Atmosphere-Land coupling in the ECMWF model
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• Introduction
• Land surface scheme and its coupling to the atmosphere
• Coupling of the water cycle?
• Thermal coupling

Thanks to: Anna Agusti-Panareda, Gianpaolo Balsamo, Souhail Boussetta, Emanuel Dutra, Patricia de Rosnay, Irina Sandu, and many others
Mean and standard deviation of 60- and 72-hour forecasts of 2m temperature over Europe (verified against SYNOP observations)
Mean and standard deviation of 60- and 72-hour forecasts of 2m dew point over Europe (verified against SYNOP observations)
Mean bias of 48-72 hour precipitation forecasts with respect to SYNOP’s over Europe
Forecast range at which 1-SEEPS precipitation score reaches 0.45
The tiling concept for land surface coupling

The tile scheme allows for a simple representation of surface heterogeneity.

**HTESSEL**

Hydrology - Tiled ECMWF

Scheme for Surface Exchanges over Land

**FLAKE (DWD-version)**

Fresh water Lake scheme

Each tile has its own skin temperature. The skin temperatures are solved in an Penman-Monteith type energy balance equation including ground heat flux. Fluxes are averaged according to tile fraction.
Turbulent diffusion schemes and land coupling schemes with fast surface processes (e.g. $T_{\text{skin}}$) suffer from instabilities involving the diffusion or transfer coefficients.

Example of sensible heat flux for each tile

Only partially implicit for tiles with less fraction

Fully implicit with Best et al. coupler
Best et al. (2005) land atmosphere coupling strategy
Climate; Low vegetation cover; T1279 mean:0.43; max:1
Climate; High vegetation cover; T1279  mean:0.33; max:1
Lake cover/depth

Sizeable fraction of land surface has sub-grid lakes: different radiative, thermal roughness characteristics compare to land → affect surface fluxes to the atmosphere

LAKE COVER FRACTION

- Lake cover & lake bathymetry are among the surface important fields to describe size and volume of the water bodies that are associated to thermal inertia.
- source: ESA-GlobCover/GLDBv1

<table>
<thead>
<tr>
<th>Region</th>
<th>Points</th>
<th>Fraction</th>
</tr>
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<tbody>
<tr>
<td>Canada</td>
<td>309/754</td>
<td>41%</td>
</tr>
<tr>
<td>USA</td>
<td>175/482</td>
<td>36%</td>
</tr>
<tr>
<td>Europe</td>
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<td>Siberia</td>
<td>104/467</td>
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</tr>
<tr>
<td>Amazon</td>
<td>81/629</td>
<td>13%</td>
</tr>
<tr>
<td>Africa</td>
<td>74/584</td>
<td>13%</td>
</tr>
</tbody>
</table>
Energy fluxes: Diurnal cycles
Manrique-Suñén et al. (2013, JHM)

Very good representation by the model of diurnal cycles and particularities of each surface

Main difference between lake & forest sites is found in energy partitioning
Impact of water bodies in the next IFS version

**Summer experiment**

(Temperature scores)

In CY40R3 forecast of 2m temperature are improved in proximity of lakes and coastal areas

Winter RMSE impact is positive as well but around 1% improvement

In summer the impact is estimated in 2-3% relative improvement in RMSE of T1000hPa significant up to 7 days

In summer also the Z500 mean error is reduced

**Winter experiment**

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ASCAT SSM data assimilation

de Rosnay et al. (2013, QJRMS)

- Satellite data: surface soil moisture (top cm of soil)
- Data Assimilation (DA) to retrieve root zone soil moisture
- Started in 2008 (H-SAF DVPT), operational since 2012 (H-SAF CDOP2)

ECMWF Atmospheric conditions

SYNOP
T2m RH2m

ASCAT
Surface SM
MetOp A&B

EKF
Soil Moisture Analysis on entire profile

- SYNOP and ASCAT are complementary information in the analysis

Root zone soil moisture
IFS 41r1 soil analysis: Forecast impact

15 June – 30 July 2013

Error in 40r1

Too cold

Too warm

Absolute error  diff 41r1 – 40r1

Improved

Degraded

Too dry

Too wet

T2m (K)

RH2m (%)

Model too cold / too wet in Eastern US and too warm / too dry in South Africa, Russia.
Land water storage and its link to soil hydrology

Balsamo et al. (2009 JHM)

\[
\frac{\partial TWS}{\partial t} = -\nabla Q + \frac{\partial TCWV}{\partial t} - R
\]

\[
\frac{\partial TWS}{\partial t} = P - E - R
\]

