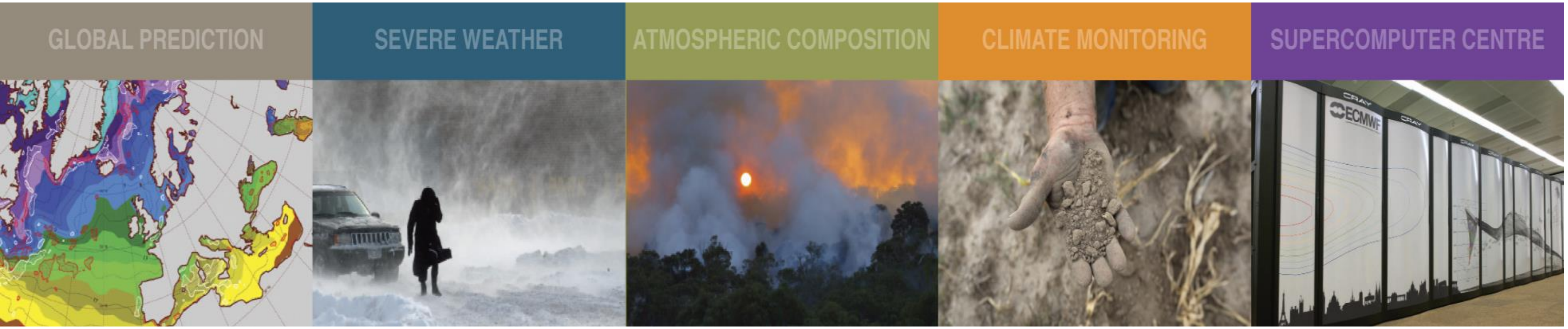
Land, ocean, sea ice, wave coupled model developments

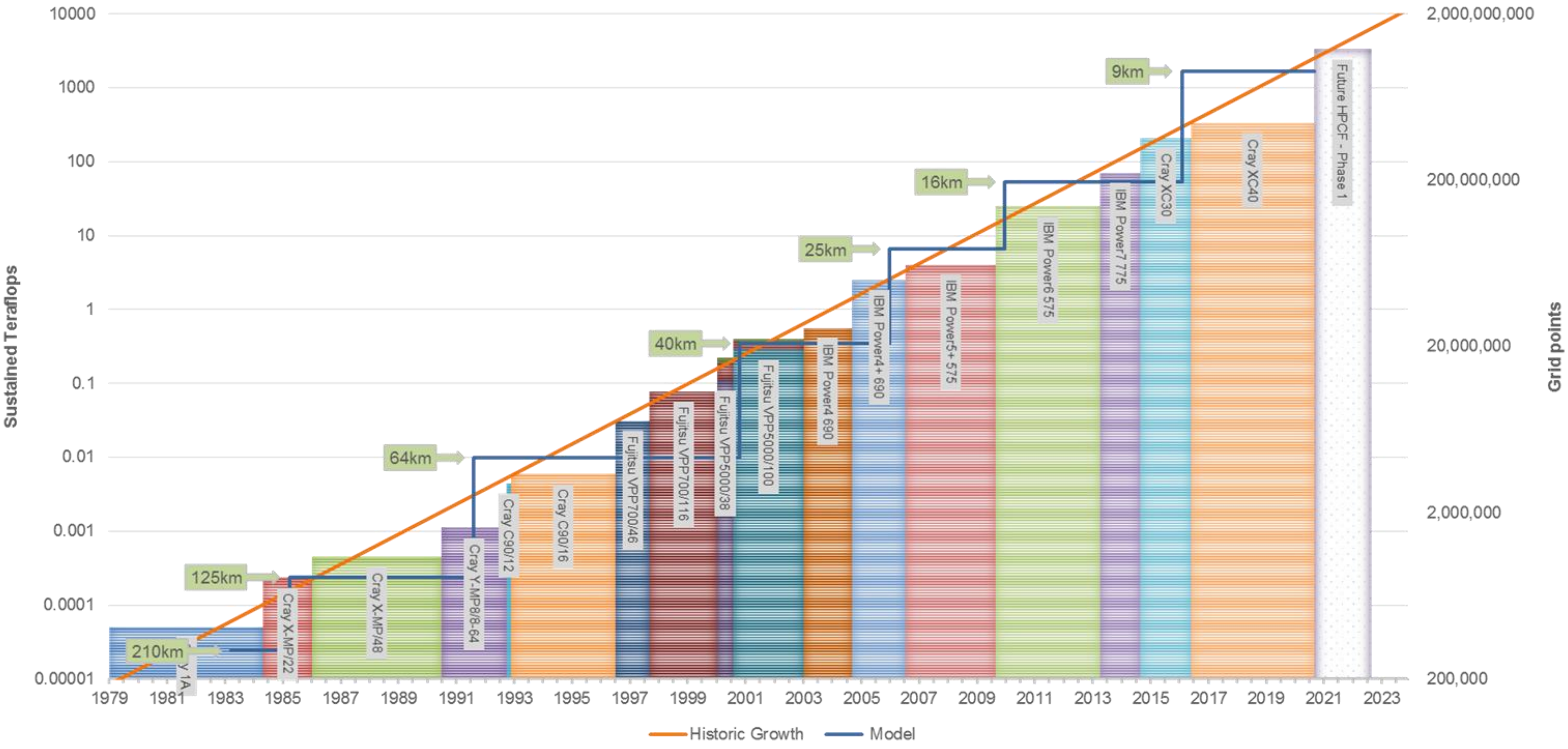
Nils P. Wedi, Gabriele Arduini, Gianpaolo Balsamo, Anton Beljaars, Jean Bidlot,
Souhail Boussetta, Margarita Choulga, Joe McNorton, Sarah Keeley, Kristian Mogensen, Dominic Salisbury,
European Centre for Medium-Range Weather Forecasts (ECMWF)



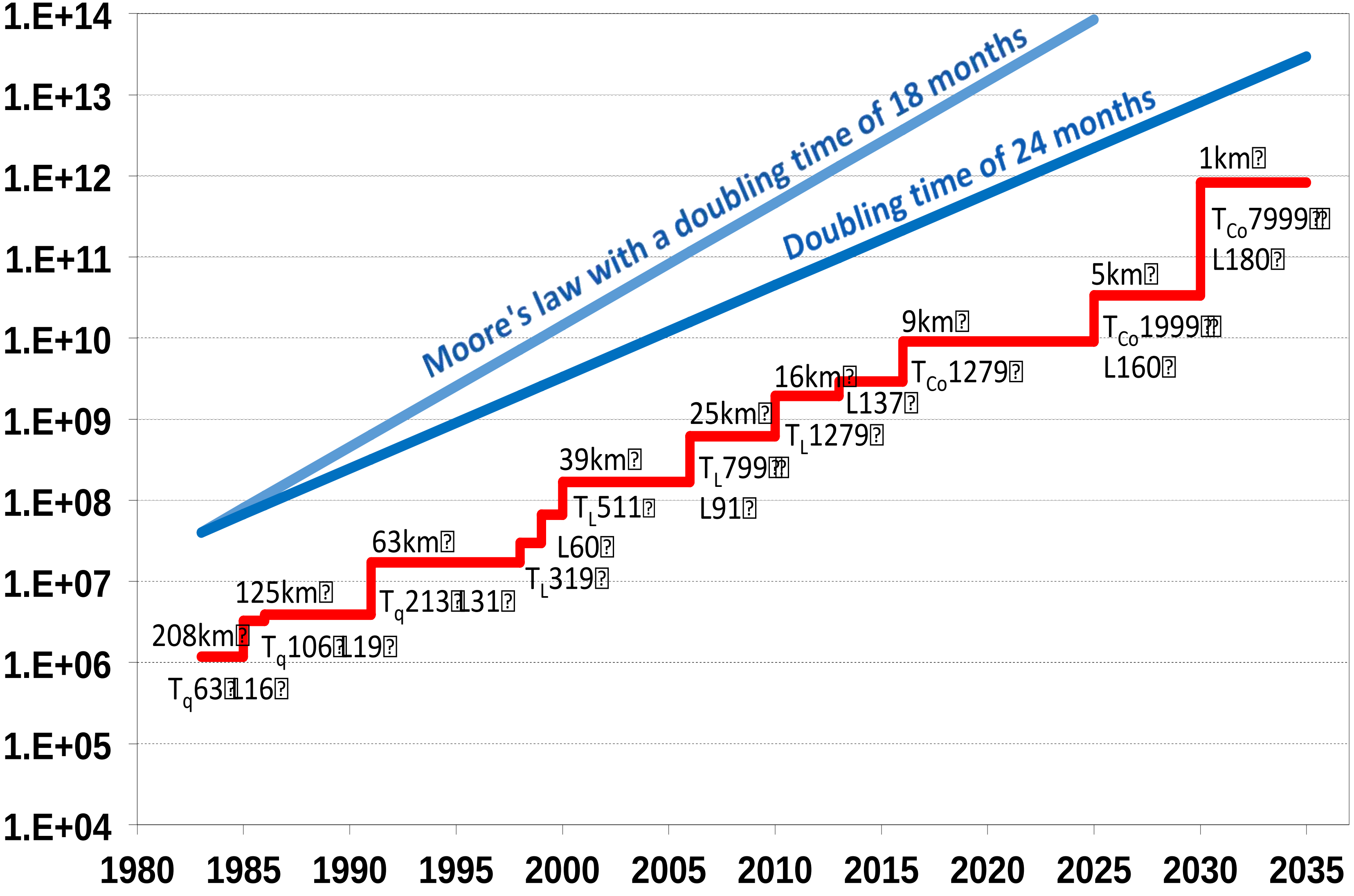
Outline

- Numerical weather prediction, a brief (HPC) history
- Evolving Earth-System complexity
  - Atmosphere
  - Land
  - Lakes
  - Ocean
  - Sea-Ice
  - Waves
- (Macro) coupling the ESM components
- Vertical coupling of (heterogenous) model surfaces and why details matter
- Recent developments and challenges

Sustained HPC performance



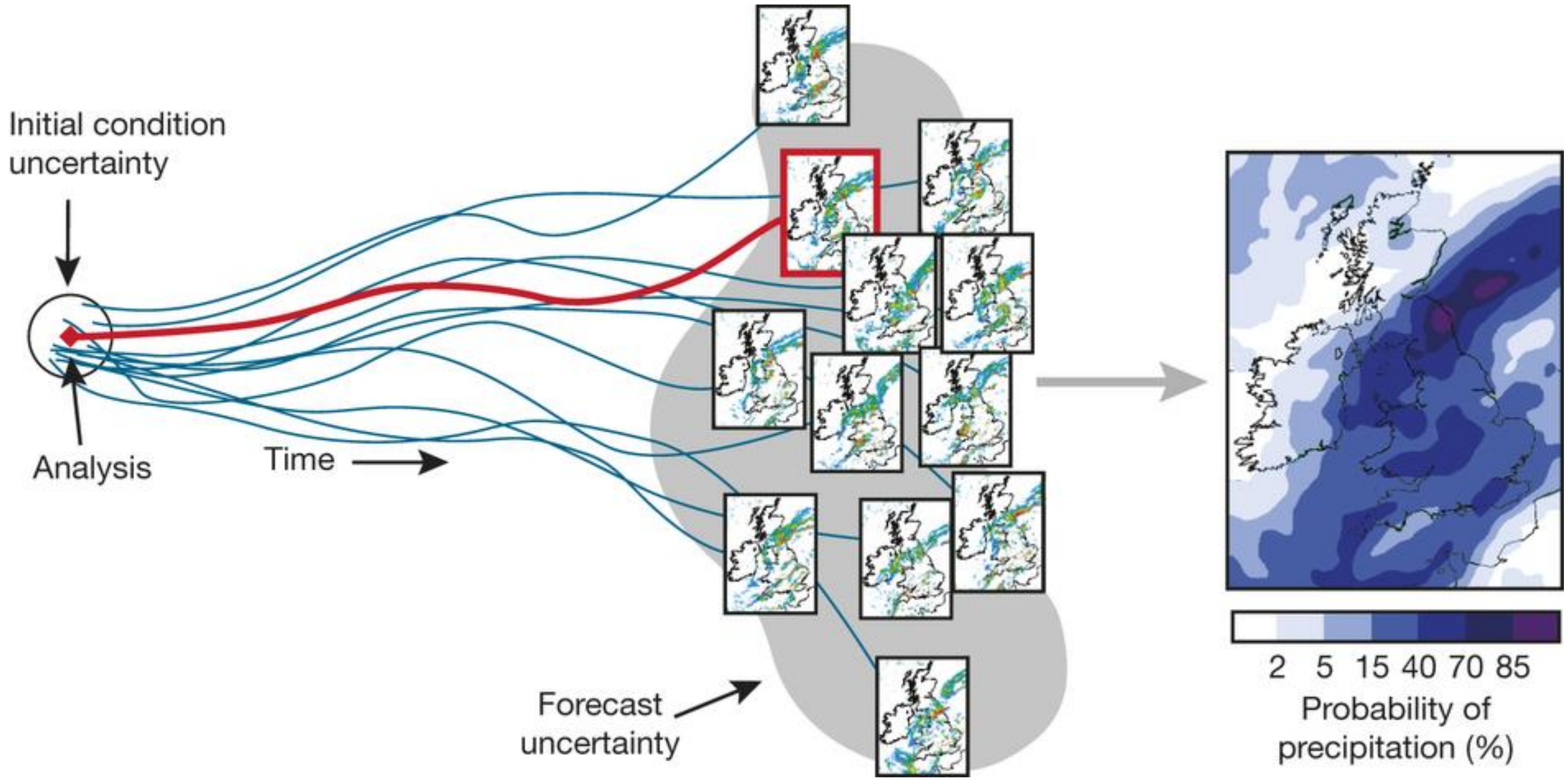
Computational power drives spatial resolution



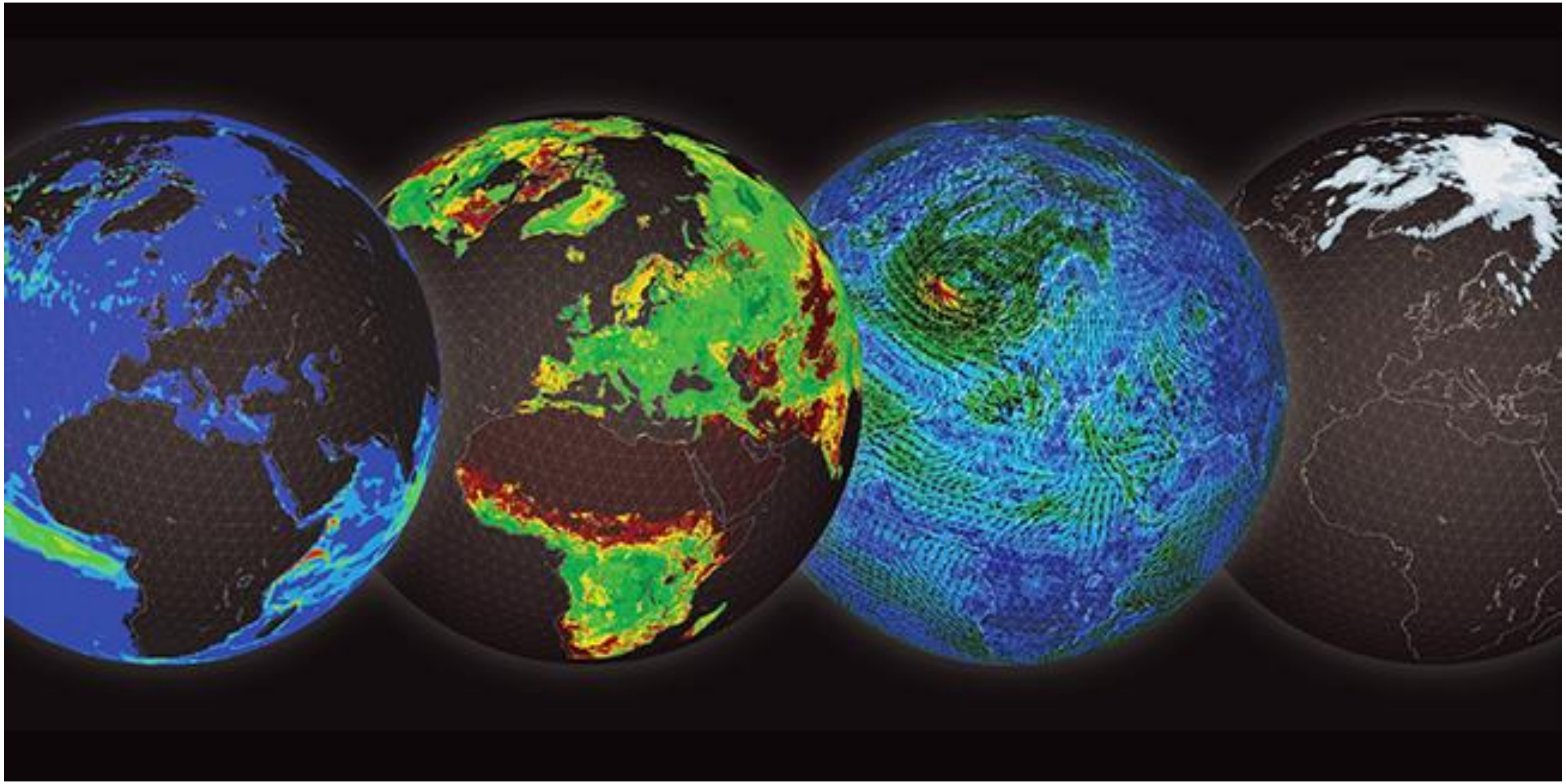
(Schulthess et al, 2018)

ECMWF's progress in degrees of freedom
(levels x grid columns x prognostic variables)

Ensemble of assimilations and forecasts



Ocean – Land – Atmosphere – Sea ice



Challenge: Monitoring atmospheric CO_2

CO_2 OBSERVATIONS

GOSAT CO_2 (IUP- Uni Bremen)

CO_2 SURFACE FLUXES

Vegetation (CTESSEL)
Fires (GFAS)
Ocean (inventory)
Anthropogenic (inventory)

TRANSPORT (ECMWF)

PBL mixing
Advection
Convection

CHEMISTRY

Oxidation of CO
(not yet represented in model)

Graphic: A Agusti-Panareda, S Massart (ECMWF)

Earth surface modelling components @ECMWF in 2018

- **NEMO3.4**

  NEMO3.4 (Nucleus for European Modelling of the Ocean)

  Madec et al. (2008)

  Mogensen et al. (2012)

  ORCA1_Z42: 1.0° x 1.0°

  ORCA025_Z75 : 0.25° x 0.25°

- **EC-WAM**

  ECMWF Wave Model

  Janssen, (2004)

  Janssen et al. (2013)

