Climate and the Hydrological Cycle

Peter Troch – University of Arizona/Wageningen University

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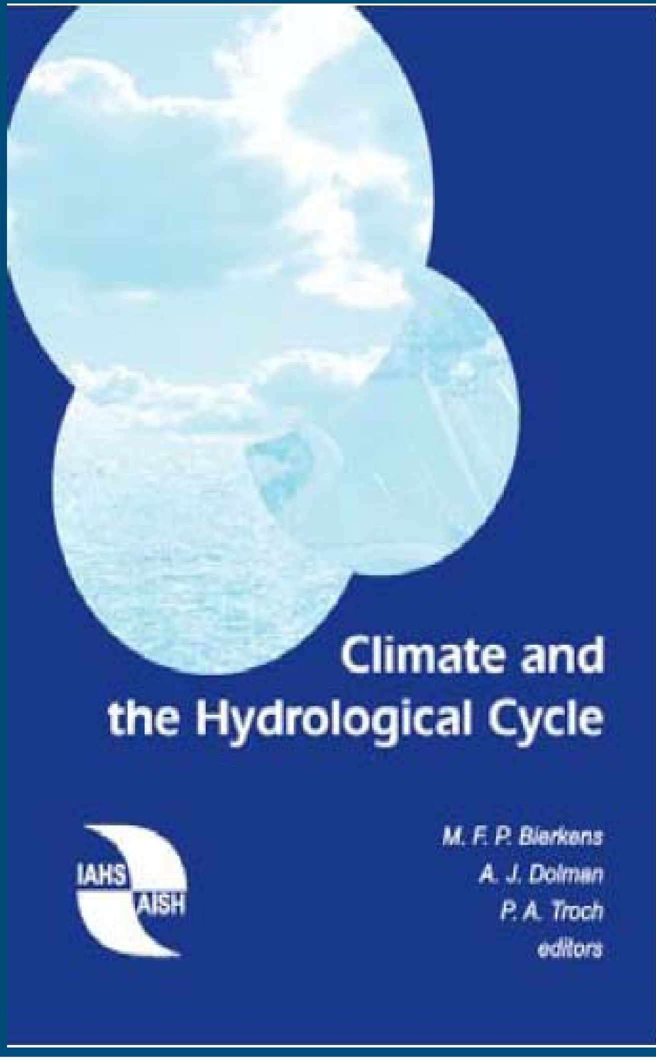
Summer Course



Content

- Monday June 8: Is the hydrological cycle accelerating?
- Tuesday June 9: Hydrologic impact studies
- Thursday June 11: Vegetation controls on inter-annual variability of catchment water balance

Climate change and the acceleration of the hydrologic cycle

Peter A. Troch (with contribution from J. Sheffield, E.F. Wood, J. Dolman, M. Waterloo and A. Teuling)

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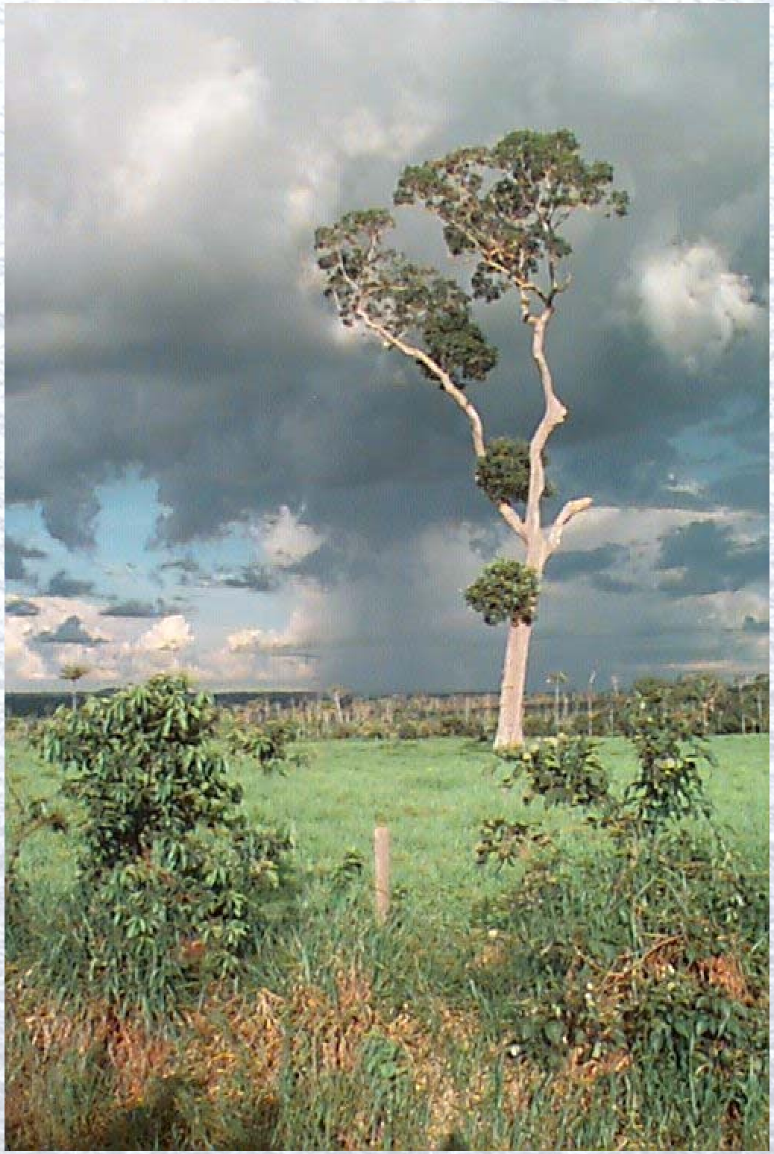
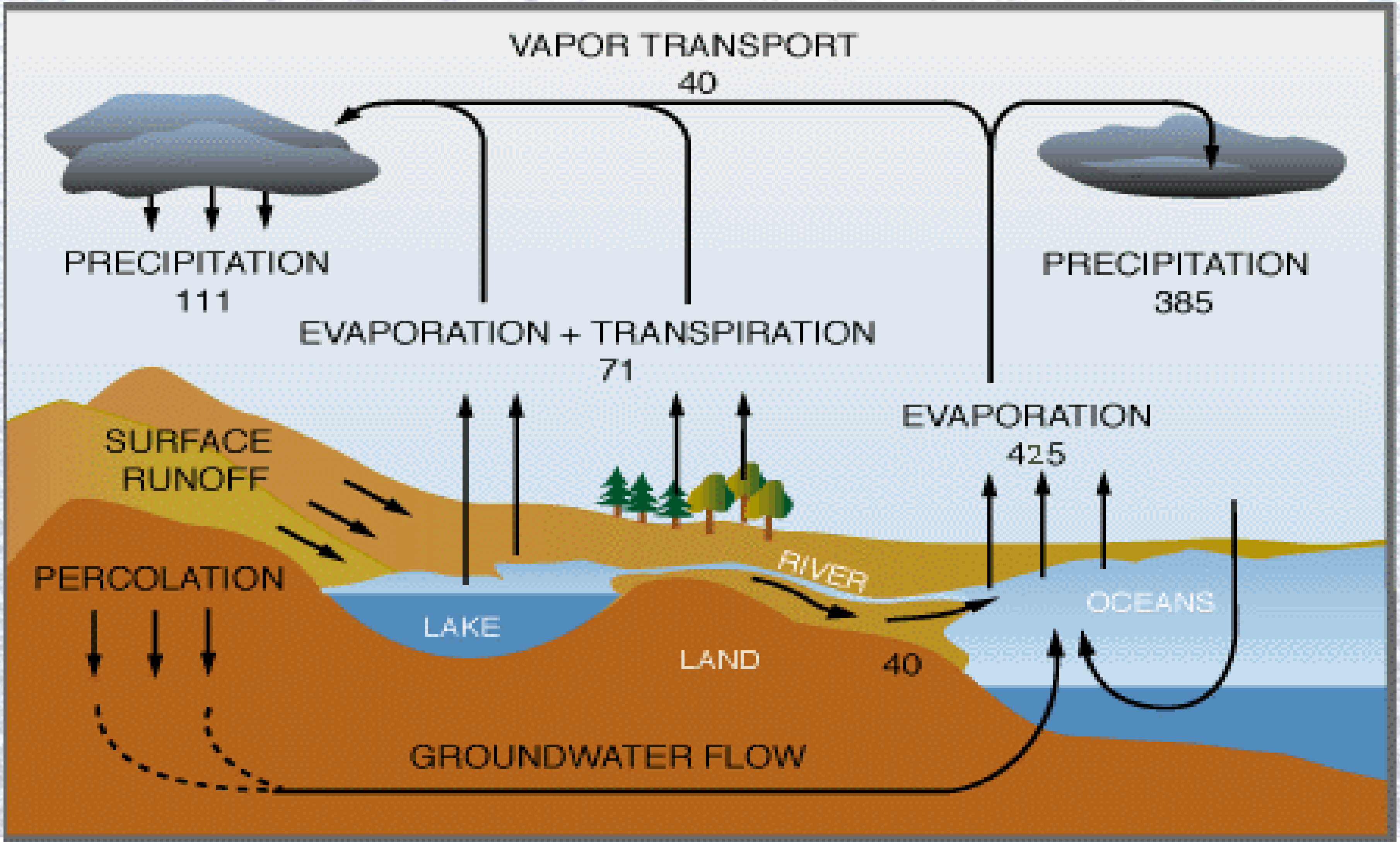
The Hydrological Cycle

Does global warming lead to an intensification of the hydrological cycle? Can we observe this already?



Global hydrological cycle (in 10^{12} m^3)



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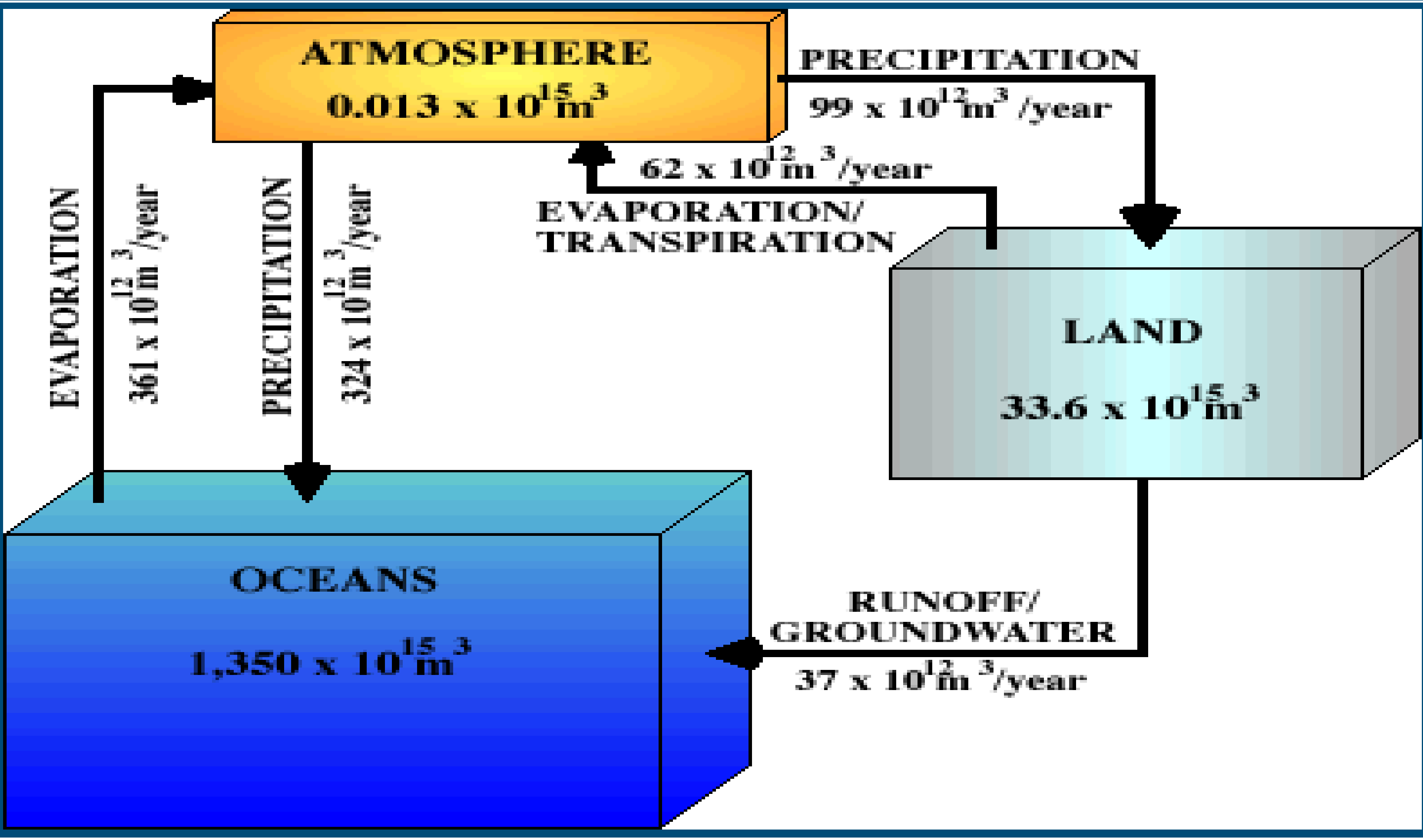
Residence times

