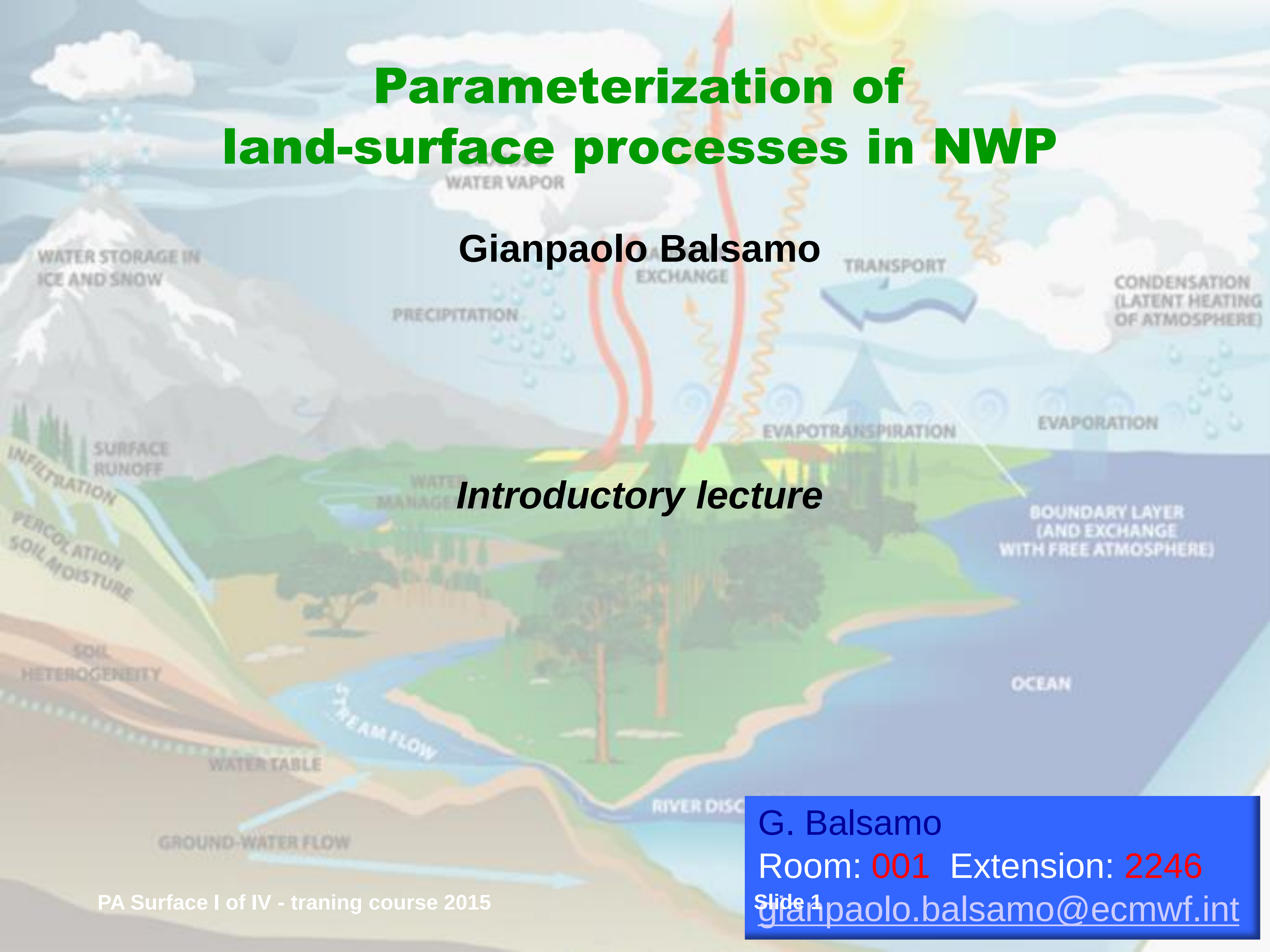


Parameterization of land-surface processes in NWP

Gianpaolo Balsamo

Introductory lecture

G. Balsamo
Room: 001 Extension: 2246
gianpaolo.balsamo@ecmwf.int

Few words about me...

RESEARCH INTERESTS

Land surface Modelling & Data Assimilation, Interaction of Water Energy Carbon cycles,

Land-Atmosphere predictability studies

UNIVERSITY PATHWAY

2012 HDR (Habilitation) in Meteorology from University UPS–TOULOUSE III, France.

2003 PHD (Doctorate) in Meteorology from University UPS–TOULOUSE III, and University of Genoa, Italy (co-tutored).

1999 « Laurea in Fisica » General Physics Degree (4-year, with Atmospheric Physics spec.) University of Turin, Italy.

1997, Meteorology (BSc/MSc courses as ERASMUS student) Department of Meteorology, University of Reading, UK.

PROFESSIONAL PATHWAY

2009 Senior Scientist, **ECMWF**, U.K. : Responsible for the land surface modelling in NWP

2006 Scientist, ECMWF, U.K. : Land Surface Modelling in NWP

2004 Visiting Scientist **Canadian Meteorological Centre**, Montréal: Land Data Assimilation System in NWP

2003 Post-doc **CNRM/Météo-France**, Toulouse: Assimilation of land surface observations in a NWP model.

1999 Forecaster for the Piedmont Regional Meteorological Centre (**ARPA-Piemonte**), Turin, Italy.

Layout of these lectures

- Introduction
- General remarks
- Model development and validation
- The Earth energy budget
- Soil/Water contrasts
- Snow hydrology
- Snow atmosphere coupling
- Vegetation cycle
- Carbon dioxide

Lecture 1

Lecture 2

Lecture 3

Lecture 4

The challenges for Land Surface Modeling

- **Capture natural diversity of land surfaces (heterogeneity) via a simple set of equations**

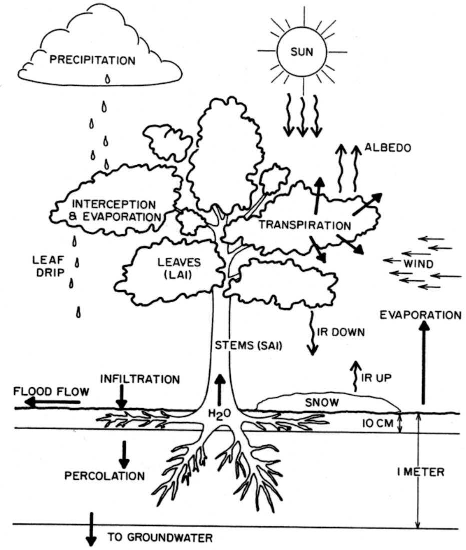
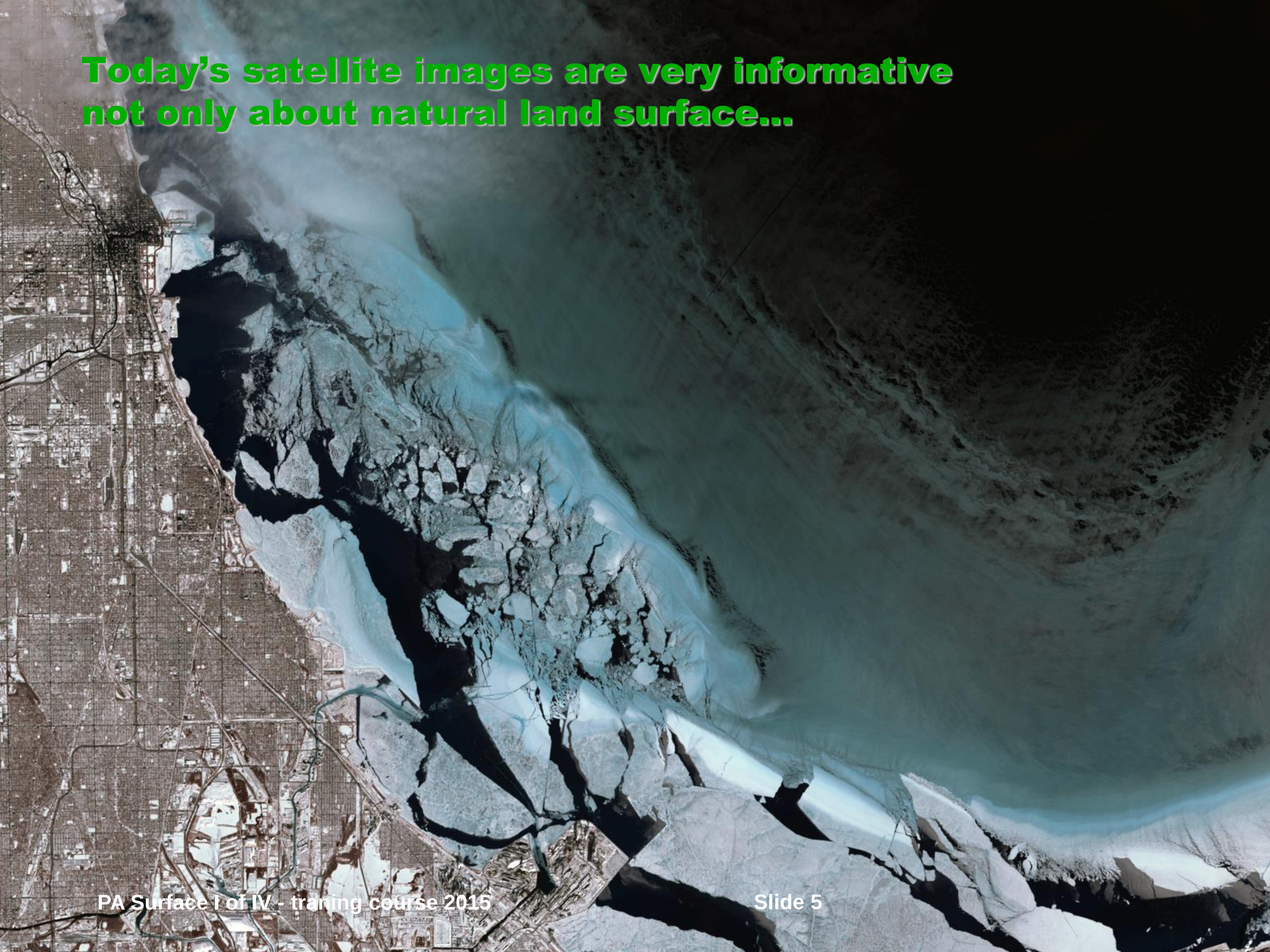


Figure 7
Water and energy processes at the Earth surface in the presence of vegetation.

- **Focus on elements which affects more directly weather and climate (i.e. soil moisture, snow cover).**

Today’s satellite images are very informative not only about natural land surface…



Methodology

- **Plant and soil science (a bite)**
- **ECMWF model and its evolution**
- **Justification and examples**

Further readings

- **Terrestrial Hydrometeorology, by *W.J. Shuttleworth***
- **Environmental Soil Physics, by *D. Hillel***
- **and few links to lecture notes by *P. Viterbo***

http://www.ecmwf.int/newsevents/training/lecture_notes/pdf_files/PARAM/Land_surf.pdf

http://www.ecmwf.int/newsevents/training/lecture_notes/pdf_files/PARAM/Rol_land.pdf

http://www.ecmwf.int/newsevents/training/lecture_notes/pdf_files/PARAM/Surf_ass.pdf

Earth energy cascade

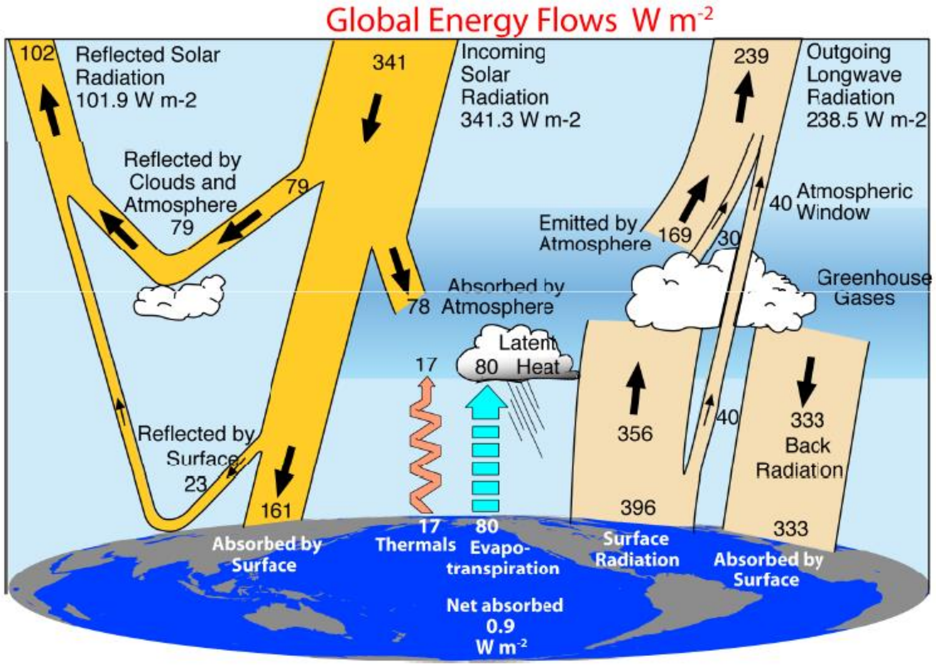
- The sun emits 4×10^{26} W
- the Earth intercepts 1.37 kW/m^2
- This energy is distributed between
  - Direct reflection (~30%)
  - Conversion to heat, mostly by surface absorption (~43%), re-radiated in the infrared
  - Evaporation, Precipitation, Runoff (~22%)
  - Rest of the processes (~5%, Winds, Waves, Convection, Currents, Photosynthesis, Organic decay, tides, …)

