Early land surface schemes for large scale atmospheric models

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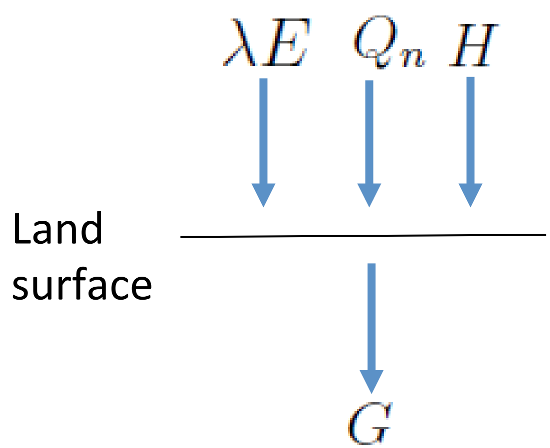
Thanks to: Gianpaolo Balsamo, Pedro Viterbo and many colleagues.

Overview

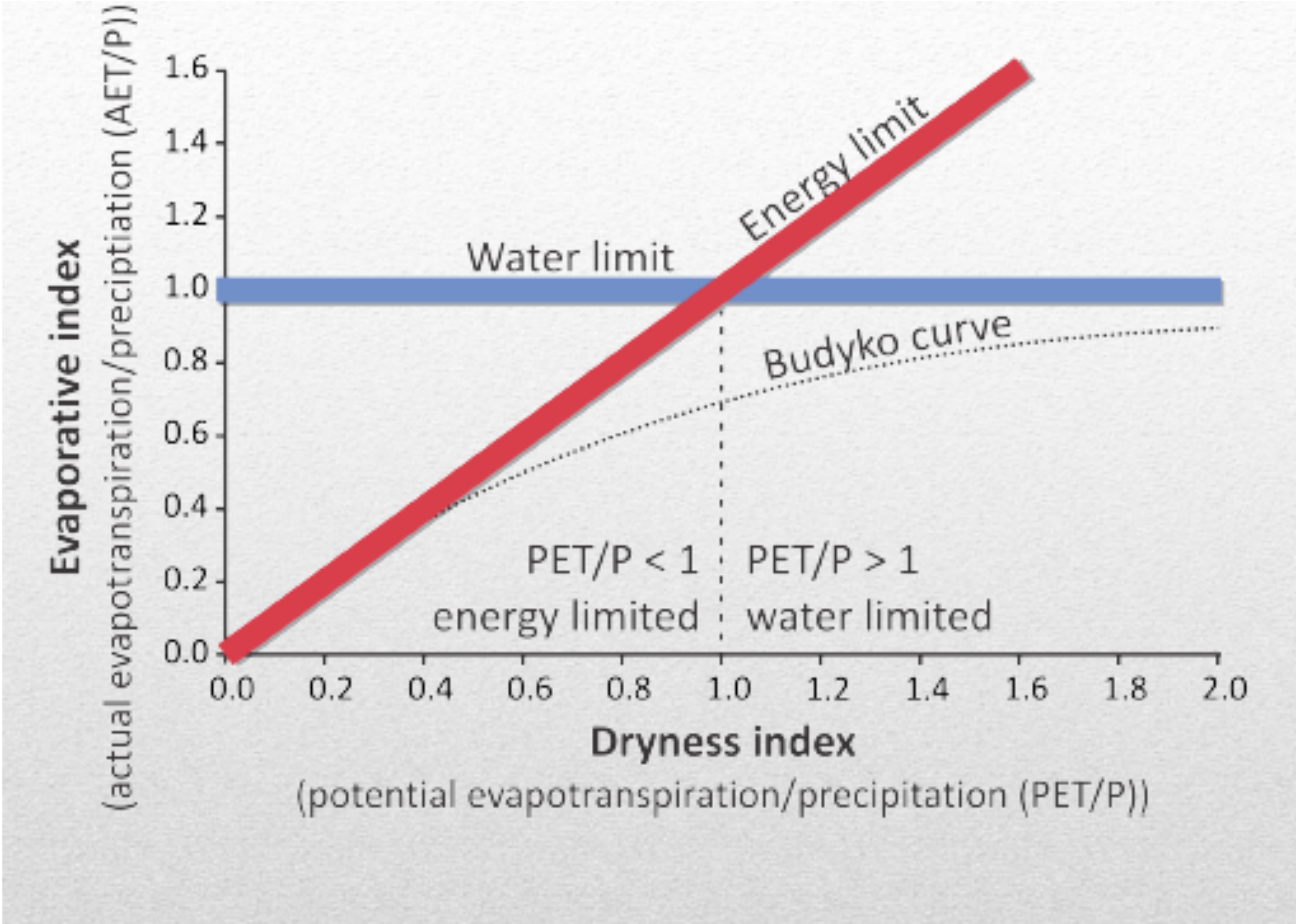
1. Evaporation estimation before 1990
2. Early land surface models
3. Lessons for the future

Surface energy balance

$$Qn + \lambda E + H = G$$



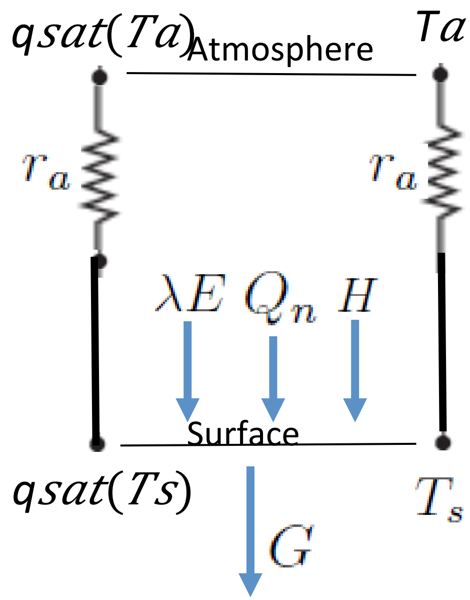
Budyko curve: annual coupled water-energy budget

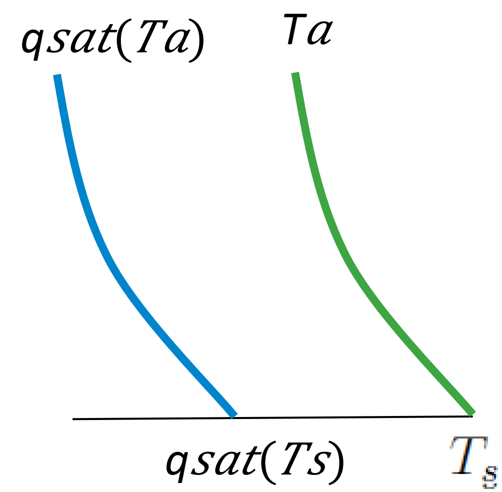


Note:
Potential evaporation is defined here as the net radiative energy at the surface, available for evaporation.

Budyko, M.I. (1961): The heat balance of the earth's surface. *Soviet Geography*, *2*(4), pp.3-13.