- Residence time (t_r) is the average time that water spends in a particular reservoir

- t_r can be calculated by dividing the amount of water stored in a reservoir (S) by the flow (Q) through that reservoir:

$$t_r = S/Q$$

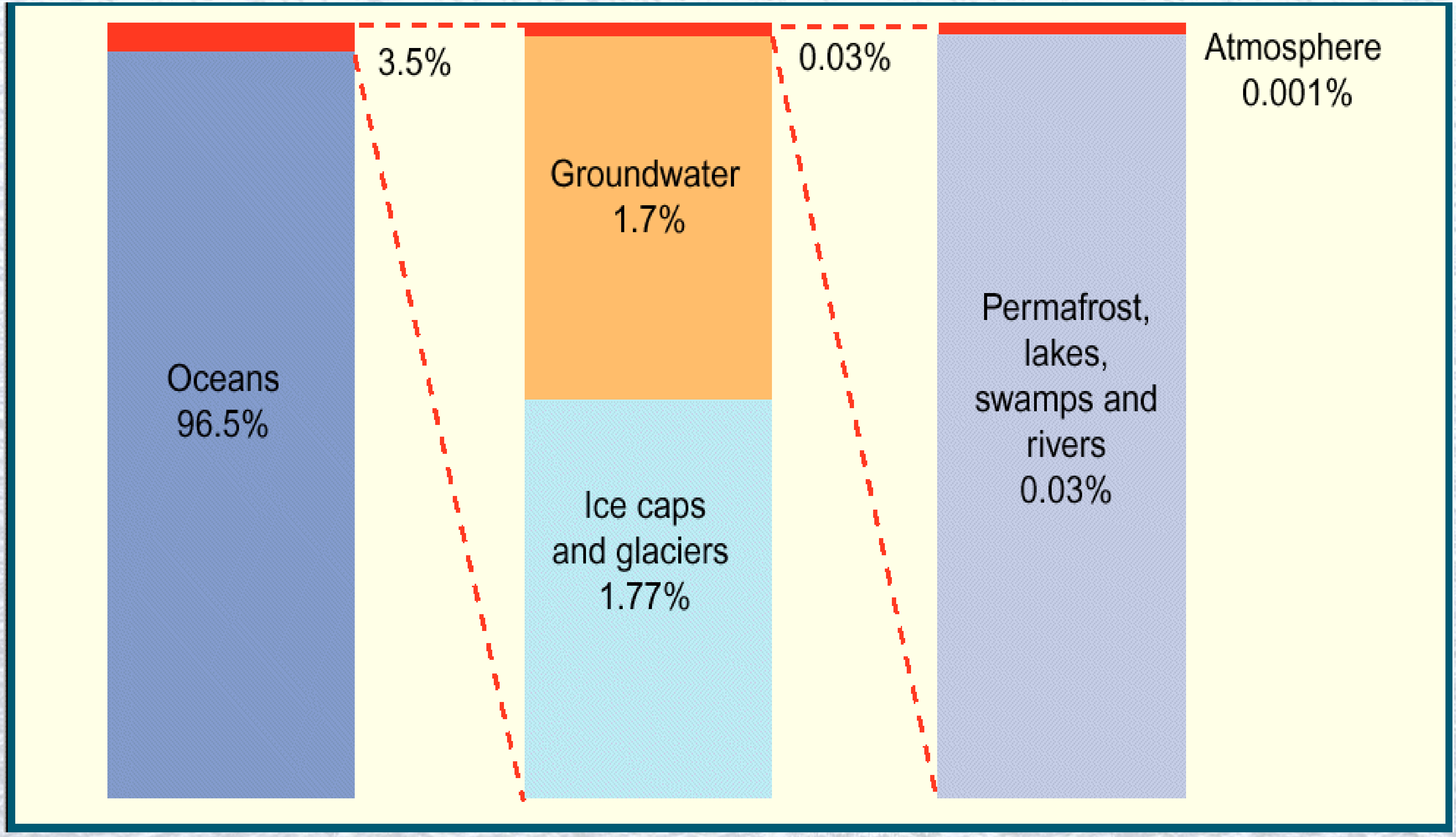
Global stores and fluxes of water



Residence times

- atmosphere: $0.013*10^{15}$ m^3 / $423*10^{12}$ m^3 y^{-1} = 0.03 y = 11 days
- rivers: 10-20 days
- groundwater 100 - 10,000 years
- oceans: 3700 years
- glaciers: 10,000 years

Global distribution of fresh water



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Global use of water resources

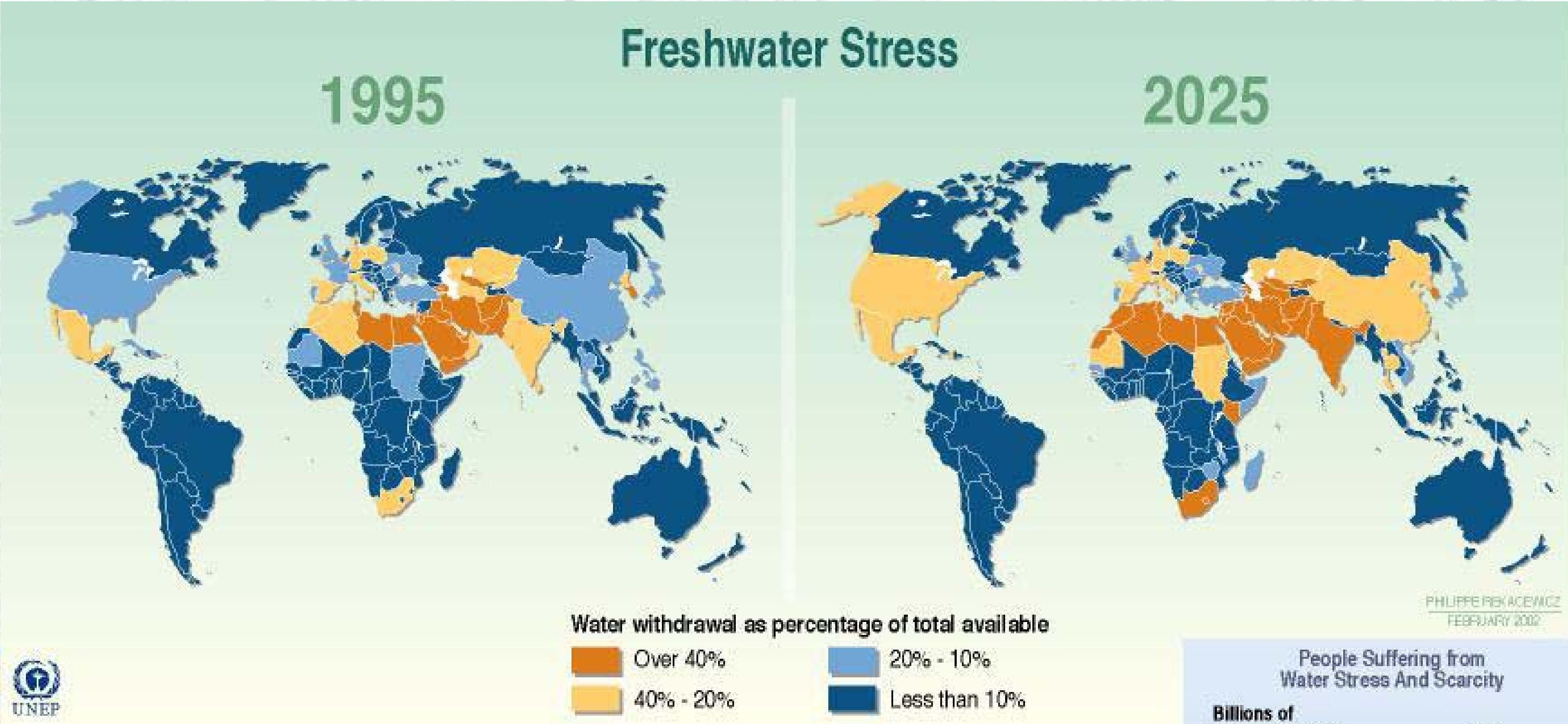
• Agriculture:	82%
• Losses in reservoirs (evaporation):	12%
• Industry:	4%
• Municipalities:	2%

Main water sources are: surface water, groundwater, rainfall and desalinisation plants

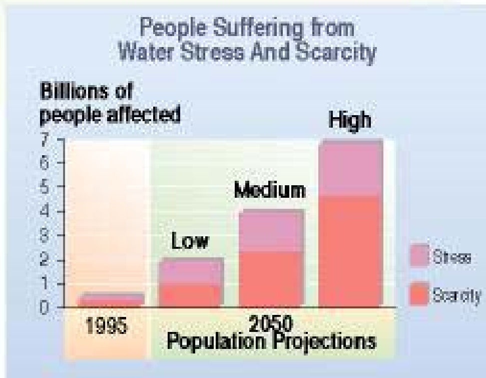
Importance of water: scarcity...

- Freshwater is an everyday problem for more than one billion people.
- More than 50 countries cannot provide safe and adequate freshwater for domestic use.
- By 2025, 12 more African countries will join the 13 that already suffer from water stress or water scarcity
- Mining occurs in arid countries: Groundwater extraction in Israel is 15-20% above capacity. Agricultural sector supplies 5% of the gross national product, but drains 70% of the country's water.

Global freshwater stress,1995 & 2025



Source: World Meteorological Organisation (WMO), Geneva, 1996; Global Environment Outlook 2000 (GEO), UNEP, Earthscan, London, 1999.



The water balance equation

- To quantify the hydrological cycle of an area we apply the principle of mass conservation:

$$\frac{dM}{dt} = Inflow - Outflow$$

- This is called the water balance or water budget equation, often applied to a *catchment* area.
- If density ρ can be assumed constant you can use volumes instead of mass ($M=\rho V$) :

$$\frac{dV}{dt} = Inflow - Outflow$$

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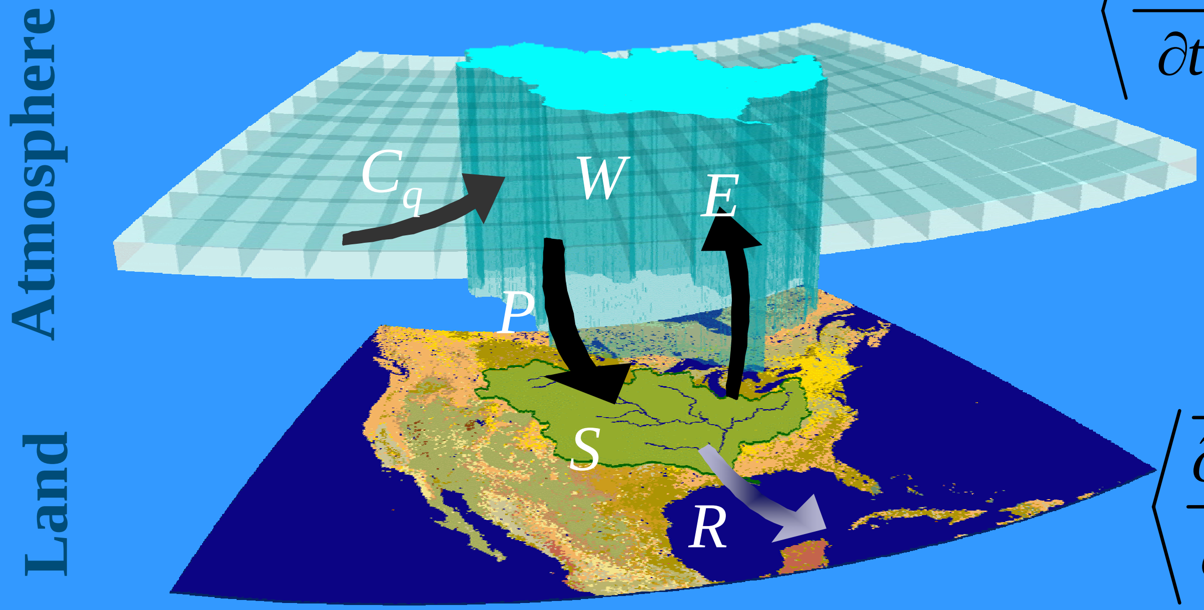
Catchments

