What do we need to know about mass transport and Earth dynamics for the nine benefit areas of GEO?

Hans-Peter Plag,
Nevada Bureau of Mines and Geology and Seismological Laboratory, University of Nevada, Reno, NV, USA

Anny Cazenave
LEGOS-CNES, Toulouse, France

Dork Sahagian
Earth and Environmental Sciences, Lehigh University, Bethlehem, PA, USA

Overview

- EOS, GEO, GEOSS and GGOS
- The Nine Benefit Areas of Earth Observations
- GEO User Requirements
- GGOS User Groups and Requirements
- Why Focus on Mass Transport and Dynamics?
- The Benefit Areas and Mass Transport
- The Benefit Areas and Dynamics
- Example: Water, the Global Water Cycle
- Example: Disasters, Geohazards
- How to Progress to get a Complete Overview of the Requirements?

EOS, GEO, GEOSS and GGOS

2002: World Summit on Sustainable Development in Johannesburg, South Africa:

Urgent need for coordinated observations relating to the state of the Earth

June 2003: G8 Meeting in Evian

affirmed importance of Earth Observations

July 2003: First Earth Observation Summit (EOS-I) in Washington, DC: 33 Countries+EC and 21 international Organisations:

- *Established the ad hoc Intergovernm. Group on Earth Observations (ad hoc GEO)*
- *Task of ad hoc GEO: initial 10 year Implementation Plan by February 2005*

April 2004: EOS-II in Tokyo, 43 Countries + EC plus 25 international organisations:

- Adoption of 'Framework Document': definition of **nine benefit areas for Earth observations**

February 2005: EOS-III in Brussels:

- Adopts the 10 Year Implementation Plan for a Global Earth Observation System of Systems (GEOSS)
- Establishes the Group on Earth Observations (GEO) with the task to implement GEOSS

EOS, GEO, GEOSS and GGOS

IAG is a Participating Organization in GEO

GGOS is one of the systems constituting GEOSS

The Nine Benefit Areas of Earth Observations

Second Earth Observation Summit (EOS-II) in Tokyo April 2004 identified nine Benefit Areas of Earth Observation:

- **Disaster**: reducing lost of life and property from natural and human-made disasters
- **Health**: understanding environmental factors affecting human health and well being
- **Energy resources**: improving management of energy resources
- **Climate**: understanding, assessing, predicting, mitigating, and adopting to climate variability and change
- **Water**: improving water resource management through better understanding of the water cycle
- **Weather**: improving weather information, forecasting, and warning
- **Ecosystems**: improving the management and protection of terrestrial, coastal, and marine ecosystems
- **Agriculture**: supporting sustainable agriculture and combating desertification
- **Biodiversity**: understanding, monitoring and conserving biodiversity

GEO User Requirements

Approach to User Requirements in the *ad hoc* GEO Phase:

- Subgroup on 'User requirements and Outreach': studies with UR examples
- Countries did UR studies (Canada, Netherlands, ...)
- For each benefit area:
  - a set of requirements in terms of quantities,
  - assessment of the current status of availability of observation

Recommendations in the GEOSS Reference Document:

- Establish and maintain a distinct and common user requirement database.
- Should be oriented on the CEOS/WMO database of user requirements and observation system capabilities.
- Database should provide a gap analysis mechanism.

GEO User Requirements

Parameter	1	2	3	4	5	6	7	8	9
Deformation	x								
Subsidence	x		x						
Strain	x								
Fields	x								
Field anomalies			x						
Groundwater	x			x	x				
Tides	x		x						
Sea level	x		x	x	x		x		
Ice									
Snow				x	x				
Moisture (air)	x				x	x	x		
Extreme weather			x			x			
Precipitation	x	x		x	x	x	x		
Soil moisture	x	x			x				
Glacier and Ice caps				x	x				
Water cycle variables				x	x	x	x	x	

Benefit areas:

1: Disaster
2: Health
3: Energy resources
4: Climate
5: Water
6: Weather
7: Ecosystem
8: Agriculture
9: Biodiversity

*Extracted from *GEO (2005)*.

GEO User Requirements

Quantities and status:

Deformation:	monitoring, 3-D, over broad areas	3
Subsidence:	maps	3
Strain:	strain and creep monitoring, specific features or structures	2
Fields:	gravity, magnetic, electric fields - all scales	3
Field anomalies:	Gravity and magnetic field anomaly data	2/3
Groundwater:	groundwater level and pore pressure	4-1
Tides:	coastal water levels	1
Sea level:	long-term changes, local, regional and global scales	2-1
Ice:	glacier and ice caps	2
Snow:	snow cover	2
Moisture (air)	moisture content of atmosphere/water vapor	2
Extreme weather	Extreme weather and climate event forecasts	3
Precipitation	Monitoring on all spatial and temporal scales	3-1
Soil moisture	Monitoring on local to regional scales, all temporal scales	3-1

Status classes:

0:	ok
1:	marginally acceptable accuracy & resolution
2:	could be ok within two years
3:	could be available in six years
4:	still in research

*Extracted from *GEO (2005)*.

GGOS User Groups and Requirements

Here we distinguish three classes of users:

Scientific users:

- geosciences
- global change and Earth system dynamics
- others

Earth Observation:

- Global Earth Observation System of Systems (GEOSS): Nine benefit areas
- Integrated Global Observing Strategy Partnership (IGOS-P): Several themes
- Non-geodetic applications (atmosphere, ionosphere)

Non-scientific users:

- many economic fields depend on
    * stable, accessible reference frame
    * easy access to positions
    * increasingly monitoring of processes

All three user classes addressed by GGOS2020

GGOS User Groups and Requirements

How approach user's needs?

The (convenient) view from the provider:

"The users needs what we can provide."

(Most likely true for Science,
but not for the nine Benefit Areas)

Why Focus on Mass Transport and Dynamics?

Chao (2003):

“After three decades and three orders of magnitude of advances, space **geodesy is poised for prime time in observing the integrated mass transports** that take place in the Earth system, from high atmosphere to the deep interior of the core. As such **space geodesy has become a new remote sensing tool**, in monitoring climatic and geophysical changes with ever increasing sensitivity and resolution.

The **transport of mass and energy are key processes that determine the dynamics of our Earth system**. The Earth system can be conveniently viewed through its components, so-called geophysical fluids - the atmosphere, hydrosphere, cryosphere, biosphere, lithosphere, and the deep interior of mantle and cores. All geophysical fluids undergo a host of mass transports for various reasons, external as well as internal. Studying these processes is undoubtedly a most interdisciplinary field in all of Earth sciences. **However, mass transport has not received due attentions.** “

Why Focus on Mass Transport and Dynamics?

Thesis: At the accuracy level of 1 ppb, the geodetic observing system is inherently an Earth system mass transport and dynamics observing system.

Rationale: Mass transport (in the fluid envelop) of the Earth

- changes local gravity;
- if in the upper layers of the solid Earth: leads to surface displacements;
- changes the external gravity field (if mainly horizontal)
- can result in a surface load, which
  - changes the shape of the Earth,
  - induces a secondary gravity signal,
  - changes the moment of inertia and thus Earth rotation;
- can be associated with changes in atmospheric and oceanic circulation and
  - affects angular momentum transfer,
  - changes Earth rotation.

Question: What phenomena/problems related to the nine benefit areas affect geodetic quantities at the 0.1 to 1 ppb level?