  ENS-WAM : 0.25° x 0.25°

  HRES-WAM: 0.125° x 0.125°

- **LIM2**

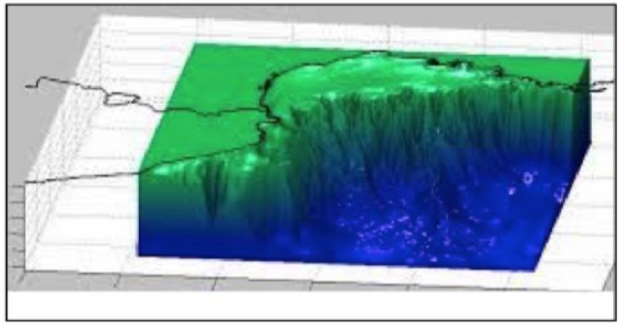
  The Louvain-la-Neuve Sea Ice Model

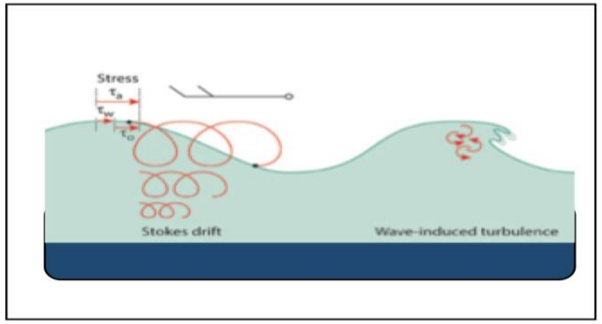
  Fichefet and Morales Maqueda (1997)

  Bouillon et al. (2009)

  Vancoppenolle et al. (2009)

  ORCA025_Z75 : 0.25° x 0.25°





- **Hydrology-TESSEL**

  Balsamo et al. (2009)
  van den Hurk and Viterbo (2003)

  Global Soil Texture (FAO)

  New hydraulic properties

  Variable Infiltration capacity & surface runoff revision

- **NEW SNOW**

  Dutra et al. (2010)

  Revised snow density

  Liquid water reservoir

  Revision of Albedo and sub-grid snow cover

- **NEW LAI**

  Boussetta et al. (2013)

  New satellite-based

  Leaf-Area-Index

- **SOIL Evaporation**

  Balsamo et al. (2011),

  Albergel et al. (2012)

- **H_2O / E / CO_2**

  Integration of

  Carbon/Energy/Water

  Boussetta et al. 2013

  Agusti-Panareda et al. 2015

- **Lake & Coastal area**

  Mironov et al (2010),

  Dutra et al. (2010),

  Balsamo et al. (2012, 2010)

  Extra tile (9) to for sub-grid lakes and ice

  LW tiling (Dutra)

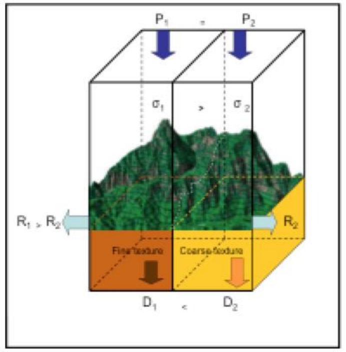
- **Enhance ML**

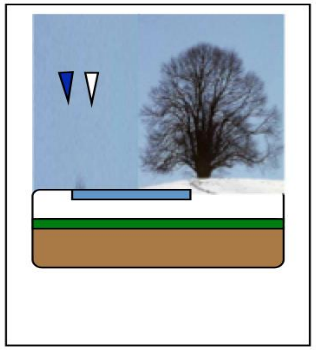
  Snow ML5

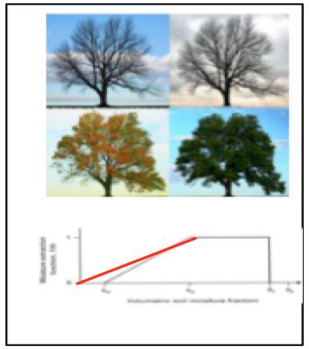
  Soil ML9

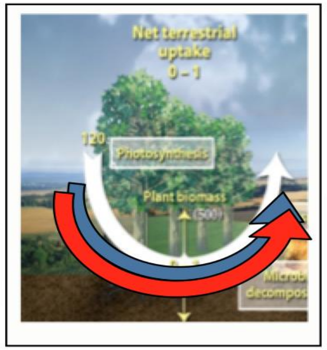
  Dutra et al. (2012, 2016)

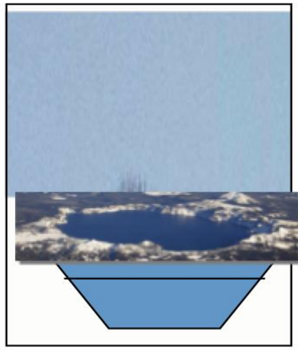
  Balsamo et al. (2016)

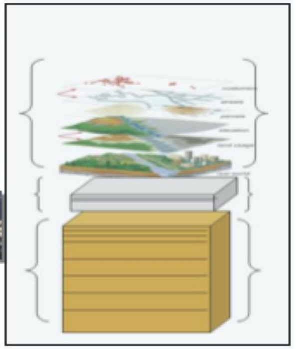












Atmos Land Resol.	**ECMWF in 2018**
80 km	ERAI
32 km	ERA5+ SEAS5+*
18 km	ENS+*
9 km	HRES+*

*Ocean
used across forecast systems and in Ocean reanalysis

(*migration completed with HRES-coupled operational from the 5th June 2018)

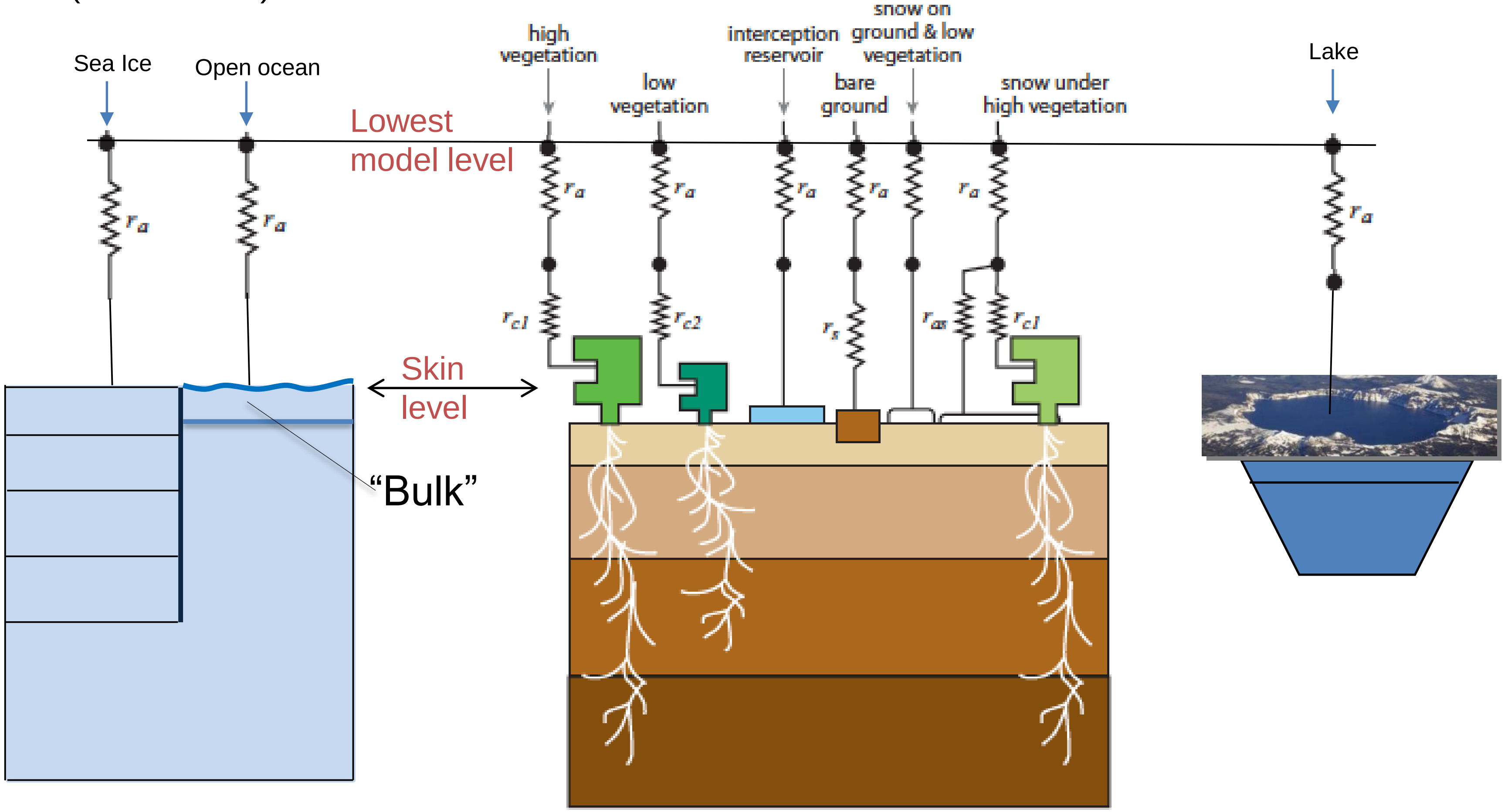
+Land
used across forecast systems and new Climate reanalysis

The tile scheme allows for a simple representation of **surface heterogeneity** over land and for fractional sea ice over the ocean

NEMO (**N**ucleus for **E**uropean **M**odelling of the **O**cean) + **WAM** (**Wa**ve **M**odel)

HTESSEL (Hydrology -Tiled ECMWF Scheme for Surface Exchanges over Land)

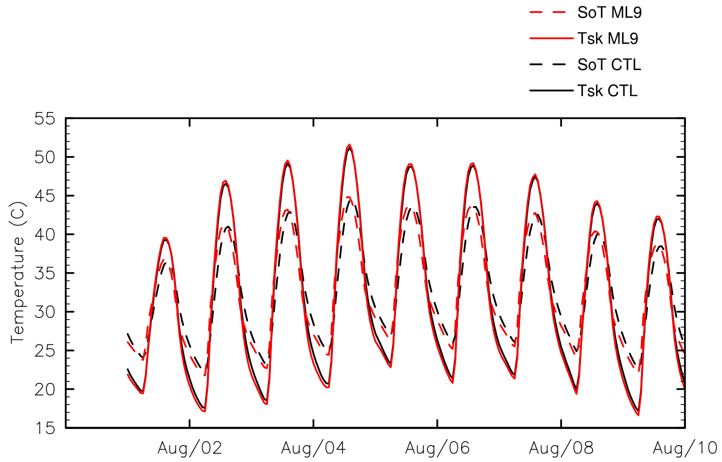
FLAKE (Fresh water Lake scheme)

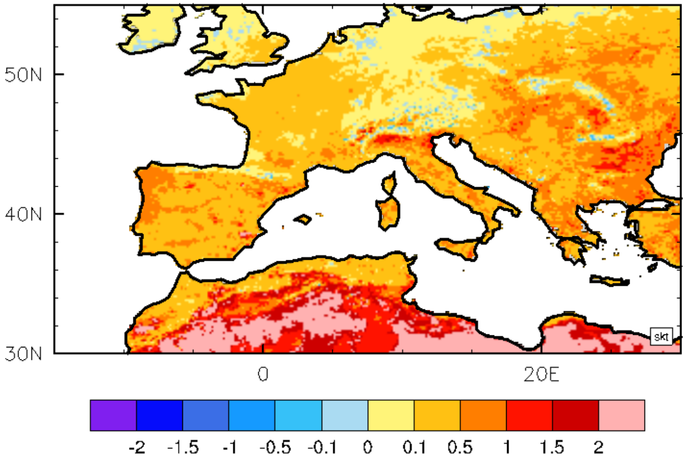


Impact of the soil model vertical resolution: heatwaves severity

During summer 2017 the effect of multi-layer is examined for European heatwave, here shown for Corboba (Spain) where temperatures went above 40º Celsius on the 6th of August 2017

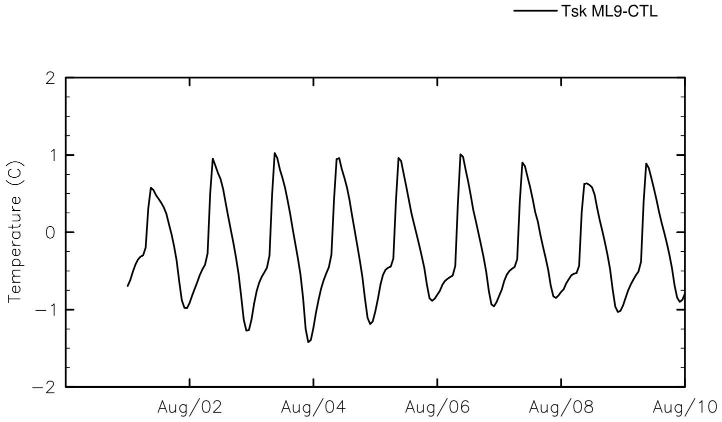
ECMWF Land model ML9 & ML4 (offline)





Differences in the maximum skin temperature ML9-ML4

Difference ML9-ML4 soil model (offline)



An enhanced soil vertical discretisation is increasing the amplitude of the diurnal cycle. Extremes heatwave are up to 1 K hotter

Vertical surface fluxes

Roughness lengths

$$z_{0m} = \delta * \nu / u_* + \alpha u_*^2 / g$$
$$z_{0h} = \delta * \nu / u_*$$

friction velocity² (correlated with momentum flux)

$$u_*^2 = \left[\frac{\kappa^2}{\ln^2(z_1/z_{0m})} \right] * F_m(z_{0m}, z_{0h}, Ri_b) * |v_1|^2$$

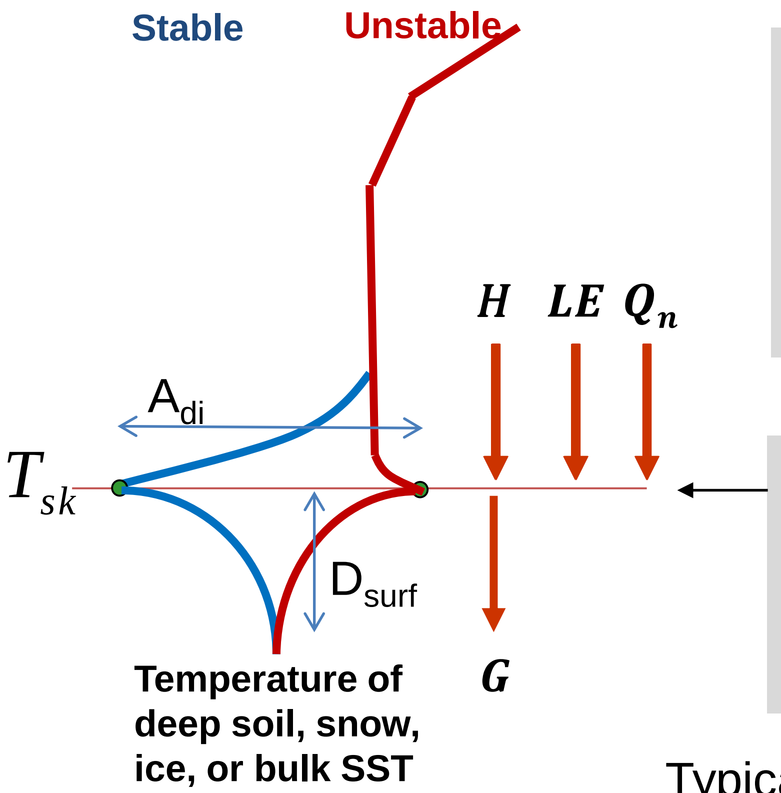
Lowest model level or 10m wind speed

latent heat flux

$$\overline{w'q'}_0 = \left[\frac{\kappa^2}{\ln(z_1/z_{0m}) \ln(z_1/z_{0q})} \right] * F_q(z_{0m}, z_{0q}, Ri_b) * |v_1| * (q_S - q_1)$$

sensible heat flux

$$\overline{w'\theta'}_0 = \left[\frac{\kappa^2}{\ln(z_1/z_{0m}) \ln(z_1/z_{0h})} \right] * F_h(z_{0m}, z_{0h}, Ri_b) * |v_1| * (\theta_S - \theta_1)$$



Surface energy balance:

$Q_n + H + LE = G$

Q_n : Net radiation (solar + thermal)

H : Sensible heat flux

LE : Latent heat flux

G : Heat flux into the surface

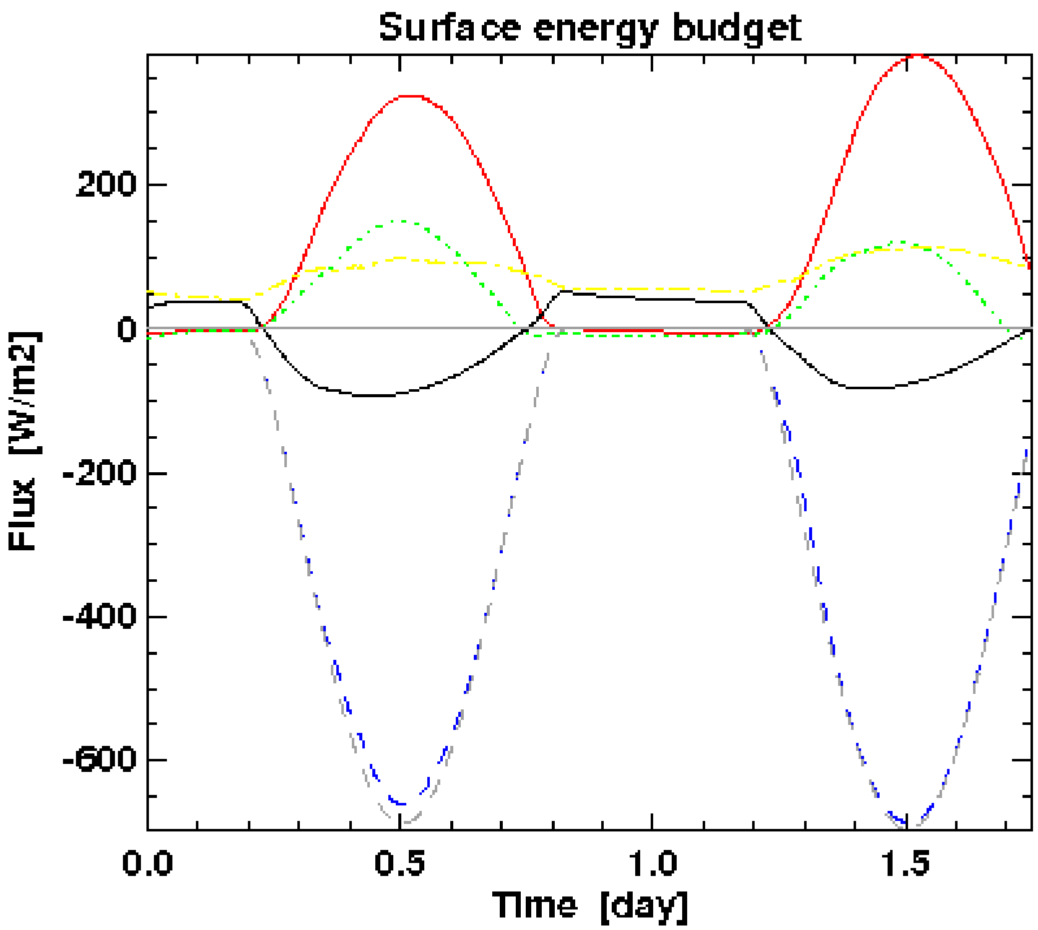
T_{sk}: Radiation intercepting/emitting level, e.g. SST, ice surface , vegetation canopy, litter layer on top of bare soil, top of snow layer, or combination of these in a heterogeneous configuration