Robinson & Henderson-Sellers, 1999

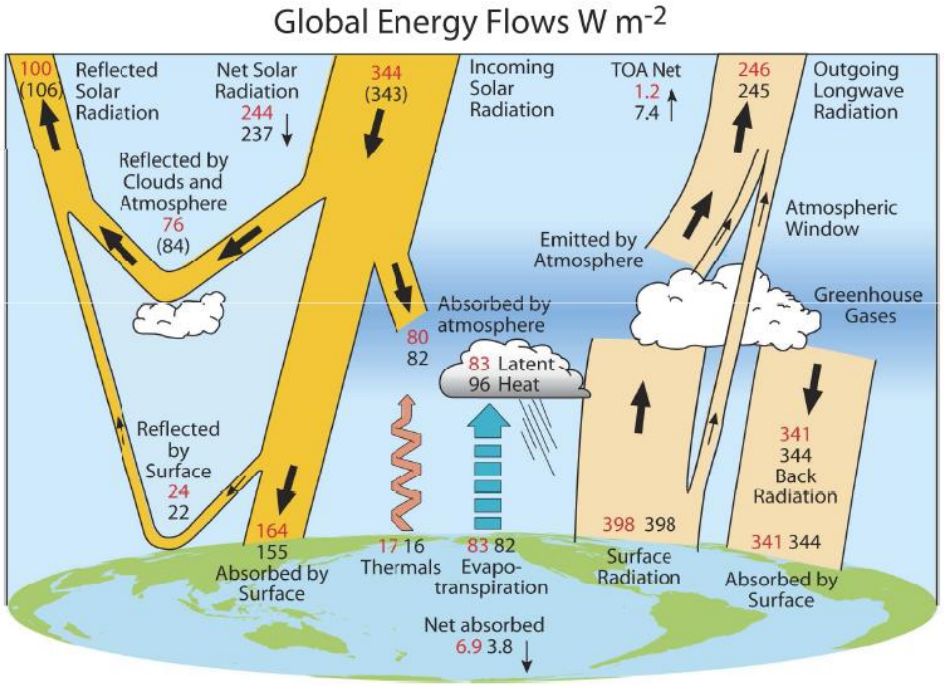
Role of land surface (1)

- **Atmospheric general circulation models need boundary conditions for the enthalpy, moisture (and momentum) equations: Fluxes of energy, water at the surface.**

Trenberth *et al.* 2009:
Earth's global energy budget



ERA-Interim 1989-2008 ERA-40 1989-2001



Role of land surface at ECMWF

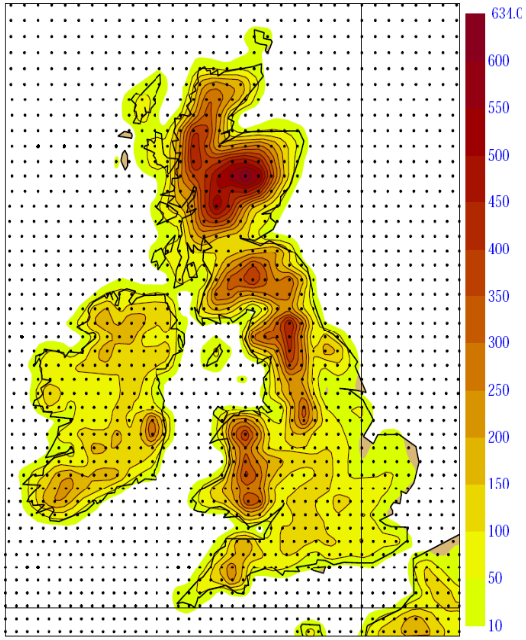
ECMWF model(s) and resolutions

	Length	Horizontal	Vertical	Remarks
- Deterministic	10 d	T1279 (16 km)	L137	00+12 UTC
- Monthly/VarEPS (N=51)	0-10d 11-32d	T639(30 km) T399(60 km)	L91 L91	(SST tendency) (Ocean coupled)
- Seasonal forecast	6 m	T159 (125 km)	L62	(Ocean coupled)
- Assimilation physics	12 h	T255(80 km)/ T159(125 km)	L137	T95(200 km) inner
- ERA-40 Reanalysis	1958-2002	T159(125 km)	L60	3D-Var+surface OI
- ERA-Interim Reanalysis	1989-today	T255(80 km)	L91	4D-Var+surface OI

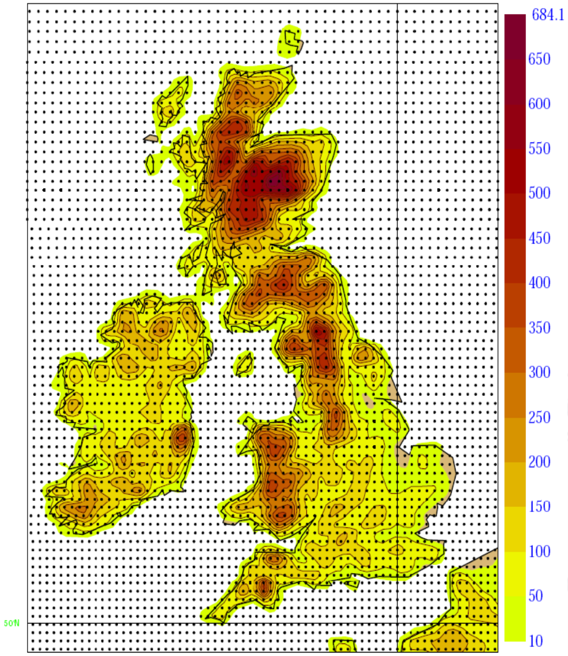
Land surface modelling (and data assimilation systems) need flexibility & upscalability (conservation) properties to be used by at a wide range of spatial resolutions in spite of natural heterogeneity of land surfaces.
Errors in the treatment of land surface are likely to affect all forecasts products.

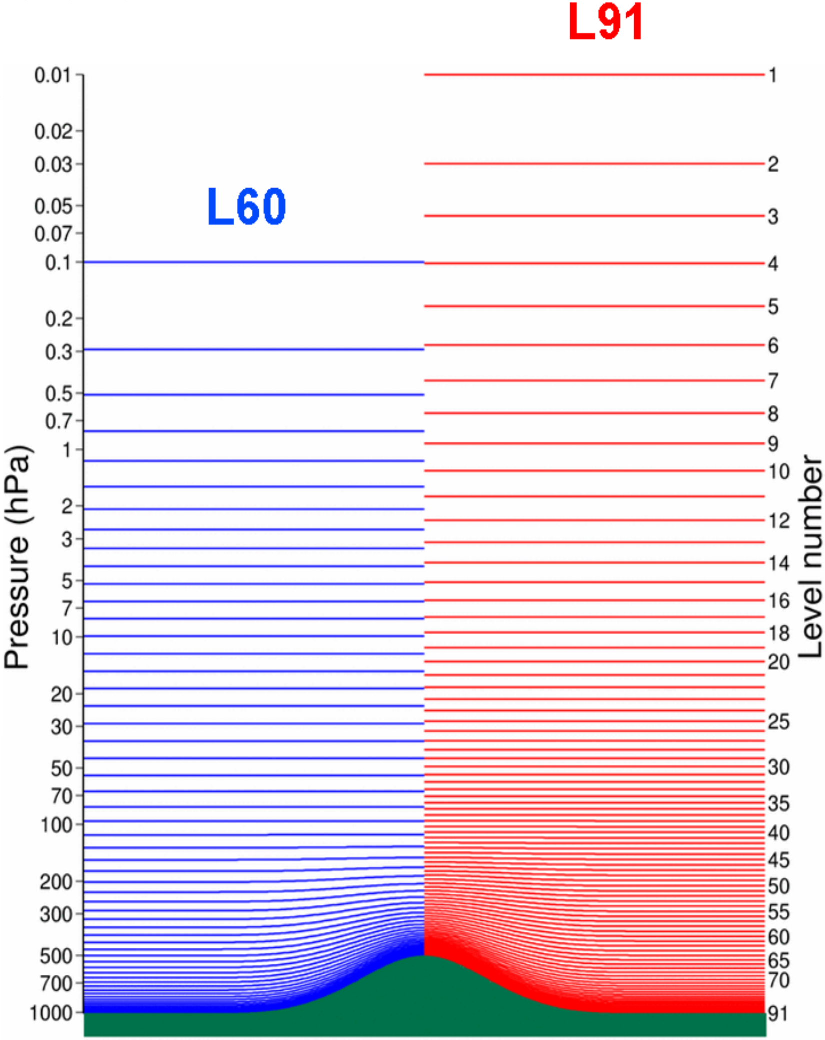
ECMWF deterministic model

T799



T1279





12 levels 15 levels

<850 hPa

Horizontal resolution upgrades:

T511 ~ 40km (21 Nov 2000)

T799 ~ 25 km (1 Feb 2006)

T1279 ~ 16 km (26 Jan 2010)

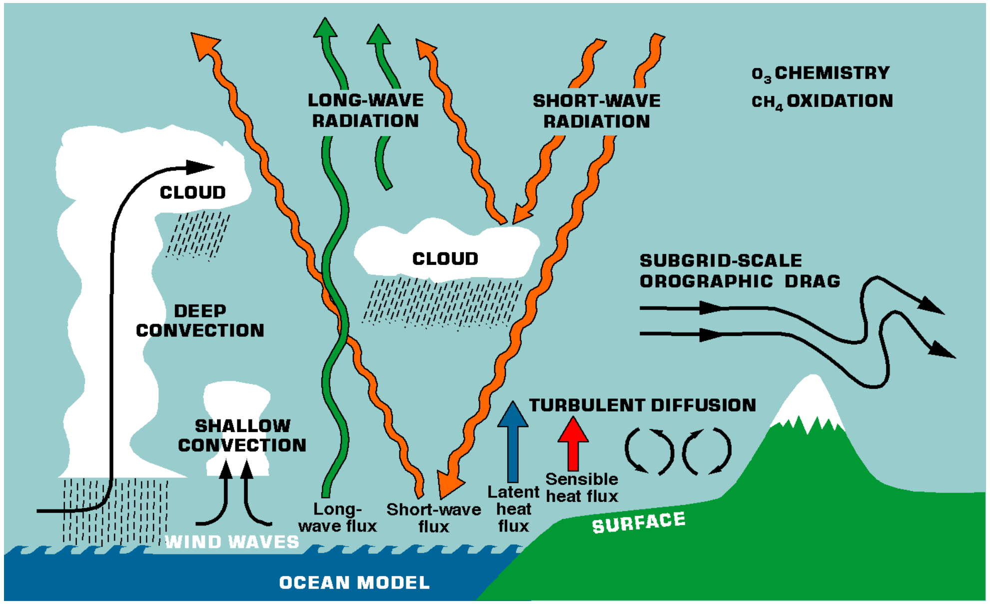
T2047 ~ 10 km (in 2015, TBC)

Vertical resolution upgrades:

L60 (21 Nov 2000) L91 (1 Feb 2006) L137 (June 2013)

Role of land surface (3)

- **Feedback mechanisms for other physical processes, e.g.:**
  - **Surface evaporative fraction[1] (*EF*), impacting on low level cloudiness, impacting on surface radiation, impacting on …**
  - **Bowen ratio[2] (*Bo*), impacting on cloud base, impacting on intensity of convection, impacting on soil water, impacting on …**



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(1) *EF* = (Latent heat)/(Net radiation)

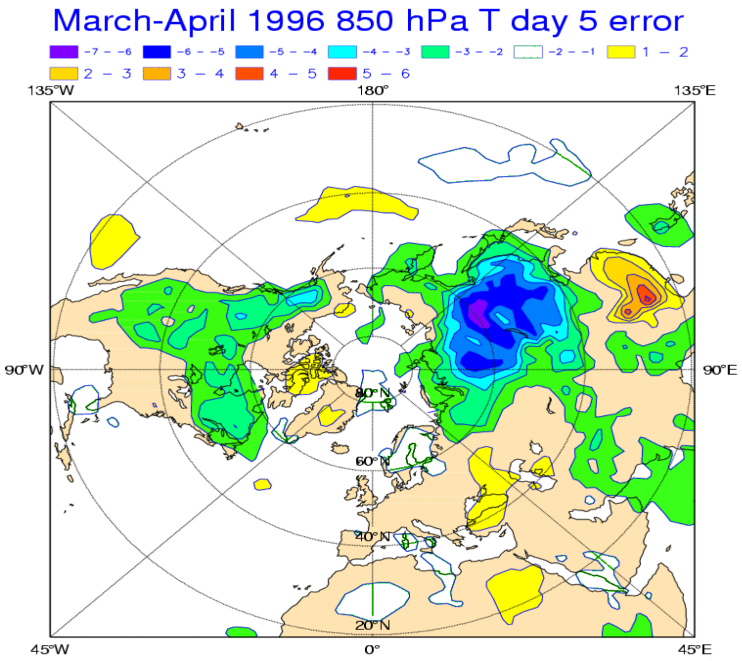
(2) *Bo* = (Sensible heat)/(Latent heat)

Role of land surface (4)

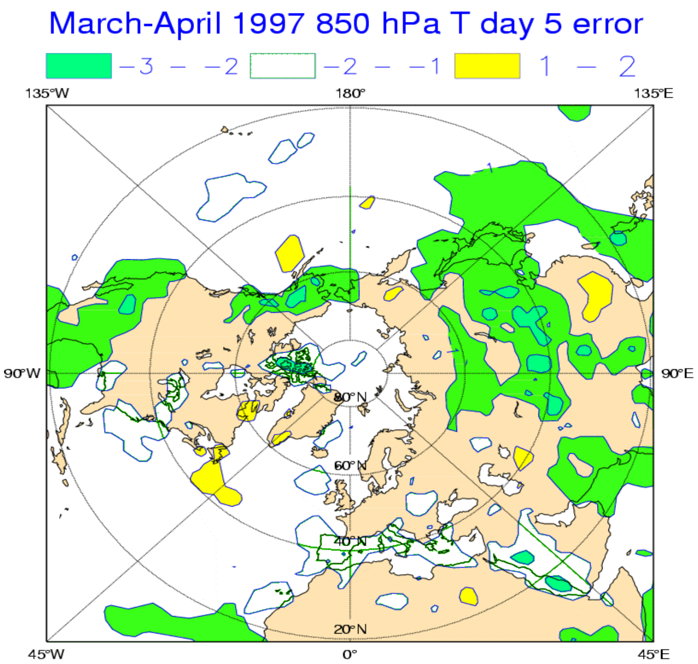
- **Partitioning between sensible heat and latent heat determines soil wetness, acting as one of the forcings of low frequency variability (e.g. extended drought periods).**
- **At higher latitudes, soil water only becomes available for evaporation after the ground melts. The soil thermal balance and the timing of snow melt (snow insulates the ground) also controls the seasonal cycle of evaporation.**
- **The outgoing surface fluxes depend on the albedo, which in turn depends on snow cover, vegetation type and season.**
- **Surface (skin) temperatures of sufficient accuracy to be used in the assimilation of TOVS satellite radiances (over land there is no measured input field analogous to the sea surface temperature)**