- **Catchment**, **watershed** or **drainage basin**: area of land in which water flowing across the land surface drains into a stream or river and ultimately flows out through a single point on that stream or river
- The **catchment boundary** is the divide (ridges, hills)

Coupled land-atmosphere water balance



$$\left\langle \frac{\partial \overline{W}}{\partial t} \right\rangle + \left\langle \nabla_H . \vec{Q} \right\rangle = \left\langle \overline{E} - \overline{P} \right\rangle$$

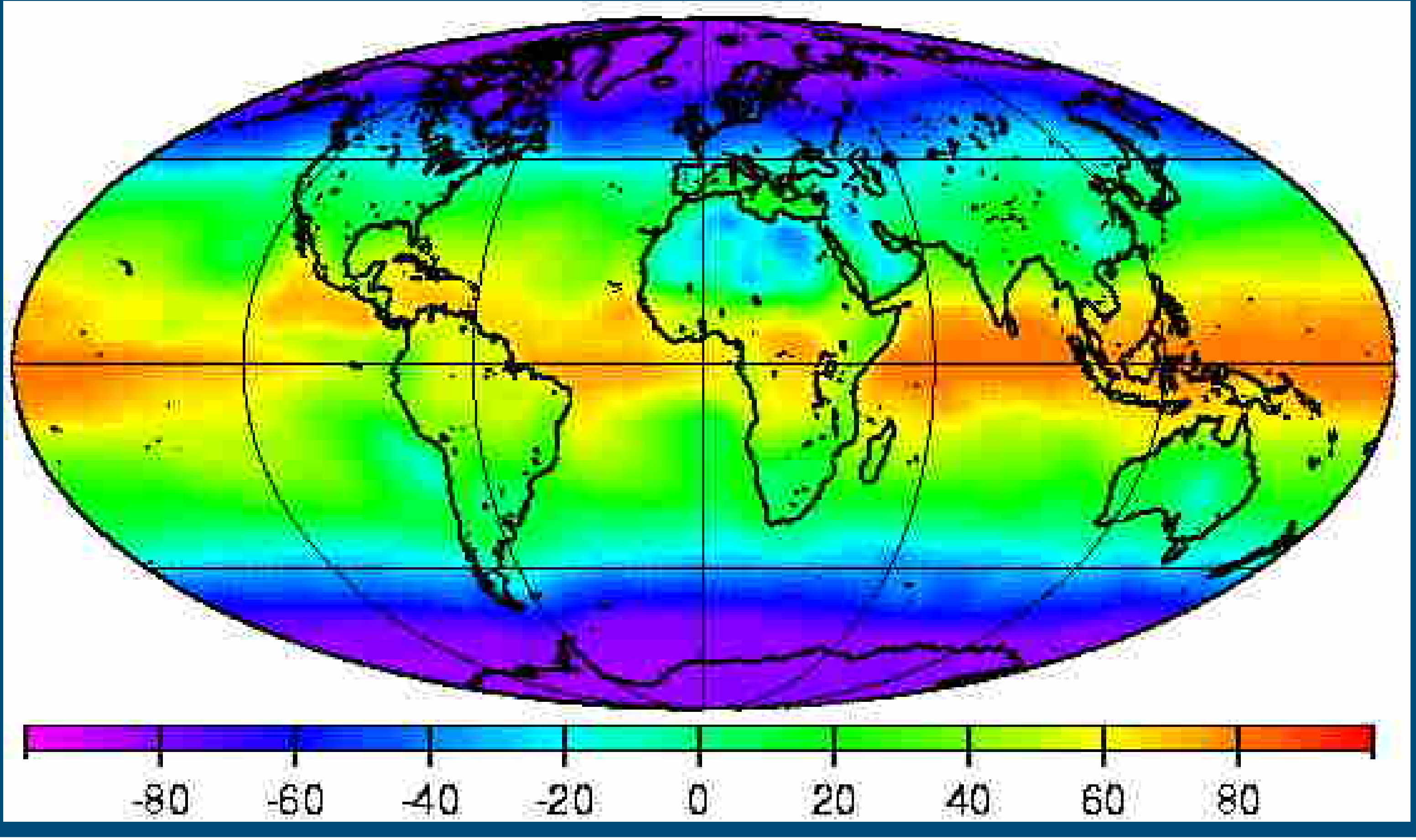
$$C_q = -\nabla_H . \vec{Q}$$

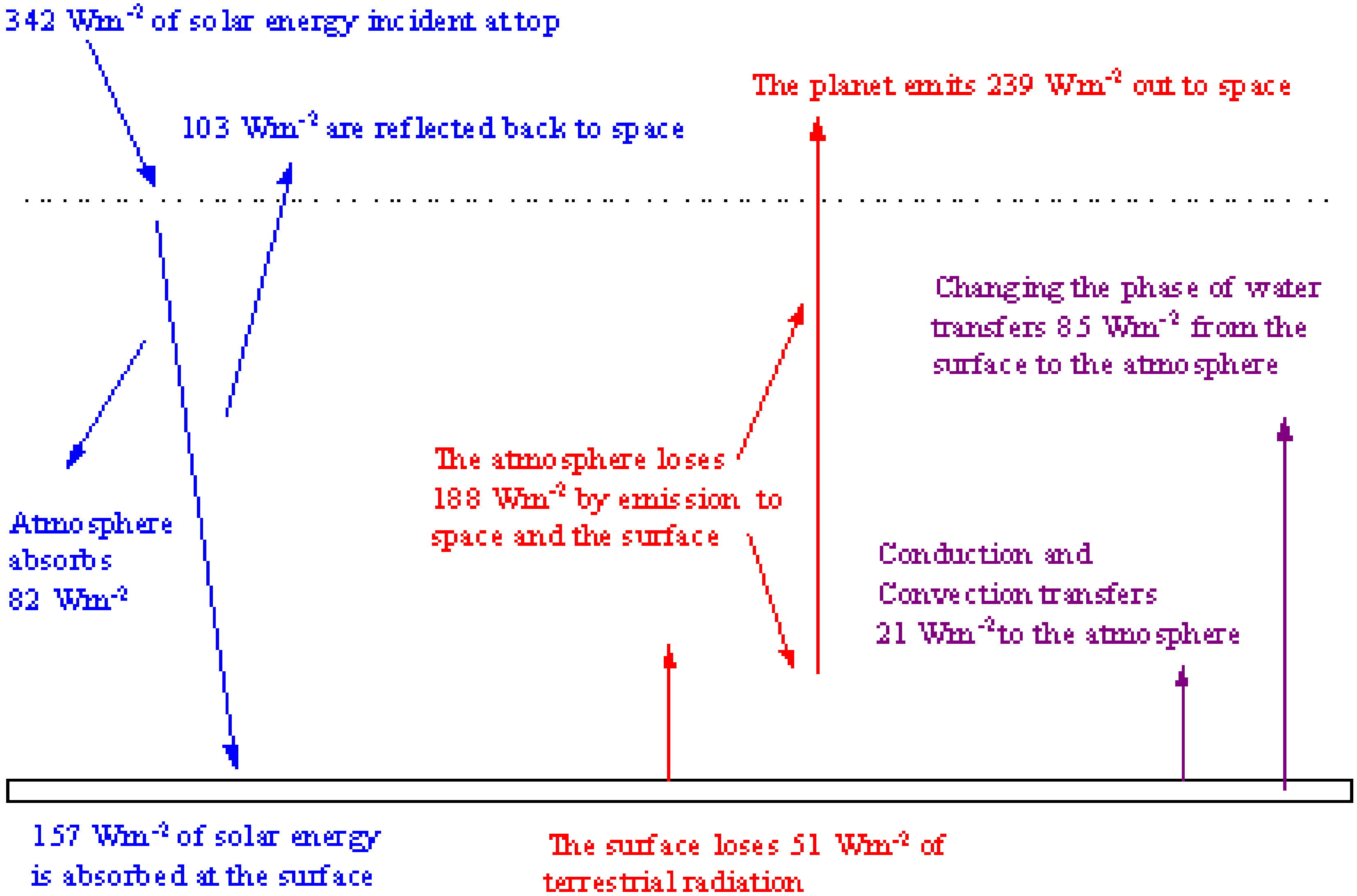
$$\left\langle \frac{\partial \overline{S}}{\partial t} \right\rangle = \left\langle \overline{P} - \overline{E} \right\rangle - \left\langle \overline{R} \right\rangle$$

$$\boxed{\left\langle \frac{\partial \overline{S}}{\partial t} \right\rangle = -\left\langle \frac{\partial \overline{W}}{\partial t} \right\rangle - \left\langle \nabla_H . \vec{Q} \right\rangle - \left\langle \overline{R} \right\rangle}$$

Hydrological cycle driven by solar radiation

Global annual mean radiative budget (Wm^{-2})



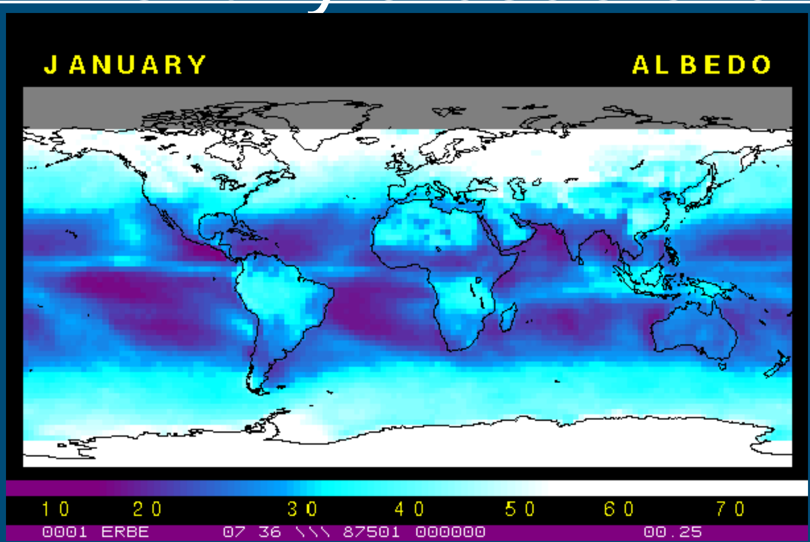


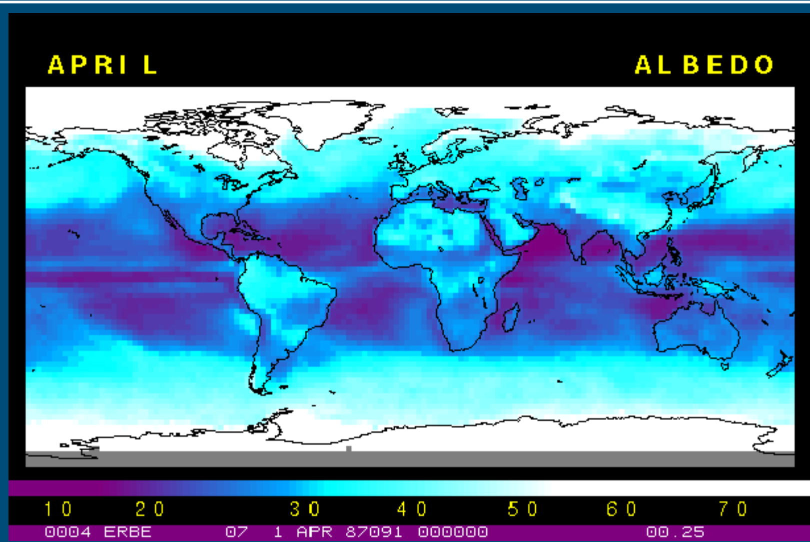
$$R_n = H + \lambda E (+G)$$

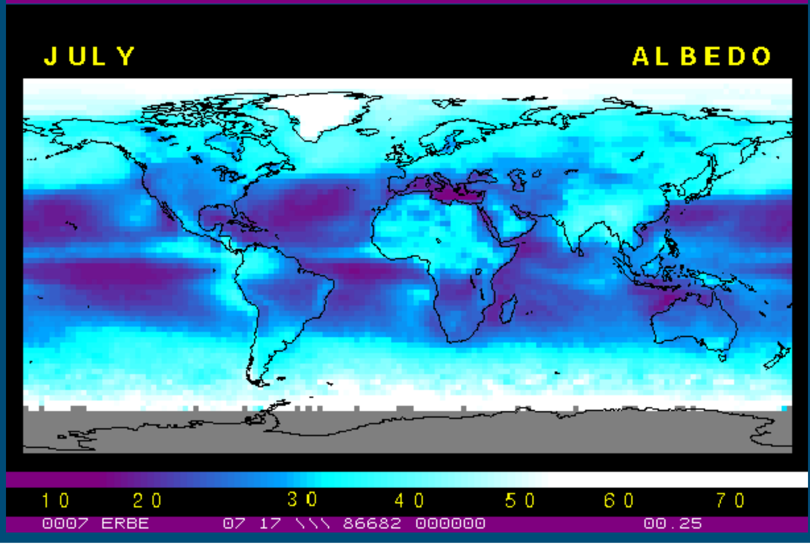
How can radiative budget change?