Typical numbers

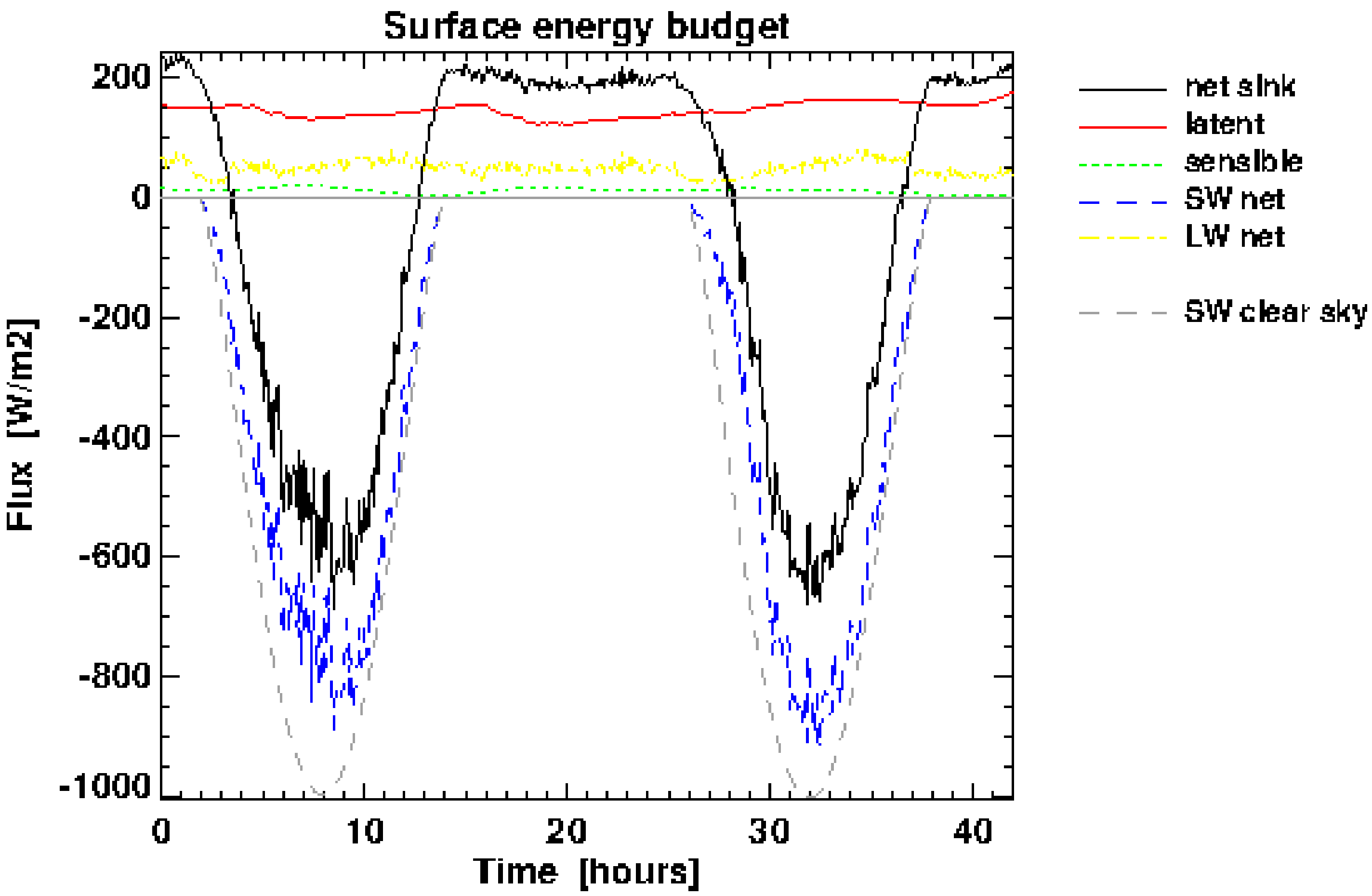
	A_{di} (K) Diurnal cycle amplitude of Tsk	D_{surf} (cm) Surface penetration depth of diurnal cycle
Land	10 -30	10
Snow	0 - 10	5
Ice	0 -10	10
Open ocean	0 - 2	100

uncoupled (SCM) diurnal fluxes

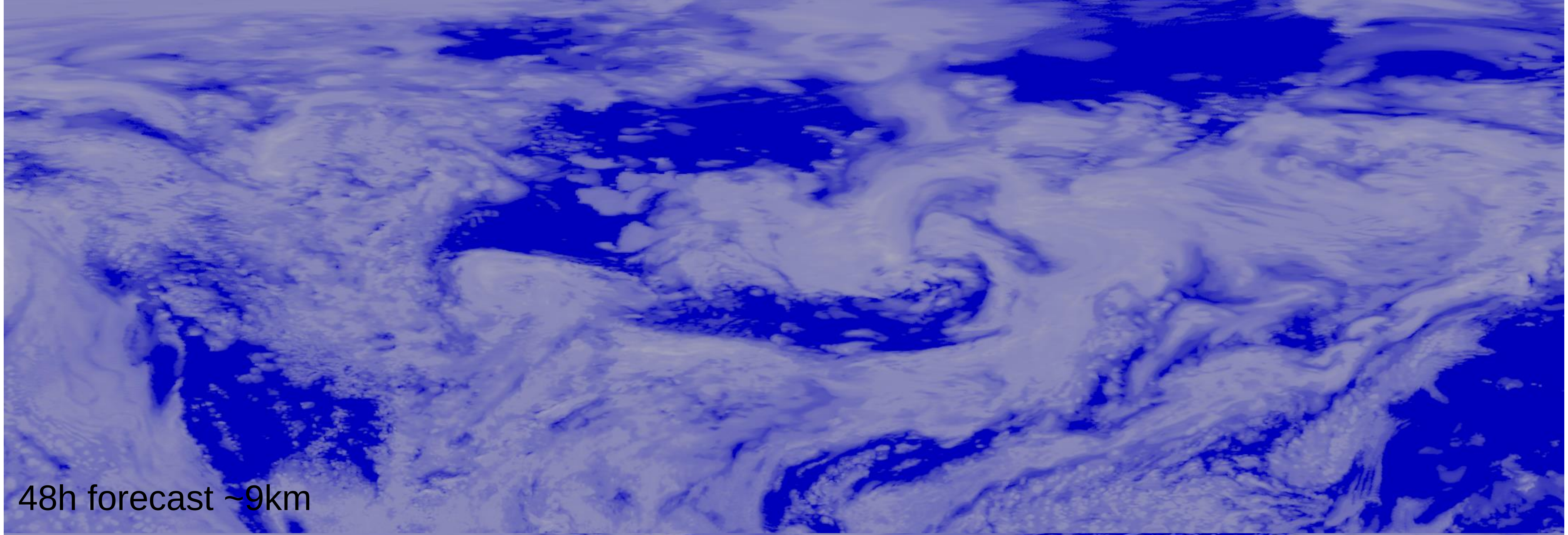
Benson, UK

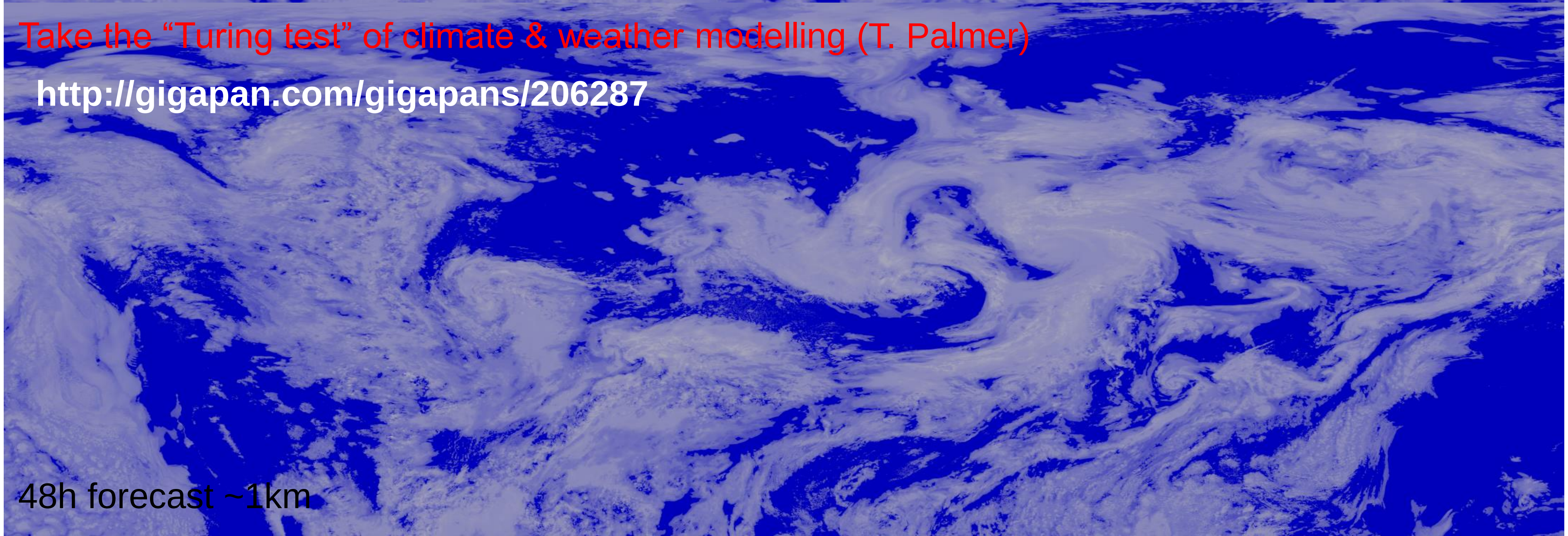


Tropical Pacific

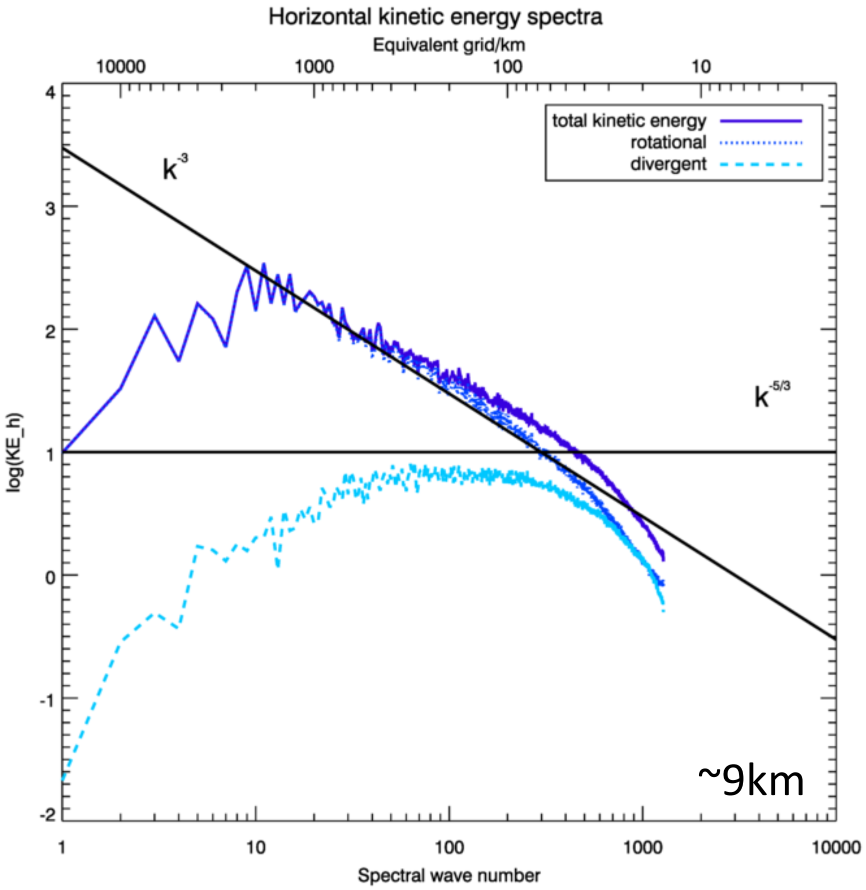


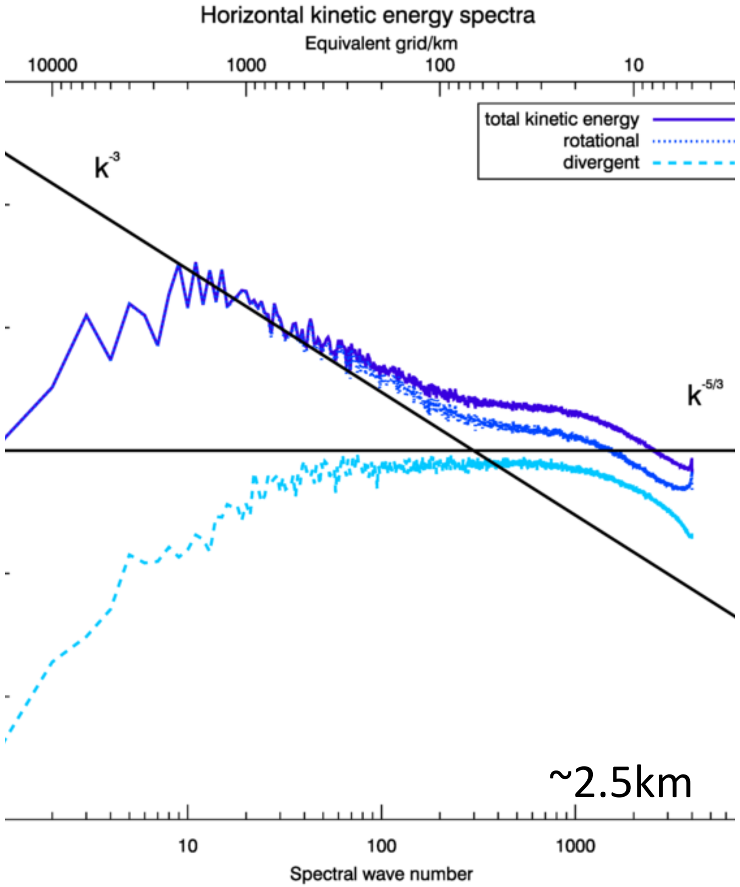
(Importance of Bowen ratio for convective organisation, Sakradzija & Hohenegger, 2017)

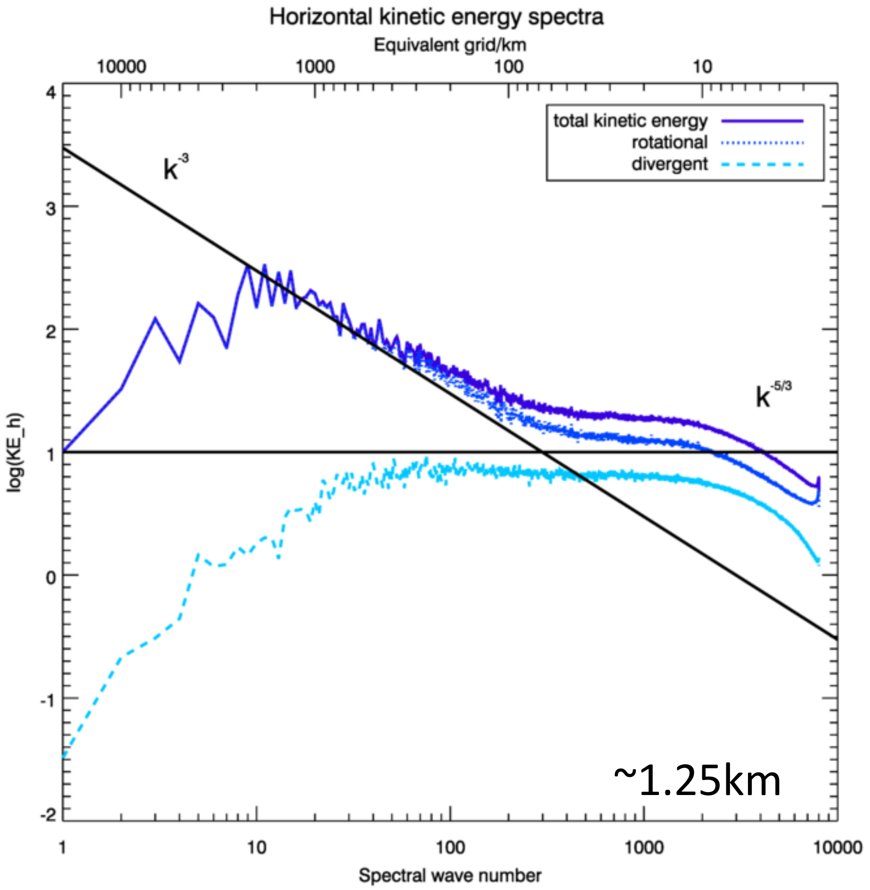

48h forecast ~9km


Take the "Turing test" of climate & weather modelling (T. Palmer)
http://gigapan.com/gigapans/206287
48h forecast ~1km

