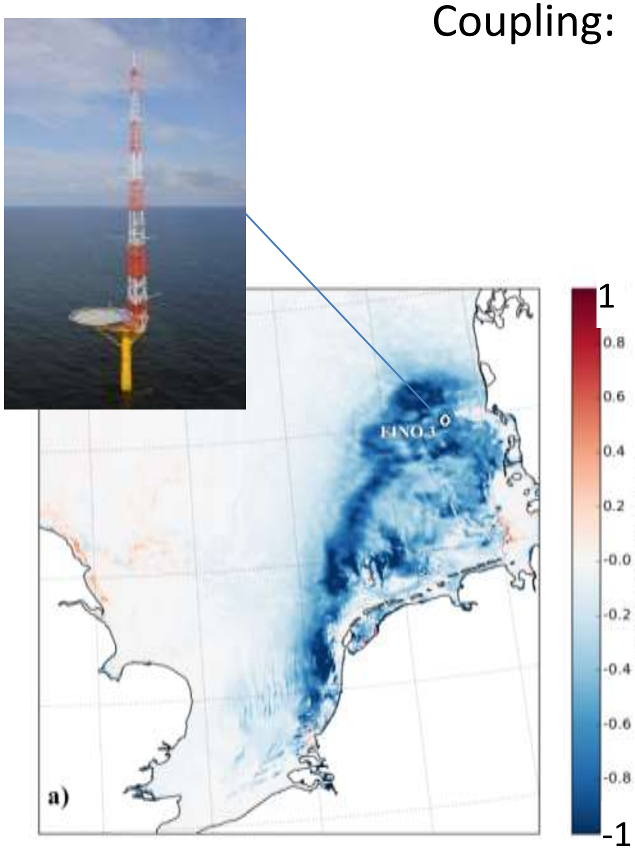
ΔSST ⟵ Δ Atmosphere

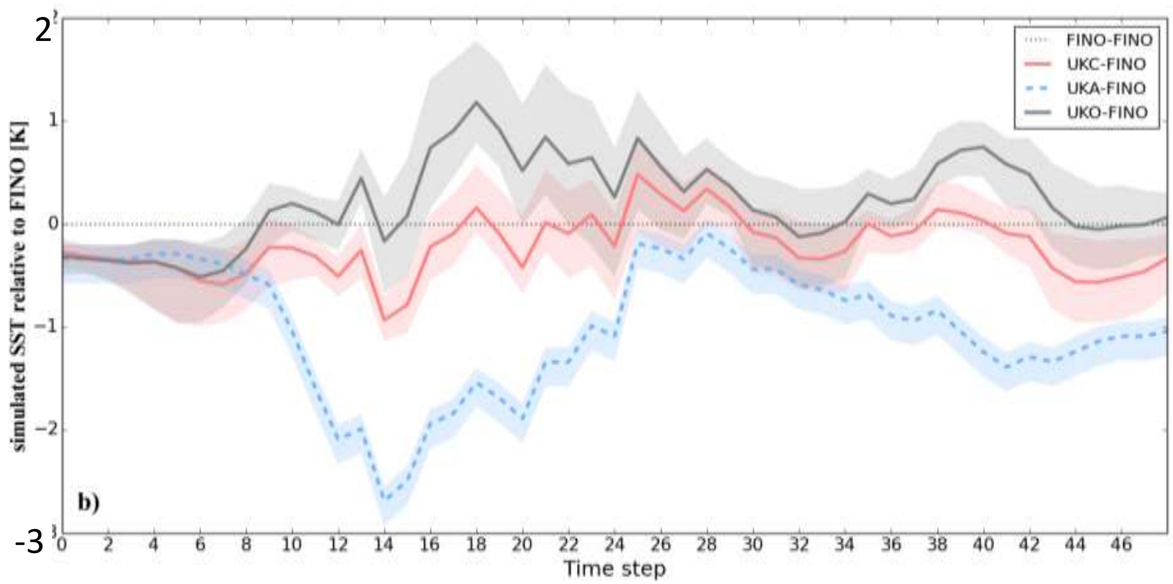
Coupling:



Coupled - Uncoupled

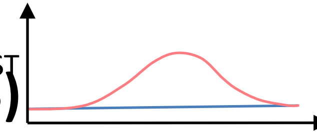
Impact of cloud cover in coupled run on cooling SSTs can be inferred by comparison with ocean model forced with uncoupled meteorology





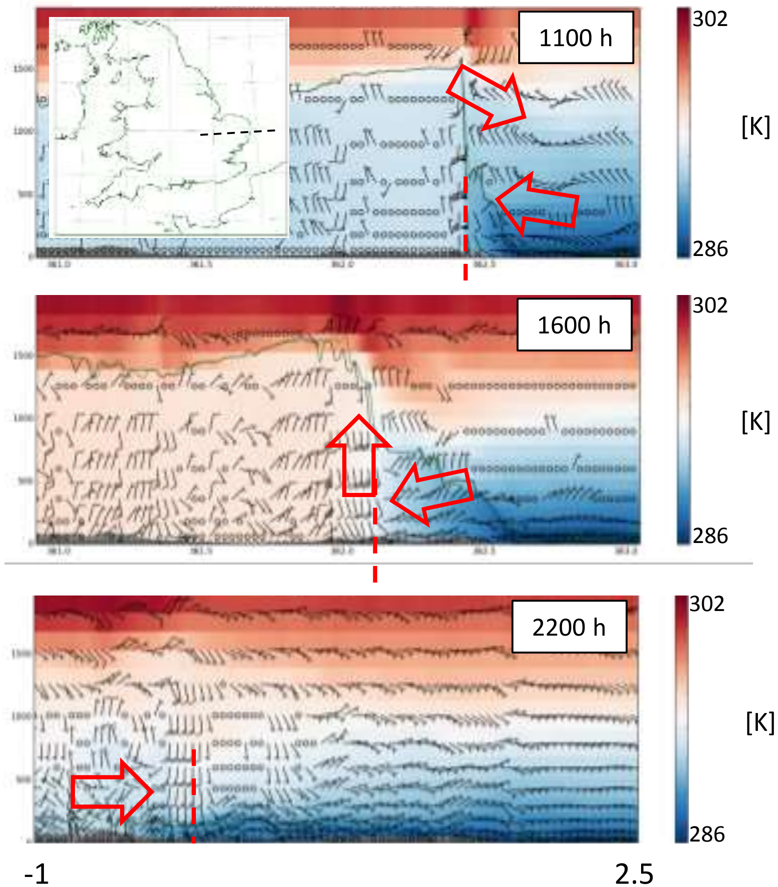
Fallmann et al. 2017 (GRL)

Sensitivity analysis – Sea Breeze (5-day case July 2013)



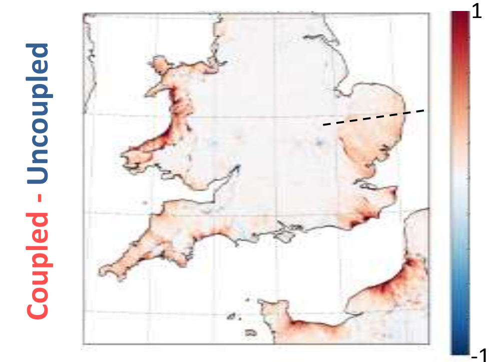
Coupled

Tpot and wind direction 5 July 2013



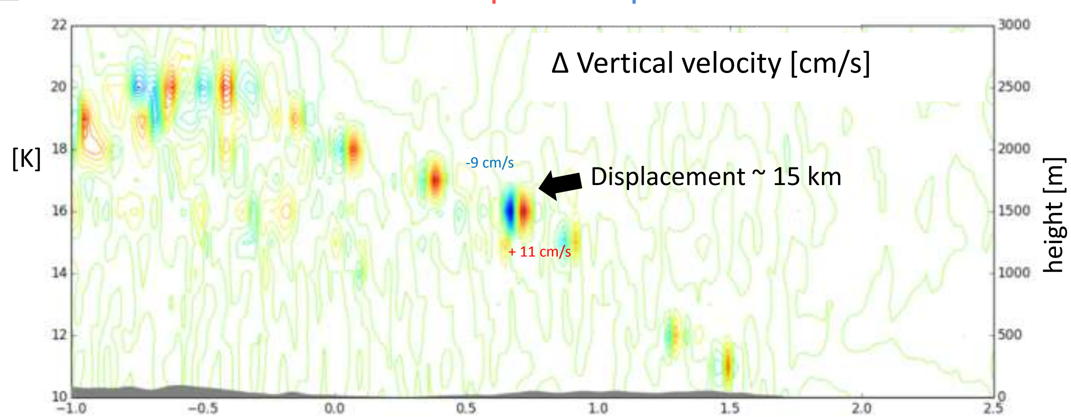
Wind direction and location of sea breeze fronts (1100h)

Effect of SST increase on Tair by coupling (2000h)



Hovmoller plot for vertical velocity shows the diurnal evolution of the sea breeze front – differences indicate displacement

Coupled - Uncoupled

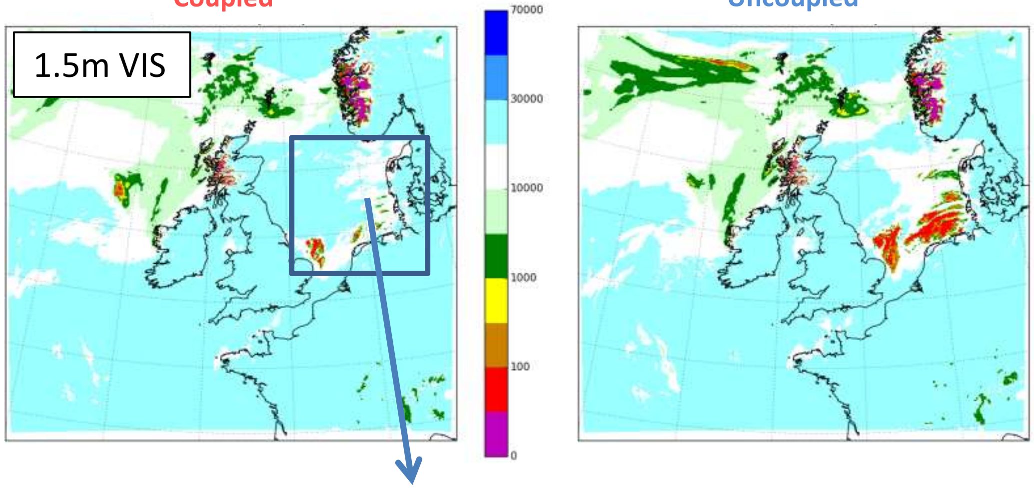


Sensitivity analysis – SST/coastal fog (July 2013)

Visibility - Fog [m] – Southern North Sea

Coupled

Uncoupled

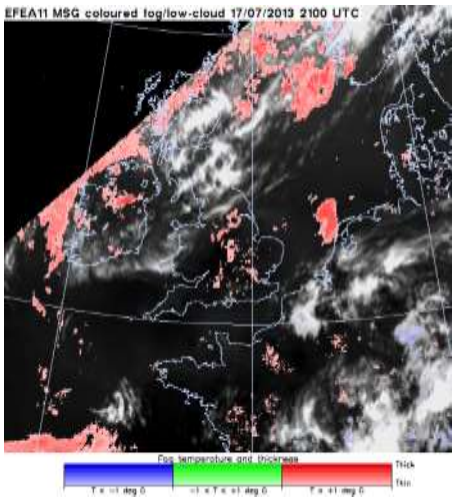


70

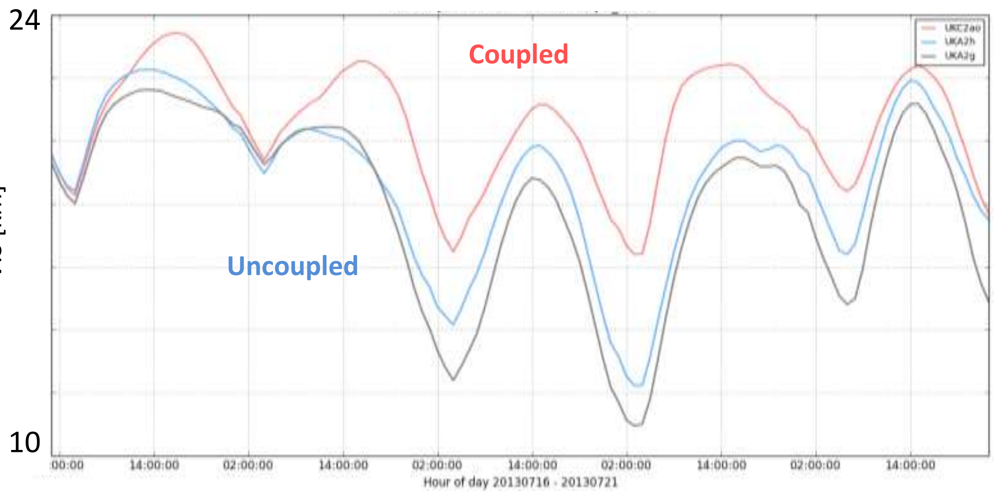
VIS [km]