Monthly Terrestrial Water Storage (TWS) changes (left panel) for the Central European catchments Wisla, Odra, Elbe, Weser, Rhine, Seine, Rhone, Po, North-Danube (the coverage is shown in the right panel). The curves are for TESSEL (GSWP-2-driven, green line), H-TESSEL (GSWP-2-driven, blue line), TESSEL in ERA-40 (black dashed line). The red diamonds are the Hirschi et al. (2006) monthly values derived from atmospheric moisture convergence and runoff for the years 1986–1995.
Atmosphere to land coupling through the water cycle
- June, ERA-I climatology
- Average 2001-2010
- TP: Total precipitation
- E: Evaporation (up=negative)
- MCNV: Atmospheric moisture convergence
- January, ERA-I climatology
- Average 2001-2010
- **TP**: Total precipitation
- **E**: Evaporation (up=negative)
- **MC**: Atmospheric moisture convergence

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**WEATHER FORECASTS**

Valsavarenche 1 July 2015
Long integrations

- Initial date: 20030401
- 4 member ensemble (only averages are presented)
- Length: 5 months
- Two experiments with soil moisture initial conditions (set according to local soil type):
  1. Field capacity everywhere (wet)
  2. Permanent wilting point everywhere (dry)
Valsavarenche 1 July 2015

**Wet**

Evaporation (mm/day); Jun, Wet (gczp)

**Dry**

Evaporation (mm/day); Jun, Dry (gczp)

**June**

Total precipitation (mm/day); Jun, Wet (gczp)

Total precipitation (mm/day); Jun, Dry (gczp)

E

TP
Accumulated fluxes and soil moisture (top 100 cm); area USA 32-40N/99-85W

**Wet**

Expver=gczp (wet); USA1 (Lat:32-40N Lon:95-85W)

**Dry**

Expver=gcz0 (dry); USA1 (Lat:30-40N Lon:90-75W)
Precipitation July 1993
Daily 48-72 hour forecasts averaged from 5 to 29 July 1993

Precipitation
Old model
Dry soil

Precipitation
New model
Wet soil
Daily 48-72 hour forecasts averaged from 5 to 29 July 1993

Precipitation difference New-Old

Evaporation difference New-Old
Averages of daily 78-hour forecasts 9-25 July at 40N/95W, verifying at 18 UTC

**New model**
- Wet soil

**Old model**
- Dry soil
Accumulated fluxes and SM; area Europe 32-40N/99-85W

**Wet**

```
expver=gczp (wet); EUR1 (Lat:44-54N Lon:18-28E)
```

**Dry**

```
expver=gczo (dry); EUR1 (Lat:44-54N Lon:18-28E)
```
Averaged of daily 54/60/66/72-hour forecasts 9-25 July 1993
area: 28-38N/93-103W
Averaged of daily 54/60/66/72-hour forecasts 9-25 July 1993
area: 28-38N/93-103W
Diurnal cycle is large: day time mixed layer is heated from the surface and also through the inversion.

Diurnal cycle is small: during the day, moistening from the surface is to a large extent compensated by drying through the inversion.
Conclusions about precipitation / evaporation coupling over land

• Precipitation and evaporation in the ECMWF model show strong coupling in summer in extra-tropics (positive feedback)

• Quality of precipitation will also depend on quality of evapotranspiration

• It is difficult to know whether the model has realistic coupling:
  • Does evaporation respond correctly to the soil moisture (profile) ?
  • Does the convection scheme respond realistically to boundary layer moisture?
Thermal coupling of atmosphere and land
IPCC 4th assessment, projection for 2100

Scenario for GHG emissions from 2000 to 2100 (in the absence of additional climate policies) and projections of surface temperatures

Mean absolute error of minimum 2T in ECMWF short range forecasts for January 2011

Zonal mean average of absolute error of minimum 2T in ECMWF model

Global GHG emissions (GtCO2-eq/yr)

Global surface warming (°C)

Geographical pattern of surface warming

2T mean abs err of [36R4(0001)-AN(0001)]; Sunrise [Steps 24, 30, 36, 42] 20110102-20110131

(°C)

2T Error [K]

2100
How is the winter and night time cooling at the surface controlled?

1. Which fraction of radiative cooling is taken from the atmosphere through sensible heat flux and which fraction from the land surface?

