# Land Surface processes in climate models

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- **Climate models are mathematical representations of the climate system, expressed as computer codes that run on powerful computers**
- **They are used for a variety of purposes from study of the dynamics of the weather and climate system to projections of future climate.**

## Outline

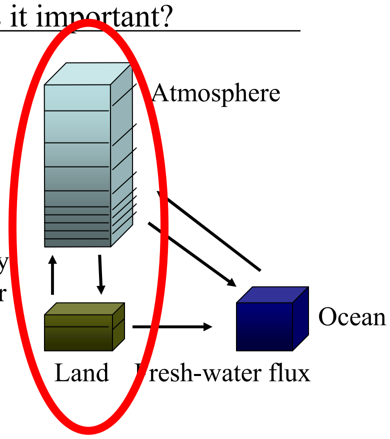
- What is an LSS and why is it important
- Types of LSSs
- Moisture and thermal regimes in LSSs
- Deeper configuration of LSSs and application in permafrost modelling
- "Hot-spots" of Land-atmosphere interaction

## What is a Land surface scheme?

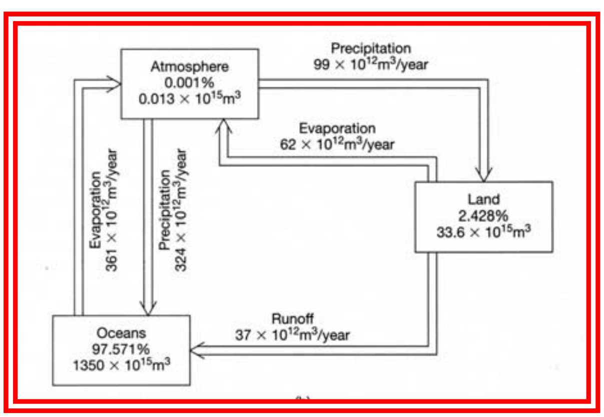
• an algorithm for determining the exchanges of energy, mass and momentum between the atmosphere and the land surface.

## Why is it important?

Supply correct energy momentum and water fluxes




## Hydrologic cycle




**Glaciers and ice sheets =1.8%**

**Streams, lakes and groundwater =0.6%**

## Hydrologic Cycle

### Average residence time of water

| | |
|---|---|
| **Atmosphere** | 10 days |
| **Terrestrial water** | |
| Rivers | 2 weeks |
| Lakes | 10 weeks |
| Soil | 2-50 weeks |
| Biota | 1-20 days |
| Ground water | 1-10,000 years |
| **Oceans** | 3600 years |
| **Polar ice** | 15000 years |

Residence time: the average duration for a water molecule to pass through a subsystem of the hydrologic cycle

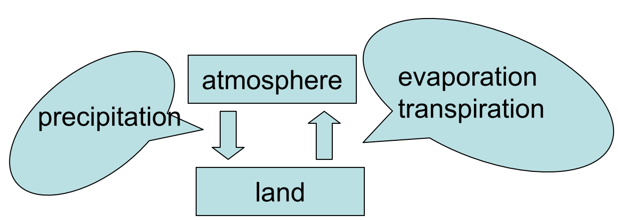
## Terrestrial and atmospheric branches of the hydrologic cycle

**Atmospheric**

Atmospheric transport of water, mainly in the vapor phase

**Terrestrial**

Inflow, outflow and storage of water occurs in various forms



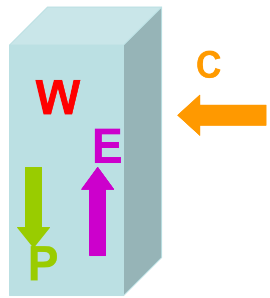
## Hydrologic cycle

### Atmospheric Branch

Water budget equation for an atmospheric column

$$\frac{\partial W}{\partial t} = (E-P) - \nabla_H . Q$$

where, $$Q = \int_{p_s}^{p_{top}} qV \frac{dp}{g}$$




W is precipitable water (kg m$^{-2}$)

E is evapotranspiration rate (kg m$^{-2}$ s$^{-1}$)

P is precipitation rate (kg m$^{-2}$ s$^{-1}$)

Q is the vertically integrated horizontal water vapour flux

$\nabla_H$ is horizontal divergence

V is the horizontal velocity vector

$$C = -\nabla_H . Q$$

C is convergence

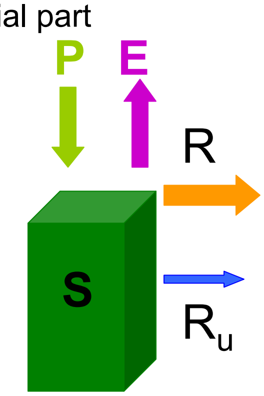
$$\frac{\partial W}{\partial t} = (E-P) + C$$

## Hydrologic cycle

### Terrestrial branch

Water budget equation for the terrestrial part

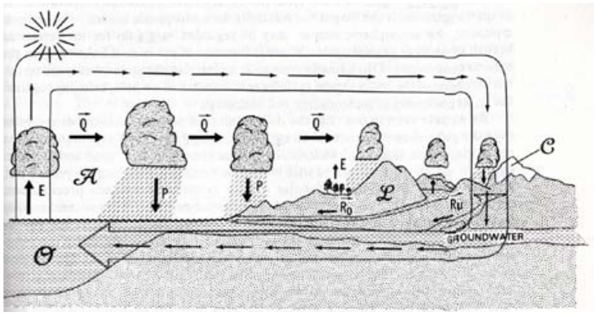
$$\frac{\partial S}{\partial t} = P - E - R - R_u$$

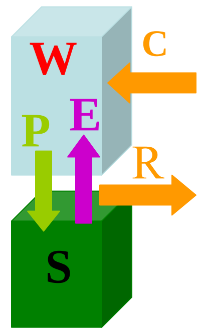



S= rate of storage of water (kg m$^{-2}$)
P= precipitation rate (kg m$^{-2}$ s$^{-1}$)
E= evaporation rate (kg m$^{-2}$ s$^{-1}$)
R= surface runoff (kg m$^{-2}$ s$^{-1}$)
$R_u$= subterranean runoff(kg m$^{-2}$ s$^{-1}$)

# Hydrologic cycle

Relation between the terrestrial and atmospheric branches




$$\frac{\partial W}{\partial t} = (E - P) + C$$ Atmospheric branch

$$\frac{\partial S}{\partial t} = P - E - R$$ Terrestrial branch

$$-\frac{\partial W}{\partial t} + C = \frac{\partial S}{\partial t} + R$$

For long period of time and for large regions

$$[\overline{C}] = [\overline{R}]$$

# Hydrologic cycle

**TABLE • 7.1.** Estimated mean annual values of the precipitation rate $P$, evaporation rate $E$, runoff rate $(P - E)$, evaporation ratio $E/P$ (an aridity index), and runoff ratio $(P - E)/P$ for 10° latitude belts, the hemispheres, and the globe from Baumgartner and Reichel (1975). For comparison, Sellers' (1965) estimates for $P$ and $E$, and Peixoto and Oort's (1983) independent estimates of $P - E$ as computed from Table 12.1 are shown in parentheses.

| | *Surface area* | $P$ | $E$ | $P - E$ | $E/P$ | $(P - E)/P$ |
|---|---|---|---|---|---|---|
| 80–90 °N | 3.9 | 46 (120) | 36 (42) | 10 (93) | 0.78 | 0.22 |
| 70–80 °N | 11.6 | 200 (185) | 126 (145) | 74 (124) | 0.63 | 0.37 |
| 60–70 °N | 18.9 | 507 (415) | 276 (333) | 231 (224) | 0.54 | 0.46 |
| 50–60 °N | 25.6 | 843 (789) | 447 (469) | 396 (250) | 0.53 | 0.47 |
| 40–50 °N | 31.5 | 874 (907) | 640 (641) | 234 (156) | 0.73 | 0.27 |
| 30–40 °N | 36.4 | 761 (872) | 971 (1002) | − 210 (23) | 1.28 | − 0.28 |
| 20–30 °N | 40.2 | 675 (790) | 1110 (1246) | − 435 (− 435) | 1.64 | − 0.64 |
| 10–20 °N | 42.8 | 1117 (1151) | 1284 (1389) | − 167 (− 322) | 1.15 | − 0.15 |
| 0–10 °N | 44.1 | 1885 (1934) | 1250 (1235) | 635 (478) | 0.66 | 0.34 |
| 0–10 °S | 44.1 | 1435 (1445) | 1371 (1304) | 64 (144) | 0.96 | 0.04 |
| 10–20 °S | 42.8 | 1109 (1132) | 1507 (1541) | − 398 (− 342) | 1.36 | − 0.36 |
| 20–30 °S | 40.2 | 777 (857) | 1305 (1416) | − 528 (− 312) | 1.68 | − 0.68 |
| 30–40 °S | 36.4 | 875 (932) | 1181 (1256) | − 306 (− 128) | 1.35 | − 0.35 |
| 40–50 °S | 31.5 | 1128 (1226) | 862 (895) | 266 (150) | 0.76 | 0.24 |
| 50–60 °S | 25.6 | 1003 (1046) | 553 (520) | 450 (278) | 0.55 | 0.45 |
| 60–70 °S | 18.9 | 549 (418) | 229 (174) | 320 (245) | 0.42 | 0.58 |
| 70–80 °S | 11.6 | 230 (82) | 54 (45) | 176 (98) | 0.23 | 0.77 |
| 80–90 °S | 3.9 | 73 (30) | 12 (0) | 61 (32) | 0.16 | 0.84 |
| 0–90 °N | 255.0 | 970 (1009) | 897 (944) | 73 (39) | 0.92 | 0.07 |
| 0–90 °S | 255.0 | 975 (1000) | 1048 (1064) | − 73 (− 39) | 1.07 | − 0.07 |
| Globe | 510.0 | 973 (1004) | 973 (1004) | ... | 1.00 | ... |
| Units | $10^6$ km$^2$ | mm yr$^{-1}$ | mm yr$^{-1}$ | mm yr$^{-1}$ | ... | ... |