Global KE - Spectra ~500hPa

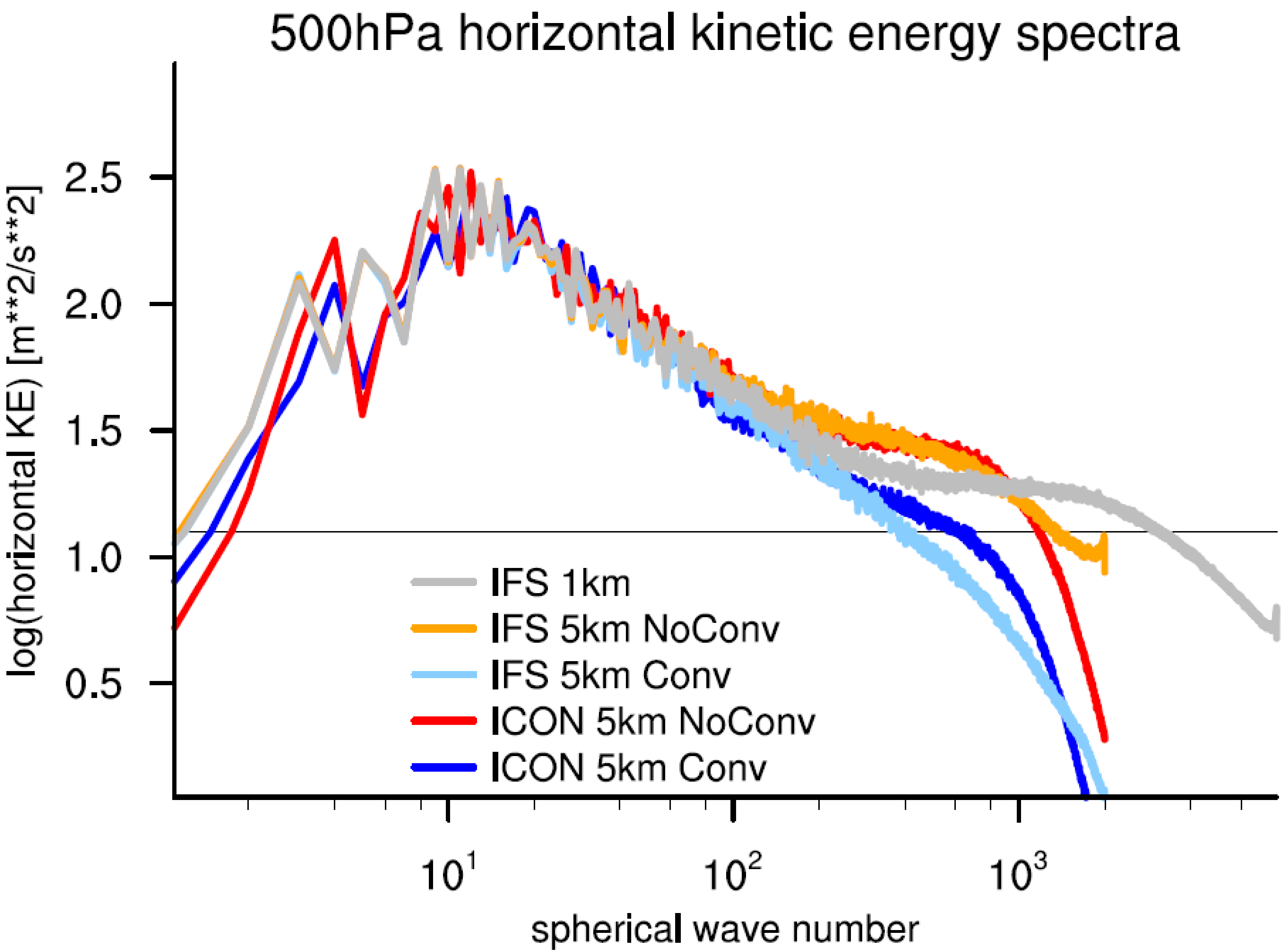






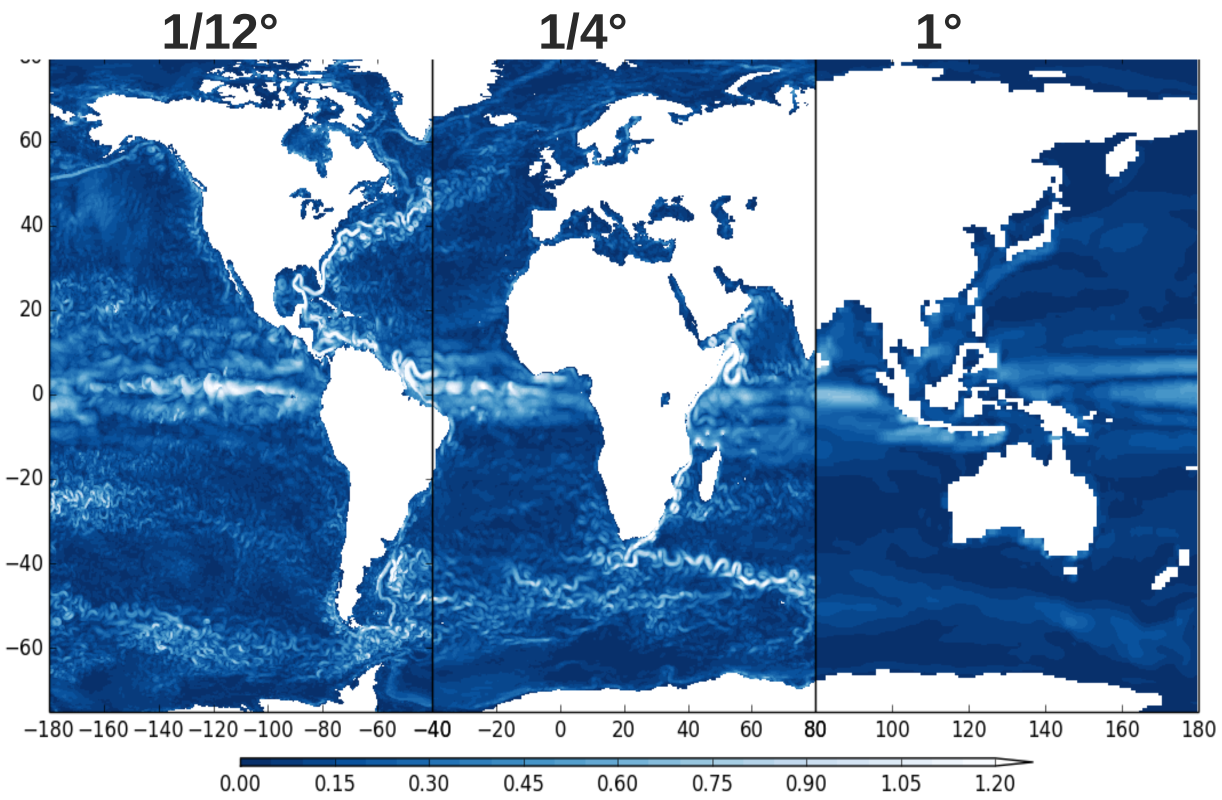
Resolve rather than parametrize much of the crucial vertical transport of momentum and heat

ECMWF

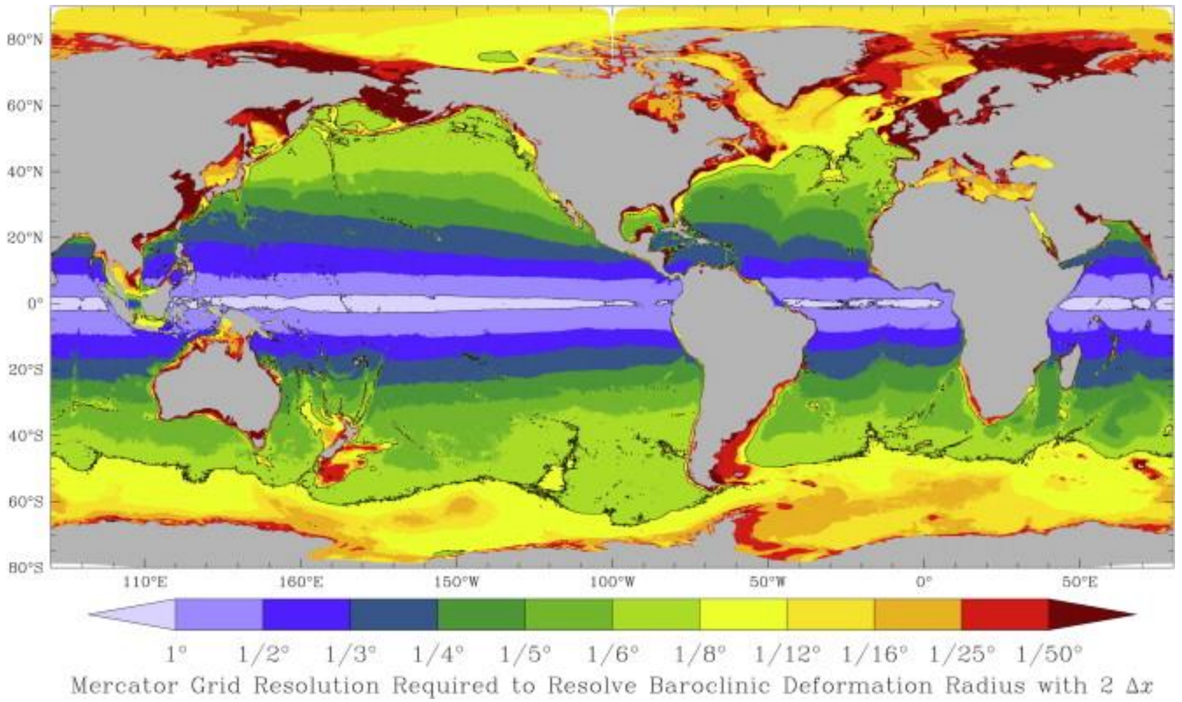


(Daniel Klocke, DWD)

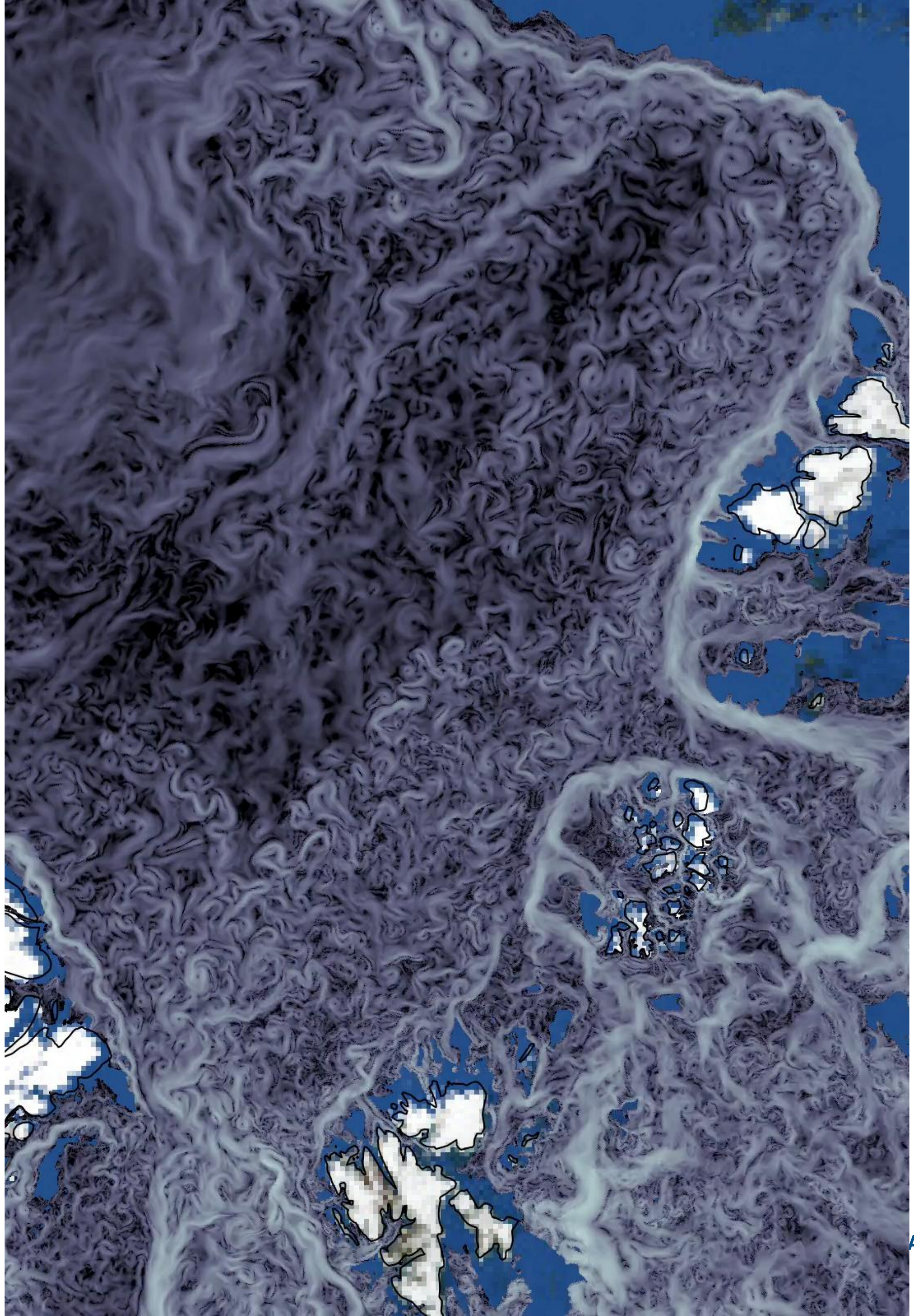
Ocean model - resolution



Hewitt et al. (2017)



Hallberg (2013)



Arctiv Ocean circulation at ~1km

AWI FESOM2 team
Animation: Nikolay Koldunov (AWI)

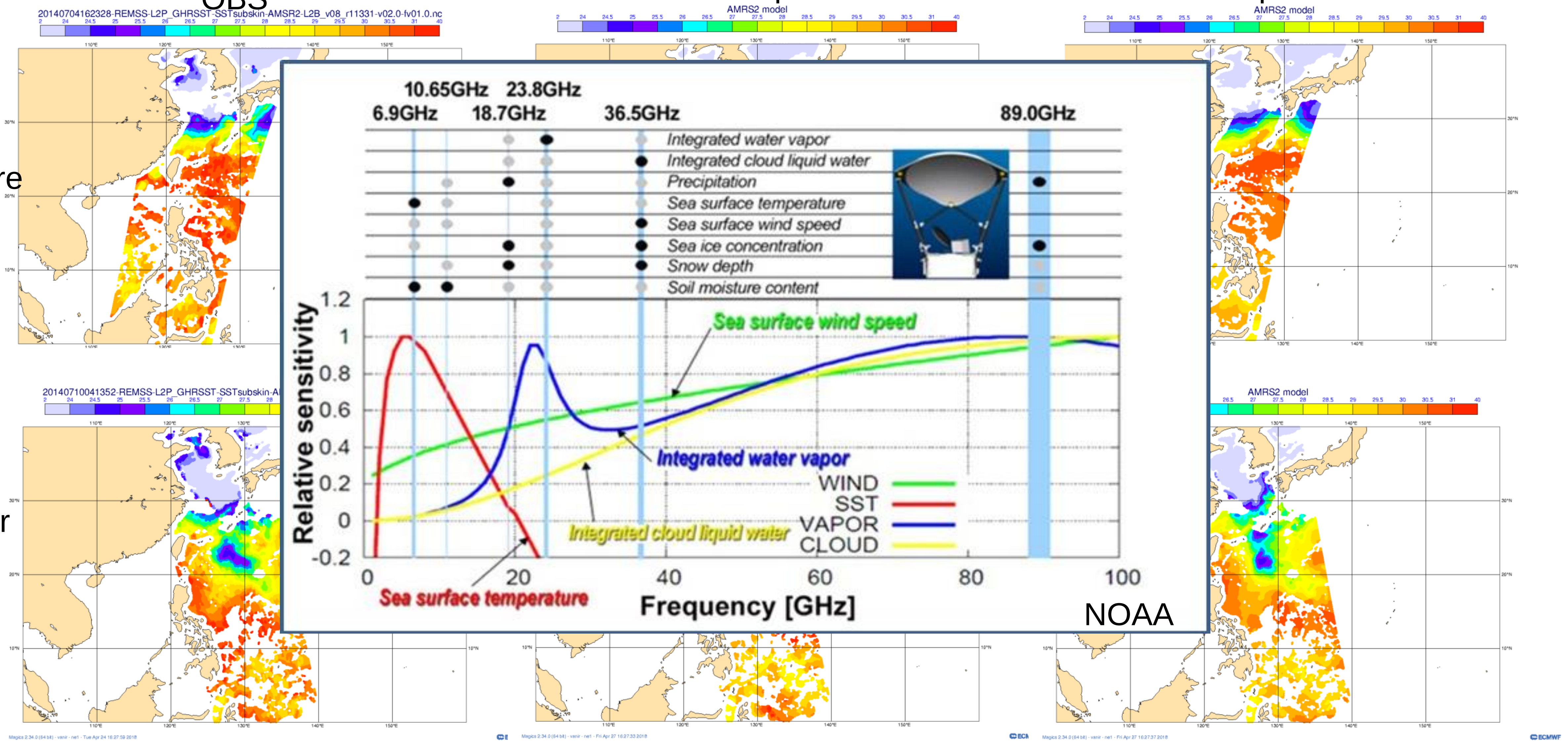
4 months/day, time step 2 min,
1700 Broadwell cores on Cray CS400

TC Neoguri 2014: AMSR2 MW SST and model SKT from before and after

OBS | Uncoupled | Coupled

Before

After



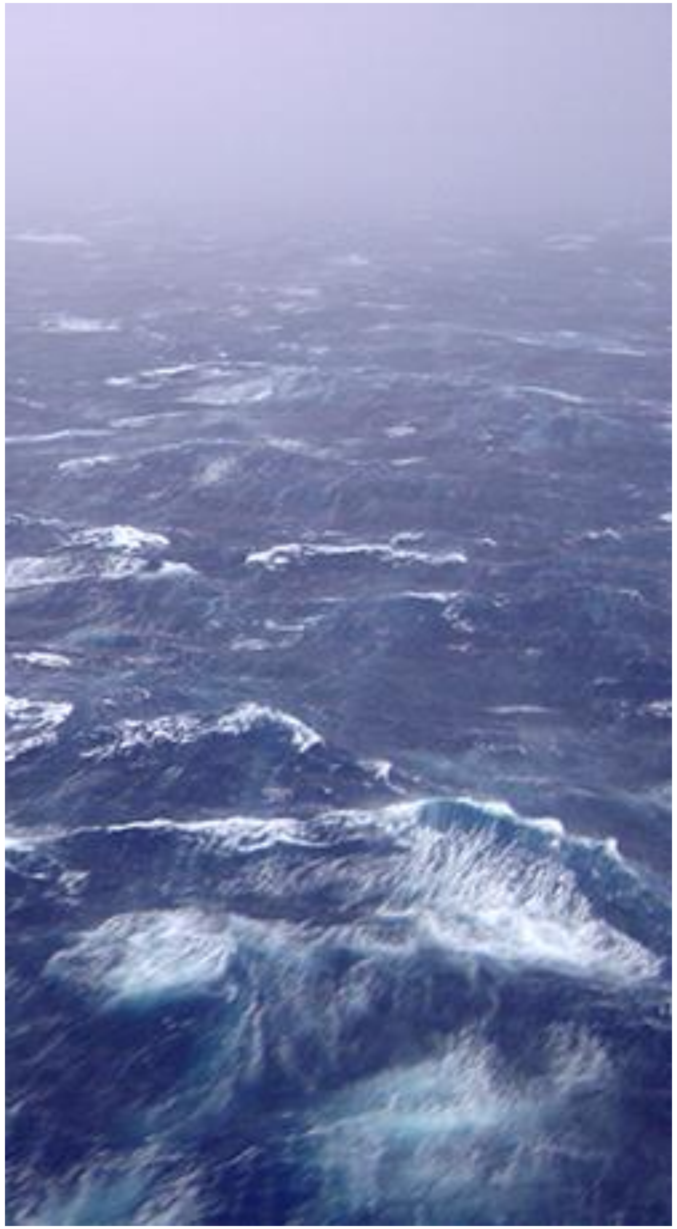
NOAA

Sea ice

- Heterogeneous surface
  - Snow (albedo 0.8 compared to water/black ice 0.1)
  - Melt ponds
  - Ridges and rafted ice (variable thickness)
  - Leads (open water)

1) Impact on the atmosphere
   - Heat flux with / without ice cover, roughness // ocean wave distribution
2) Thin ice vs thick ice
   - Requires multi-layered/multi-category ice thickness distribution
   - Impact on Rheology (breakage; can be affected by waves as well)
3) Impact on ocean
   - change in the density (melting ice) and temperature/salinity profile of the upper ocean

Permanent Ice shelves are modelled as land (but Ross sea / Weddell sea ice from -77 S)

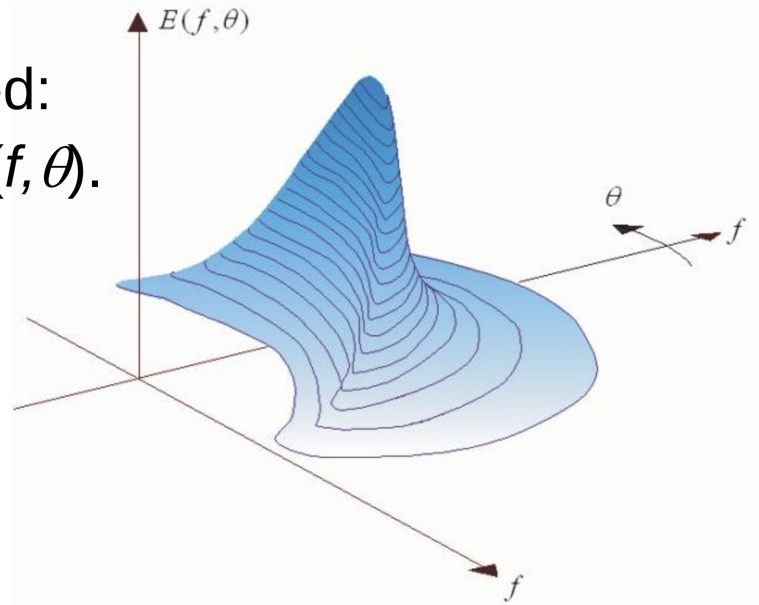


Ocean Waves

- The irregular water surface can be decomposed into a number of simple sinusoidal components with different <u>frequencies</u> (*f*) and propagation <u>directions</u> (θ).