0

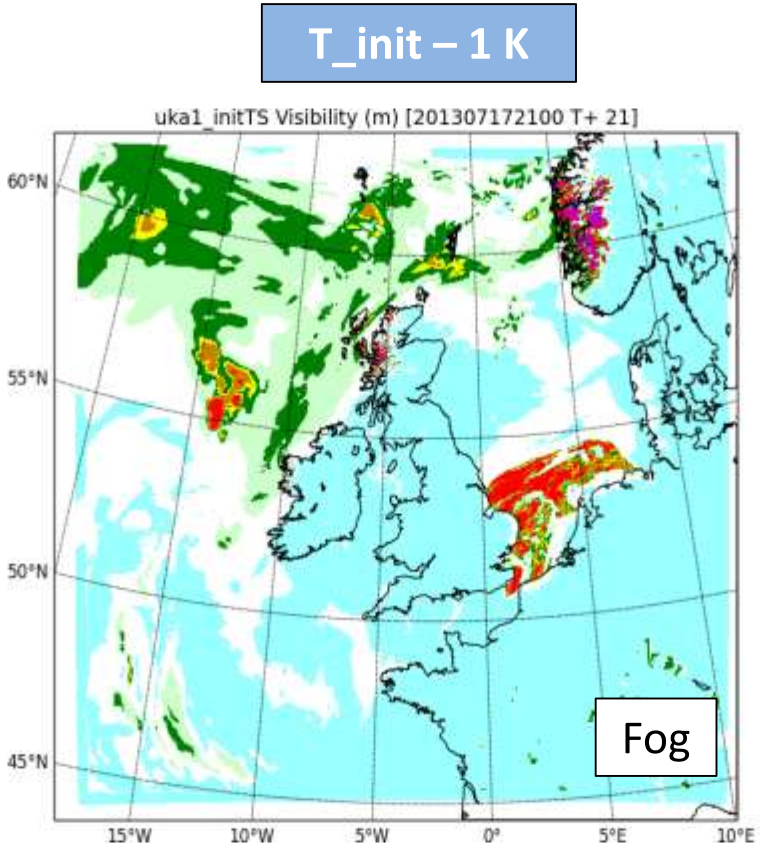
Meteosat Fog temperature and thickness

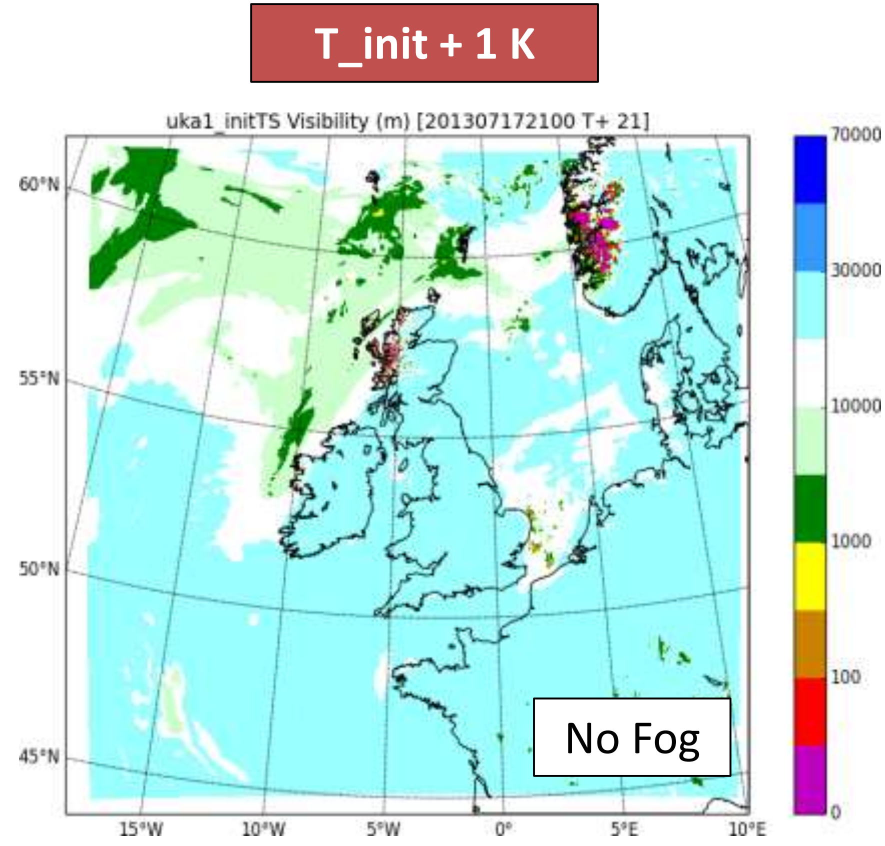


Average visibility over southern North Sea



Experiment - Atmospheric feedback to 1 K warmer sea surface



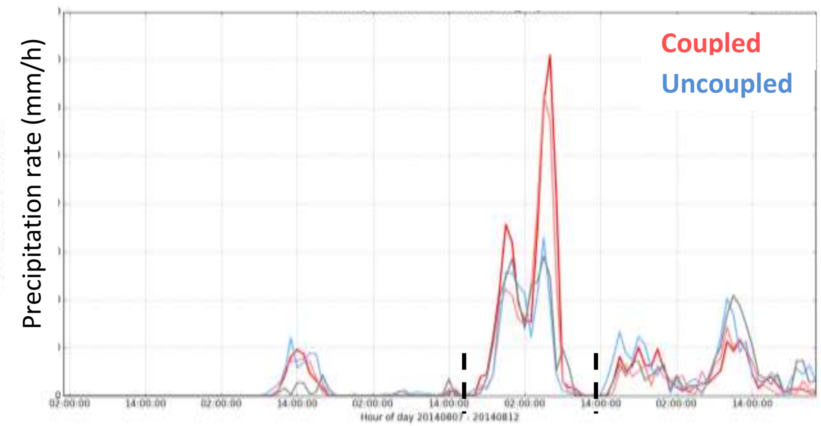


Sensitivity analysis – Precipitation

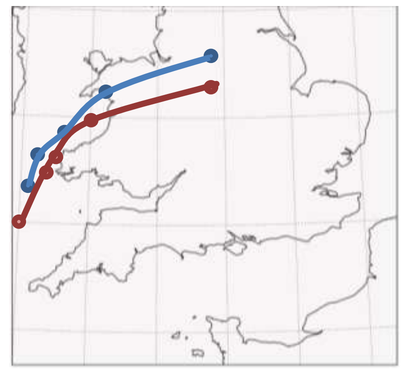
August 2014

Precipitation [mm/h] – SW-England

Accumulated grid cells over land (SW-England)