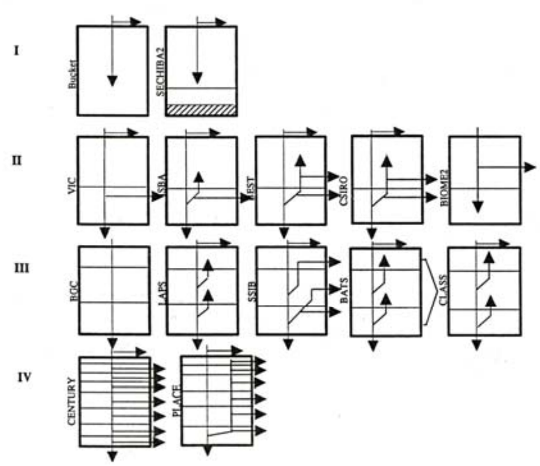
## Classification of Land Surface Schemes

First generation
- no canopy
- «bucket» model
- e.g., Manabe 1969

Second generation
- with canopy
- SVATs,
- e.g., Verseghy 1991; Verseghy et al. 1993

Third generation
- with canopy
- Biophysical exchanges
- e.g., Xiao et al., 1998; Tian et al., 1999

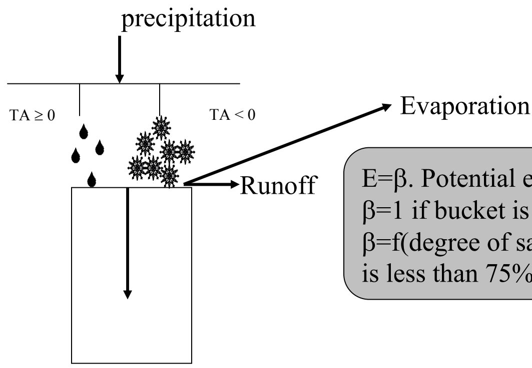
## Classification of Land Surface Schemes




Schematic illustration of runoff plus drainage in some LSSs.
(Ref: Shao and Henderson-Sellers (1996))

## Moisture handling in the first generation type LSS

Beautified bucket model

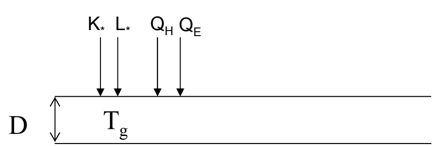



E=β. Potential evaporation
β=1 if bucket is 75% or more full
β=f(degree of saturation) if bucket is less than 75% full

## Thermal regime in earlier LSSs

Force-restore method

Ground energy balance equation:




$K_*$: Net shortwave radiation
$L_*$: net longwave radiation
$Q_H$: sensible heat flux
$Q_E$: latent heat flux

$$C\frac{\partial T_g}{\partial t} = K_* + L_* + Q_H + Q_E - F \pm S$$

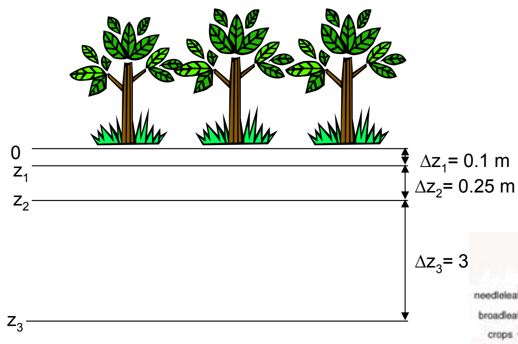
Forcing term

Restoring term

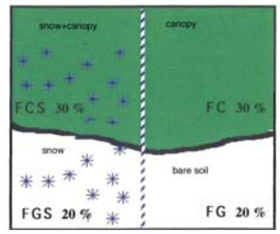
Source/sink term

## Land surface scheme of second generation

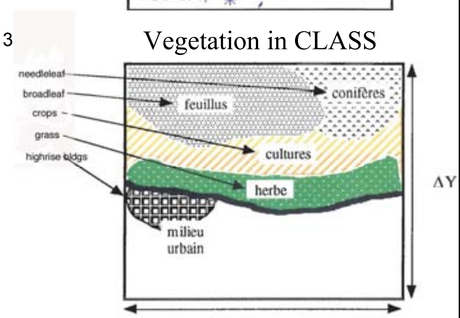
CLASS (Canadian LAnd Surface Scheme; Verseghy 1991, Verseghy et al. 1993)




Sub-regions in CLASS

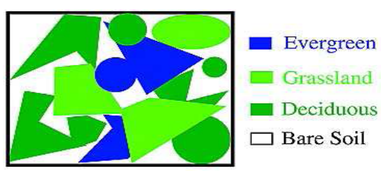



Vegetation in CLASS



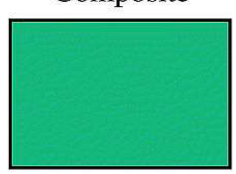

## Schematic of aggregation techniques

Hypothetical Grid Square

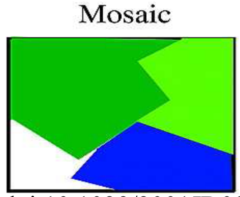



Dominant

Composite



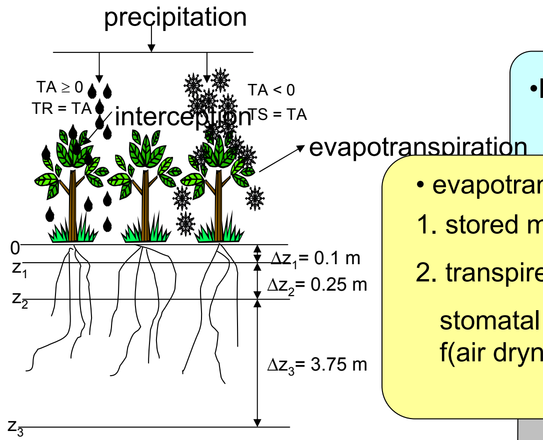
Mosaic



Ref: Molod A and Salmun H
J. Geophys. Res. 107(D14), 4217, doi:10.1029/2001JD000588, 2002

## Moisture Regime in CLASS

Moisture storage in the canopy




- Interception = f(skyview factor $\chi$)
  - $\chi$ = exp(-0.5 LAI) (needleleaf trees)

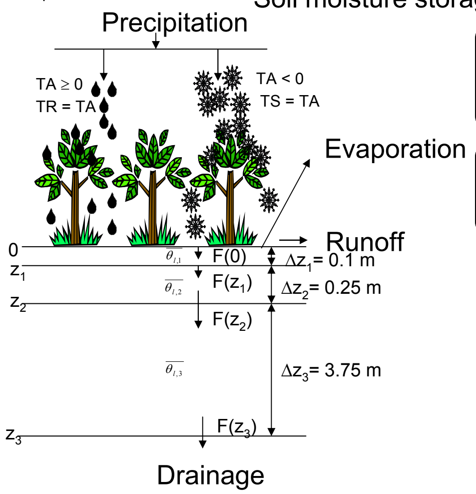
- evapotranspiration
  1. stored moisture
  2. transpired water

  stomatal resistance=f(light)
  f(air dryness) f(soil dryness) f(temp)

Grass: 1

## Moisture Regime in CLASS

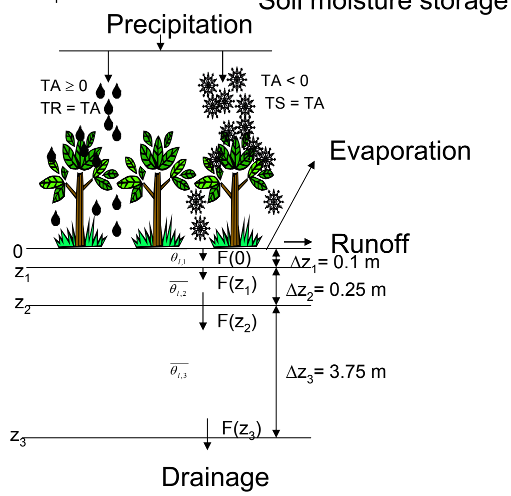
Soil moisture storage




- change in liquid soil moisture: 1D water conservation equation
- F(z1), F(z2) and F(z3) 1D Darcy's equation for fluid flow
- F(z3)=k(z3)
- F(0)=E or I

## Moisture Regime in CLASS

Soil moisture storage




**Infiltration**

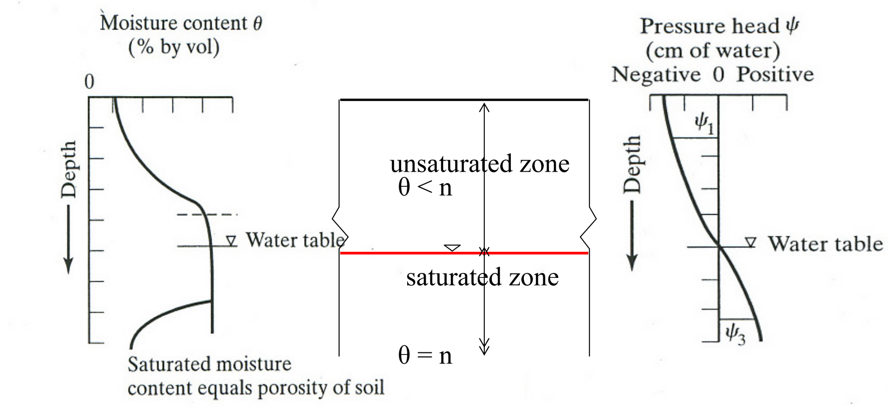
## Infiltration

- Process of water entry into the soil, generally by downward flow through all or part of the soil surface

Infiltration capacity:
maximum rate at which water enters the soil

Infiltration rate:
rate at which water enters the soil at a given time

# Hydrologic horizons




$$\theta = \frac{\text{volume of water}}{\text{total volume}} \qquad n = \frac{\text{volume of voids}}{\text{total volume}}$$

# Principles of soil water movement

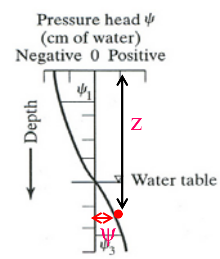
- Flow in saturated soils: Darcy's law

$$q = -K\frac{dH}{dz}$$

$q$ : flux
$K$ : hydraulic conductivity
$\frac{dH}{dz}$ : hydraulic gradient

hydraulic head = pressure head + elevation head

$$H = h + z$$




- Flow in unsaturated soils:

Buckingham-Darcy equation

$$q = -K(\theta)\frac{dH}{dz} \qquad H = \psi(\theta) + z$$

$K(\theta)$ : unsaturated hydraulic conductivity
$\psi(\theta)$ : capillary suction

## Infiltration estimates

- (1) Empirical, (2) physically based and (3) approximate approaches
  - Examples
    1. Horton equation
    2. Richard's equation
    3. Green-Ampt equation

## Infiltration estimates: empirical approach

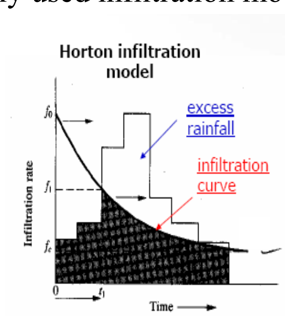
- Horton's equation is a widely used infiltration model with three parameters

$$f(t) = f_c + (f_0 - f_c)e^{-kt}$$

$f_o$ : initial infiltration capacity

$f_c$ : final infiltration capacity

$\beta$ : recession constant




- Parameters $f_0$ and $k$ have no physical basis
- Cannot be determined from soil water properties and must be ascertained from experimental data

## Infiltration estimates: physical approach

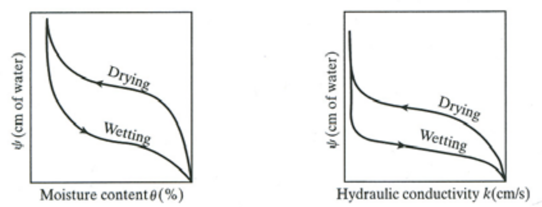
- Richard's equation is the physically based eqn. used for describing water flow in soils
- Combining Darcy's equation and with the continuity equation: $\frac{\partial \theta}{\partial t} = \frac{\partial q}{\partial z}$ $\qquad \frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}\left[K(\theta)\frac{\partial \psi(\theta)}{\partial z}\right] - \frac{\partial K(\theta)}{\partial z}$

$\theta$ : volumetric moisture content

$\psi(\theta)$ : capillary suction

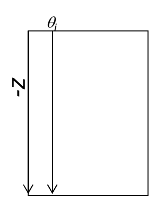
$K(\theta)$ : unsaturated hydraulic conductivity

- Characteristic curves



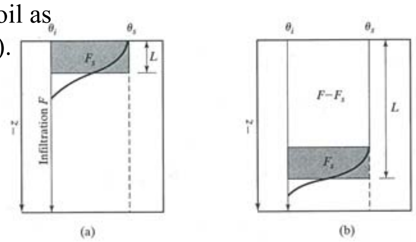

## Infiltration estimates: approximate approach

- Green-Ampt Model:
  - Simple model
  - Has a theoretical base on Darcy's law (not strictly empirical)
  - Parameters have physical significance that can be computed from soil properties
- Derivation of Green-Ampt equation
  1. Consider column of homogeneous soil of unlimited depth with an initial water content $\theta_i$
  2. Consider a rainfall of constant intensity $i$



## Infiltration estimates

3. Water is assumed to move into dry soil as a sharp wetting front (i.e piston flow).




4. Amount of infiltration

$$F = (\theta_s - \theta_i)L = M_d L$$

$\theta_i$ : initial moisture content

$\theta_s$ : saturated moisture content

5. Darcy's equation

$$q = -K(\theta)\frac{\partial H}{\partial z}$$

$q$ : Darcy velocity

z : depth below surface

H : potential head = $z + \psi$

$\psi$ : suction

K($\theta$) : unsaturated hydraulic conductivity

$\theta$ : volumetric moisture content

$$q = -f \cong -K_s \frac{(H_{surf} - H_{wf})}{z_{surf} - z_{wf}}$$

$$H_{wf} = z + \psi \cong -L + \psi$$

$$-f = -K_s \frac{[0-(-L+\psi)]}{[0-(-L)]}$$

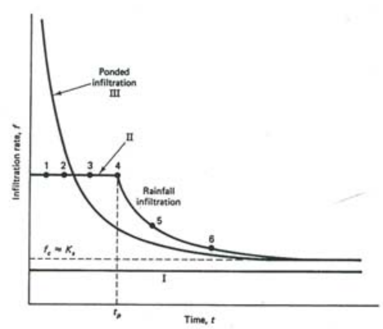
$$f = K_s(1 - \psi / L)$$

$$f = K_s(1 - M_d \psi / F)$$

**Green-Ampt equation**

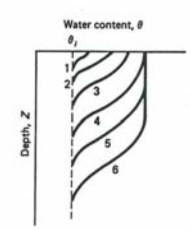
## Three distinct cases of infiltration

1. *$i<K_s$* : when rainfall intensity, *i*, is less than the saturated hydraulic conductivity, $K_s$ *(supply or flux controlled)*




2. *$i>K_s$* : rainfall intensity is greater than the saturated conductivity
   - *preponding infiltration (supply or flux controlled)*
   - *Rainpond infiltration* (surface or profile controlled)

3. Rainpond infiltration: rainfall intensity that exceeds the capacity of soil to infiltrate water from the beginning, water is always ponded on the surface (surface or profile controlled)



## Parameters of Green-Ampt model

$$f = K_s(1 - M_d \psi / F)$$

1. Suction at wetting front ($\Psi$)
2. Hyraulic conductivity ($K_s$)
3. Soil porosity (n): $M_d = \theta_s - \theta_i$

- Parameters can be ascertained from the physical properties of soil

## Wetting front suction with texture

Rawls et al. (1990)

$$Sf = \exp[6.53 - 7.326(\phi) + 0.00158(C^2) + 3.809(\phi^2) + 0.000344(S)(C) - 0.04989(S)(\phi)$$
$$+ 0.0016(S^2)(\phi^2) + 0.0016(C^2)(\phi^2) - 0.0000136(S^2)(C) - 0.00348(C^2)(\phi)$$
$$- 0.000799(S^2)(\phi)]$$

Where :
S = Percent Sand
C = Percent Clay
$\phi$ = Porosity

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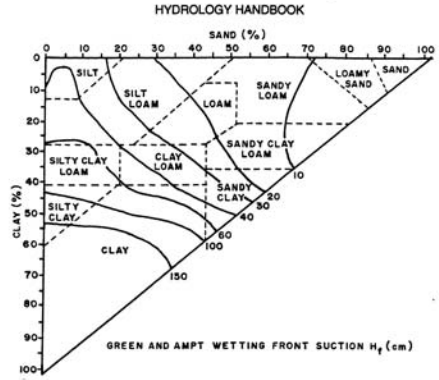



*Figure 3.40.—Green-Ampt Wetting Front Suction Classified According to Soil Texture (Rawls et al., 1990).*

## Saturated hydraulic conductivity for USDA soil texture triangle

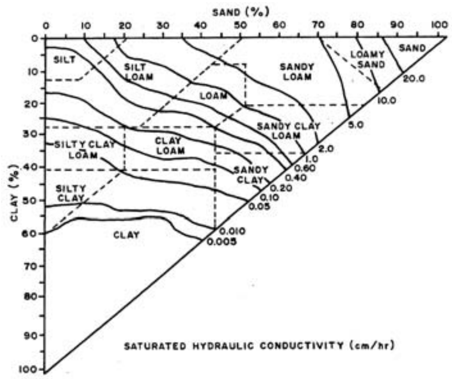



*Figure 3.42.—Saturated Conductivity Classified by Soil Texture (Rawls et al., 1990).*

## Green-Ampt infiltration parameters

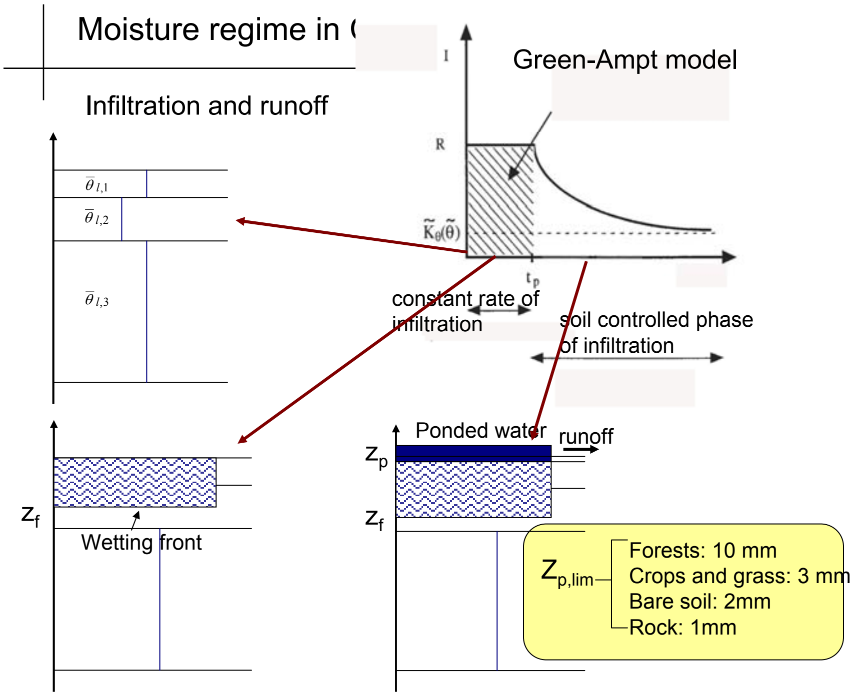
TABLE 2.17 GREEN-AMPT INFILTRATION PARAMETERS

| Soil texture class | Porosity $\theta_s$ | Wetting front soil suction head $S_f$, cm | Effective hydraulic conductivity $K_s$, cm/h |
|---|---|---|---|
| Sand | 0.437<br>(0.374–0.500) | 4.95<br>(0.97–25.36) | 11.78 |
| Loamy sand | 0.437<br>(0.363–0.506) | 6.13<br>(1.35–27.94) | 2.99 |
| Sandy loam | 0.453<br>(0.351–0.555) | 11.01<br>(2.67–45.47) | 1.09 |
| Loam | 0.463<br>(0.375–0.551) | 8.89<br>(1.33–59.38) | 0.66 |
| Silt loam | 0.501<br>(0.420–0.582) | 16.68<br>(2.92–95.39) | 0.34 |
| Sandy clay loam | 0.398<br>(0.332–0.464) | 21.85<br>(4.42–108.0) | 0.15 |
| Clay loam | 0.464<br>(0.409–0.519) | 20.88<br>(4.79–91.10) | 0.10 |
| Silty clay loam | 0.471<br>(0.418–0.524) | 27.30<br>(5.67–131.50) | 0.10 |
| Sandy clay | 0.430<br>(0.370–0.490) | 23.90<br>(4.08–140.2) | 0.06 |
| Silty clay | 0.479<br>(0.425–0.533) | 29.22<br>(6.13–139.4) | 0.05 |
| Clay | 0.475<br>(0.427–0.523) | 31.63<br>(6.39–156.5) | 0.03 |

*Source:* Rawls and Brakensiek (1993).