The distribution of wave energy among those components is called: "wave energy spectrum", $\rho_w\, g\ F(f,\theta)$.

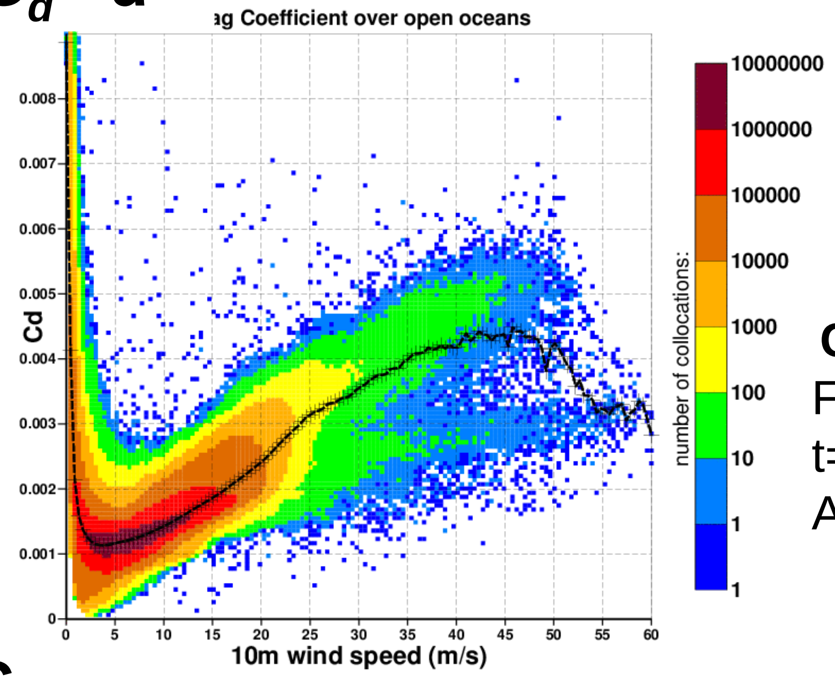
water density: ρ_w and gravity: g



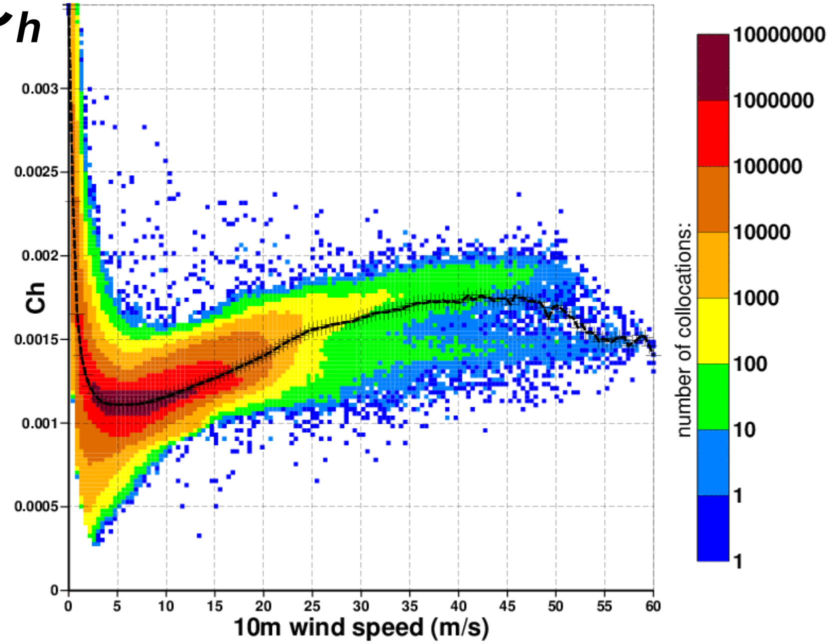
ECMWF

Sea state dependency on momentum and heat fluxes

$C_d = \alpha$



C_h



$$z_{0m} = \delta * \nu / u_* + \alpha u_*^2 / g$$

$$z_{0h} = \delta * \nu / u_*$$

CY45R1

Forecast from 20170904 (Irma)

t=6 to 240 by 6, TCo1999 (5km)

All open ocean grid points.

Increase of drag with increasing wind, opposite to smooth surface

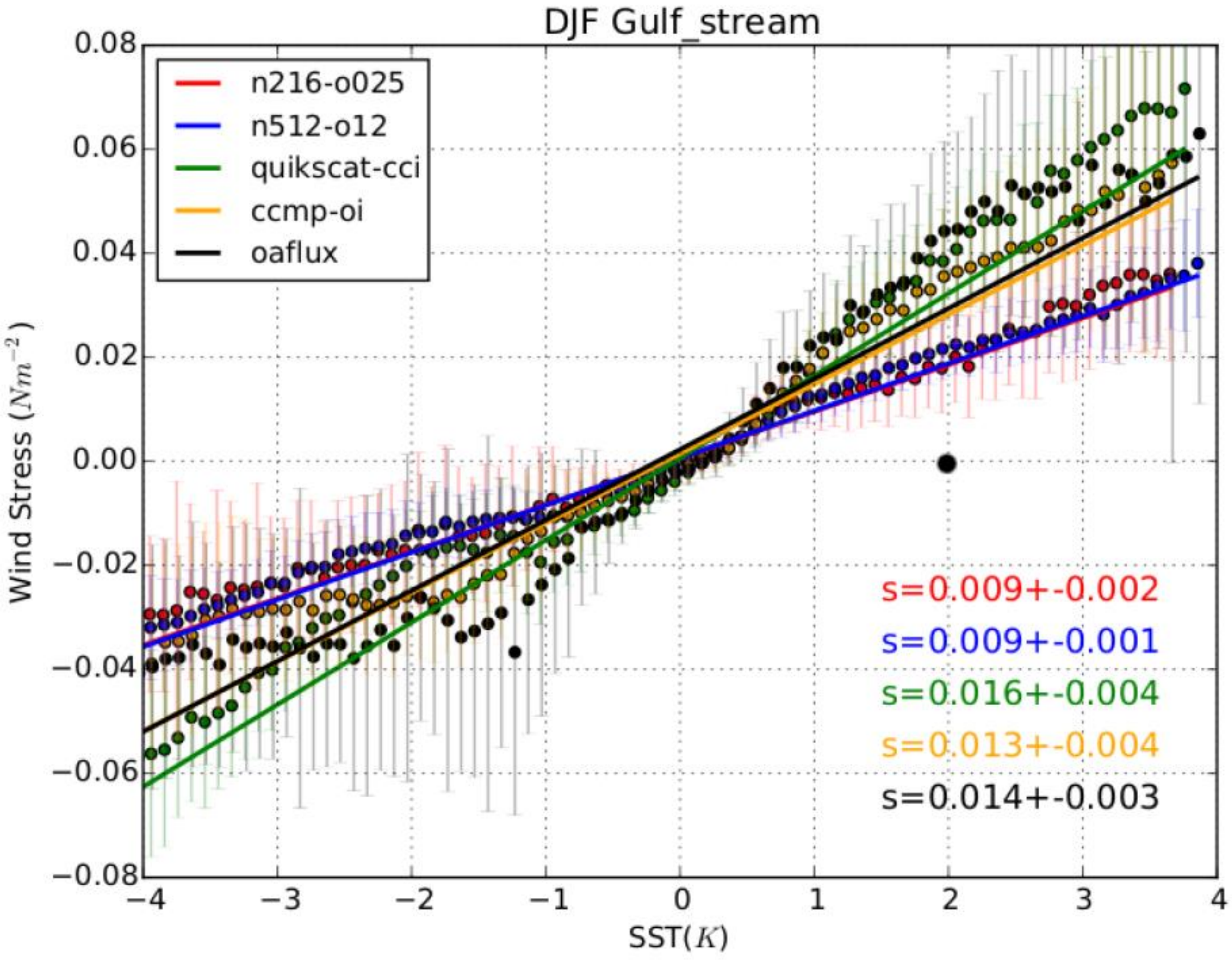
Breakdown of relationship at very high wind speeds ?

Both Cd and Ch (less pronounced) are sea state and wind speed dependent

Met Office

SST-windstress relationship

- Positive correlations indicate where ocean leads atmosphere
- Ocean becomes more important as resolution increases
- Once eddies and fronts present, not strongly sensitive to resolution
- Deficiency in physics of atmospheric boundary layer parameterisations? (Song et al., 2009)

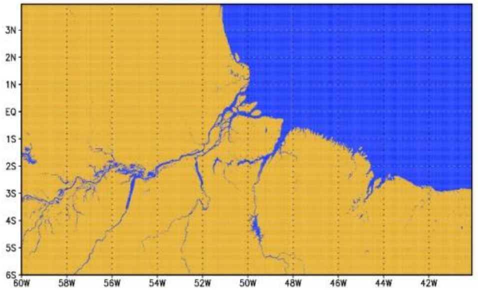


(H. Hewitt, 2018)

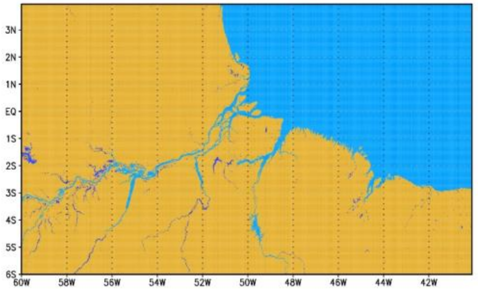
Mapping continuously the surface at 1km: water bodies to improve surface fluxes

Classifying automatically inland water bodies is a complex task. A 1-km water bodies cover and bathymetry have been produced

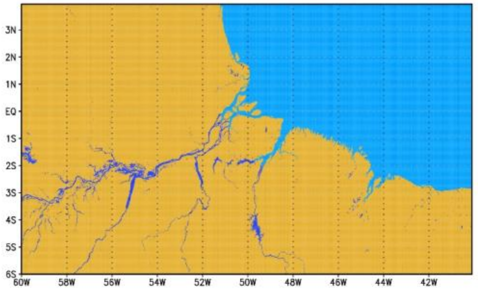
ESA GlobCOVER has no water class



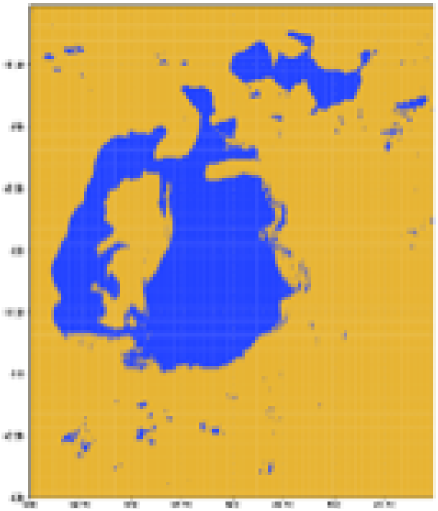
Flooding allows classify, problems w. large rivers

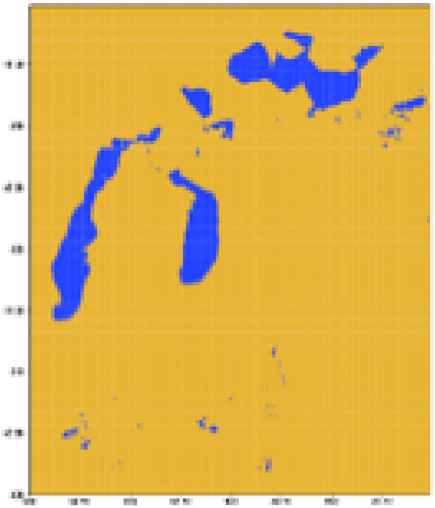


New classification algo works well at 1km



A new 1-km global bathymetry and water body map





Aral Sea in 1998 (left) and 2015 (right) as observed by Landsat

ESA GlobCOVER is combined with JRC/GLCS to detect Lake cover changes

NEWS ECMWF Newsletter No. 150 – Winter 2016/17

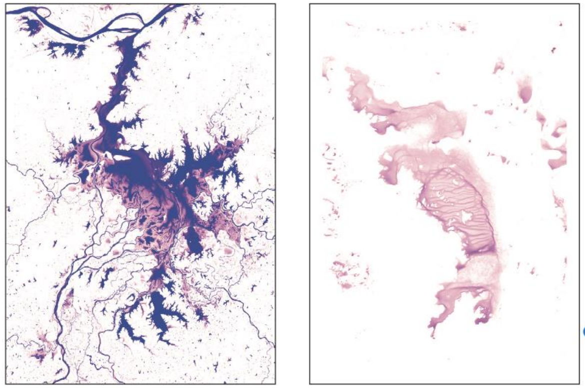
Lakes in weather prediction: a moving target

GIANPAOLO BALSAMO (ECMWF), **ALAN BELWARD** (Joint Research Centre)

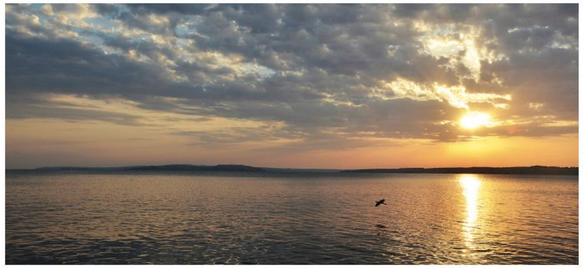
Lakes are important for numerical weather prediction (NWP) because they influence the local weather and climate. That is why in May 2015 ECMWF implemented a simple but effective interactive lake model to represent the water temperature and lake ice of all the world's major inland water bodies in the Integrated Forecasting System (IFS). The model is based on the version of the FLake parametrization developed at the German National Meteorological Service (DWD), which uses a static dataset to represent the extent and bathymetry of the world's lakes.

However, new data obtained from satellites show that the world's surface water bodies are far from static. By analysing more than 3 million satellite images collected between 1984 and 2015 by the USGS/NASA Landsat satellite programme, new global maps of surface water occurrence and change with a 30-metre resolution have been produced. These provide a globally consistent view of one of our planet's most vital resources, and they make it possible to measure where the world's surface water bodies really can be found at any given time.

As explained in a recent *Nature* article (doi:10.1038/nature20584), the maps show that over the past three decades almost 90,000 km^2 of the lakes and rivers thought of as permanent have vanished from the Earth's surface. That is equivalent to Europe losing half of its lakes. The losses are linked to drought



Dynamic lakes. The size of Poyang Lake (left), one of China's largest lakes, fluctuates dramatically between wet and dry seasons each year while overall decreasing. Lake Gairdner in Australia (right), which is over 150 km long, is an ephemeral lake resulting from episodic inundations. Both maps show the occurrence of water over the past 32 years: the lighter the tone the lower the occurrence. (*Images: Joint Research Centre/Google 2016*)



Lake Victoria. Lakes in tropical areas are linked with high-impact weather by contributing to the formation of convective cells. (*Photo: MHGALLERY/iStock/Thinkstock*)

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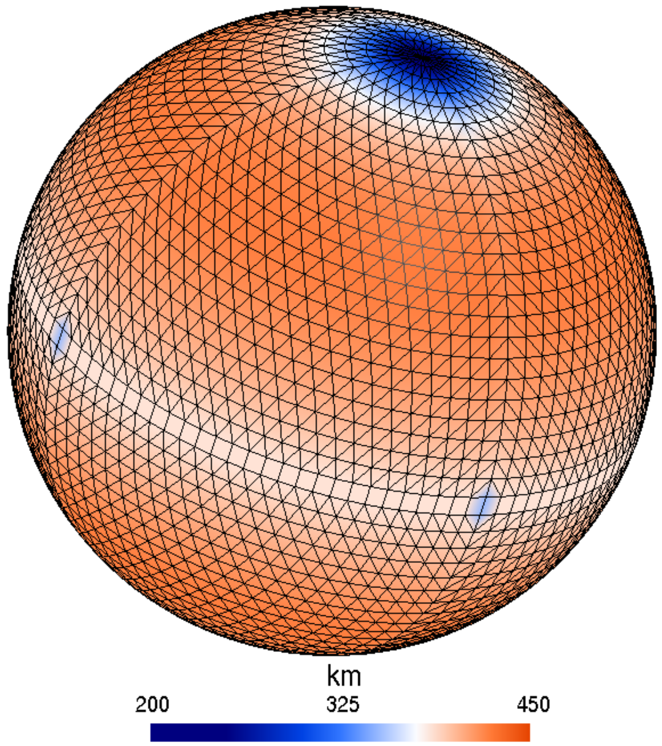
ECMWF