‚frontogenesis‘

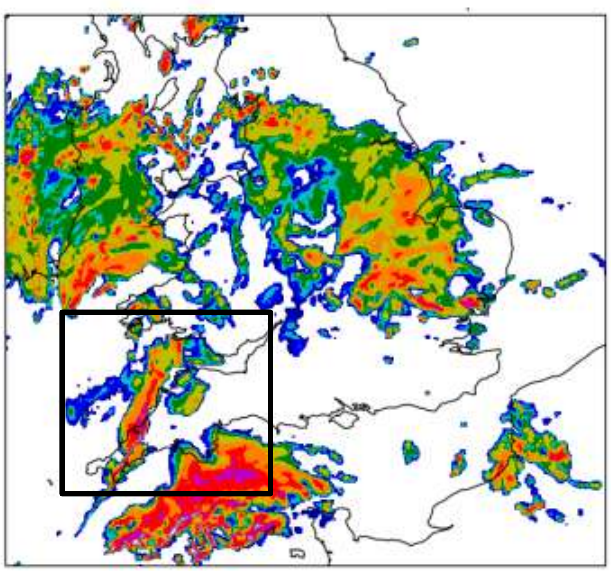


Precipitation [mm/12h] at 06:00
Weather station ‚Chivenor ‘

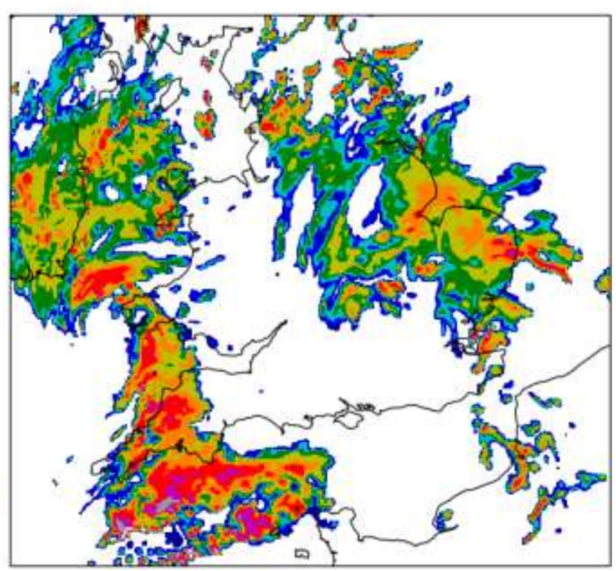
OBS: 17 mm/12h
UM-forecast: 6.2 mm/12h

Coupled: 15.2mm/12h

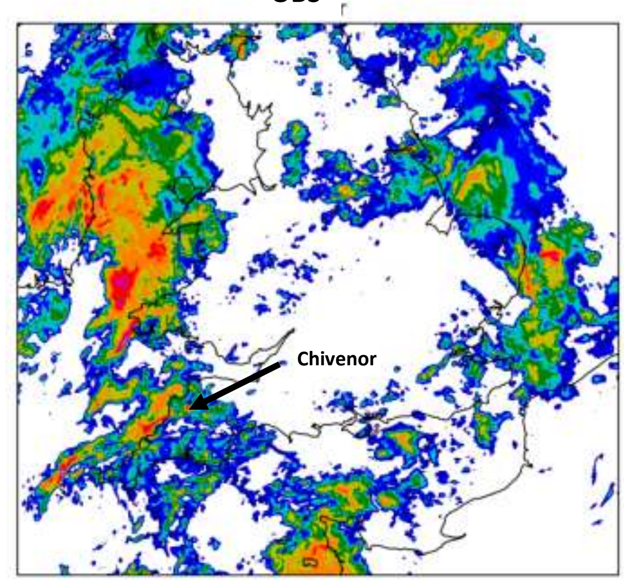
Uncoupled

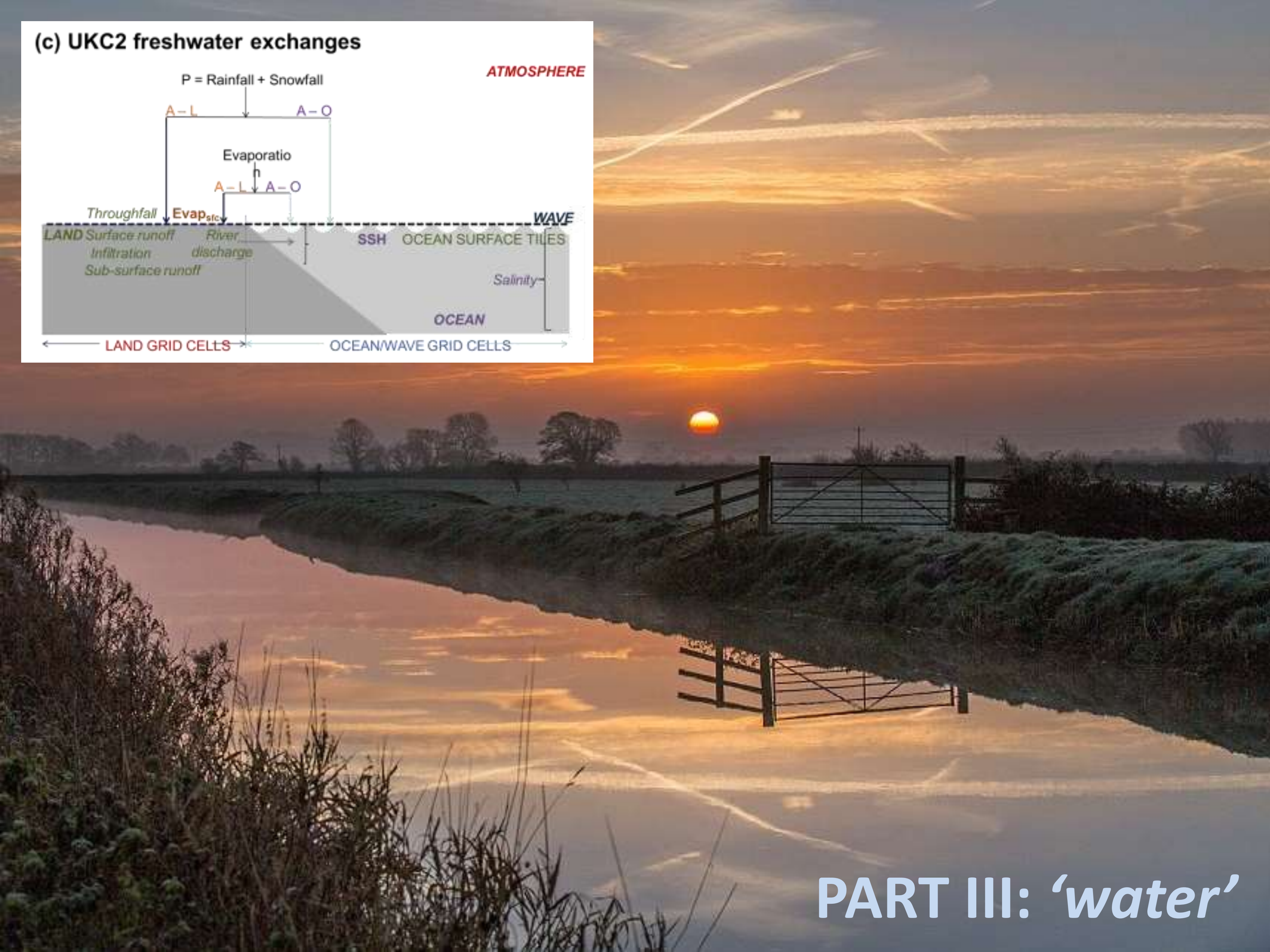


Coupled



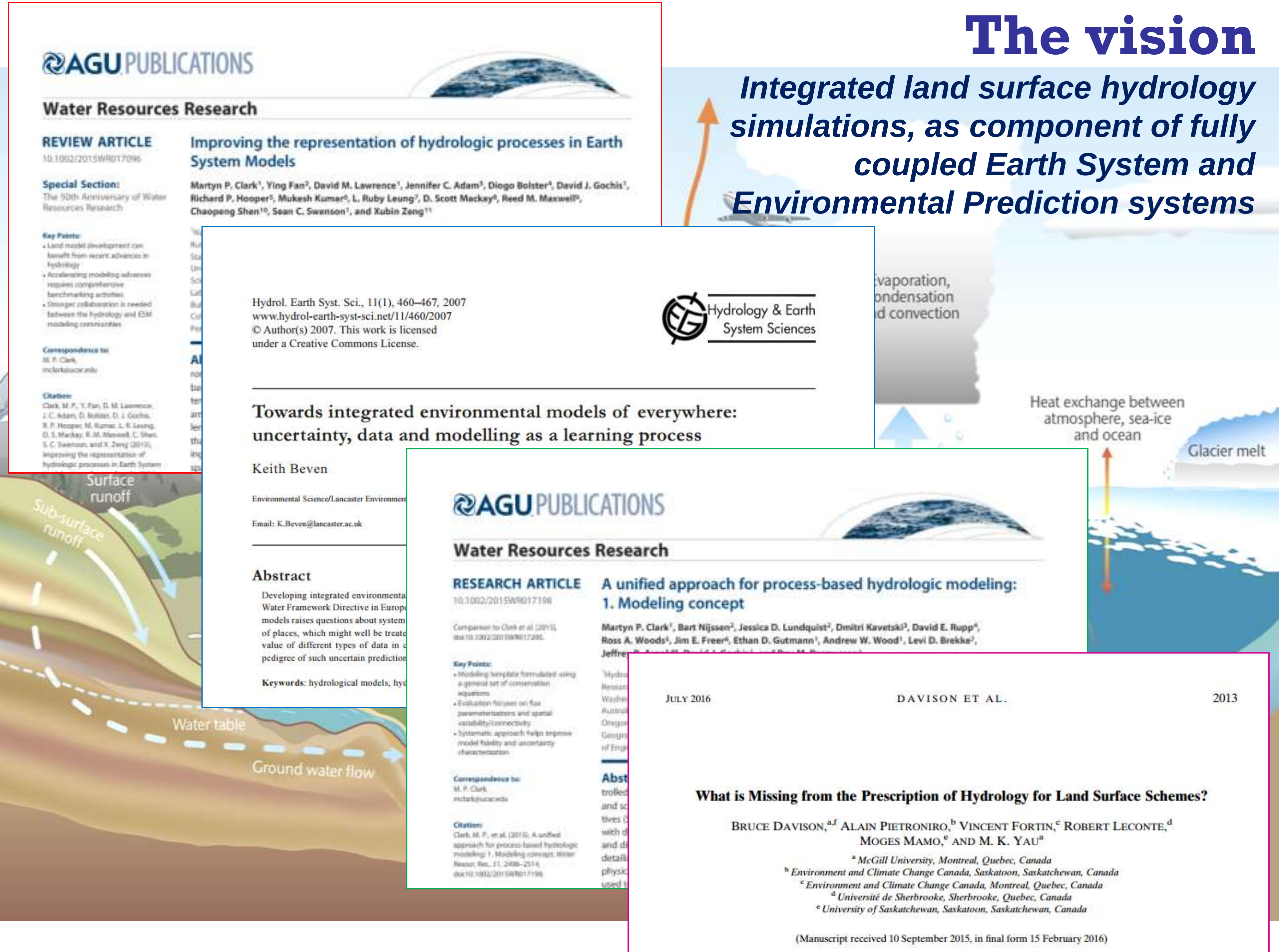
OBS




(c) UKC2 freshwater exchanges
ATMOSPHERE
P = Rainfall + Snowfall
A – L
A – O
Evaporatio
n
A – L
A – O
Throughfall
Evap_sfc
WAVE
LAND Surface runoff
Infiltration
Sub-surface runoff
River
discharge
SSH
OCEAN SURFACE TILES
Salinity
OCEAN
LAND GRID CELLS
OCEAN/WAVE GRID CELLS
PART III: 'water'

The vision

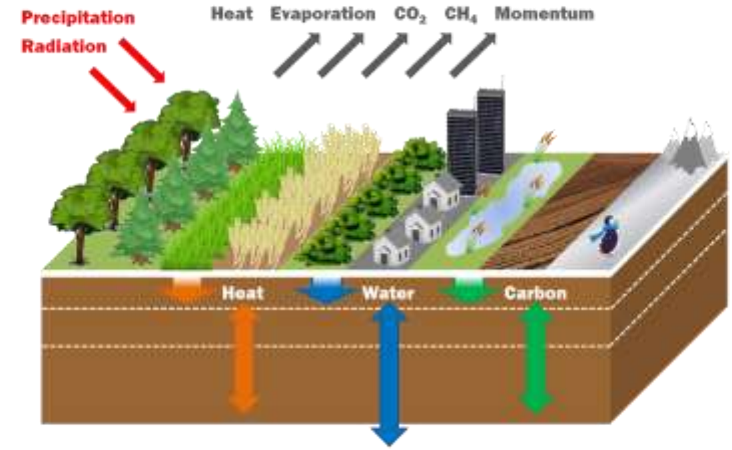
Integrated land surface hydrology simulations, as component of fully coupled Earth System and Environmental Prediction systems



Met Office

JULES

Joint UK Land Environment Simulator



- Includes various surface types, including:
  - ➢ Vegetation (+canopy water): Bare soil: Lakes: Urban
- Snow processes, including:
  - ➢ Multiple layer snowpack, solid and liquid components, ageing density, Precip accumulation
- Currently has 4 soil layers
  - ➢ Temperature: Moisture: Phase changes: Energy transport: Soil properties
- Representation of shallow groundwater
  - ➢ Soil moisture heterogeneity: Keeps track of water table
- Surface and sub-surface runoff

Some challenges

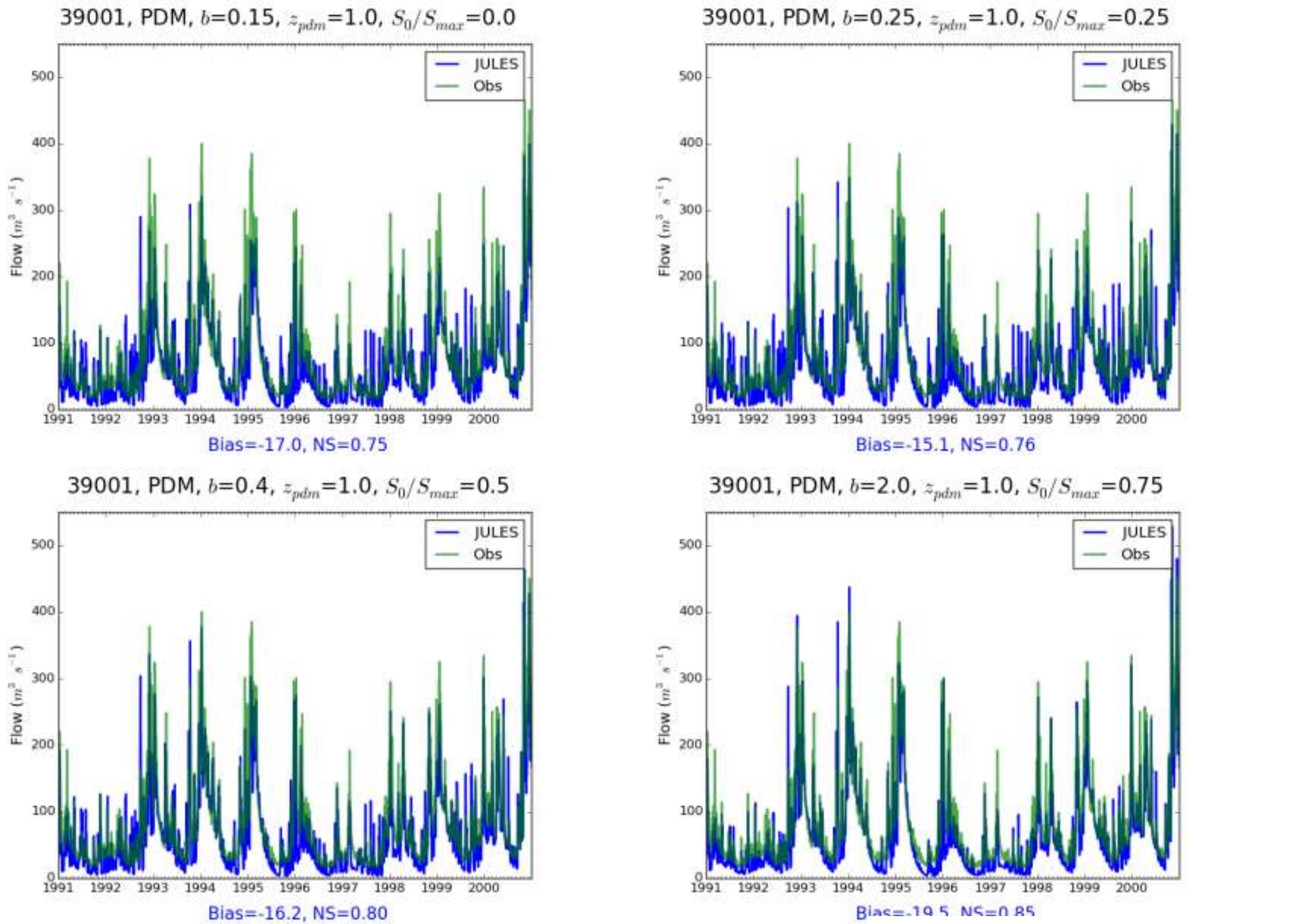
- Skilful hydrology predictions everywhere, all the time?

- Additional model complexity, additional constraints
- Additional model parameters (and calibration?)

- Moving from 1D vertical problem to 3D connectivity

- River flow assimilation and balance with sfc exchange
- Initialisation strategy?
- Consistency between ‘online’ and ‘offline’…

The building blocks are in place…

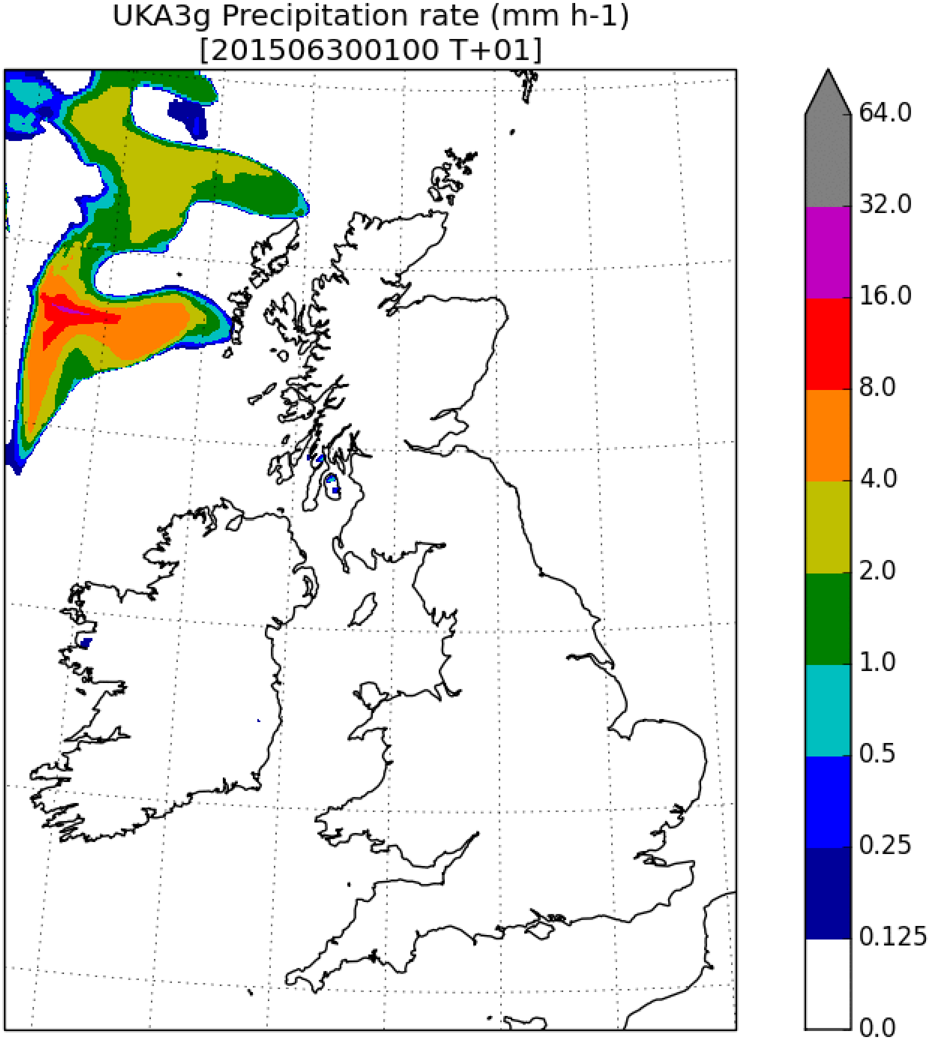


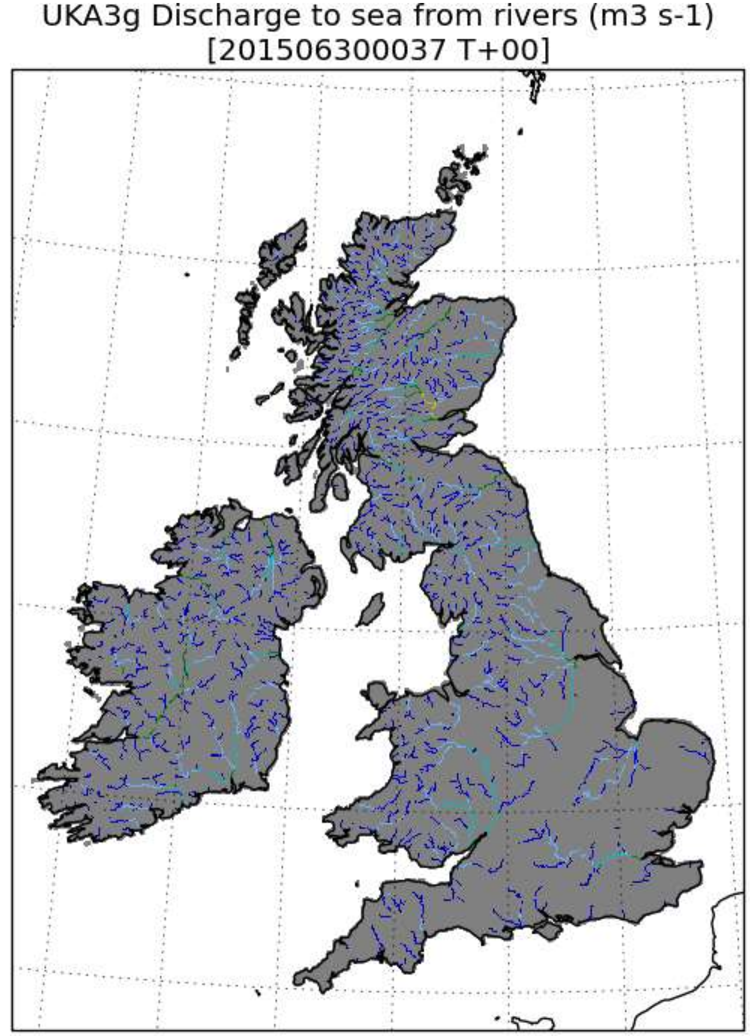
[Alberto Martinez de la Torre, CEH]