Priestley-Taylor formulation





$$\lambda E = \alpha - \Delta (Qn - G)/\Delta + \gamma$$

$$Q_n + \lambda E + H = G \quad \gamma = C_p/\lambda$$

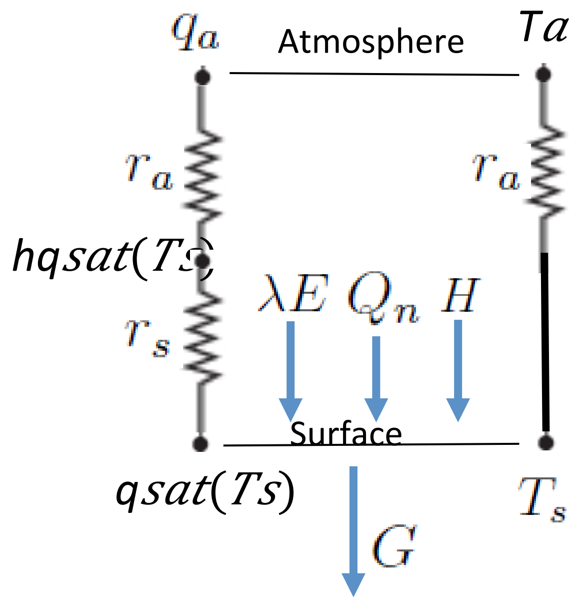
$$\alpha = 1.26 \; to \; 1.28$$

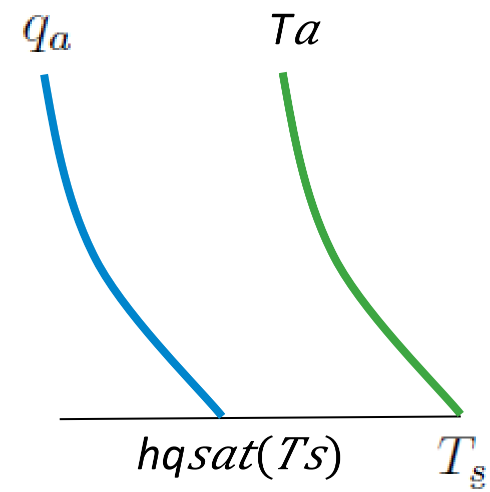
Assume saturated air and add empirical coefficient.

This formulation is remarkably robust for day-time where G is typically 0.1Qn It has the essential dependencies on available energy and temperature, but can not be used at night.

Penman (1948): Natural evaporation from open water, bare soil and grass, *Proc. Roy. Soc.*, **A193**, 120-146.
Monteith, J.L. (1965): . Evaporation and environment, in: G.E. Fogg (ed.), *The state and movement of water in living organisms*, Symp. Soc. Exp. Biol., **19**, 205-234, Academic Press.
Jarvis, P.G. (1976): The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the filed, Phil. Trans. R. Soc. Lond., B273.927, 593-610.

Penman-Monteith equation





Linearize saturation specific humidity curve, and eliminate T_s

$$\lambda E = -\Delta(Qn - G) + \varrho Cp[qa - qsat(Ta)]/ra/\Delta + \gamma(1 + rs/ra)$$

Although not used explicitly in most models, the results during daytime will behave like PM, because the numerics of the land surface eliminates Ts.

$Q_n + \lambda E + H = G$ $\gamma = C_p/\lambda$

Canopy resistance (rs) depends on radiation, temperature, air humidity deficit and soil moister (Jarvis, 1976)

Penman (1948): Natural evaporation from open water, bare soil and grass, *Proc. Roy. Soc.*, **A193**, 120-146.
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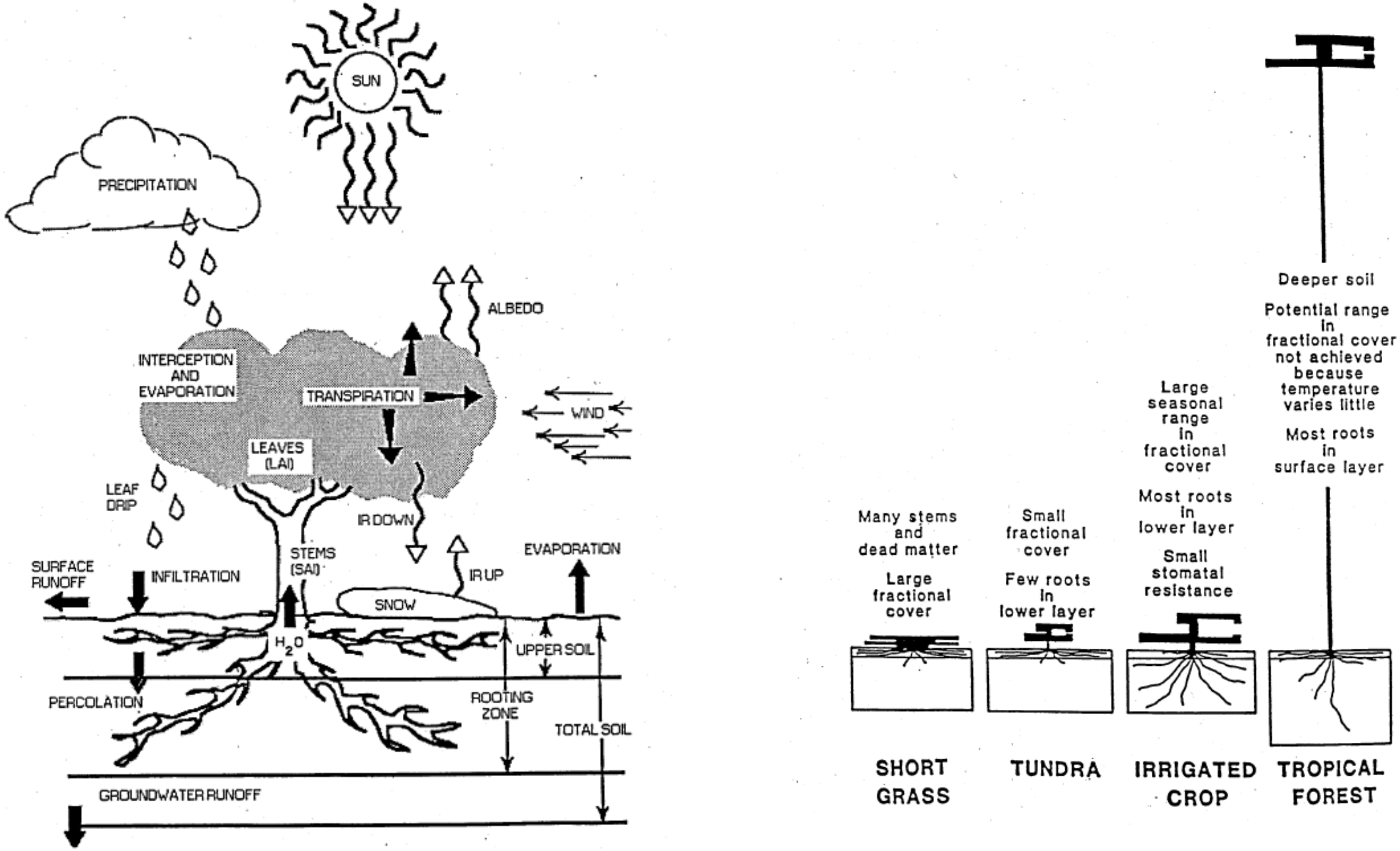
GFDL model with bucket model according to Manabe (1969)

- Land surface coupling based on surface energy balance and ideas developed by Bodyko (1956).
- The ground heat flux is put to zero and an equilibrium (unstressed) evaporation (E_e) is computed according to Penman Monteith with zero canopy resistance.
- Real evaporation depends on water availability: $E=E_e W/W_s$, where W is the water content of the bucket and W_s is the bucket size.
- Hydrology is very simple: if the bucket overflows it is called runoff.
- Bucket size is recognized to be dependent on soil field capacity and rooting depth. Both are highly variable. Due to lack of data, 150 mm for a typical soil depth of 1 m has been selected.

