Representing natural land surface heterogeneity in Numerical Weather Prediction and Earth System models:

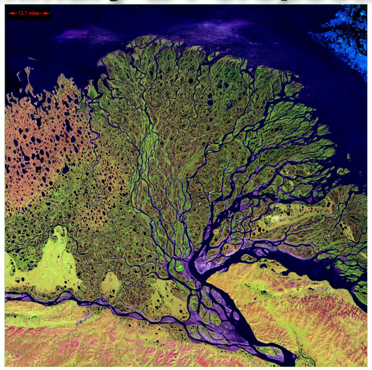
Benefits and Limitations of current schemes in presence of large contrasts

presented by

Gianpaolo Balsamo

Outline:

Introduction: about models and information cycle
TESSEL LSM scheme and its evolution
forest/snow contrasts
forest/lakes contrasts
complexity: when does it pay off?
Summary & Perspectives



Acknowledgements:

Anton Beljaars, Andrea Manrique-Sunen, Souhail Boussetta, Emanuel Dutra, Clement Albergel, Patricia de Rosnay, Anna Agusti-Panareda, Thomas Haiden

Abstract

Natural and anthropogenic variability that characterizes the Earth's surface is very much a driver for **complexity** and increased resolution in NWP and ESS models, with existing or upcoming **support** from **Earth-Observation datasets** such as those derived from MODIS, SPOT, PROBA-V, Sentinels ESA's program satellites, all attaining sub-kilometer remote-sensing capabilities. While a higher **resolution** improves the description of contrasting surfaces such as land-water or snow-forest, large part of these **contrasts** is bound to remain a **sub-grid** parameterization's issue due to fractal nature of the surface: coastlines, rivers, lakes, forests, urban-areas are rarely pure land-use categories even when approaching kilometric scales. Representing those contrasts is important for partitioning energy and water fluxes but also for carbon-exchange and therefore have received attention both in NWP and ESM. The **land surface tiling** is often a method used for such purposes as it can accommodate several parameterizations for the different surface types. We have examined the capacity of the tiling to represent large natural contrasts in presence of snow, forests and lakes, in the framework of the land surface scheme operationally used at ECMWF. The **benefits** on representing the fluxes and the **limitations** coming from lateral decoupling (lack of mixing) are highlighted in a set of field-site examples and the impact is evaluated in global sensitivity experiments. Preliminary ideas to go beyond the tiling concepts will be discussed.

Models: projection of our understanding

How do we learn?

The information cycle (from *E. Morin, "On complexity"*):

- **Information → Knowledge → Wisdom**

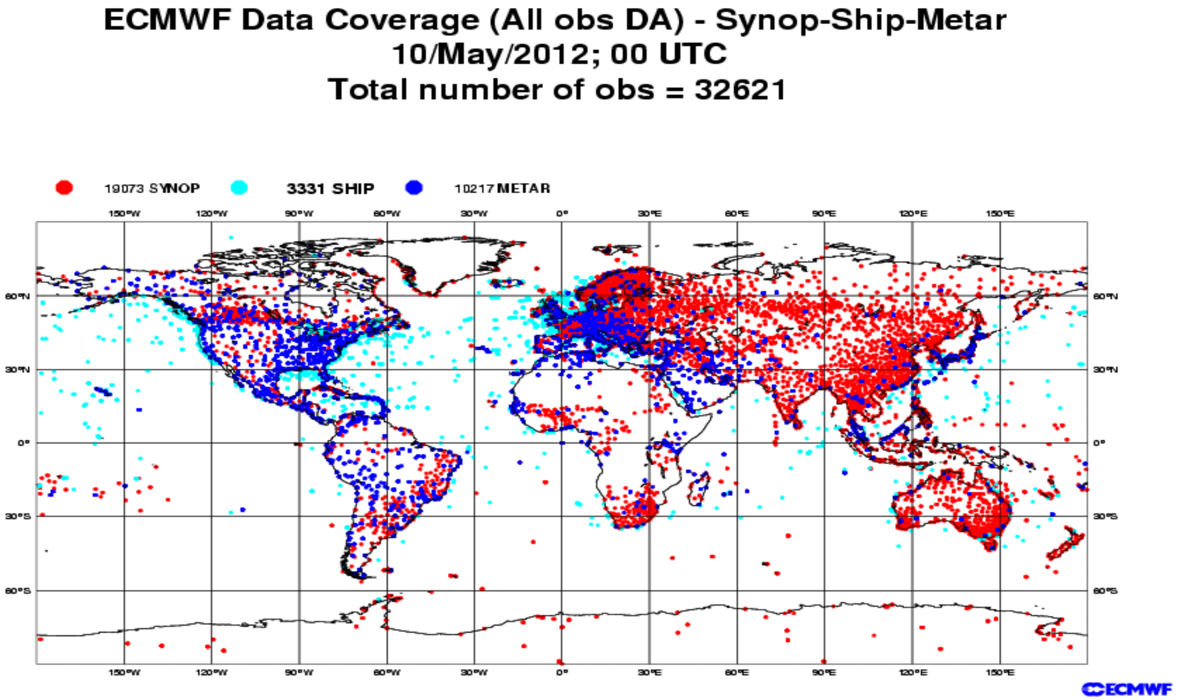
In the scientific world:

- **Data & Obs → Model → Monitor & Prediction**

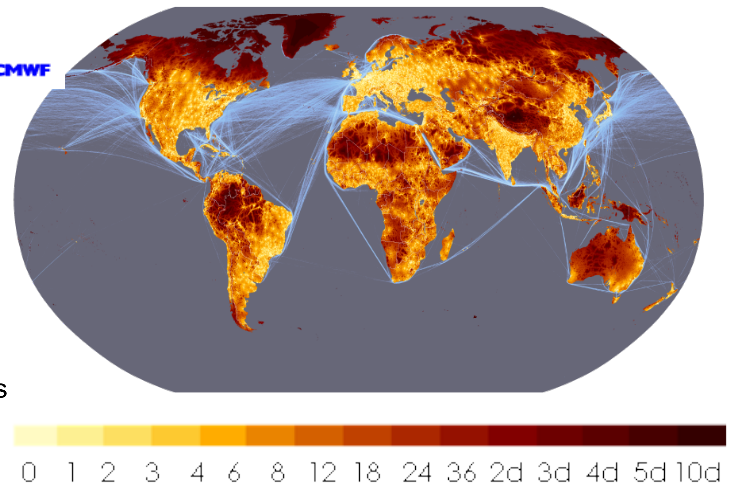
In the decision-makers world:

- **Products → Cost-Loss → Action & Planning**

The conventional surface observations



Surface based conventional observation networks are sparse and heterogeneous in coverage.



Travel time to major cities
(>50k inhabitants)
expressed in hours/days.
Source:JRC

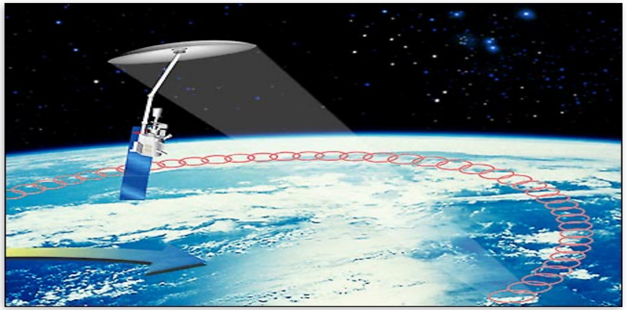
Land surface satellite remote sensing

Great potential to have a more homogeneous coverage of the land surface…several challenges in extracting information content

L-band Tb

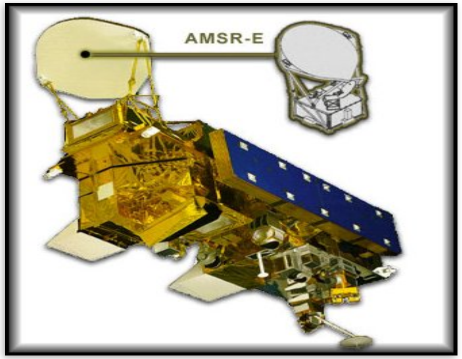
SMOS ESA mission

SMAP NASA mission



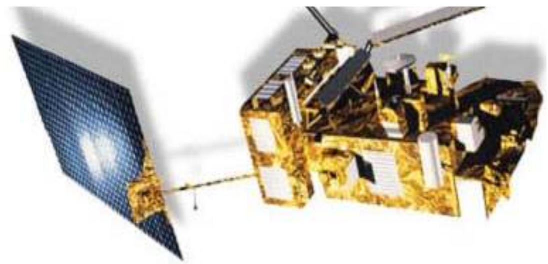
C-band passive Tb

AQUA AMSR-E instrument (05/2002)



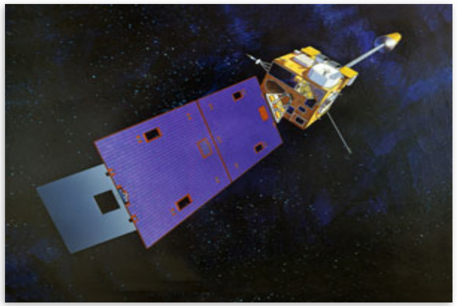
C-band active

MetOP ASCAT (2008-)

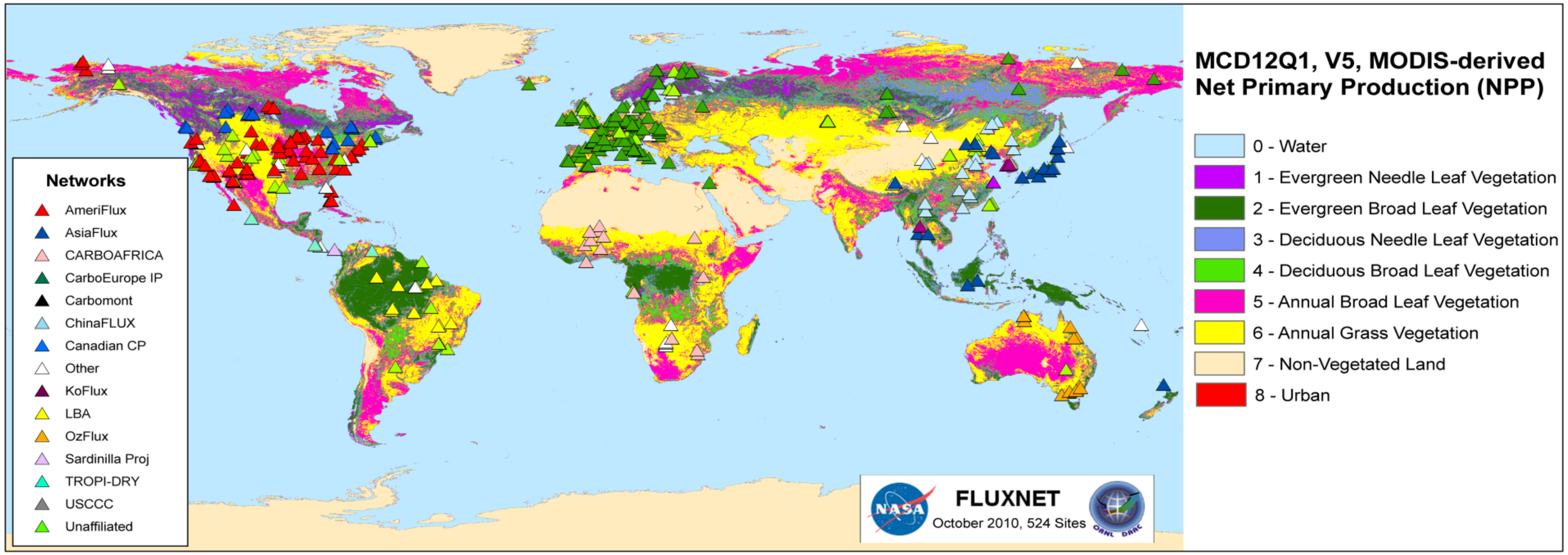


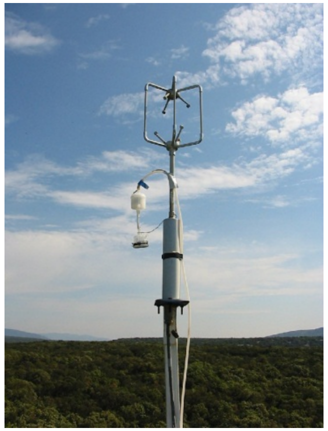
IR Ts

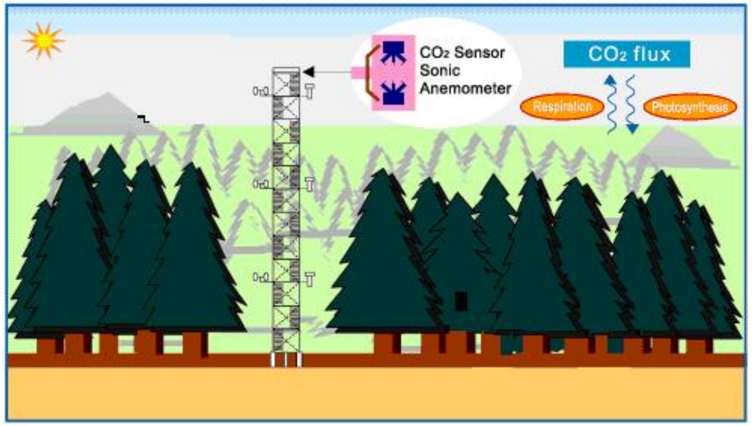
GOES-E GOES-W
MSG MTSAT



FLUXNET: An example of research network







The in-situ research networks are also fundamental for “fit-for-purpose” model development.

Another good example is the ISMN for soil moisture (maintained by TU-Wien)

ECMWF

The ECMWF TESSEL scheme (main tiles)

- Tiled ECMWF Scheme for Surface Exchanges over Land

van den Hurk et al (2000)

Viterbo et al (1999)

Viterbo and Beljaars (1995)

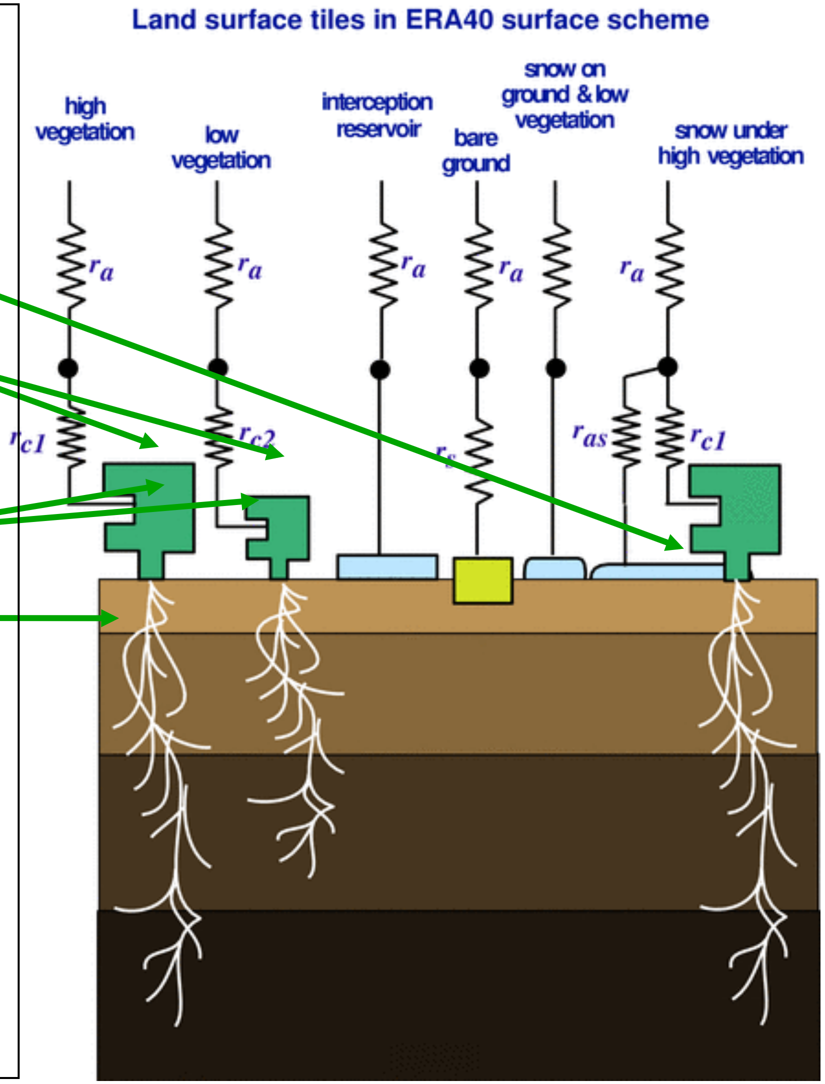
Treatment of snow under high vegetation

Canopy resistances, including air humidity stress on forest

High and low vegetation treated separately

Variable root depth

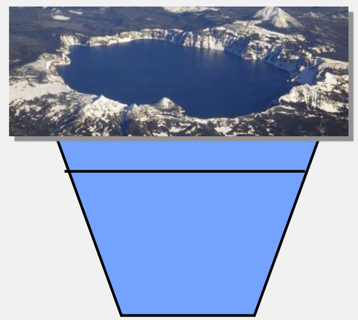
ERA-Interim LSM version (2006)



