Land, ocean, sea ice, wave coupled model developments

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

(Schulthess et al, 2018)
Ensemble of assimilations and forecasts
Ocean – Land – Atmosphere – Sea ice
**Challenge: Monitoring atmospheric CO₂**

**CO₂ OBSERVATIONS**
- GOSAT CO₂ (IUP- Uni Bremen)

**CO₂ 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 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)
- Integration of Carbon/Energy/Water
  - Boussetta et al. 2013
  - Aquist-Panombat et al. 2015

**SOIL Evaporation**
- Balsamo et al. (2011), Albernet et al. (2012)

**Atmosphere**
- H₂O / E / CO₂
  - 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)

**Lake & Coastal area**
- Enhance ML
  - Snow ML5
  - Soil ML9
  - Dutra et al. (2012, 2016)
  - Balsamo et al. (2016)

**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

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<table>
<thead>
<tr>
<th>Atmos Land Resol.</th>
<th>ECMWF in 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 km</td>
<td>ERAI</td>
</tr>
<tr>
<td>32 km</td>
<td>ERA5⁺ SEAS5⁺*</td>
</tr>
<tr>
<td>18 km</td>
<td>ENS⁺⁺</td>
</tr>
<tr>
<td>9 km</td>
<td>HRES⁺⁺</td>
</tr>
</tbody>
</table>
The tile scheme allows for a simple representation of surface heterogeneity over land and for fractional sea ice over the ocean.

**NEMO** (Nucleus for European Modelling of the Ocean) + **WAM** (Wave Model)

**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 40°C on the 6th of August 2017.

ECMWF Land model ML9 & ML4 (offline)

Differences in the maximum skin temperature ML9-ML4

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

Friction velocity\(^2\) (correlated with momentum flux)

\[
\begin{align*}
    \frac{u^2}{*} &= \left[ \frac{k^2}{\ln^2(z_1/z_{0m})} \right] \times F_m(z_{0m}, z_{0h}, Ri_b) \times |v_1|^2
\end{align*}
\]

Latent heat flux

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

Sensible heat flux

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

Roughness lengths

\[
\begin{align*}
    z_{0m} &= \delta \times \nu / u_* + \alpha u_*^2 / g \\
    z_{0h} &= \delta \times \nu / u_*
\end{align*}
\]

Lowest model level or 10m wind speed
Typical near surface diurnal cycle structure of temperature profiles:

Temperature of deep soil, snow, ice, or bulk SST

$T_{sk}$: 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.

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

Typical numbers:

<table>
<thead>
<tr>
<th></th>
<th>$A_{di}$ (K)</th>
<th>$D_{surf}$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td>10 -30</td>
<td>10</td>
</tr>
<tr>
<td>Snow</td>
<td>0 - 10</td>
<td>5</td>
</tr>
<tr>
<td>Ice</td>
<td>0 -10</td>
<td>10</td>
</tr>
<tr>
<td>Open ocean</td>
<td>0 - 2</td>
<td>100</td>
</tr>
</tbody>
</table>
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
Resolve rather than parametrize much of the crucial vertical transport of momentum and heat.
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

Before

OBS

Uncoupled

Coupled

After

NOAA

ECMWF
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 frequencies \( f \) and propagation directions \( \theta \).

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

*water density: \( \rho_w \) and gravity: \( g \)
Sea state dependency on momentum and heat fluxes

\[ z_{0m} = \delta \frac{\nu}{u_*} + \alpha \frac{u_*^2}{g} \]

\[ z_{0h} = \delta \frac{\nu}{u_*} \]

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

\[ C_d = \alpha \]

\[ C_h \]
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)
Classifying automatically inland water bodies is a complex task. A 1-km water bodies cover and bathymetry have been produced through mapping continuously the surface at 1 km, which improves surface fluxes. Flooding allows classification, but problems with large rivers exist. ESA GlobCOVER has no water class, while new classifications work well at 1 km. A new 1-km global bathymetry and water body map is combined with JRC/GLCS to detect Lake cover changes. An example is the Aral Sea, observed by Landsat in 1998 (left) and 2015 (right). Lakes in weather prediction: a moving target.
Transformations in time (averaging) and space (grids) at each coupling exchange

Ocean waves

Octahedral Gaussian grid

Atmosphere/land-surface

Ocean/Sea-ice

Latitud/Longitude grid

Gung-Ho developments

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

From atmosphere:
- Neutral wind
- Gustiness
- Air density

From ocean waves:
- Charnock

From ocean waves:
- Stress (ocean)
- Stokes-Coriolis
- Turbulent energy

From ocean/ice:
- Ice fraction
- (Ice thickness)

Fields in () are not currently used in operations

From atmosphere:
- Stress (ice)
- Solar heat (ice/ocean)
- Non-Solar heat (ice/ocean)
- Fresh water (ice/ocean)
- Precip (solid/liquid)
- (Cloud Cover)

From ocean/ice:
- SST
- Ice fraction
- Surface current
- (Ice temperature)
- (Ice thickness)
- (Ice albedo)
- (Ice snow thickness)
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. \(< 1\) h)

- 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 (e.g. 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 ...

Works with any tiles, atmosphere sees aggregated fluxes

*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)*
Implicit coupling of fast processes

\[ a_k T_{k+1} + b_k T_k + c_k T_{k-1} = r h S_k \]

\[ T_k = \alpha_k T_{k+1} + \beta_k \]

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

\[
H_0 = \lambda \times (T_{S}^{n+1} - T_{1}^{n+1})
\]

Flux

With

\[
T_{1}^{n+1} = \alpha_1 \times H_0 + \beta_1
\]

From the atmosphere

\( H_0 \) not explicitly known yet

\[
T_{S}^{n+1} = \alpha_{S0} \times H_0 + \beta_{S0}
\]

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

Explicit flux coupling

Explicit flux coupling with implicit Tsk

Fully implicit
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)

\[
\tilde{T}^{n+1}_S = \tilde{\alpha}_S \times H_0 + \tilde{\beta}_S
\]

\[
T^n_S \bigg|_{z=-\delta} \quad \text{Function of } \Delta t, \quad \text{heat capacity, diffusion coefficient, density}
\]
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$_{\text{max}}$ – T$_{\text{min}}$
- 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**

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

**Difference (ML – SL) of the monthly-mean T$_{2m}$ minima for Feb 2015**

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

- 11% GP_DYNAMICS
- 17% SI_SOLVER
- 14% SP_TRANSFORMS
- 31% PHYSICS+RAD
- 25% WAVEMODEL
- 14% OCEANMODEL

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 cannot readily be assimilated. A way forward is to optimize the relevant land parameters through data assimilation.
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 ($\tau_w$) which otherwise would have gone directly into the ocean ($\tau_0$).

**Stokes-Coriolis forcing:** The Stokes drift sets up a current in the along-wave direction. Near the surface it can be substantial ($\sim 1\text{m/s}$). 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.

![Diagram showing stress and wave effects](image)
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 $n+1$:

$$S_l^{n+1} = A_s H + B_s$$
$$q_l^{n+1} = A_q E + B_q$$

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

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1) Best et al. (2004); J. Hydrometeor., 5, 1271-1278