Comment I: In well watered conditions this formulation strongly overestimates evaporation due to the humidity deficit term in PM. However, this model can and has been improved by using a finite canopy resistance (i.e. plants in a bucket), which makes it rather competitive.
Comment II: GISS model (Arakawa, 1972), used by Charney(1975) has similar approach

Manabe (1969): Climate and ocean circulation, I The atmospheric circulation and the hydrology of earth's surface, *Mon. Wea. Rev.*, **97**, 739-6774.

NCAR's Biosphere-Atmosphere Transfer Scheme (BATS) for the Community Climate Model (CCM)



Vegetation is seen as crucial player for evaporation (e.g. through stomatal control), and interception evaporation.

Dickinson et al. (1986, 1993): Biosphere-Atmosphere Transfer Scheme for the NCAR Community Climate Model. NCAR Tech. Notes 275, 387. Also

BATS vegetation types and parameters

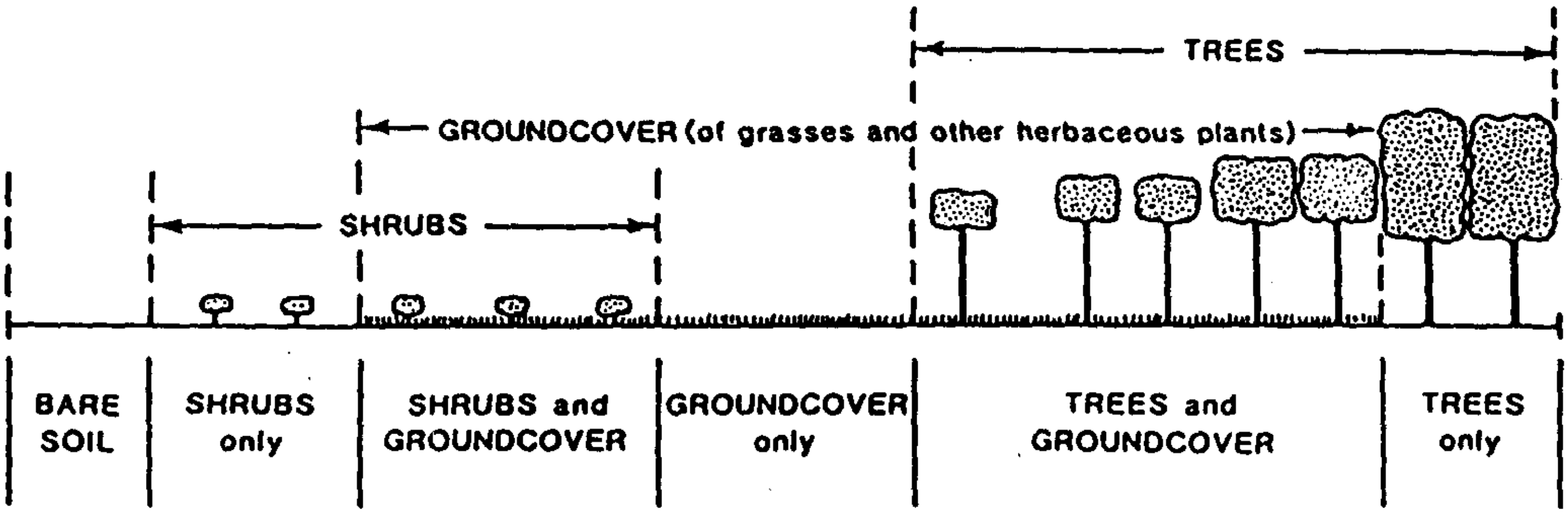
1. Crop/mixed farming
2. Short grass
3. Evergreen needleleaf tree
4. Deciduous needleleaf tree
5. Deciduous broadleaf tree
6. Evergreen broadleaf tree
7. Tall grass
8. Desert
9. Tundra
10. Irrigated crop
11. Semi–desert
12. Ice cap/glacier
13. Bog or marsh
14. Inland water
15. Ocean
16. Evergreen shrub
17. Deciduous shrub
18. Mixed Woodland

TABLE 2. VEGETATION/LAND COVER PARAMETERS

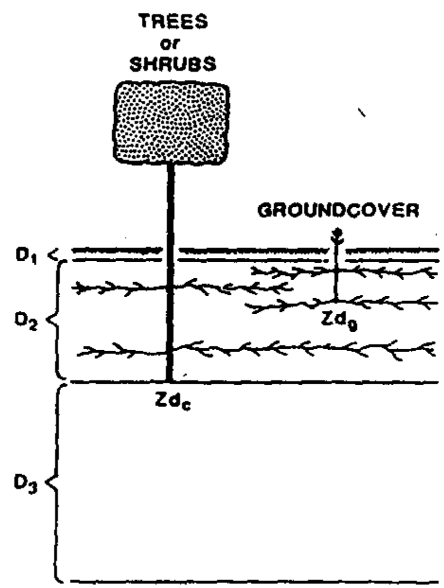
	Parameter	Land Cover/Vegetation Type*																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
a)	Maximum fractional vegetation cover	0.85	0.80	0.80	0.80	0.80	0.90	0.80	0.0	0.60	0.80	0.10	0.0	0.80	0.0	0.0	0.80	0.80	0.80
b)	Difference between maximum fractional vegetation cover and cover at temperature of 269 K	0.6	0.1	0.1	0.3	0.3	0.5	0.3	0.0	0.2	0.6	0.1	0.0	0.4	0.0	0.0	0.2	0.3	0.2
c)	Roughness length (m)	0.06	0.02	1.0	1.0	0.8	2.0	0.1	0.05	0.04	0.06	0.1	0.01	0.03	0.0024	0.0024	0.1	0.1	0.8
d)	Depth of the rooting zone soil layer (m)**	1.0	1.0	1.5	1.5	2.0	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0
e)	Depth of the upper soil layer (m)**	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
f)	Fraction of water extracted by upper layer roots (saturated)	0.3	0.8	0.67	0.67	0.5	0.8	0.8	0.9	0.9	0.3	0.8	0.5	0.5	0.5	0.5	0.5	0.5	0.5
g)	Vegetation albedo for wavelengths <0.7 μm	0.10	0.10	0.05	0.05	0.08	0.04	0.08	0.20	0.10	0.08	0.17	0.80	0.06	0.07	0.07	0.05	0.08	0.06
h)	Vegetation albedo for wavelengths >0.7 μm	0.30	0.30	0.23	0.23	0.28	0.20	0.30	0.40	0.30	0.28	0.34	0.60	0.18	0.20	0.20	0.23	0.28	0.24
i)	Minimum stomatal resistance ($s\ m^{-1}$)	120	200	200	200	200	150	200	200	200	200	200	200	200	200	200	200	200	200
j)	Maximum LAI	6	2	6	6	6	6	6	0	6	6	6	0	6	0	0	6	6	6
k)	Minimum LAI	0.5	0.5	5.0	1.0	1.0	5.0	0.5	0.0	0.5	0.5	0.5	0.0	0.5	0.0	0.0	5.0	1.0	3.0
l)	Stem (& dead matter area index	0.5	4.0	2.0	2.0	2.0	2.0	2.0	0.5	0.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
m)	Inverse square root of leaf dimension ($m^{-1/2}$)	10	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
n)	Light sensitivity factor ($m^2\ W^{-1}$)	0.02	0.02	0.06	0.06	0.06	0.06	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.06