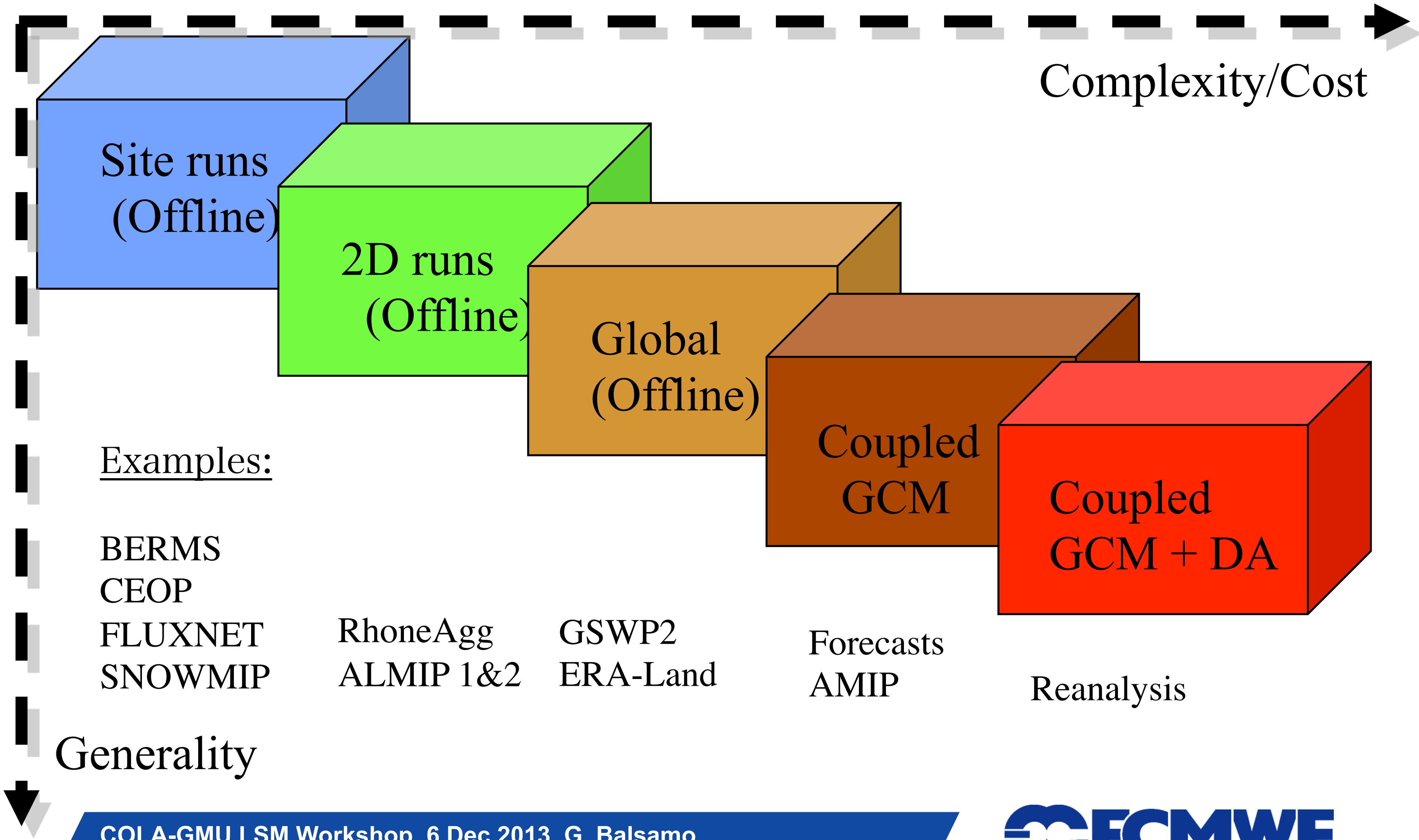
- **Lake tile (in progress)**

Mironov et al (2010),
Dutra et al. (2010),
Balsamo et al. (2010)
Balsamo et al. (2012)
Balsamo (2013)

Extra tile (9) to account for sub-grid lakes

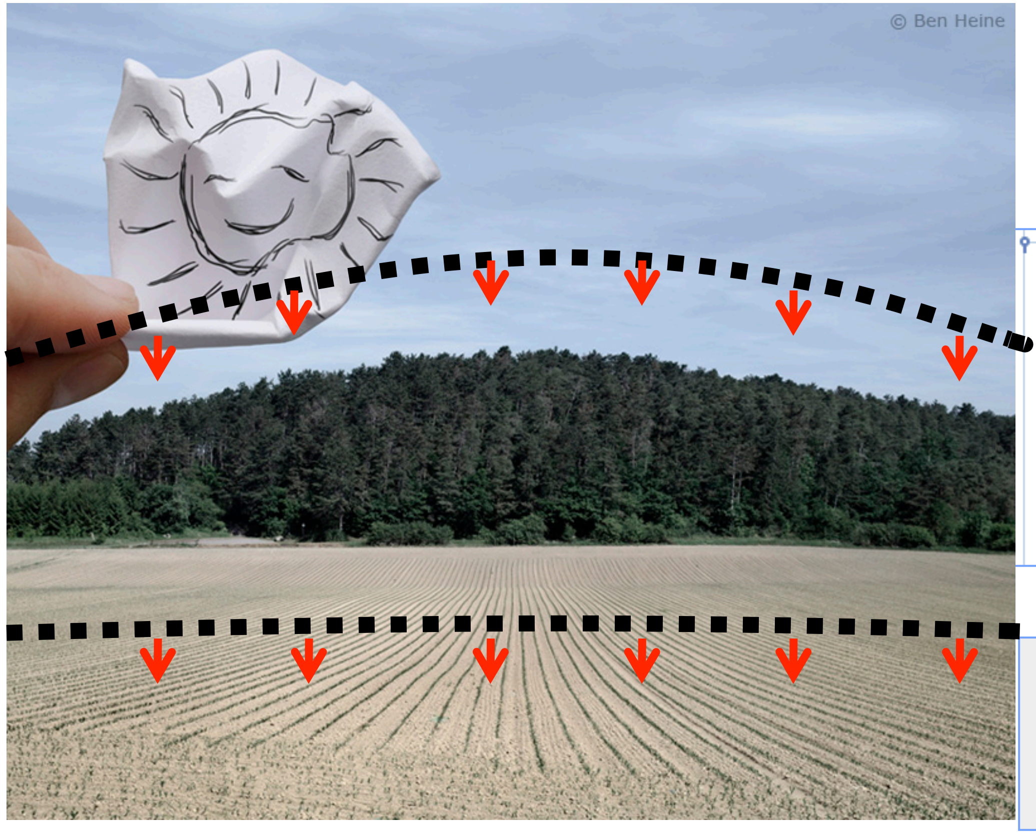


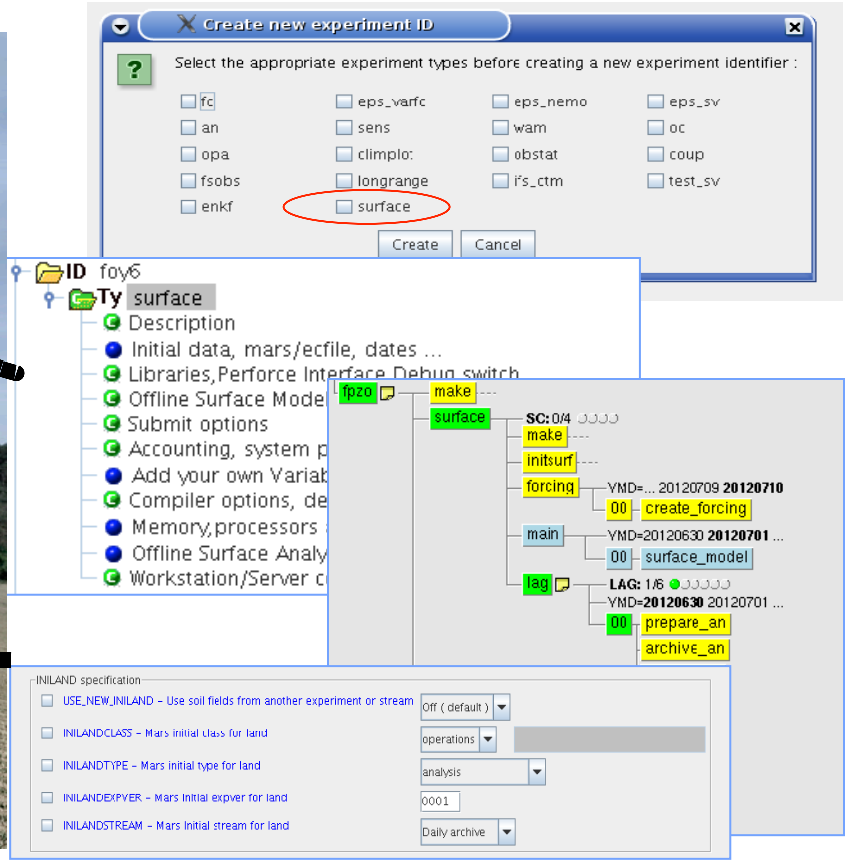
A step-wise approach to model complexity



Integration of the offline surface system

Driving the surface offline with <u>imposed meteorological forcing</u> is a practical way to break the complexity of the Earth system and it has enabled R&D at reduced computational cost. This is fully integrated in ECMWF software (PrepIFS/Xcdp/MARS) and has enabled the generation of **ERA-Interim/Land**





Balsamo et al. (2013), ERA-Interim/Land: http://www.hydrol-earth-syst-sci-discuss.net/10/14705/2013/hessd-10-14705-2013.html

Land surface model evolution since ERA-I

2007/11	2009/03	2009/09		2010/11	2011/11 2012/06

- **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. (2011)

  New satellite-based

  Leaf-Area-Index

- **SOIL Evaporation**

  Balsamo et al. (2011),

  Albergel et al. (2012)

- **H_2O / E / CO_2**

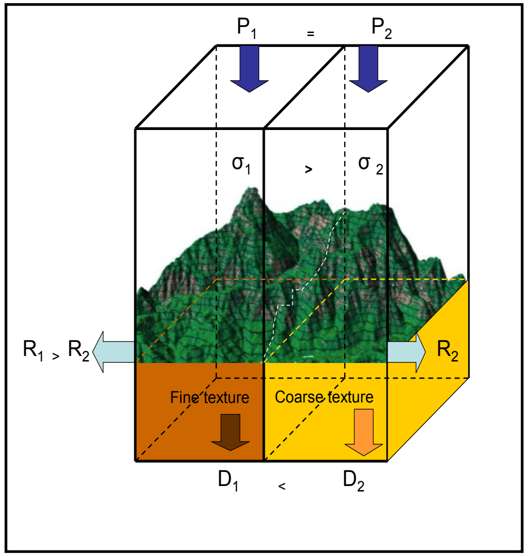
  Integration of Carbon /

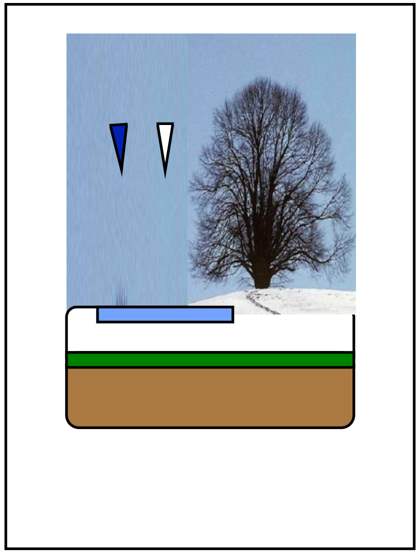
  Energy / Water cycles

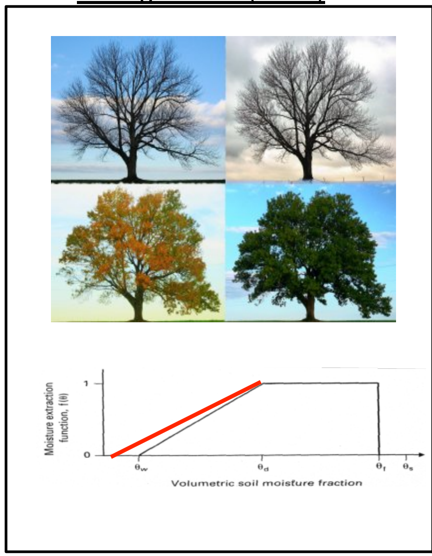
  at the surface (GEOLAND-2

  based & GMES funded)

  Calvet et al. (1998)
  Jarlan et al (2007)
  Boussetta et al. (2013a,
  Boussetta et al. 2013b)







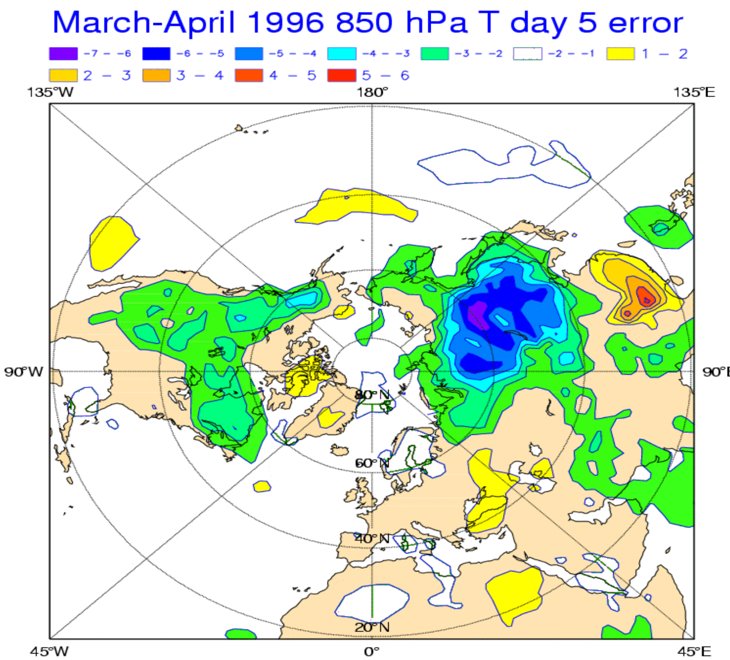
Representing land surface contrasts

- Snow-Forest
- Lakes-Forest

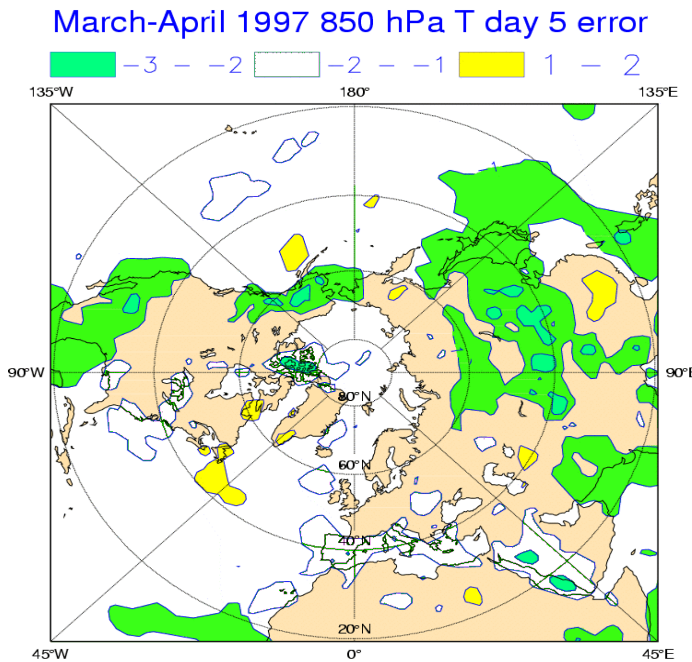
Why Forest & Snow contrasts matters?

A lower albedo of snow+forest tile in the boreal forests (1997) reduced dramatically the spring (March-April) error in day 5 temperature at 850 hPa

1996 operational bias



1997 operational bias



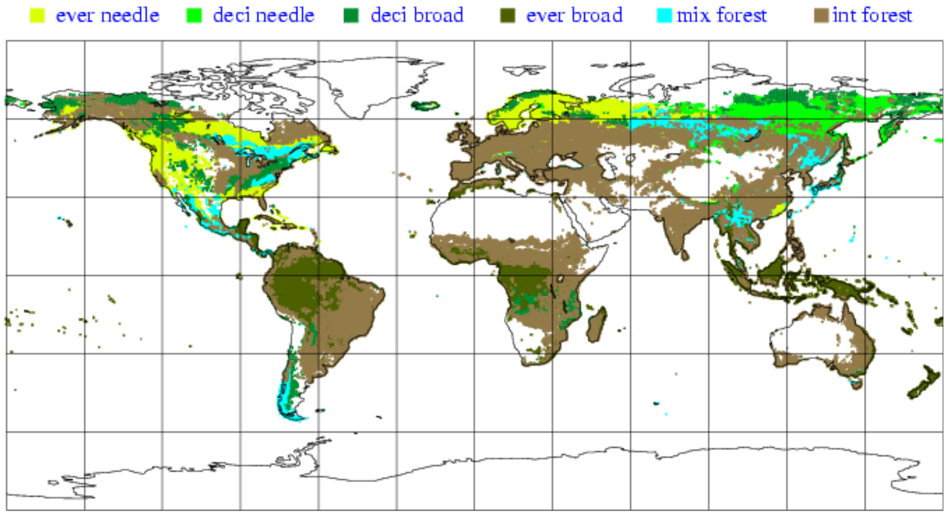
Viterbo and Betts, 1999

ECMWF

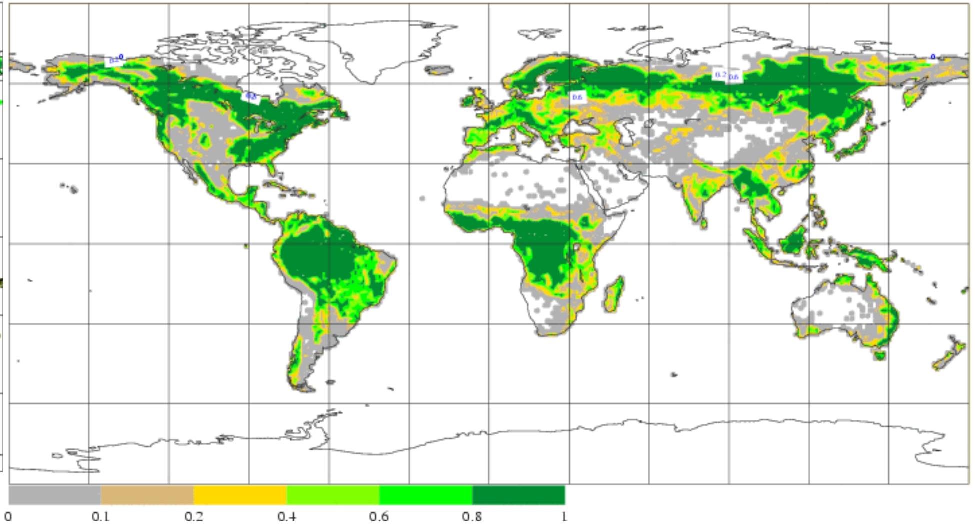
Representation of Vegetation (forest)

The dominant forest type and its cover are prescribed by GLCC v1.2 global static map (Loveland et al. 1998)

