Reservoirs & fluxes of H_2O on the Earth:

Figure 1.1 from Berner summarizes the fluxes between the various surface reservoirs — this is known as the hydrological cycle.

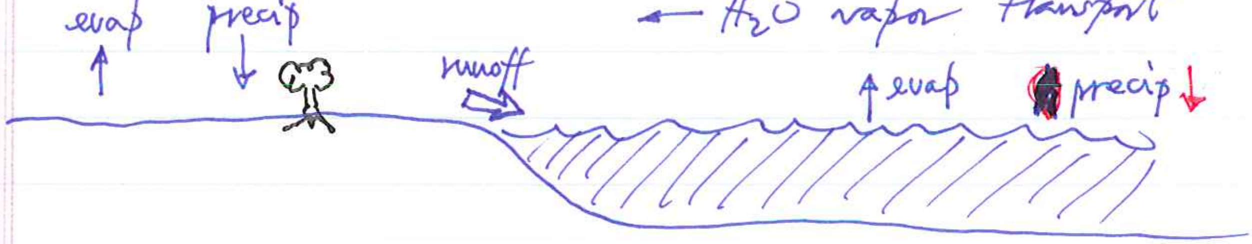
The fluxes are in $\frac{10^6 \text{ km}^3}{\text{yr}}$

Can convert this to an equivalent rainfall rate, spread over the ⊕'s surface

$$\frac{10^6 \text{ km}^3/\text{yr}}{4\pi (6371)^2 \text{ km}^2} = 2 \cdot 10^{-3} \frac{\text{km}}{\text{yr}} = 2 \text{ m/yr}$$

actually 1.96

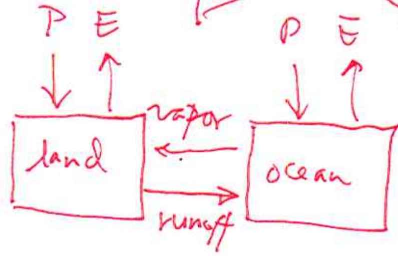
So, multiply by 2000 get the equivalent rainfall rate in mm/yr



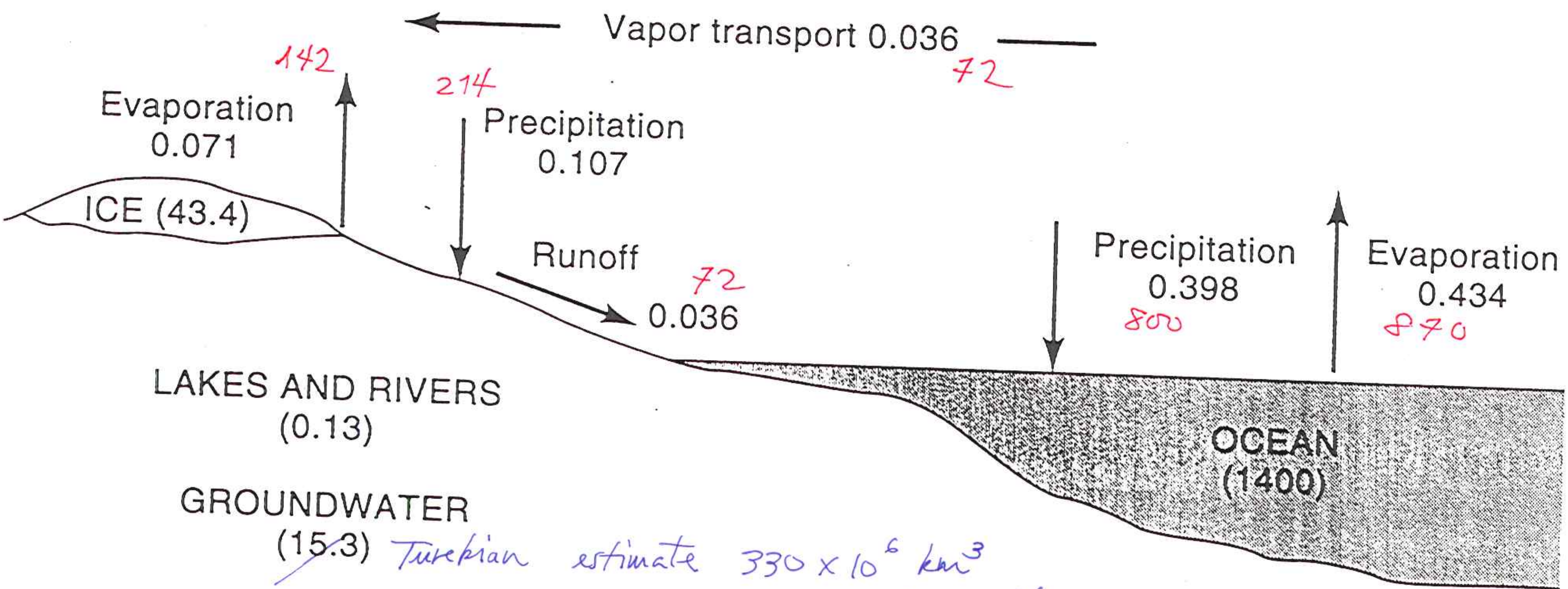
Which of these can most easily be measured?