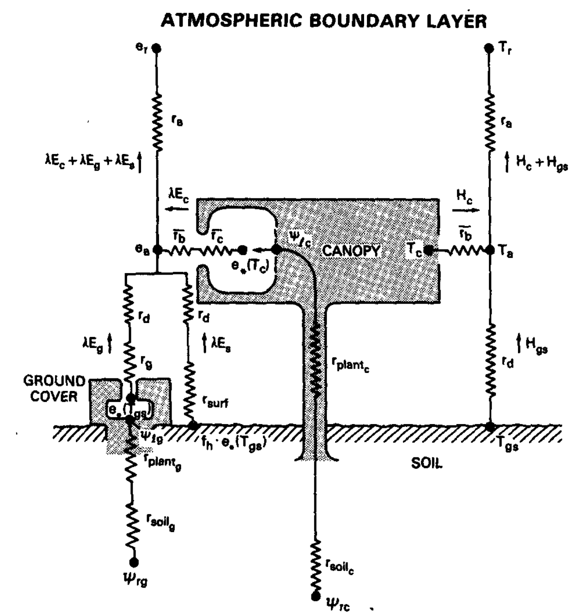
The careful description of vegetation allows for "deforestation" experiments (Dickinson and Henderson-Sellers, 1988).

Simple Biosphere Model (SiB) for use within GCM's



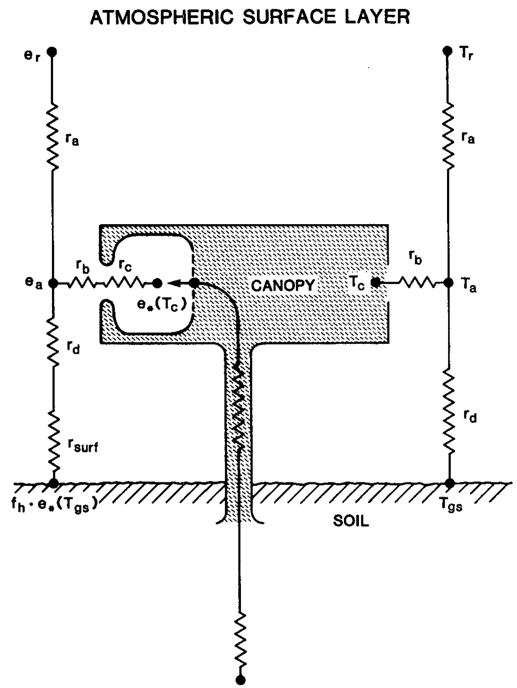
SiB has complex vegetation structure, complex root structure and many empirical paremeters





Sellers and Mintz (1986): A simple biosphere model (SiB) for use within general circulation models, *J. Atmos. Sci.*, **43**, 505-531.

A simplified SiB



Xue and Sellers reduce the complexity of Sib. The number of input parameters is reduced from 44 to 21. Only one vegetation layer is used.

Xue and Sellers (1991): I simplified biosphere model for climate studies, J. Clim., **4**, 345-364.

NWP models

- In general NWP models paid little attention to the land surface model: direct model output of near surface parameters were of poor quality and hardly used.

- Meteo-France used a very simple Force restore method.

- ECMWF had a 3-layer model, where the deep layer was specified by a monthly climatology. Surface fluxes and near surface parameters were poor.

BTW:
A key element that allowed progress towards more realistic land surface models was the development at Meteo-France of land surface temperature and soil moisture data assimilation based on SYNOP observations of temperature and humidity (Mahfouf, 1991; Bouttier et al., 1993).

Mahfouf, J.F. (1991): Analysis of soil moisture from near-surface parameters: A feasibility study. *J. Appl. Meteor.*, ***30***, 1534-1547.
Bouttier, F., Mahfouf, J.F. and Noilhan, J. (1993): Sequential assimilation of soil moisture from atmospheric low-level parameters. Part I: Sensitivity and calibration studies. *J. Appl. Meteor.*, ***32***, 1335-1351.

Results from GCM's: Sensitivity experiments

Charney (1975) studied the sensitivity of circulation to reduction of vegetation in the Sahel. The increase of albedo reduces the heating which is compensated for by heating from more subsidence which reduces precipitation (positive feedback).

Charney (1975): Dynamics of deserts and drought in the Sahel, *Q. J. R. Meteor. Soc.*, **101**, 193-202.

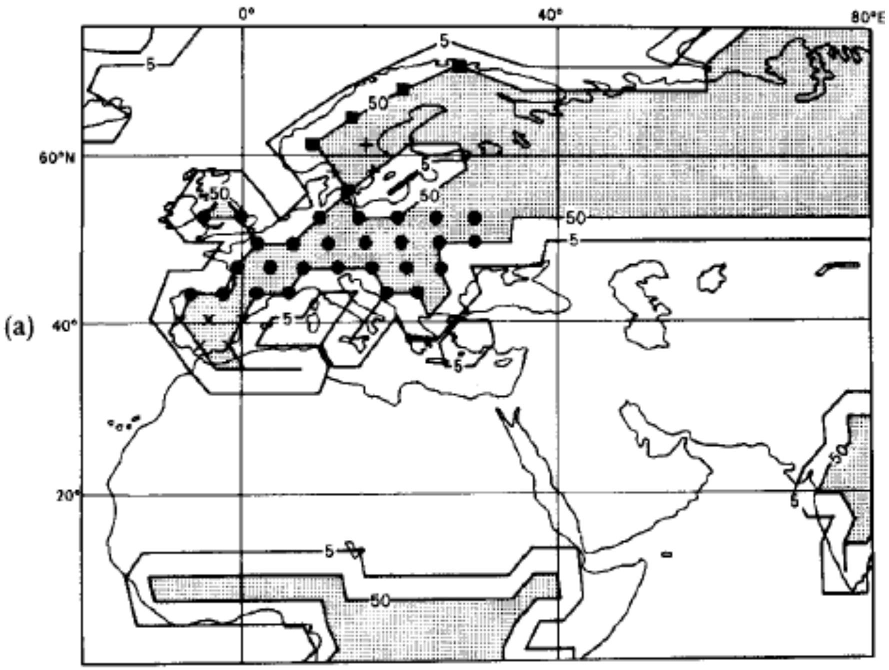
Dickinson and Henderson-Sellers study deforestation effects in the Amazon and find a temperature increase of 3-5 K by replacing forest by grass.