FOREST TYPE



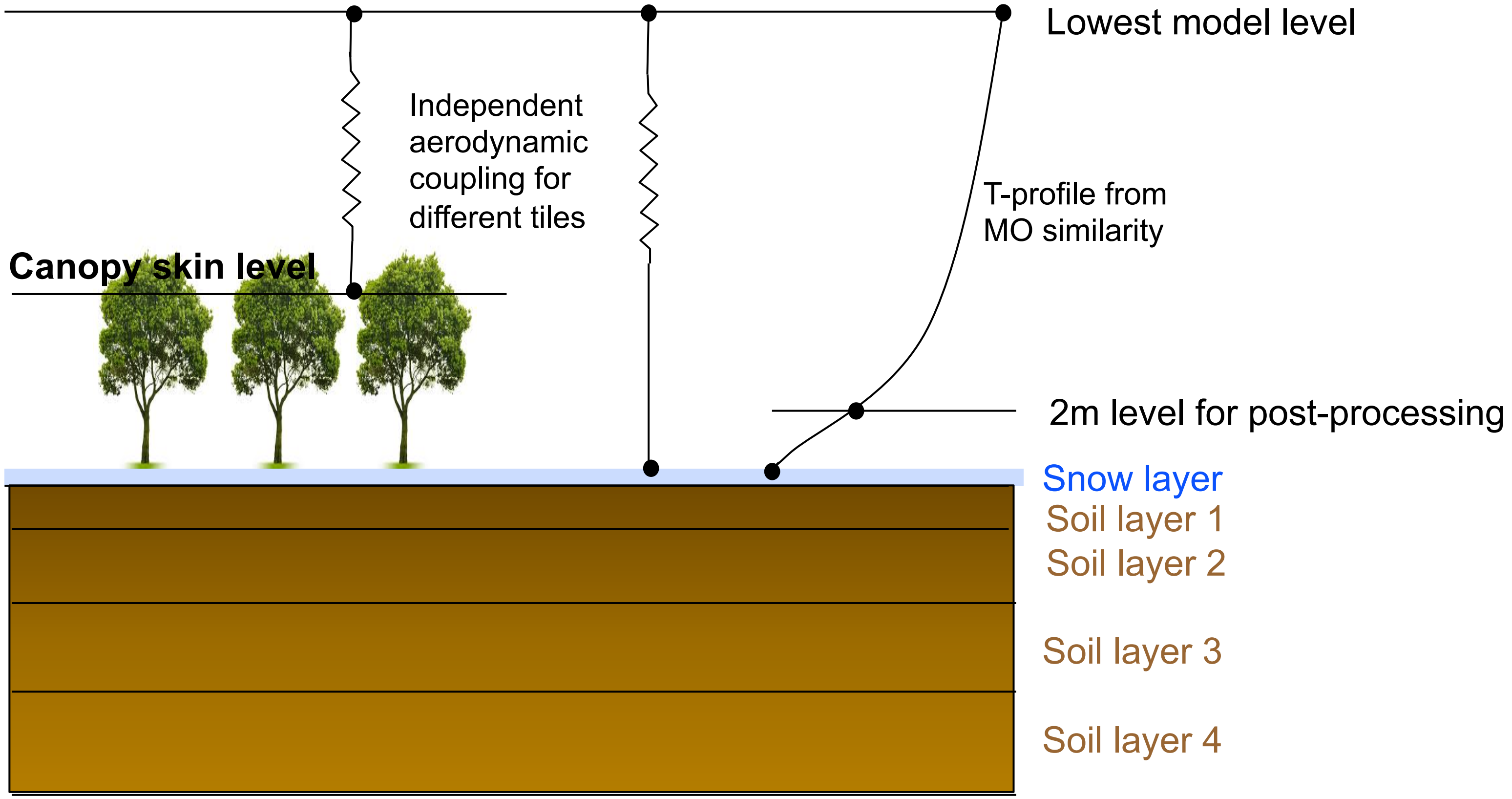
FOREST COVER FRACTION



Aggregated from GLCC 1km

Can we simulate snow-forest T contrasts?

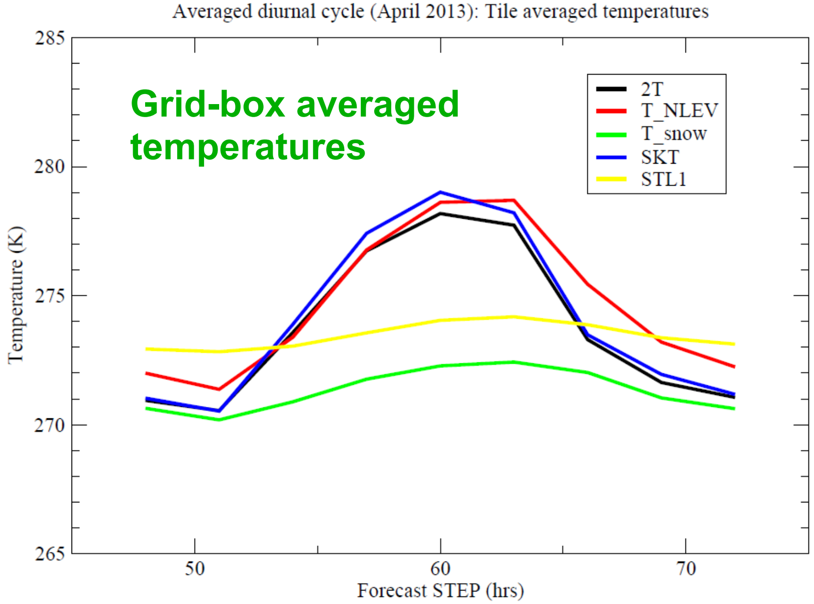
(i) tile with snow under vegetation and (ii) tile with exposed snow

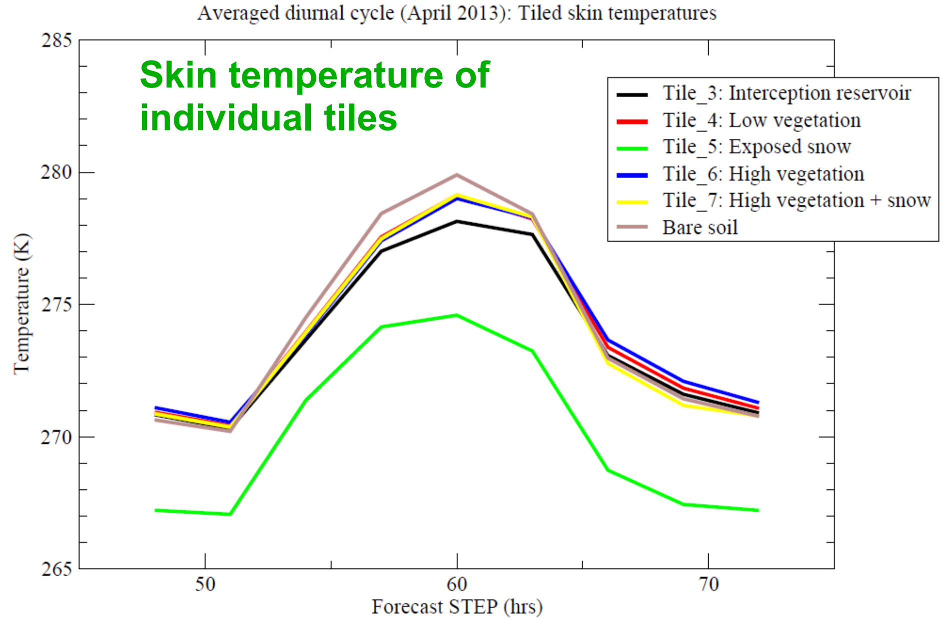


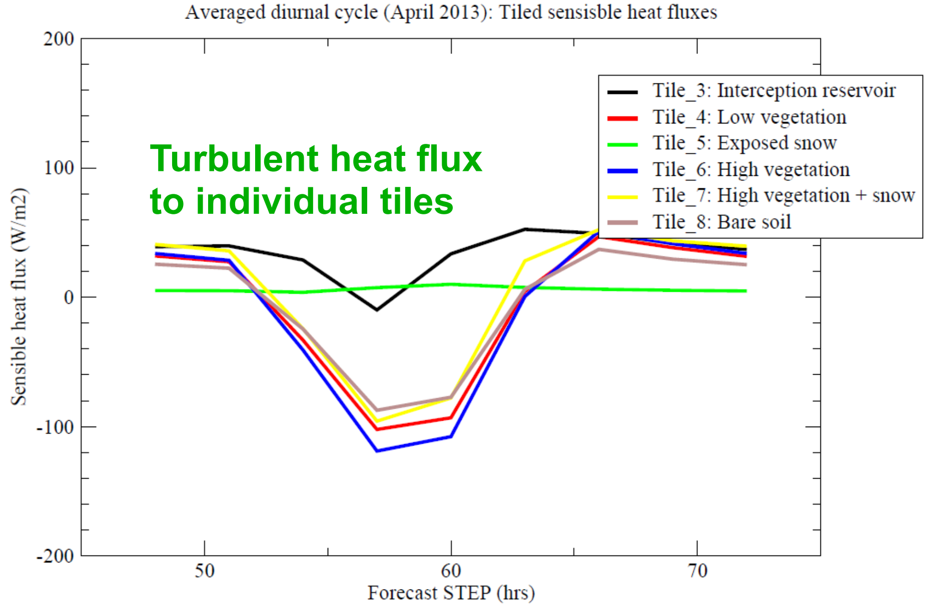
Even if the forest is dominant, the vertical interpolation to the 2m level is done for the exposed snow tile (SYNOP stations are always in a clearing).

During day time, the forest heats the atmosphere. At sunset exposed snow tile becomes very stable cutting off turbulent exchange. Therefore snow temperature and T2 drop too much. In reality forest generated turbulence will maintain turbulent exchange over the clearing and prevent extreme cooling.

Tiles temperature split is too strong

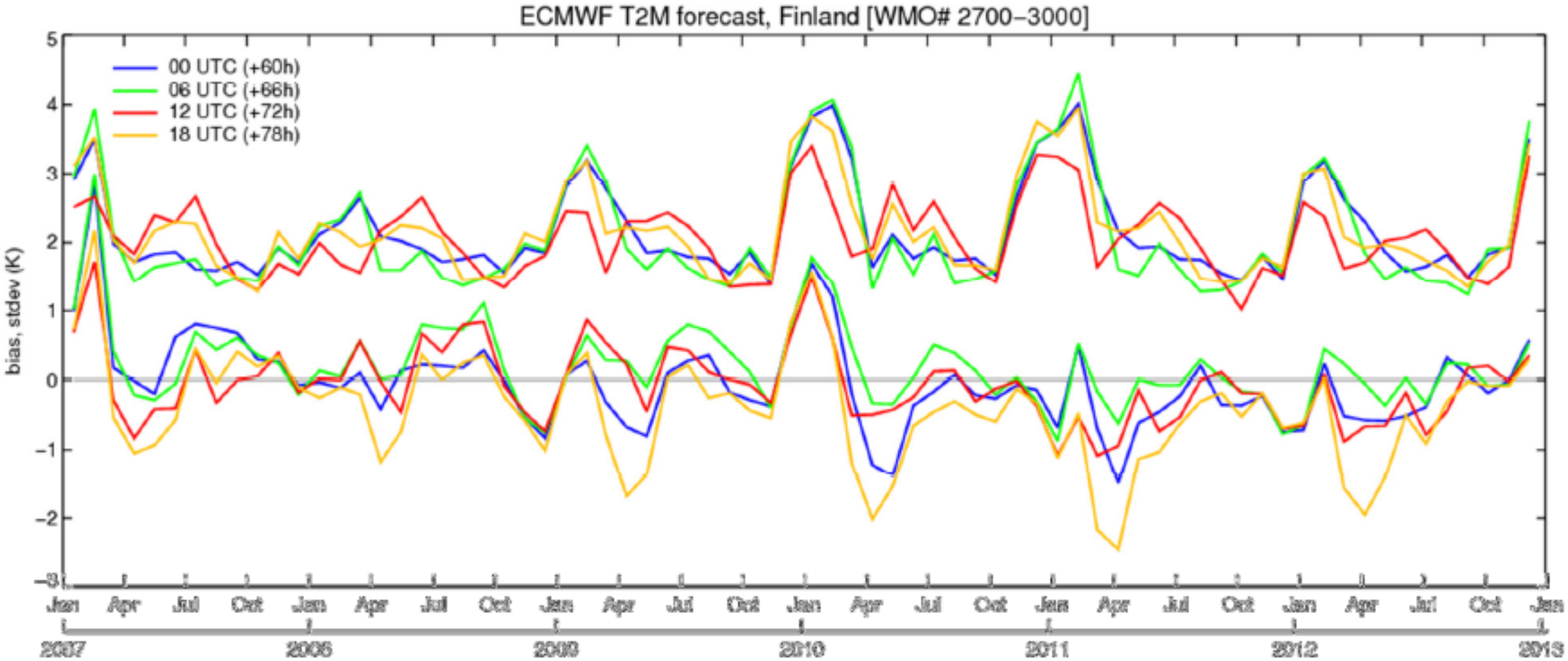






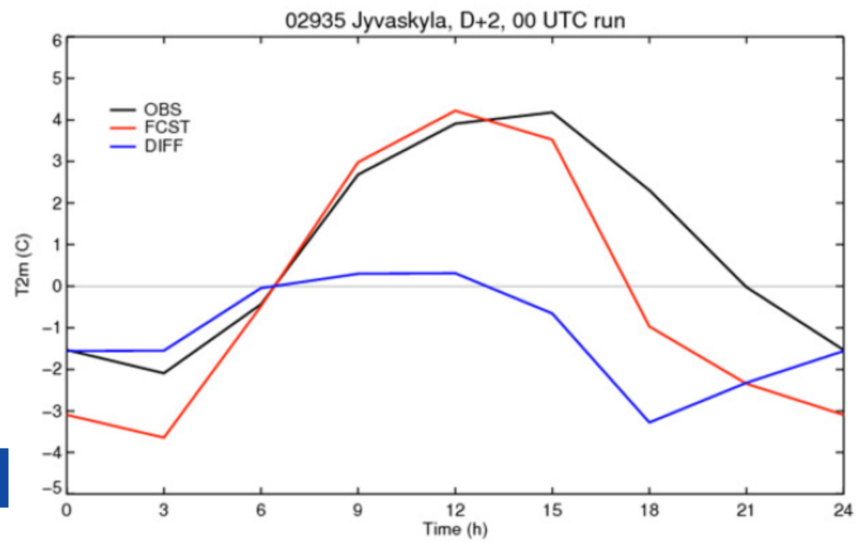
The heat flux towards the exposed snow is nearly zero!
This is unrealistic and show a shortcoming of tiling.
Do we see it in NWP scores?

Spring temperature biases over Scandinavia



Scandinavian countries show a spring time cold bias mainly at 18 UTC related to snow melt in forested areas. The bias has a distinct diurnal cycle.

by Thomas Haiden

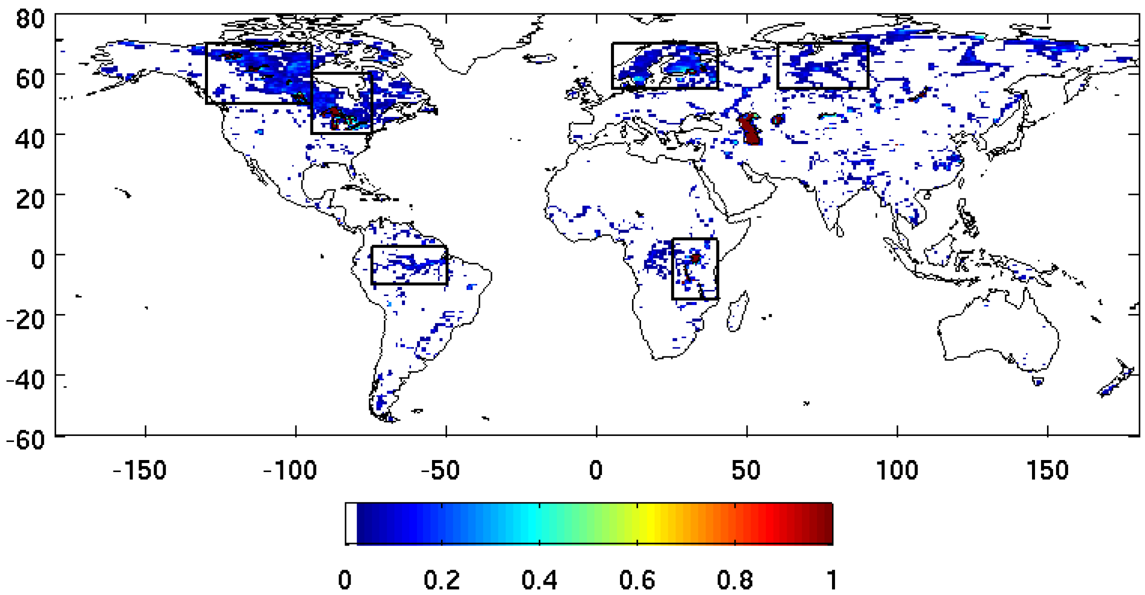


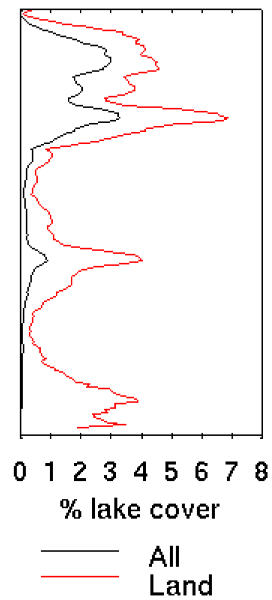
Representing lakes in LSM: Motivations

E. Dutra, V. Stepaneko, P. Viterbo, P. Miranda, G. Balsamo, 2010 BER

Motivation: a sizeable fraction of land surface has sub-grid lakes

LAKE COVER FRACTION





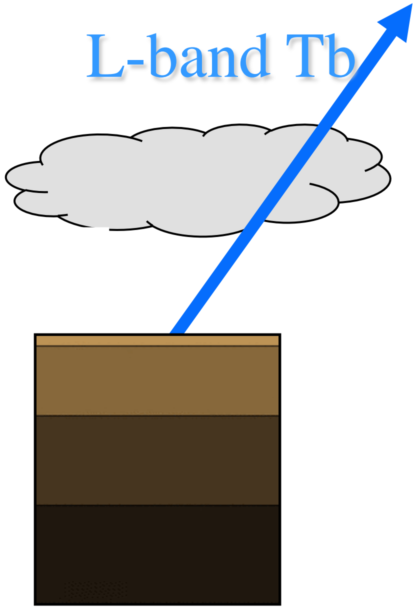
N° Points 0.05< Clake<0.5

Canada	309/754 **41%**
USA	175/482 **36%**
Europe	170/385 **44%**
Siberia	104/467 **22%**
Amazon	81/629 **13%**
Africa	74/584 **13%**