Regional coupled prediction at high resolution
1.5 km river flow predictions

Met Office Unified Model rainfall

JULES kinematic wave routing river flow



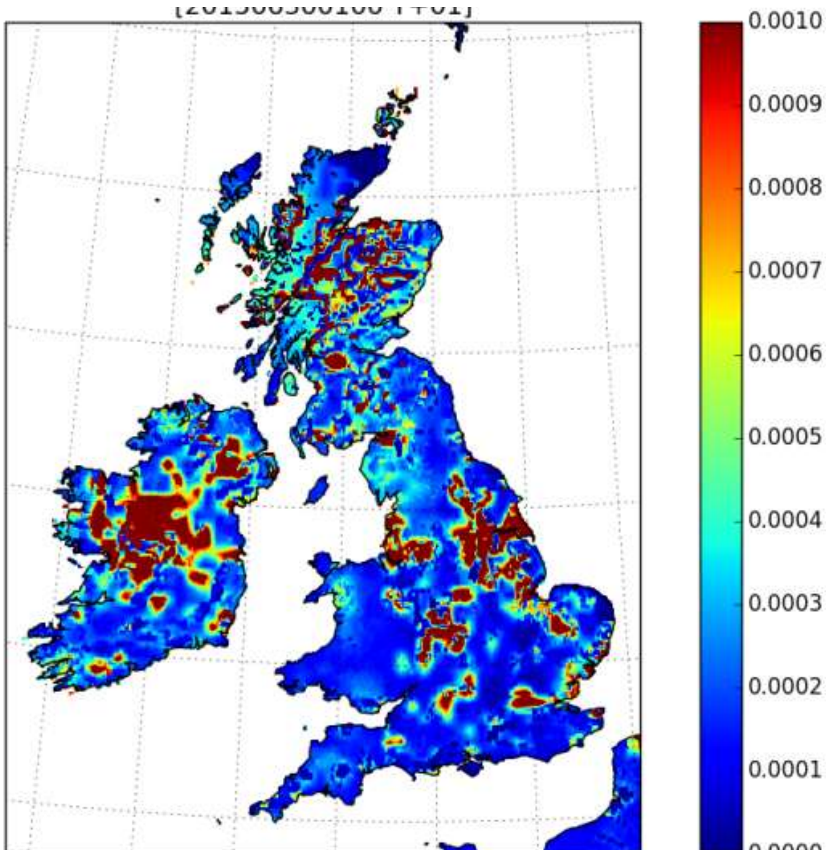


Implementation in UKC2 vs UKC3

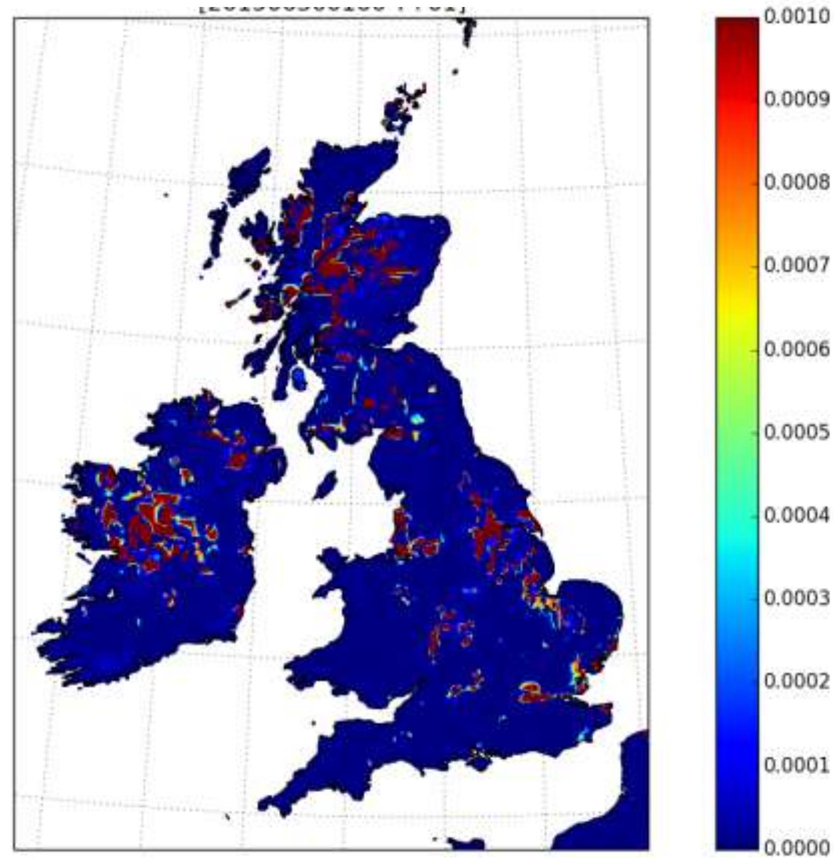
UM-JULES

Met Office

UM10.6 + JULES4.7



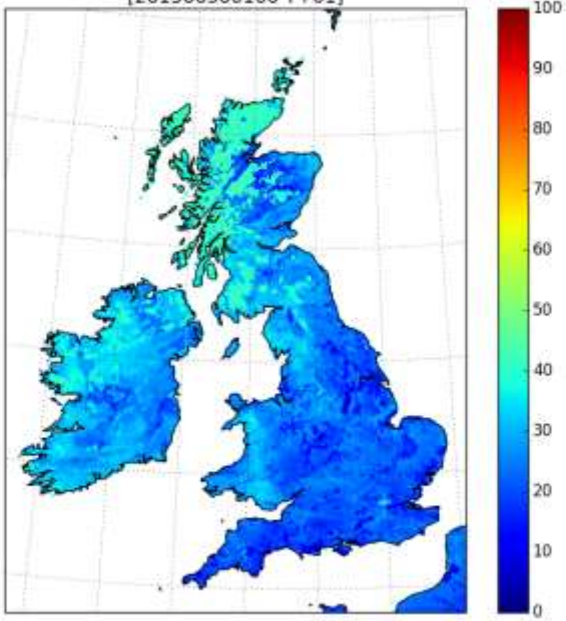
UM10.1 + JULES4.2



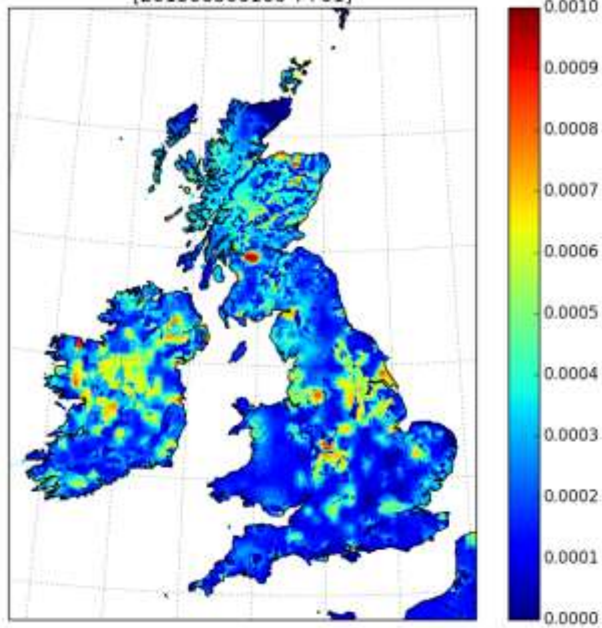
e.g. Initialising sub-surface runoff

Potential impact UKV soil moisture analysis

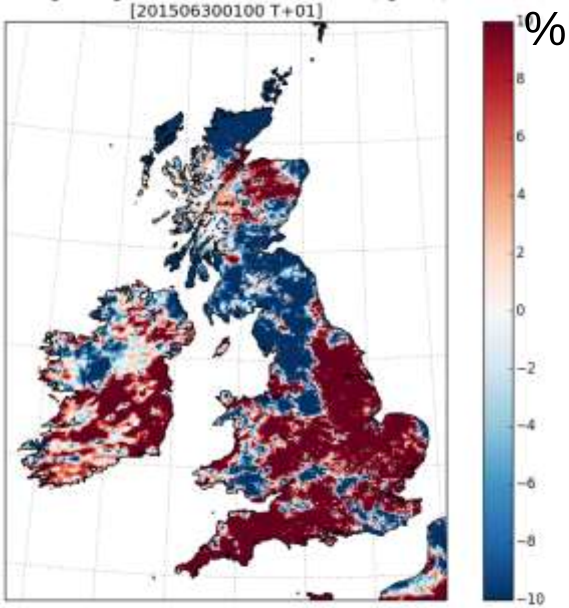
UKA3gs Soil Moisture Content (kg m -2)
[201506300100 T+01]



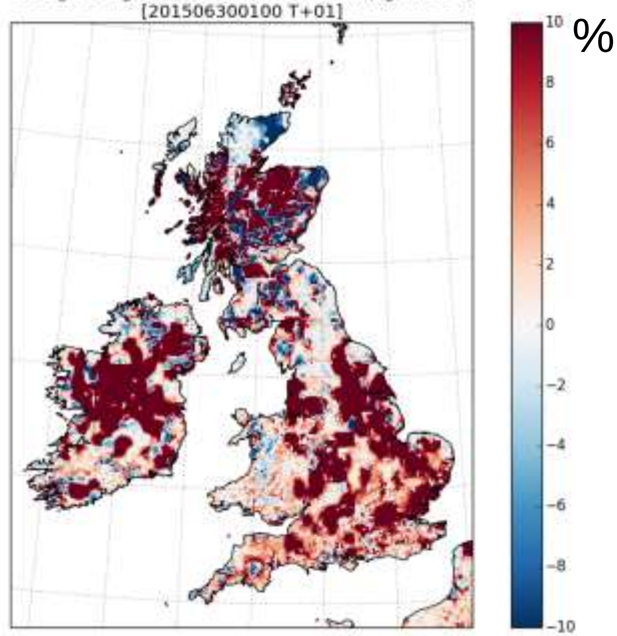
UKA3gs Sub-surface runoff (kg m-2 s-1)
[201506300100 T+01]



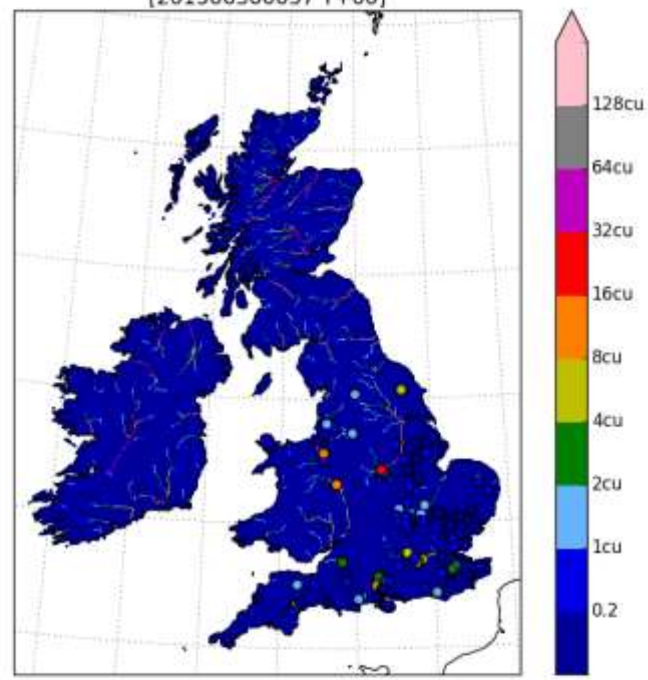
UKA3g-UKA3gs DIFF Soil Moisture Content (kg m -2)
[201506300100 T+01]