Dickinson and Henderson-Sellers (1988): Modelling tropical deforestation: A study of GCM land-surface parametrization, *Q. J. R. Meteor. Soc.*, **114**, 439-462.

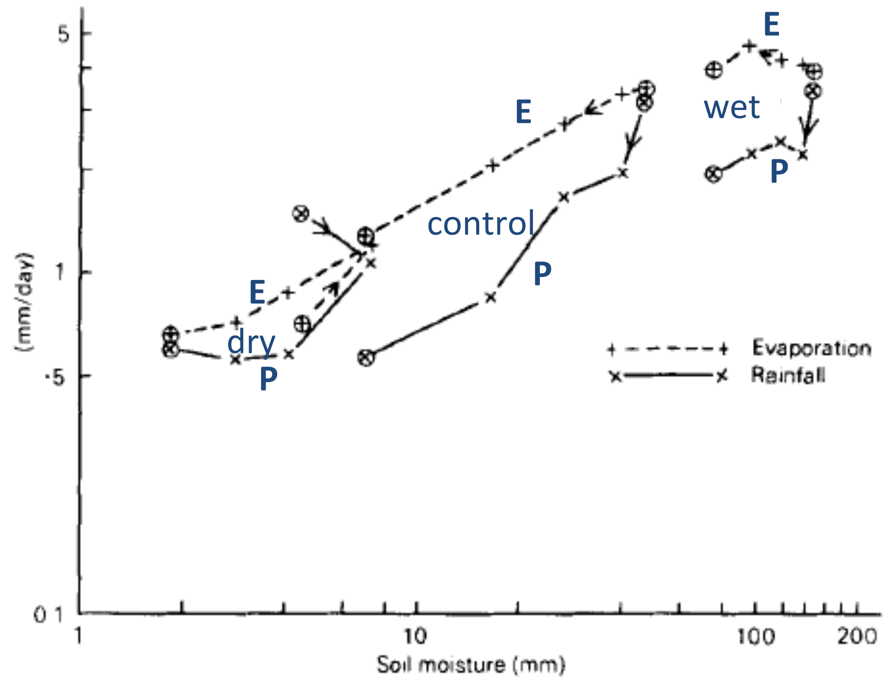
Results from GCM's: Precipitation

Experiments by Rowntree and Bolton (1983) in which the grid points over Europe (with dots) are initialized to field capacity (Wet), wilting point (Dry), realistic values (Control).

Initial soil moisture in control experiment



Evolution of P and E against SM over the first 10 days of the simulation



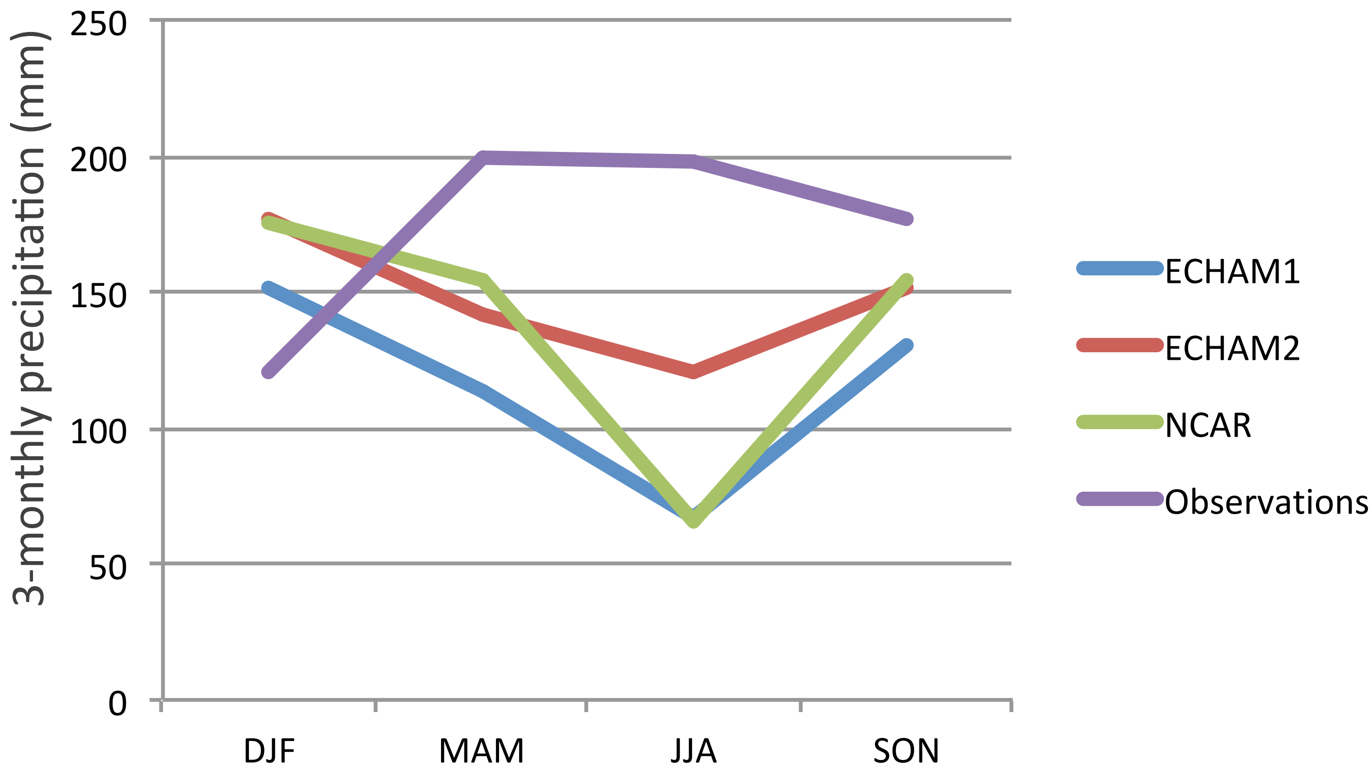
Conclusions:

(i) model shows a strong response to initial soil moisture

(ii) model dries out very quickly

Rowntree and Bolton (1983): Simulation of the atmospheric response to soil moisture anomalies over Europe, *Q. J. R. Meteor. Soc.*, **109**, 501-526.

Results from GCM's: Precipitation over Northern Europe



Nearly all models had difficulties with the annual cycle of precipitation over land (too dry summers).

Raisanen (1994): A comparison of the results of seven GCM experiments in Northern Europe, *Geophysica*, **30**, 1-30.