Precipitation and runoff in streams are the easiest

SKETCH THIS ON BLACKBOARD



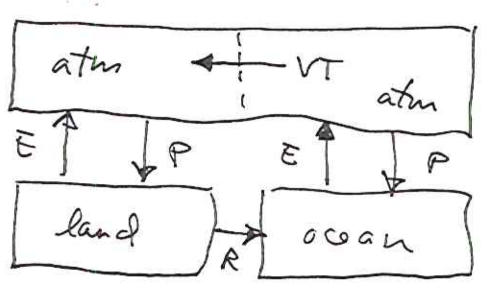
red: worldwide rainfall equivalent in mm/yr



Turekian estimate 330×10^6 km^3 seems more reasonable

Figure 1.1 The hydrologic cycle. Numbers in parentheses represent inventories (in 10^6 km^3 = 10^{18} kg) for each reservoir. Fluxes are in 10^6 km^3/yr (10^{18} kg/yr). (Data from Table 1.1 and NRC 1986.)

better box model



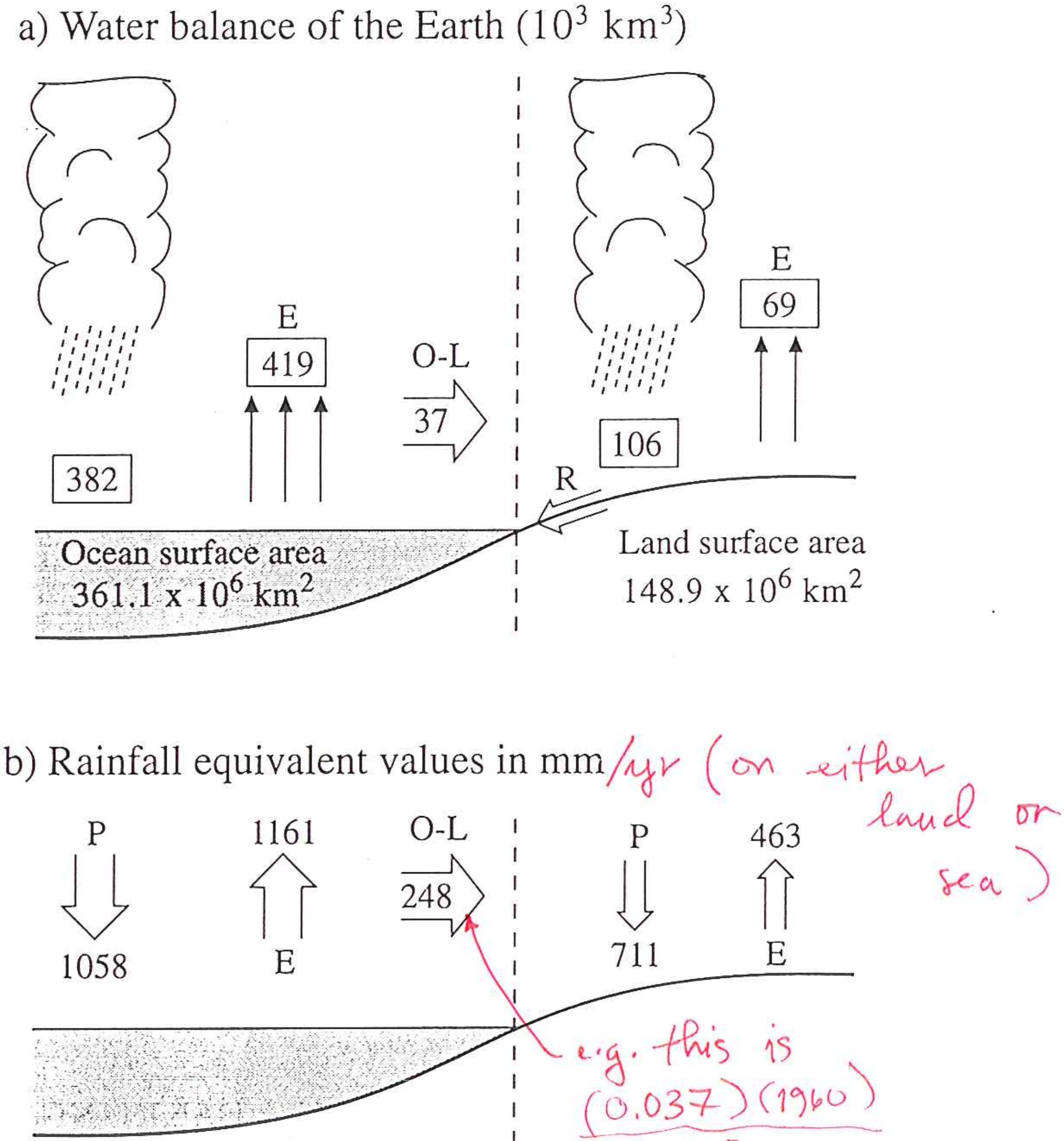


Figure 4.13 Estimated component values of the water balance of the Earth calculated by Mather for 1969 (data source Jaeger, 1983). E, evaporation; P, precipitation; R, runoff; O-L, ocean to land surface