## Moisture regime in (

Infiltration and runoff




## Thermal regime in CLASS

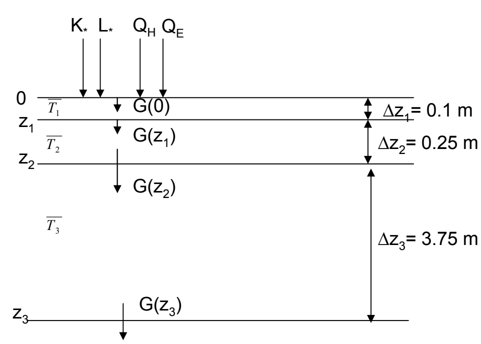
ground temperatures obtained by iterative solutions of the energy balance equation:

| | |
|---|---|
| $K_*$: | Net shortwave radiation |
| $L_*$: | net longwave radiation |
| $Q_H$: | sensible heat flux |
| $Q_E$: | latent heat flux |

Soil temperature:
1-D heat conservation equation

$$K_* + L_* + Q_H + Q_E = G(0)$$

$$G(z3) = 0$$

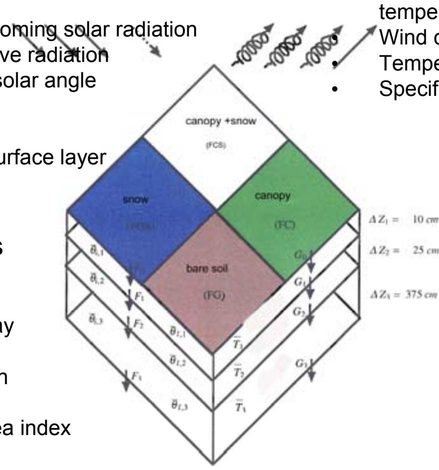


Input to CLASS

- Wind components at top of surface layer
- Temperature at top of surface layer
- Specific humidity at top of surface layer
- Incoming solar radiation in visible band
- Incoming solar radiation in near infrared band
- Diffuse part of incoming solar radiation
- Incoming long wave radiation
- Cosine of zenith solar angle
- Precip rate
- Surface pressure
- Height of top of surface layer

CLASS Output

- surface sensible heat flux
- Surface latent heat flux
- Surface drag coefficient
- Surface albedo
- Surface radiative temperature
- Wind components at 10 m
- Temperature at 1.5 m
- Specific humidity at 1.5 m




Geophysical fields

- Depth to bedrock
- Percent sand and clay
- Porosity
- Fraction of vegetation
- Canopy mass
- Min and max leaf area index
- Root depth
- Soil temperature and moisture

## Intercomparison of land surface models

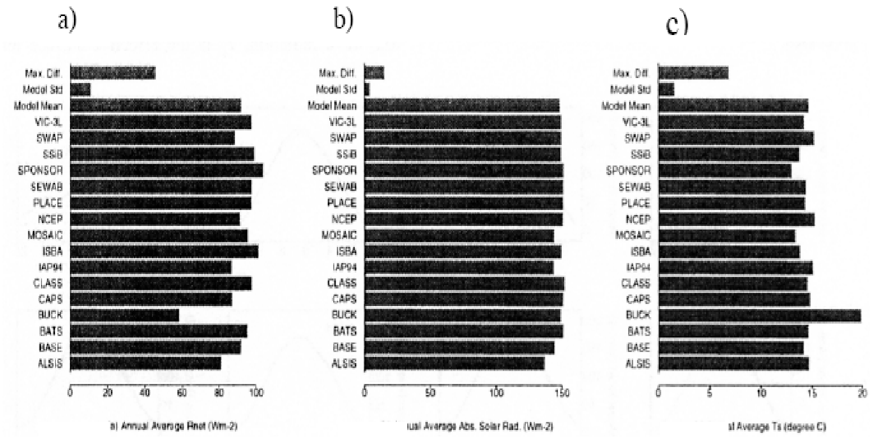
**PILPS: <u>Project for Intercomparison of Land-Surface Parameterization Schemes</u>**

**Initiated in 1992**

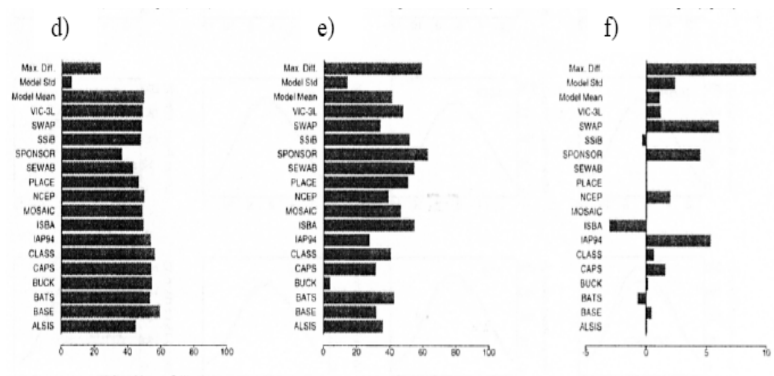
**Four phases**

- **phase 1: point evaluation of LSMs (using atmospheric forcing generated from a GCM ) FOR TWO GRID POINTS**
- **Phase 2: LSMs driven using observed meteorological data**
- **Phase 3: LSMs evaluated as an interactive component of the atmospheric GCMs**
- **Phase 4: LSMs evaluated within fully coupled ocean-atmosphee global climate models**

**PILPS – Phase 2**
**Results from Liang et al. (1998)**




**Model simulated (a) net radiation, (b) absorbed solar radiation and (c) surface temperature for the 1980-1986 period**




**Model simulated (d) latent, (e) sensible and (f) ground heat flux for the 1980-1986 period**

## Current/future developments with LSSs

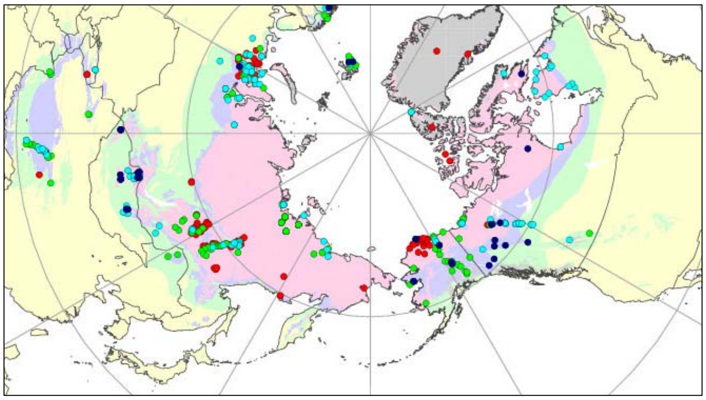
- **Lakes**
- **Dynamic vegetation**
- **Permafrost**
- **Organic material**

# Permafrost

**What is Permafrost?**
Permafrost is defined based on temperature, as soil or rock that stays below 0°C for at least two consecutive years

**What is Active Layer?**
The layer above permafrost, that is subjected to annual freeze/thaw cycle

## Permafrost

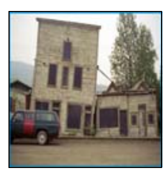


| |
|---|
| Continuous (90-100%) |
| Discontinuous (50-90%) |
| Sporadic (10-50%) |
| Isolated (< 10%) |

• 24%, approximately 4 million km$^2$ of Canada is covered by permafrost

## Motivation

- Analysis of the soil temperature observations from northern Canada since 1990s indicates a deepening of the active layer (Nelson, 2003)

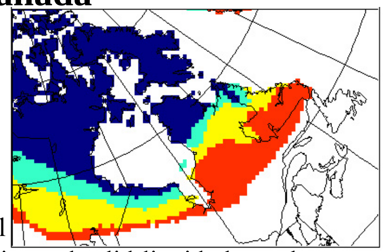


http://www.amap.no/acia/Highlights.pdf

- Climate model projections indicate a rise in the global average temperatures over the next century (IPCC, 2007)

# Offline modeling of current and future soil thermal regime for North-East Canada

## Study domain

## Goodrich model

- 1-D heat conduction model
- non-linear material properties and solid-liquid phase change
- thermal effect of snow cover
- does not include capillary moisture transport or convective flows

## Soil model configuration

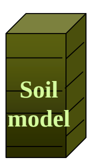
- depth of model: 45m deep
- vertical resolution: 0.1m–1m from surface to bottom
- total soil layers: 85
- horizontal resolution: 45 km
- Δt: 1 day

## Soil properties

Wilson and Henderson-Sellers (1985)
CRCM 30-year climatology

# Offline soil model simulations

## Boundary conditions

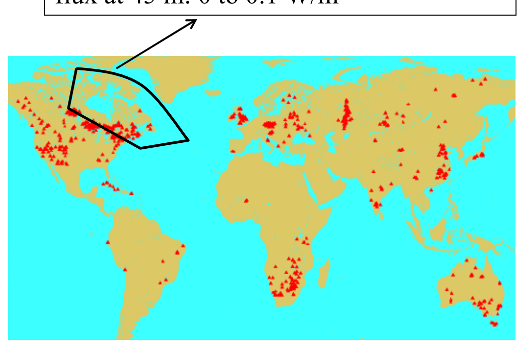



**surface temperature**
**snow cover**

**geothermal flux**

constant flux: 0.06 W/m$^2$

flux at 45 m: 0 to 0.1 W/m$^2$

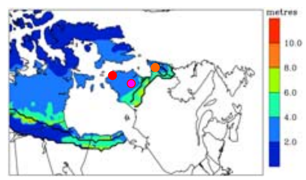


borehole temperature and climate reconstruction database
http://www.geo.lsa.umich.edu/climate/