Microwave channels (and L-band in particular) is very sensitive to lake presence (even 1-2%) and lake temperature: SMOS/SMAP forward modelling impact

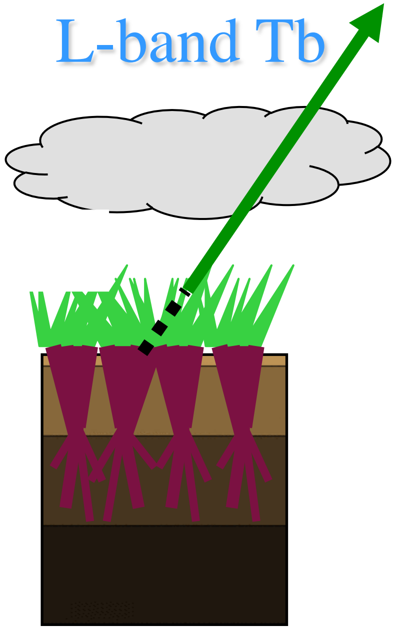
ECMWF

Microwave Remotely sensing from space: Relevance of open-water in forward modelling



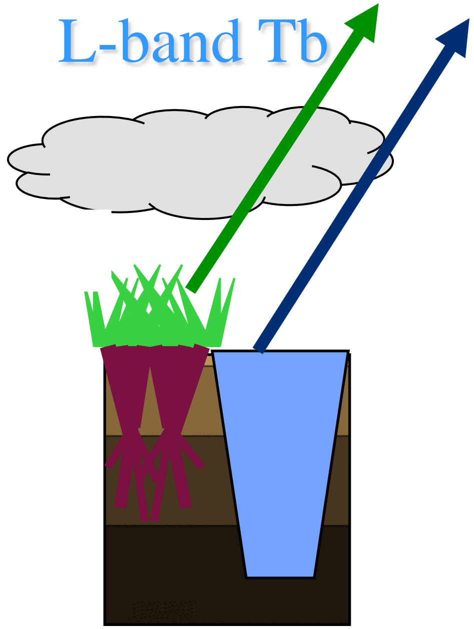
<u>Soil moisture</u> modifies
soil dielectric constant→ emissivity ε

$T_{b\_soil} = \varepsilon\, T_s$



<u>Vegetation</u> attenuates
soil emission + emits its own TB

T_b influenced by
vegetation layer [f(LAI)]



<u>Lakes</u> create a strong cold signal,
masking the signal of soil

T_b varying with lake
temperature [f (T_skin)]

	Sounding soil depth	Frequency	Wavelength	Atmospheric absorption
L-band Tb	**~5 cm**	1.4 GHz	21 cm	**Negligible**
C-band Tb	~1cm	6.9 GHz	5 cm	Low (except rainy area)

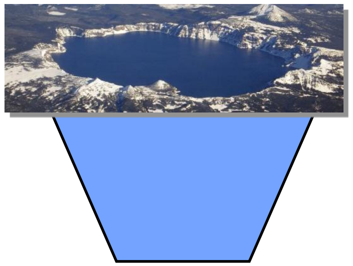
Can we simulate Forest and Lakes contrasts?

Andrea Manrique-Sunen et al (2013, JHM)

Meteorological forcing: ERA-Interim reanalysis

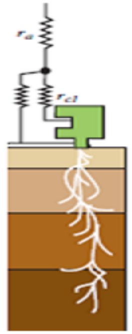
Model was run for the year 2006, doing 3 iterations

LAKEHTESSEL



Lake: Full coverage of inland water
Lake depth = 4 m
Water extinction coefficient = 3 m^{-1}

HTESSEL



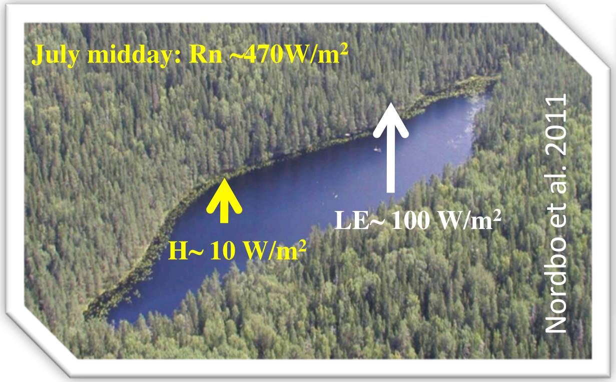
Forest: Full coverage of high vegetation
Vegetation type: Evergreen needleleaf trees
Soil type: Medium texture

Energy balance in the surface $R_n + SH + LE = G$

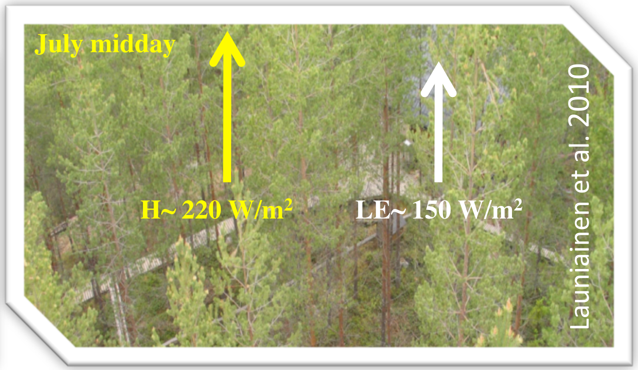
A Finnish lake case study

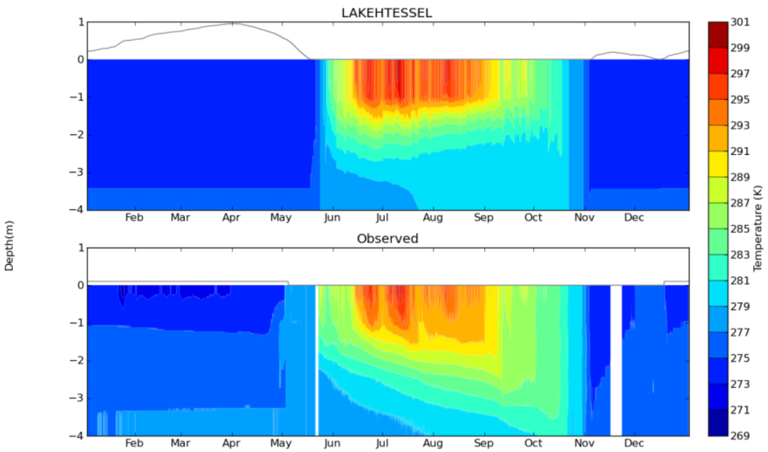
Manrique-Suñén et al. (2013, JHM)

LAKEHTESSEL



HTESSEL





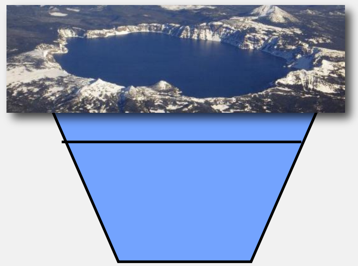
Over a lake specialized site observations can be compared with FLake (Mironov et al. 2010) model output as provided by the LAKEHTESSEL model version.

Collaboration with Annika Nordbo & Ivan Mammarella (U. Helsinki)

- **FLake**

Mironov et al (2010), Dutra et al. (2010), Balsamo et al. (2010) Balsamo et al. (2012)

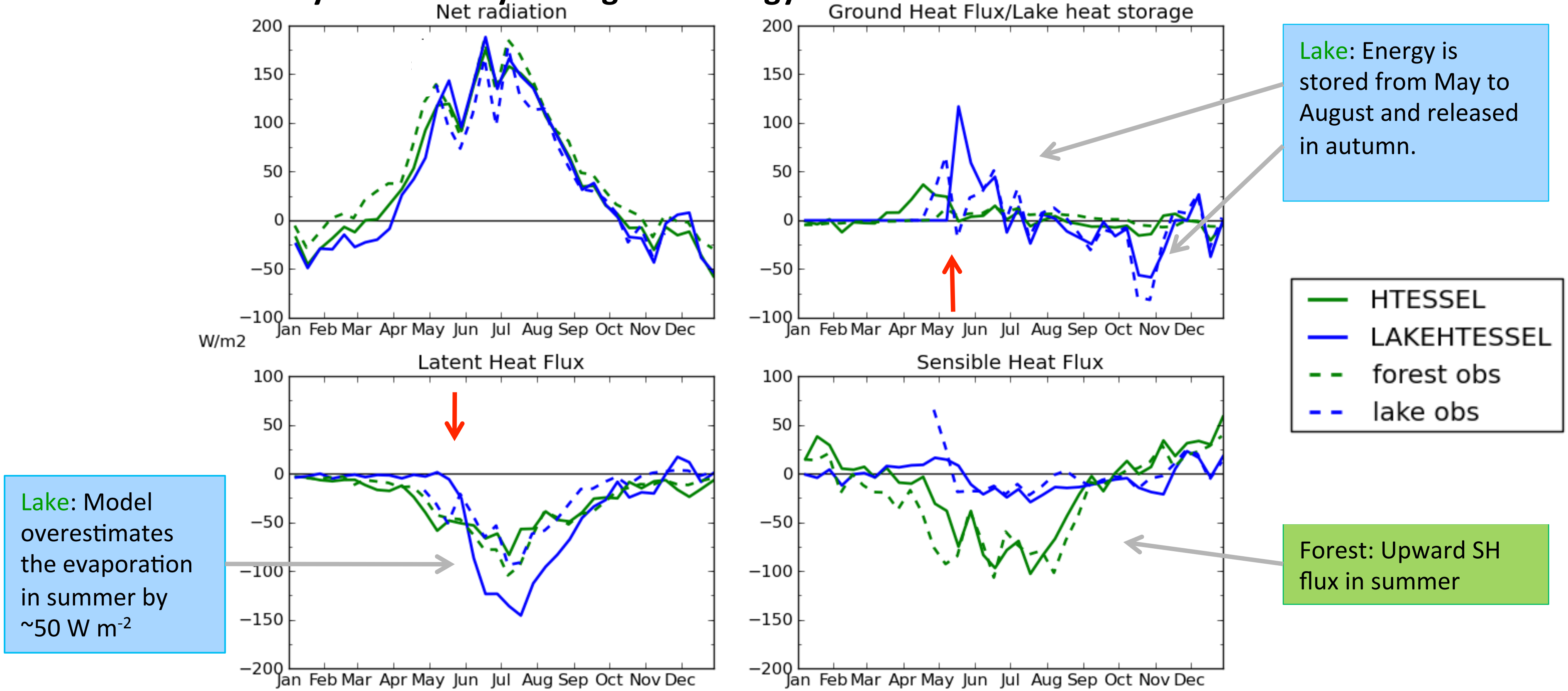
Extra tile (9) to account for sub-grid lakes



ECMWF

Energy fluxes: Seasonal cycles

Seasonal cycle of 10 day averages of energy fluxes



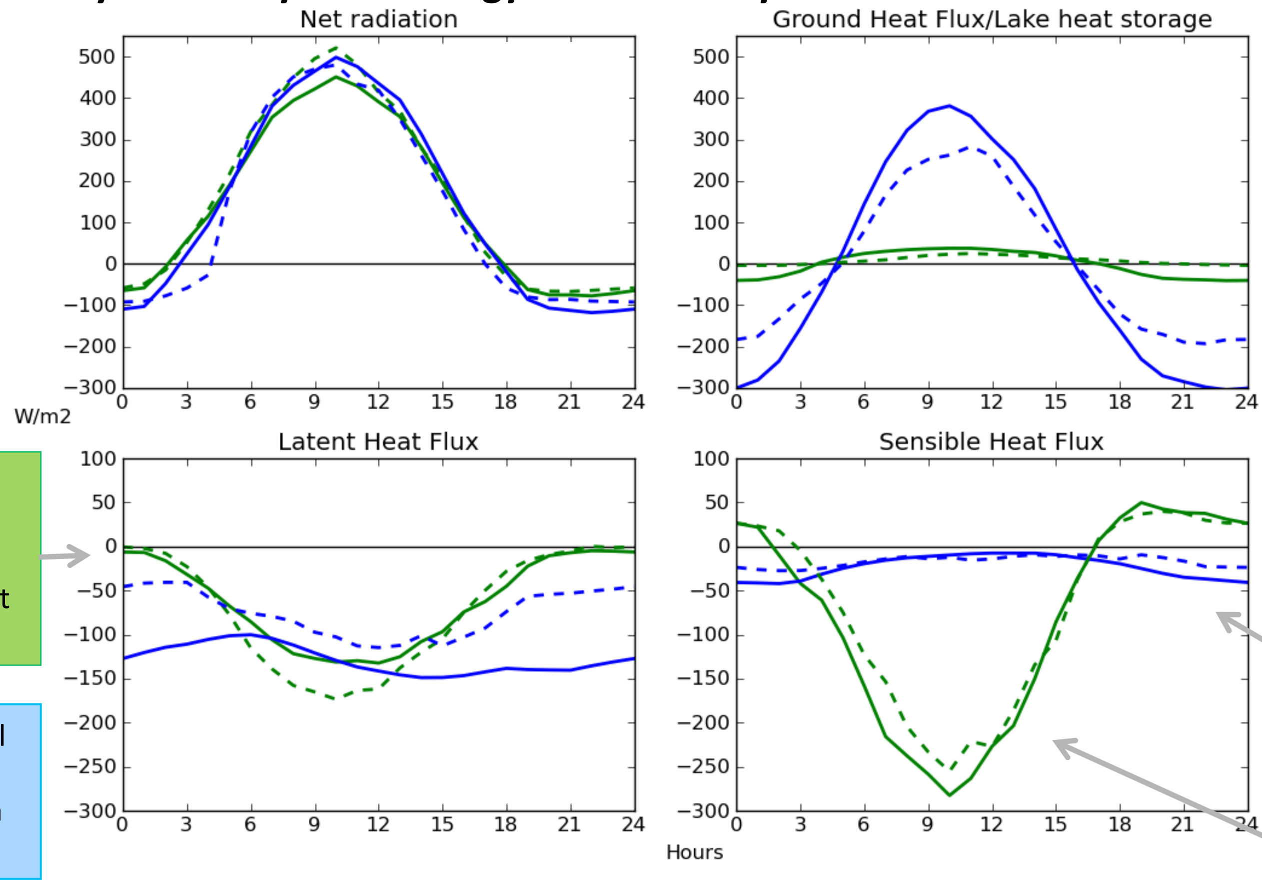
Sign convention: Positive downwards

The timing of the lake's energy cycles is influenced by the ice cover break up, and it is delayed by 14 days in the model

Main difference between both sites is found in the energy partitioning into SH and G

Energy fluxes: Diurnal cycles

Monthly diurnal cycle of energy fluxes for July



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

Forest evaporation is driven by vegetation, so it is zero at night

Lake LH diurnal cycle: overestimation in evaporation

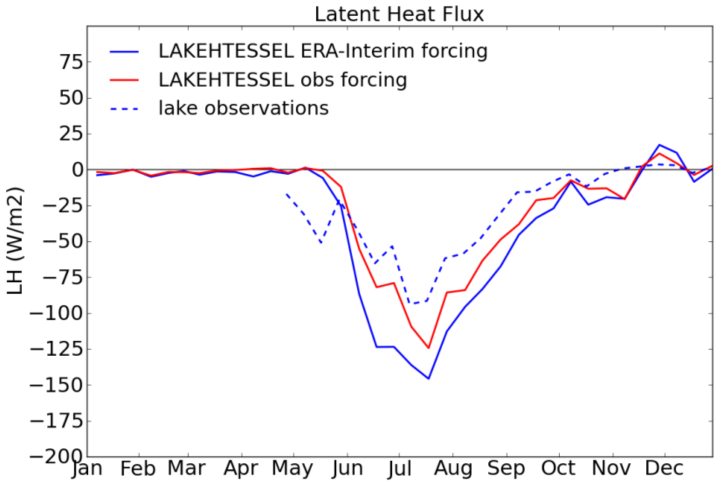
Lake SH maximum is at night

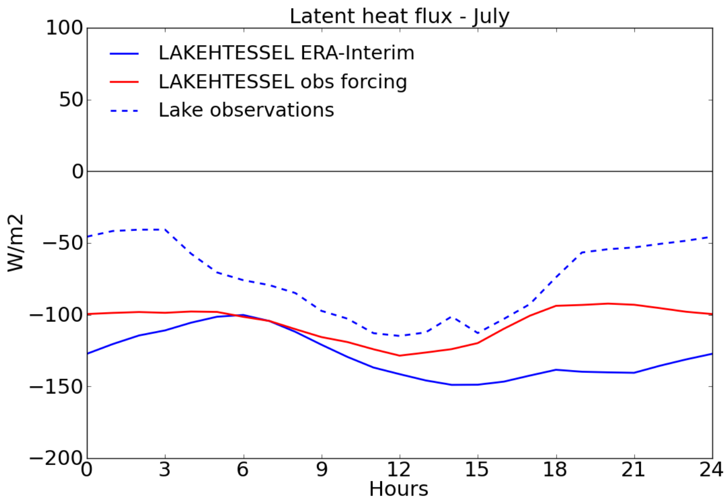
Forest SH maximum is at midday

Main difference between both sites is found in the energy partitioning into SH and G

ECMWF

Use of observed forcing vs ERA-Interim for the lake site: highlight tiling shortcoming





Seasonal cycle:
The use of observed forcing reduces the RMSE in evaporation from 32 W m^{-2} to 19 W m^{-2}