The Benefit Areas and Mass Transport

(The list of questions is not intended to be complete!**)**

Disaster:

- Landslides: submarine landslides (excitation of tsunamis):
  - low-latency detection is an unsolved problem;
  - could gravity field measurements help?
- Tsunamis detection with low-latency:
  - can land-based gravity/displacement measurements help?
  - gravity field variations?
  - detection of sea surface displacements?
- Earthquakes:
  - changes in crustal density: how much is the gravity signal?
  - Surface displacements constrain the seismic moment in near-real time.
- Volcanic eruptions:
  - subsurface mass transport: surface displacements and gravity signal
  - mass ejected by large eruptions in the atmosphere?
  - mass ejected as lava?

The Benefit Areas and Mass Transport

Health:
- water cycle variables (soil moisture, ect.)

Energy (Oil, gas, coal, other resources):
- Exploration (gravity field anomalies)
- Local and regional signals caused by exploitation (gravity and deformation)
- What are the mass transports associated with these resources?

Climate:
- permafrost:
  - what is the change in mass or is there none?
  - When do intermediate lakes disappear?

Water:
Global and regional hydrological cycle:
- annual and secular fluxes between reservoirs
- intraannual variability
- Where are the uncertainties? How to reduce them?

The Benefit Areas and Mass Transport

Weather:

- extreme precipitation:
  - what mass transport is involved?

Ecosystem:

- What mass transport is involved in the major biogeochemical cycles?
- Net Primary Production?
- sea level, water cycle variables

Agriculture:

- Sedimentation:
  - sediment transport has fluctuated very much over the last few hundred years. How much?

Biodiversity: ?

The Benefit Areas and Dynamics

Dynamics and geodesy (in relation to the benefit areas):

- Earth rotation is affected by atmospheric and oceanic circulation (angular momentum transfer);
- Earth rotation is affected by mass relocations (changes in moment of inertia);
- Kinematics of the Earth's surface is related to dynamical processes in the solid Earth.

Disaster:

- pre-, co- and post-seismic deformations and gravity signals
- early warning: high-frequency, low-latency observations of geodetic quantities, what can they help
- constraints from Earth rotation on mass transport (e.g. during a large earthquake)

The Benefit Areas and Dynamics

Climate:

- Changes in the long-term angular momentum of the atmosphere and ocean
- validation of climate models on the basis of geodetic quantities
- validation/comparison of observational datasets, particularly reanalysis results
- ENSO

Weather:

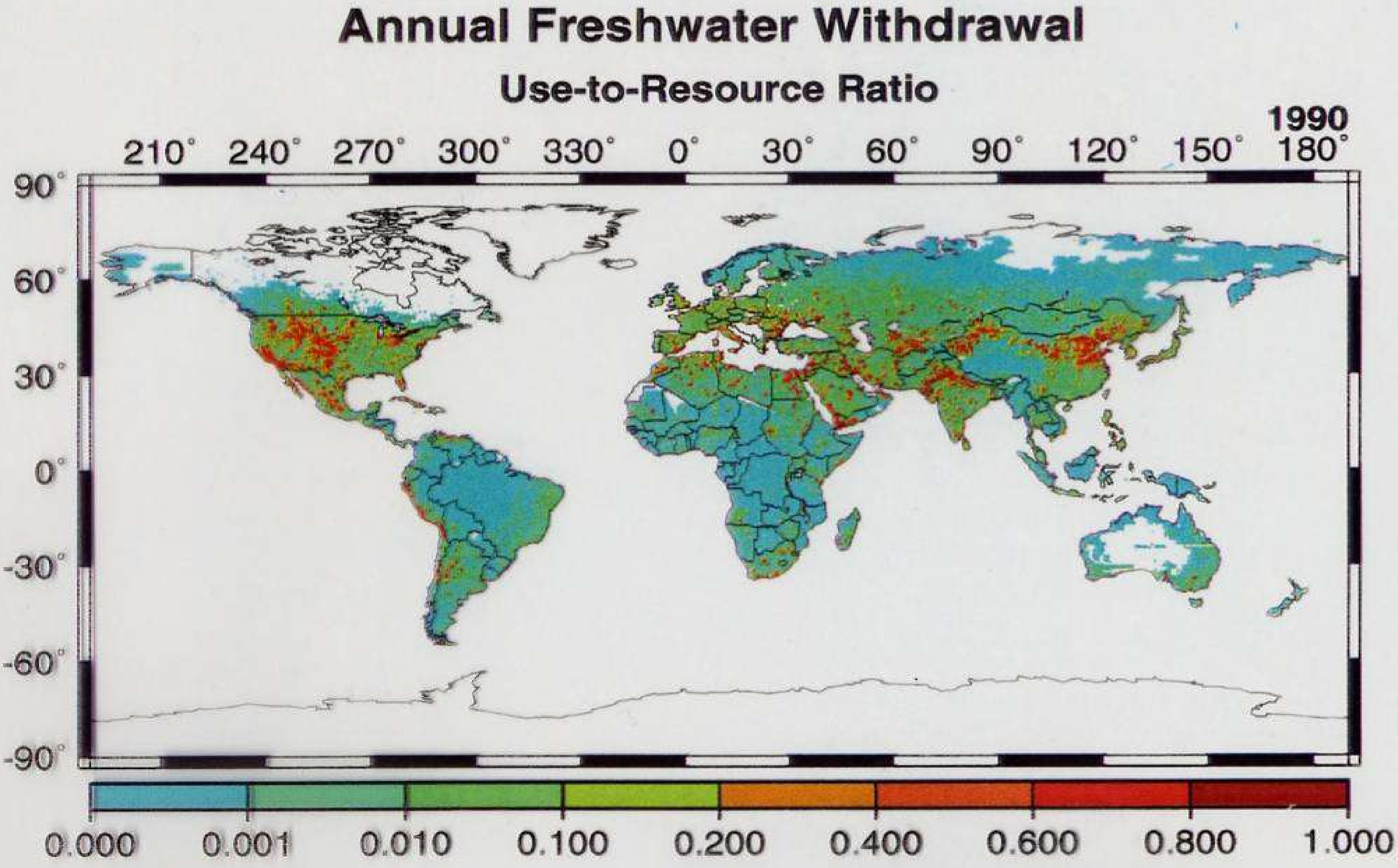
- Dynamical effects of extreme events (hurricanes, storm surges, floods)?

Water: Global Water Cycle

Water:

Improving water resource management through better understanding of the water cycle

Water: Global Water Cycle



WATER MANAGEMENT: A PROBLEM IN BUDGETTING WITH INADEQUATE DATA

SUPPLY (INCOME)

PRIMARY SOURCE:
PRECIPITATION

RESERVE (SAVINGS

USE (EXPENDITURE)