## Simulated average ALT for current and future climates

**1961-1990**

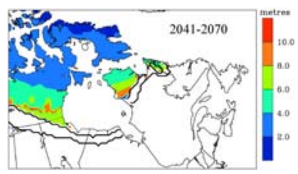
0 – 6 m




- Salluit
- Kangiqsualuujuaq
- Tasiujaq

**2041-2070**

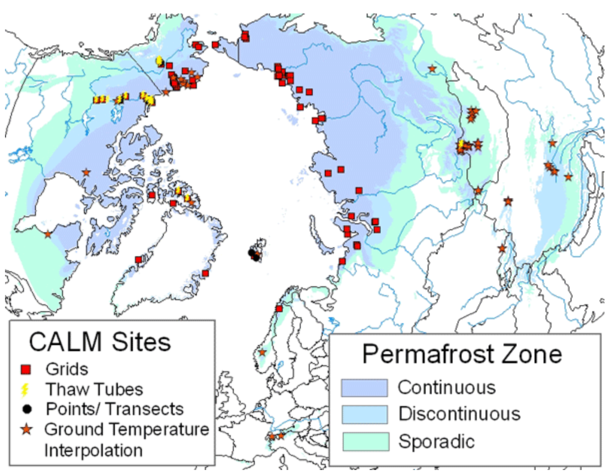
0 – 9 m

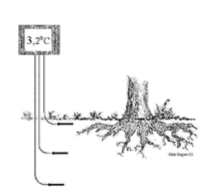



# Permafrost

CALM

*Circumpolar Active Layer Monitoring*



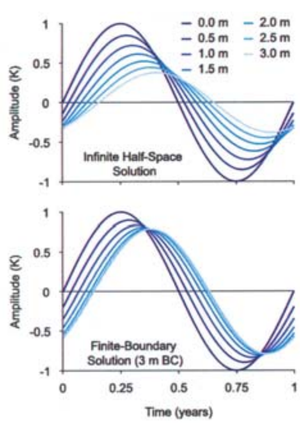



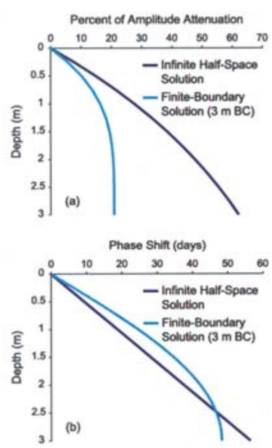
# Permafrost

- **Heat conduction models (run offline) are traditionally used to model ALT and permafrost**
  - **Coupled simulations required to capture the feedbacks**
  - **Moisture fluxes need to be included**
  - **Can an LSS such as CLASS be used to model permafrost?**

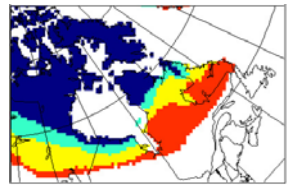
Smerdon and Stieglitz (2006, GRL)

**Infinite half space** | **3m thick slab with zero flux boundary condition**



## Case study using the improved last version of the Canadian Land Surface Scheme (CLASS)



**1. Sensitivity to model depth**

### Experimental setup

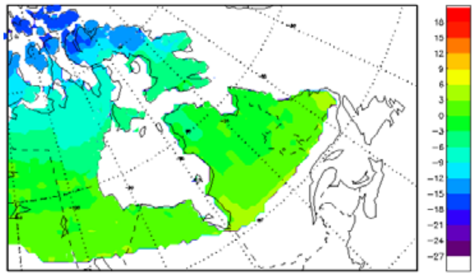
- **Model run for the 1961-2000 period, using ERA40 data, over a domain covering permafrost regions in North-east Canada, using two different soil-layer configurations (shallow vs. deep)**
- **Shallow version is 4.1 m deep with three layers that are 0.1, 0.25 and 3.75 m thick as in the earlier version of CLASS2.7**
- **Deeper version has 17 layers with layer thickness increasing exponentially with depth (0.1, 0.2, 0.3, 0.5, 0.9, 1.5, 2.5, 4.0, 6.0, 8.0, 13.0, 22.0, 36.0, 60.0, 97.0,160.0, 265.0 m)**

## Case study using the improved last version of the Canadian Land Surface Scheme (CLASS)

### Initial conditions

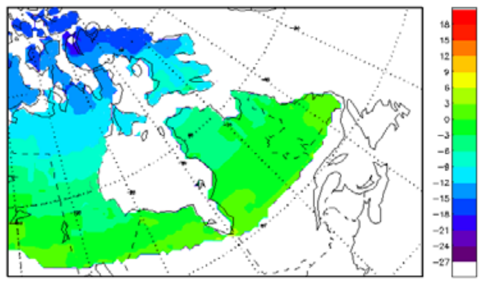
- **GCM ECHO-g simulated, millenial, paleoclimatic histories were forward modelled by Stevens et al. (2008) to arrive at the sub-surface thermal profiles, which were validated over North-America, against available borehole measurements**
- **The above forward modelling was done for the period 1000-1990 and the profiles from 1961 were used as initial conditions for the experiments with the deeper version of CLASS3.4**

**1971-2000 average annual temperatures of soil layer 1 for the shallow and deep versions of CLASS3.4 (off-line)**




3-layer shallow configuration

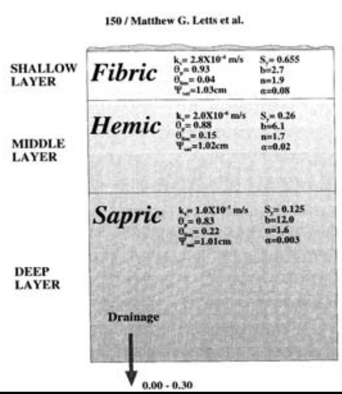
**Average annual soil temperatures obtained with the shallow version are warmer than those obtained with the deeper version**



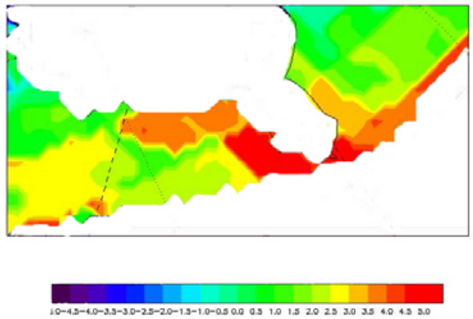

17-layer deep configuration

**2. Sensitivity to organic soil parameterization**

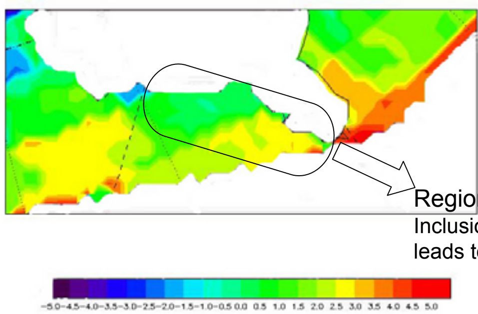
- Simulations performed, with and without organic soils, in CLASS3.4 off-line
- Parameterization of organic soil follows Letts et al. (2000), where properties are determined based on the peat texture (fibric, hemic or sapric), reflecting its degree of decomposition
- Allows more realistic simulations to be performed without constraining drainage



Simulated annual-mean temperature for the top soil layer, with and without organic material, with the shallow configuration of the CLASS3.4 off-line

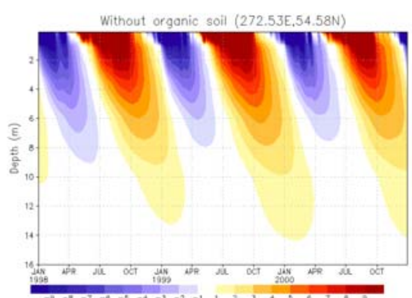


3-layer
**No organic** parameterization

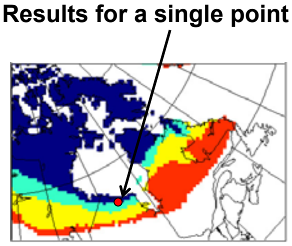


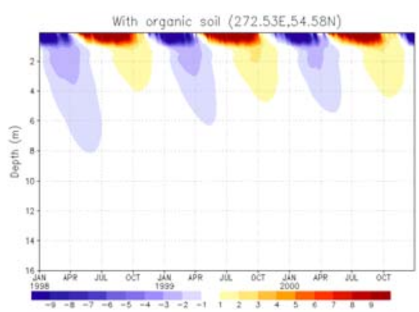
3-layer
**with organic** parameterization

Region with organic soil
Inclusion of the organic soil parameterization leads to much cooler temperatures




**Results for a single point**






**Model simulated soil temperatures for the top 16 m, with (bottom panel) and without (top panel) organic material, using the deep layer configuration**

**Simulated ALT is much larger for the case without organic soil**

Hot Spots of Land Atmosphere Coupling

GLACE

**Global Land-Atmosphere Coupling Experiment**

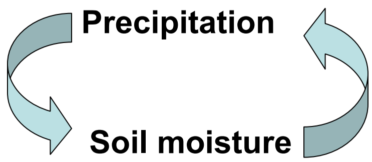
**Focusses on land-atmosphere coupling strength**

↓

**The degree to which atmosphere responds to anomalies in land surface state in a consistent manner**

Koster et al., 2006, Journal of Hydrometeorology, 7, 590–610
Koster et al., 2004, Science, 305, 1138–1140.

# GLACE




Do land surface moisture and temperature states affect the evolution of weather and the generation of precipitation?