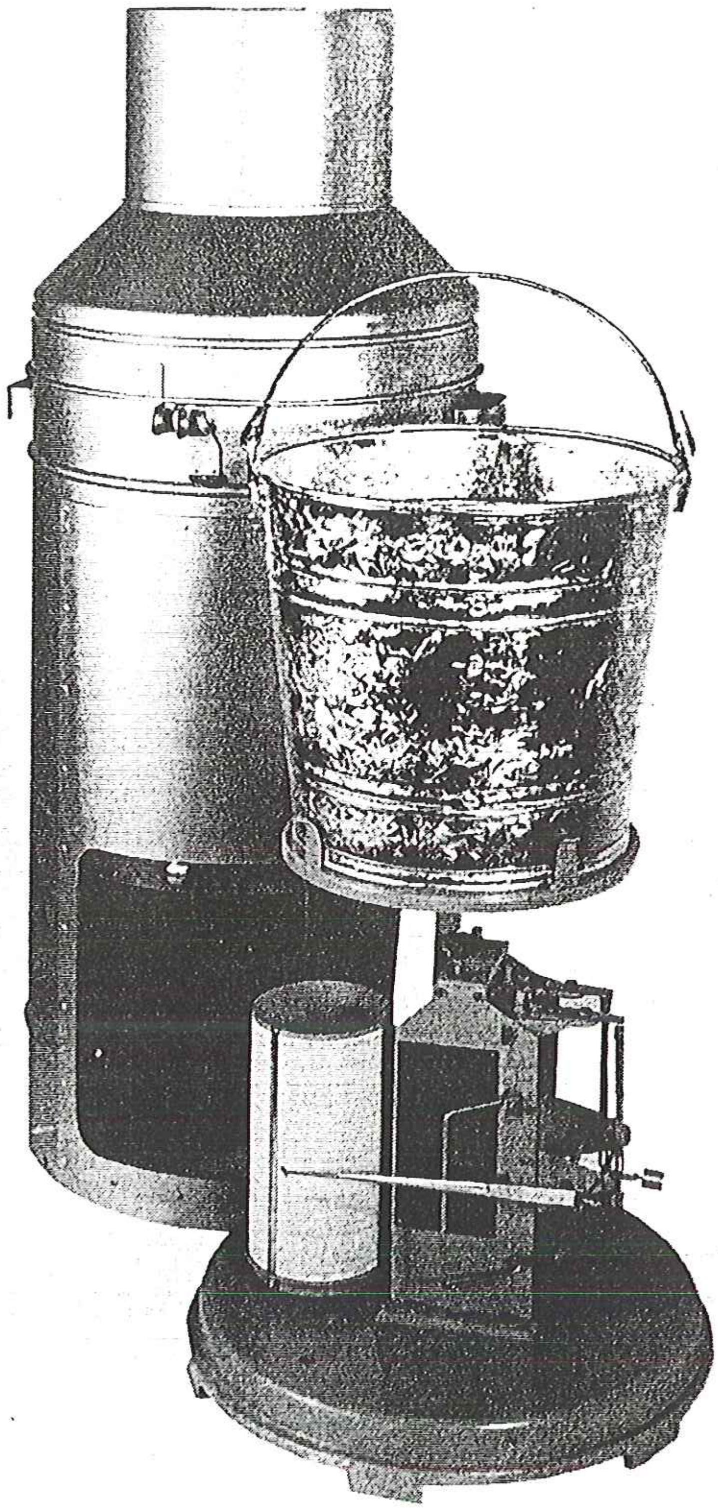


Figure 4.8 Recording, weighing-type precipitation gage (source: National Weather Service).

Figure 4.10 Locations where precipitation is regularly measured in the contiguous United States (source: National Weather Service).

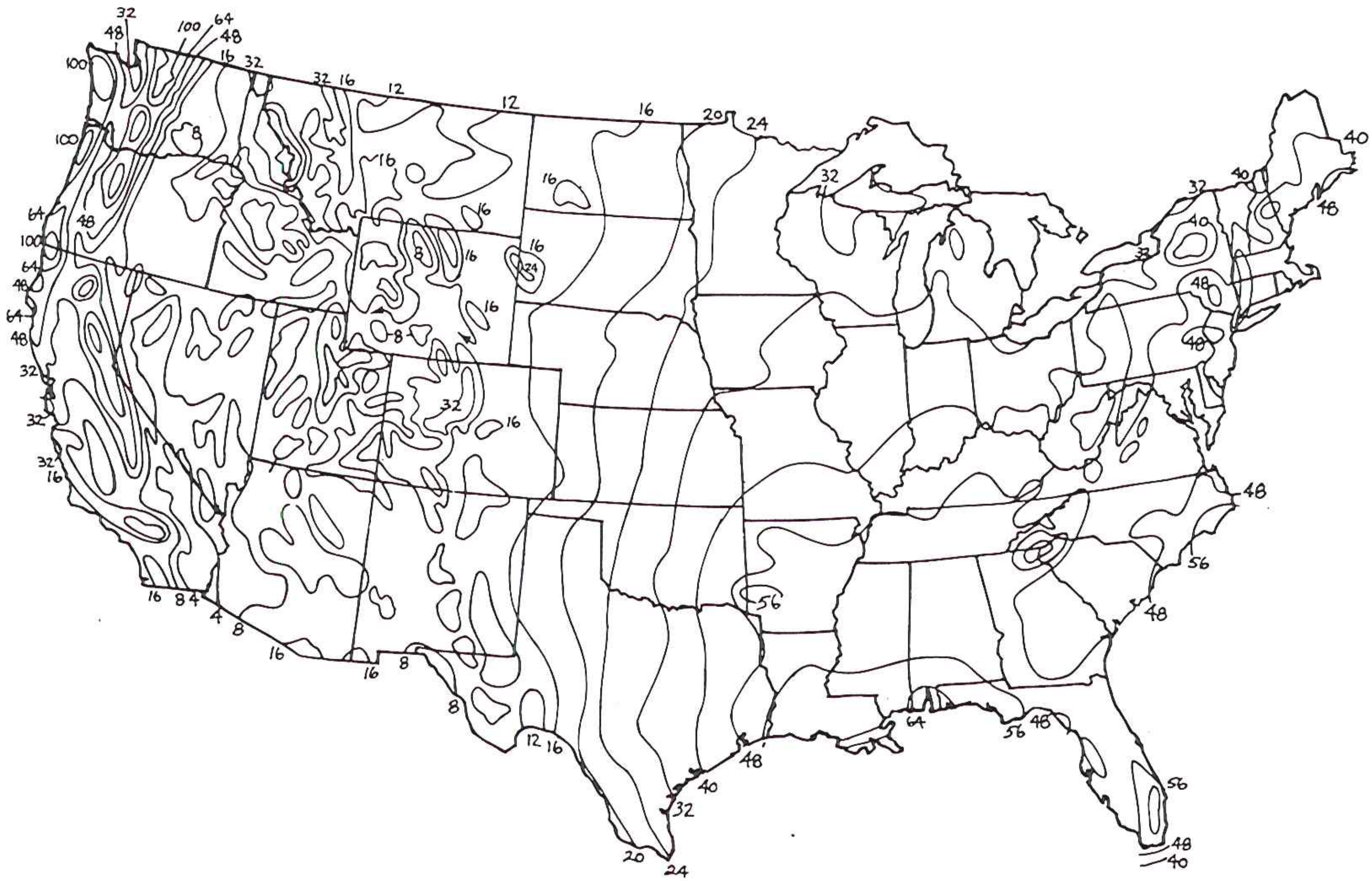


Figure 4.11 Mean annual precipitation in the United States (source: National Weather Service).