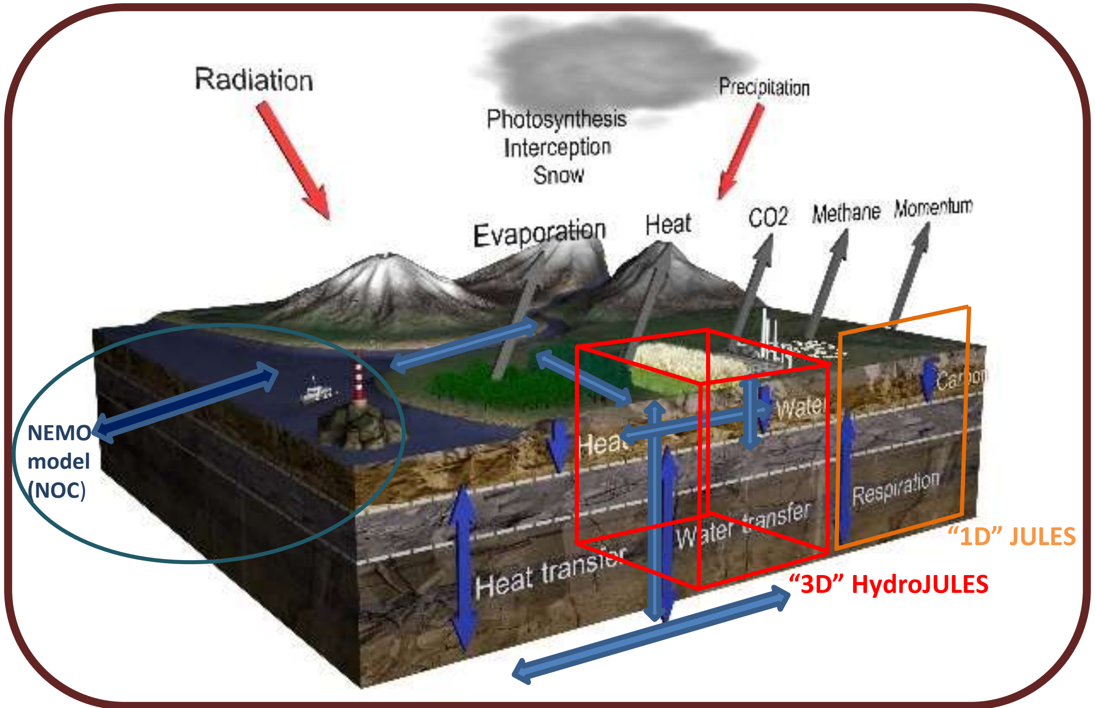
UKA3g-UKA3gs DIFF Sub-surface runoff (kg m-2 s-1)
[201506300100 T+01]



UKA3gs Discharge to sea from rivers (m3 s-1)
[201506300037 T+00]



Future progress: Hydro-JULES



Above ground processes (CEH / NCAS). Land-surface and hydrological modelling, meteorological / climatological analysis,
Platforms, model code and coupling tools

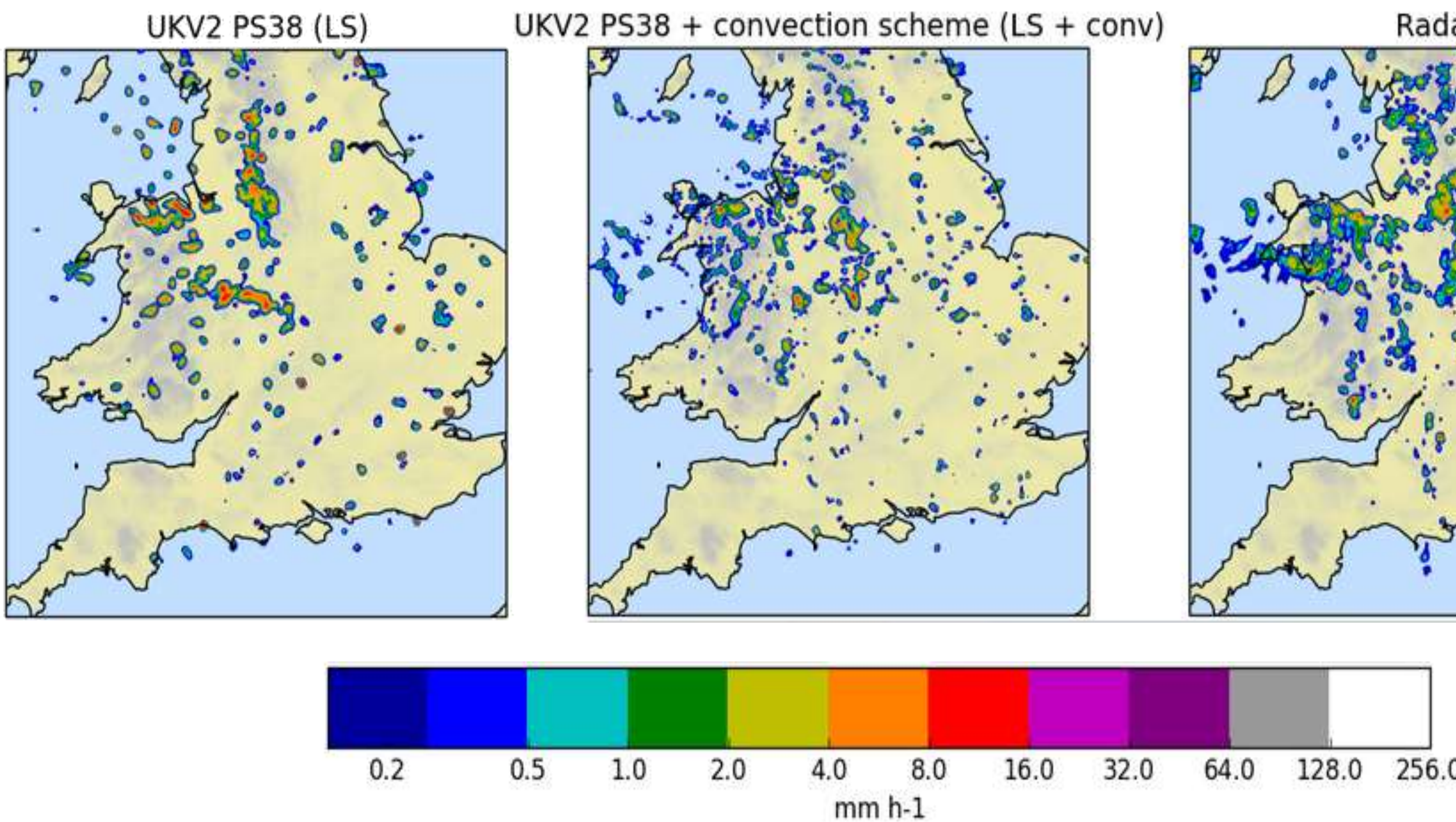
Surface / sub-surface processes (CEH / BGS) Hydrological, land-surface, groundwater and hydraulic modelling, soil physics, coupling

UK Environmental Prediction

Underpinning skills: Model framework architecture development, programming, software design, system testing, web developers, data processing, GIS, data assimilation, statistics.
Integrated, open source coupled modelling system of the terrestrial hydrological cycle. (CEH, NCAS and BGS)

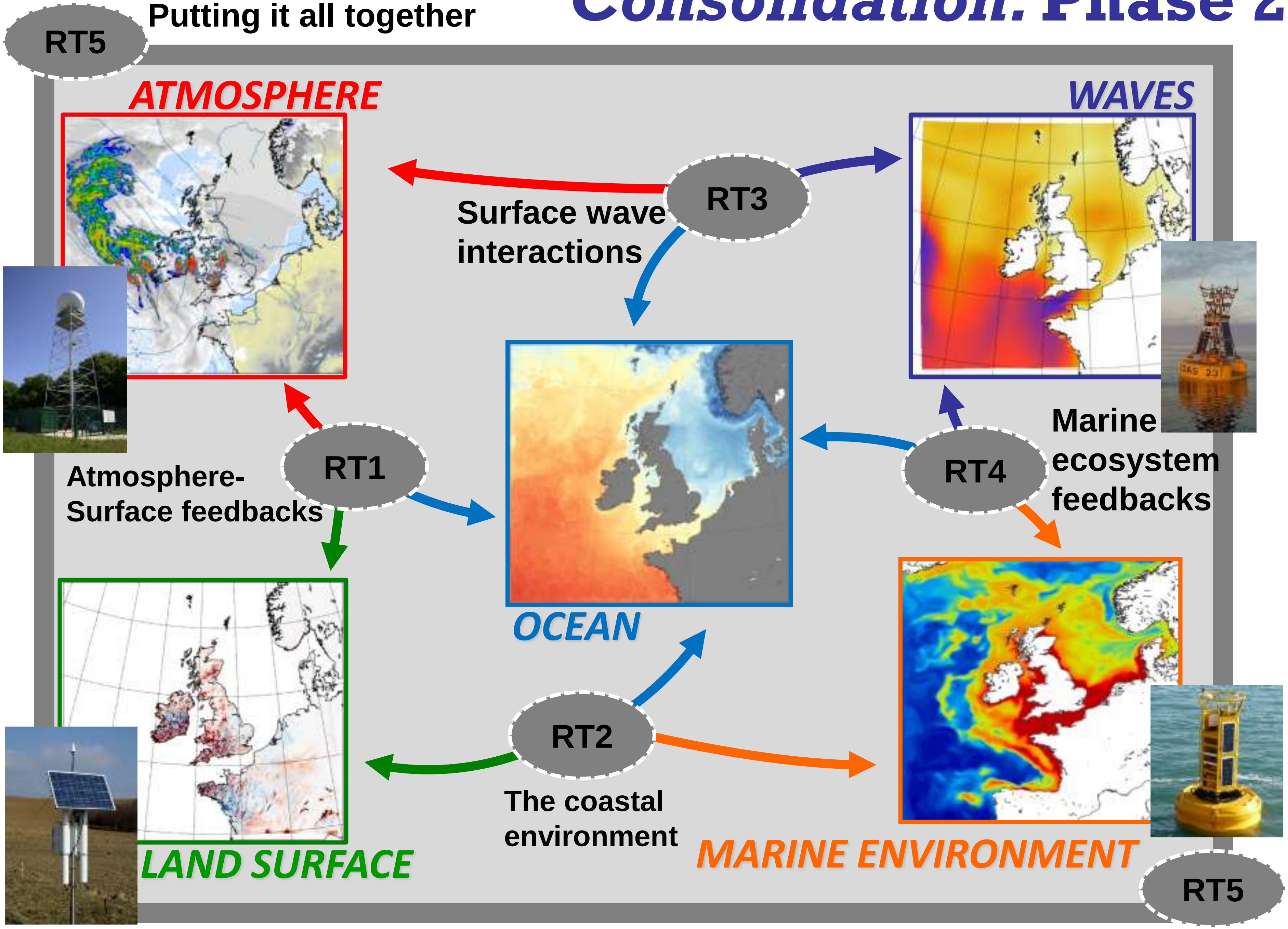
Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

And not to forget….
…forcing characteristics continue to evolve!