- Research largely performed with numerical models of global weather and climate due to lack of observations
- One major caveat is model dependency of experimental results

# GLACE

## Land-atmosphere coupling strength

- Not explicitly prescribed or parameterized
- It is a net result of complex interactions between numerous complex process parameterizations, such as those for evapotranspiration, boundary layer development, moist convection
- Though a fundamental element of the system, it is rarely examined closely and is almost never objectively quantified
- Objective quantification and documentation of the coupling strength across a broad range of models would be valuable

# GLACE

- GLACE extends the four-model inter-comparison study of Koster et al. (2002)
- Participation from a wider range of models (12 AGCM groups)
- Glace utilized boreal summer simulations as Coupling strength should be highest during summer, when evaporation rates are highest

# GLACE

| Model | Resolution |
|---|---|
| BMRC (Zhong et al. 2001; Colman et al. 2001; Desborough 1999; Desborough et al. 2001) | T47 |
| CCCma (McFarlane et al. 1992; Boer et al. 1992; Verseghy 1991, 2000; Verseghy et al. 1993) | T32, 3.75° × 3.75° |
| CCSR (Numaguti 1993; Numaguti et al. 1997; Nozawa et al. 2001) | T42 |
| COLA (Kinter et al. 1997; Xue et al. 1991; Dirmeyer and Zeng 1999) | T63, 1.875° |
| CSIRO-CC3 (McGregor and Dix 2001; McGregor 1996; Kowalczyk et al. 1994) | 2° × 2° |
| GEOS (Conaty et al. 2001; Sud and Walker 1999a,b; Mocko and Sud 2001) | 2.5° × 2° |
| GFDL (Milly and Shmakin 2002; GFDL Global Atmospheric Model Development Team 2004; but with different parameterizations for boundary layer turbulence, prognostic clouds, and cumulus processes) | 2.5° × 2° |
| HadAM3 (Pope et al. 2000; Cox et al. 1999; Essery et al. 2003) | 3.75° × 2.5° |

| Model | Resolution |
|---|---|
| CAM3 (Collins et al. 2004; Bonan et al. 2002; Oleson et al. 2004) | T42 (~2.8° × 2.8°) |
| GFS/OSU (Kalnay et al. 1996; Moorthi et al. 2001; Pan and Mahrt 1987) | T62, 1.875° |
| NSIPP (Bacmeister et al. 2000; Koster and Suarez 1996) | 2.5° × 2° |
| UCLA (Xue et al. 2001, 2004) | T42, 2.5° × 2° |

# GLACE

## Experimental design

each AGCM → three 16-member ensembles
For the period 1 June – 31 August → W, R, S

**W**

- Standard set of AGCM simulations, with prescribed sea surface temperatures (AMIP-2 for 1994)
- One simulation (W1), chosen randomly, for which the land prognostic variables are archived every time step
- Soil moisture content/temperature at all vertical levels, canopy interception reservoir content, variables characterizing snow

**R**

- Same prescribed sea surface temperatures and the same 16 sets of atmospheric ICs.
- All member simulations are forced to maintain the same time series of land surface states (generated in W1)

**S**

- Similar to ensemble R, except that only soil moistures corresponding to soil layers with centers 5 cm or more below the surface are reset from W1

# GLACE

W

R

S

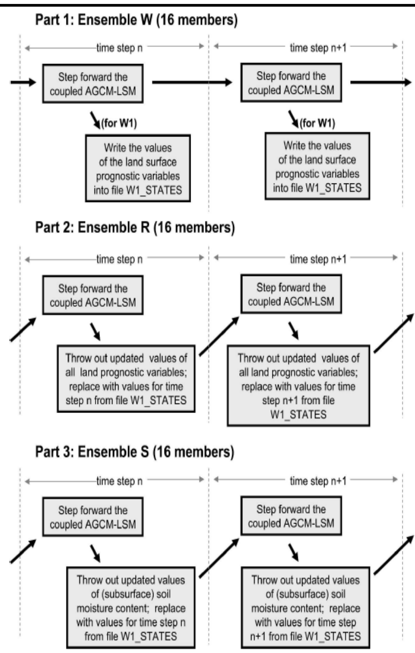



Fig. 1. Basic design of the experiment, as performed by all participating models.

# GLACE

**Land surface's control on "synoptic scale" precipitation variability**

- **Time series of 6-day totals**
- **Simulations are 92 days long; lead to 14 six day totals after ignoring the first 8 days**

$$\Omega_p = \frac{16\sigma_{\hat{p}}^2 - \sigma_p^2}{15\sigma_p^2}$$

**Key Diagnostic**

$\sigma_p$ is the temporal standard deviation of precipitation of an ensemble computed across the resulting 224 six - day totals

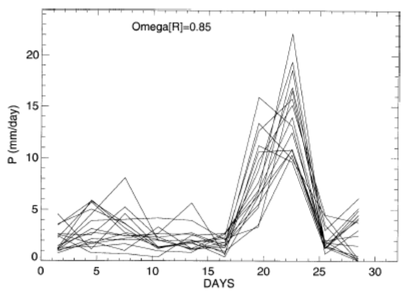
$\sigma_{\hat{p}}$ is the standard deviation of the ensemble mean time series

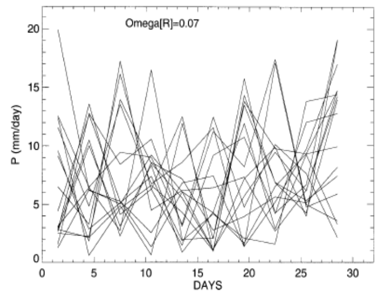
**Measures the degree to which the 16 precipitation time series generated by the ensemble members are similar**

# GLACE

$\Omega_p$ varies from 0 to 1

higher values implying greater similarity



## GLACE

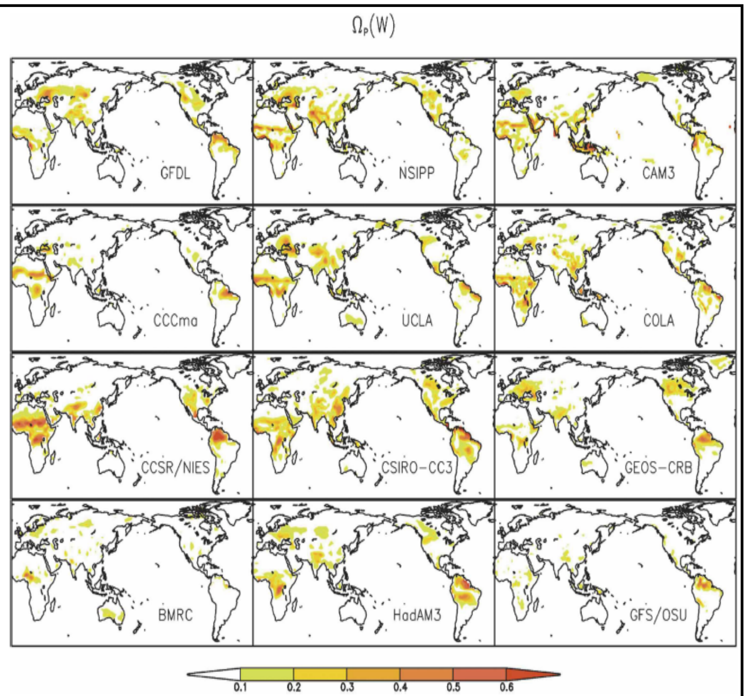



FIG. 2. Global distributions of $\Omega_p(W)$ for the models participating in GLACE.

**High values clustered in the Tropics and in few mid-latitude regions**

## GLACE

**In ensemble R, the similarity of precipitation between the ensemble members has the following two distinct sources:**

**(a) Prescribed land variables**

**(b) Background seasonal behaviour that contributes to $\Omega_p$(W)**

**Isolates the impact of prescribed land variables on synoptic-scale precipitation variance**

$$\Omega_p(R) - \Omega_p(W)$$

**This difference in similarity gives a measure of the land-atmosphere coupling strength associated with the prescription of all land variables.**

## GLACE

Patterns and magnitudes controlled mostly by "fast" land surface prognostic variables

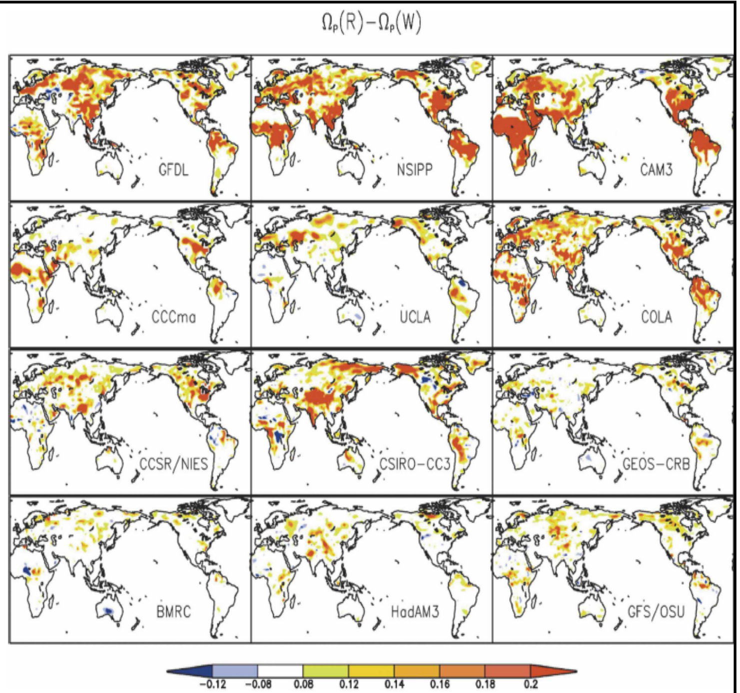



FIG. 4. Global distributions of $\Omega_P(R) - \Omega_P(W)$ for the models participating in GLACE.