IRRIGATION FOR
FOOD PRODUCTION

DRINKING FOR
SURVIVAL

WATER TO MAINTAIN
ECOSYSTEM HEALTH

**IF EXPENDITURES > INCOME + SAVINGS
FOR THE LONG TERM THERE IS
A MAJOR PROBLEM!!**

From Lawford, 2006

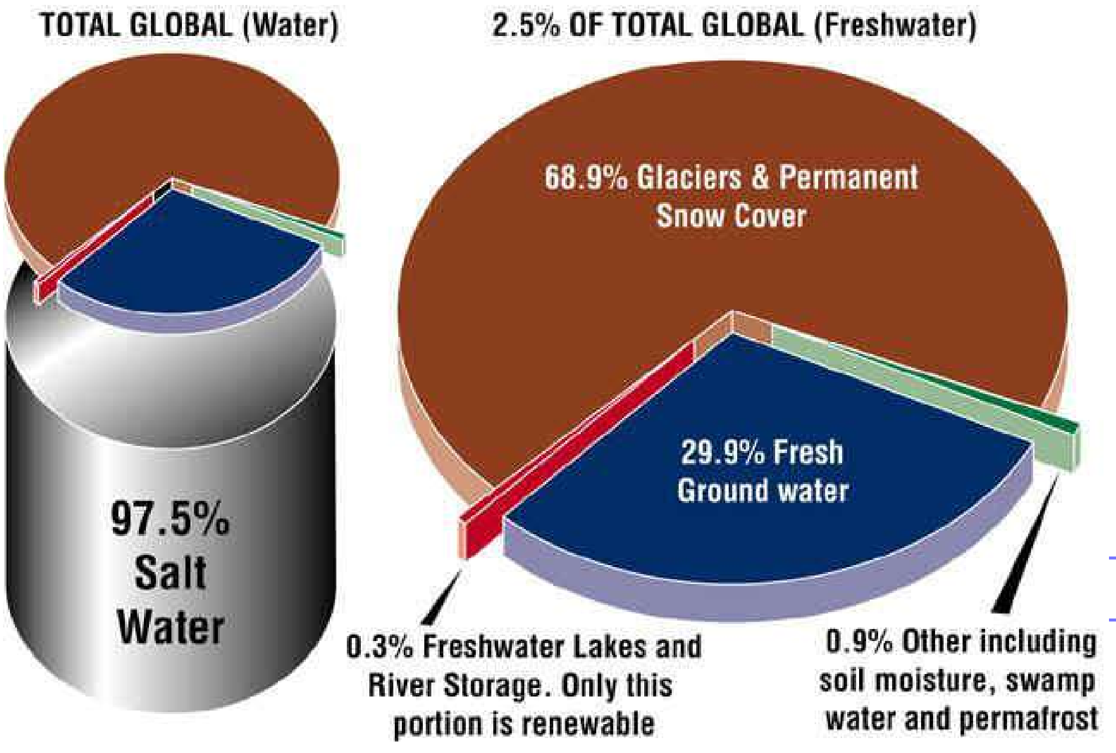
Water: Global Water Cycle

Lawford (2006), IGOS-P Theme on Observation of the water cycle, IGWCO:
“It is our view that we are on the threshold of a new epoch in water management provided we can mobilize our capabilities to observe together with our understanding and ability to model the global water cycle.”

Factors supporting the development:

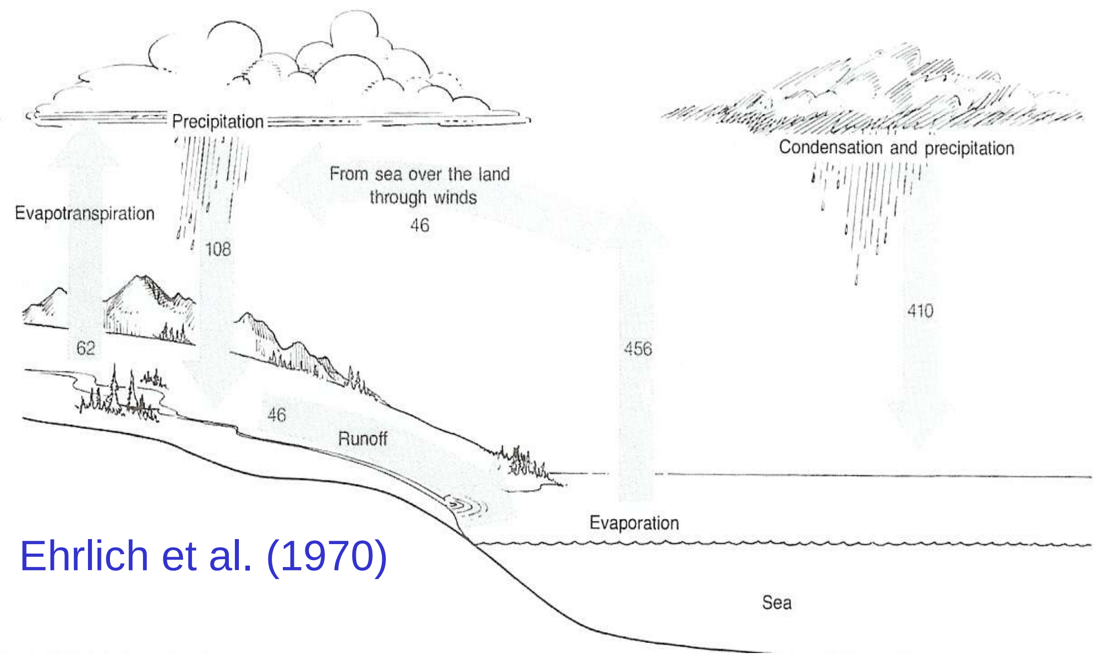
- expanding capability to **observe** hydrometeorological variables **from space**
- evolving capability to assimilate observations and predict water cycle
- increasing demands on national and regional water sources
- communities which seeks to address the need for security of water supply, reliable water quality, and responsible use of ground water with an integrated water resources management

Water: Global Water Cycle

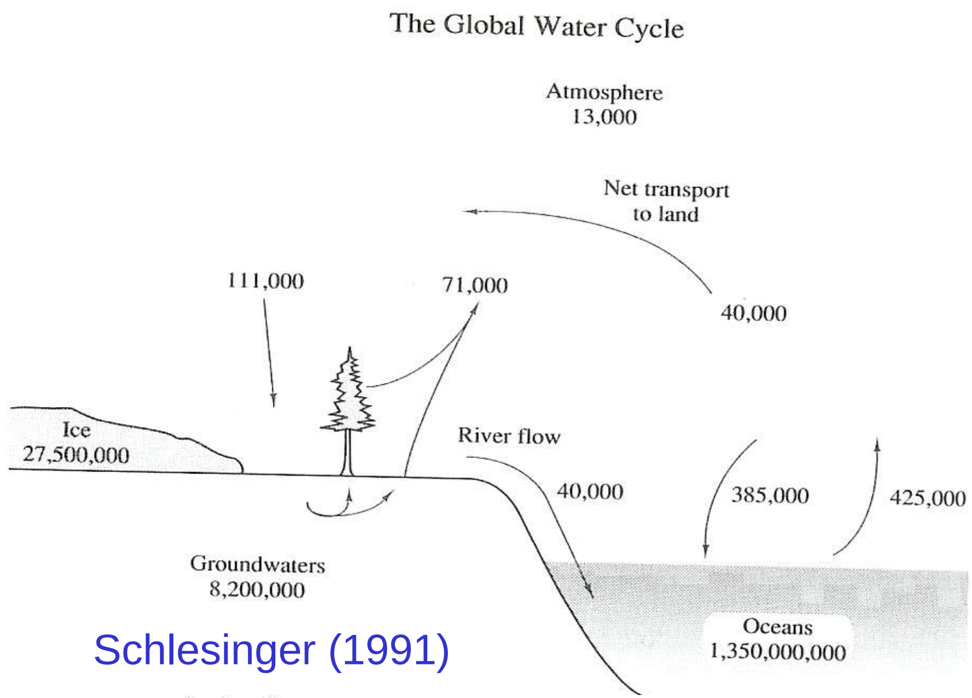


Water of Hydrosphere	Period of renewal
World Ocean	2500 years
Ground water	1400 years
Polar ice	9700 years
Mountain glaciers	1600 years
Ground ice of the permafrost zone	10000 years
Lakes	17 years
Bogs	5 years
Soil moisture	1 years
Channel network	16 days
Atmospheric moisture	8 days
Biological water	several hours