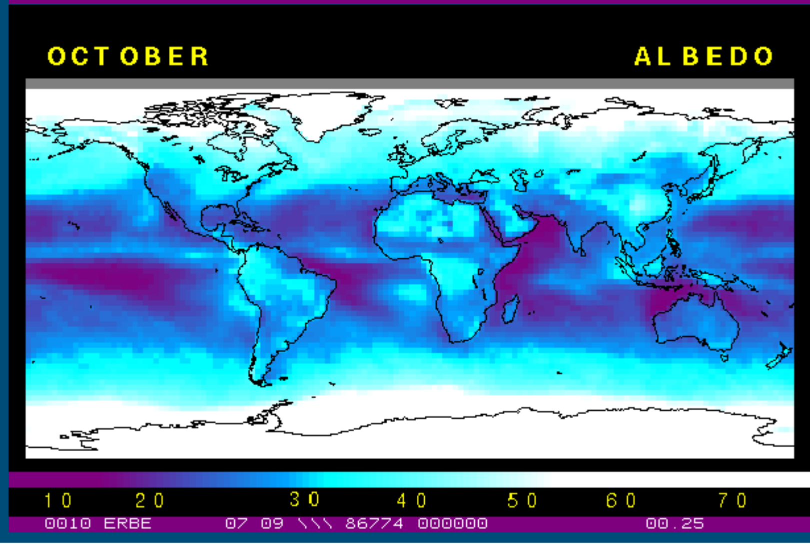
- **Amount of energy received** can be different, because for example of the variation of the tilt of the axis of Earth rotation. Contrasts between latitudes and between seasons is larger when obliquity is larger. Climate changes due to astronomic variations are defined by Milankovitch theory.
- **Amount of energy reflected** (albedo) can change if cloud cover or Earth's surface parameters, such as amount of ice, oceans, and forest change. For example, a colder climate would lead to more polar ice and therefore an enhancement of mean global albedo, increasing temperature fall. This is a positive feedback.
- **Amount of energy kept by the planet** can change if the greenhouse effect is modified.

Monthly albedo changes









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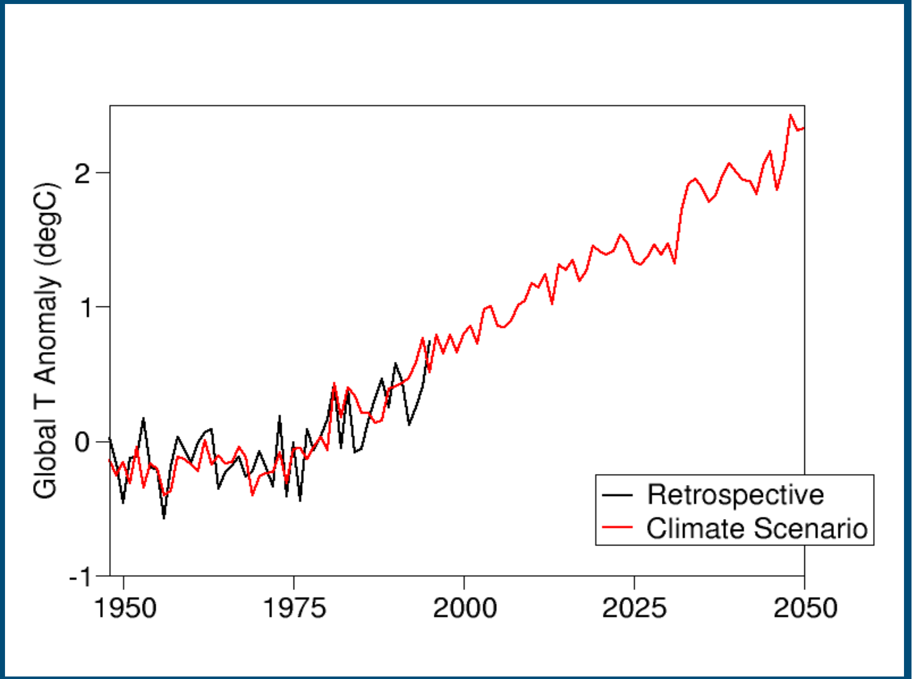
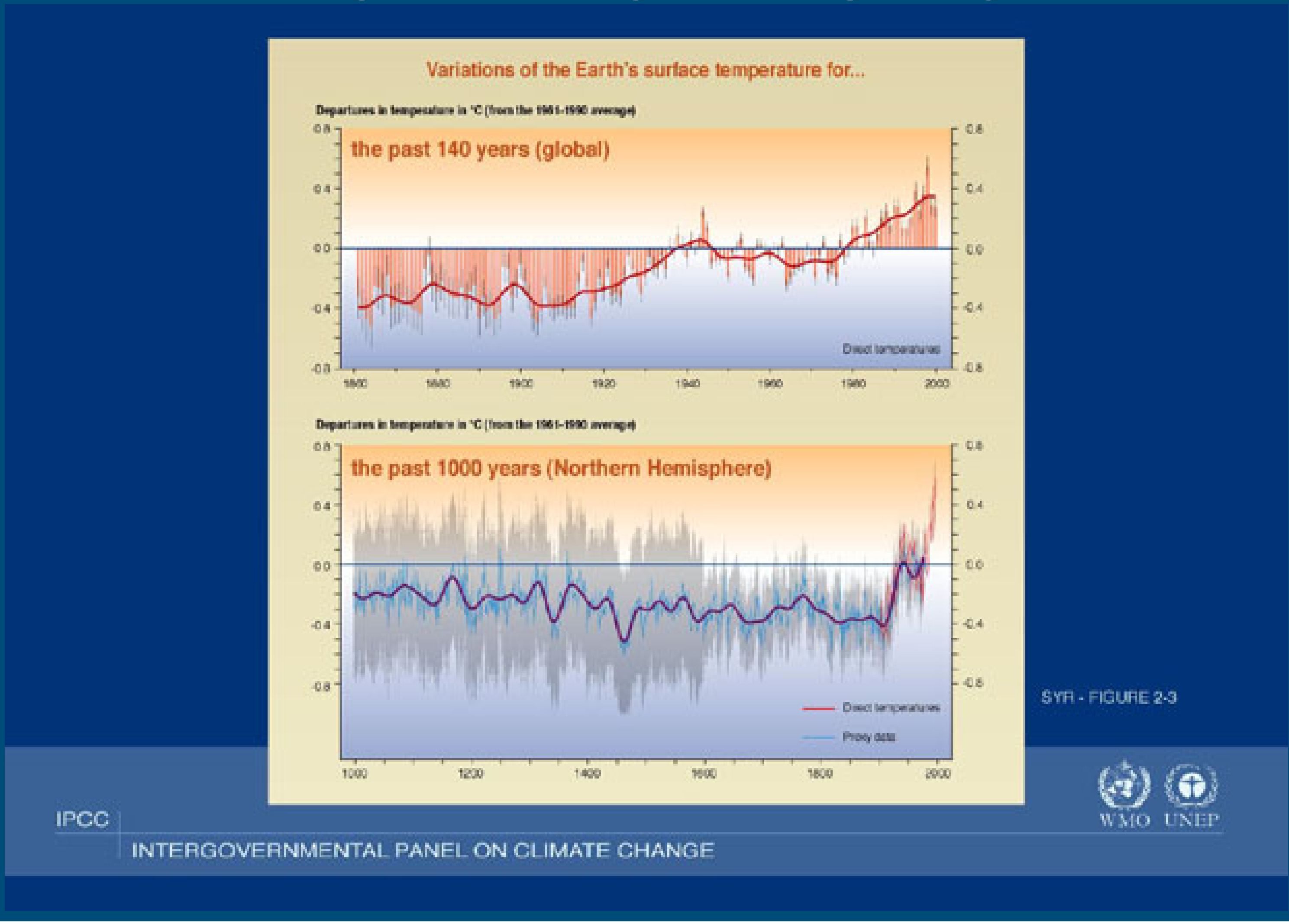
Climate change and hydrologic cycle

- Global surface temperature rise has been observed in the last half century
- Hydrologists' interest: how large change has occurred/will occur in the hydrologic cycle?
- Many research has been done to detect changes occurred in each component of hydrologic cycle

Global Land Air Temperature



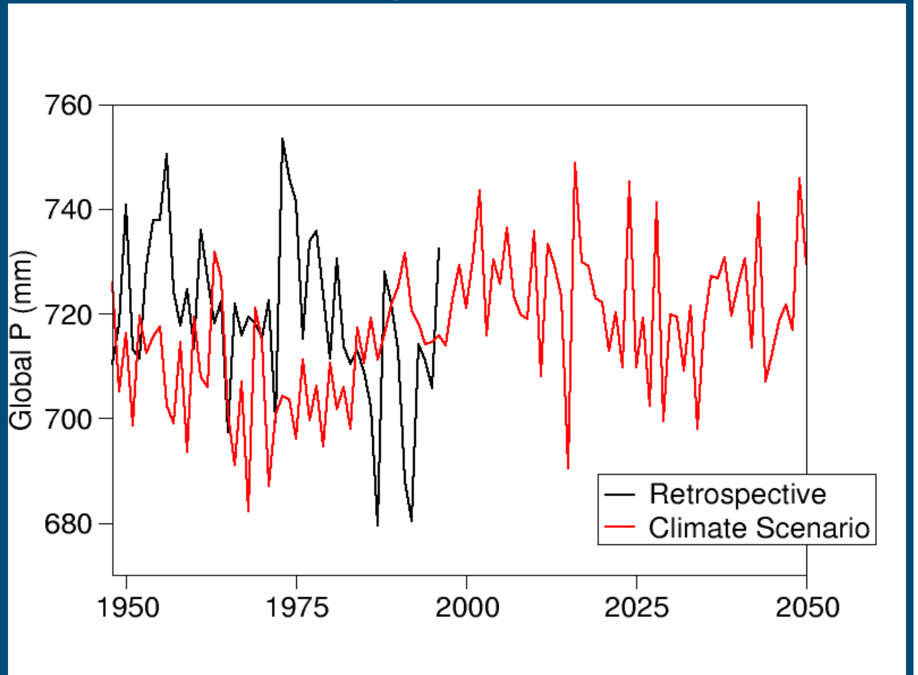
Climate change and hydrologic cycle



Changes in hydrologic cycle

- Precipitation has been studied using operational, satellite-based and model-based measurements
- According to IPCC report,
  - Global average precipitation has increased by 2%/century
  - But, non-uniform in time and space (e.g. significant precipitation decrease in Canada)