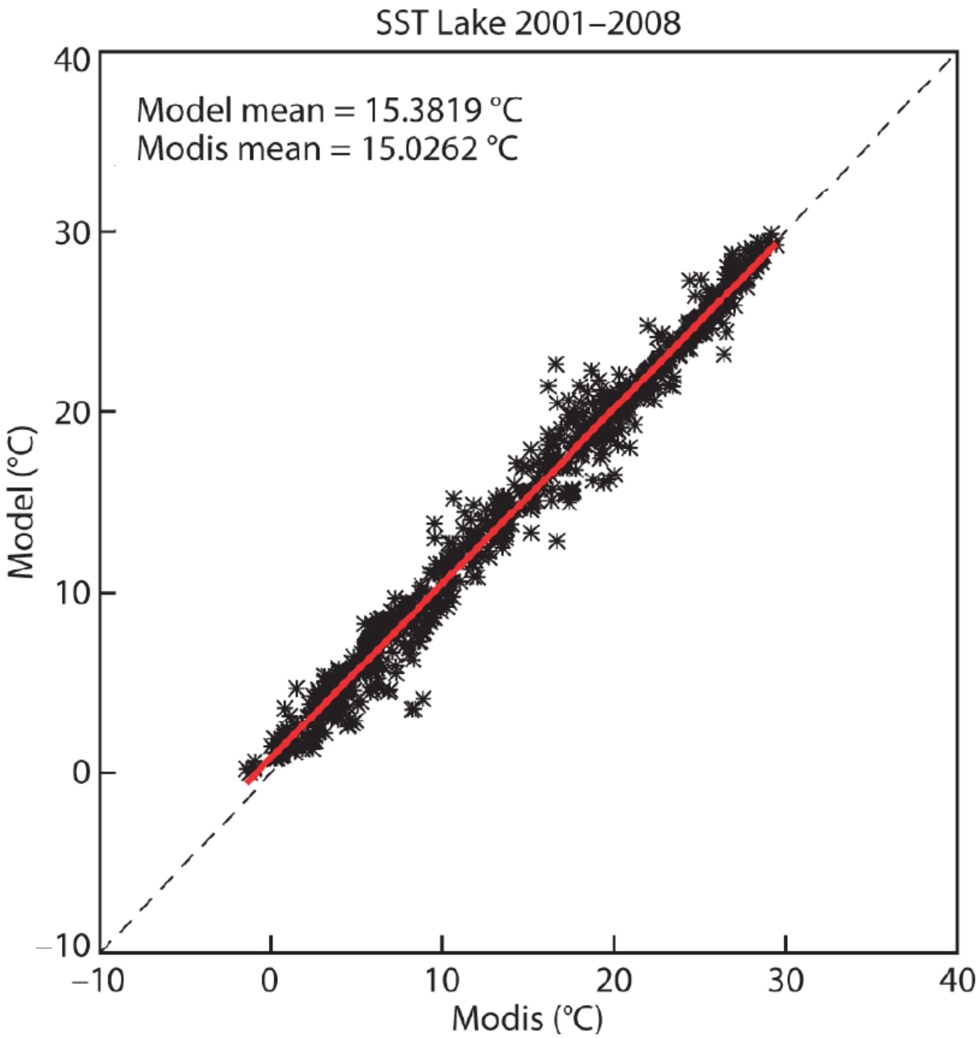
Diurnal cycle for July:
The evaporation is reduced, but errors remain at night. The model's transfer coefficients might not be appropriate for a calm situation

Manrique-Suñén et al. (2013, JHM)

ECMWF

Lakes surface temperature (global validation)

Balsamo et al. (2012, TELLUS-A) and TM 648



- FLAKE Lake surface temperature is verified against the MODIS LST product (from GSFC/NASA)
- Good correlation

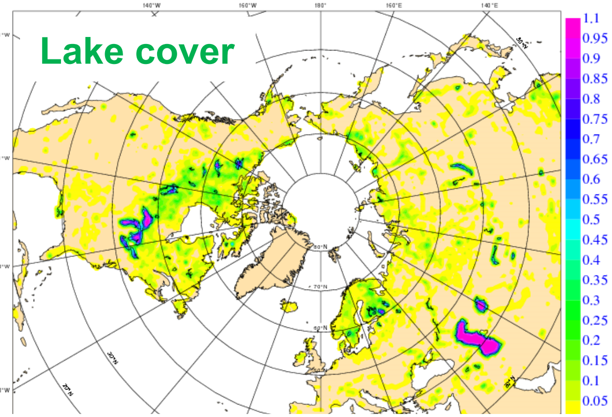
  R=0.98
- Reduced bias

  BIAS (Mod-Obs) < 0.3 K

ECMWF

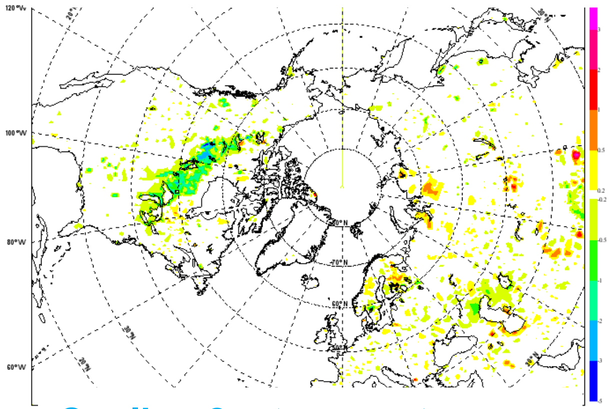
Impact of lakes in NWP forecasts

Balsamo et al. (2012, TELLUS-A) and ECMWF TM 648



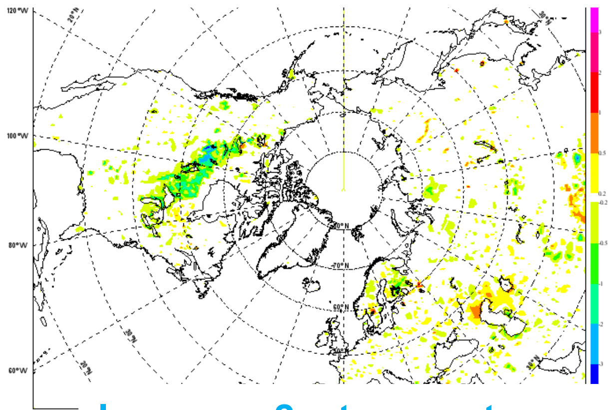
- **Forecasts sensitivity and impact is shown to produce a spring-cooling on lake areas with benefit on the temperatures forecasts (day-2 (48-hour forecast) at 2m.**

Forecast sensitivity



Cooling 2m temperature
Warming 2m temperature

Forecast impact



Improves 2m temperature
Degrades 2m temperature

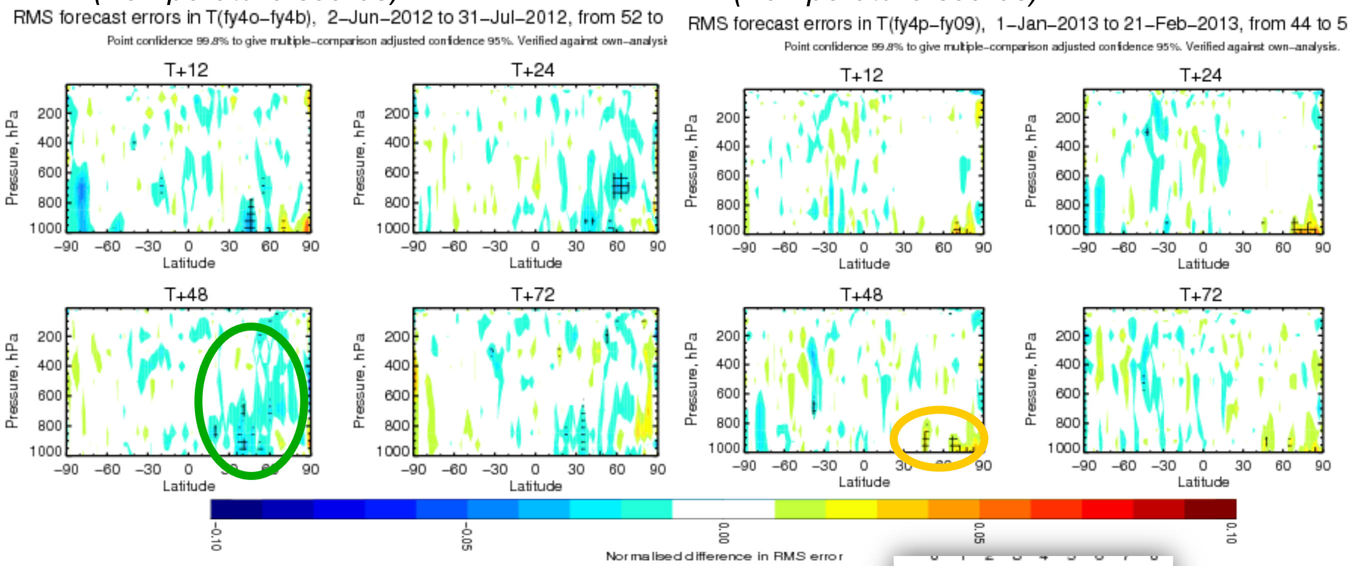
ERA-Interim forced runs of the FLAKE model are used to generate a lake model climatology which serves as IC in forecasts experiments (Here it is shown spring sensitivity and error impact on temperature when activating the lake model).

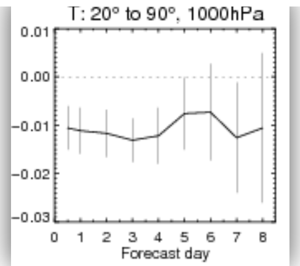
Implementation of lakes in FC/AN/ENS

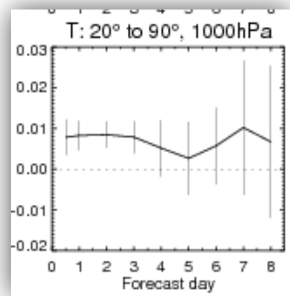
AN cycling and initialisation

Summer experiment | *Winter experiment*

(Temperature scores) | *(Temperature scores)*







- Modelling transitions of lake open water to lake-ice is very challenging and may require a careful initialisation
- Sea-ice is probably in a similar situation (predictive skill severely affected by lack of atmospheric predictability in winter)

Balsamo (2013, ECMWF Autumn Newsletter)

The initial conditions for lakes will play a very important role, and are particularly relevant for lake icing/open water.

ECMWF

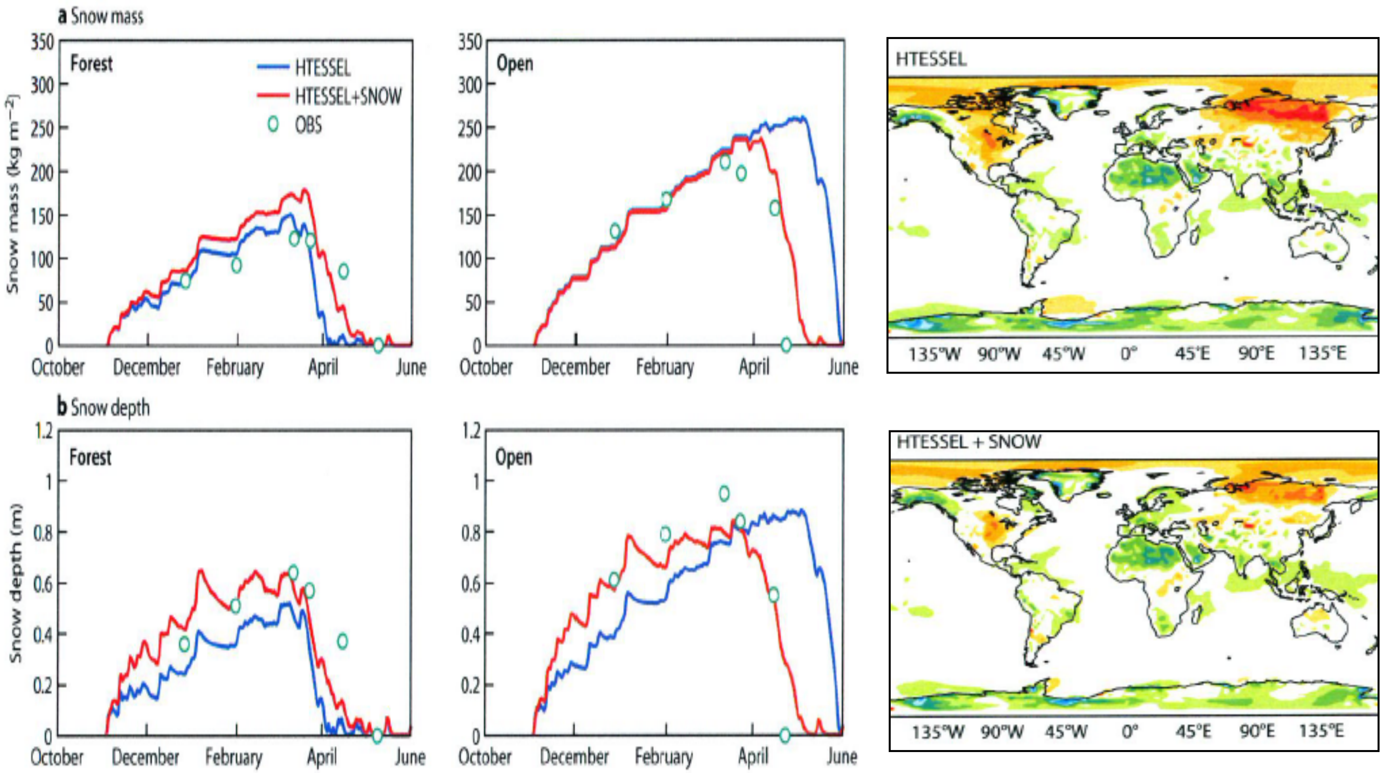
Complexity calls?

- Snow timescales and its links to hydrology

- Vegetation treatment and its links to carbon cycle

Snow: A good call for complexity?

(Dutra et al. 2010 JHM, Balsamo et al. 2011 EC-NL)



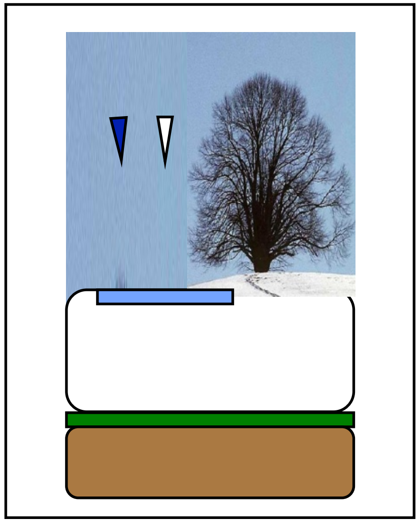
- **SL1 SNOW**

  Dutra et al. (2010)

  Improved snow density

  Liquid water (diagnostic)

  Revision of Albedo and sub-grid snow cover



The key elements of the current ECMWF snow schemes are in the treatment of snow density (including the capacity to hold liquid water content in the snowpack). The SNOWMIP 1&2 projects with their observational sites have been essential for the calibration/validation of the new scheme which was and improved with respect to the ERA-Interim snow scheme.

ECMWF

A multi-layer snow scheme (research)

(Dutra et al. 2011 JGR, Dutra et al. 2012, JHM)

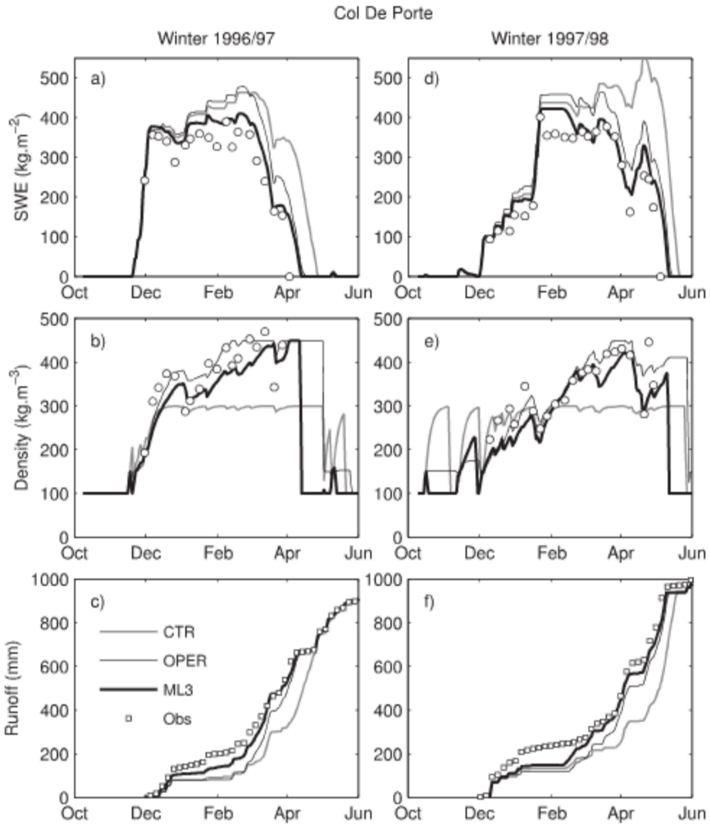


FIG. 1. Simulation results for CTR (gray), OPER (thin black), and ML3 (thick black) for the (a)–(c) 1996/97 and (d)–(f) 1997/98 winter seasons at Col de Porte site: (a),(d) snow mass, (b),(e) snow density, and (c),(f) runoff. Observations are represented by open circles. Runoff was accumulated since 1 Dec of each year and is defined as liquid precipitation and snowmelt that is in excess of the snow-cover holding capacity.

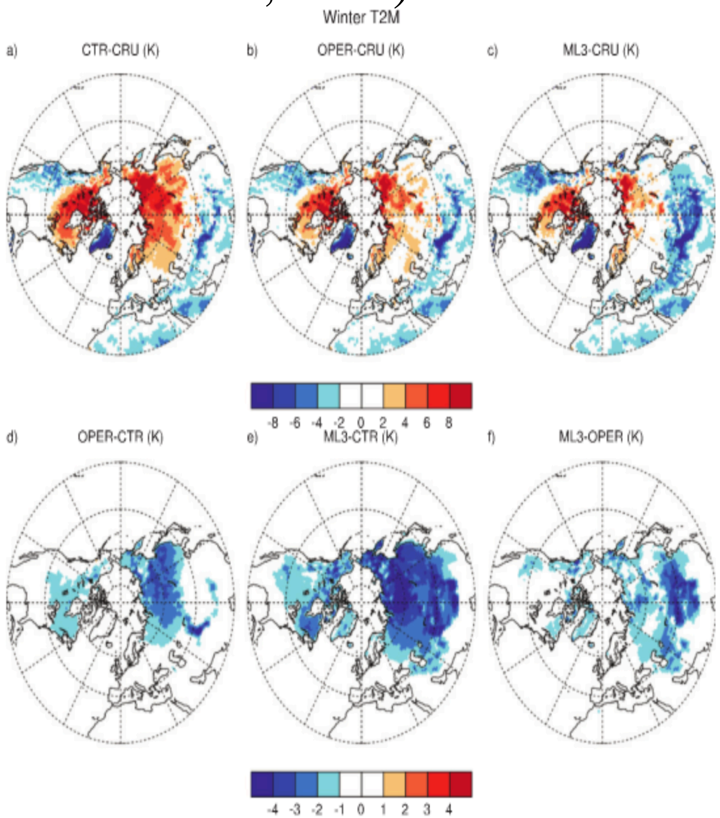


FIG. 13. Simulated winter 2-m temperature (K) biases of (a) CTR, (b) OPER, and (c) ML3 compared against CRU, and differences between (d) OPER and CTR, (e) ML3 and CTR, and (f) ML3 and OPER. Only differences significant at $p < 0.05$ are represented. Note the different color scales between (a)–(c) and (d)–(f).