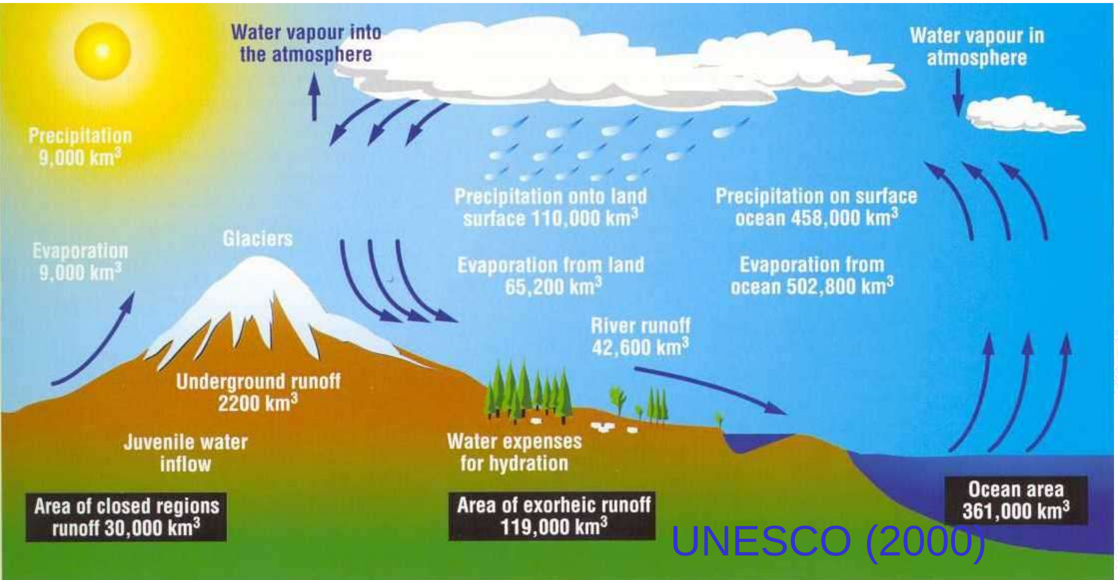
Water: Global Water Cycle



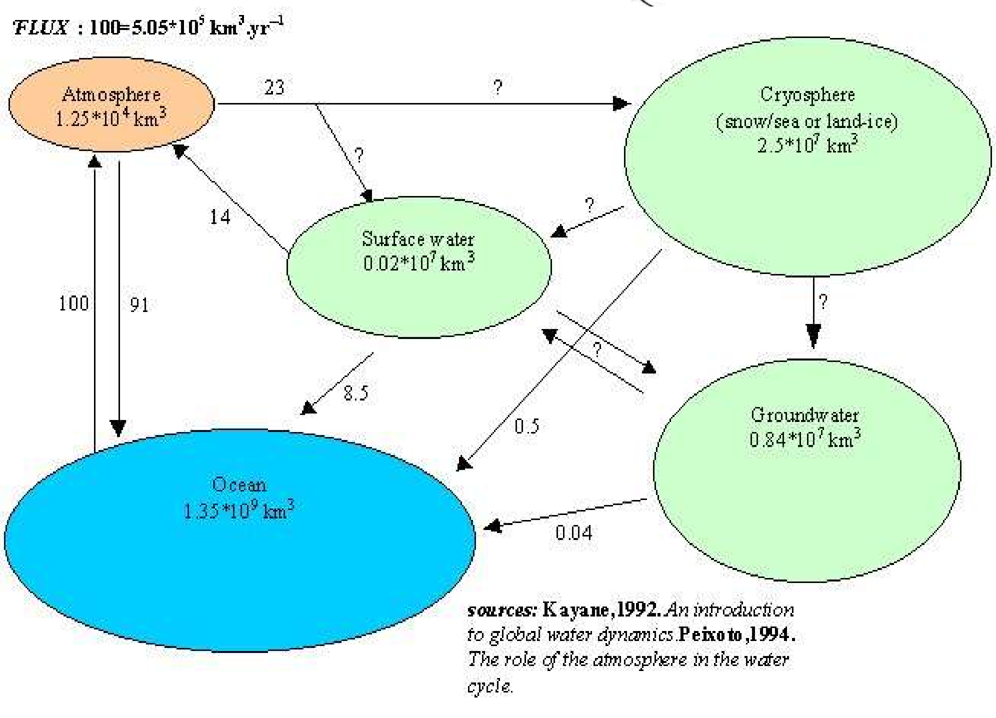
Ehrlich et al. (1970)



Schlesinger (1991)



UNESCO (2000)



Global hydrological cycle and waterbalance. (Ovals are reservoirs, arrows are fluxes)

Water: Global Water Cycle

Fluxes in 1000 Gt/yr

Sources	Ehrlich et al. (1970) Schlesinger (1991) UNESCO (http://www.unesco.org/science/waterday2000/Cycle.htm) unidentified				
Reservoir	Ocean	Atmosphere	Land	Groundwater	Cryosphere
		456		n.a.	n.a.
Ocean	-	425		n.a	n.a
		503		?	-
		505	-	-	
	410		108	n.a	n.a
Atmosphere	385	-	111	n.a	n.a
	458		110	n.a	n.a
	460		116(?)	-	?
	46	62			
Land	40	71	-	n.a	n.a
	45	65		n.a	n.a
	43	71		?	-
	n.a.	n.a.	n.a		n.a
Groundwater	n.a.	n.a.	n.a	-	n.a
	2.2	-	-		-
	0.2	-	?		-
	n.a.	n.a.	n.a	n.a	
Cryosphere	n.a.	n.a.	n.a	n.a	-
	n.a.	n.a.	n.a	n.a	
	2.5	?	?	?	

Water: Global Water Cycle

$$0 = \dot{M}_{\mathrm{O}} + \dot{M}_{\mathrm{A}} + \sum_{i=1}^{8} \dot{M}_{\mathrm{T}_i} + \sum_{j=1}^{3} \dot{M}_{\mathrm{C}_i}.$$

O:	Ocean
A:	Atmosphere
t1:	surface water (rivers, lakes, and land surface)
t2:	soil moisture
t3:	groundwater
t4:	snow
t5:	water stored in vegetation
t6:	water stored in the interior of the solid Earth
t7:	man-made reservoirs
t8:	rice fields
c1:	continental glaciers
c2:	Greenland ice sheet
c3:	Antarctic ice sheet

$$\vec{M}(t) = \vec{M}(t_0) + \int_{t_0}^{t} F(t) \cdot \vec{u} dt$$

$$\vec{M}^T = (M_{\mathrm{O}}, M_{\mathrm{A}}, M_{\mathrm{T}_1}, ..., M_{\mathrm{T}_7}, M_{\mathrm{C}_1}, ..., M_{\mathrm{C}_1})$$

$$\vec{u}^T = (1, ..., 1).$$

F: Matrix containing all fluxes.

Water: Global Water Cycle

Some questions related to the Water cycle (Strategic Plan for the U.S. Climate Change Science Program; Final Report, July 2003):

What are the **mechanisms and processes** responsible for the maintenance and variability of the water cycle?

Are the **characteristics** of the cycle **changing** and, if so, to what extent are human activities responsible for those changes?

How do **feedback processes** control the interactions between the global water cycle and other parts of the climate system (e.g., carbon cycle, energy), and how are these feedbacks changing over time?

What are the key **uncertainties in seasonal to interannual predictions** and long-term projections of water cycle variables, and what improvements are needed in global and regional models to reduce these uncertainties?