Global Land Precipitation



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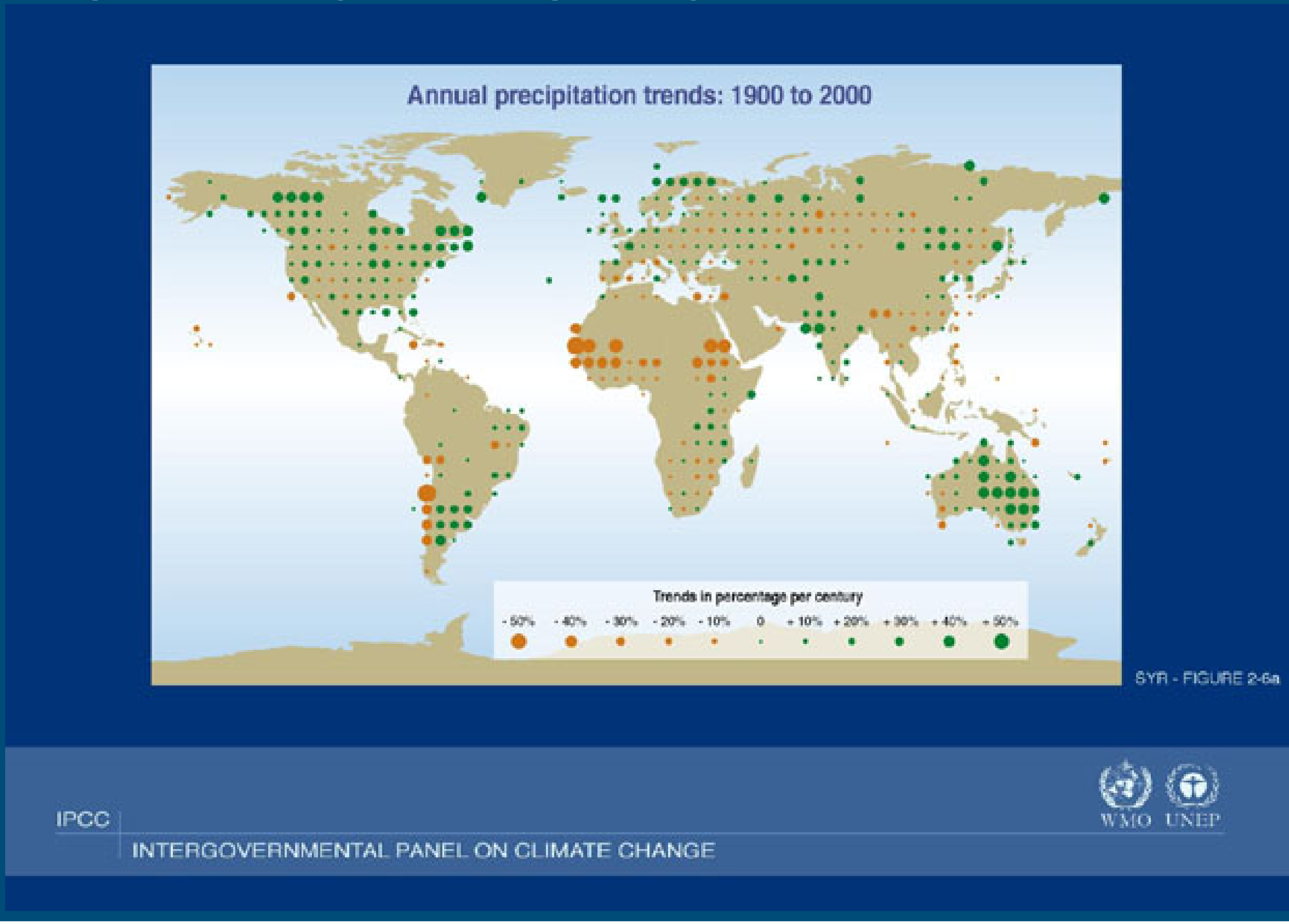
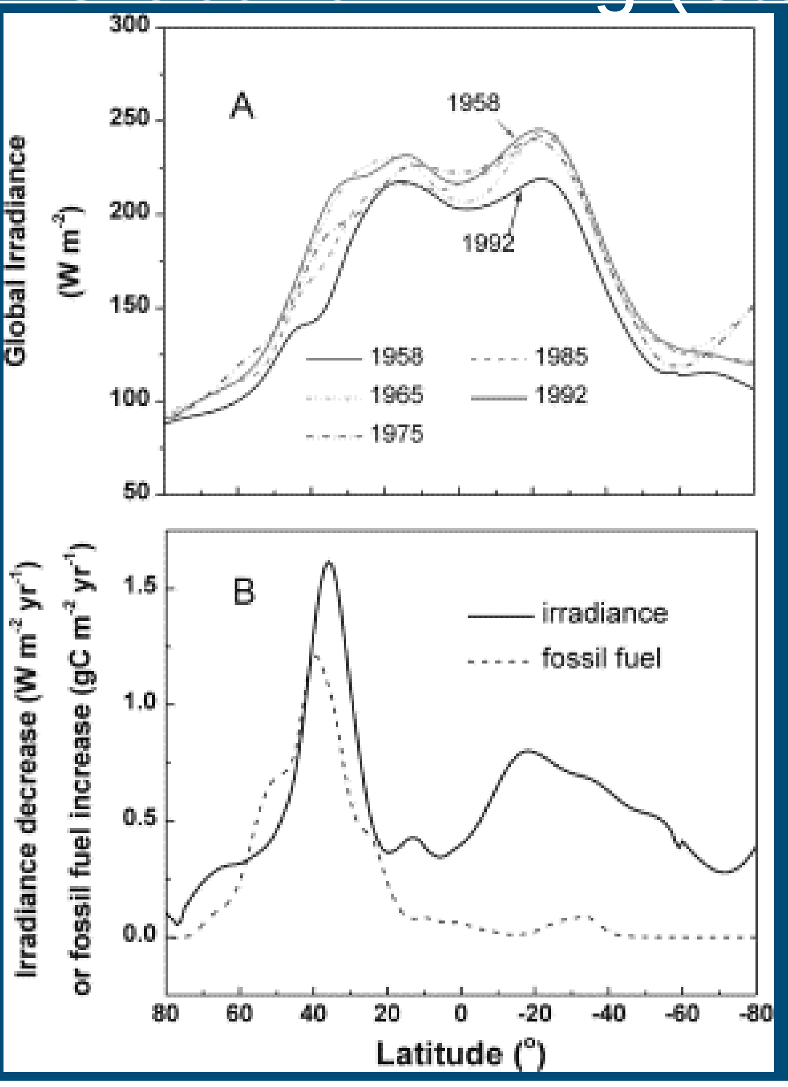
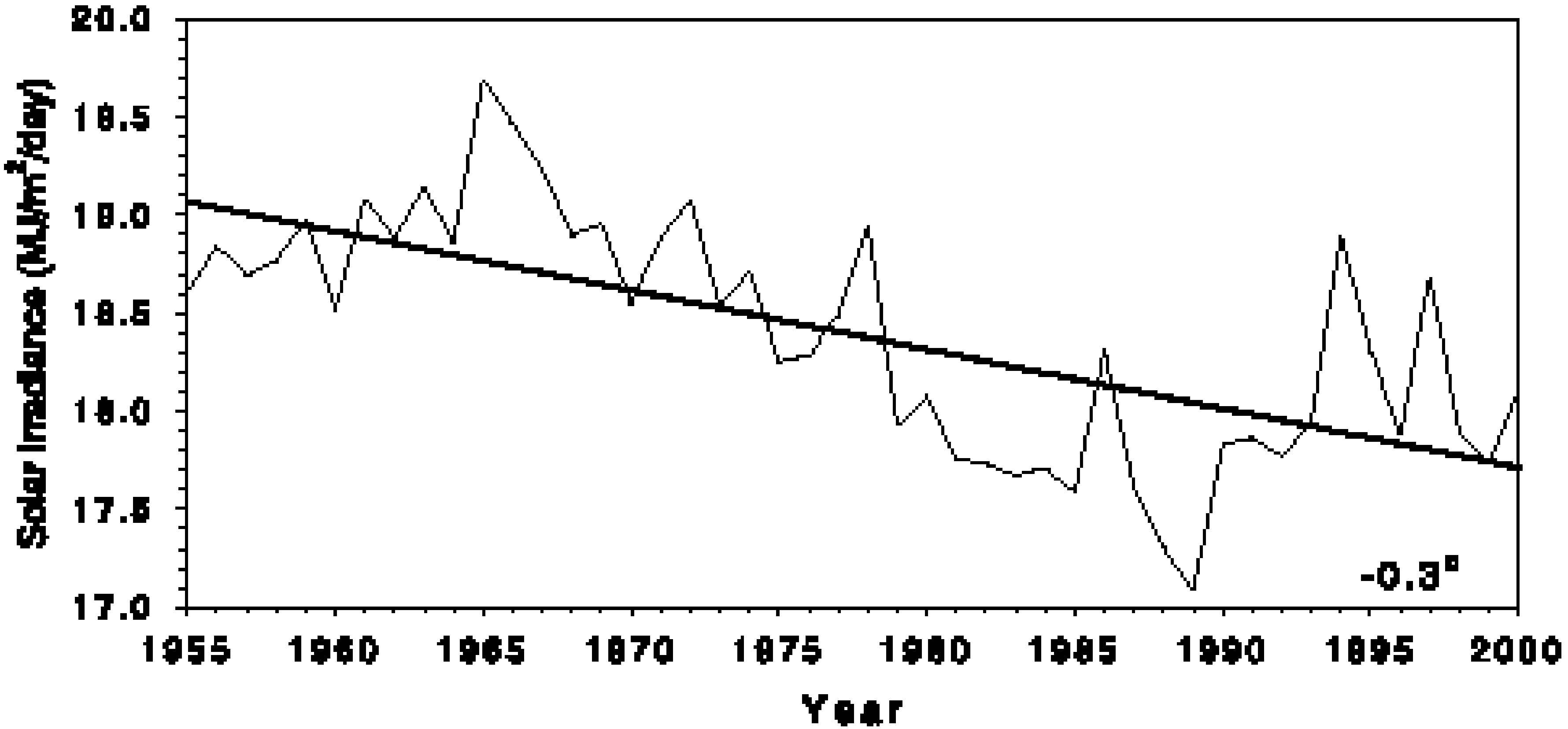
Changes in hydrologic cycle



Global dimming (*Stanhill and Cohen*, 2001)



Global dimming (*Liu et al.*, 2004)



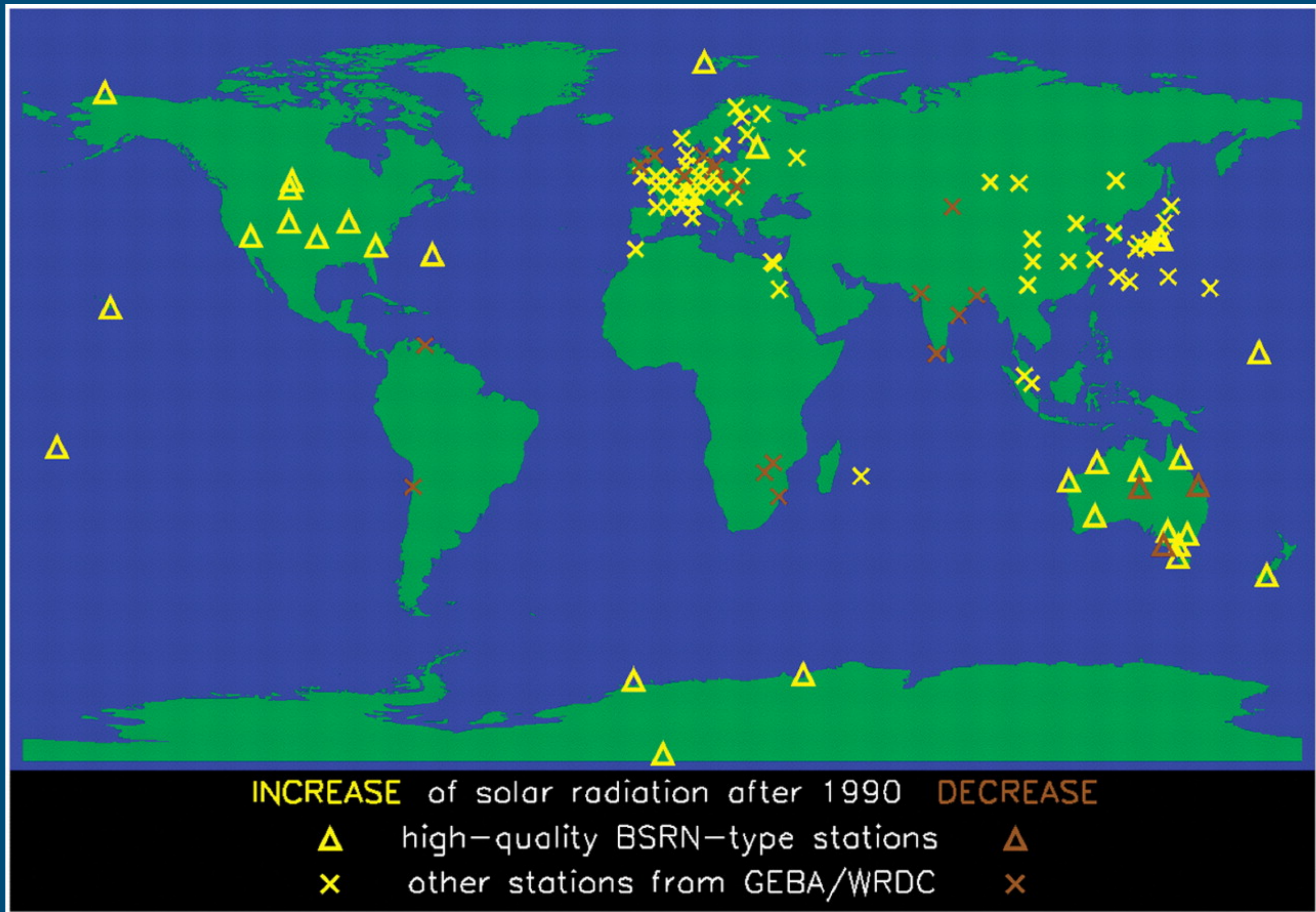
Role of aerosols in Earth's radiation budget