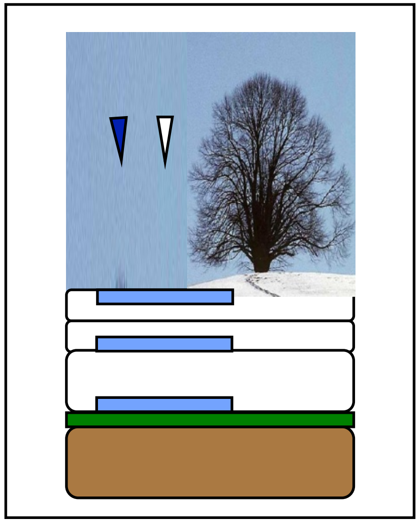
- **ML3 SNOW**

  Dutra et al. (2012)

  Up to 3 layers

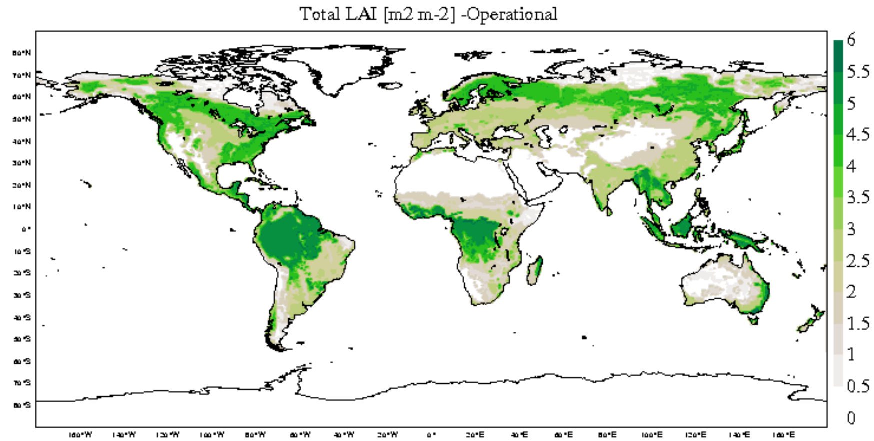
  Liquid water (prognostic)

  Larger diurnal cycles (due to



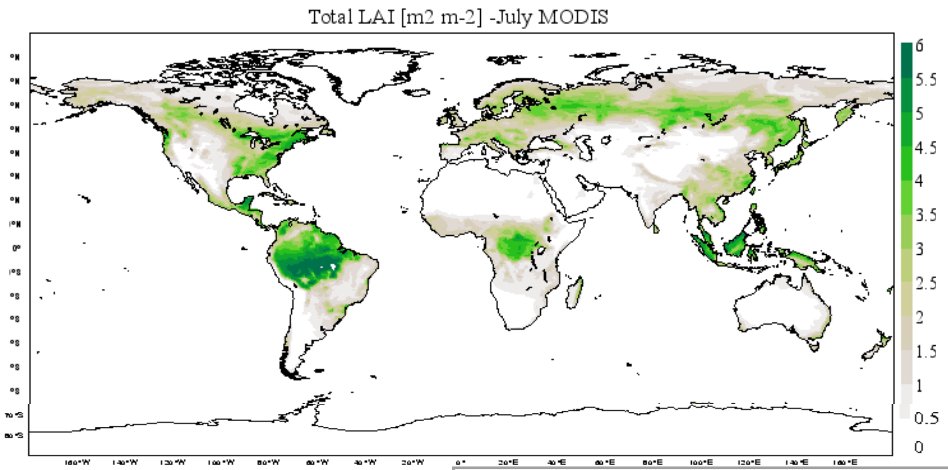
A research version multi-layer snow scheme has been developed for climate application (e.g. EC-Earth) and will be studied in EartH2Observe project. This includes up to 3 layers, an improved water cycle and further reduction of temperature bias (cooling effect in deep snow).

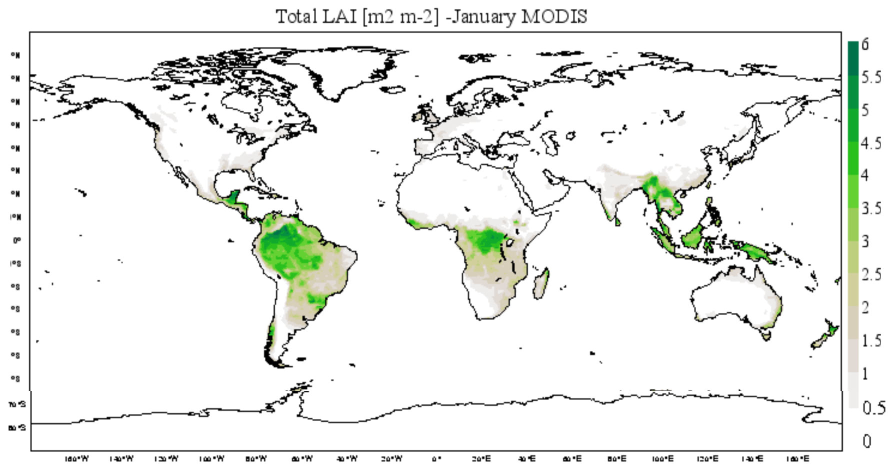
Vegetation seasonality



OPER LAI (van den Hurk et al. 2000, ECMWF TM)

MODIS LAI (Boussetta et al., 2011, IJRS, Myneni et al., 2002)

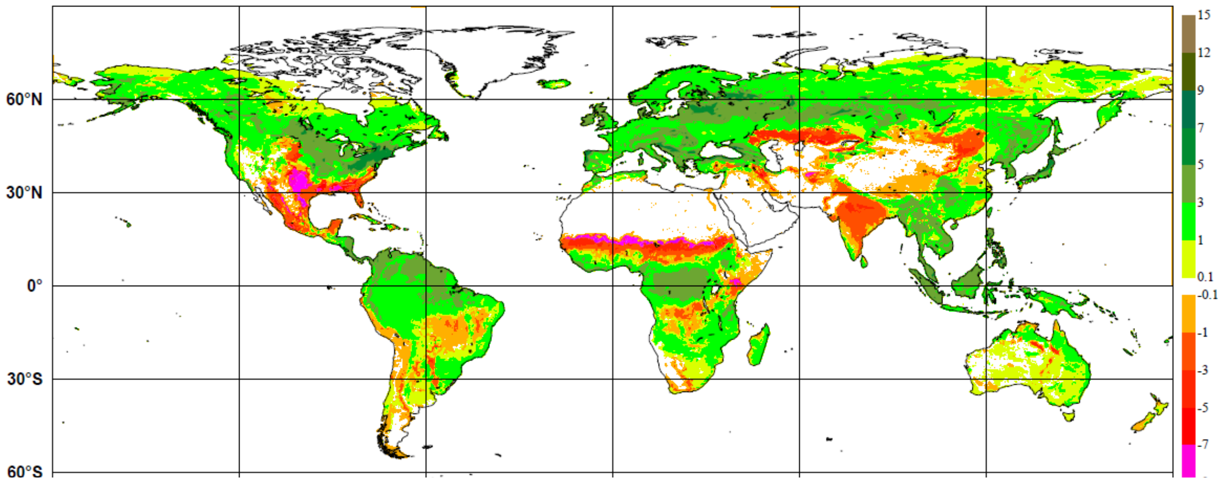




9years (2000-2008) collection 5 LAI (Jarlan et al. 2008)

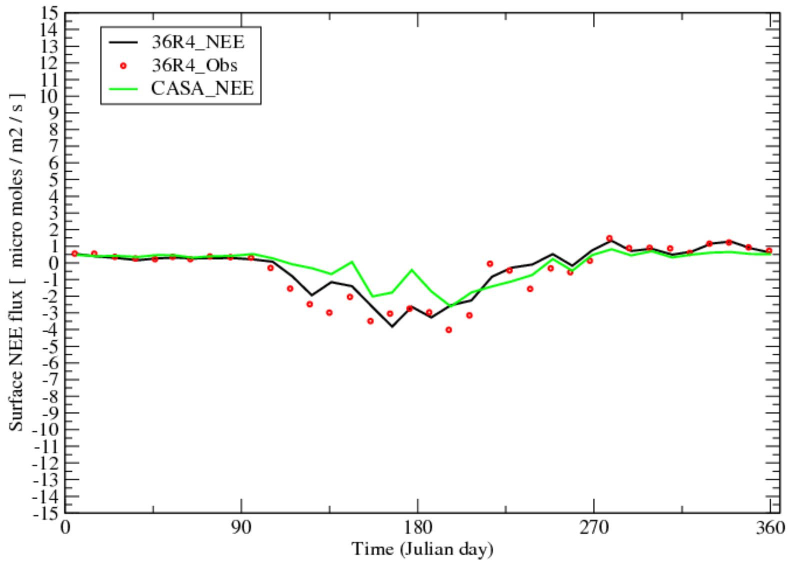
Land Carbon dioxide fluxes

Boussetta et al. (2013, JGR) and ECMWF TM 675



Example of Average 10 days forecast NEE (natural CO2 exchange) from the 1st of June 2011 extracted from the pre operational run (e-suites) [micromoles/m2/s] – Operational from November 2011

GEOLAND-2 R&D support



Example of NEE (micro moles /m^2/s) predicted over the site **Fi-Hyy** by **CTESSEL** (black line) and **CASA** (green-line)

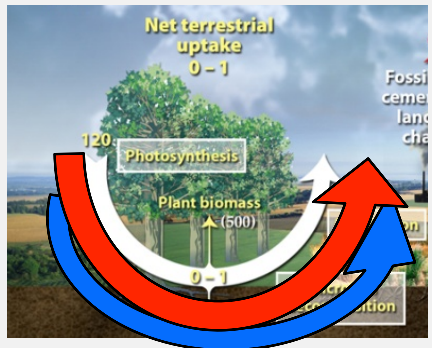
Land Natural CO_2

land carbon uptake

Calvet et al. (1998)

Jarlan et al (2007)

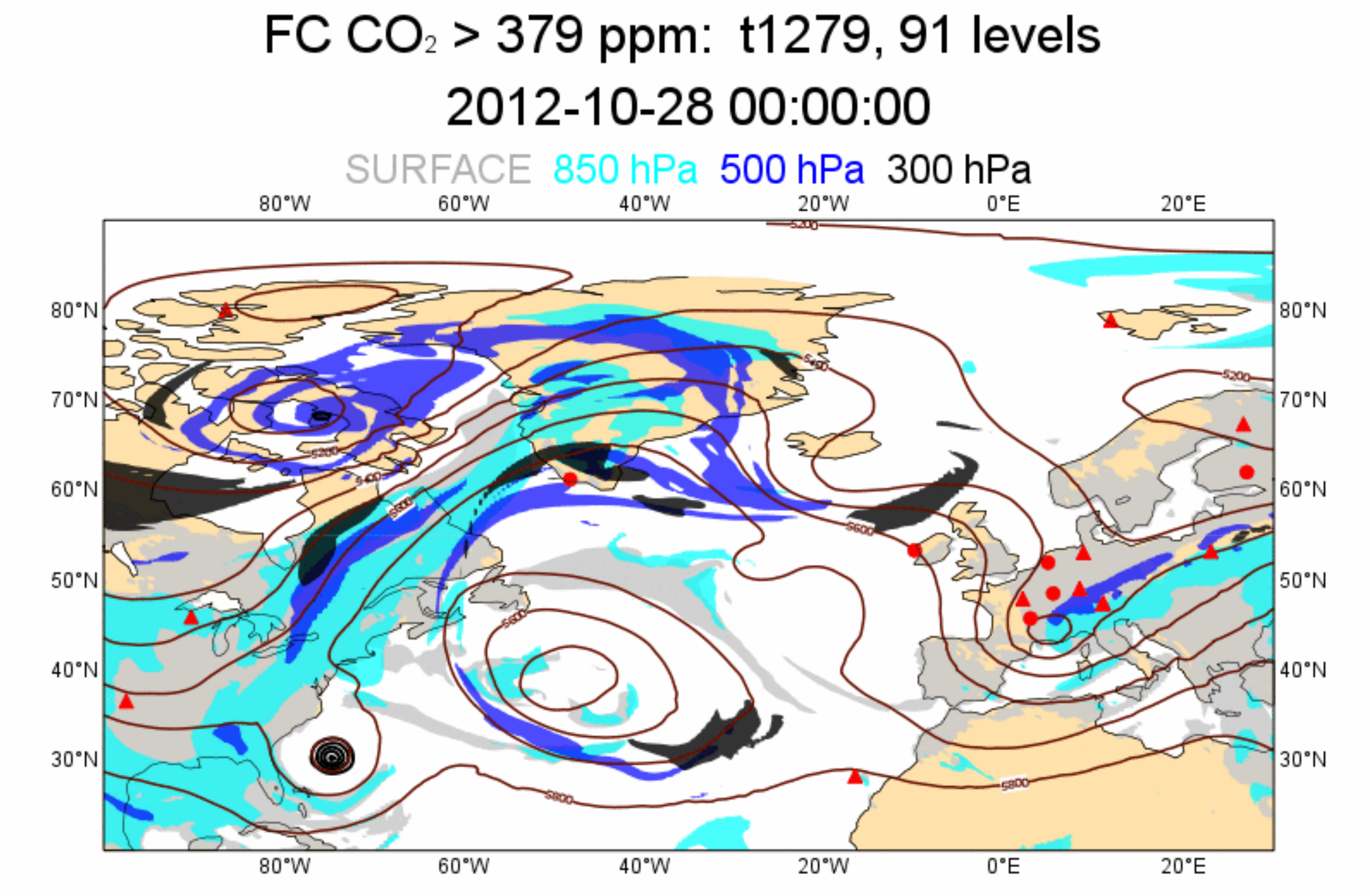
Boussetta et al. (2013)



Near Real Time CO_2 concentration & meteorology

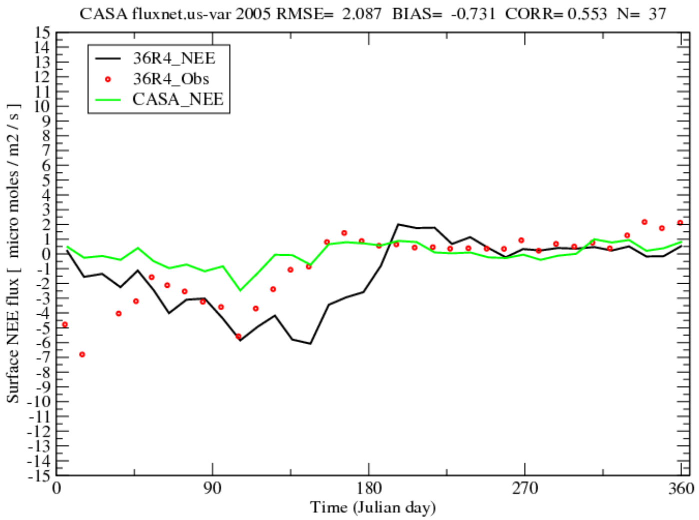
Agusti-Panareda et al. (2013, ACP)

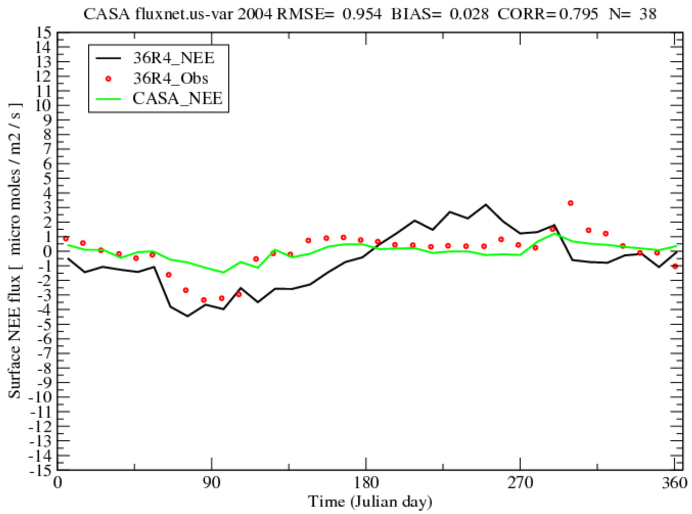
Hurricane Sandy (2012) from different perspective



ECMWF

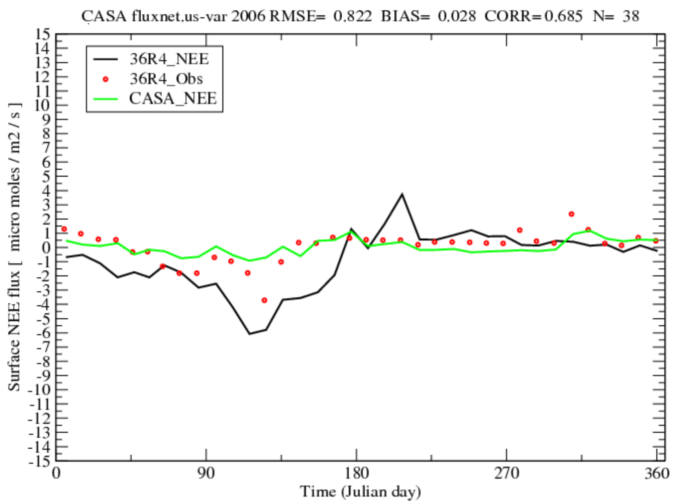
Current shortcomings: LAI variability?





Comparison of 3 different years show the current shortcoming of the use of LAI climatology => presence of large interannual variability? Harvest period not matched?