inches / year

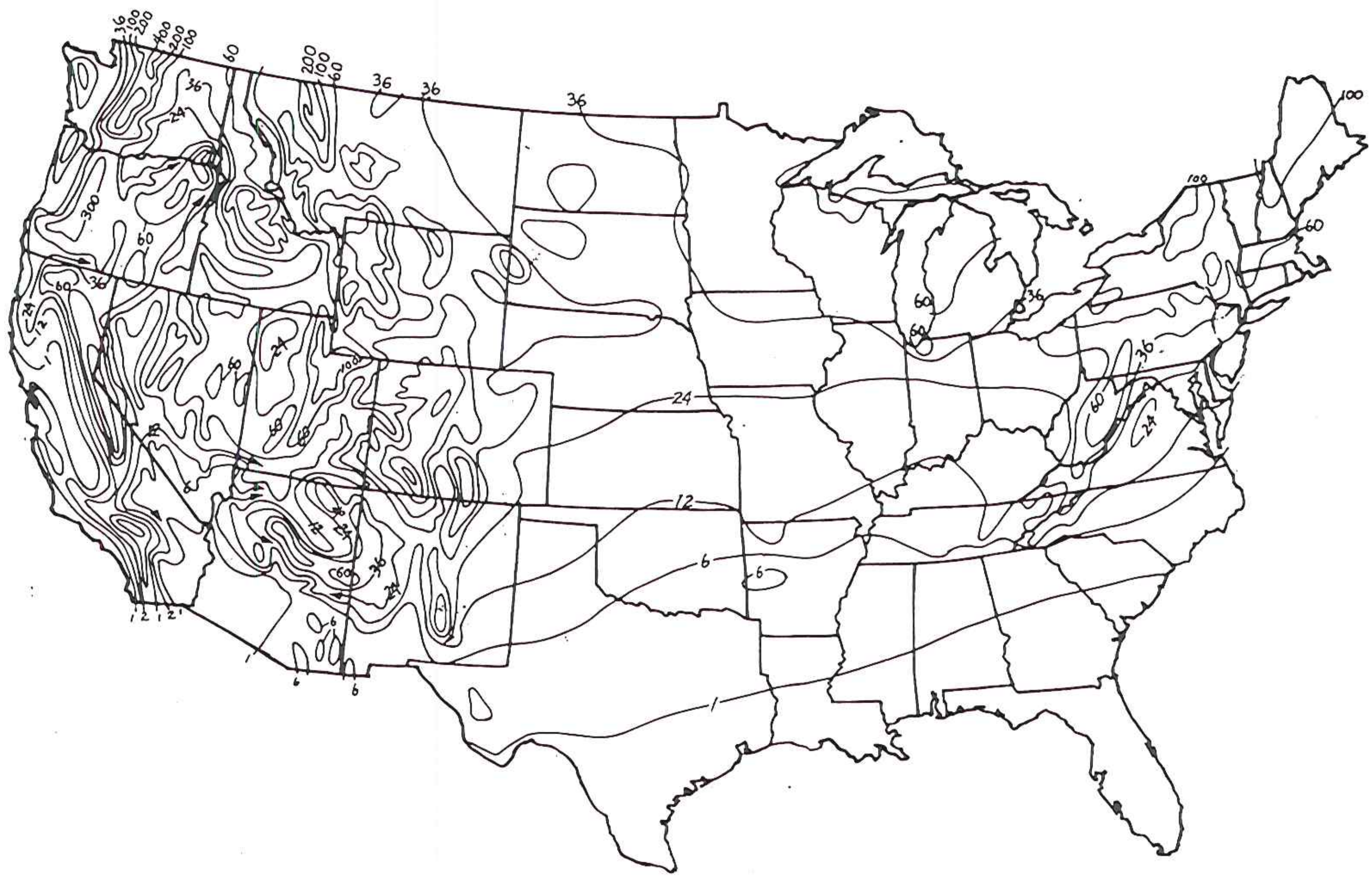


Figure 4.16 Mean annual snowfall (inches) in the United States (source: National Weather Service).