- Aerosols increase reflection of short-wave radiation to space, but effect on long-wave radiation is minor;
- Aerosols also absorb solar radiation which reduces solar radiation at surface;
- Aerosols increase droplet number concentration in clouds, leading to increase in reflection to space (First indirect effect);
- If condensed moisture inside cloud is not altered, droplet radius will decrease resulting in decrease in precip. efficiency (clouds live longer: Second indirect effect);

Role of aerosols in Earth's radiation budget (2)

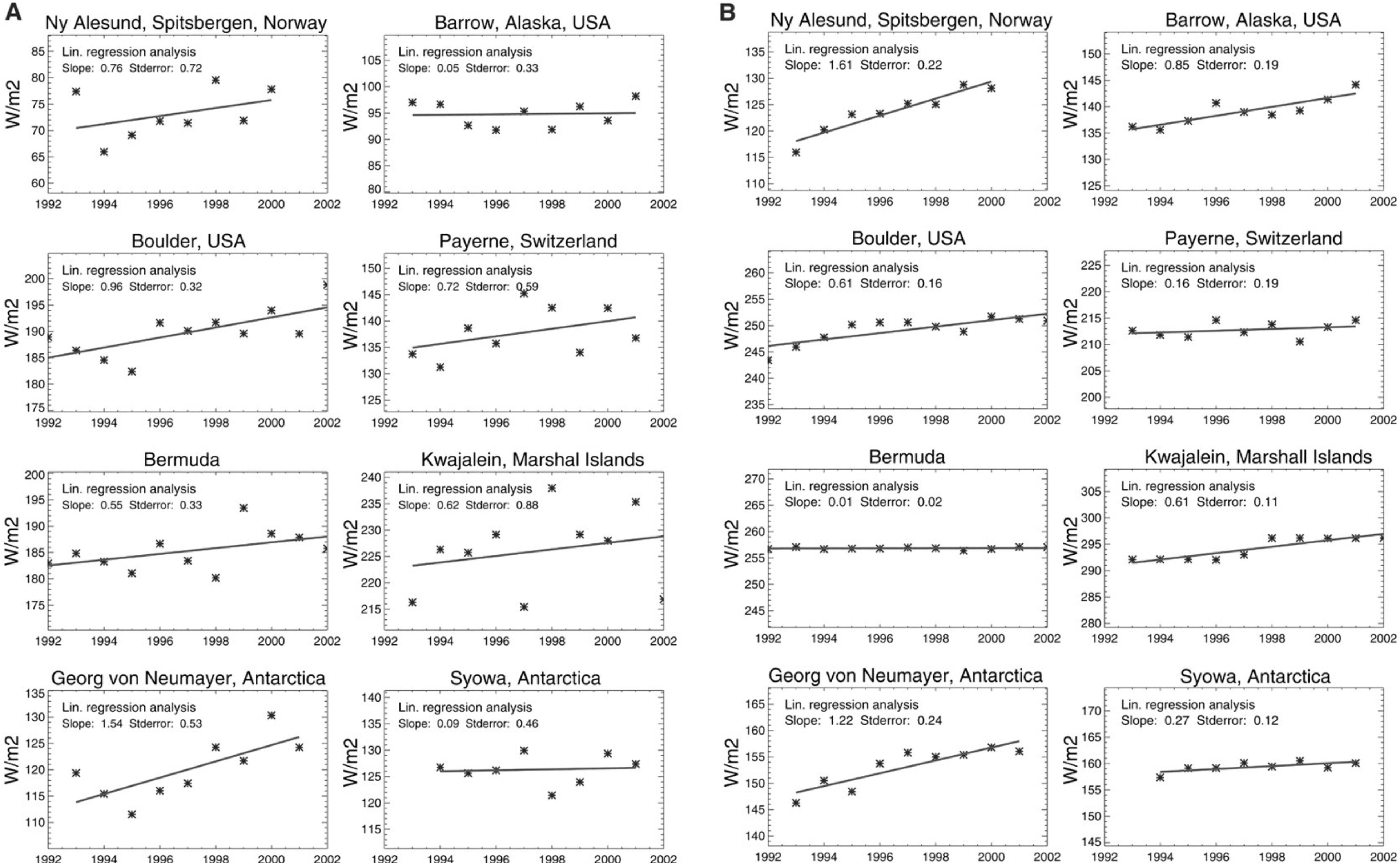
- Aerosols lifetime is typical one week or less and have highest concentrations near source, whereas GHG are long-lived and uniformly distributed within atmosphere;
- GHG and aerosols have competing effects on climate, thus cooling effect of aerosols can regionally exceed global surface warming due to GHGs;
- This can be key control on the observability of regional effects of GHG-induced CC on the hydrological cycle
- See Ramanathan et al. (2001) for more on this…

…or is it getting brighter? (*Wild et al.*, 2005)



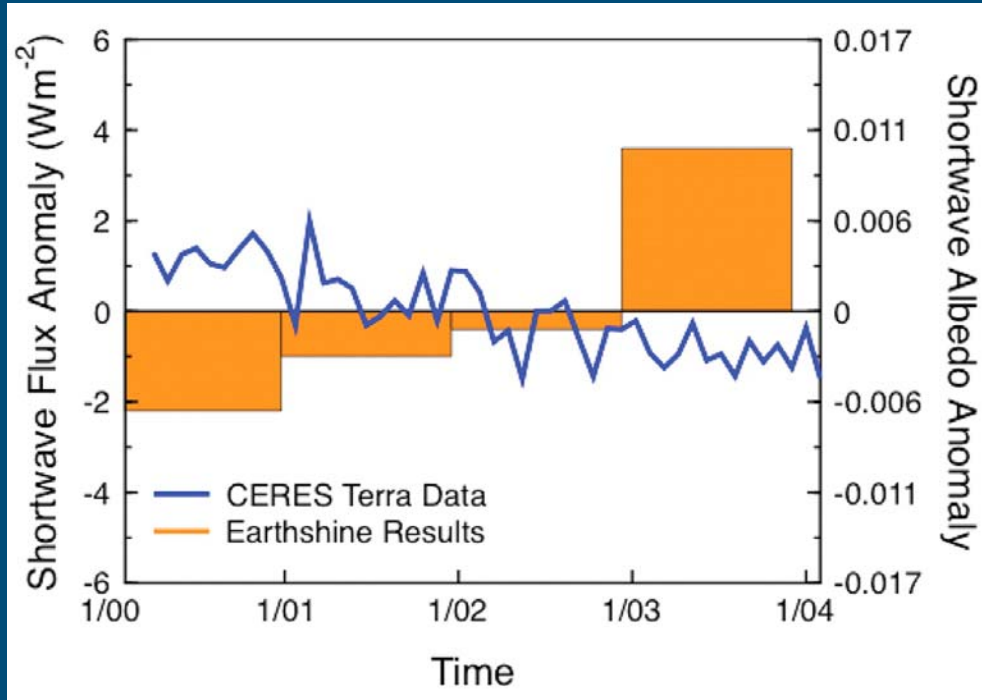
…or is it getting brighter? (*Wild et al.*, 2005)

all-sky conditions | clear-sky conditions



Earth's albedo measurements from space

- Eartshine results: albedo increase with 0.017 (*Pallé et al*., 2004)
- CERES Terra data: albedo decrease with 0.006 (*Wielicki et al*., 2005)
- 1% δalbedo = 3.4 Wm^{-2} (similar in impact of doubling CO_2 in atmosphere)



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Consequences of changes in Earths albedo

- If Wielicki et al. (2005) are correct, and albedo decrease is related to land surface and aerosols, than the Earth will warm up;
- If Pallé et al. (2004) are correct, a global cooling twice the level of the Pinatubo eruption would be expected (not observed, yet);
- For more reading: Pallé et al. (2004) and Wielicki et al. (2005) (both in *Science*!).

Trends in precipitation

- Global mean value of precipitable water in atmosphere is about 1 inch (25 mm);
- After a rain event, 70% of available water remains in atmosphere, so about 7.5 mm is available for precip.;
- Global average precip. Rate (including non-rainy days) is about 2.8 mm day^{-1} (same as global evaporation rate);
- The average rain rate when it rains is 45 mm day^{-1};
- Moisture supply comes from low-level convergence.

Clausius-Clapeyron equation

- C-C equation governs water holding capacity of the atmosphere:

$$\frac{de_s}{e_s} = \frac{\lambda dT}{RT^2}$$

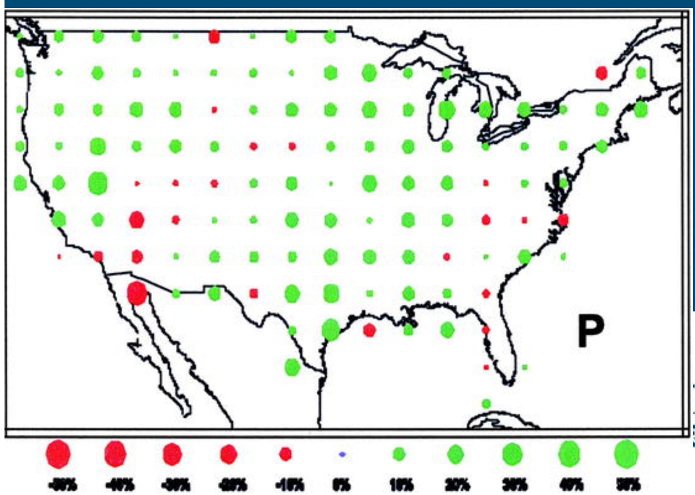
  - e_s: saturation vapor pressure at T
  - λ: latent heat of vaporisation (40.7 kJ mol^{-1})
  - R: ideal gas constant (8.3144 J^{-1} mol K^{-1})
- Predicts 7% increase of water holding capacity per K^{-1}
- Increase of global precipitation is 2% per K^{-1}

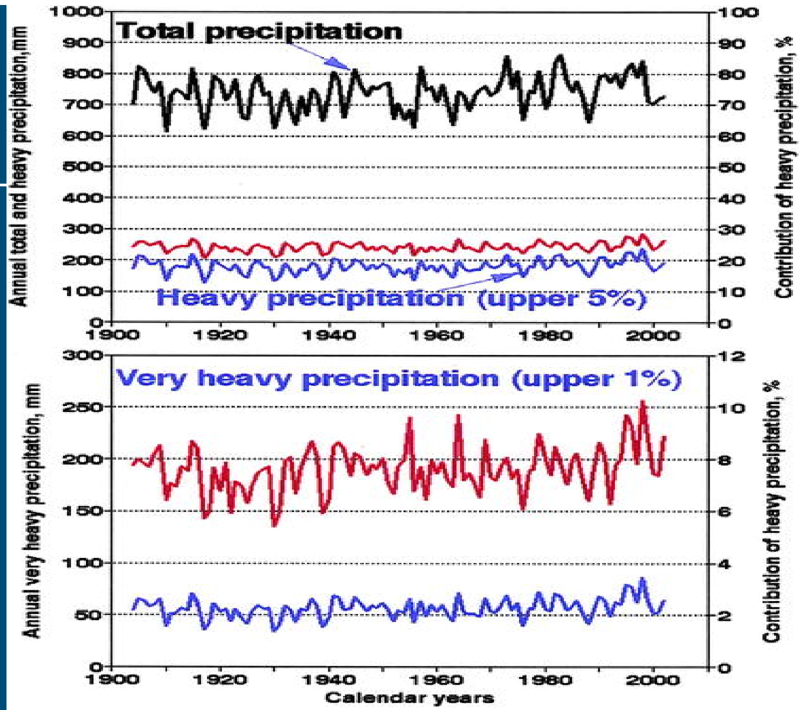
How should precip change as climate changes?