NEE (micro moles /m^2/s) predicted over the site US-Var by **CTESSEL** (black line) and **CASA** (green-line)



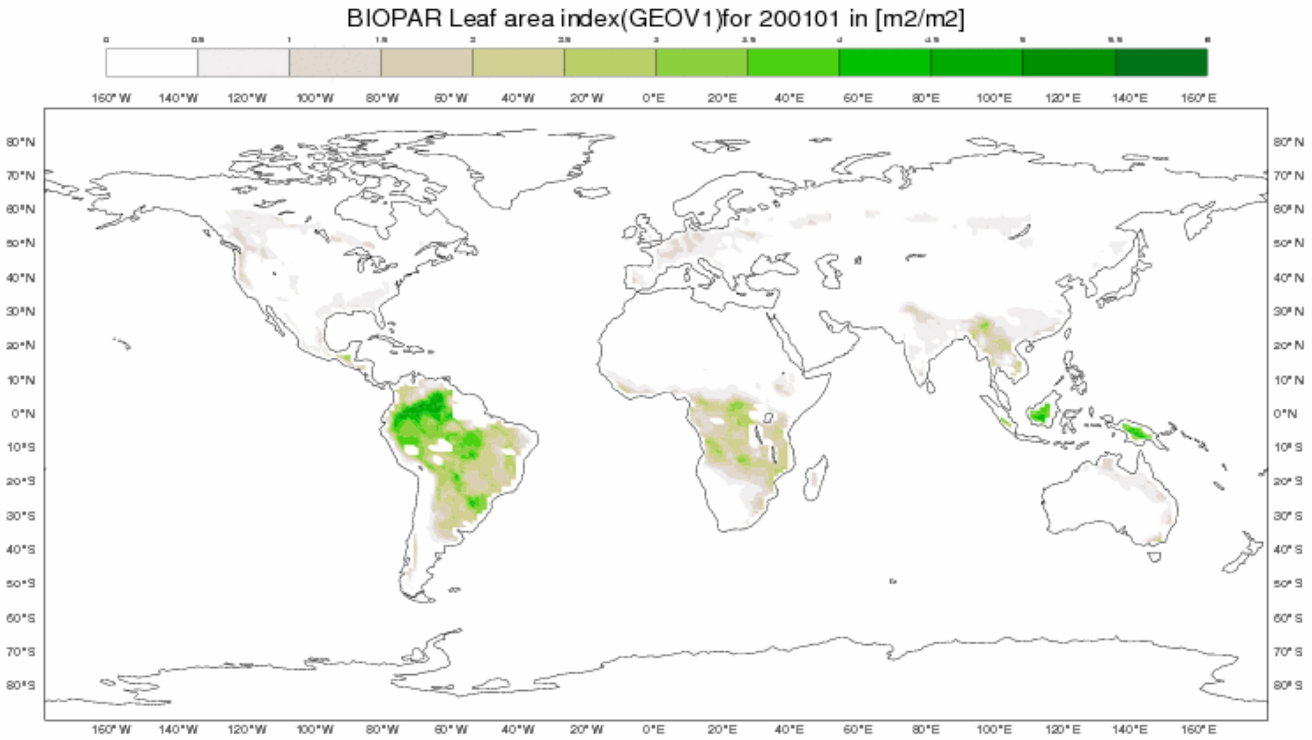
ECMWF

Vegetation inter-annual variability (R&D)

geoland 2

Imagines

A 10-year global LAI (and Albedo) product (10-day frequency) has been provided by the geoland2 BIOPAR (GEOV1 product) and continues in IMAGINES project. Our plan is to assimilate in the ECMWF system to test the impact fluxes and forecasts. Preparing for SENTINEL ESA satellites.



http://fp7-imagines.eu/

Summary & Outlook

- **The ECMWF land surface scheme and its evolution**
    - Uses the tiling concept to represent sub-grid land variability including forest and forest+snow tiles, and upcoming a lake dedicated tile (cy40r1)
- **Benefits of the tiling in presence of large contrasts**
    - Each tile has its process description (no ad-hoc or effective parameters)
- **Shortcomings of the tiling**
    - No surface boundary layer mixing (blending height hypothesis)
    - Too strong decoupling of snow surface (2m temperature forest bias)
    - Single soil layer underneath
- **Outlook: How approach calls for complexity? What comes first?**

The enhanced representation of snow and vegetation + introduction of a SBL scheme to account for mixing are foreseeable developments with NWP relevance

References

PDFs of published articles available as ECMWF TM or via web-sharing networks

Land surface ongoing&future developments

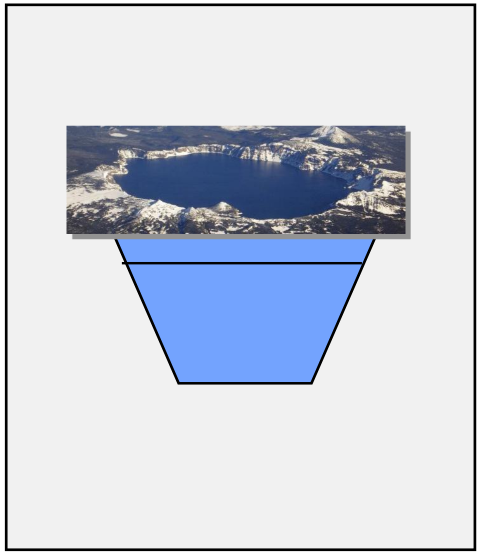
2013	2014-2015	2015-2020

- **FLake**

  Mironov et al (2010), Dutra et al. (2010), Balsamo et al. (2010) Balsamo et al. (2011)

  Extra tile (9) to account for sub-grid lakes

  Lake Climatology used in S4

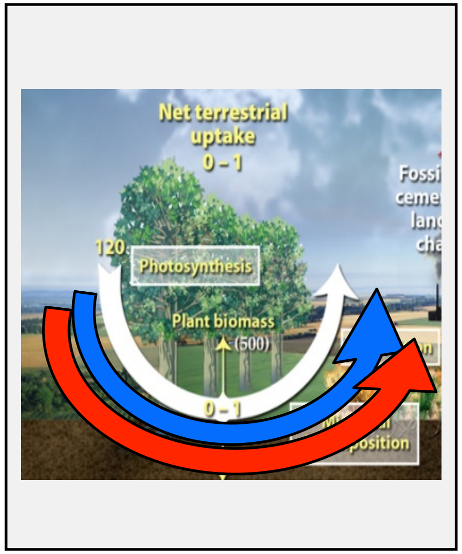


- **H_2O / E / CO_2**

  Carbon-driven vegetation scheme at the surface,

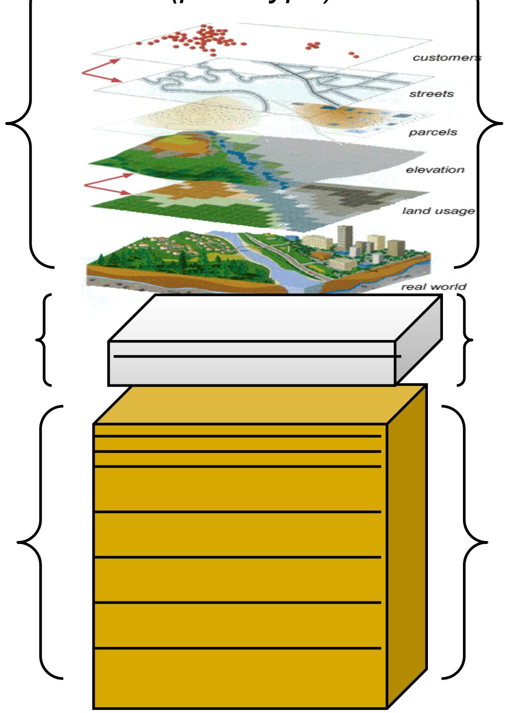
  Atmospheric CO_2 + DA

  (FP7 & Copernicus)



- Towards **Interactive Ecosystem** modelling to respond to several applications needs

  (prototype)



Land surface data assimilation status

1999	2004	2010/2011

OI screen level analysis

Douville et al. (2000)
Mahfouf et al. (2000)

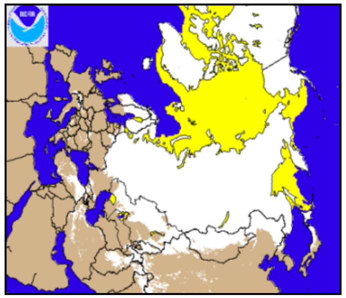
Soil moisture 1D OI analysis
based on Temperature and relative humidity analysis

SYNOP Data

Revised snow analysis

Drusch et al. (2004)

Cressman snow depth analysis using SYNOP data improved by using NOAA / NSEDIS Snow cover extend data (24km)

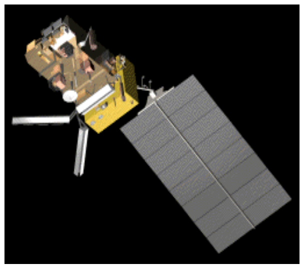


NOAA/NESDIS IMS

Optimum Interpolation (OI) snow analysis
Pre-processing NESDIS data
High resolution NESDIS data (4km)
de Rosnay et al., 2012

SEKF Soil Moisture analysis
Simplified Extended Kalman Filter
Drusch et al. GRL (2009)
de Rosnay et al (2012)

Use of satellite data



METOP-ASCAT
de Rosnay et al., 2011

SMOS
Sabater et al., 2011

Validation activities
Albergel et al. 2011, 2012, 2013

The land water storage verification

The soil moisture and the snow depth produced with the current land surface model simulation are part of the new "ERA-Interim/Land" dataset available from ECMWF.

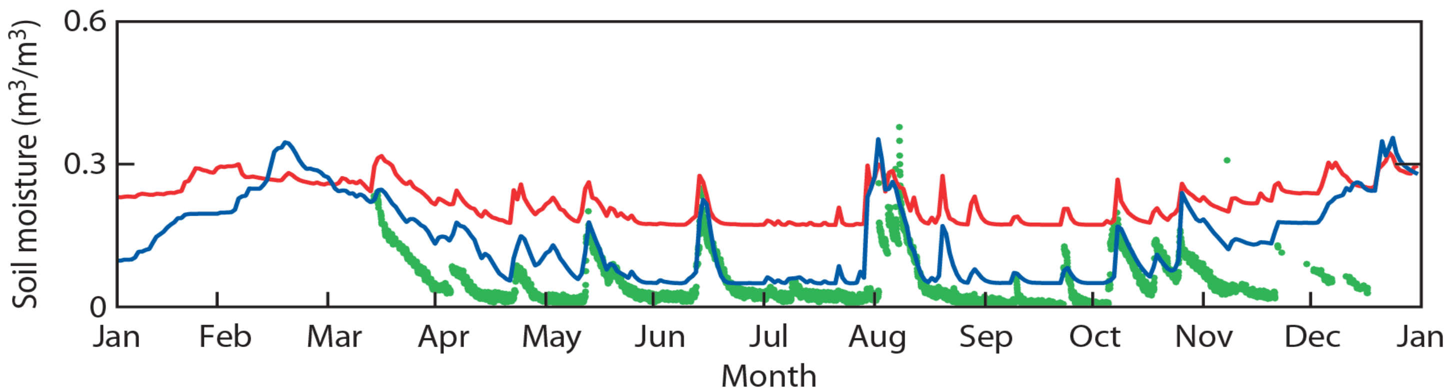


Figure 1: Evolution of volumetric soil moisture at a site in Utah for the year 2010. In-situ observations in green, ERA-Interim estimates in red, and ERA-Interim/Land estimates in blue.

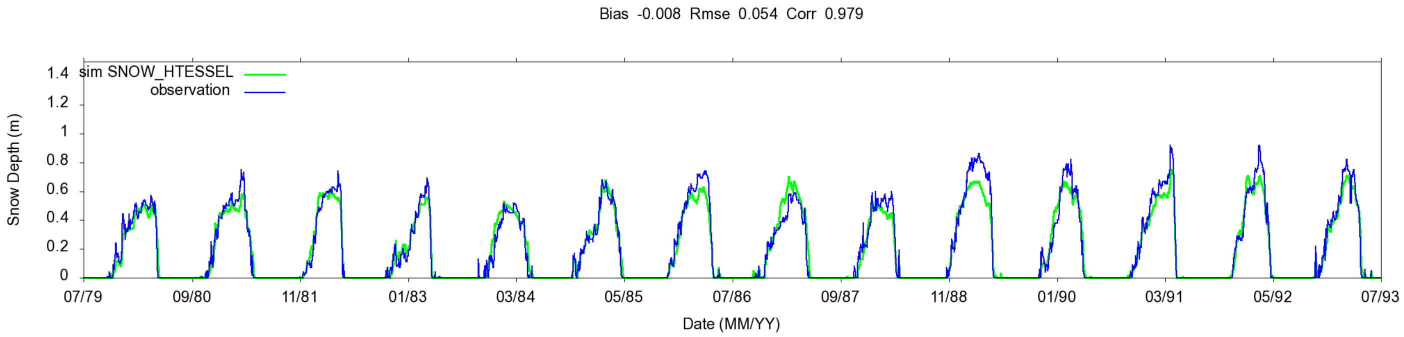


Figure 2: Long term evolution of the HTESSEL snow-depth (in green) compared with in-situ measurements (in blue) from 1979 to 1993 at Perm station (58.0N, 56.5E).

Balsamo et al. (2012), ERA-Rep 13 http://www.ecmwf.int/publications/library/do/references/show?id=90553

The land water fluxes verification

The ERA-Interim/Land fluxes are validated with independent datasets used as benchmarking.

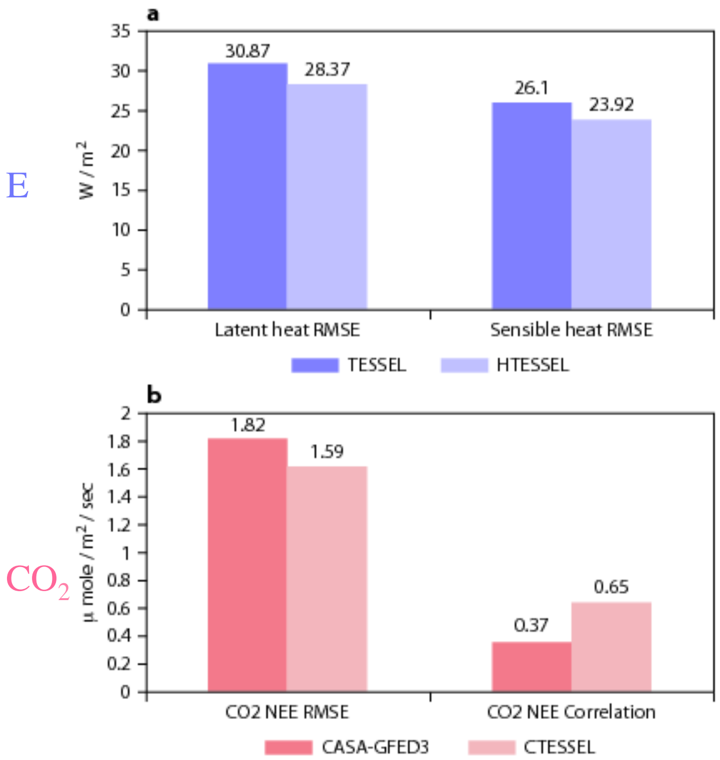
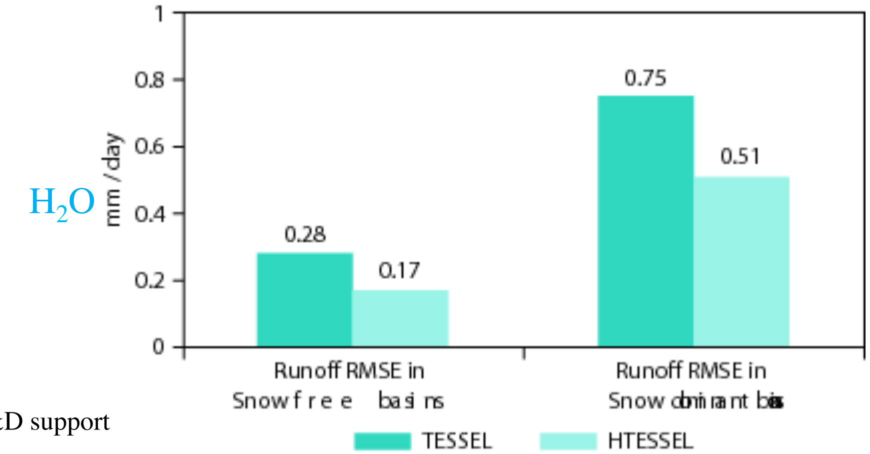


Figure 1: Mean errors over 36 stations with hourly data from FLUXNET & CEOP networks (decadal-averages) in 2006 for HTESSEL, TESSEL scheme versions (with latent and sensible heat fluxes RMSE shown in (a)) and HTESSEL and CHTESSEL (with Net Ecosystem Exchange RMSE and Correlation in (b)).

Validation of H_2O / E / CO_2 cycles



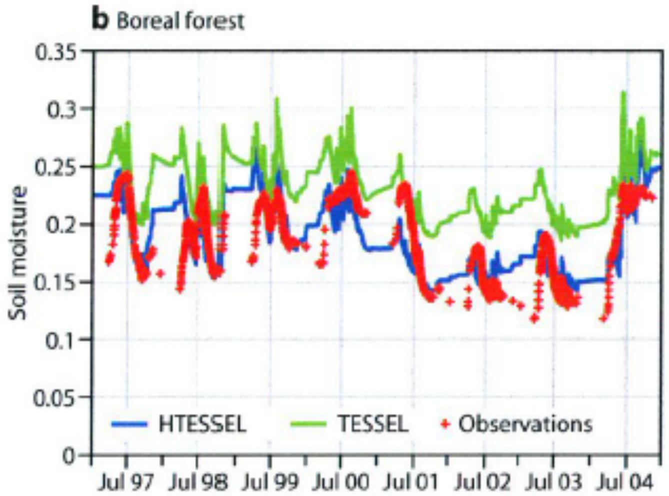
GEOLAND-2 R&D support

Figure 2: Runoff root-mean-square error (RMSE) for GSWP2 global offline land simulations (1986–1995) verified with GRDC monthly river discharge observations on mainly snow-free basins (North-East and Central Europe) and snow-dominated basins (Yukon, Podka, Lena, Tom, Ob, Yenisei, Mackenzie, Volga, Irtish and Neva).
The mean RMSEs are area-weighted and show the TESSEL and HTESSEL scheme versions.

Balsamo et al. (2012), BAMS July (AMS conference summary).