Systematic errors 850 hPa T

1996 operational bias



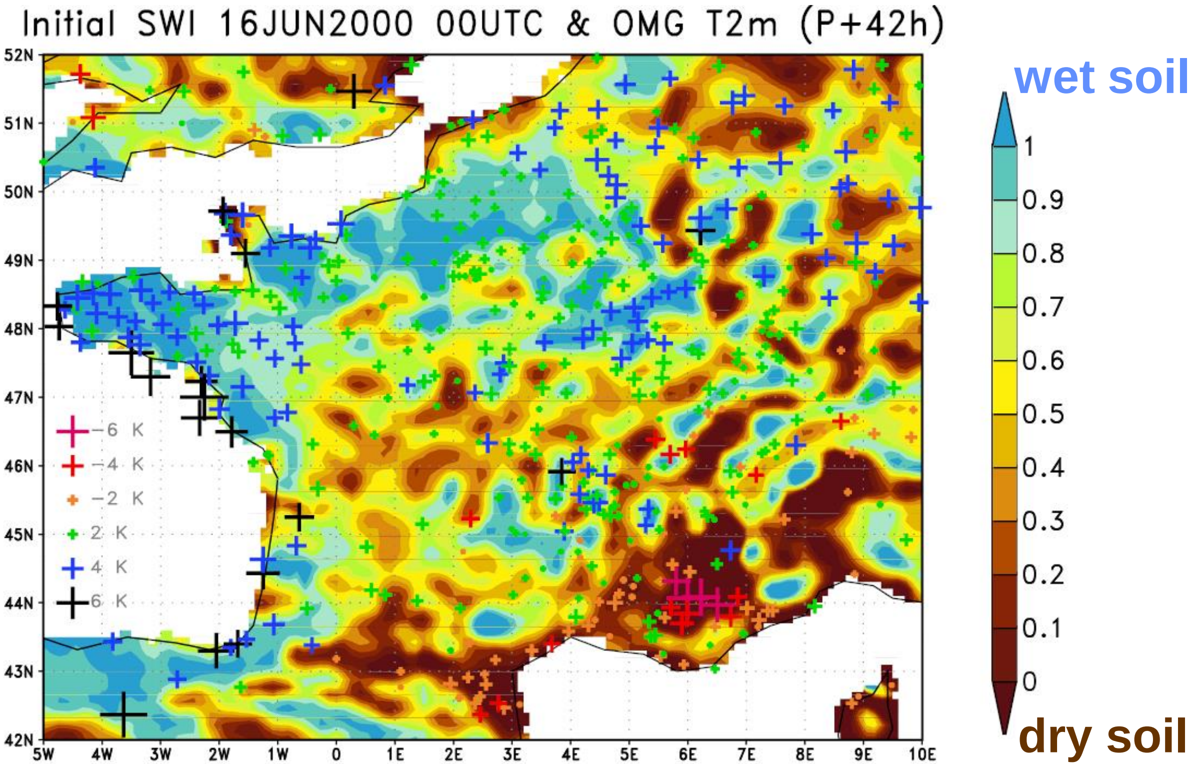
1997 operational bias



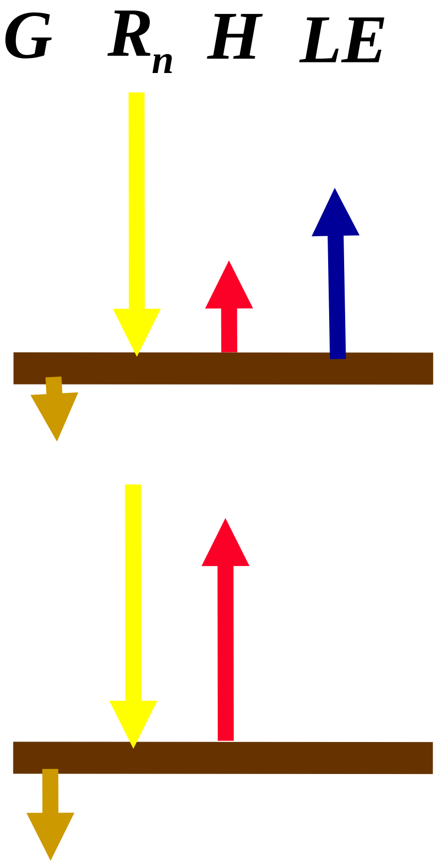
Viterbo and Betts, 1999

- **A smaller albedo of snow in the boreal forests (1997) reduces dramatically the spring (March-April) error in day 5 temperature at 850 hPa**

Near surface atmospheric errors



Balsamo, 2003



- In the French forecast model (~10km) local soil moisture patterns anomalies at time t_0 are shown to correlate well with large 2m temperature forecast errors (2-days later)

Global budgets (1)

- Mean surface energy fluxes (Wm^{-2}) in the ERA40 atmospheric reanalysis (1958-2001); positive fluxes downward

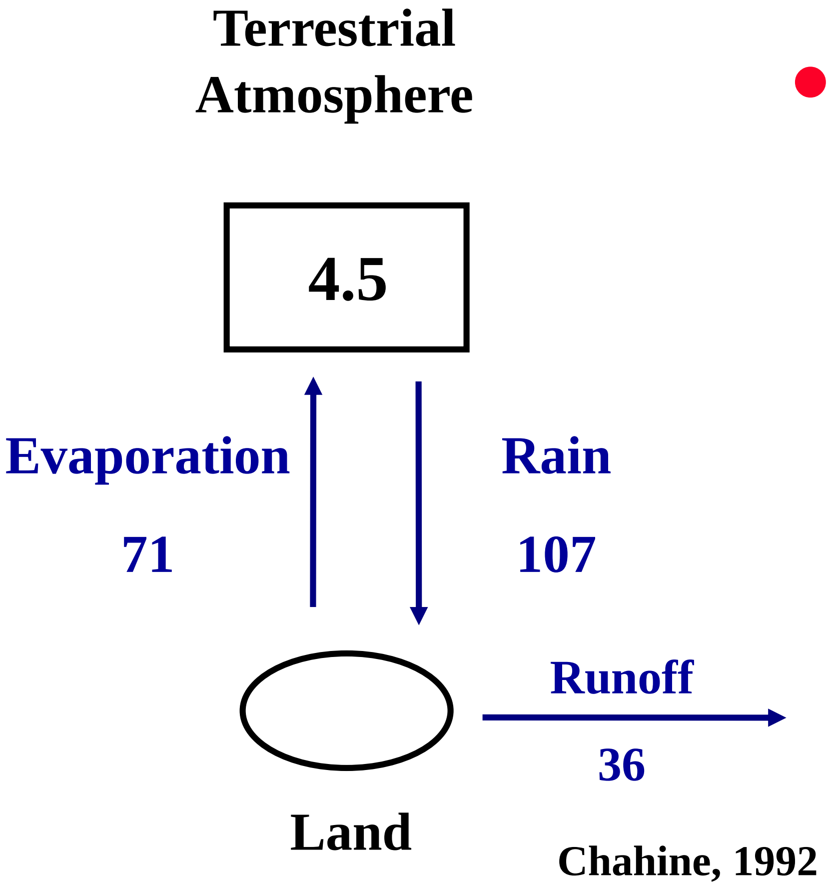
	R_S	R_T	H	LE	G	$Bo=H/LE$
Land	134	-65	-27	-40	2	0.7
Sea	166	-50	-12	-102	3	0.1

- Land surface
  - The net radiative flux at the surface (R_S+R_T) is downward. Small storage at the surface (G) implies upward sensible and latent heat fluxes.
- Bowen ratio: Land vs Sea
  - Different physical mechanisms controlling the exchanges at the surface
    - Continents: Fast responsive surface; Surface temperature adjusts quickly to maintain zero ground heat flux
    - Oceans: Large thermal inertia; Small variations of surface temperature allowing imbalances on a much longer time scale

Global budgets (2)

- **Surface fluxes and the atmosphere**
  - **Sensible heat (*H*) at the bottom means energy immediately available close to the surface**
  - **Latent heat (*LE*) means delayed availability through condensation processes, for the whole tropospheric column**
  - **The net radiative cooling of the whole atmosphere is balanced by condensation and the sensible heat flux at the surface. Land surface processes affect directly (*H*) or indirectly (condensation, radiative cooling, …) this balance.**

Terrestrial atmosphere time scales



Chahine, 1992

- Atmosphere recycling time scales associated with land reservoir

-Precipitation	4.5/107 = 15 days
-Evaporation	4.5/71 = 23 days

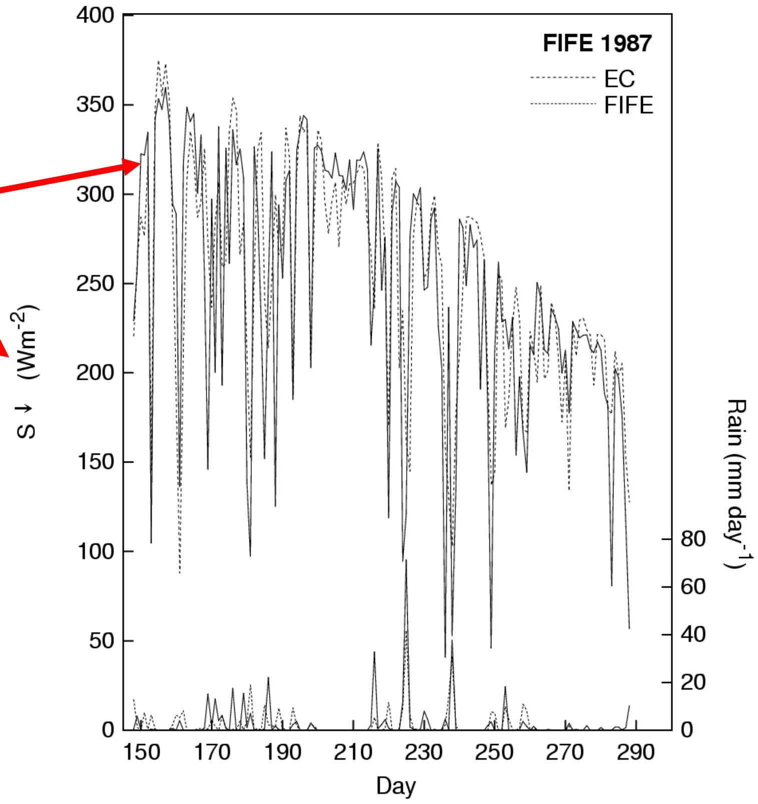
▭ [•] = 10^{15} kg = teratons

⟶ [•] = 10^{15} kg yr^{-1}

Surface time scales (memory) (1)

- Diurnal time scale
  - Forcing time scale determined by the quasi-sinusoidal radiation modulated by clouds

Downward solar radiation

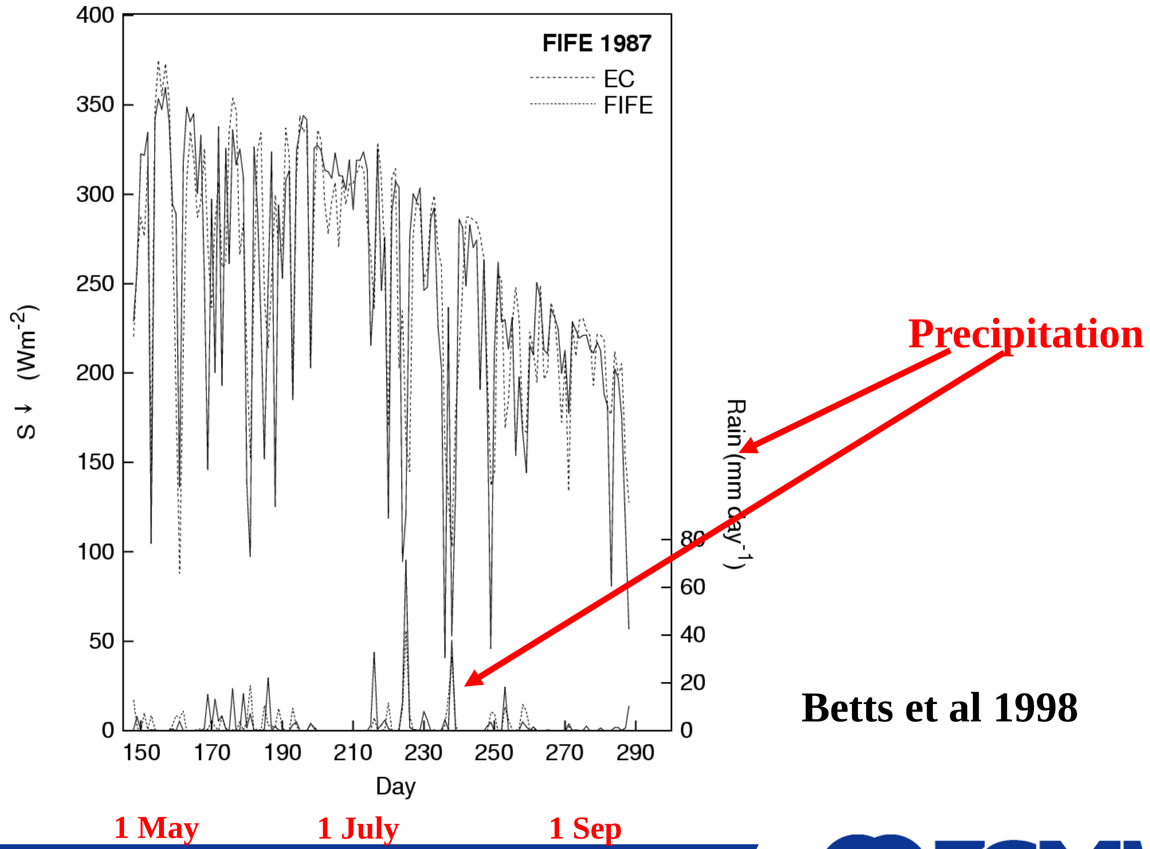


1 May 1 July 1 Sep

Betts et al 1998

Surface time scales (memory) (2)