## GLACE

Isolates the contribution of prescribed subsurface soil temperature to precipitation variability

Soil moisture variability explains about 20% of the synoptic-scale precipitation variability

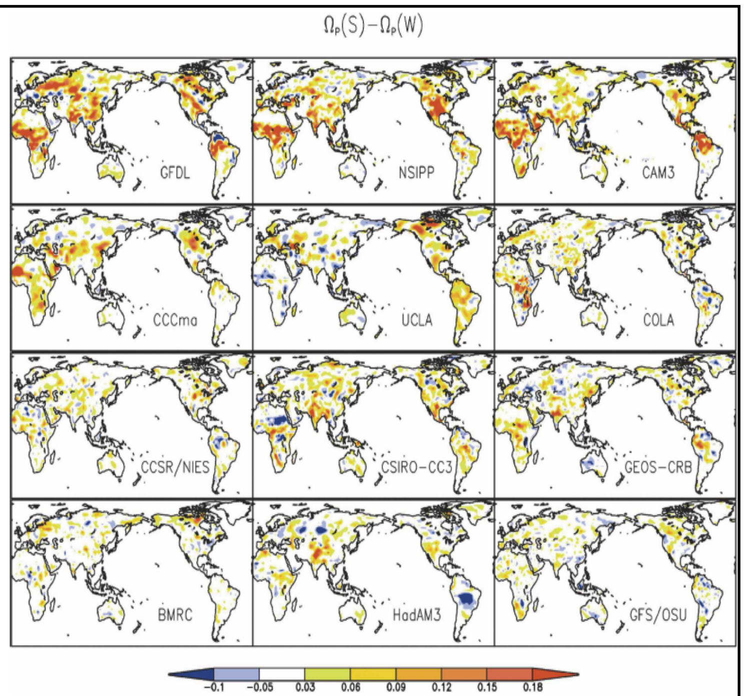


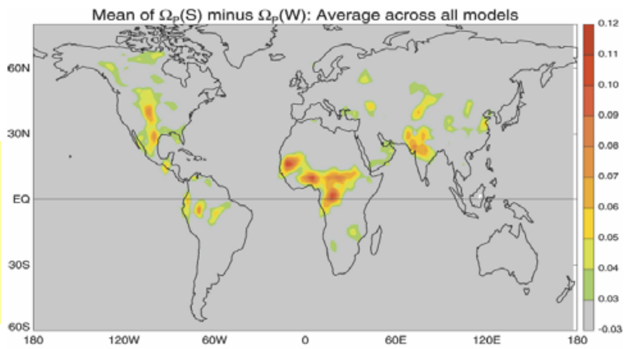

FIG. 5. Global distributions of $\Omega_P(S) - \Omega_P(W)$ for the models participating in GLACE.

## GLACE

$$\Omega_p(S) - \Omega_p(W)$$

**Hot Spots**

**Impacts of soil moisture on rainfall are strong only in the transition zones between dry and wet areas**

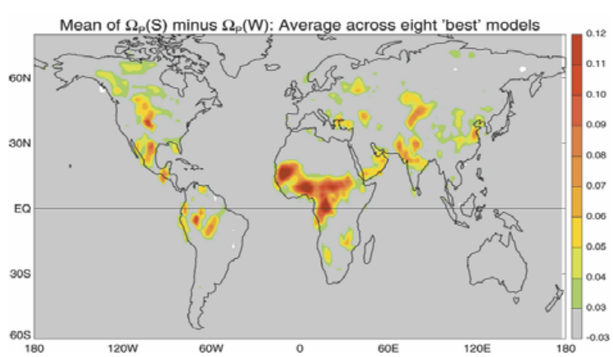



**Arithmetic average across the 12 models**
**Hot spots appear in**

- **Central Great Plains of North America**
- **Northern India**
- **Sahel**
- **Equatorial Africa**

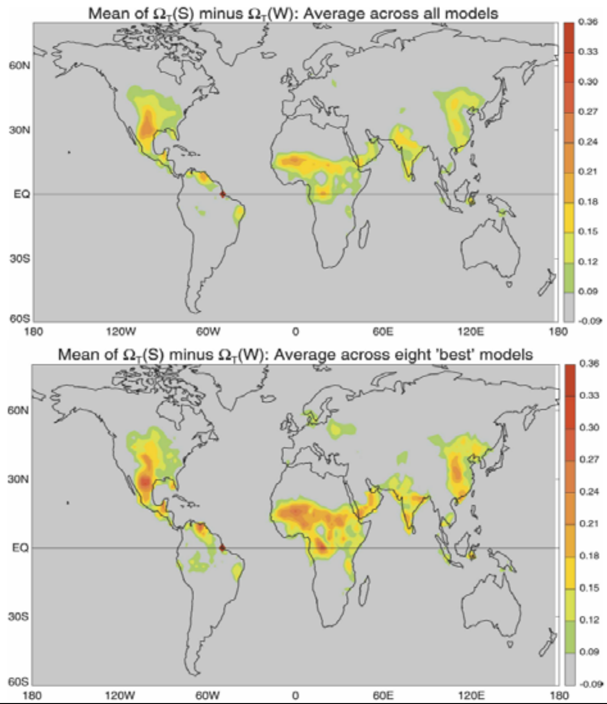
## GLACE

$$\Omega_p(S) - \Omega_p(W)$$




**Values averaged across the eight models, that for a given cell, best reproduce the observed climatological average precipitation for June through August**

## GLACE




## GLACE

**What causes the geographical variations in coupling strength?**

- **Existence of "hot-spots" in these areas is because of the coexistence of high sensitivity of ET to soil moisture and a high temporal variability of the ET signal**
- **In wet climates, ET is controlled not by soil moisture, but by atmospheric demand.**
- **In dry climates, ET rates are sensitive to soil moisture, but typical variations are too small to affect rainfall generation**

# Land-atmosphere coupling and climate change

**Europe was struck by an unprecedented heatwave and serious drought in 2003, while cool summers with devastating flood occurred in 2002 and 2005.**


# L-A coupling and climate change

- **It is estimated that around 20,000 people died as a result of the heatwave in August 2003**
- **the hottest in Europe for perhaps 500 years**
- **The UK experienced its highest temperature on record.**

**Source: UK Met Office**

# L-A coupling and climate change

Interannual variability for the European summer climate

- Simulations driven by increasing greenhouse gas concentrations predict an increase in the interannual variability for the European summer climate
- Seneviratne et al (2006, nature) studied the role of land-atmosphere coupling in these projected changes to interannual climate variability during the extratropical summer season
- Four 30-year experiments were performed with a regional climate model.

1960-1989 | 2070-2099 | A2 Scenario

CTL | SCEN

$CTL_{uncoupled}$ | $SCEN_{uncoupled}$

# L-A coupling and climate change

CTL | SCEN

- CTL and SCEN experiments represent unperturbed simulations
- $CTL_{uncoupled}$ and $SCEN_{uncoupled}$ have the same set up as above, except for the soil-moisture evolution, which is replaced every time step with the climatology of CTL and SCEN

$CTL_{uncoupled}$ | $SCEN_{uncoupled}$

- This removes interannual variability of soil moisture and effectively uncouples the land surface from the atmosphere

## L-A coupling and climate change

<u>Diagnostics used to measure soil-moisture-temperature coupling</u>:

•Variance analysis: percentage of interannual variance explained by L-A coupling

$$\frac{\sigma^2_{T(coupled)} - \sigma^2_{T(uncoupled)}}{\sigma^2_{T(coupled)}}$$

•GLACE type coupling strength parameter

$$\Omega_T = \frac{20\sigma_{\bar{T}}^2 - \sigma_T^2}{19\sigma_T^2}$$

represents interannual similarity in each experiment

$$\Omega^{CTL}_{T_{uncoupled}} - \Omega^{CTL}_{T}$$

represent extent to which removal of interannual variability of soil moisture Increases interannual similarity (or decrease the interannual variability)

•Correlation between summer temperature and evapotranspiration

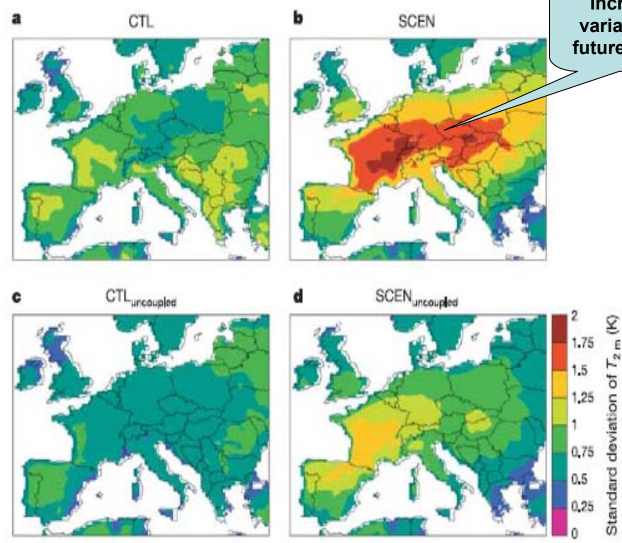
## L-A coupling and climate change

Differences in set-up compared to GLACE

- ‘Ensemble members’ are simulations for 20 individual summers
- Correspond to differing SSTs and atmospheric conditions
- Detrended time series considered

# L-A coupling and climate change

Increased variability in future climate

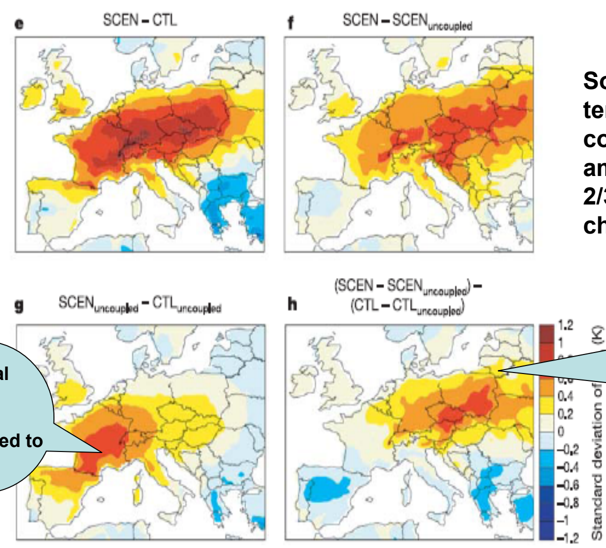



Trend induced inflation of the standard deviation is removed using linear detrending

Temperature variability expressed in terms of the standard deviation of the summer (June-August) two meter temperature


Seneviratne et al. (2006)
Vol 443|14 September 2006|doi:10.1038/nature05095


# L-A coupling and climate change




Soil-moisture-temperature coupling in SCEN amounts to about 2/3rds of the climate change signal

Variability increases due to land-atmos coupling dominate central and eastern Europe

External effects mostly restricted to France

Relative contributions to the climate-change signal of changes in external factors (circulation, SSTs), computed as $SCEN_{uncoupled}$-$CTL_{uncoupled}$ (g), and changes in land-atmosphere coupling (h)