skiers take note

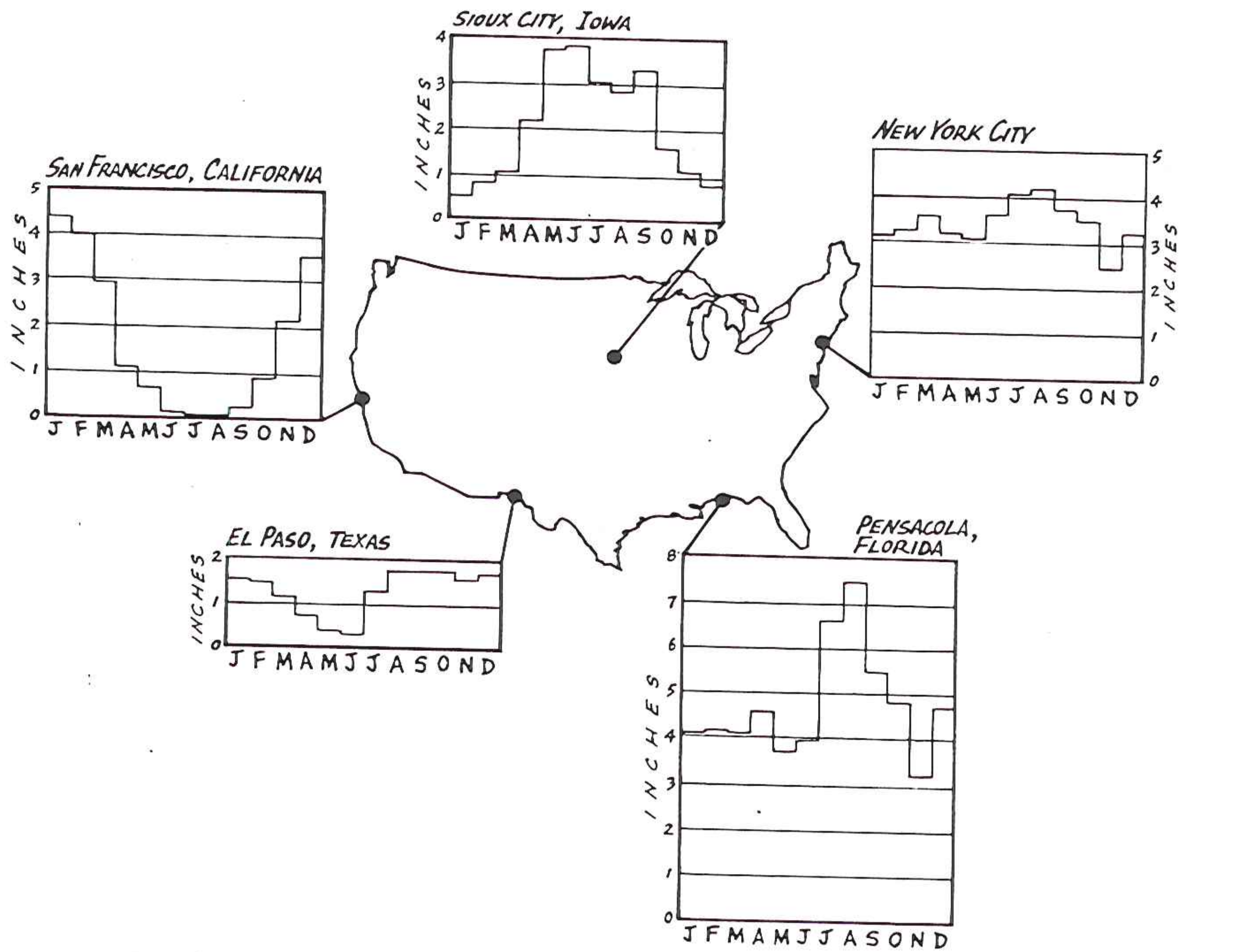


Figure 4.12 Regional precipitation patterns in the contiguous United States (data from the National Weather Service).