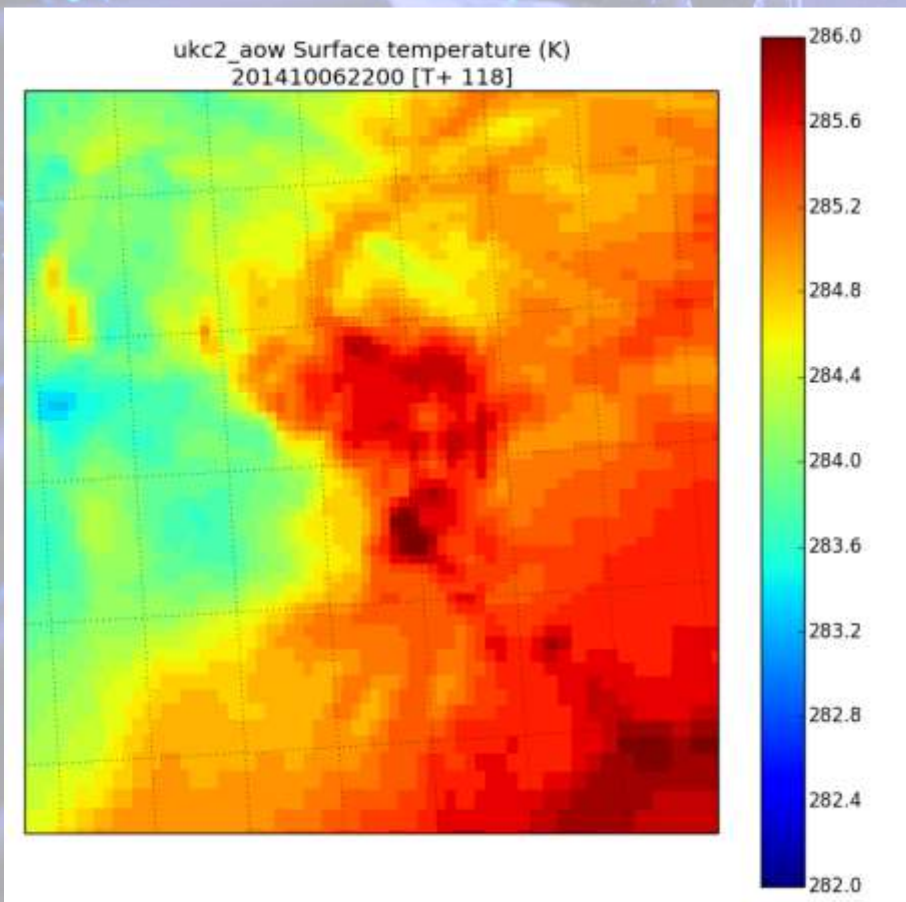

Future directions and more challenges

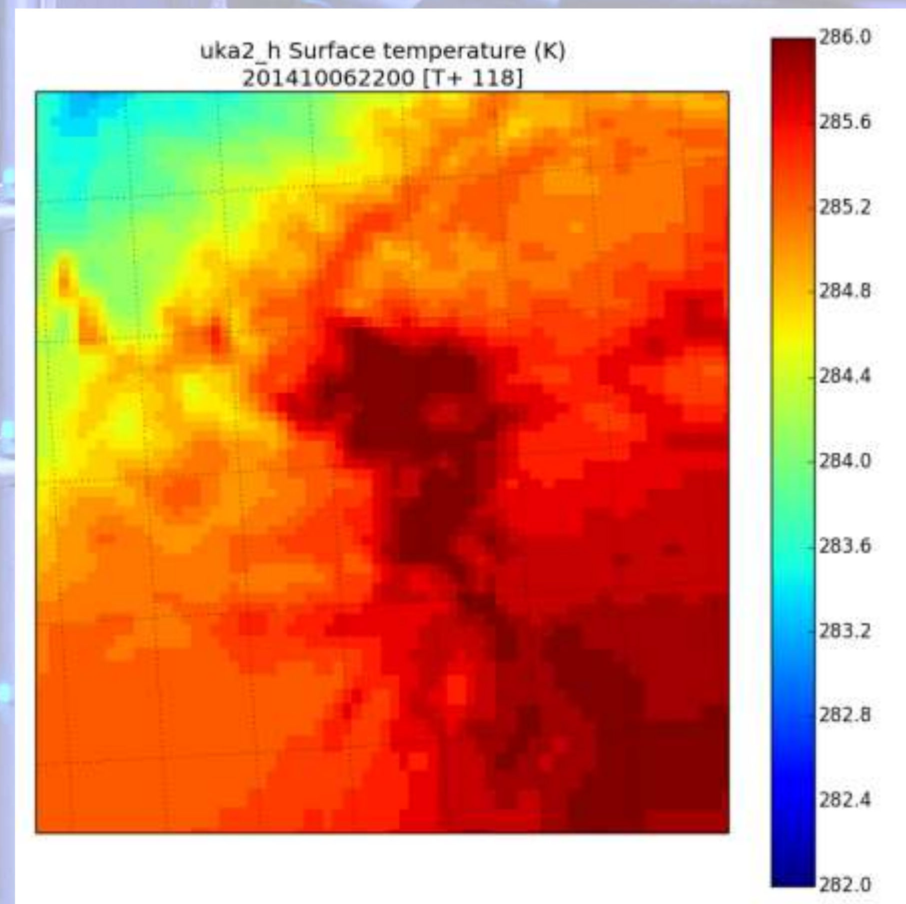
Consolidation: Phase 2



‘Phase 2’ opportunities

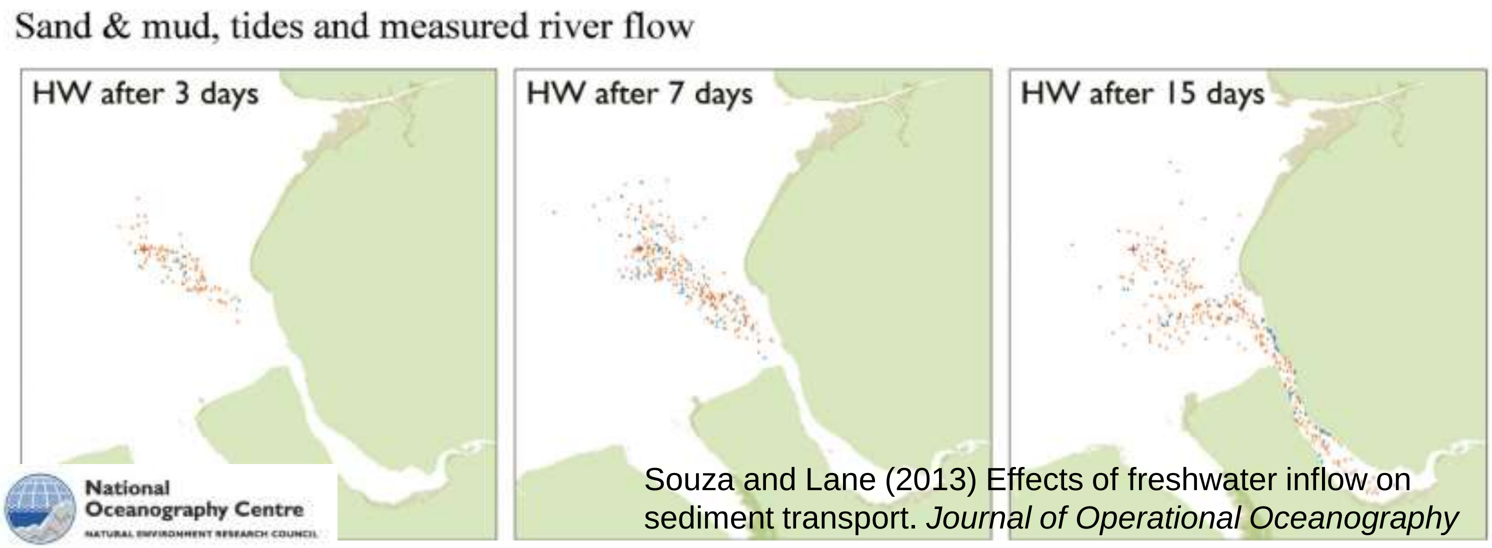
Ongoing UKCx evaluation and research





e.g. Sea breezes and the urban heat island?

‘Phase 2’ opportunities

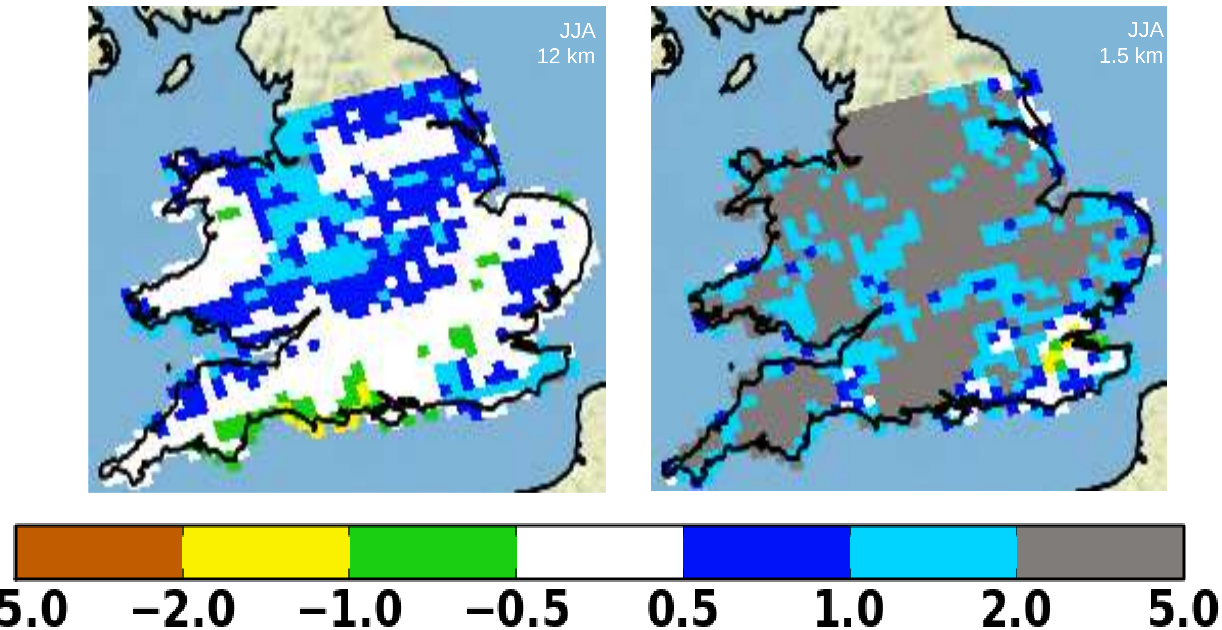


Souza and Lane (2013) Effects of freshwater inflow on sediment transport. *Journal of Operational Oceanography*

Where the land meets the sea!

Integrated climate impacts scenarios

Kendon et al. (2014) Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change*, 4, 570-576.



‘Phase 2’ opportunities

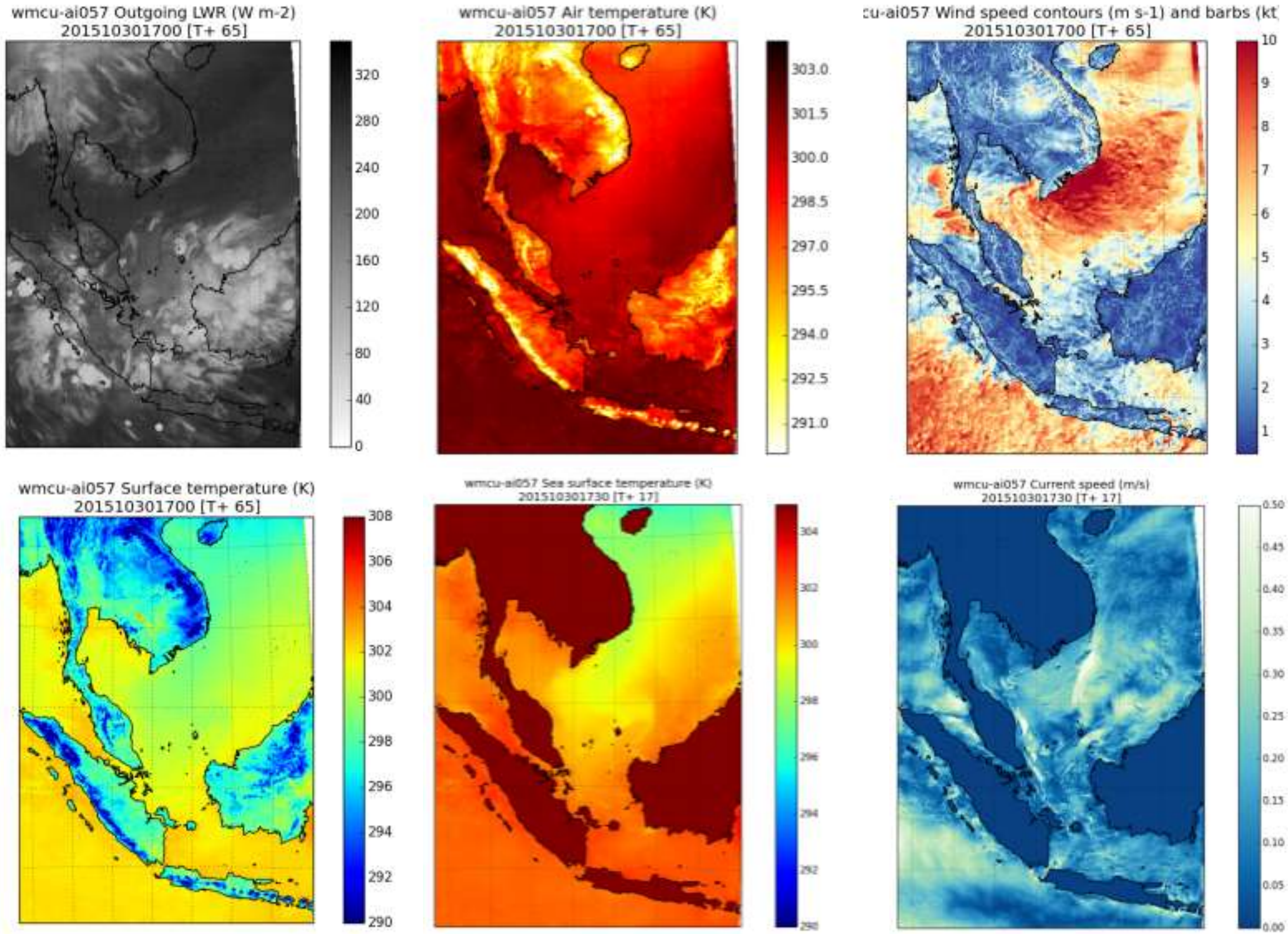
International context (e.g. Years of Maritime Continent)