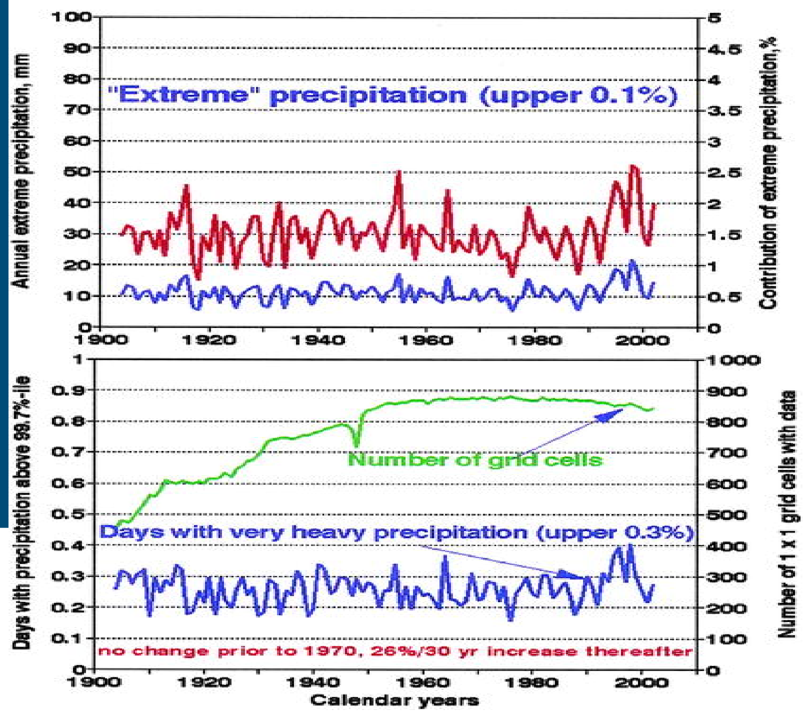
- *Trenberth* (1998) has argued that rainfall intensity should increase at about the same rate as the moisture increase, viz 7% K^{-1}
- Therefore, changes in rain rates (when it rains) are at odds with 2% K^{-1} predicted increase of total rainfall amount
- Implication: decrease in light to moderate rains and/or decrease in frequency of rain events
- Prospect: fewer but more intense rainfall events

Observational evidence

- Groisman et al. (2004) present analysis of 20th century data over contiguous US
- while mean total precipitation increased, heavy and very heavy precip increase was significantly greater (especially over past 30 years)







Changes in terrestrial evaporation

- Evaporation from the land surface
  - has no long-term measurement
  - recent growing interest is that pan evaporation may serve as an index of the land surface evaporation
- Pan evaporation is operationally measured world-wide over past 50-60 years

Pan observations

- Decrease in pan evaporation in the US, Former Soviet Union (FSU), China and Australia (*Peterson et al*., 1995; *Liu et al*., 2004; *Roderick and Farquhar*, 2004)
- Pan evaporation ~ potential evaporation (= wet surface evaporation)
- Suggests the decrease in terrestrial evaporation
  - “evaporation loses its strength”

Bouchet's complementary relationship

- Bouchet (1963): "When transport of water vapor to the atmosphere is restricted, the relation between pan evaporation and actual evaporation is symmetric":

$$E_a + E_{pan} \cong 2E_p$$

- Actual evaporation from well-watered surface:

$$E_a = E_p = aE_{pan}$$

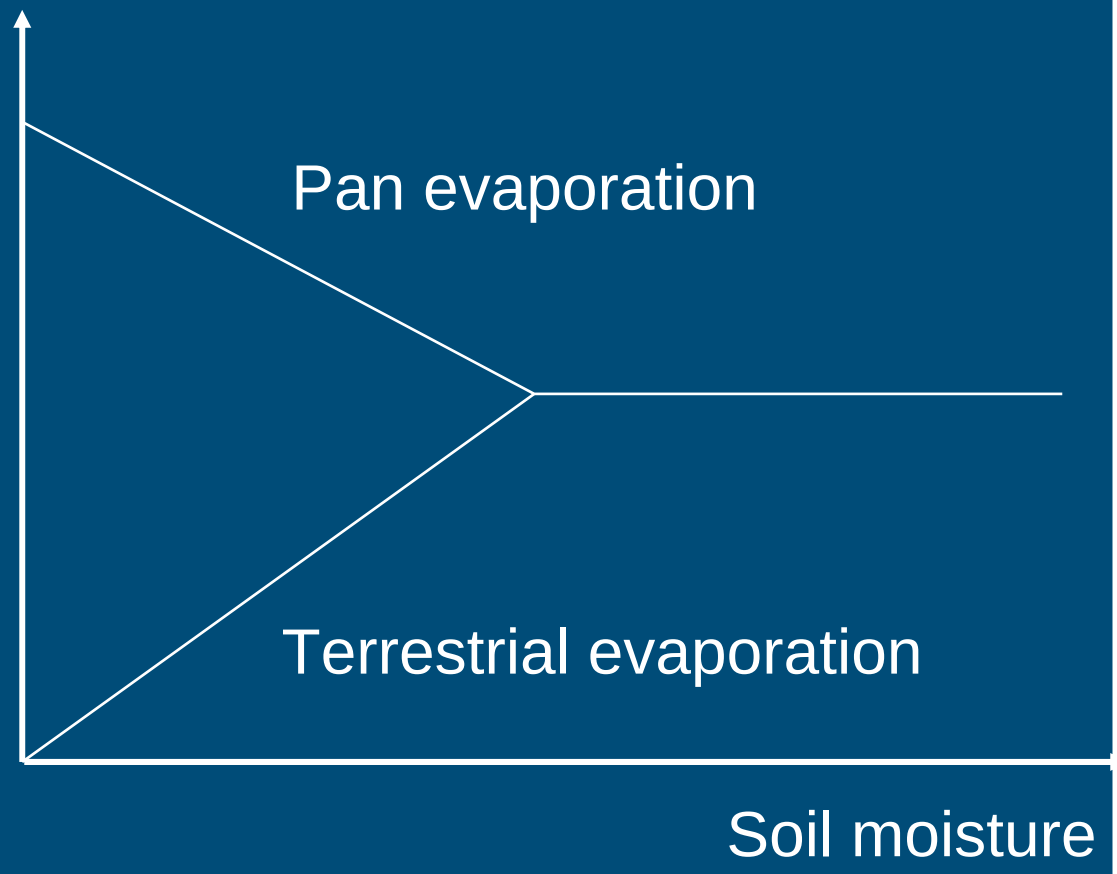
- Under water-limited conditions (a and b are slightly > 1):

$$E = E_p - \Delta H$$

$$aE_{pan} = E_p + b\Delta H$$

Brutsaert and Parlange (1998, Nature)

- Decrease in pan evaporation leads to increase in terrestrial evaporation (Bouchet’s complementary relationship)
- Increase in terrestrial evaporation leads to increase in precipitation
  - Thus, acceleration of the hydrological cycle

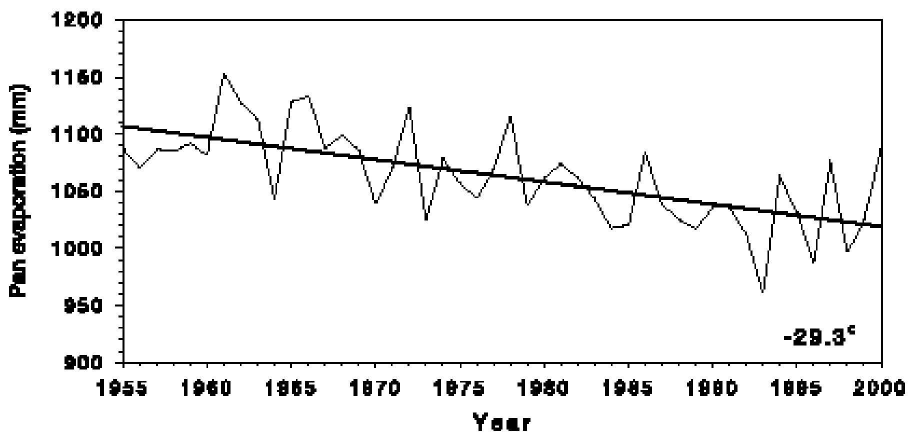


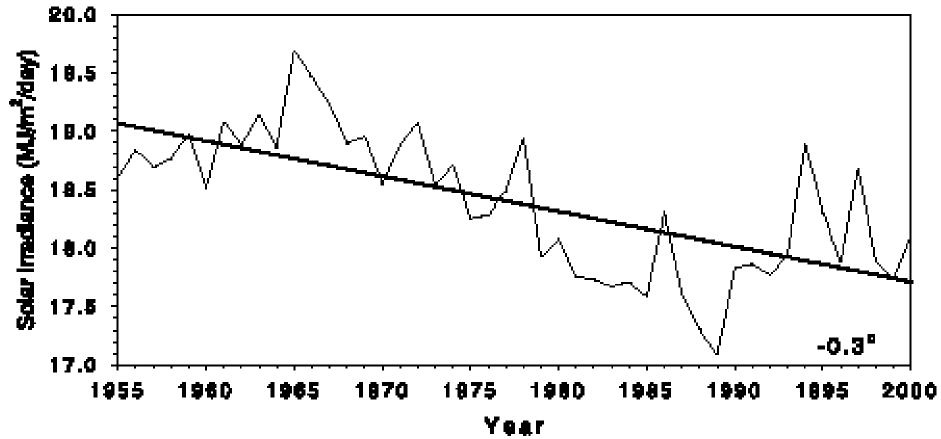
Golubev et al. (2001, Geophys. Res. Letters)

Table 1: Estimates of Pan and Actual Evaporation Changes in Russia and Latvia

Site	Lat.	Lon.	Climatic zone	Sign of trends in evap. Actual	Pan	Ratio of trends
Volgograd	49N	44E	Dry steppe	+	-	-0.7
Kamennaya	51N	40E	Tall grass steppe	+	-	-0.5
Nizhned.	52N	38E	Forest-steppe	+	-	-0.6
Kostroma	57N	41E	Forest	+	-	-0.6
Valdai	58N	33E	Taiga	-	-	0.7
Kandalaksha	67N	32E	Taiga	-	-	1.4

Roderick and Farquhar (2002, Science)





- Increase in cloud amount and aerosols caused decrease in solar irradiance (1960-1990) and consequently a decrease in the pan evaporation as well as in terrestrial evaporation

But, land evaporation must increase in a warming climate, no?

- Well, that depends on trends in solar irradiance and water vapor pressure deficit, D

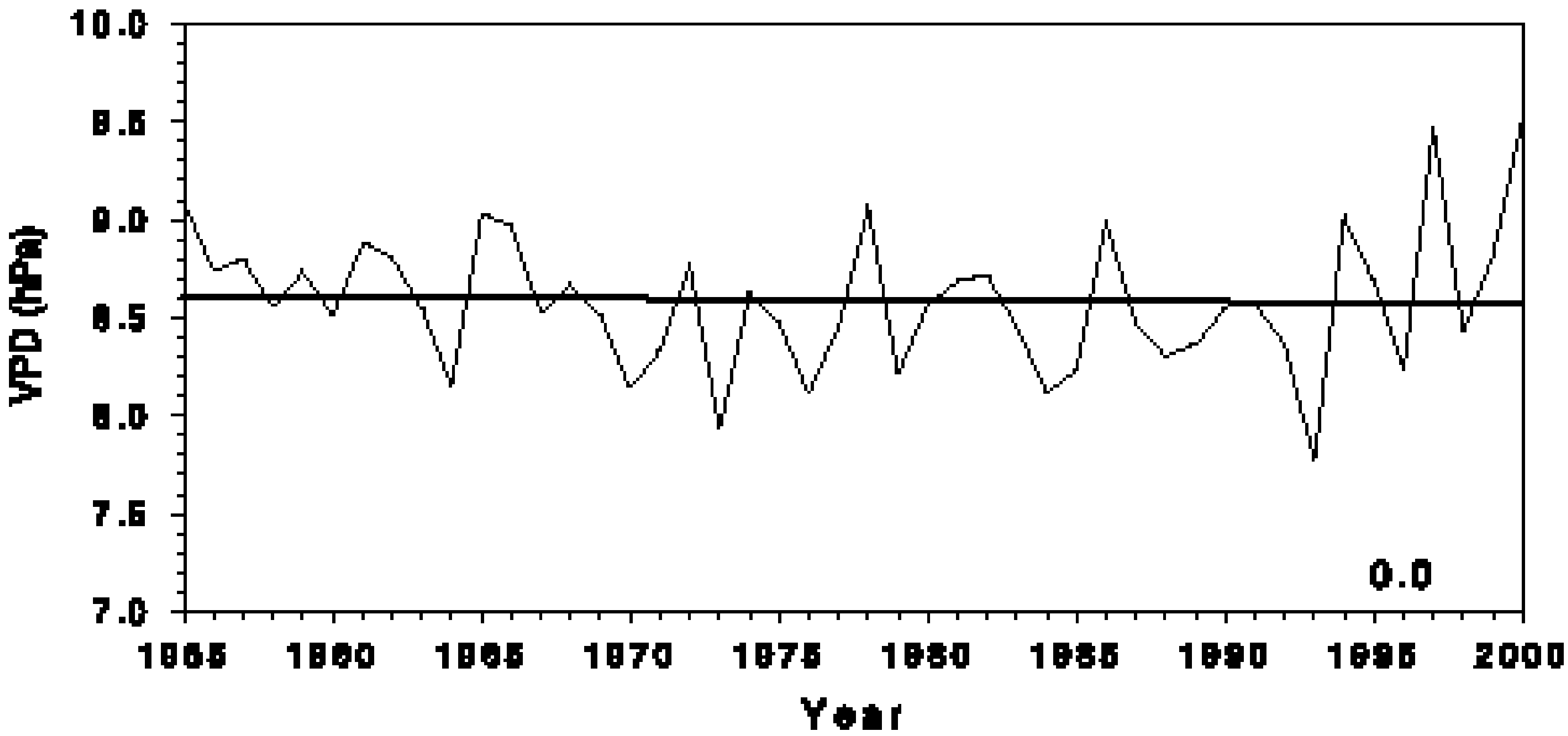
$$D = e_s(T) - e(T) = e_s(T) - e_s(T_d)$$

- *Roderick and Farquhar* (2002) demonstrate that D can remain constant if $T_{\min}$ increase faster than T

$$\delta D = s\delta T - s_d \delta T_d$$

- If $\delta T_d / \delta T$ equals s/s_d (typically of the order of 2)
- $T_{\min}$ increases twice as fast as mean surface temperature

Observational evidence (Liu et al., 2004)



Conclusion…?