What are the consequences over a range of space and time scales of water cycle variability and change for human societies and ecosystems, and how do they **interact with the Earth system to affect sediment transport and nutrient and biogeochemical cycles**?

Water: Global Water Cycle

Some Examples

Water: Global Water Cycle

Lake level variations: How much groundwater is affected?

Simple approach:

$$\delta V = \frac{A}{A_0} \cdot \frac{\xi}{2} \cdot h$$

A_0: area of the lake
A: area of affected groundwater level
ξ: the mean porosity of the ground around the lake
h: Lake level change

Lake Aral:
A/A0 = 25
Xi = 0.3
delta V = 25*0.3/2 V = 3V

Water: Global Water Cycle

Lake level variations: How much groundwater is affected?

Lake Mead (USA):

Over 5 years, lost 25 m in lake level = 6 qkm

Assumptions:

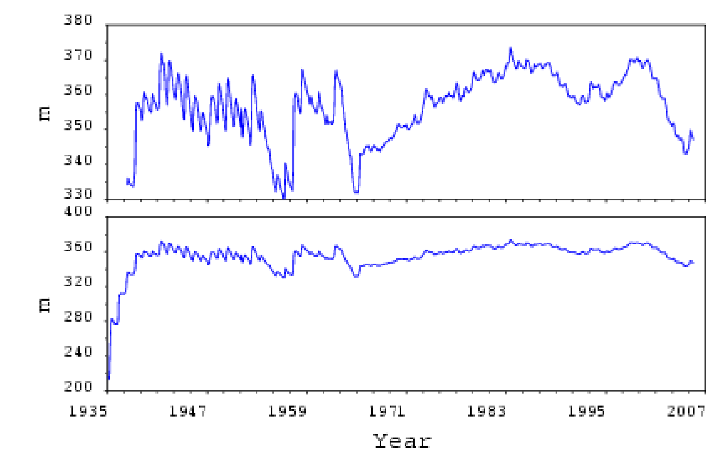
A/A0 = 4,

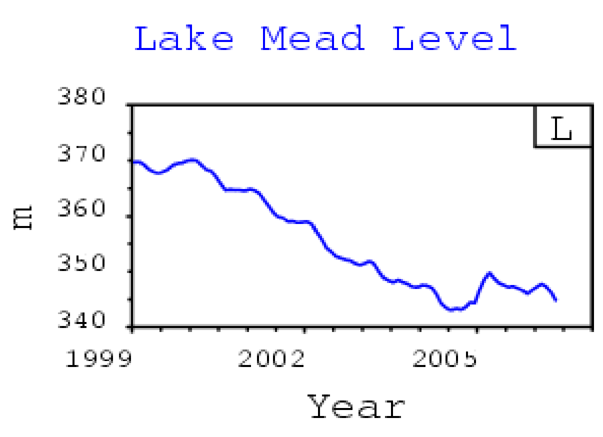
Xi = 0.2,

Effect of dam: -25%:

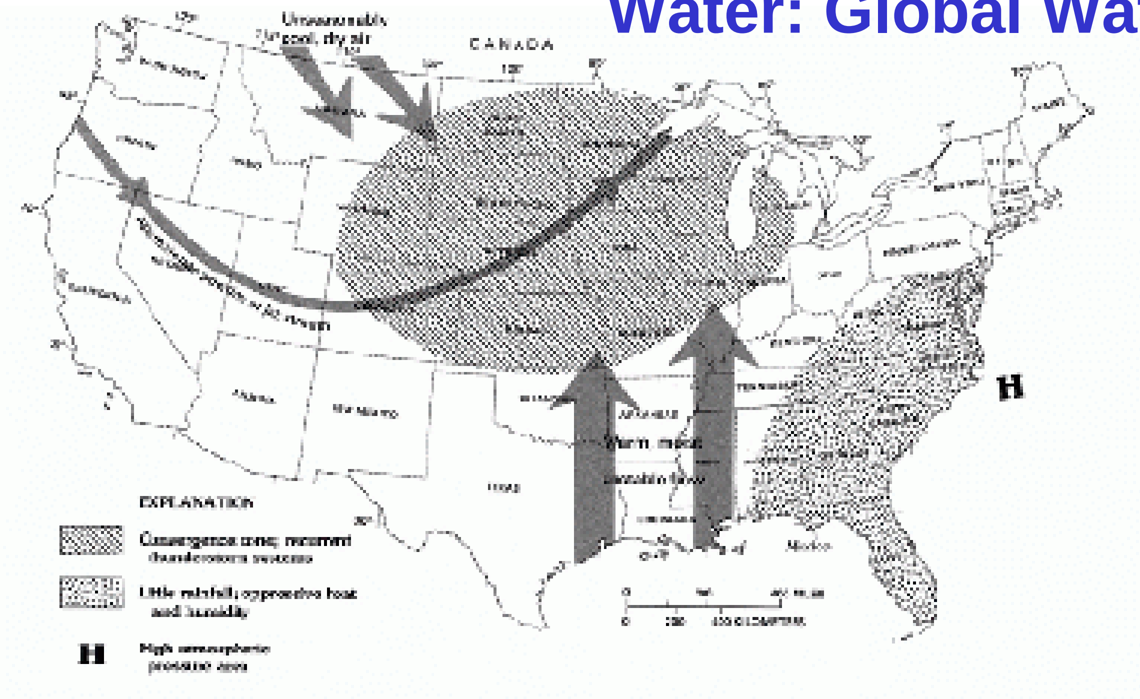
delta V = 4 x 0.2 / 2x0.75 = 0.3 V (0.3+-0.2)

Groundwater: 0.6 to 3 qkm (?)





Water: Global Water Cycle



Flooding: How long does the anomaly last?

Example: The 1993 Mississippi River Floods

Water: Global Water Cycle

What has been achieved?

Water: Global Water Cycle

Annual amplitude (mass over total domain) in Gt.

Sources:

1: Wu et al. (2006)

2: Blewitt and Clark (2003)

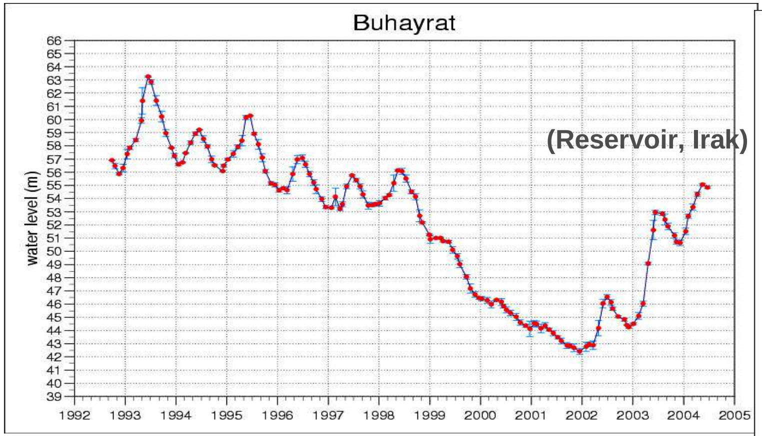
3: Chambers et al. (2004)