# L-A coupling and climate change

**Why such a large impact of land-atmosphere coupling for future temperature variability in Europe?**

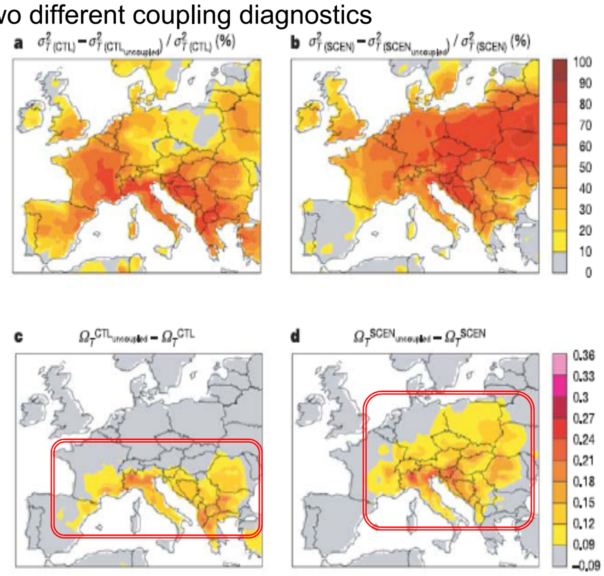
# L-A coupling and climate change

Soil-moisture-temperature coupling in present and future climate in terms of two different coupling diagnostics

**Percentage of interannual summer temperature variance due to L-A coupling**

**L-A coupling parameter for temperature computed as for GLACE**

**Shift of the region of highest soil-moisture-temp coupling from the Mediterranean to central and eastern Europe**



# L-A coupling and climate change

## Possible reasons for the differences in soil-moisture-temperature coupling in the Mediterranean region compared to GLACE experiment

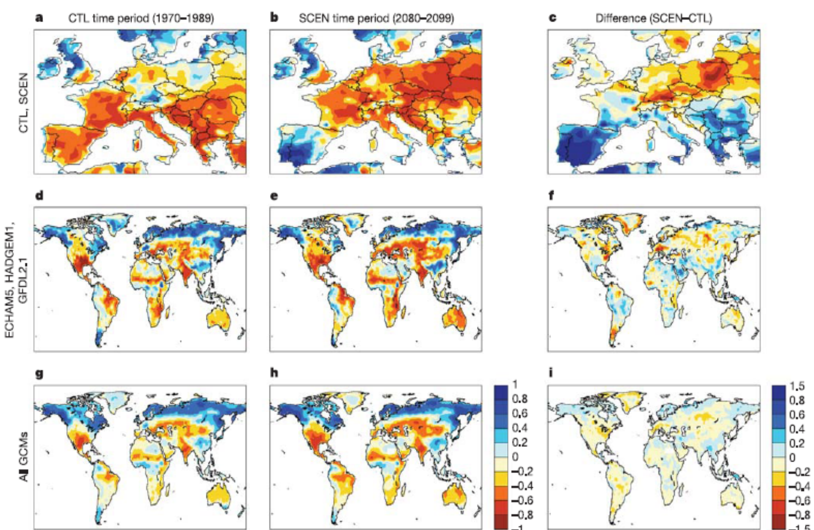
- Higher resolution in Seneviratne et al.
- Representation of interannual variaions in SSTs
- Differences in model sensitivity, presumably due to parameter choices

**Correlation between evapotranspiration and temperature:**

- Negative correlations point to a strong control of soil moisture upon ET and temperature
- Positive correlations generally point to a strong atmospheric control on ET

**Correlation of summer ET and temperature in the RCM and IPCC AR4 GCM experiments**

3 GCMS found to have high-quality circulation patterns in Europe



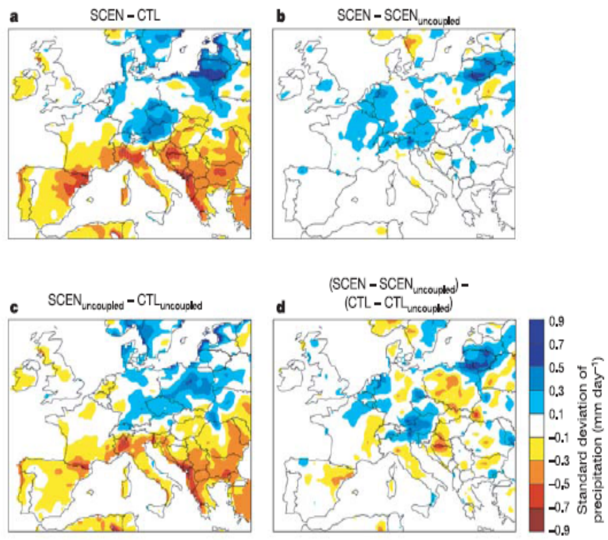

Large bands of –ve values show patterns similar to those of the "hot-spots" of GLACE experiment

Presence of interannual SST variations is the dominant mechanism explaining the differences betn Glace and this one

More soil-moisture controlled ET regime in central Europe

**Effects of L-A coupling on greenhouse-gas-induced changes in interannual variability of summer precipitation**

Regions where an increase of precipitation variability is simulated (particularly in the Alpine region) the signal is atleast partly caused by L-A coupling.




# L-A coupling and climate change

- L-A coupling is significantly affected by global warming and is itself a key player for climate change
- Enhanced greenhouse gas concentrations lead to a northward shift of climatic zones within the European continent
- Central and eastern Europe becomes a new transitional zone betn dry and wet climates

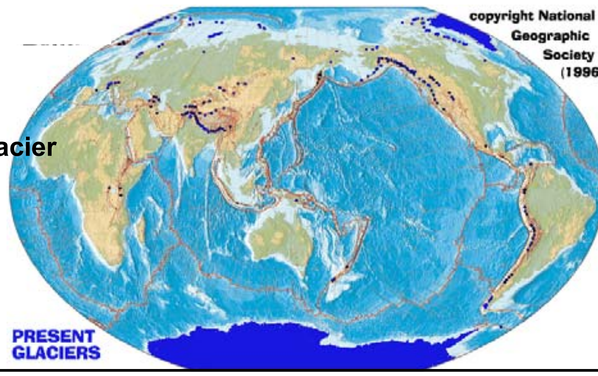
Glaciers

# GLACIERS

What is a Glacier?

- A body of ice and recrystallized snow (plus refrozen meltwater), on land (or, if floating, then connected to land) and moving by deformation under its own weight.
- Most of the world's glaciers are found near the Poles, but glaciers exist on all of the world's continents, even Africa.

Distrbution de glacier




# Glaciers

- 10% of the Earth is covered with Glaciers
- 75% of the earth's freshwater is in glaciers
- Glaciers have a profound effect on the Earth's climate

**Classification of Glaciers**

| Not strongly constrained by underlying topography | Strongly constrained by underlying topography |
|---|---|
| Ice sheet<br>Ice dome<br>Outlet glacier<br>Ice shelf | Ice field<br>Valley glacier<br>Cirque glacier |

# Glaciers

Ice sheet

Largely or entirely covers the topography

Ice sheets smaller than 50,000 km2 are called ice caps

only current ice sheets are in Antarctica and Greenland

# Glaciers

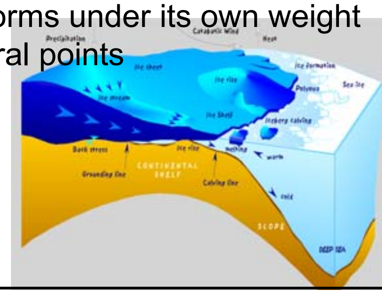

- Antarctic ice sheet is the largest single mass of ice on Earth.
- It covers an area of almost 14 million km² and contains 30 million km³ of ice.
- If melted, would cause sea levels to rise by 61.1 meters
- 
- the Transantarctic mountains divide Antarctica into two unequal sections called the East Antarctic ice sheet (EAIS) and the smaller West Antarctic Ice Sheet (WAIS)
- The EAIS rests on a major land mass but the bed of the WAIS is, in places, more than 2,500 meters below sea level.

# Glaciers

- The Greenland ice sheet occupies about 82% of the surface of Greenland, and if melted would cause sea levels to rise by 7.2 metres.
- Estimated changes in the mass of Greenland's ice sheet suggest it is melting at a rate of about 239 km3 per year


# Glaciers

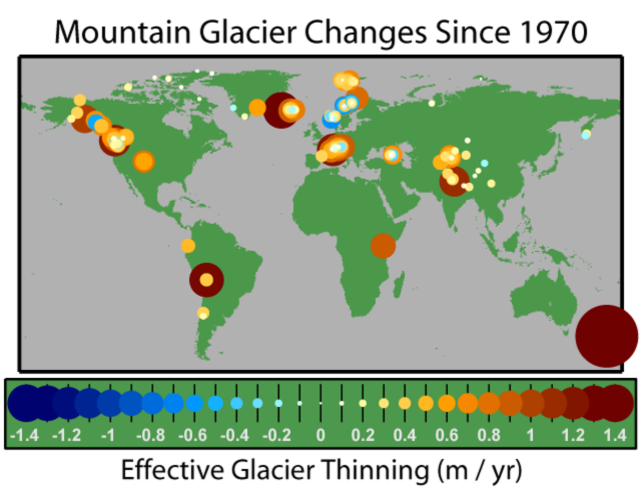
- Ice dome
  - The main component of an ice sheet or ice cap. It has a convex surface form, of parabolic shape, and tends to develop symmetrically over a land mass. Its thickness often exceeds 3000 m.
- Outlet glacier
  - A stream of ice that extends beyond an ice dome and drains it
- Ice Shelf
  - A floating ice sheet that deforms under its own weight
  - Has to be anchored at several points



# Glaciers

- Ice field
  - An approximately level area of ice
  - Flow reflects the underlying bedrock topography
- Valley glacier
  - River of ice that flows down a mountain valley
  - Fed from an ice field or a cirque
- Cirque glacier
  - A small ice mass, fairly wide relative to its length
  - Occupies a bedrock hollow or basin, usually on a mountain slope

# Glaciers



# Glaciers

- www.pbs.org/wgbh/nova/sciencenow/3210/03.html

  Greenland's Jakobshavn glacier