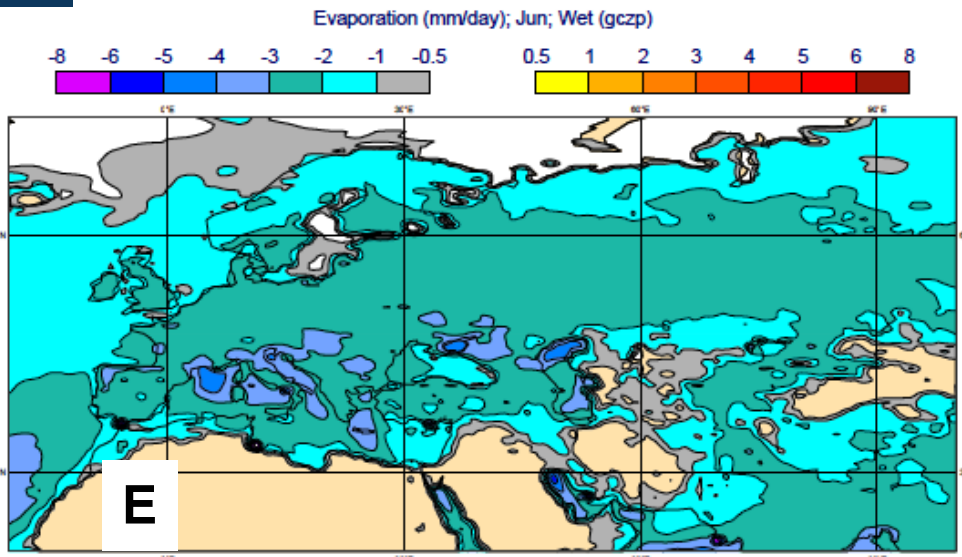
Long integrations

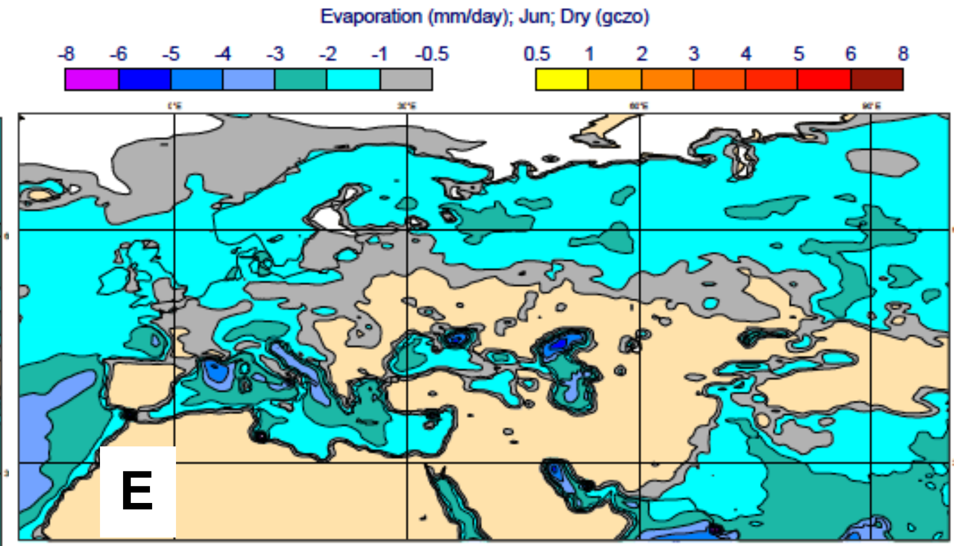
- Initial date: 20030401
- 4 member ensemble (only averages are presented)
- Length: 5 months
- Two experiments with soil moisture initial conditions (set according to local soil type):
  1. Field capacity everywhere (wet)
  2. Permanent wilting point everywhere (dry)

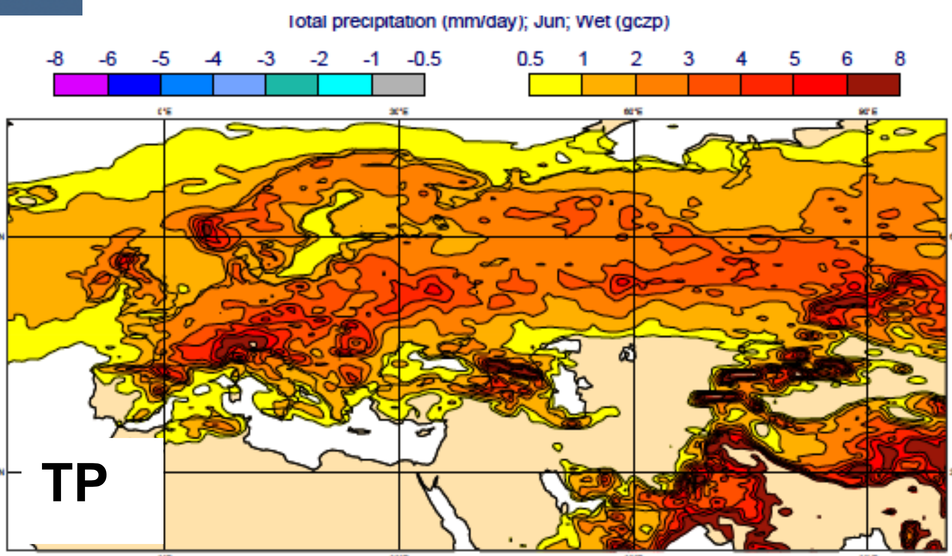
June

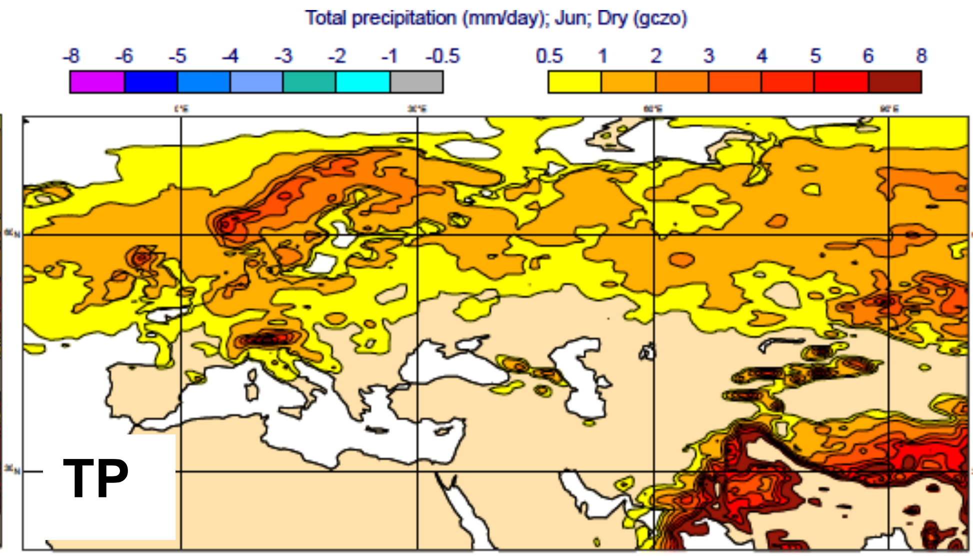
Wet

Dry


Evaporation (mm/day); Jun; Wet (gczp)
-8 -6 -5 -4 -3 -2 -1 -0.5 0.5 1 2 3 4 5 6 8
E


Evaporation (mm/day); Jun; Dry (gczo)
-8 -6 -5 -4 -3 -2 -1 -0.5 0.5 1 2 3 4 5 6 8
E


Total precipitation (mm/day); Jun; Wet (gczp)
-8 -6 -5 -4 -3 -2 -1 -0.5 0.5 1 2 3 4 5 6 8
TP