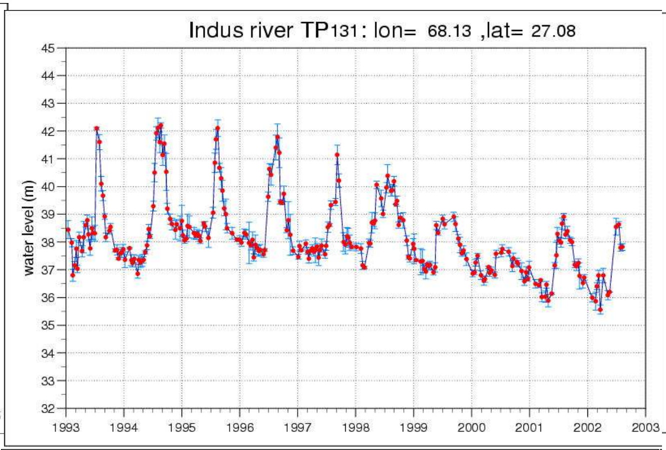
	Technique	Atmosphere+Ocean	Ocean	Antarctica	Greenland
1	GPS/OBP	2772	1440		
1	GPS/OBP/GRACE	3240	2304	552	99
1	Supplemented GRACE	3132	2376	842	147
1	Supplemented GRACE+ATM			193	83
2	GPS		3000		
3	GRACE		3024		

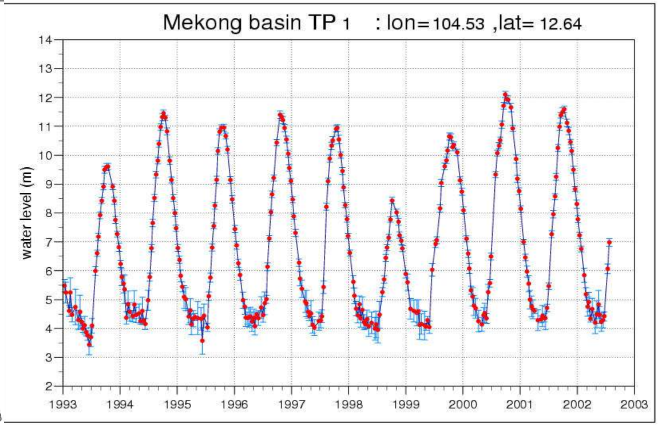
Annual ocean mass variation on the order of

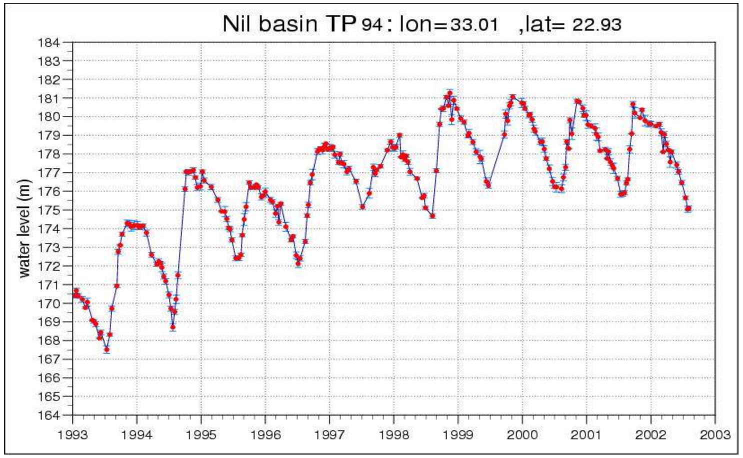
- 1% of ocean-atmosphere flux,
- 10% of the ocean-land flux