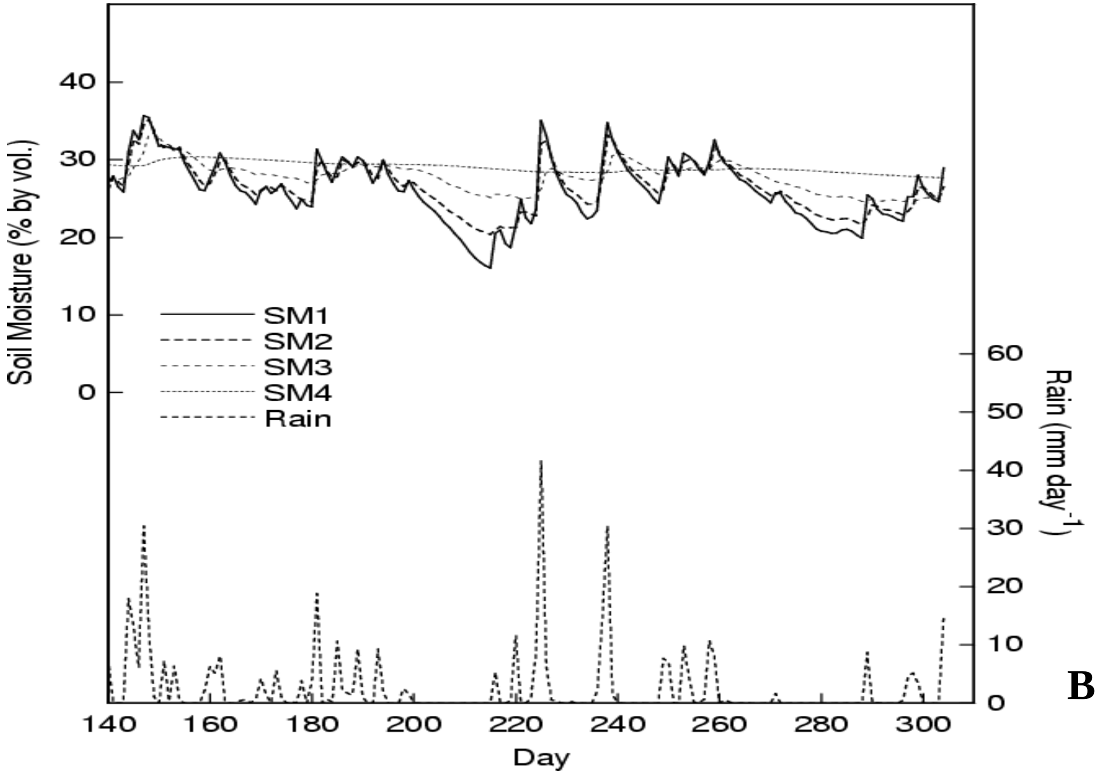
- Diurnal/weekly time scale
  - Forcing time scale determined by the “quasi-random” precipitation (synoptic/mesoscale)



Betts et al 1998

Surface time scales (memory) (3)

- **Weekly/monthly time scale**
  - **Internal time scale determined by the physics of soil water exchanges/transfer**



Betts et al 1998

Surface time scales (memory) (4)

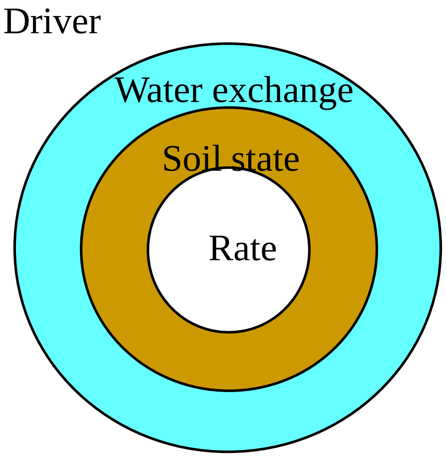
- Weekly/monthly time scale
  - Evaporation time scale determined by the ratio (net radiative forcing)/(available soil water)

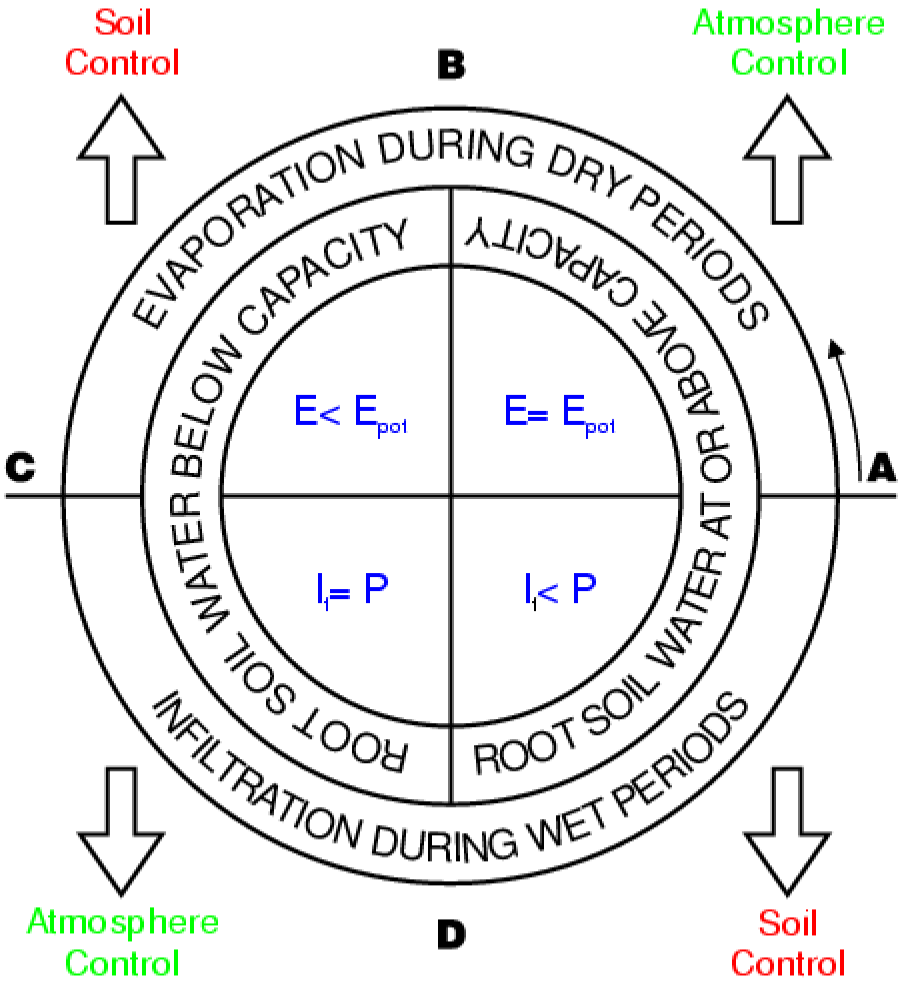
R_n=150 Wm^{-2} ~ (5 mmd^{-1})

Soil water=150 mm

(5 mmd^{-1})/(150 mm) = 30 days

The hydrological rosette





Dooge, 1992

A diversity of land models !!!

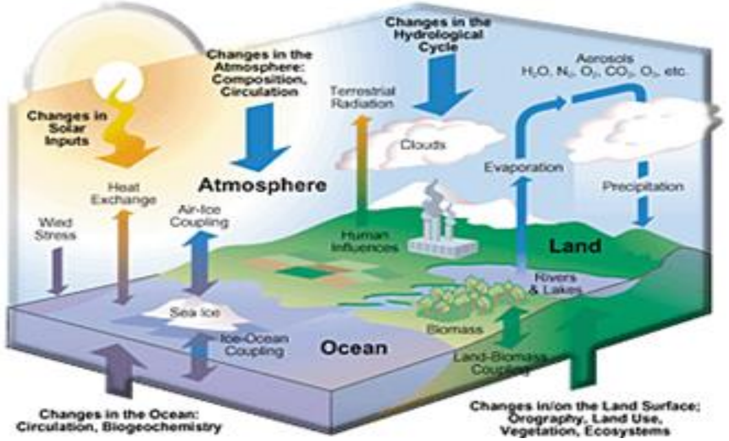
Key Model	Number Canopy Layers	Inter-ception Treated	Number of Layers Included for			Canopy	Rationale for Temperature	Rationale for Soil moisture	Reference
			T	Θ	Roots				
A BATS1E	1	yes	2	3	2	Penman/Monteith	force-restore	Darcy's Law	Dickinson *et al* (1986, 1993)
B BEST	1	yes	3	2	2	Penman/Monteith	force-restore	Philip-de Vries	Pitman *et al* (1991) Cogley *et al* (1990)
C BUCKET	0	no	0	1	1	-	instantaneous surface heat balance	bucket + variation	Robock *et al* (1995)
D CLASS	1	yes	3	3	3	Penman/Monteith	heat diffusion	Darcy's Law	Verseghy (1991) Verseghy *et al* (1993)
E CSIRO	1	yes	3	2	1	aerodynamic	heat diffusion	force-restore	Kowalczyk *et al* (1991)
F GISS	1	yes	6	6	6	aerodynamic	aerodynamic	Darcy's Law	Abramopoulos *et al* (1988)
G ISBA	1	yes	2-3	2	1	aerodynamic	force-restore	force-restore	Noilhan and Planton (1989)
H TOPLATS	1	yes	1	2	1	Penman/Monteith	heat diffusion	Philip-de Vries	Famiglietti and Wood (1995)
I LEAF	1	yes	7	7	3	Penman/Monteith	heat diffusion	Darcy's Law	Avissar and Pielke (1989)
J LSX	2	yes	6	6	6	Penman/Monteith	heat diffusion	Philip-de Vries	-
K MAN69	0	no	1	1	1	-	-	bucket	Manabe (1969)
L MILLY	0	no	1	1	1	-	-	bucket	Manabe (1969)
M MIT	0	no	3	3	3	-	heat diffusion	Darcy's Law	Abramopoulos *et al* (1988) Entekhabi and Eagleson (1989)
N MOSAIC	1	yes	2	3	2	Penman/Monteith	-	Darcy's Law	Koster and Suarez (1992a)
O NMC-MRF	1	yes	1	1	1	lumped with soil	-	-	Pan (1990)
P CAPS	1	yes	2	2	1	Penman/Monteith	heat diffusion	diffusion	Mahrt and Pan (1984)
Q PLACE	1	yes	30	30	2	Ohm's law analogy	force-restore	force-restore	Wetzel and Chang (1988)
R RSTOM	-	no	0	1	1	-	-	bucket + variation	Milly (1992)
S SECHIBA	1	yes	2	2	1	Penman/Monteith	force-restore	Choisnel	Ducoudré *et al* (1993)
T SSIB	1	yes	2	3	1	Penman/Monteith	force-restore	diffusion	Xue *et al* (1991)
U UKMO	1	yes	4	1	1	Penman/Monteith	heat diffusion	diffusion	Warrilow *et al* (1986)
V VIC	1	yes	1	2	1	Penman/Monteith or full energy balance	heat diffusion	Philip-de Vries	Liang *et al* (1994)
W BIOME	1	yes	1	1	1	Penman/Monteith	force-restore	-	

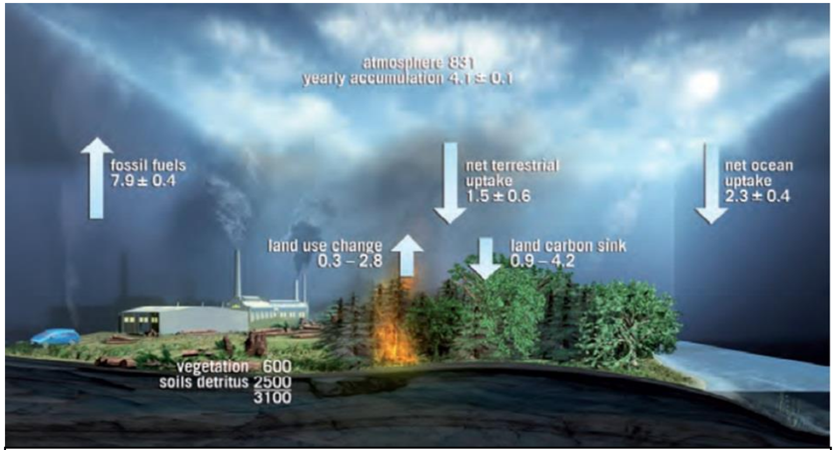
Table 3.1 *Characteristics of several land surface parametrization schemes*

Pitman et al 1993, with modifications

The Water, Energy and Carbon cycle

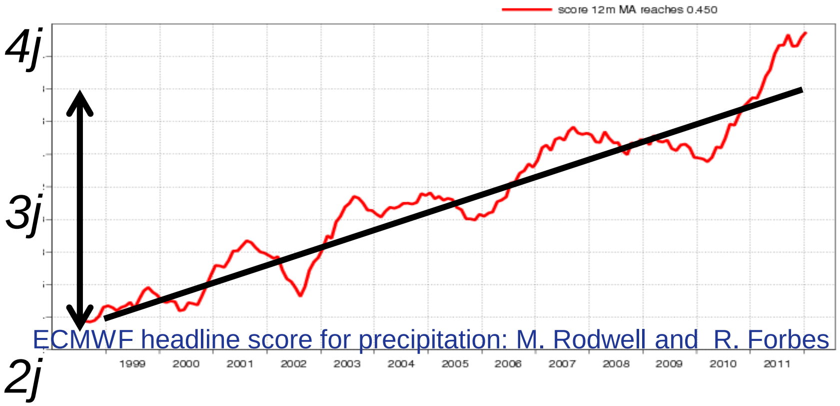
- Numerical Weather Prediction models have considerably evolved over time with respect to how the represent the land surface and its interaction with the atmosphere





CO2 budget (from ESA – BIOMASS mission report)

Precipitation forecasts improvements support (1 day/decade in skill gain) refined LSMs