Met Office

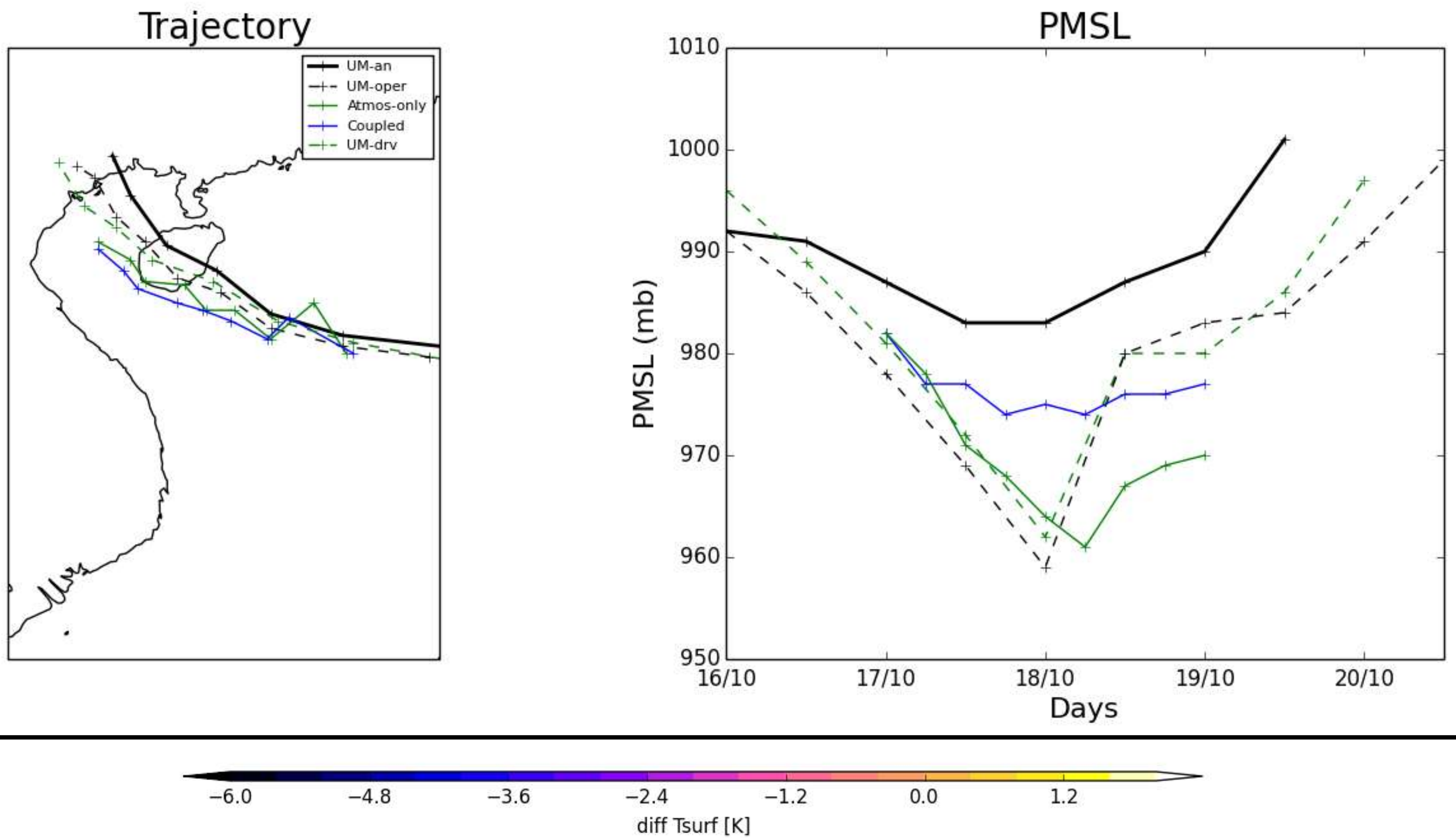
METEOROLOGICAL SERVICE SINGAPORE

First runs....

[Courtesy Claudio Sanchez, Met Office]



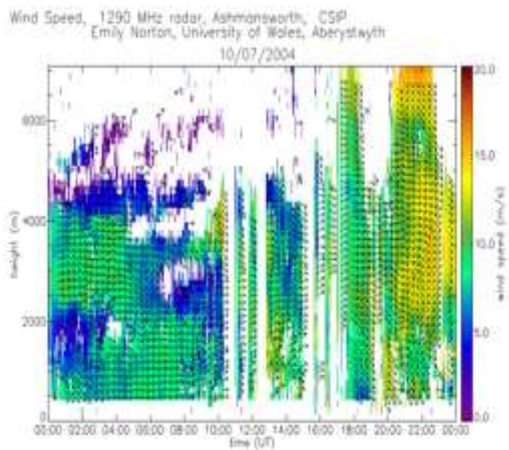
Tropical cyclone case: Typhoon Sarika
[Courtesy Claudio Sanchez, Met Office]

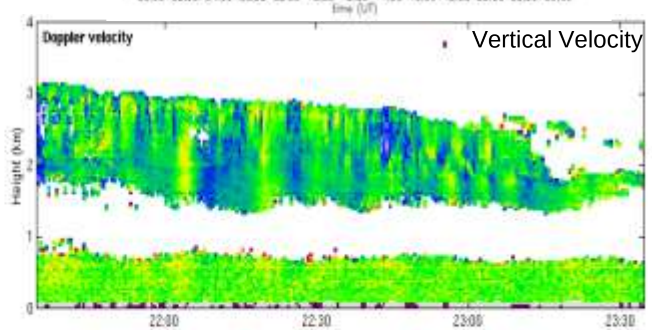


An observational challenge

How to evaluate the coupled models?

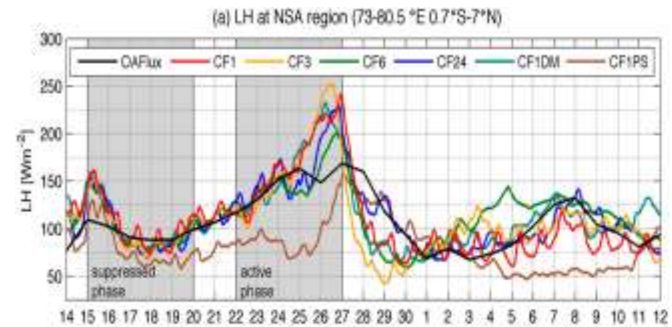
Atmospheric profiles





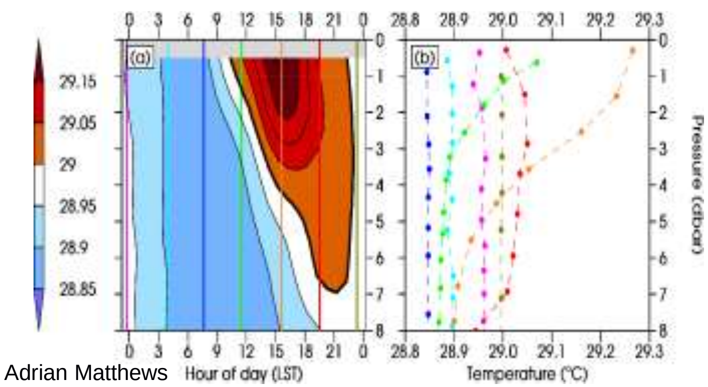
Ryan Neely

Ocean-atmosphere exchange



Seo et al. 2014

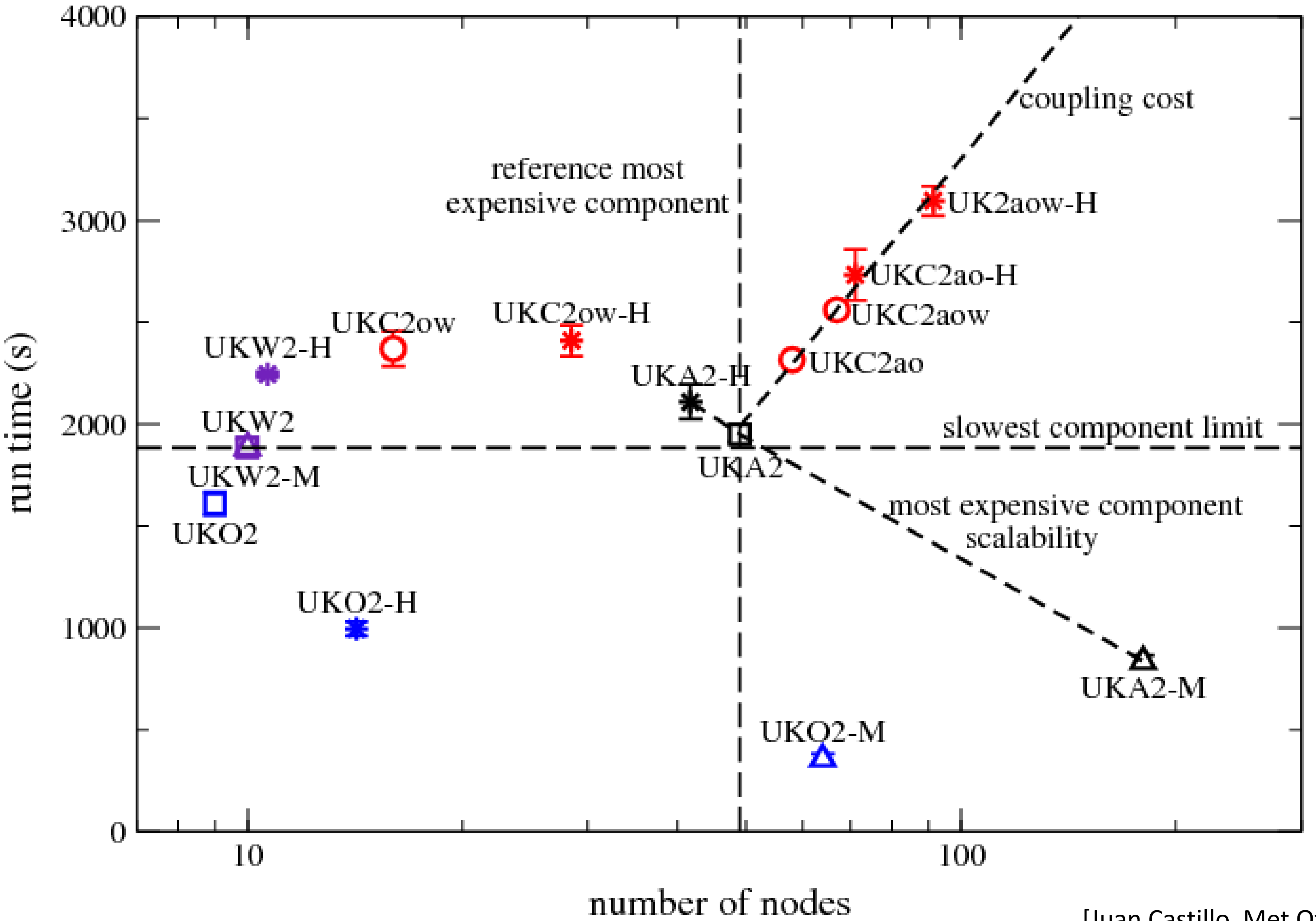
Ocean profiles



Adrian Matthews

- Complex coupled system demands detailed integrated ocean-atmosphere-land-ice observations for evaluation (and data assimilation?)
- Do we have the capability to evaluate the processes in models?

A software engineering challenge

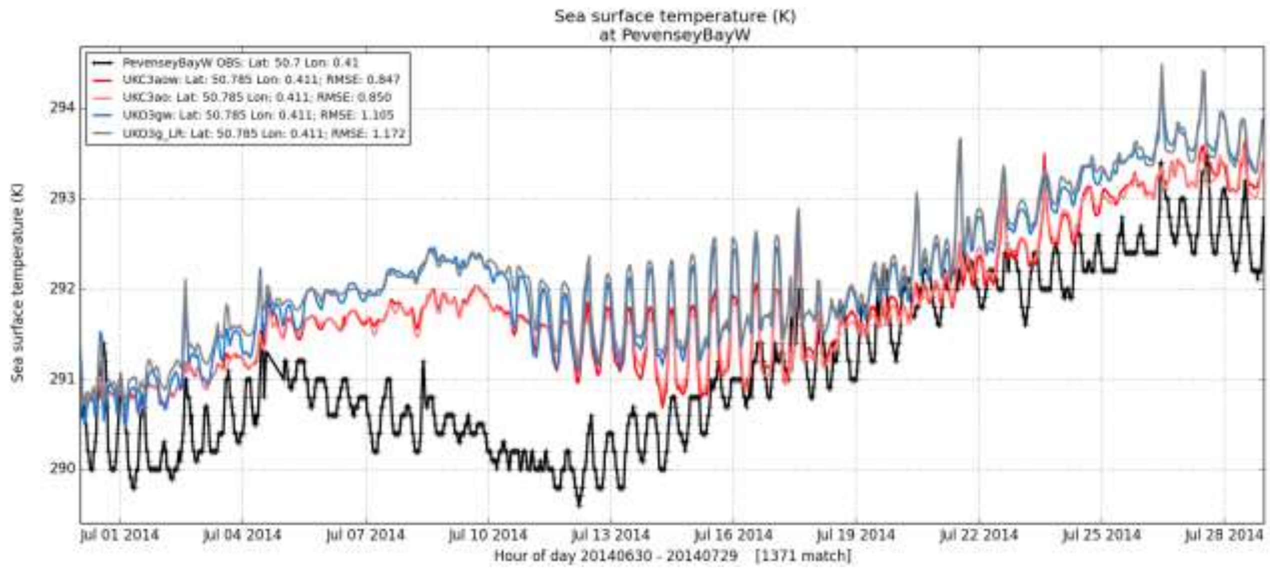


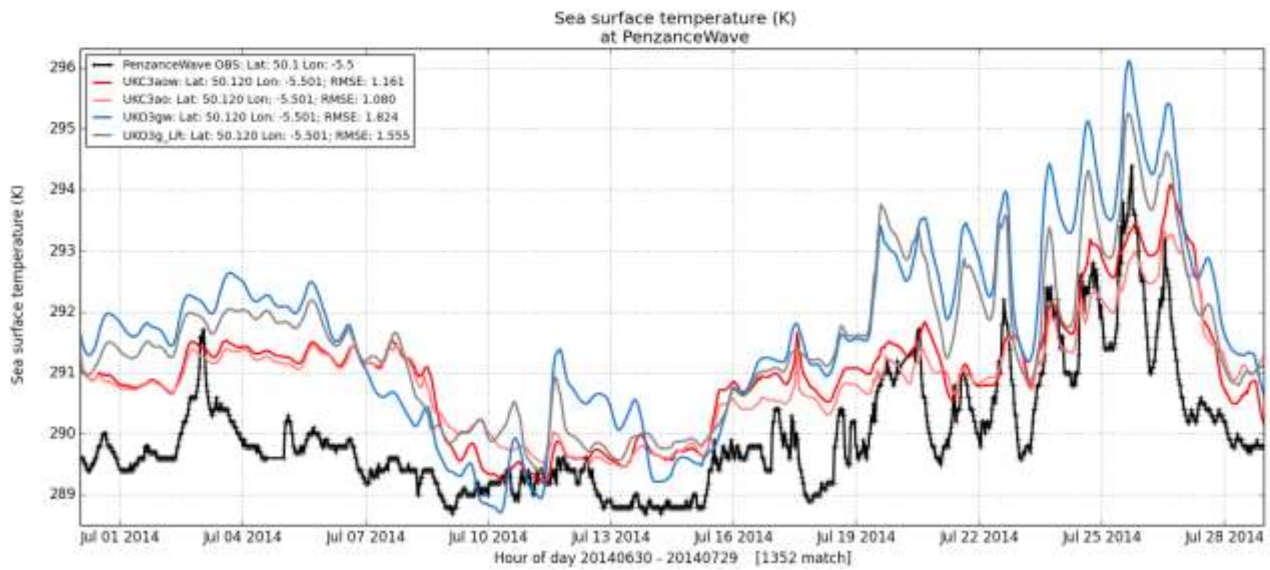
[Juan Castillo, Met Office]