Transformations in time (averaging) and space (grids) at each coupling exchange

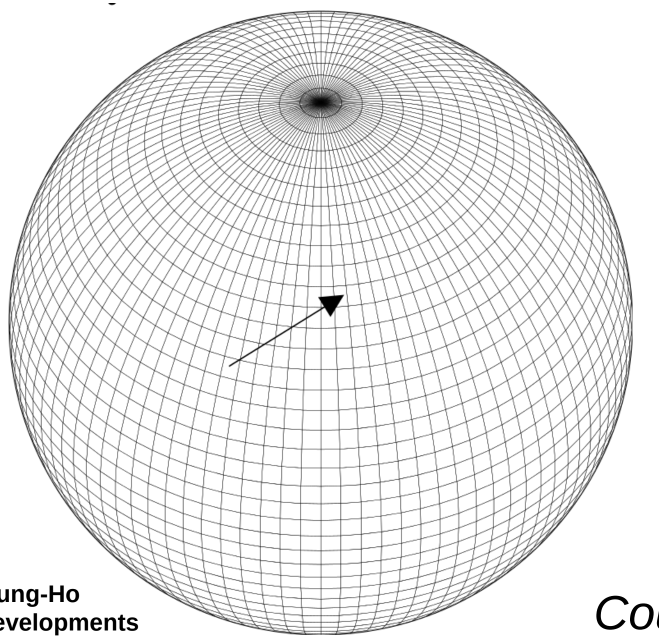
Octahedral Gaussian grid



Atmosphere/land-surface

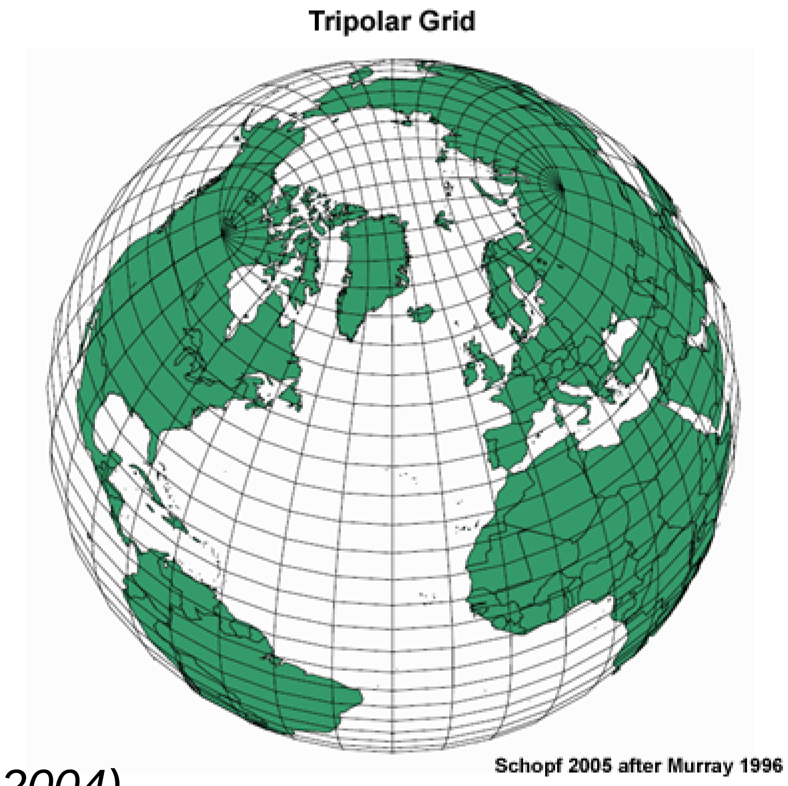
Ocean waves

Latitude/Longitude grid



Gung-Ho developments

Ocean/Sea-ice

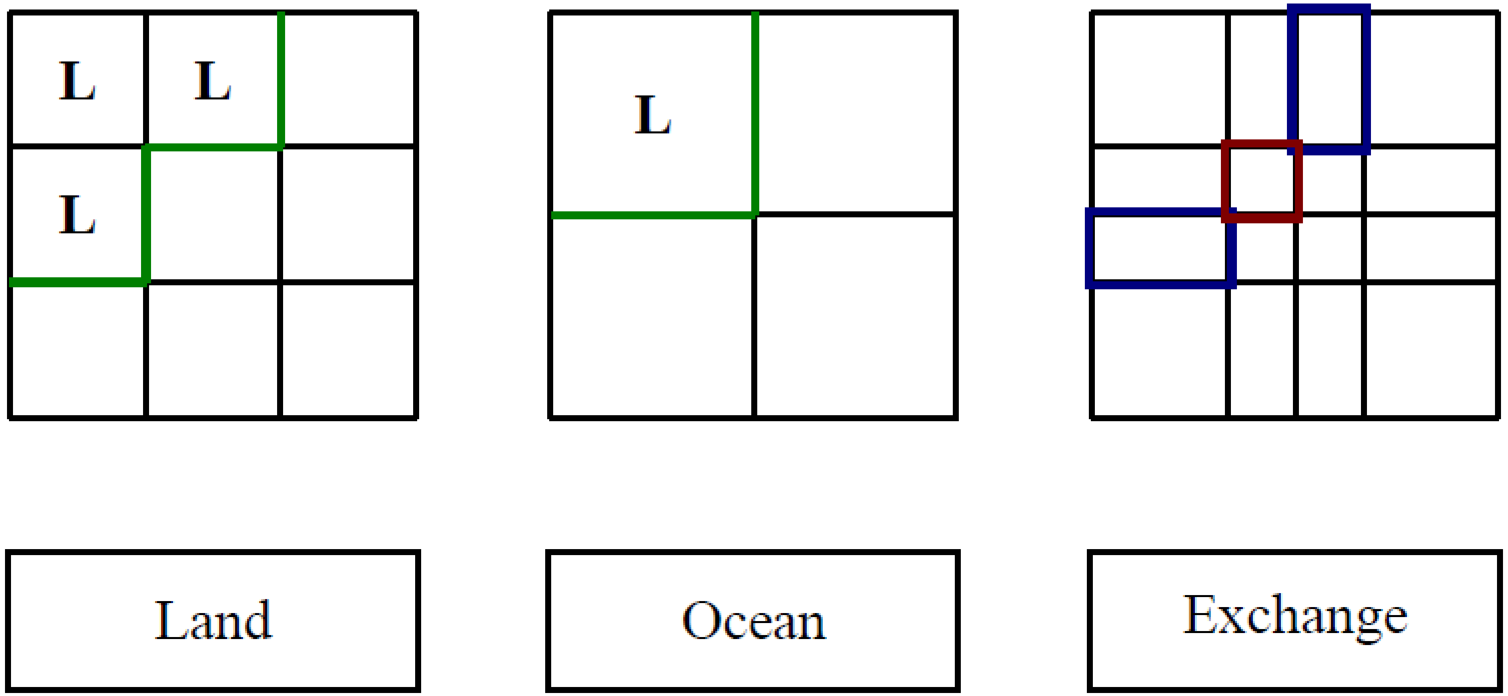


Coupling frameworks/toolkits could be used
OASIS3-MCT (Valcke, 2013); ESMF (Hill et al, 2004)

Exchange grids

- Globally conservative and stable flux computations at component interfaces
- Modularity of components
- Used at GFDL (FMS, ESM2M, ESM2G)

(Balaji et al, 2006)

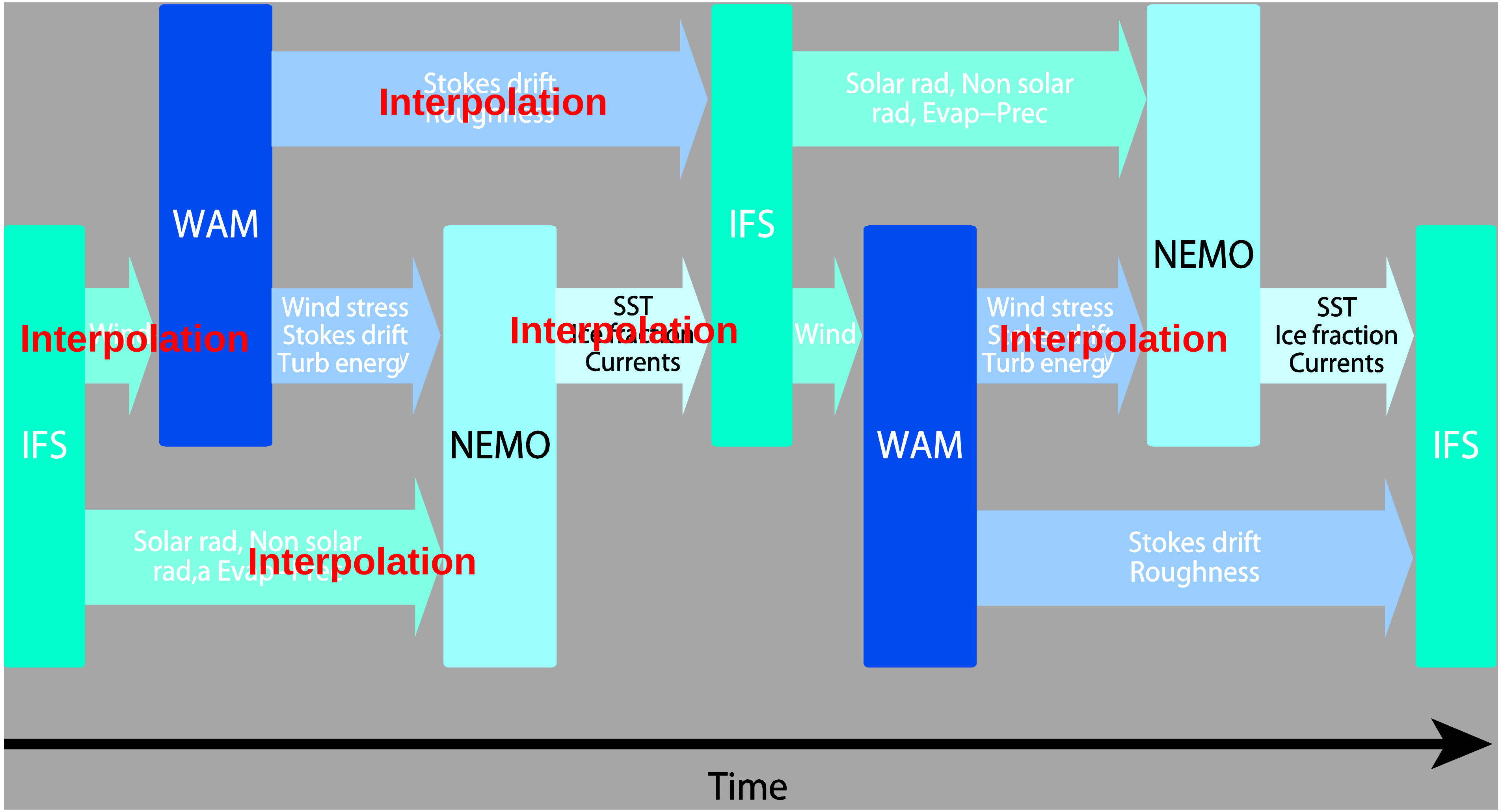


Not done at ECMWF currently:

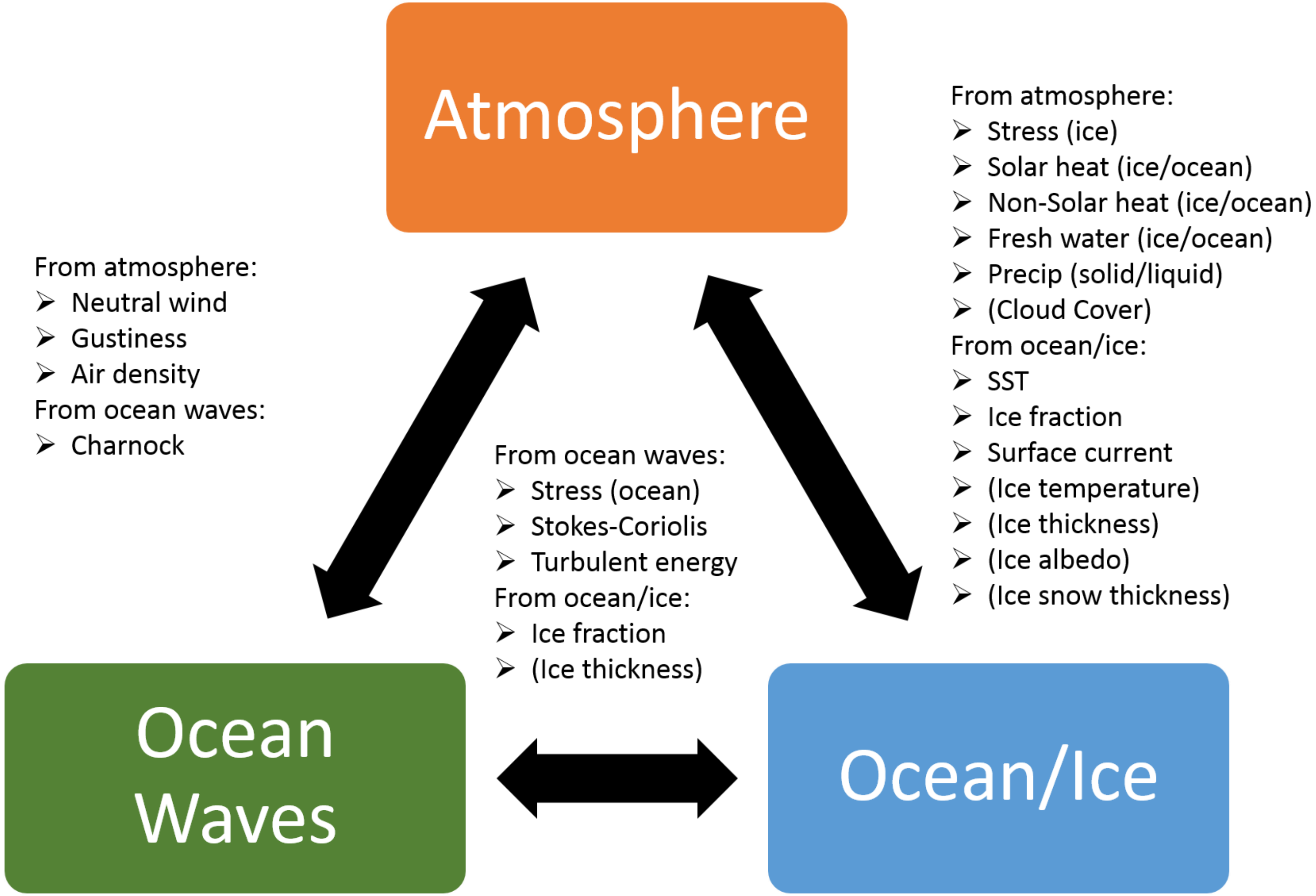
- Atmosphere much higher resolution, advantage if flux computation on atmospheric grid
- (arguably) less important for forecasts up to 1 year ahead
- Potential additional scalability challenges with exchange grids

Coupling

- Coupling is sequential, time stepping loop in the atmospheric model (IFS)
- Atmosphere → Waves → Ocean (repeated)



Data exchanges in the ECMWF coupled model



Fields in () are not currently used in operations

Vertical coupling

- Numerical (in)stabilities of coupling can be very delicate because some surface processes have very short time scales (shorter than the timestep of the atmospheric model, e.g. << 1h)

- Strategy:
  - If possible keep fast processes as part of atmospheric model, e.g. skin layer or first/few surface layers (see prognostic equation for skin temperature)
  - Applies to land, lakes, snow, ice, ocean warm layers, …
  - Horizontal exchange in soil, ice, snow, and ocean may be neglected in diurnal cycle layers (at current resolutions)
  - Fast wave solvers e.g. for the ocean barotropic mode (sfc gravity waves) could incorporate other fast processes (eg. sea ice, Balaji, pers communication)

Key design elements:

- Modularity of (ESM component) code
- Temperature or other prognostic variables at the interface evaluated at future time level (implicit coupling)
- Tiling compatible
- Exchange of fluxes rather than variables fosters modular design

The "Best" coupling may be applied to other tiles such as snow, ice, ocean warm layers …

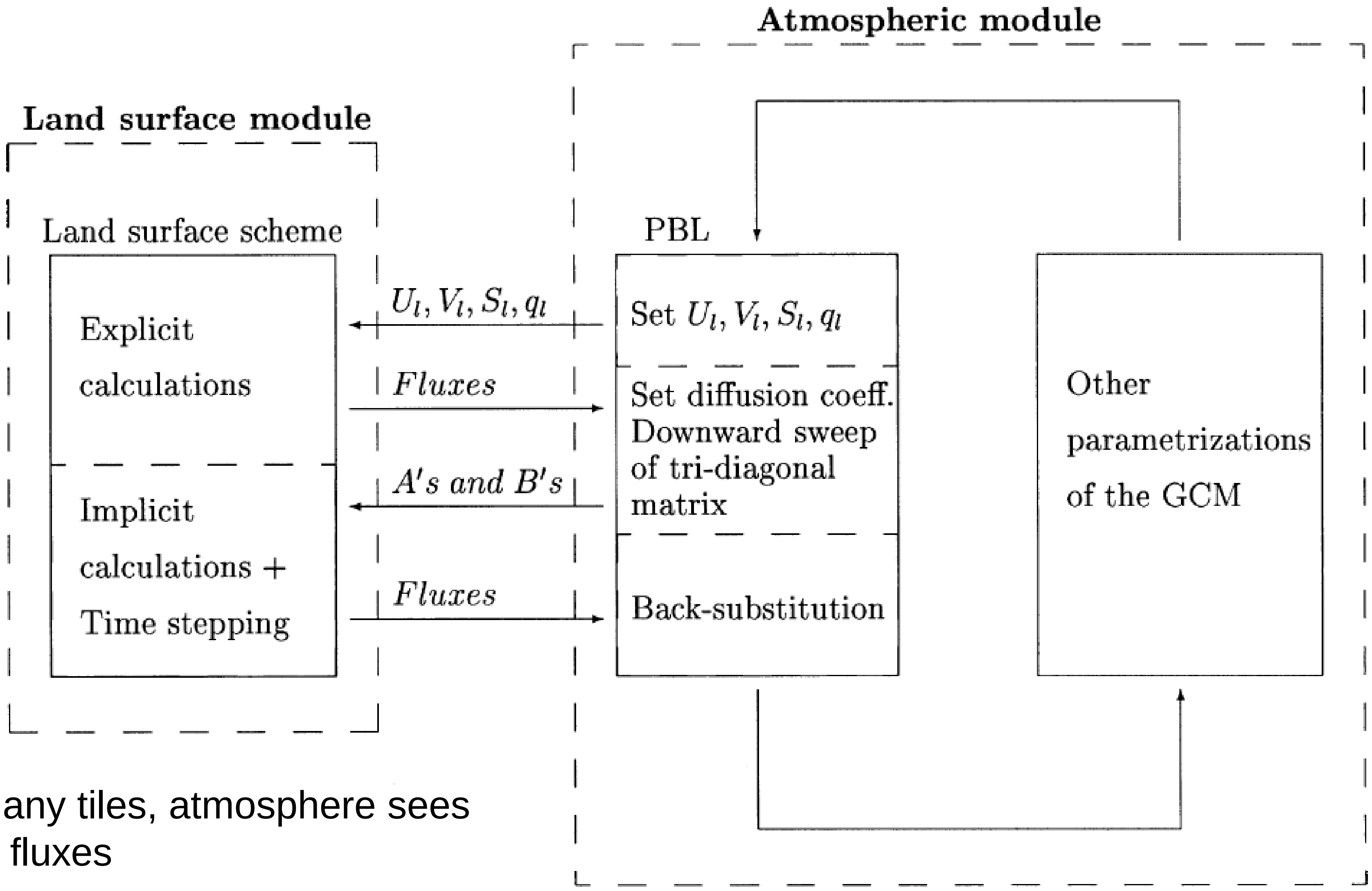


FIG. 1. Flow diagram of an example of a two-stage coupling. The full set of coupling variables is given in Table 1.