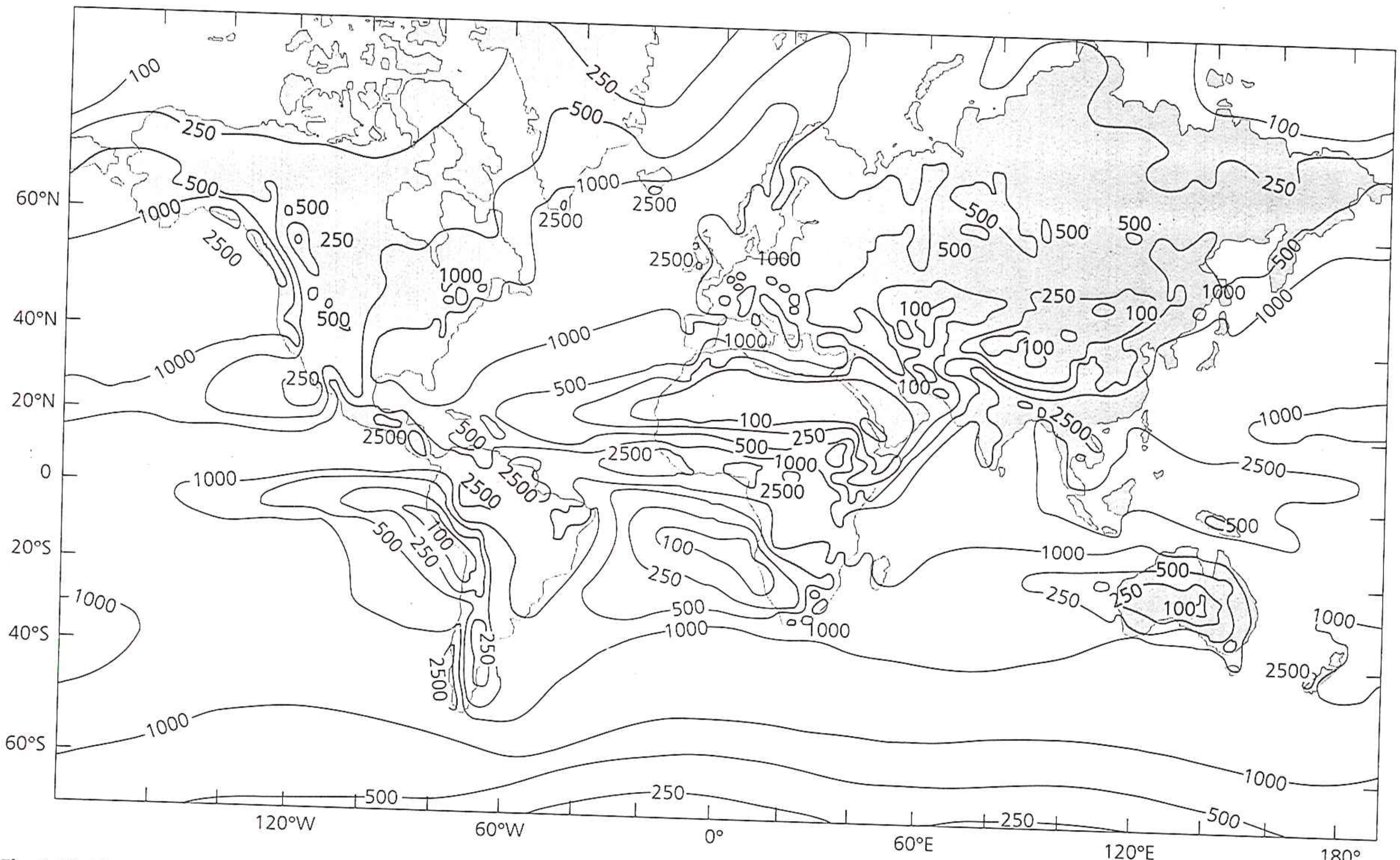


Fig. 1.17 The geographical variation of mean annual precipitation, in millimetres. After Lamb (1972) [19].

Precipitation rates are measured using (low-tech) rain gauges.

Simply collect precipitation in a bucket and weigh it

Data coverage most complete in well developed countries, worst in oceans

Lots of geographical variability

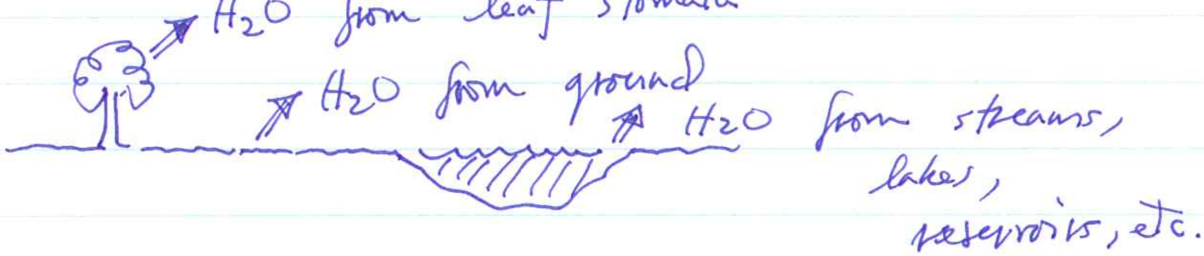
- 100 mm/yr in Sahara & Australian outback
- 2500 mm/yr in tropics (& Seattle, BC)

Must average over whole year to get annual average

- drought in San Francisco summer
- summer rainy season in Iowa
- NYC (and Princeton) ~ 3 in/month = 1000 mm/yr, very little seasonal variability

Greatest seasonal variations associated with monsoons in the tropics

Evaporation and <u>evapotranspiration</u> from plants is more difficult to measure.



There are measurement programs

But global estimates, particularly over oceans, rely primarily on models — must take into account amount of solar insolation, cloud cover, sea surface temperature, etc.

- Greatest evaporation rates (2000 mm/yr) from equatorial oceans.

Averaging these values over all continents & oceans gives Berner's numbers

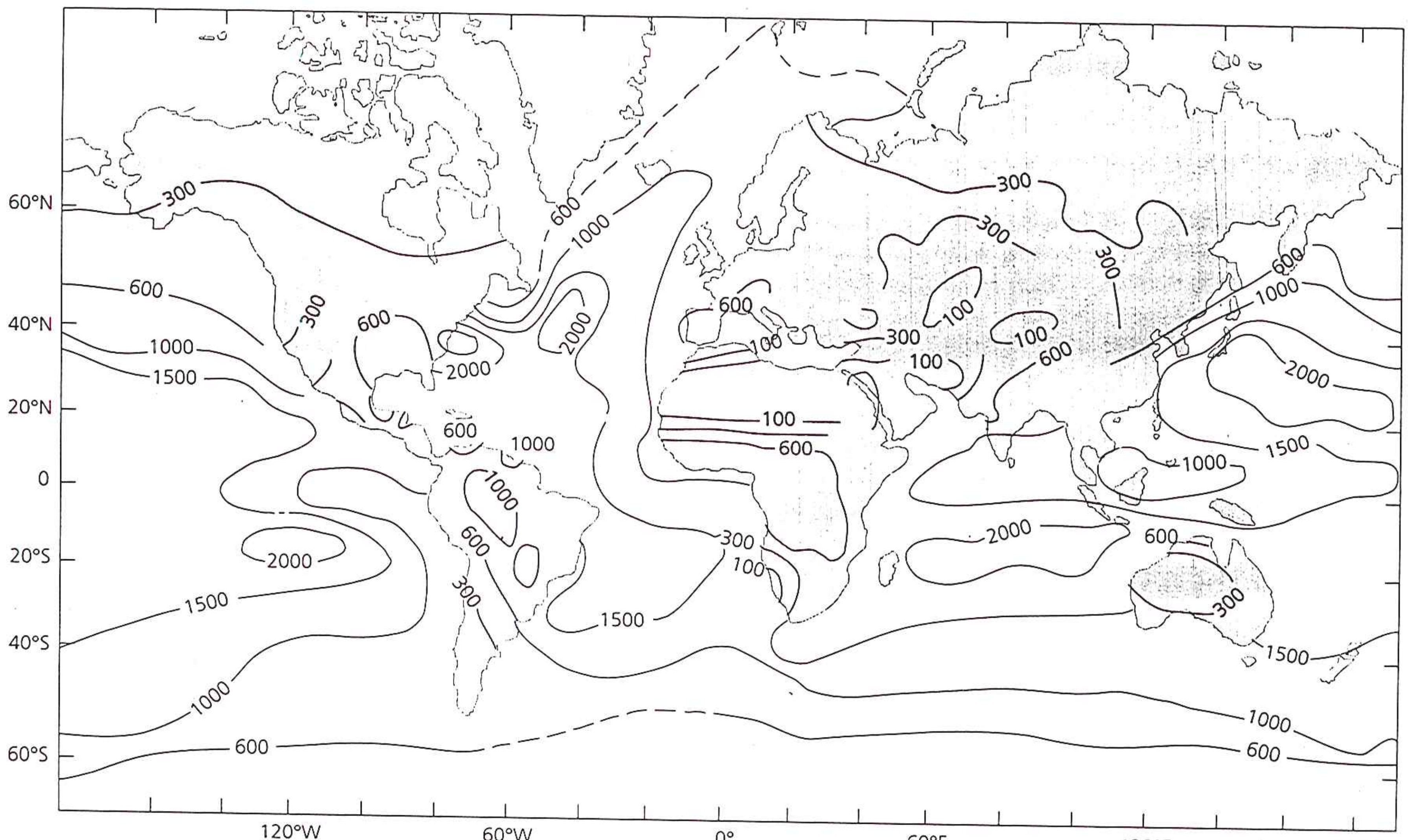
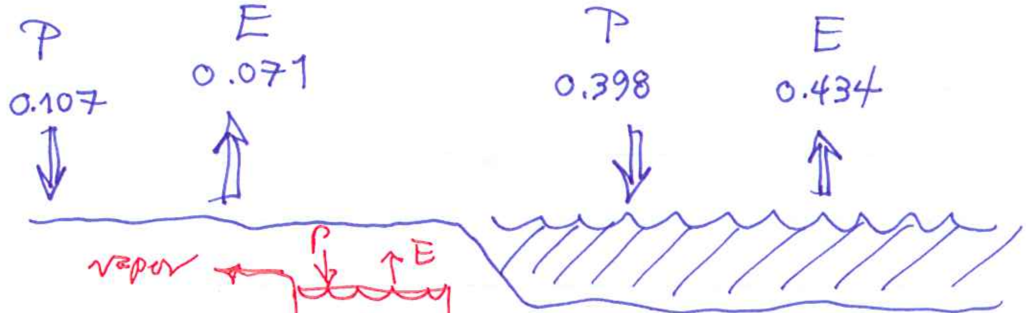