A model physics challenge

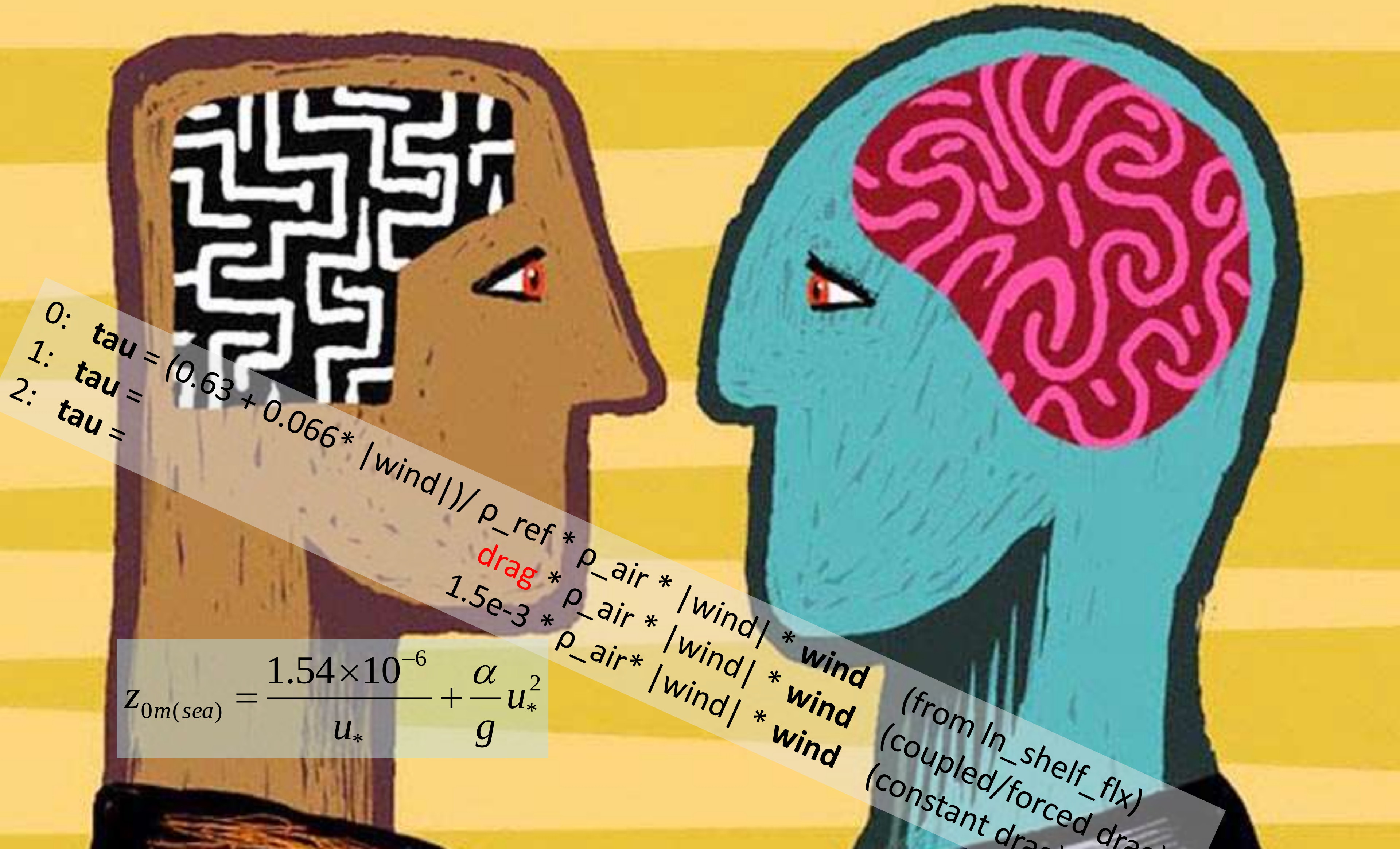
Need for continuous component model development

“Coupling alone is not a panacea for correcting all environmental model errors.”





A model physics challenge

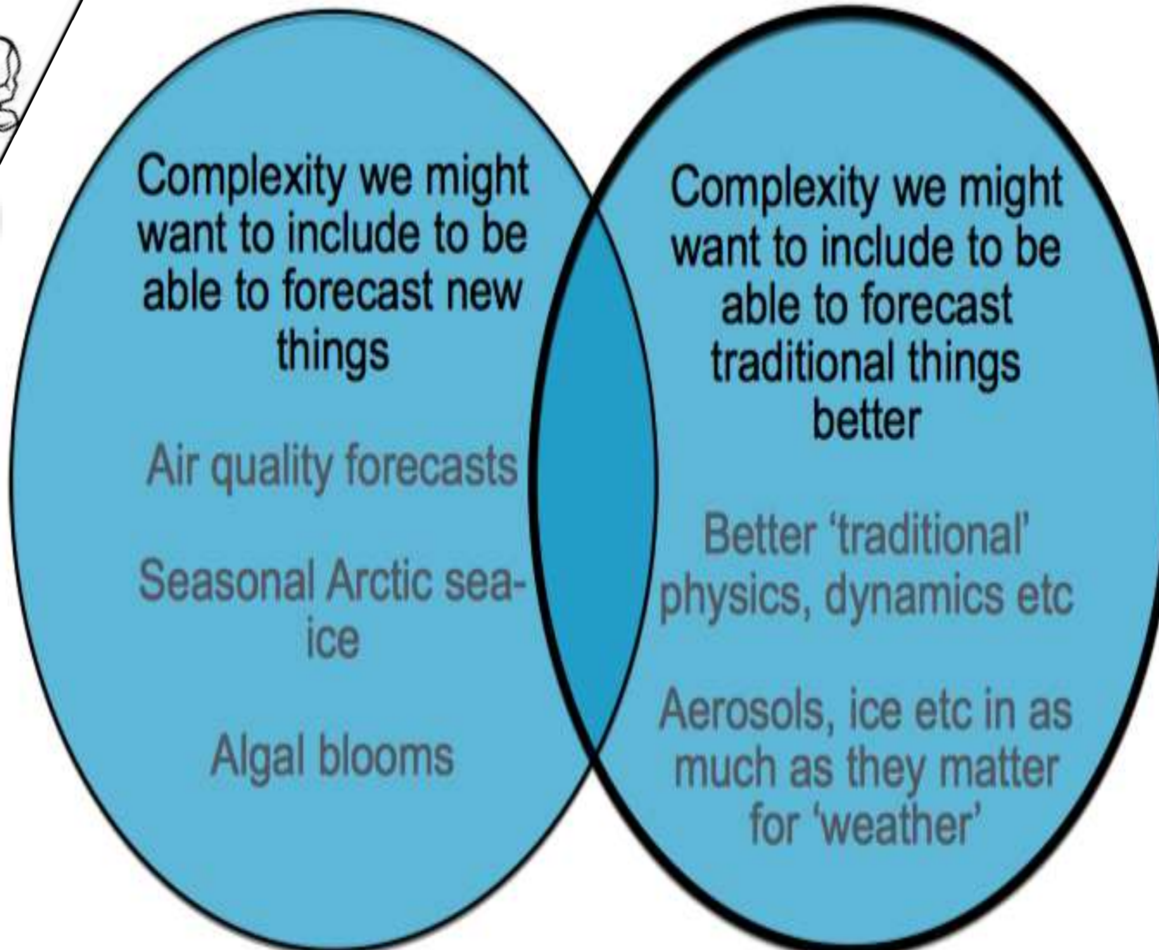


0: **tau** = (0.63 + 0.066* |wind|)/ ρ_ref * ρ_air * |wind| * **wind** (from ln_shelf_flx)
1: **tau** = drag * ρ_air * |wind| * **wind** (coupled/forced dra
2: **tau** = 1.5e-3 * ρ_air* |wind| * **wind** (constant dra

$$z_{0m(sea)} = \frac{1.54\times10^{-6}}{u_*} + \frac{\alpha}{g}u_*^2$$

A user-relevance challenge

General considerations for inclusion of new processes or more complexity



EC… …minar
Earth s… …odelling for seamles… …prediction:

Summary

NOW

- Research prototype for a fully coupled convective scale modelling system for the UK
- Case studies representing high impact weather for the UK and starting to explore longer run drifts and sensitivities
- Sensitivities shown of wave and ocean coupling on regional meteorology
- Impact of meteorological forcing on ocean and wave state
- Moving towards integrated hydrology remains a (achievable) challenge

Strong foundations…work continues

Met Office

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

PML Plymouth Marine Laboratory

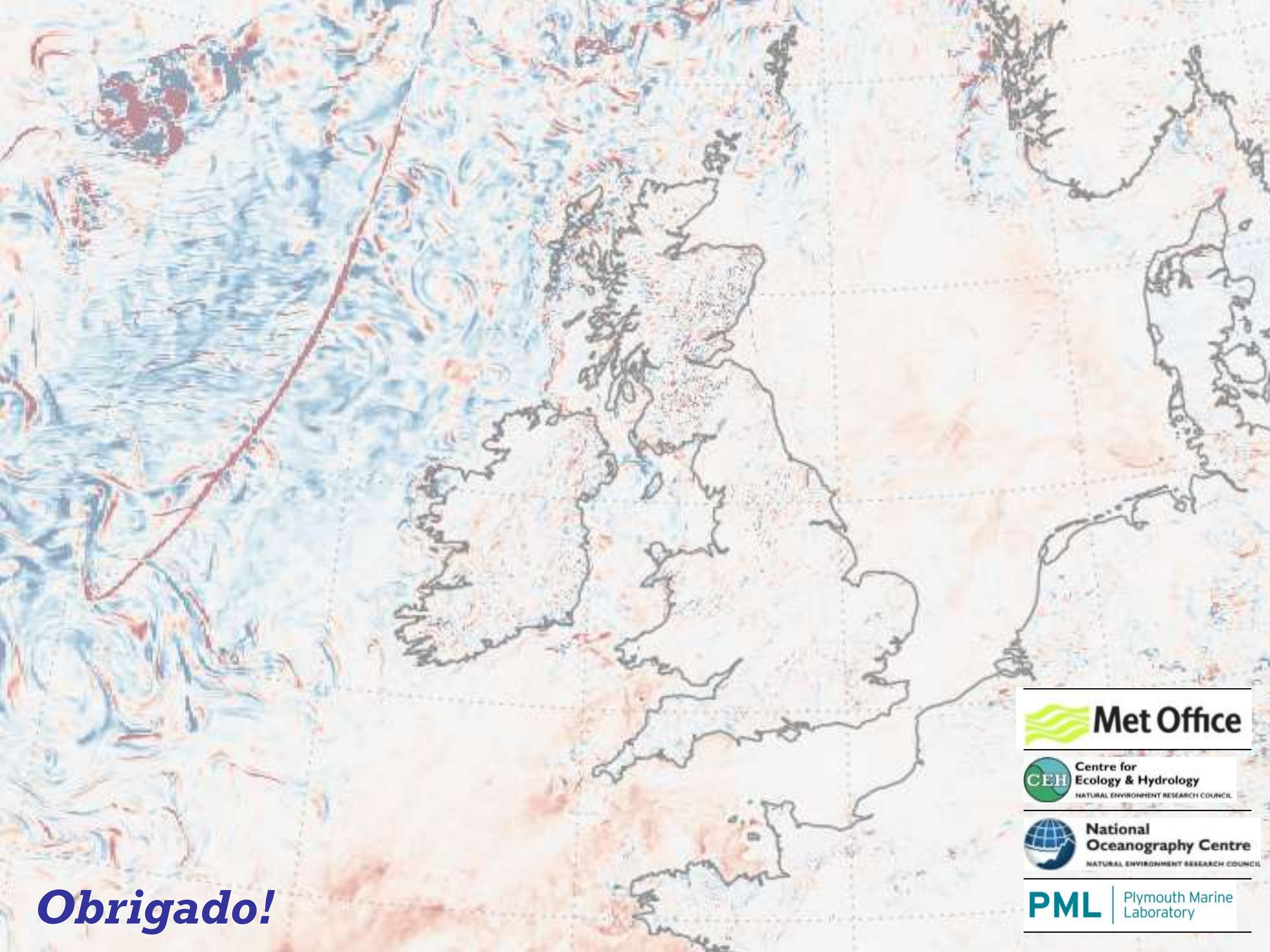
FUTURE

- Continuing to move beyond a case study approach
- Characterising air/sea interaction for UK
- Demonstrating integrated hydrology from sky to sea
- Implementing ocean biogeochemistry
- Demonstrating natural hazards context and applications

- Towards ensemble based simulations?
- Towards data assimilation?

- Towards operational implementation?

Strong foundations…work continues



Obrigado!

Met Office

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

PML Plymouth Marine Laboratory