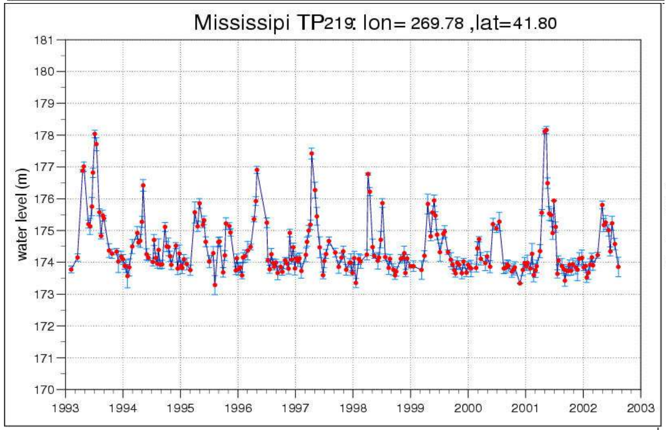
Water: Global Water Cycle

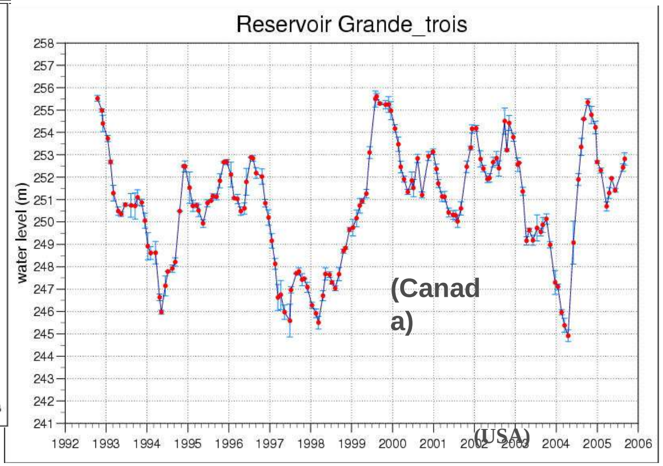


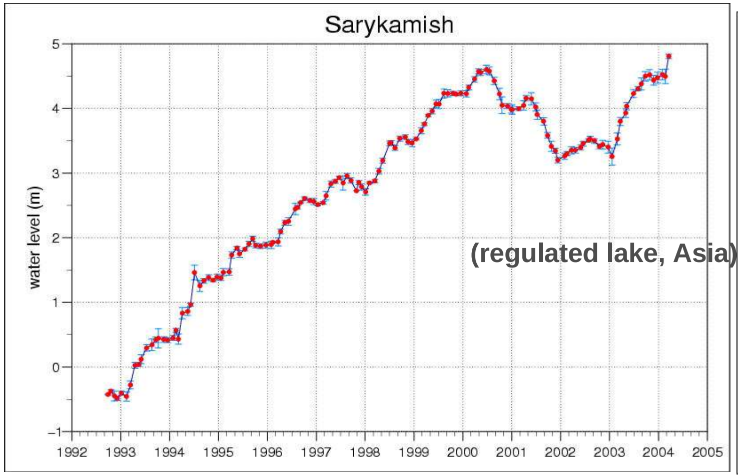


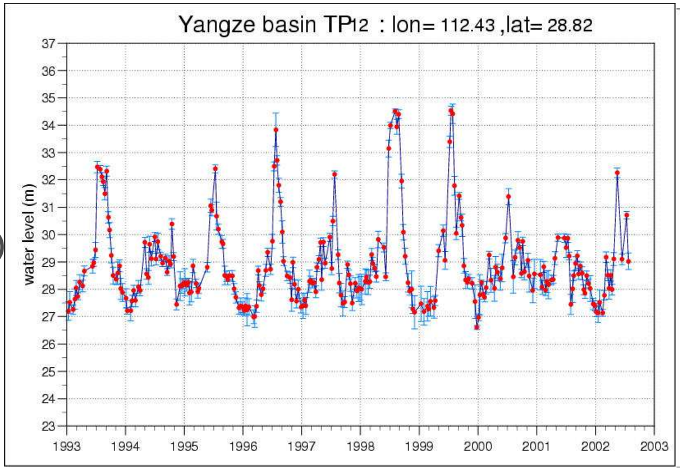


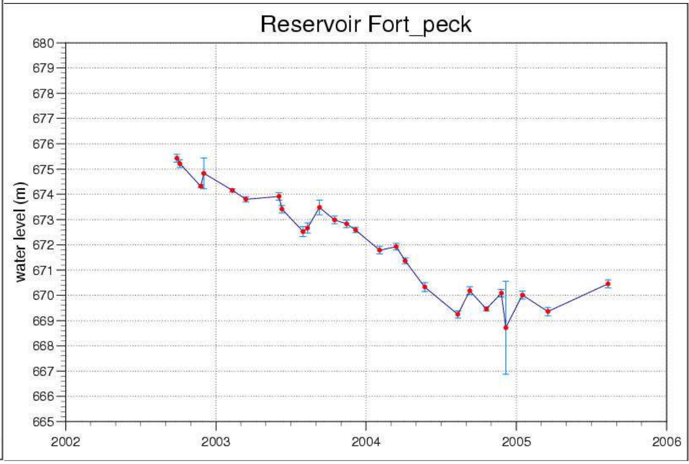




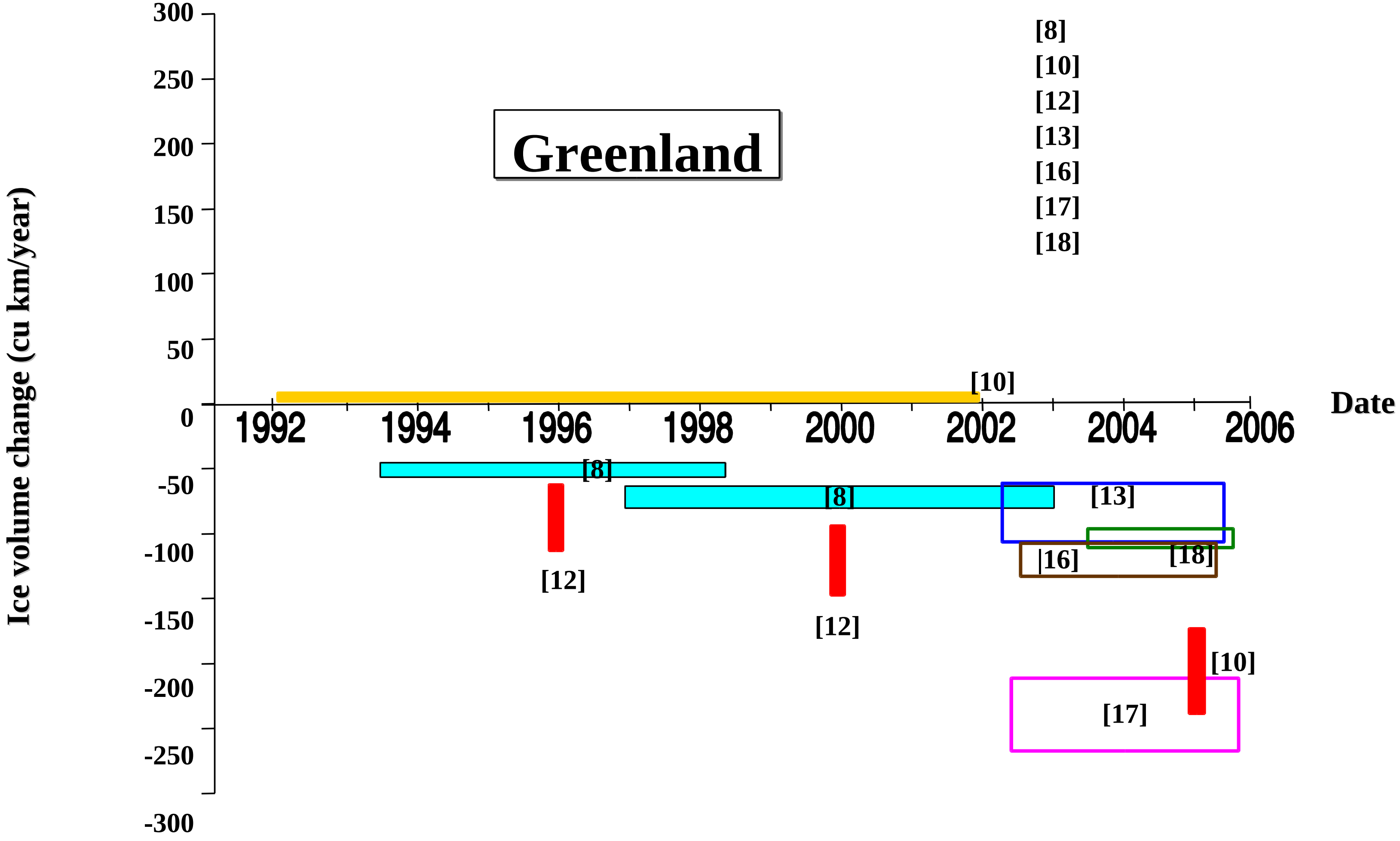




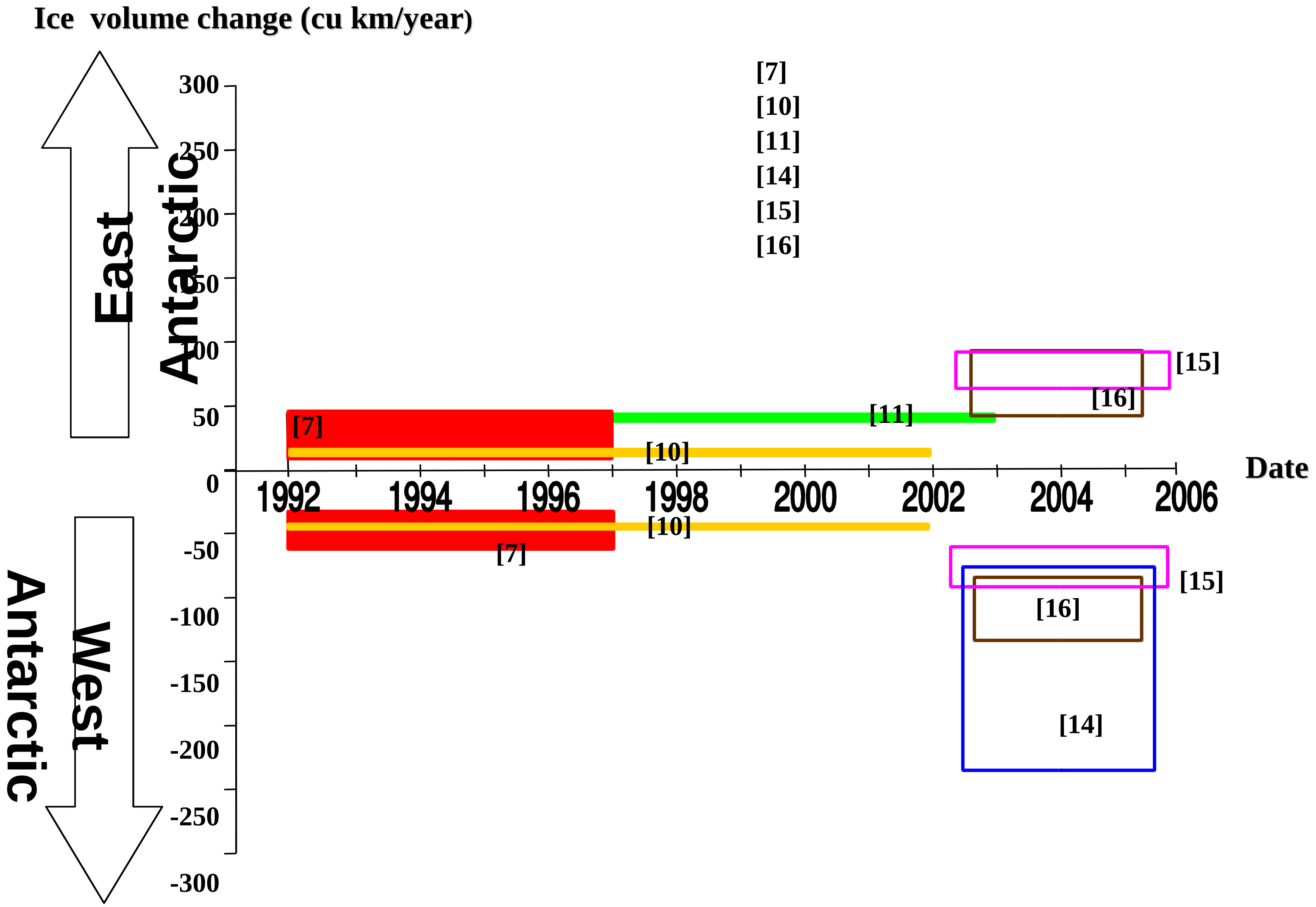




Water: Global Water Cycle



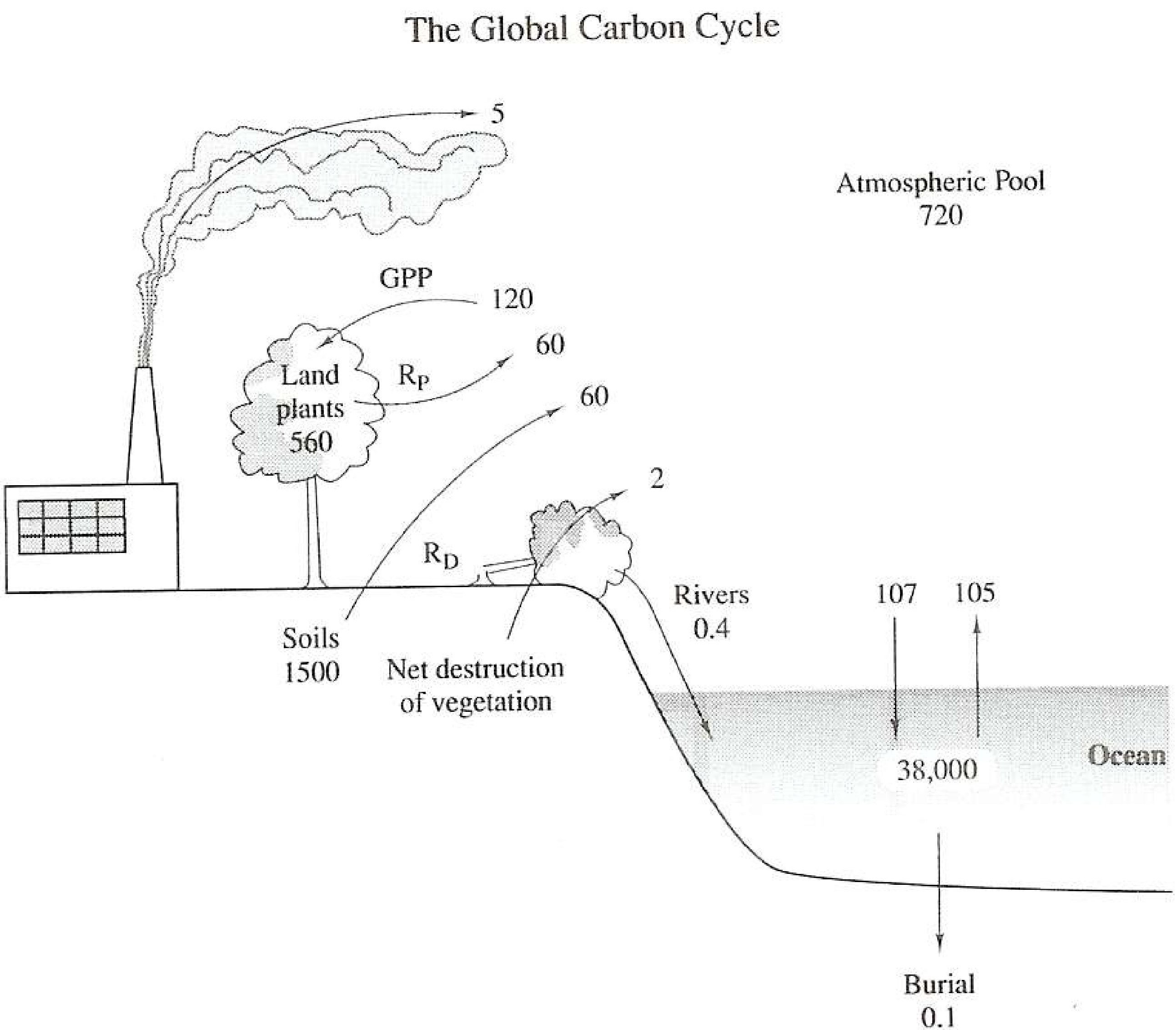
Water: Global Water Cycle



Other Global BioGeoChemical Cycles

Global Carbon Cycle

Pools in Gt C and fluxes in Gt C/yr.



Carbon: Fluxes are on the <1E-3 of the Water cycle fluxes.

Nitrogen, Phosporous, Sulfur Cycles: Fluxes on the 1E-6 of the Water cycle fluxes.

Disasters, Geohazards

Volcanic eruptions:

Ejected mass:
Krakatau: about 9 qkm of rock erupted
Mt. St. Helens: about 2.5 qkm

Comparable to Lake Mead water level variations, though on shorter time scales.

Landslides:

Stromboli, December 2002:
0.005 qkm

Cumbre Vieja Volcano, La Palma:
150 – 500 qkm
(*Ward and Day*, *2002*).

How to Progress to get a Complete Overview of the Requirements?

URs: Geoid and Gravity field

Application	Accuracy Geoid (cm)	Accuracy Gravity (mGal)	Spatial Resolution half wavelength (km)
Oceanography:			
Short scale	1-2		100 km
	0.2		200 km
Basin scale	~ 0.1		1000 km
Solid Earth:			