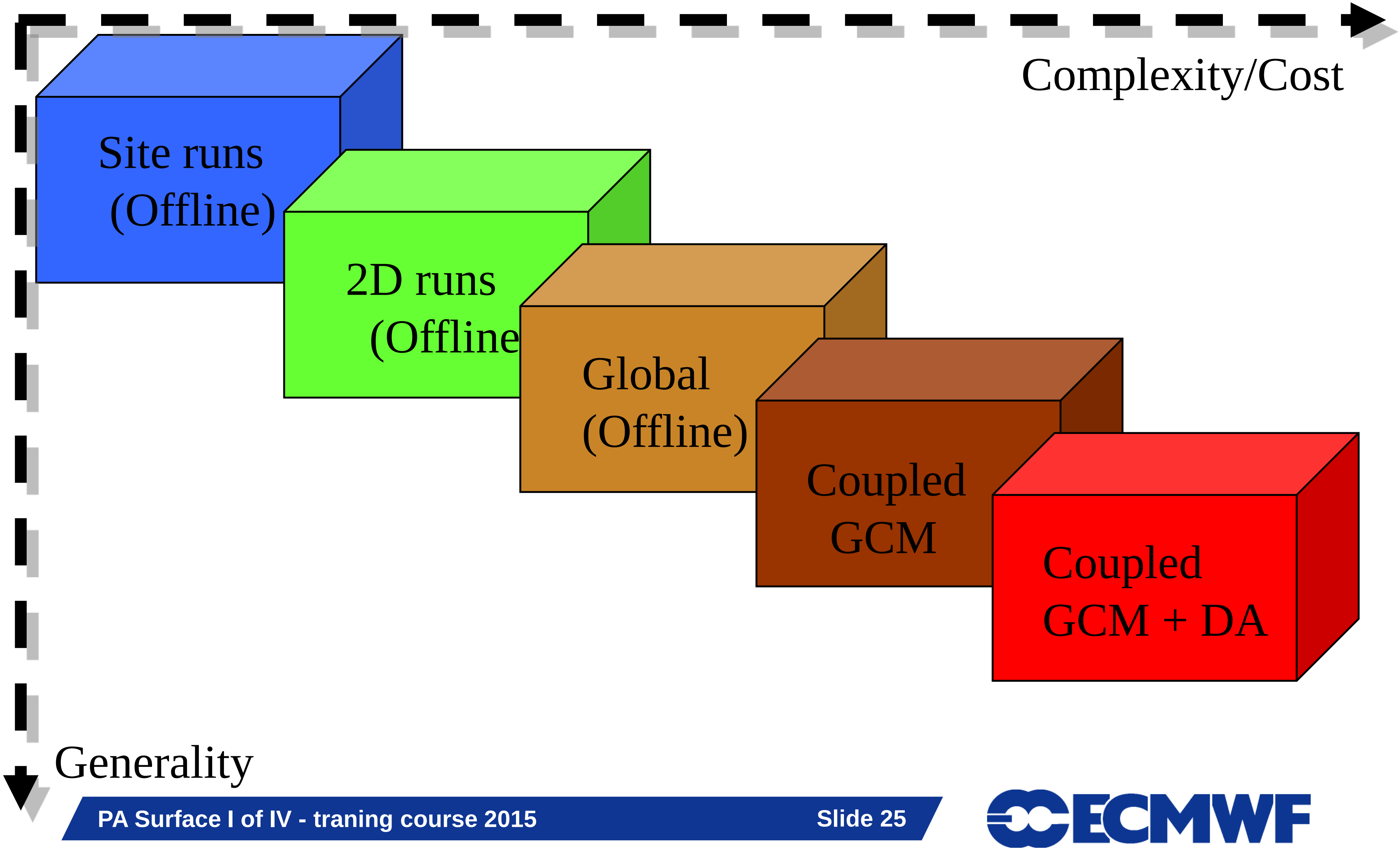


ECMWF headline score for precipitation: M. Rodwell and R. Forbes

- The needs of unification of NWP and Climated model are a driver to develope land surface schemes with increased realism

Evolving towards Earth System Models

Strategy for land surface model development at ECMWF



Complexity/Cost

Site runs (Offline)

2D runs (Offline

Global (Offline)

Coupled GCM

Coupled GCM + DA

Generality

An Integrated & Process-oriented verification to support development

Observations

SYNOPs 2m T/RH
Snow depth

FLUXNET LE/H/C

ISMN soil moisture

GRDC rivers

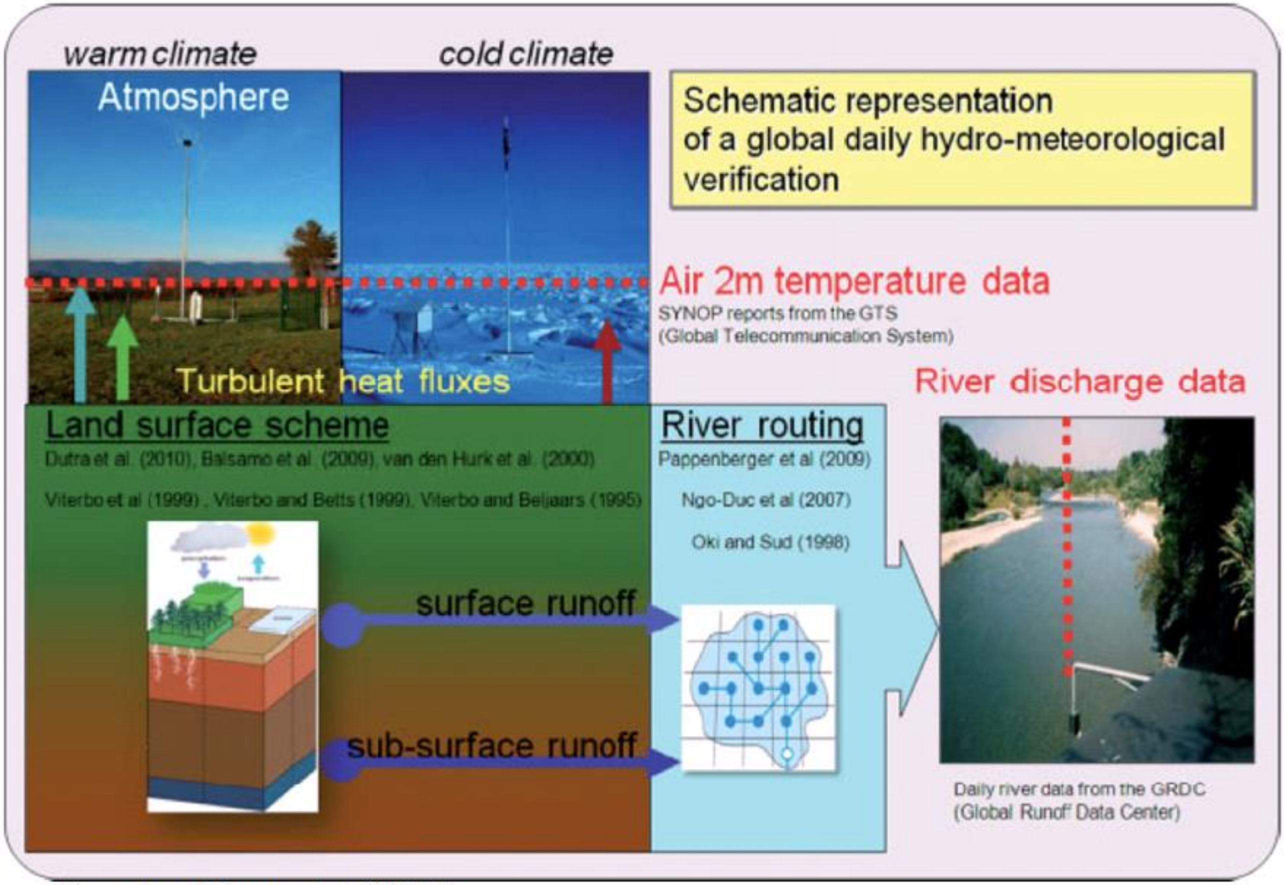
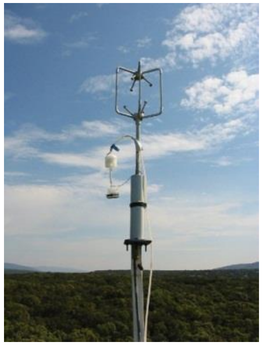


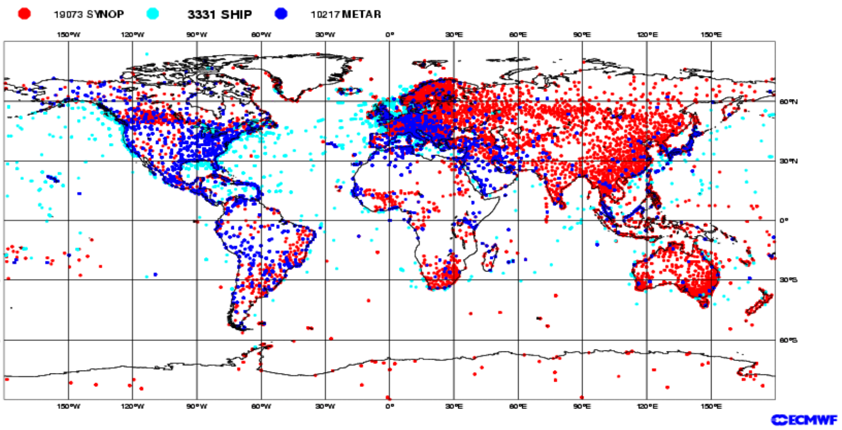
Figure from Balsamo et al. 2010 HP

FLUXNET data



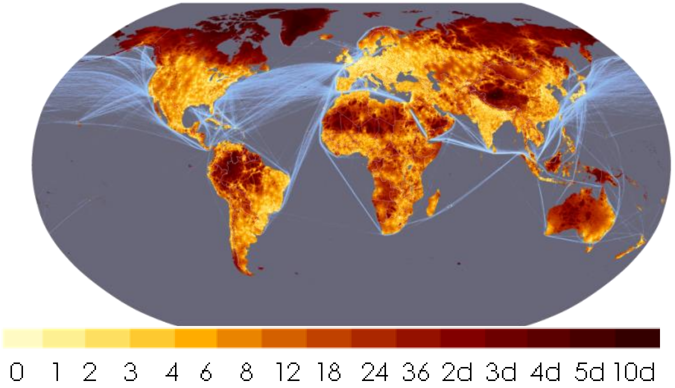
The combined verification of multiple processes permit to avoid tuning in favor of a more physically-based development

Ground-based conventional observations



SYNOP/METAR/SHIP stations

Proximity map for 50000 inhabitants settlement. Source: JRC, World-Bank)

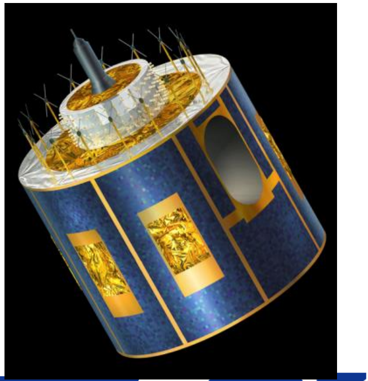


Satellite Remote Sensing

SMOS ESA

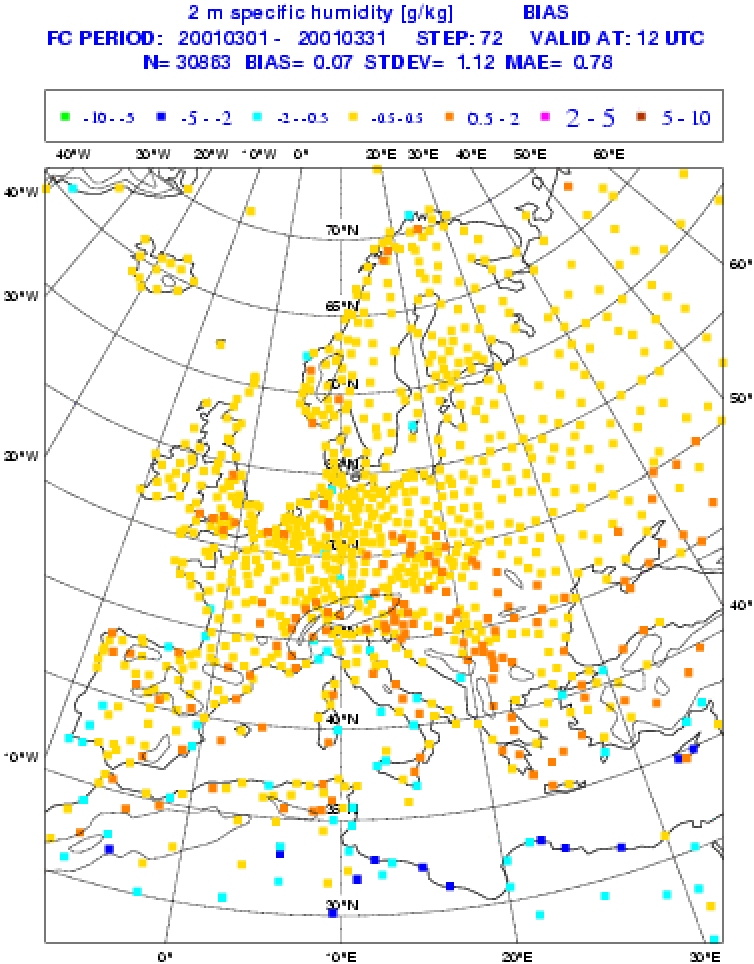
METOP ESA

METEOSAT (MSG) EUMETSAT



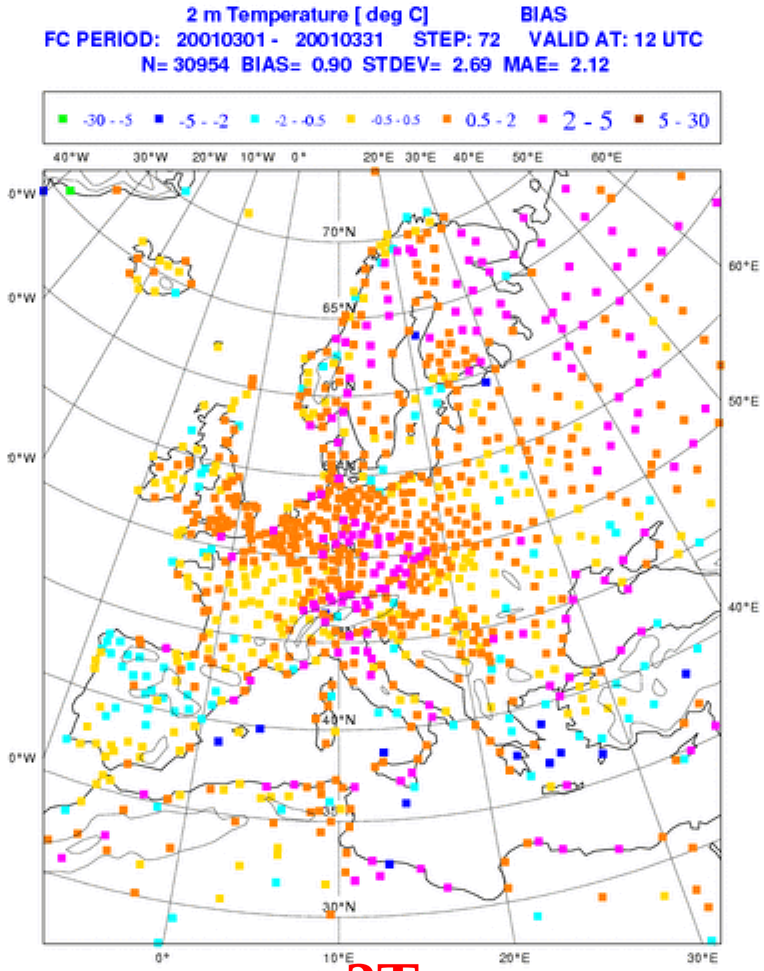
Europe 2m forecast errors for March 2001

72 H FC verifying at 12 UTC



2 m specific humidity [g/kg] BIAS
FC PERIOD: 20010301 - 20010331 STEP: 72 VALID AT: 12 UTC
N= 30863 BIAS= 0.07 STDEV= 1.12 MAE= 0.78