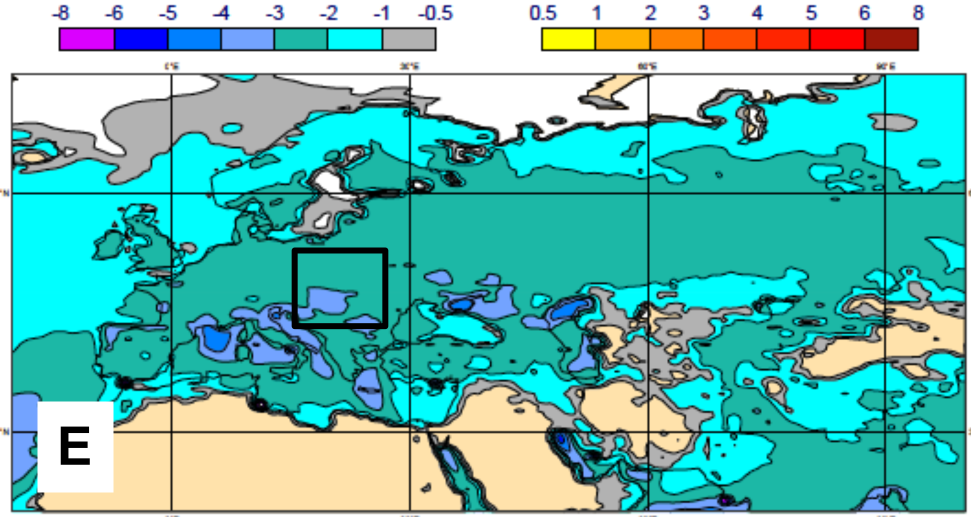

Total precipitation (mm/day); Jun; Dry (gczo)
-8 -6 -5 -4 -3 -2 -1 -0.5 0.5 1 2 3 4 5 6 8
TP

June

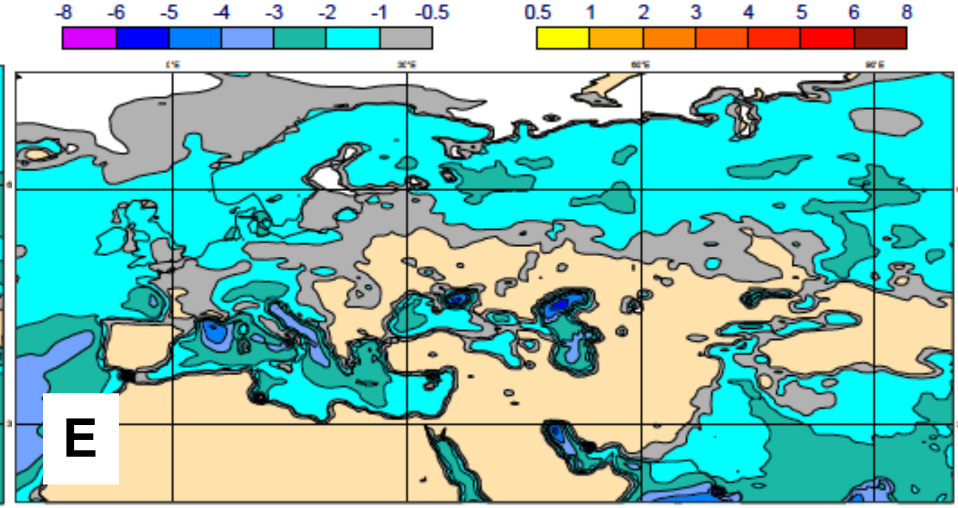
Wet

Dry

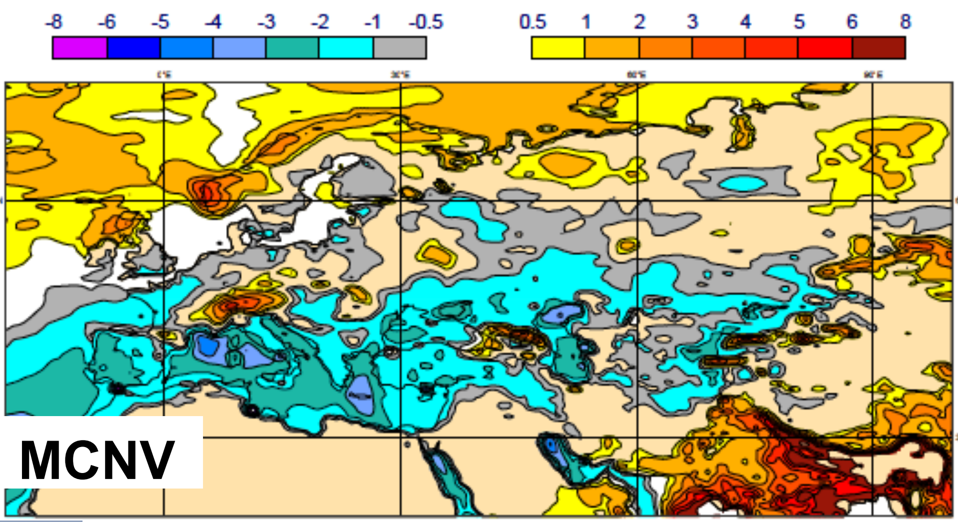
Evaporation (mm/day); Jun; Wet (gczp)



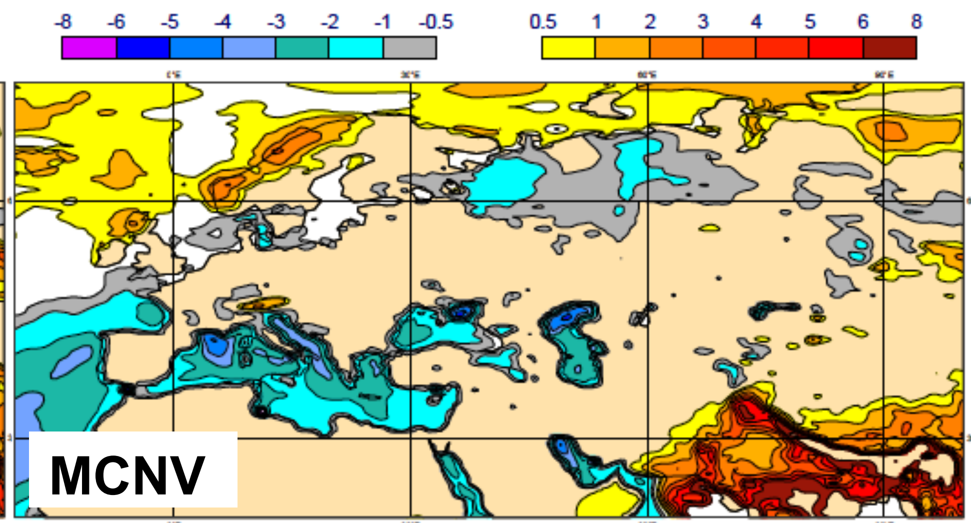
Evaporation (mm/day); Jun; Dry (gczo)



Moisture convergence (mm/day); Jun; Wet (gczp)