Fig. 1.18 Geographical variation of annual evaporation from ocean and evapotranspiration from land surface, in millimetres. After Barry (1970) [20].

$P-E = 0.036$ $E-P = 0.036$



All in 10^6 km^3/yr $= 10^{18}$ kg/yr

draw 2 side-by-side boxes as above

~~precipitation evaporation~~

evaporation exceeds precipitation by $0.036 \cdot 10^6$ km^3/yr over the oceans this is 72 mm/yr rainfall equivalent

precipitation exceeds evaporation by $0.036 \cdot 10^6$ km^3/yr over land

This implies there is a net flux of water vapor (in the form of clouds) from the ocean to the land of $0.036 \cdot 10^6$ km^3/yr $=$ 71 mm/yr equivalent

The total reservoir of H_2O vapor in the atmosphere is very small $.0155 \cdot 10^{18}$ kg
$M_{atmosphere} = 5 \cdot 10^{18}$ kg, so this is only 0.3 % of the atmosphere by weight and only 0.001 % of the total hydrosphere

better to say this later on page 7

Berner's figure is an example of a <u>steady-state box model</u>

Every reservoir is a "box"

water in $\Rightarrow$ $\boxed{\text{contains water}}$ $\Rightarrow$ water out

If the net amount of water in all the reservoirs is constant (<u>steady state</u>) then

$$\boxed{\sum \text{fluxes in} = \sum \text{fluxes out}}$$

This is certainly true for the evaporative and precipitative ~~fluxes~~ fluxes into and out of the atmosphere

Likewise, if there is a net flux of H_2O vapor from land to sea of $0.036 \cdot 10^{18}$ kg/yr, there must be a balancing land to sea flux of the same amount

stream runoff $\Leftarrow$ vapor transport $0.036 \cdot 10^{18}$ kg/yr

$0.036 \cdot 10^{18}$ kg/yr

This is the net H_2O flux of all rivers into the ocean.

This can also be measured; in fact, we shall discuss in some detail how this is done — also a lab to measure flux of Stony Brook.

But, the measurements indeed confirm that the net runoff is $0.036 \cdot 10^{18}$ kg/yr = 71 mm/yr rainfall equivalent. Fig 4.14 here

We can use such a steady-state box model to determine the residence time of an H_2O molecule in any of the various reservoirs.

Concept of residence time: example — students at Princeton.
Say you didn't know how long it took to graduate.

But you could observe:

1100 freshmen each year (flux of incoming freshman) $\Rightarrow$ $\boxed{\text{4400 students}}$ $\Rightarrow$ 1100 seniors

$\Uparrow$ size of student reservoir

The residence time of a typical student in the reservoir is then

$$\frac{4400 \text{ students}}{1100 \text{ students/yr}} = 4 \text{ years}$$

note — by measuring freshmen & seniors, can also test whether the system is steady-state.