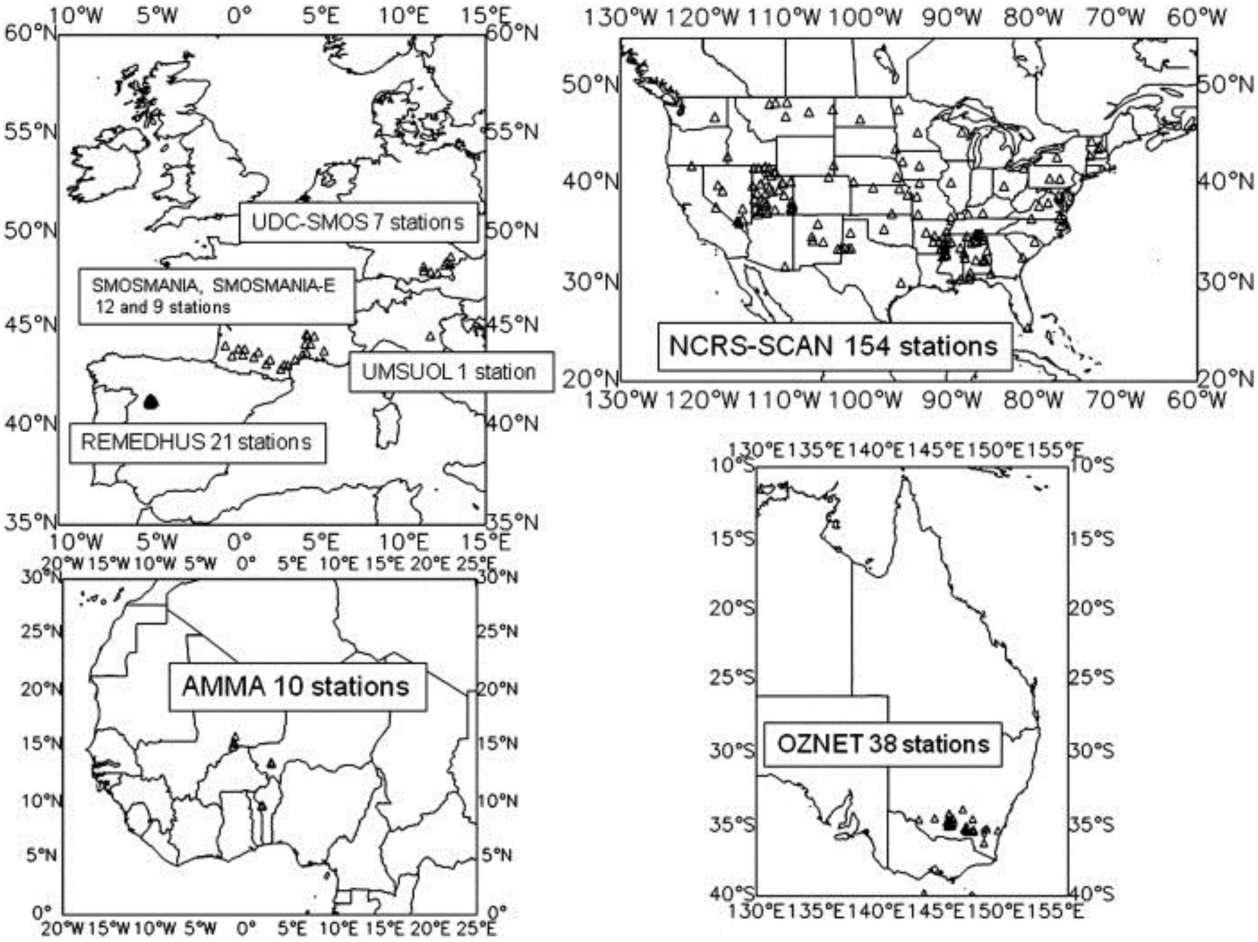
2RH



2 m Temperature [deg C] BIAS
FC PERIOD: 20010301 - 20010331 STEP: 72 VALID AT: 12 UTC
N= 30954 BIAS= 0.90 STDEV= 2.69 MAE= 2.12

2T

Soil moisture verification



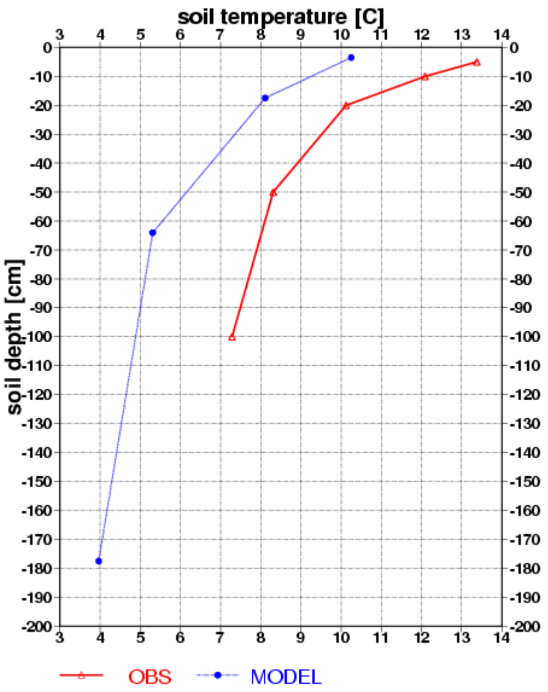
International Soil Moisture Network (ISMN) TU-Wien
http://www.ipf.tuwien.ac.at/insitu/

From Albergel et al. (2012).

Soil temperature verification

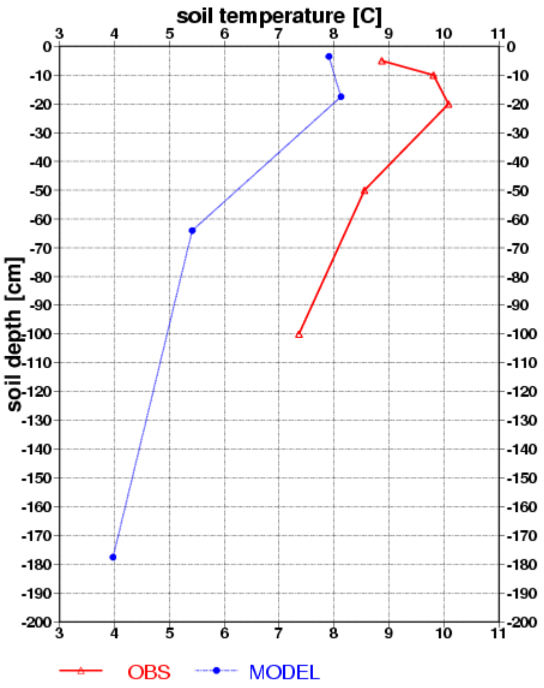
Averaged over Germany stations 26 April 2001

Vertical soil temperature profiles
FC: 2001042612 t + 3h / OBS: 2001042614-2001042616
Germany (10001-10999) 461 stations



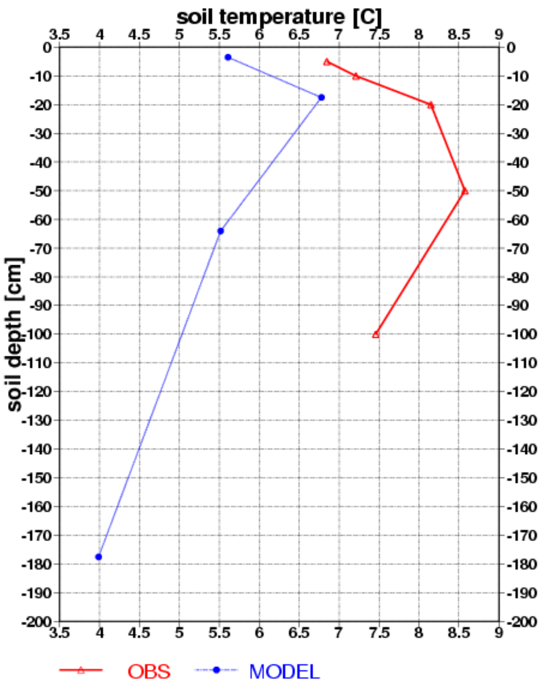
Verifying at 15 UTC

Vertical soil temperature profiles
FC: 2001042612 t + 9h / OBS: 2001042620-2001042622
Germany (10001-10999) 459 stations



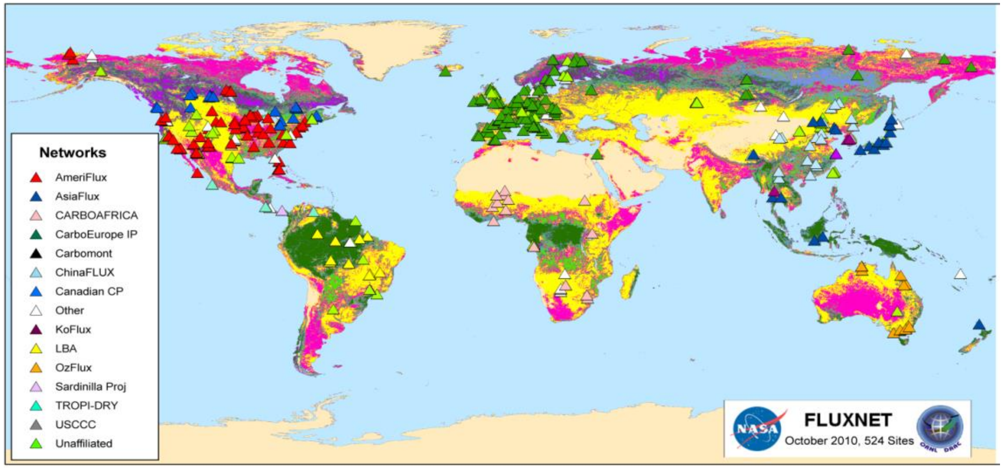
Verifying at 21 UTC

Vertical soil temperature profiles
FC: 2001042612 t + 18h / OBS: 2001042705-2001042707
Germany (10001-10999) 461 stations



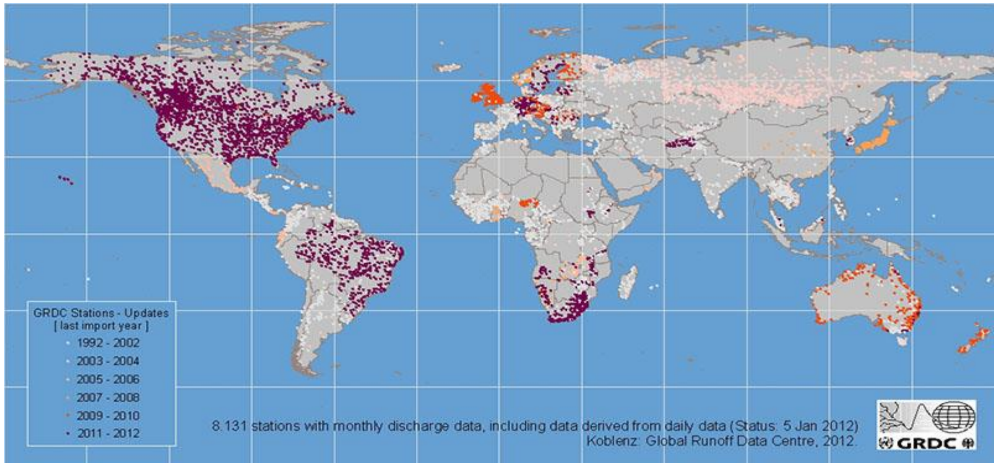
Verifying at 06 UTC

Land Fluxes (E, H_2O, CO_2) verification



***FLUXNET** tower sites:*

http://www.fluxdata.org/



8.131 stations with monthly discharge data, including data derived from daily data (Status: 5 Jan 2012)
Koblenz: Global Runoff Data Centre, 2012.

GRDC
(Global Runoff Data Centre):

http://www.gewex.org/grdc.html

ECMWF surface model milestones

Vegetation based evaporation	1989
CY48 (4 layers + …)	1993 / ERA15
Initial conditions for soil water	1994
Stable BL/soil water freezing	1996
Albedo of snow forests	1996
OI increments of soil water	1999
TESSEL, new snow and sea ice	2000 / ERA40
HTESSEL, revised soil hydrology	2007
HTESSEL+SNOW, revised snow	2009
HTESSEL+SNOW+LAI, seasonal vegetation	2010
CHTESSEL (carbon-land surface)	2012
LAKETESSEL (addition of lake tile)	2013

TESSEL model and validation

● Model Description

Viterbo and Beljaars, 1995. J. Climate, 2716-2748.

van den Hurk et al, 2000. EC Tech Memo 295.

● 1D validation

-Cabauw

Beljaars and Viterbo, 1994. BLM, 71, 135-149.

Viterbo and Beljaars, 1995. J. Climate.

-FIFE

Viterbo and Beljaars, 1995. J. Climate.

Betts et al. 1996. JGR, 101D, 7209-7225.

Betts et al., 1998. Mon. Wea. Rev., 126, 186-198.

Douville et al, 2000: MWR, 128, 1733-1756.

-ARME

Viterbo and Beljaars, 1995. J. Climate.

-SEBEX

Beljaars and Viterbo, 1999. Cambridge Univ Press.

van den Hurk et al, 2000.

-**All the above + HAPEX-MOBIHLY+BOREAS**

van den Hurk et al, 2000.

● US Summer 1993

Beljaars et al. 1996. MWR, 124, 362-383.

Betts et al. 1996. JGR, 101D, 7209-7225.

Viterbo and Betts, 1999: JGR, 104D, 19,361-19,366.

● Soil water initial conditions

Viterbo, 1996.

Douville et al, 2000.

● Soil freezing

Viterbo et al., 1999. QJRMS, 125,2401-2426.

● Snow forest albedo

Viterbo and Betts, 1999. JGR, 104D, 27,803-27,810.

● Mississippi river basins

Betts et al., 1998. J. Climate, 11, 2881-2897.

Betts et al., 1999. JGR, 104D,19,293-19,306.