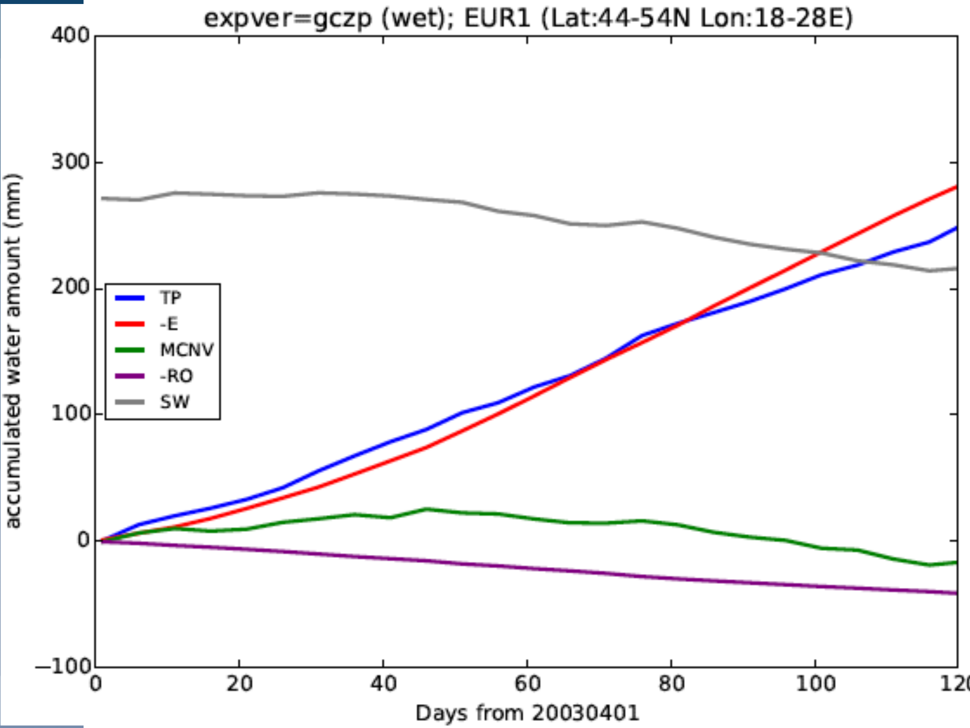


Moisture convergence (mm/day); Jun; Dry (gczo)

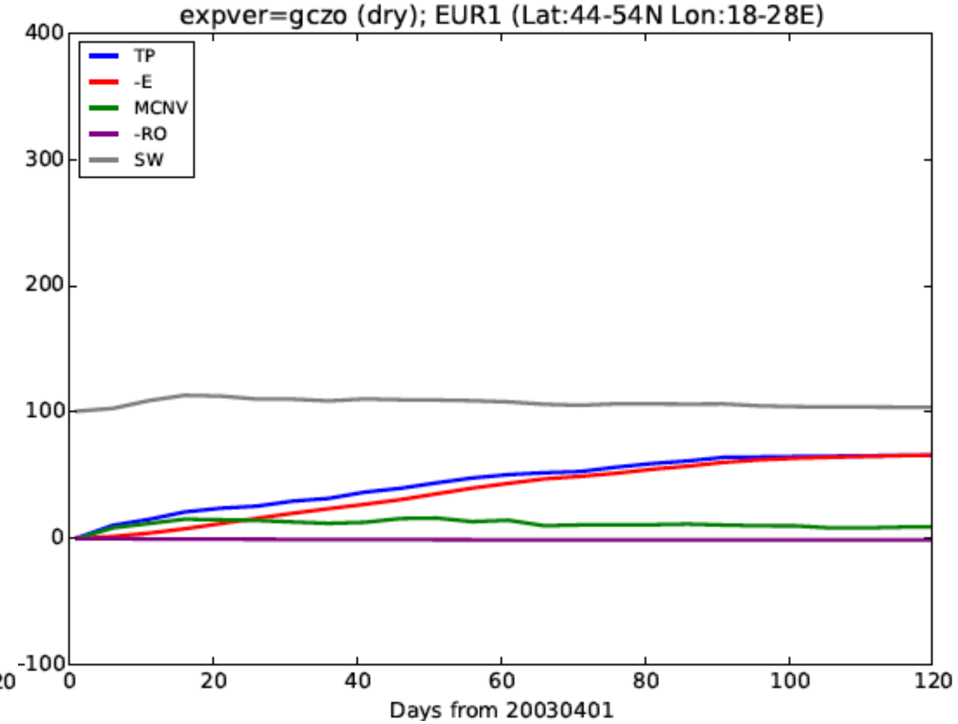


Accumulated fluxes and SM; area Europe 32-40N/99-85W

Wet



Dry



Conclusions

- Atmospheric models are sensitive to the land surface boundary condition
- Different land surface models have different impact
- Models tend to run dry in summer, i.e. evaporation and precipitation spin down over land
- Specific conclusions:
  - Models with a land surface that evaporates as a water surface overestimate evaporation (e.g. as in the early bucket model)
  - Vegetation should be represented

Response of the science community

• Compare land surface models	GEWEX initiated PILPS (see e.g. Henderson Sellers et al. 1995)
• Compare to observations; long time series are needed to cover all seasons	Field programmes were designed and long term data sets were developed e.g. HAPEX-MOBILHY (Andre et al. 1986) and HAPEX-Sahel (Goutorbe et al. 1994)
• Develop global data sets	e.g. ISLSCP (Sellers et al. 1988)
• Develop simple land models	e.g. ISBA (Noilhan and Planton 1989)

Henderson-Sellers, A., A.J. Pitman, P.K., Love, P., Irannejad, P. and Chen T.H. (1995): The Project for Inter-comparison of Land surface Parameterization Schemes (PILPS): Phases 2 and 3, *Q. J. R. Meteor. Soc.*, **114**, 439-462.

André, J.C., Goutorbe, J.P. and Perrier, A. (1986): HAPEX—MOBLIHY: A Hydrologic Atmospheric Experiment for the Study of Water Budget and Evaporation Flux at the Climatic Scale, *Bull. Amer. Meteor. Soc.*, ***67***, 138-144.

Goutorbe, J.P., Lebel, T., Tinga, A., Bessemoulin, P., Brouwer, J., Dolman, A.J., Engman, E.T., Gash, J.H.C., Hoepffner, M., Kabat, P. and Kerr, Y.H. (1994): HAPEX-Sahel: a large-scale study of land-atmosphere interactions in the semi-arid tropics. *Ann. Geophys.*, **12**, 53-64.

Sellers, P.J., Hall, F.G., Asrar, G., Strebel, D.E. and Murphy, R.E. (1988): The first ISLSCP field experiment (FIFE), *Bull. Am. Meteor. Soci.*, ***69***, 22-27.

Noilhan, J. and Planton, S. (1989): A simple parameterization of land surface processes for meteorological models, *Mon. Wea. Rev.*, ***117***, 536-549.

Meso-Gers 1984 experiment was predecessor of HAPEX experiments 4-Oct 1984 (KNMI flux station near Vic-Fezensac, South France)

$$\lambda E = \frac{-\Delta Q^* + \rho C_p (q_a - q_{sat})/r_a}{\Delta + \gamma^* (1 + r_s/r_a)}$$