(Best et al, 2004)

Works with any tiles, atmosphere sees aggregated fluxes

Implicit coupling of fast processes

$$a_k T_{k+1} + b_k T_k + c_k T_{k-1} = rhs_k$$

$$T_k = \alpha_k T_{k+1} + \beta_k$$

Tridiagonal solve of typical vertical diffusion problem

"First sweep"

Plus boundary conditions at future time n+1 on either side of the interface between 2 ESM components

flux $$H_0 = \lambda * (T_S^{n+1} - T_1^{n+1})$$

With $$T_1^{n+1} = \alpha_1 * H_0 + \beta_1$$

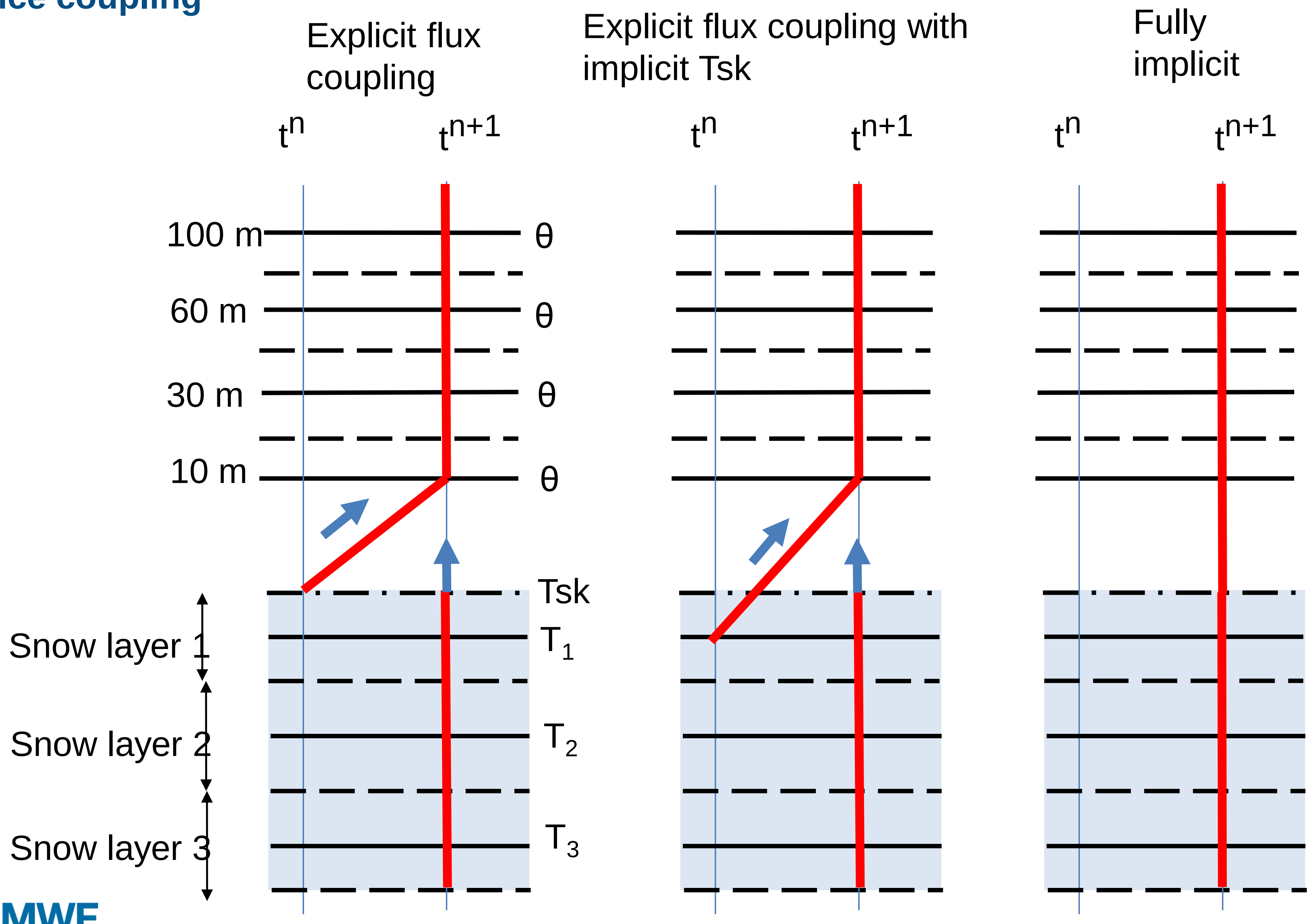
From the atmosphere
(H_0 not explicitly known yet)

$$T_S^{n+1} = \alpha_{S0} * H_0 + \beta_{S0}$$

From the ESM component (e.g. snow)
(H_0 not explicitly known yet)

"Back substitution step" to find prognostic variables at all levels in the atmosphere and (at the same time) in each ESM component

Atmosphere to snow / ice coupling



ECMWF

A (temporary) pragmatic solution avoiding instabilities

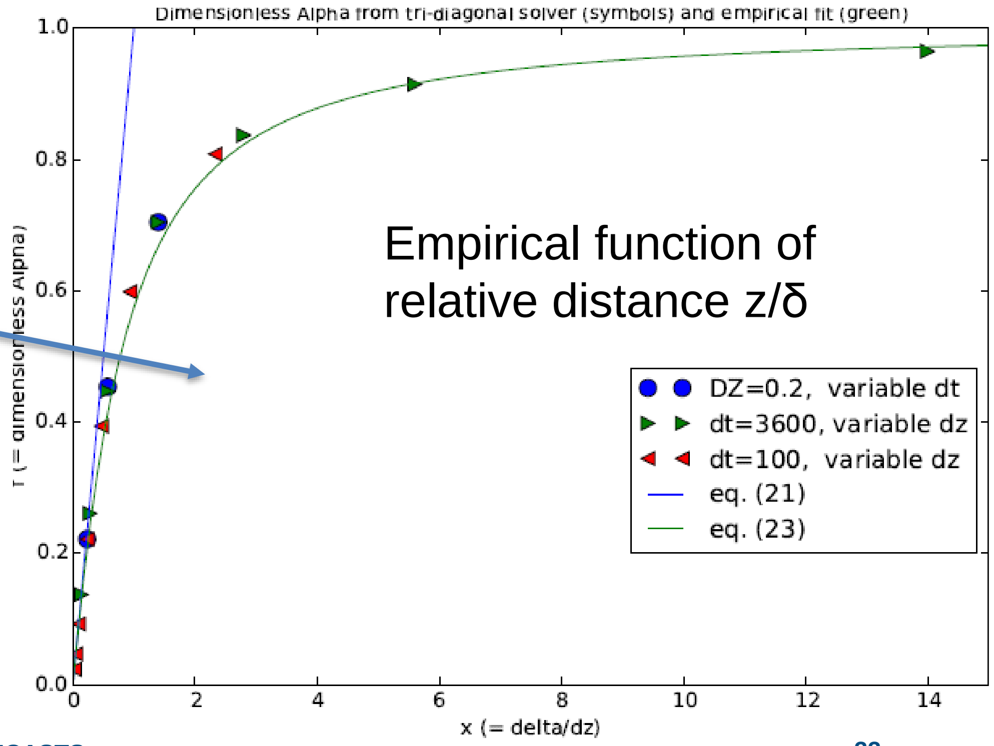
- Current SURF library code only implicit in the energy balance equation calculating skin temperature
- Not used for implicit coupling to all levels, instead an explicit flux is specified below the skin layer
- Similarly for the multi-layer snow, but here an instability was arising for thin snow layers
  - Solution: “parametrized implicit coupling”, where the prognostic variable (e.g. temperature) at the future time level is anticipated by a parametrized (approximated) value based on similarity relations for the diffusion equation.

Beljaars et al. (2017,Geosci. Model Dev., 5,1271-1278)

$$\tilde{T}_S^{n+1} = \tilde{\alpha}_{S0} * H_0 + \tilde{\beta}_{S0}$$

$$T_S^n \big|_{z=-\delta}$$

Function of Δt,
heat capacity,
diffusion coefficient, density

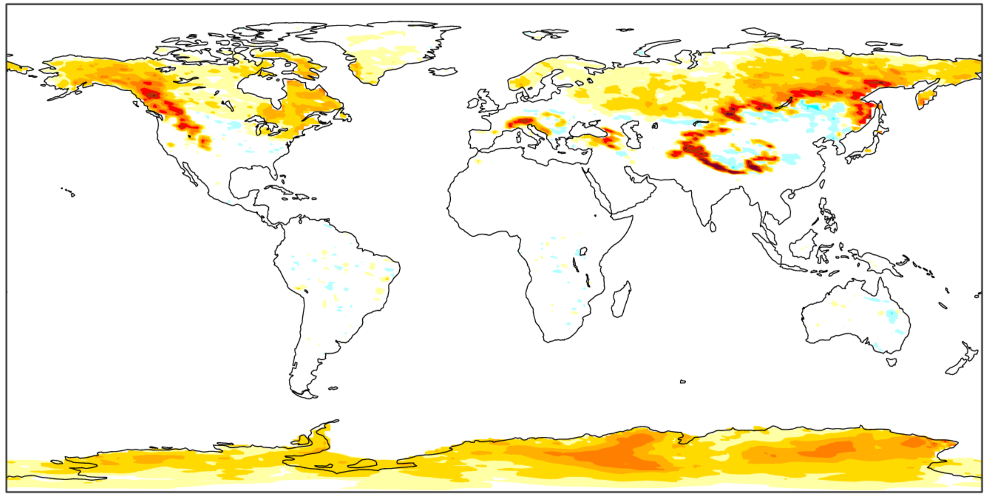


Empirical function of relative distance z/δ

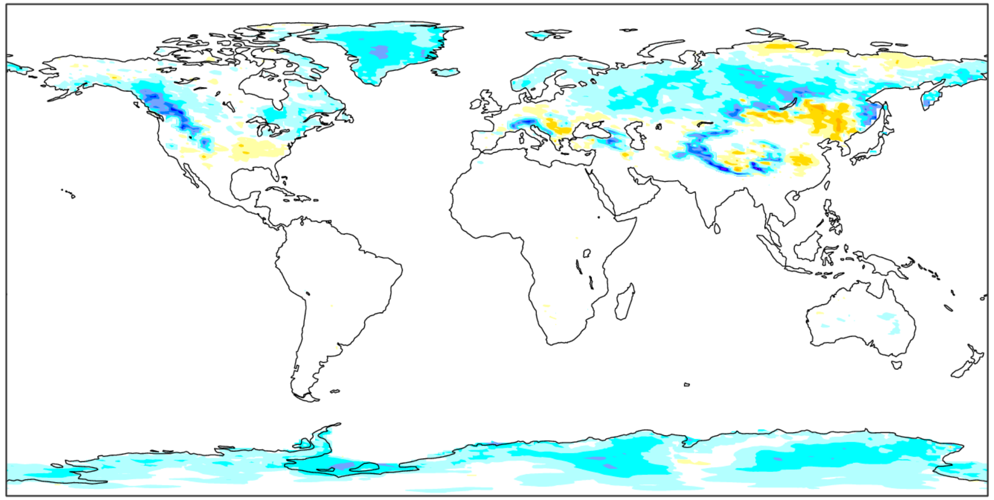
Diurnal cycle over snow-covered regions in free-running land-atmosphere experiments

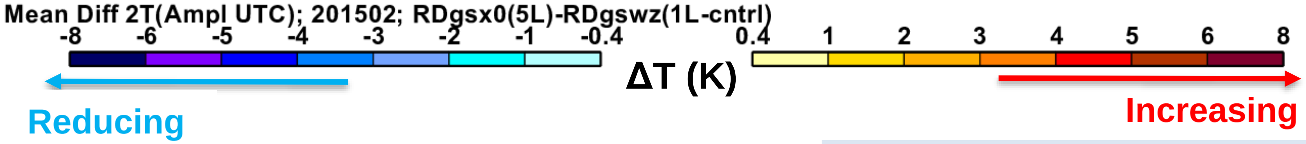
- Impact on diurnal cycle amplitude and minima of the multi-layer snow scheme (**ML**, **up to 5 layers**) compared to single-layer snow scheme (**SL**).
- Amplitude of the diurnal cycle of T_{2m} defined as $T_{max} - T_{min}$
- Continuous simulations over a full year (2015) nudged towards the reanalysis in the upper troposphere.

Difference (ML – SL) of the monthly-mean T_{2m} amplitude of the diurnal cycle for Feb 2015



Difference (ML – SL) of the monthly-mean T_{2m} minima for Feb 2015





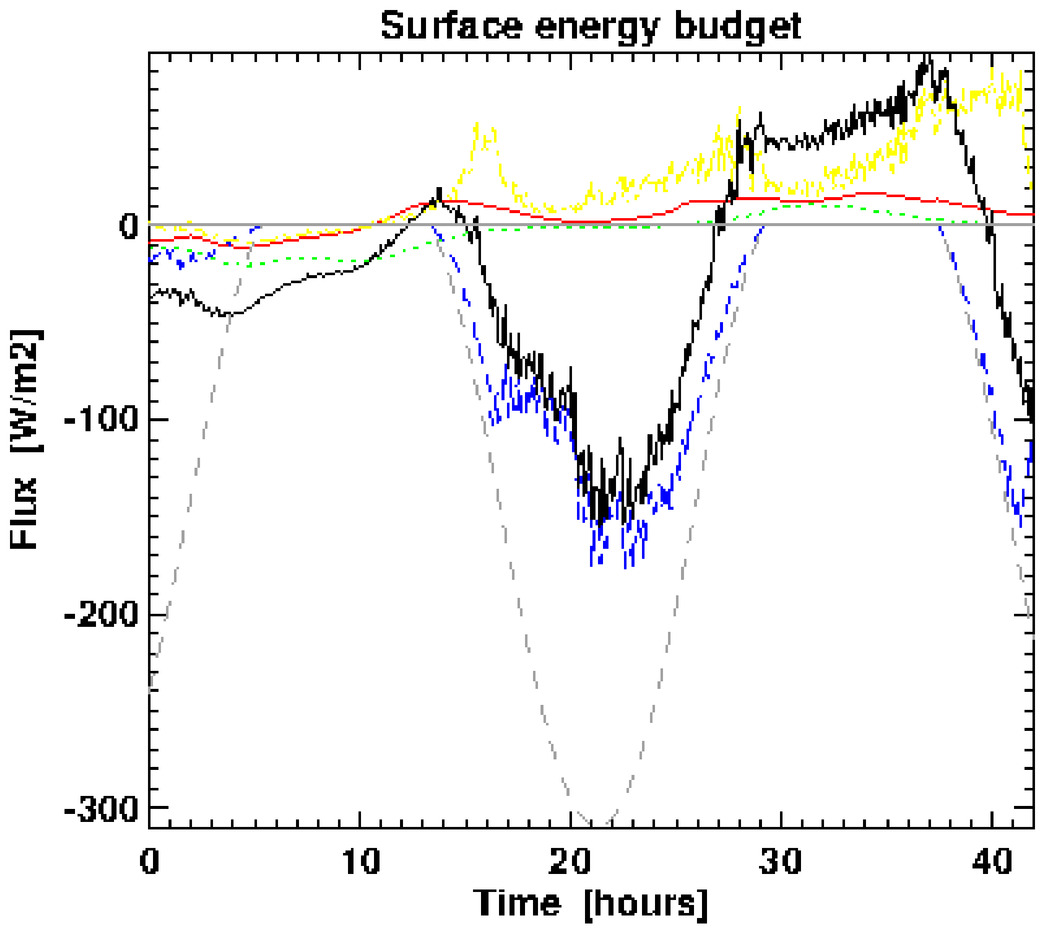
Increased amplitude of the diurnal cycle (up to 5 K) using the multi-layer snow scheme over cold regions.

Mainly decrease of T_{2m} minima using the multi-layer snow scheme due to the reduced thermal inertia of the snowpack.