A revised soil hydrology

(Balsamo et al. 2009, JHM)



Long record observations at BERMS-Canadian site have crucial to assess the hydrological performance of the new scheme

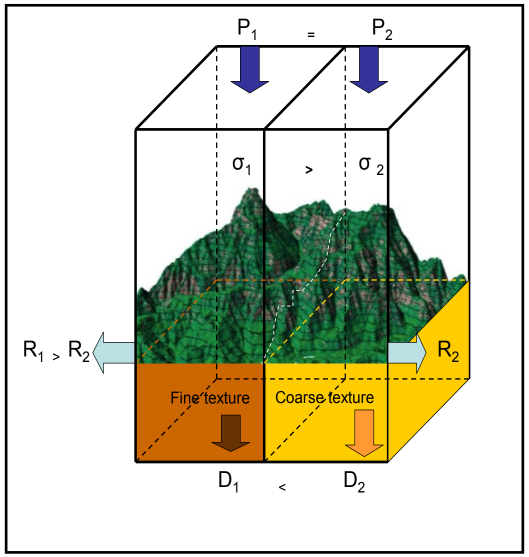
- **Hydrology-TESSEL**

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

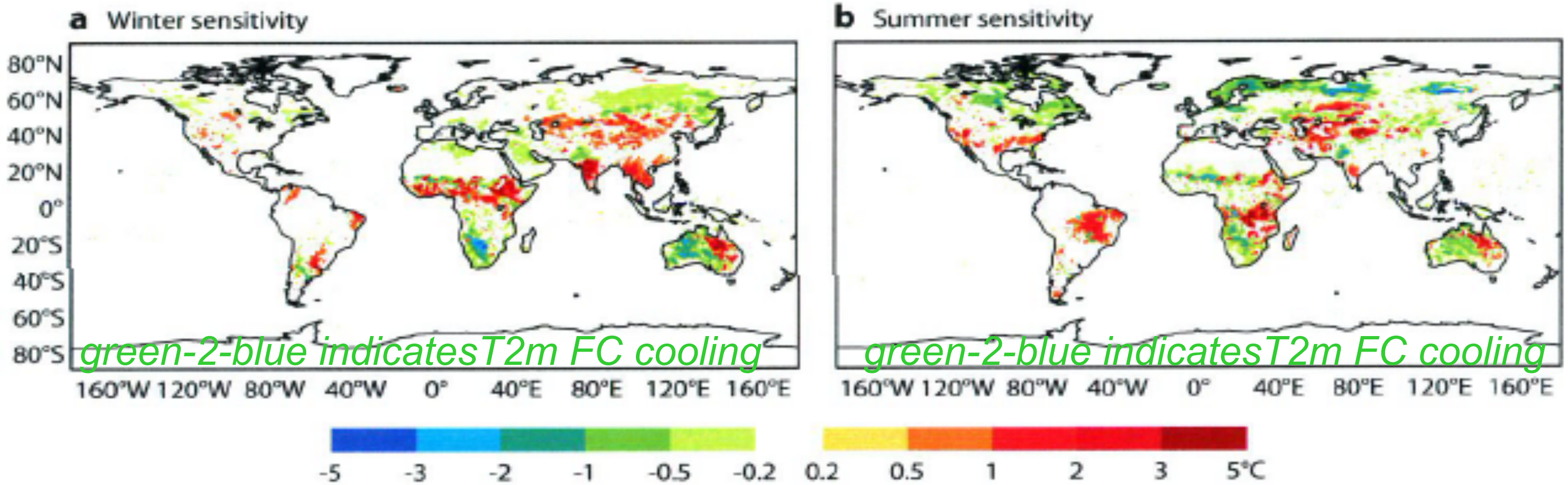
  Global Soil Texture (FAO)

  Van Genuchten hydraulic properties

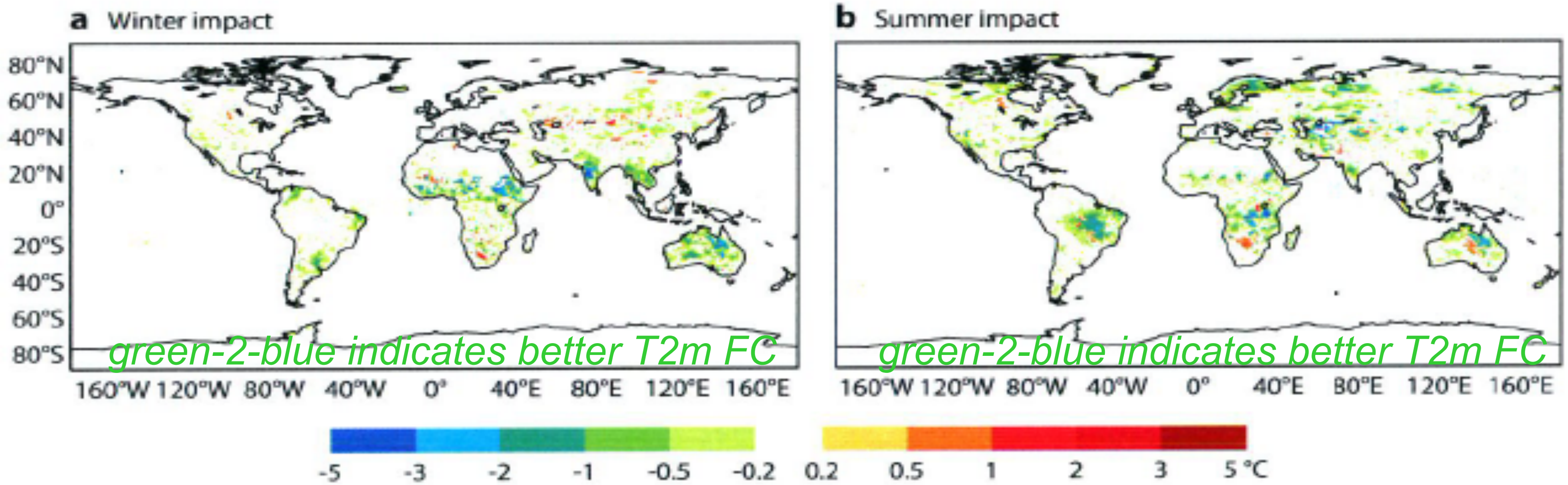
  Variable Infiltration capacity & surface runoff revision



Forecasts sensitivity and impact

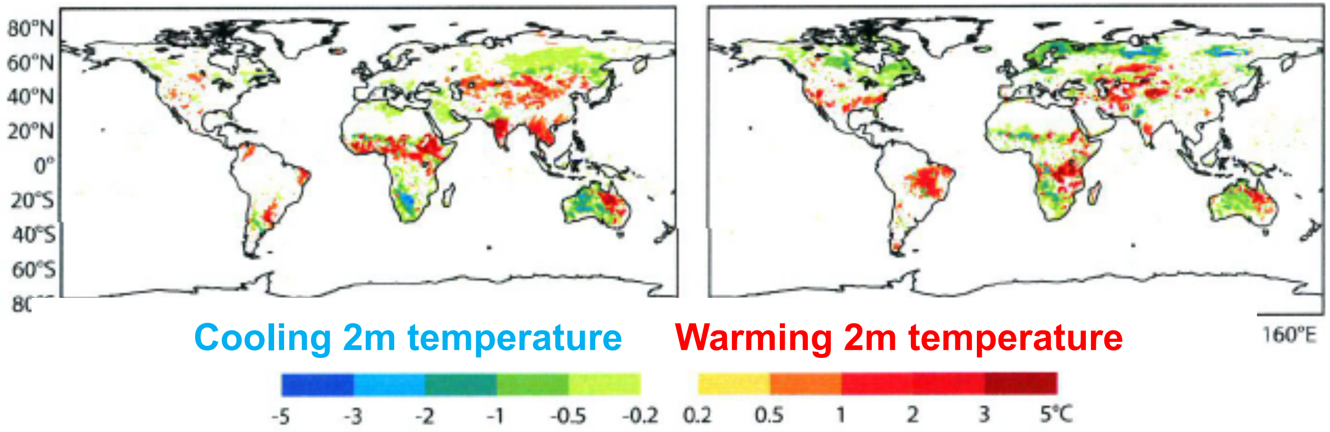


- The revised soil/snow scheme introduce additive improvements respectively in summer/winter seasons forecasts of 2m temperatures

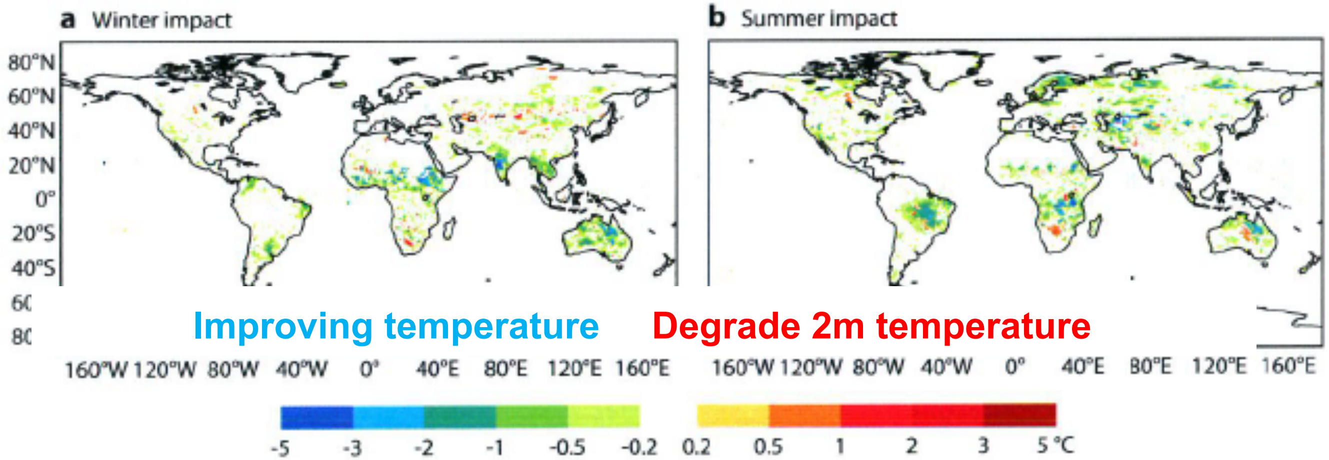


Forecasts sensitivity and impact to land

Sensitivity of a set of T2m Day-2 forecasts in winter 2008 (DJF) and Summer 2008 (JJA)



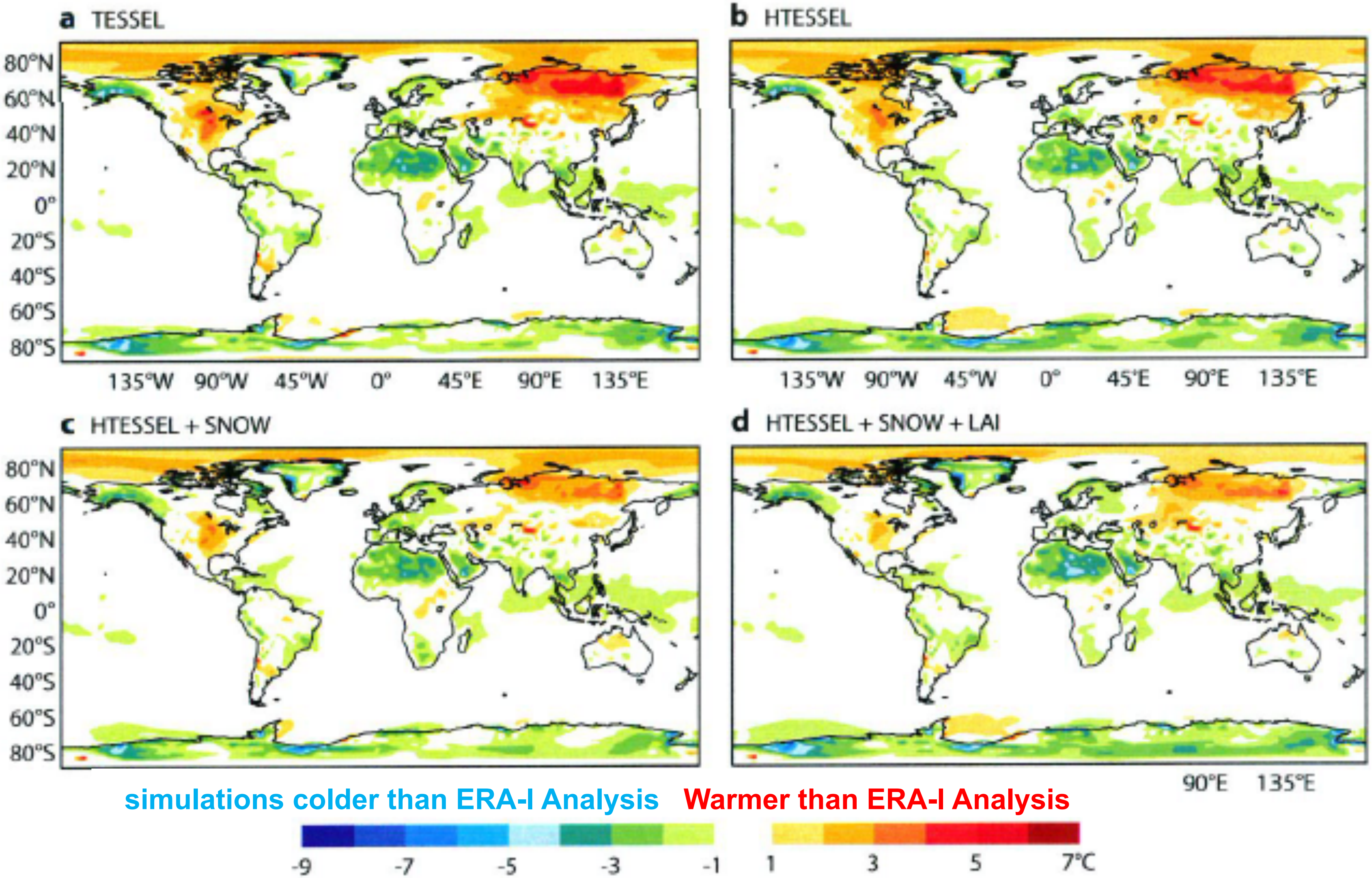
Forecast Impact (Mean Absolute Error reduction of the T2m Day-2 forecast error)



The revised land surface scheme in CY36R1 is compared to the land surface model version (CY31R2 LSM used in ERA-Interim) for its sensitivity and impact on the short-term weather forecasts of 2m temperature showing an improvement also in Day-2 range

Land-related improvements in climate runs

Hindcast (13-months integrations with specified daily SSTs). Here shown the evolution of the annual mean T2m errors compared to analysis



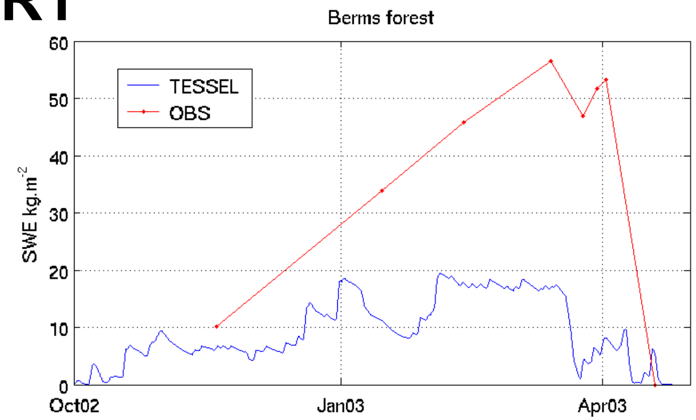
The revised land surface scheme in CY36R4 (d) is compared to the land surface model version (a, CY31R2 LSM used in ERA-Interim) for its impact on long-range forecasts of 2m temperature showing an improvement on annual mean 2m temperature

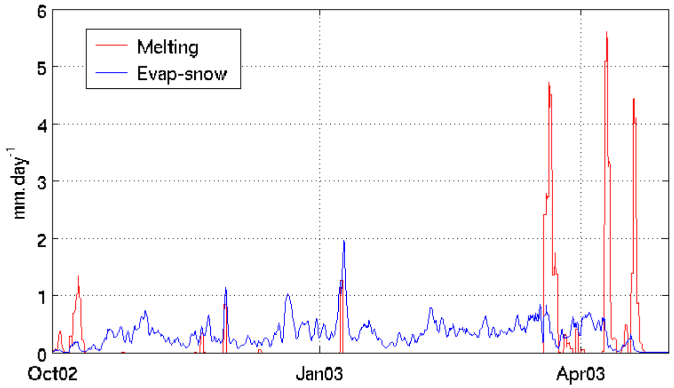
Impact of Forest+Snow Roughness Length

Dutra et al. 2009

The introduction of a vegetation dependent roughness length affecting the aerodynamic resistance show sensitivity on snow accumulation (less sublimation)

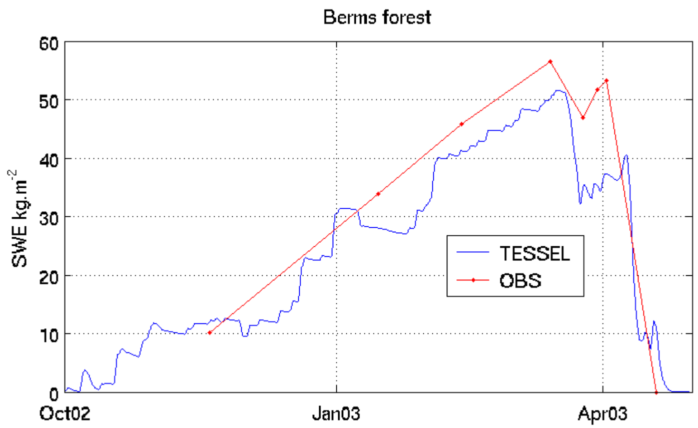
30R1

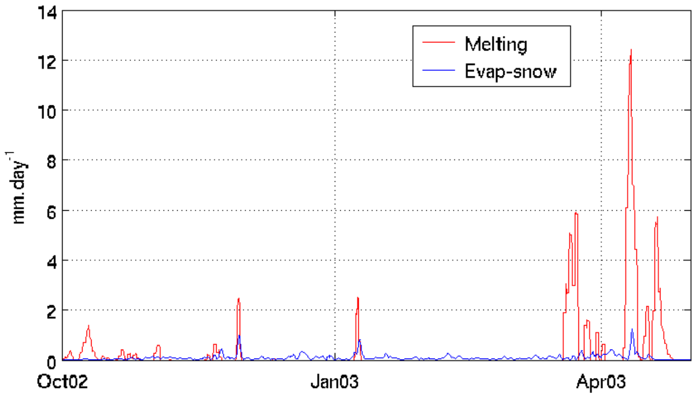




31R2, snow water equivalent

melting & sublimation





SnowMIP2: BERMS forest site simulations