2. Over what depth is the cooling distributed in the atmosphere (boundary layer depth)?
Increased diffusion of heat in stable situations

Stability (Richardson number) dependence of heat and momentum diffusion coefficients

\[ K_{M,H} = \left| \frac{\partial U}{\partial Z} \right| l^2 f_{M,H}(R_i) \]

\[ \frac{1}{l} = \frac{1}{kZ} + \frac{1}{\lambda} \]
Soil water freezing

Soil heat transfer equation during freezing

\[
(\rho C)_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \lambda_T \frac{\partial T}{\partial z} + L_f \rho_w \frac{\partial \theta_I}{\partial t}
\]

\(\theta_I\) Soil frozen water

\[
\theta_I = \theta_I (T) = f(T) \theta
\]

\[
\left[(\rho C)_s - L_f \rho_w \theta \frac{\partial f}{\partial T}\right] \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \lambda_T \frac{\partial T}{\partial z}
\]

Apparent heat capacity
Difference in 2m temperature for January 1996

From long “relaxation” integrations starting 1 Oct 1995
1994 model version

Revised BL - Control

Revised BL & soil freezing - Control
Time series of soil temperatures over Germany

1 Oct 1995 until 31 Jan 1996; Area: Germany

T_{soil, 20cm} (°C)

Day

Observations
T63 relaxation (control)
T63 relaxation (revised LTG)
T63 relaxation (revised LTG+Freezing)
Difference in 2m temperature for January 1996

From long “relaxation” integrations starting 1 Oct 1995

Effect of revised BL in 1994 model version

Effect of revised BL in 2011 model version
Difference in 2m temperature for January 1996
From long “relaxation” integrations starting 1 Oct 1995
Difference in 2m temperature for January 1996

From long “relaxation” integrations starting 1 Oct 1995

The new snow scheme (Dutra et al. 2010) has lower conductivity and therefore the winter temperature drops more over snow.

Insulating snow also increases the model sensitivity to boundary layer diffusion.

Atmospheric temperature

\[ T_{air} \]

Deep soil

\[ T_{soil} \]

\[ SH \]

\[ Q_{net} \]

\[ G \]

\[ T_{sk} \]
Summary

• Strong sensitivities have been demonstrated to boundary layer diffusion and surface coupling
• Reasonable results for temperature are obtained by optimization
• The same results can be obtained with too strong atmospheric coupling and too weak surface coupling (and vise versa)
• Given the large uncertainty in a many coupling parameters, it is likely that compensating errors exist.
• Arctic amplification will depend on relative magnitude of atmosphere and surface coupling.

Way forward:
• Consider atmosphere and land as a coupled problem and analyze relations between variables to demonstrate realism of the full system
• Use tracers as an additional constraint on the problem of atmospheric diffusion
• In all cases it implies analysis of observations in comparison to models
Energy budget over 6 hours before the “minimum temperature” (Feb 2009)

\[1 + \frac{H}{Q_n} = \frac{G_0}{Q_n}\]
Energy budget over 6 hours before “minimum temperature” (Feb 2009, land only)

\[ Q_n + LE + H = G_0 \]
Warm ERA-interim bias due to overestimated heat fluxes under very stable conditions (South Pole)
The GABLS4 Dome C (Antarctica) case in preparation: a unique opportunity to improve snow/atmosphere coupled simulations (Bazile et al.)
Data from the Boreal Ecosystem Research and Monitoring Sites (BERMS)

Three different sites less than 100 km apart in Saskatchewan at the southern edge of the Canadian boreal forest (at about 54°N/105°W):

Old Aspen (deciduous, open canopy, hazel understory, 1/3 of evaporation from understory)

Old Black Spruce (boggy, moss understory)

Old Jack Pine (sandy soil)

Thanks to the Fluxnet-Canada Research Network (A. Barr, T. A. Black, J. H. McCaughey)
Air/Soil temperatures

ERA-40 has much more temperature variation in the soil than observed.
Air temperature and snow temperatures are well connected in both ERA-40 and observations.

In ERA-40: strong response of soil temperature to air/snow temperature

In observations: weak response of soil temperature to air/snow temperature

Is the undergrowth providing an insulation layer between snow and soil?
Model and observations at Cabauw (3-hourly)

Cabauw CO2 times series

Data kindly provided by ECN/KNMI
CO2: model and observations at Cabauw (daily amplitudes of diurnal cycle)

Wind speed: model and observations at Cabauw (daily averages)
Conclusions

• To disentangle the relative role of the thermal atmosphere-surface coupling and surface-deep soil coupling it is necessary to analyse flux observations for a wide variety of surfaces (e.g. forest, low vegetation, heterogeneous terrain, snow surfaces, perma-frost).

• Diurnal cycles of CO2 can provide an additional constraint