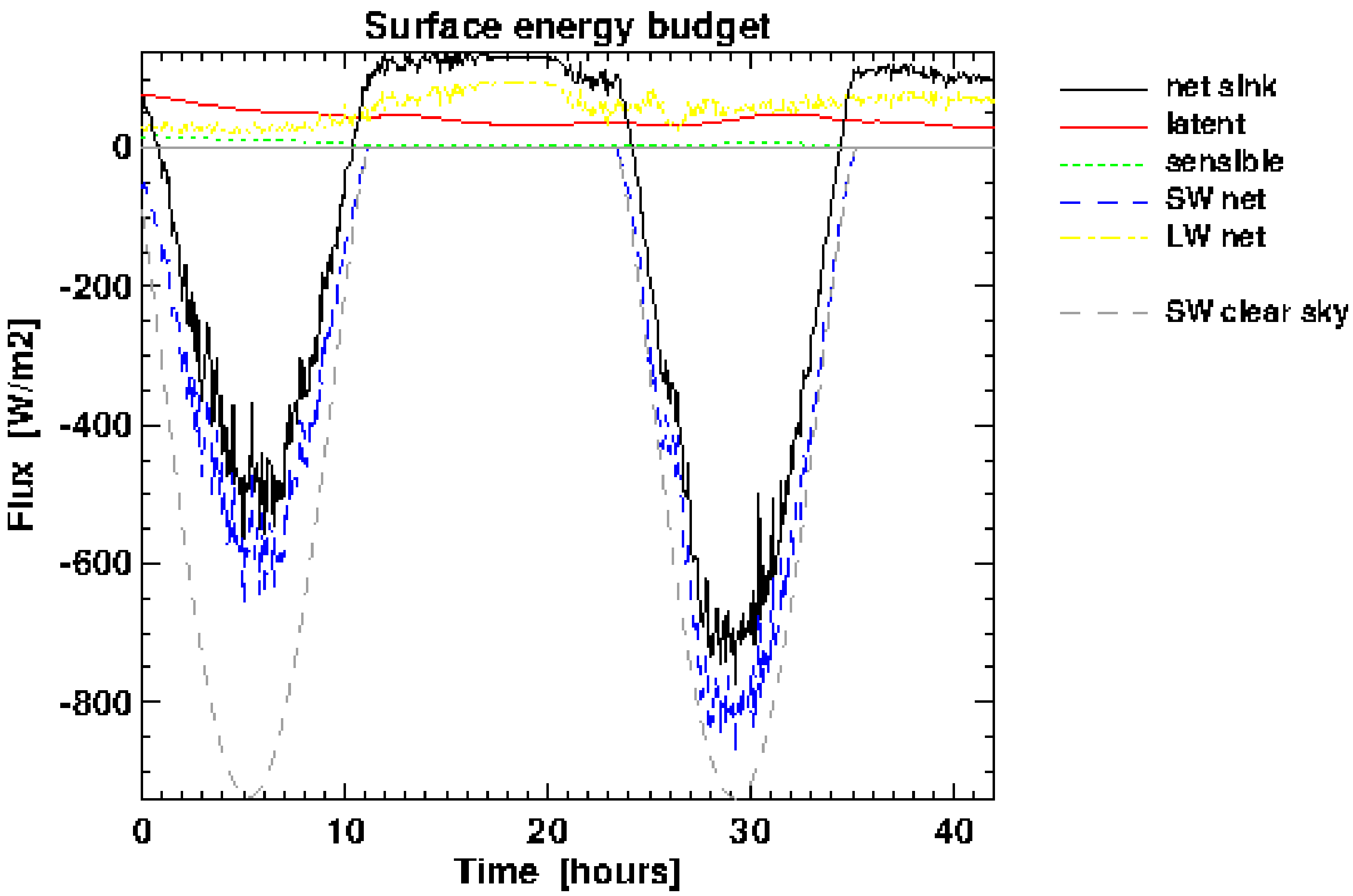
ECMWF

uncoupled (SCM) diurnal fluxes

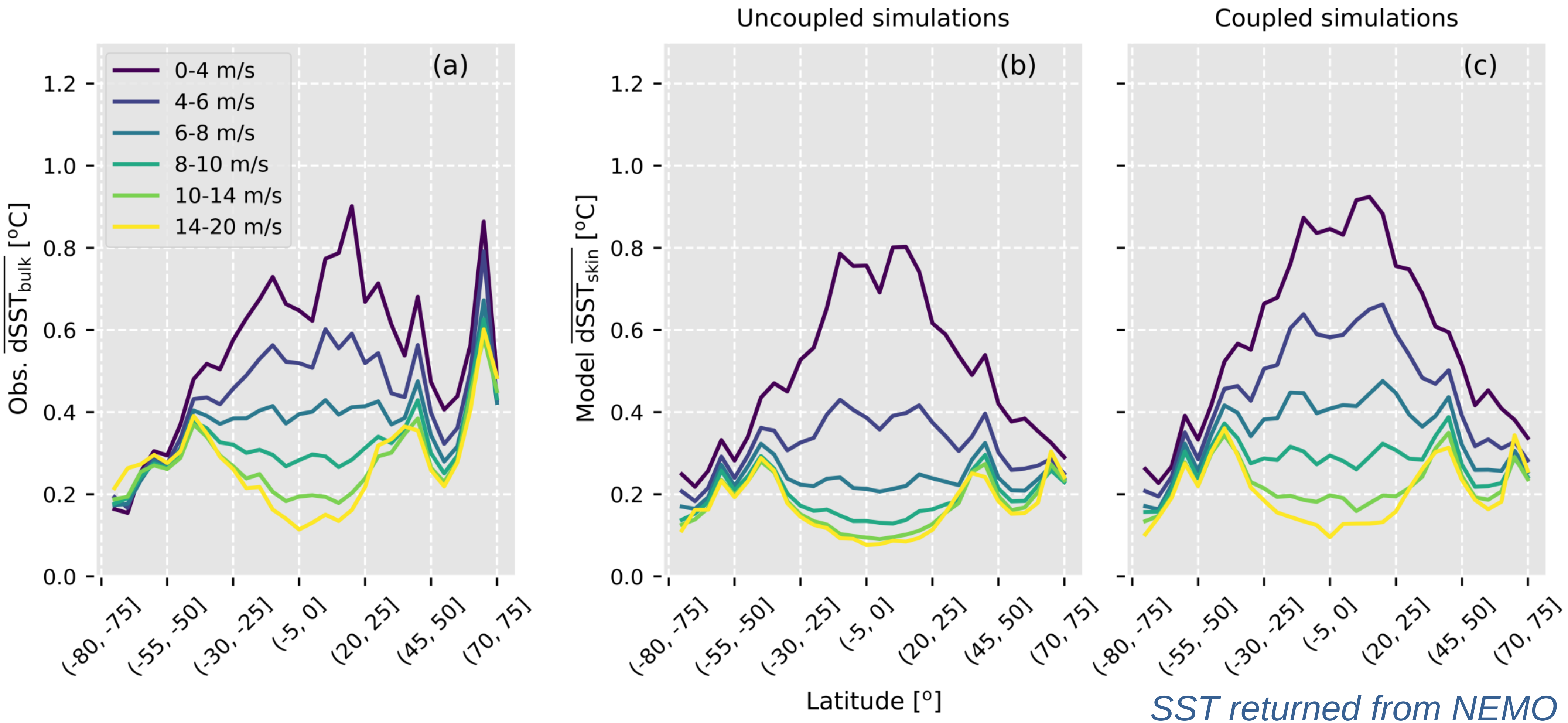
Barent Sea



Off the coast of Peru



Diurnal cycle of SST for different wind regimes



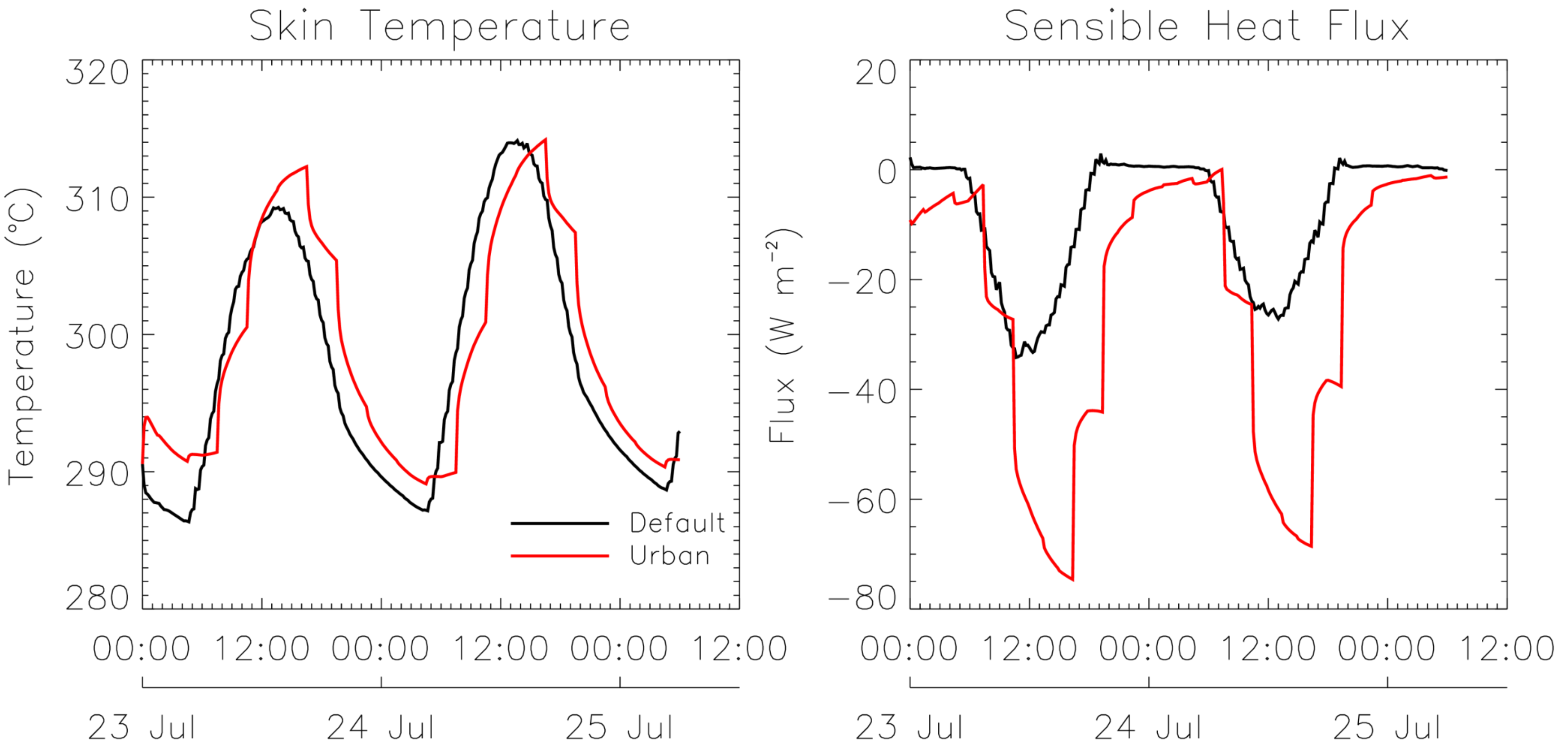
Progn equation for SST

(Zeng and Beljaars, 2005)

SST returned from NEMO 1m top layer

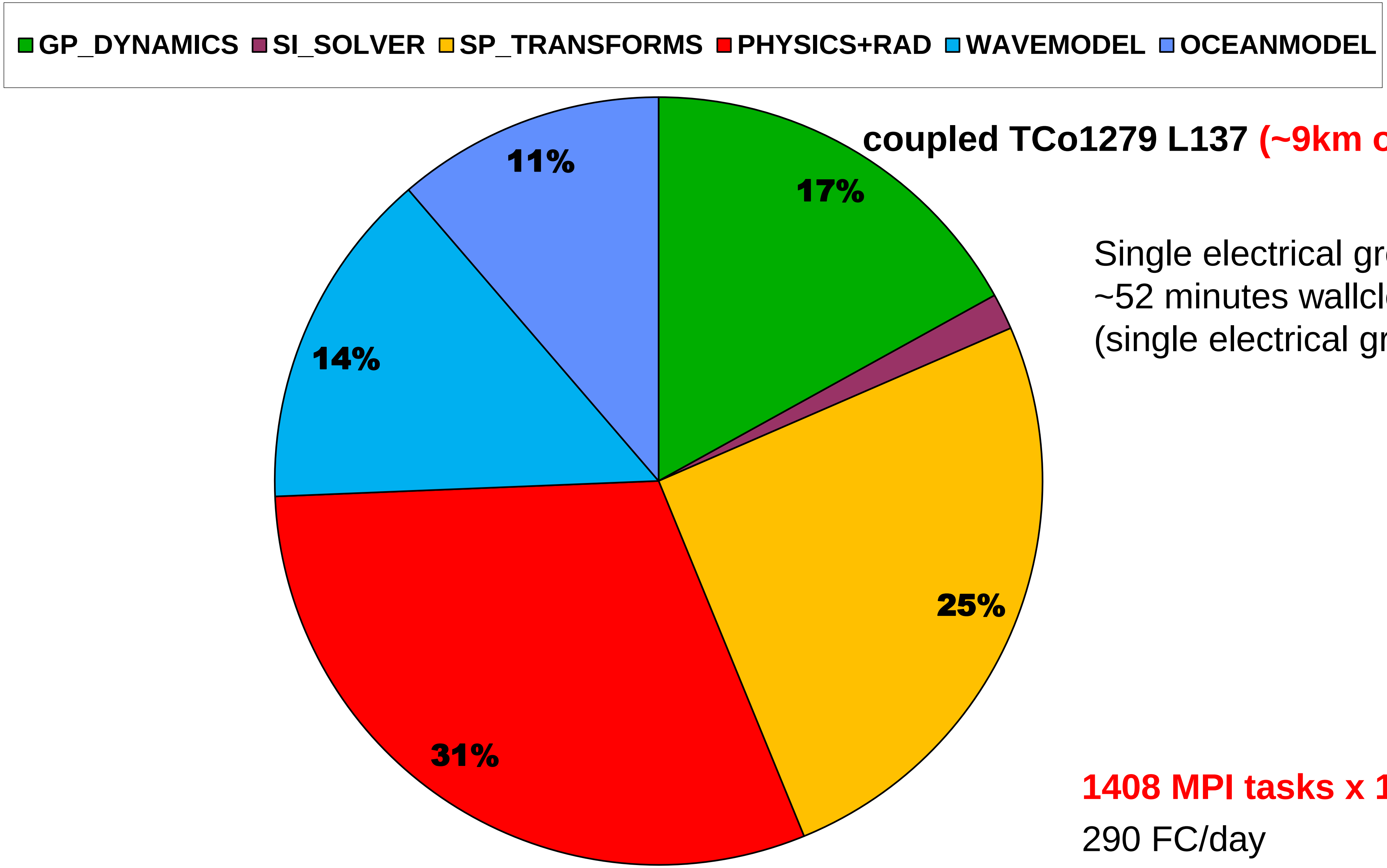
(Salisbury et al, TechMemo 826)

Diurnal cycle over land with an urban tile



CHTESSEL offline simulations covering the period 23-27 July 2012 with an urban tile over London compared with the current natural vegetated surfaces, (SUBLIME project)

Where do we spend the time ? Cycle 45r1 operations



coupled TCo1279 L137 (~9km operational) run

Single electrical group:
~52 minutes wallclock time
(single electrical group==384 nodes)

1408 MPI tasks x 18 threads

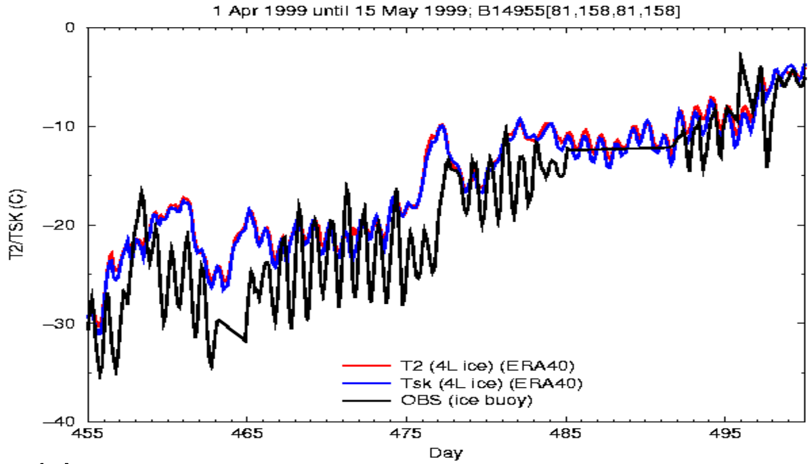
290 FC/day

A few challenges for modelling and coupled data assimilation

- Current sea ice model has only 1/3 of the observed diurnal amplitude of air temperature in spring. Solution is to add a multi-layer snow model on top of the sea ice. The challenge is to control snow cover through data assimilation. A snow model can drift away very quickly during snow melt through the albedo feedback.

- Skin temperature over land shows large errors which have complex regional patterns related to climate regime and land use. Therefore surface temperatures from satellite can not readily be assimilated. A way forward is to optimize the relevant land parameters through data assimilation.

Ice buy data 1999

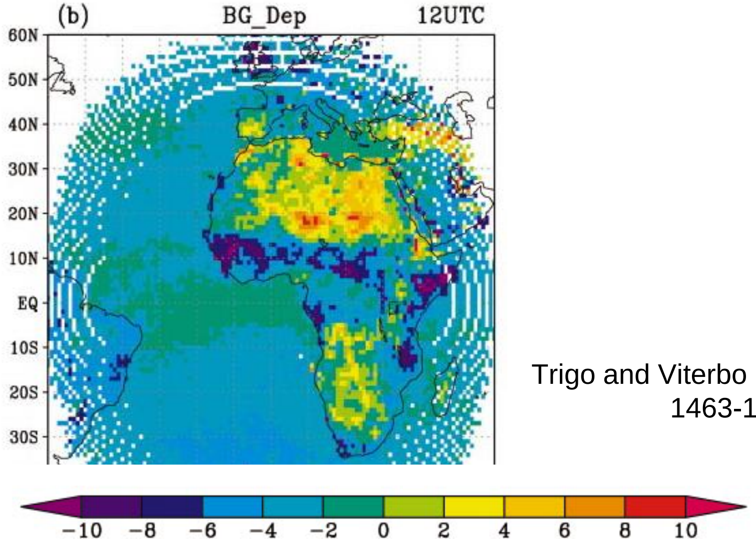


1 Apr

15 May

Beljaars et al. (2006, ECMWF annual seminar)

Tsk Meteosat – Tsk (mod)
1 – 15 July 2001, 12 UTC



Trigo and Viterbo (2001, JAM, 42, 1463-1479)

ECMWF

Conclusions and future

– **Move towards Earth-System complexity**
  - Complete the description of the hydrological and carbon cycle
  - Consolidate coupling mechanisms between ESM components for all time scales
  - Exploit novel interface observations through improved mapping and modelling of the underlying Earth surfaces using data assimilation in the process (constraining initialisation, parameter estimation, inverse surface mapping)
  - Gain understanding on systematic errors in the atmosphere through coupling

– **Supporting Copernicus Services**
  - Climate monitoring services for the atmosphere
  - European Reanalysis (currently producing ERA-5)
  - Atmospheric composition monitoring
  - Emergency alert system (Floods, Fires, …)

Additional slides

Coupling to the ocean

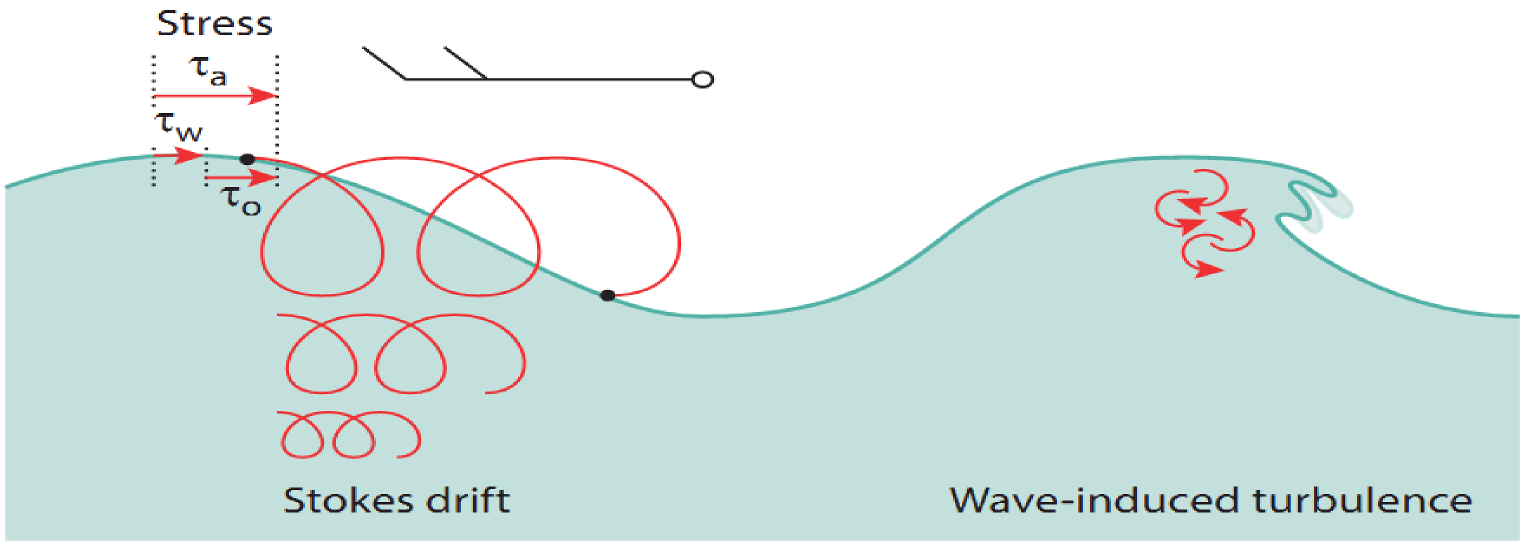
```
! Update NEMO forcing fields
  CALL NEMOGCMCOUP_UPDATE( MYPROC-1, NPROC, MPL_COMM, NGPTOT, &
       &                   ZSTRSU, ZSTRSV, ZFRSOS, ZFCHAS, ZFHUMS, &
       &                   KSTEP, LNEMOFLUXNC )
  ! NEMO time stepping
  DO JSTPNEMO=NEMOCSTEP,NEMOCSTEP+NEMONSTEP-1
    ! Advance the NEMO model 1 time step
    CALL NEMOGCMCOUP_STEP( JSTPNEMO, IDATE, ITIME )
  ENDDO
  ! Update IFS coupling fields
  CALL NEMOGCMCOUP_GET( MYPROC-1, NPROC, MPL_COMM, &
        &               NGPTOT, ZGSST, ZGICE, ZGUCUR, ZGVCUR )
```

Wave effects in NEMO

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.



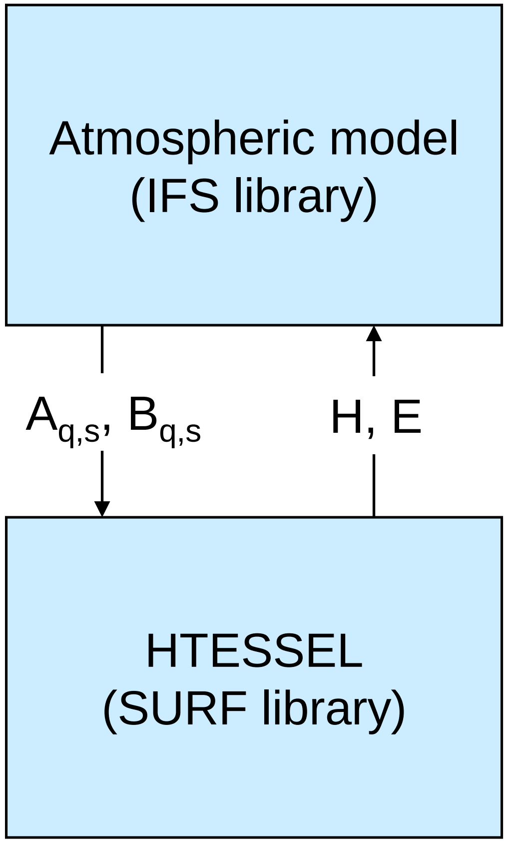
Coupling of HTESSEL to the atmosphere (Best coupler)[1]

- The atmospheric model has an implicit formulation for turbulent diffusion. After the top-down elimination of the tri-diagonal solver, a linear relation is obtained between the lowest model level q_l (specific humidity) / S_l (dry static energy) and fluxes H (heat) / E (moisture) at time level n+1:

$$\mathbf{S_l^{n+1} = A_s \overline{H} + B_s}$$

$$\mathbf{q_l^{n+1} = A_q \overline{E} + B_q}$$

- The land surface model computes skin temperatures at time level n+1, calculates fluxes for the different tiles and returns the grid box averaged fluxes to the atmosphere.
- The atmospheric model continuous with the bottom-up back-substitution of the tridiagonal solver.



Comments:

♦The atmospheric surface layer is part of the SURF library

♦The modular design allows for offline application of the land surface model

[1)]Best et al. (2004):, J. Hydrometeor., 5, 1271-1278