● Mackenzie river basin

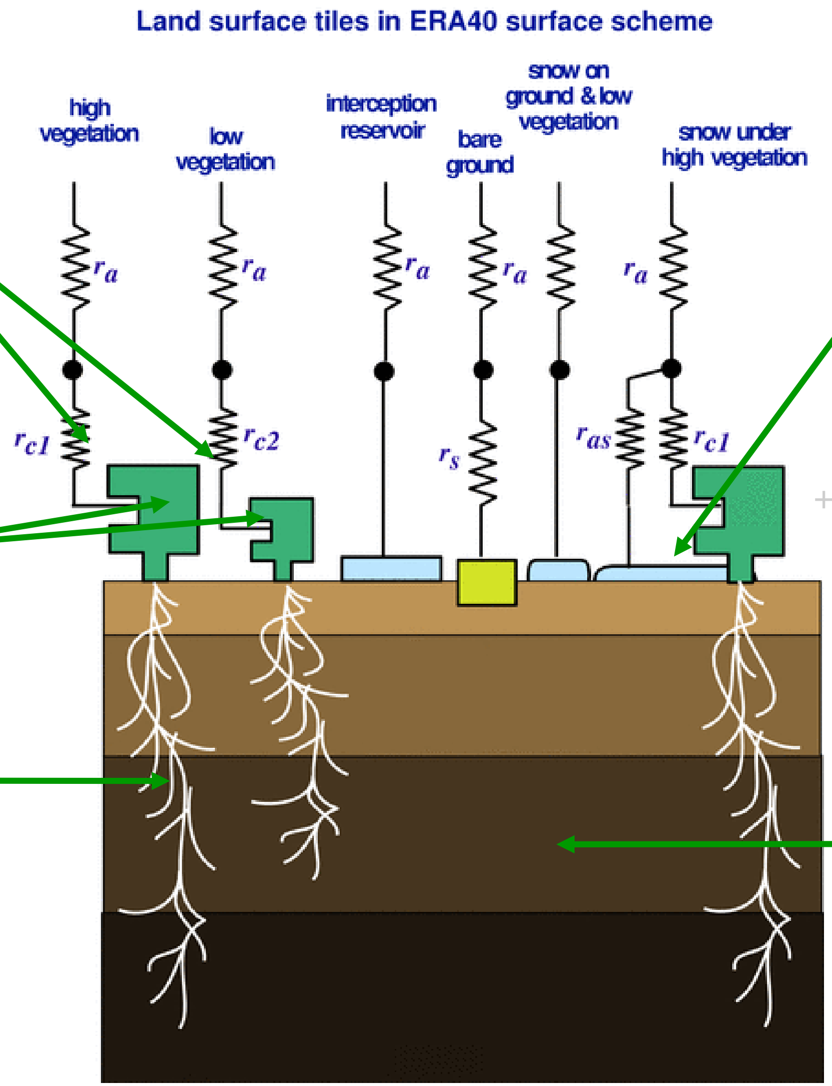
Betts and Viterbo, 2000: J. Hydrometeor, 1, 47-60.

● Impact of land on weather

Viterbo and Beljaars, 2002: Springer.

(CH)TESSEL scheme in a nutshell

- Tiled ECMWF Scheme for Surface Exchanges over Land



Revised canopy resistances, including air humidity stress on forest

High and low vegetation treated separately

Variable root depth

New treatment of snow under high vegetation

+ 2 tiles (ocean & sea-ice)

No root extraction or deep percolation in frozen soils

Land surface model evolution

2000/06	2007/11	2009/03	2009/09		2010

- **TESSEL**

  Van den Hurk et al. (2000)
  Viterbo and Beljaars (1995),
  Viterbo et al (1999)

  Up to 8 tiles (binary Land-Sea mask)

  GLCC veg. (BATS-like)

  ERA-40 and ERA-I scheme

- **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**

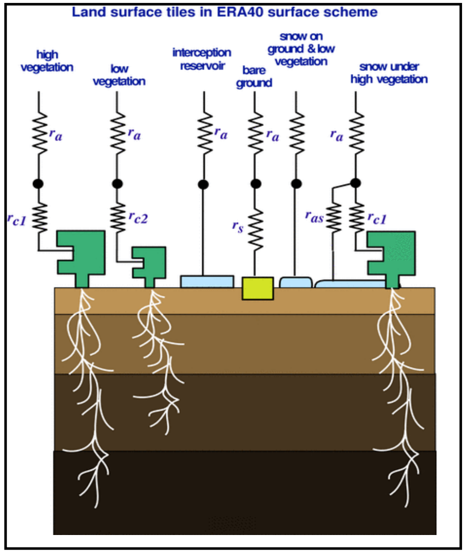
  Boussetta et al. (2010)

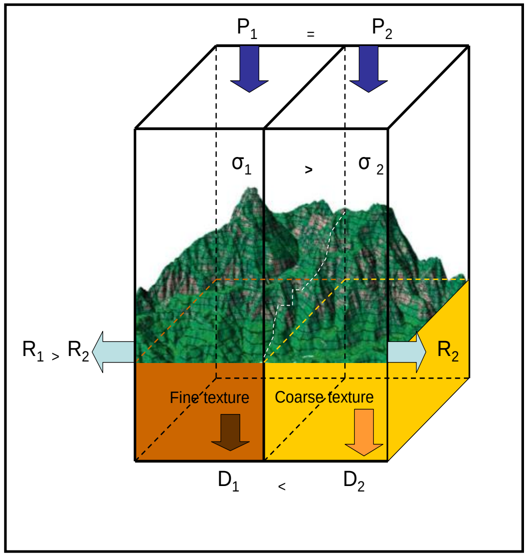
  New satellite-based

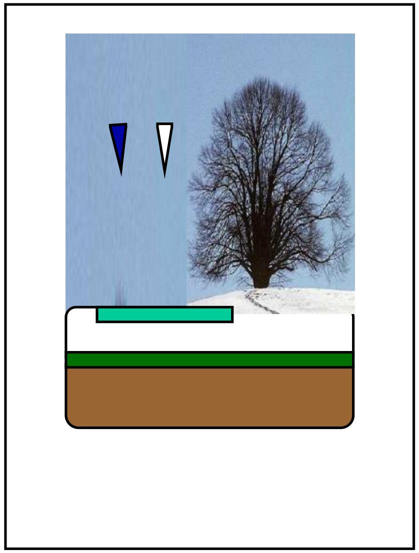
  Leaf-Area-Index

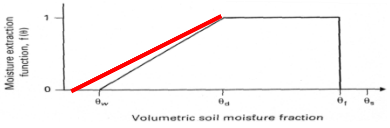
- **SOIL Evaporation**

  Mahfouf and Noilhan (1991)

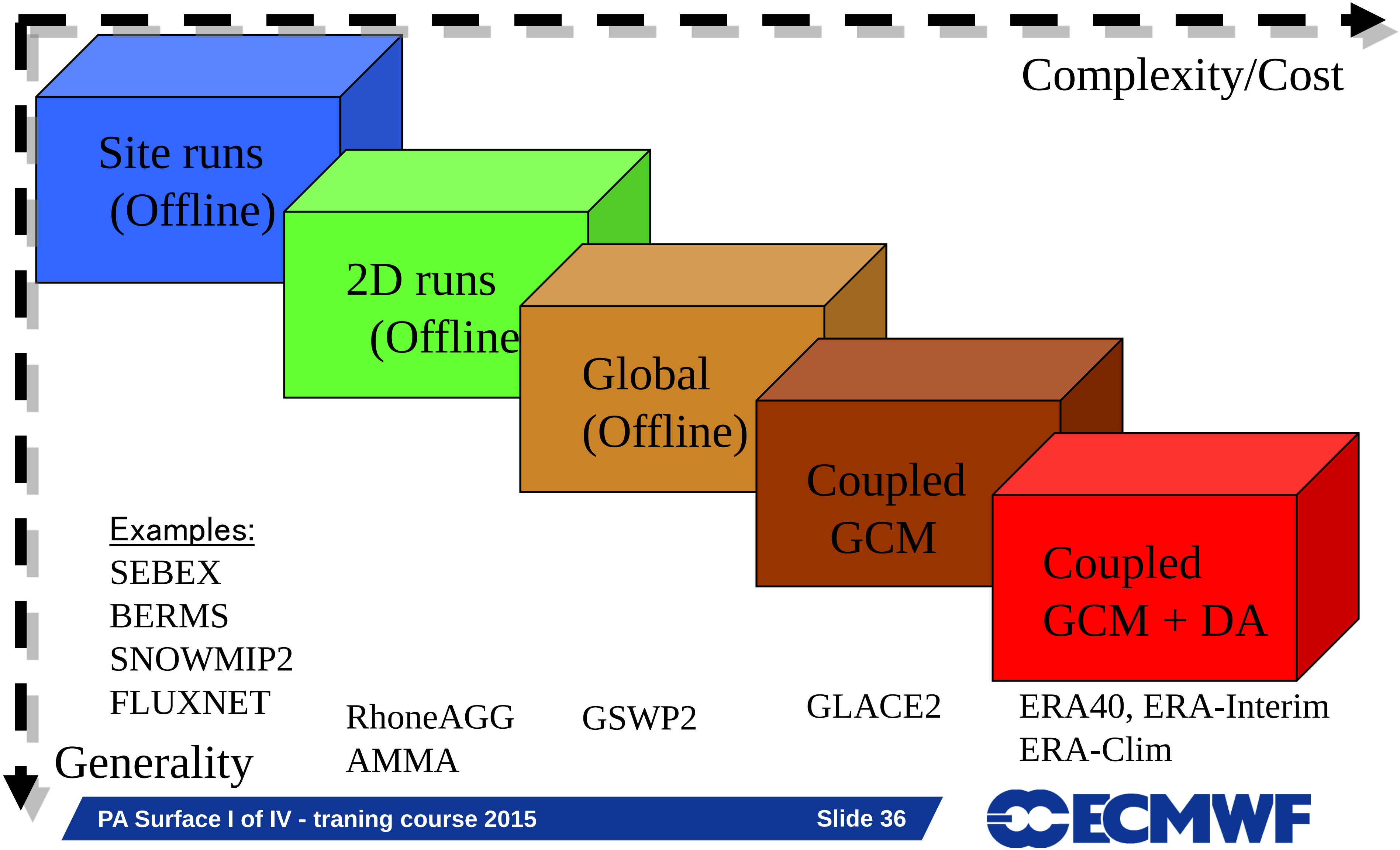








Strategy for land surface model development at ECMWF (applied)



Complexity/Cost

Site runs
(Offline)

2D runs
(Offline)

Global
(Offline)

Coupled
GCM

Coupled
GCM + DA

Examples:

SEBEX
BERMS
SNOWMIP2
FLUXNET

RhoneAGG
AMMA

GSWP2

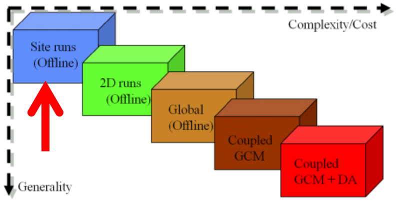
GLACE2

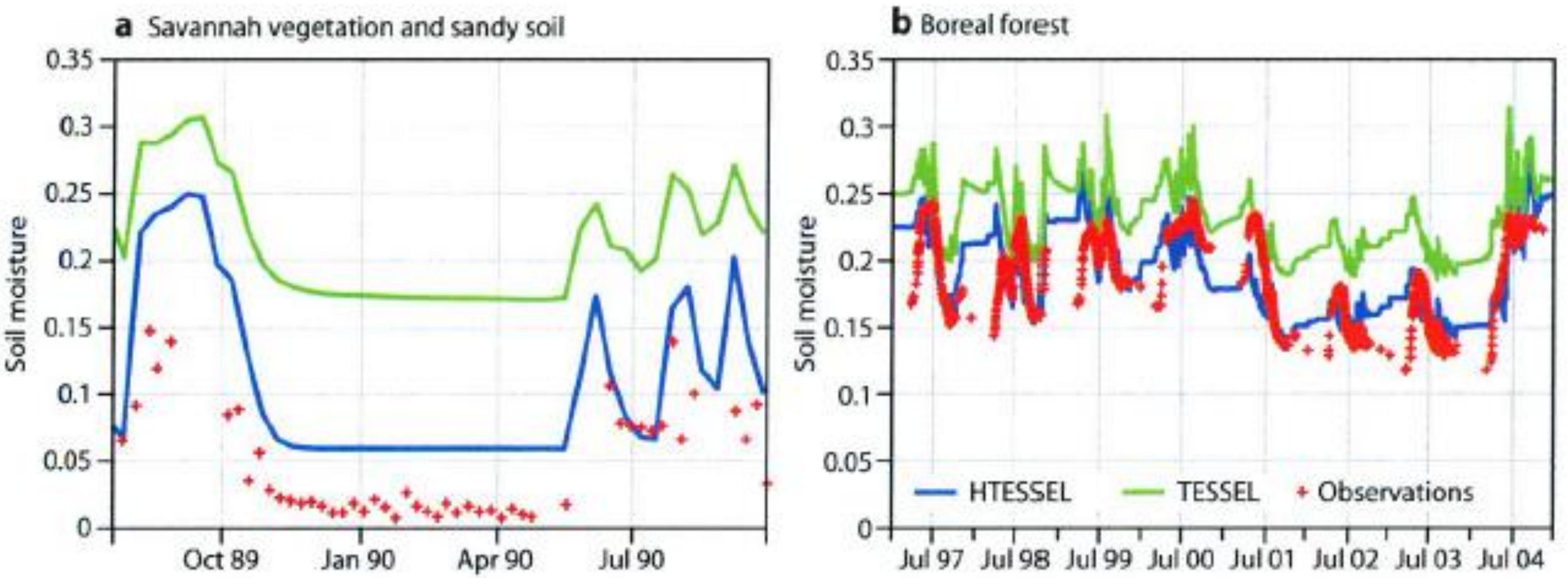
ERA40, ERA-Interim
ERA-Clim

Generality

Soil hydrology

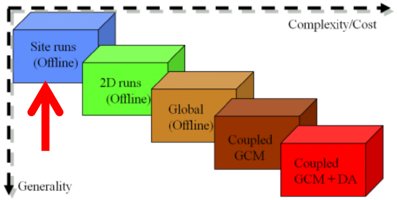
(Balsamo et al. 2009)