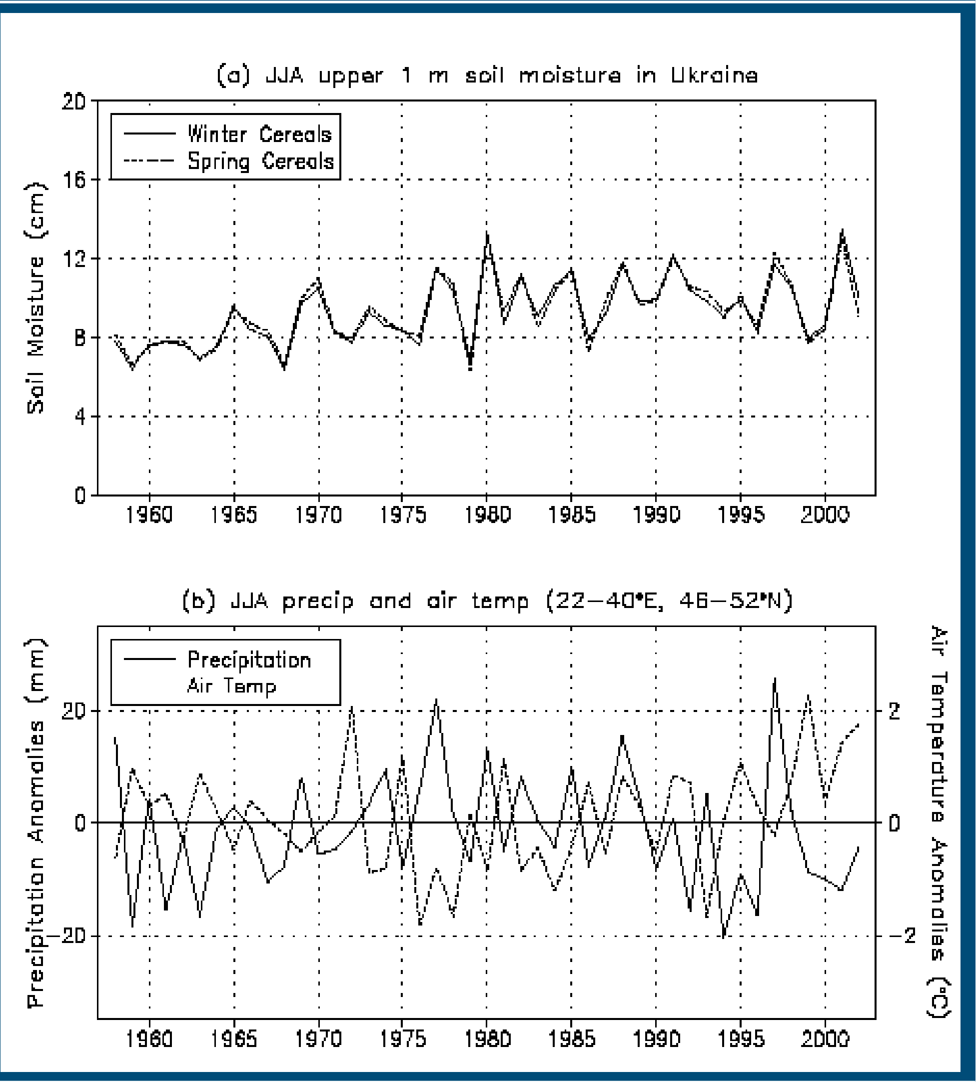
- In wet environments, the decreasing trend in pan evaporation should be interpreted as decrease in actual evaporation (Roderick and Farquhar, 2002), and is related to decreasing trend in solar irradiance at the surface;
- In dry environments, Bouchet's complementarity principle leads to conclusion of increasing actual evaporation
- Soil moisture (which integrates all soil-vegetation-atmosphere effects) should gives us the answer whether the land surface is getting wetter or drier…
- But…

Soil moisture observations are lacking…

- Despite the importance of SM for climate studies, there are very few long-term observations
- FSU: regular SM measurements since 1930s
- Several neighbours adopted Russian method shortly after
- In US, Illinois State Water Survey started data collection in 1980s
- *Robock et al*. (2005) analysed 45 years of 1-m soil moisture observations in Ukraine

Robock et al. (2005)

- 1-m soil moisture measured under winter and spring cereals shows increasing trend
- No summer desiccation (yet)
- Increasing trend seems to level off the last decade
- Is this consistent with reversal in solar irradiance in that region?



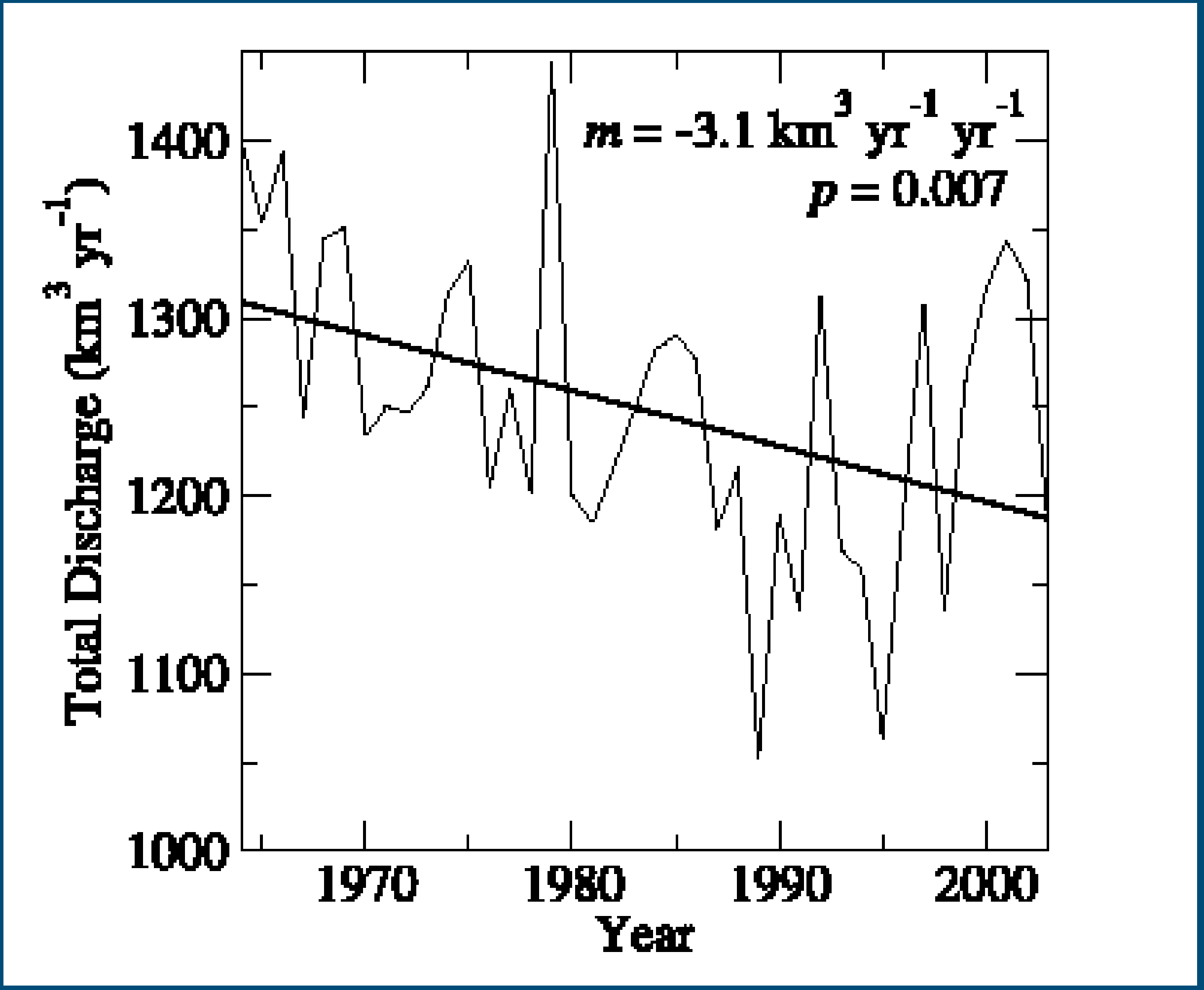
And what about river discharge?

- Streamflow integrates over the river's drainage area the local imbalance between precipitation, evaporation and storages: ideal for HC research!
- Unfortunately, many rivers are strongly influenced by human disturbance
- In literature, focus on high-latitude rivers draining to the Arctic and North Atlantic oceans

Trends in streamflow for high-latitude rivers

- *Wu et al*. (2005) predict, based on ensemble climate simulations, an increase in mean annual streamflow for Eurasian rivers, of the order of 1.8 ± 0.6 mBe yr^{-1}
- 1 Be (Bering) equals 10^3 km^3 yr^{-1}
- D*éry and Wood* (2005) report a decrease in mean annual streamflow for 64 Canadian rivers draining to the Arctic and NA oceans, of the order of 3 mBe yr^{-1}
- They found statistically-significant links with AO and ENSO

Déry and Wood (2005)



All this, needs further research...

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…which we will discuss in 4 groups

- Each group will develop a scientific methodology to test the hypothesis that during the 20th century there was (wasn't) a global intensification of the hydrological cycle;
- One spokes-person from each group will present the group's methodology (5 min)
- After the presentations, a plenary discussion will be organized.

IHC-1: the Trenberth method

- Trenberth (1998) used the global atmospheric water balance method to estimate the residence time of water in the atmosphere;
- The method uses long-term (monthly, yearly) and global average total precipitable water and precipitation;
- 1/λ is the *e*-folding time (or residence time).

$$\overline{\frac{\partial W}{\partial t}} = \overline{E} - \overline{P}$$

$$\overline{\frac{\partial W}{\partial t}} = -\overline{P}$$

$$\lambda = \overline{P} / \overline{W}$$

$$\overline{\frac{\partial W}{\partial t}} = -\lambda \overline{W}$$

$$\overline{W}(t) = \overline{W}(t_0) e^{-\lambda t}$$

IHC-2: the WVT method

- Bosilovich et al. (2005) developed the Water Vapor Tracers (WVT) method to estimate the residence time of atmospheric water;
- The method uses AGCMs that allow to trace the fate of (an initial volume of) water vapor;
- After 45 days the WVT have basically left the atmosphere and the model needs to be reset.

$$\frac{\partial q_T}{\partial t} = -\nabla_3.(q_T V) + \frac{\partial q_T}{\partial t_{turb}} + \frac{\partial q_T}{\partial t_{prec}}$$

q_T : 3D water vapor tracer

V : 3D wind field

$turb$: Denotes turbulent tendency; Not including ET

$prec$: Denotes precipitation tendency

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Comparison of the two methods