Lithosphere and upper mantle density structure		1-2	100 km
Continental lithosphere			
– Sedimentary basins		1-2	50-100 km
– Rifts		1-2	20-100 km
– Tectonic motions		1-2	100-500 km
– Seismic hazards		1.0	100 km
Ocean lithosphere and interactions with asthenosphere		0.5 - 1.0	100-200 km
Geodesy:			
Levelling by GPS	1.0		100-1000 km
Unification of worldwide height systems	1.0		100-20000 km
Inertial navigation system		~ 1-5	100-1000 km
Orbits (1 cm radial orbit error for altimetric satellites)		~ 1-3	100-1000 km
Ice sheets:			
Rock basement		1-5	50-100 km
Ice vertical movements	2.0		100-1000 km
Sea-level change:	Many of the above applications, with their specific requirements, are relevant to sea-level studies		

5

Drinkwater et al. (2003)

How to Progress to get a Complete Overview of the Requirements?

Main mass transport on time scales up to decades is in the global water cycle.

Extreme geohazards (landslides, volcanic eruptions, large earthquakes) could be significant.

Water cycle:

- Large uncertainties in fluxes between reservoirs (intraannual, annual, interannual, trends)
- Some transport is vertical: not seen from space

Understanding the requirements:

- Better database of what is known about mass transport
- Forward modeling with integrated model to get the signature in Earth shape, gravity field and rotation