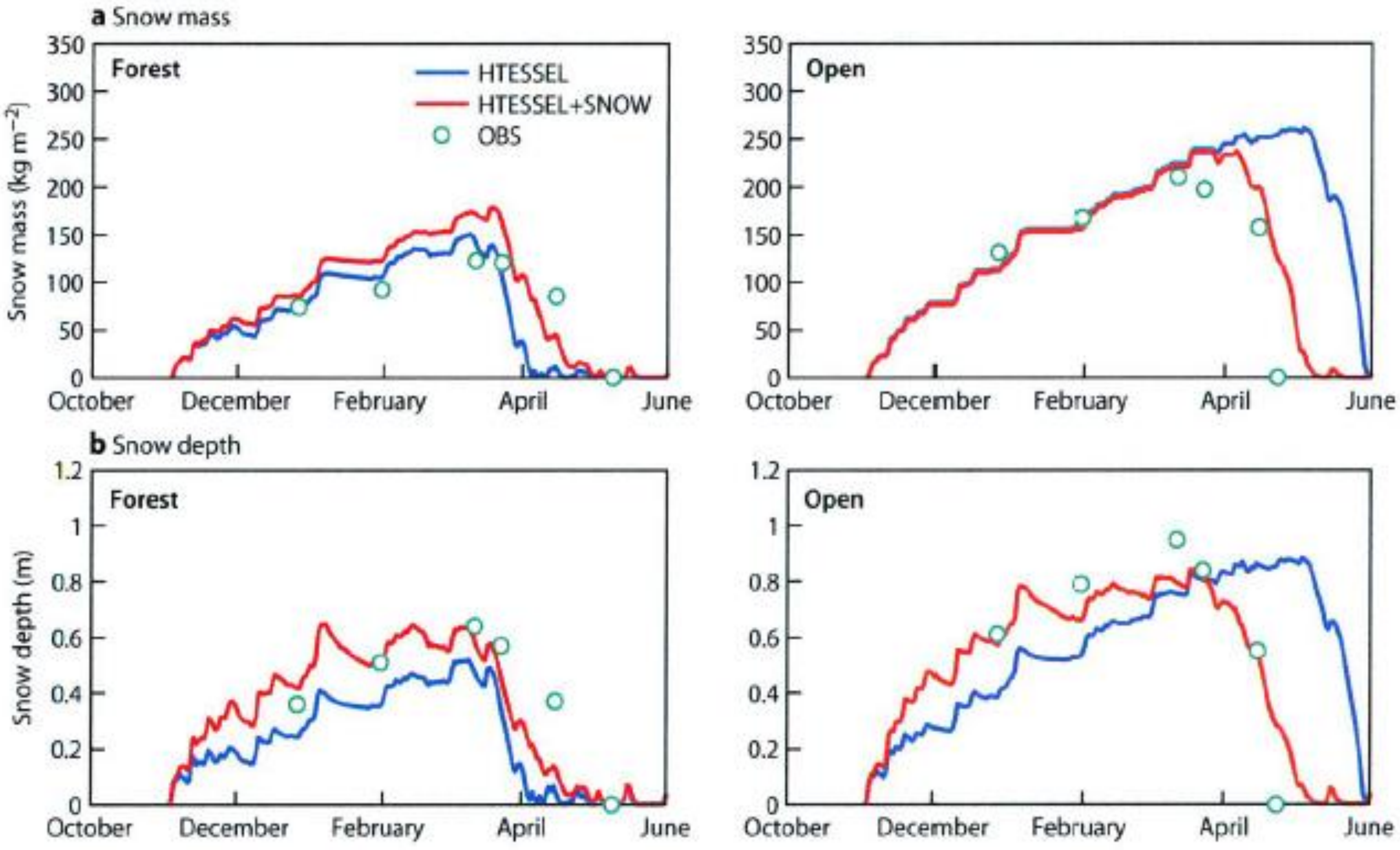




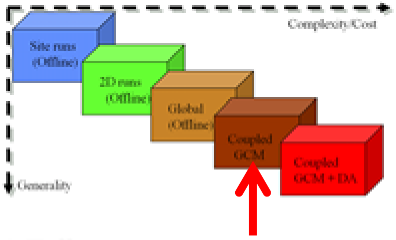
New snow scheme

(Dutra et al. 2010)

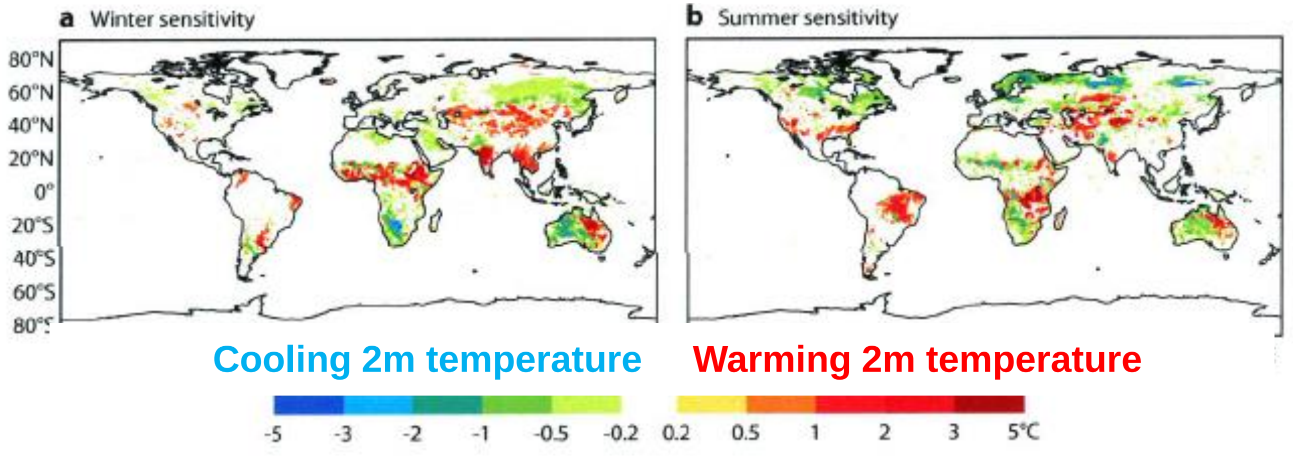




Forecasts (+36-h) impact

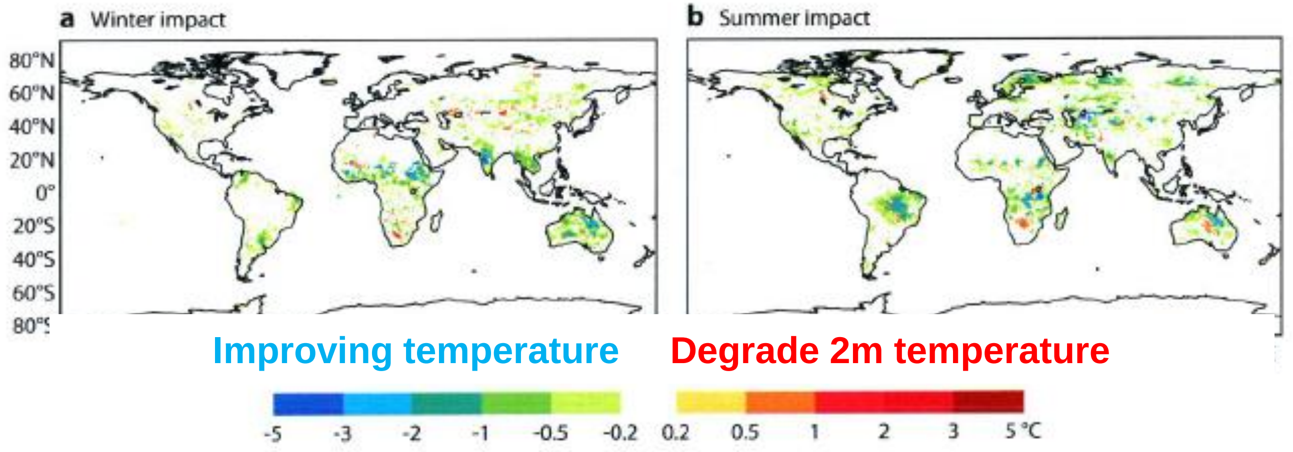


Forecast sensitivity



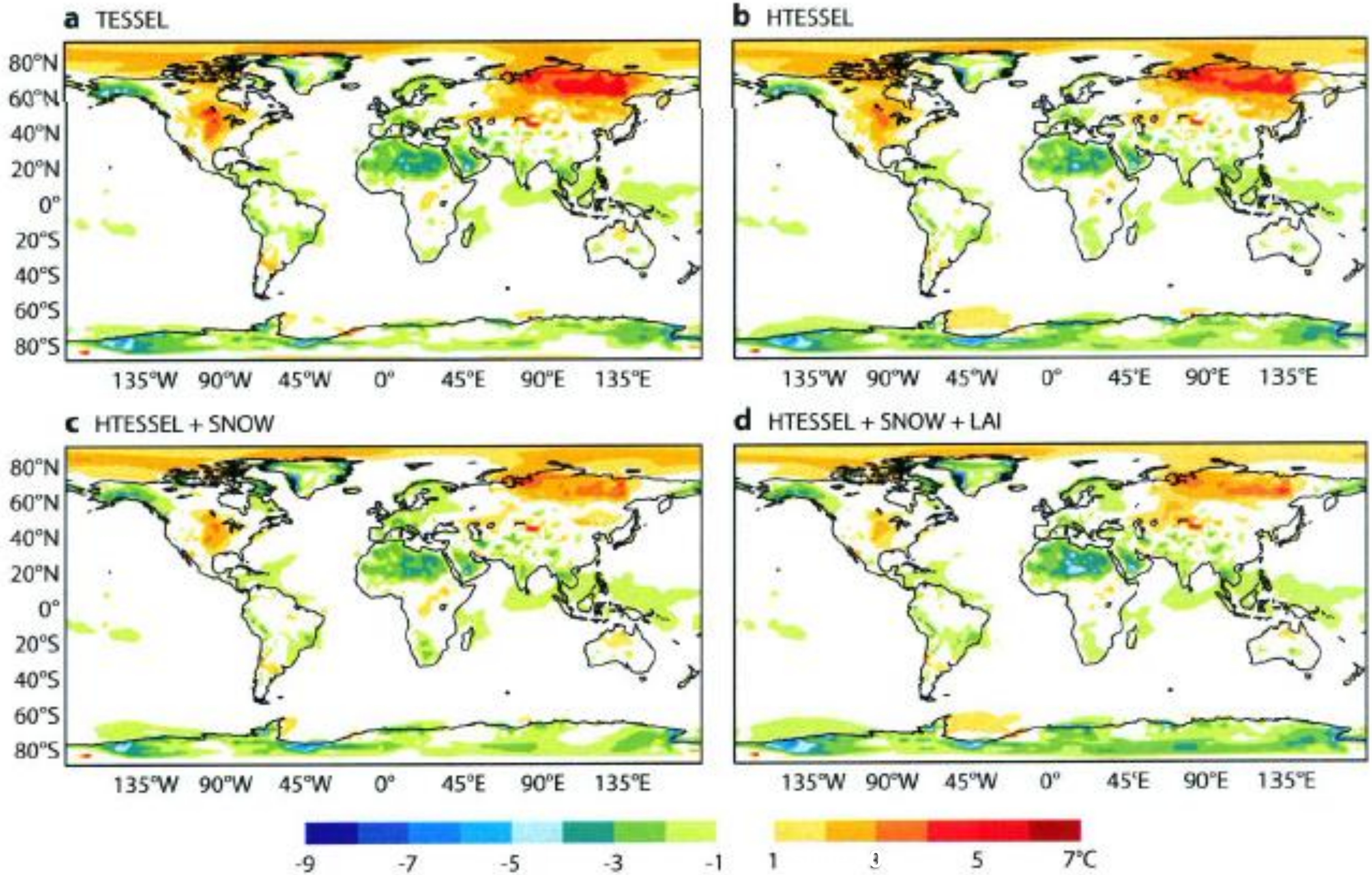
Cooling 2m temperature Warming 2m temperature

Forecast Impact



Improving temperature Degrade 2m temperature

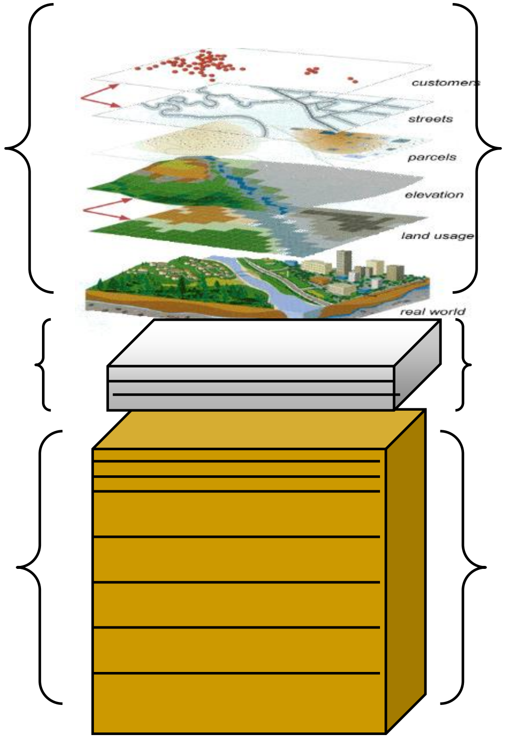
Climate simulation impact



simulations colder than ERA-Interim

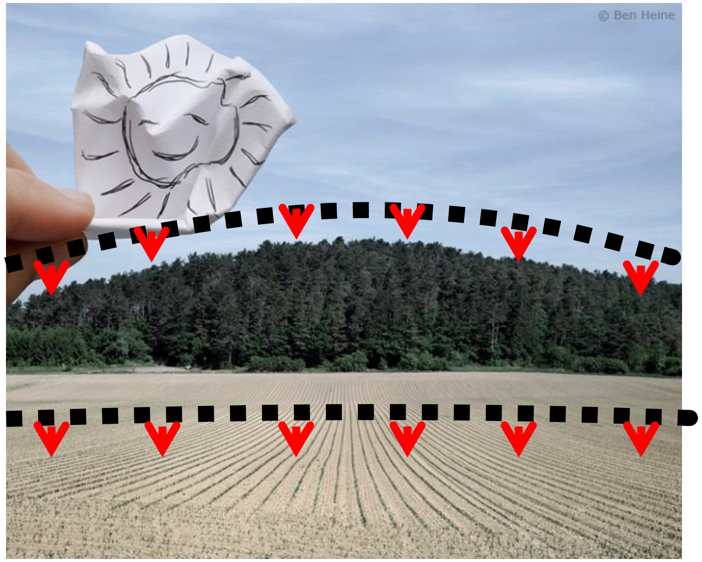
Warmer than ERA-Interim

Perspectives for the land surface in Earth System Prediction



- Better characterisation of the vertical profiles
- Better respresentation on heterogeneity and ecosystems interaction
- Unification of processes (cryosphere)

Modularity of the land system is a key to ESP model integrations and inter-operability of parameterizations



- Complexity needs a step-wise approach
- The assimilation methods are integral part of the model diagnostics
- A better coupling between sub-systems is the ultimate goal, achievable by enhanced knowledge on each sub-system and the mutual interactions

Parameterization of land-surface processes

…modelling should be always guided by observations…but in case of land surface your senses are also amazing instruments ☺

http://www.youtube.com/watch?v=jfa29pq6NFs