Interesting — shows how easy (or hard) it is to estimate these

on land

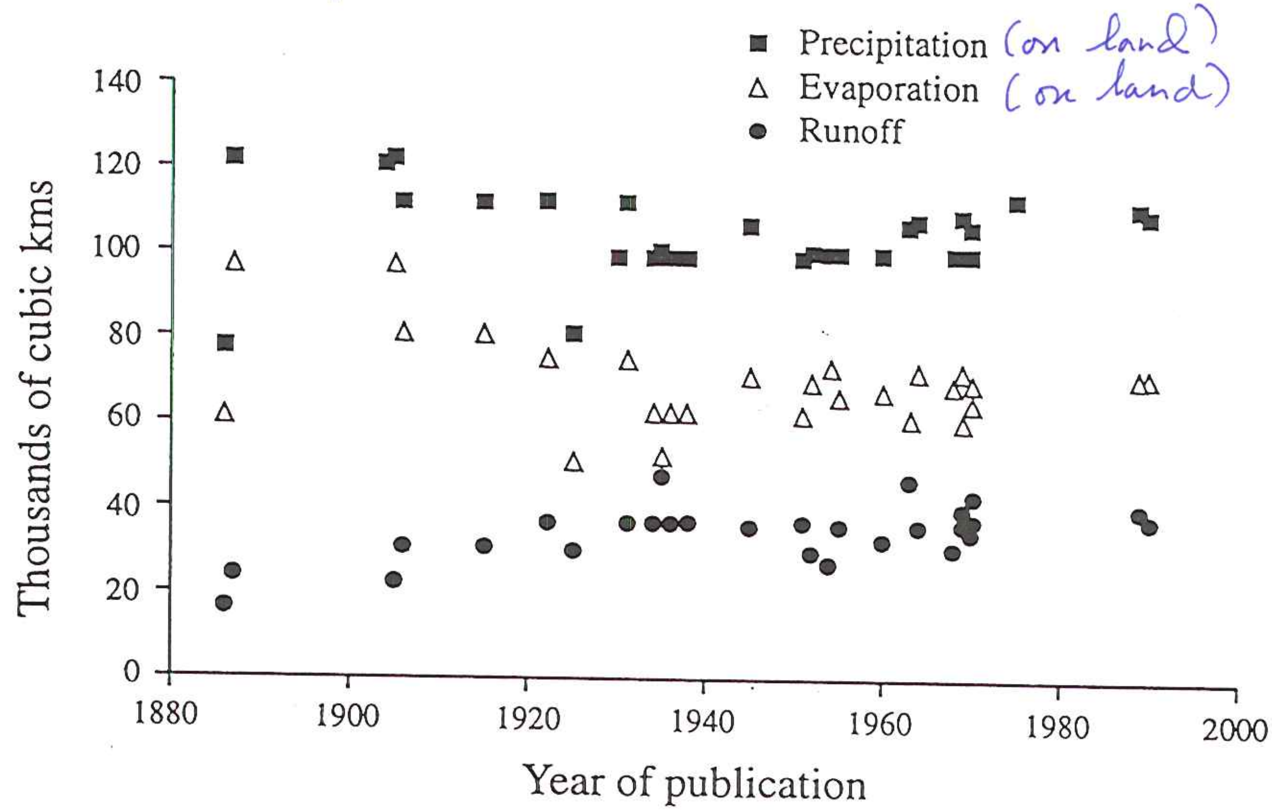


Figure 4.14 Scattergraph of various estimates of the three main components of the Global Water Balance from 1880 to 1995 (data mostly from Baumgartner and Reichel, 1975)

breakdown by continent

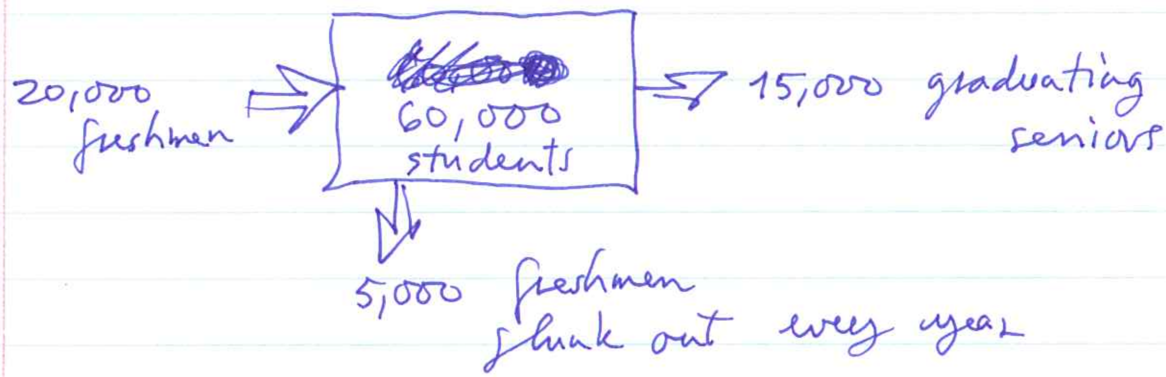
Table 1.3 Water balance of the Earth's land surface in terms of precipitation, evaporation and runoff. From Shiklomanov (1993) [21].

Continent	Precipitation (mm)	Precipitation (km^3)	Evaporation (mm)	Evaporation (km^3)	Runoff (mm)	Runoff (km^3)
Europe	790	8 290	507	5 320	283	2 970
Asia	740	32 200	416	18 100	324	14 100
Africa	740	22 300	587	17 700	153	4 600
North America	756	18 300	418	10 100	339	8180
South America	1600	28 400	910	16 200	685	12 200
Australia and Oceania	791	7 080	511	4 570	280	2 510
Antarctica	165	2 310	0	0	165	2 310
Land as a whole	800	119 000	485	72 000	315	47 000
Areas of external runoff	924	110 000	529	63 000	395	47 000*
Areas of internal runoff	300	9 000	300	9 000	34	1 000†

* Including underground water not drained by rivers.
† Lost in the region through evaporation.

More refined analysis of box models can be used to identify "missing" sinks and sources:

e.g., big State university, e.g. UCLA



What is the residence time of an H_2O molecule in the atmosphere?

see p.4 for comment

$$\frac{.0155 \cdot 10^{18}\ \text{kg}}{\underbrace{(\underset{\text{conts}}{0.107} + \underset{\text{oceans}}{0.398})}_{\text{rainfall}} \cdot 10^{18}\ \text{kg/yr}} = 0.03\ \text{yr} = \underline{11\ \text{days}}$$

This is the amount of time an average H_2O molecule remains in the atmosphere before it falls as rain or snow — not surprisingly, this is the time scale of weather changes

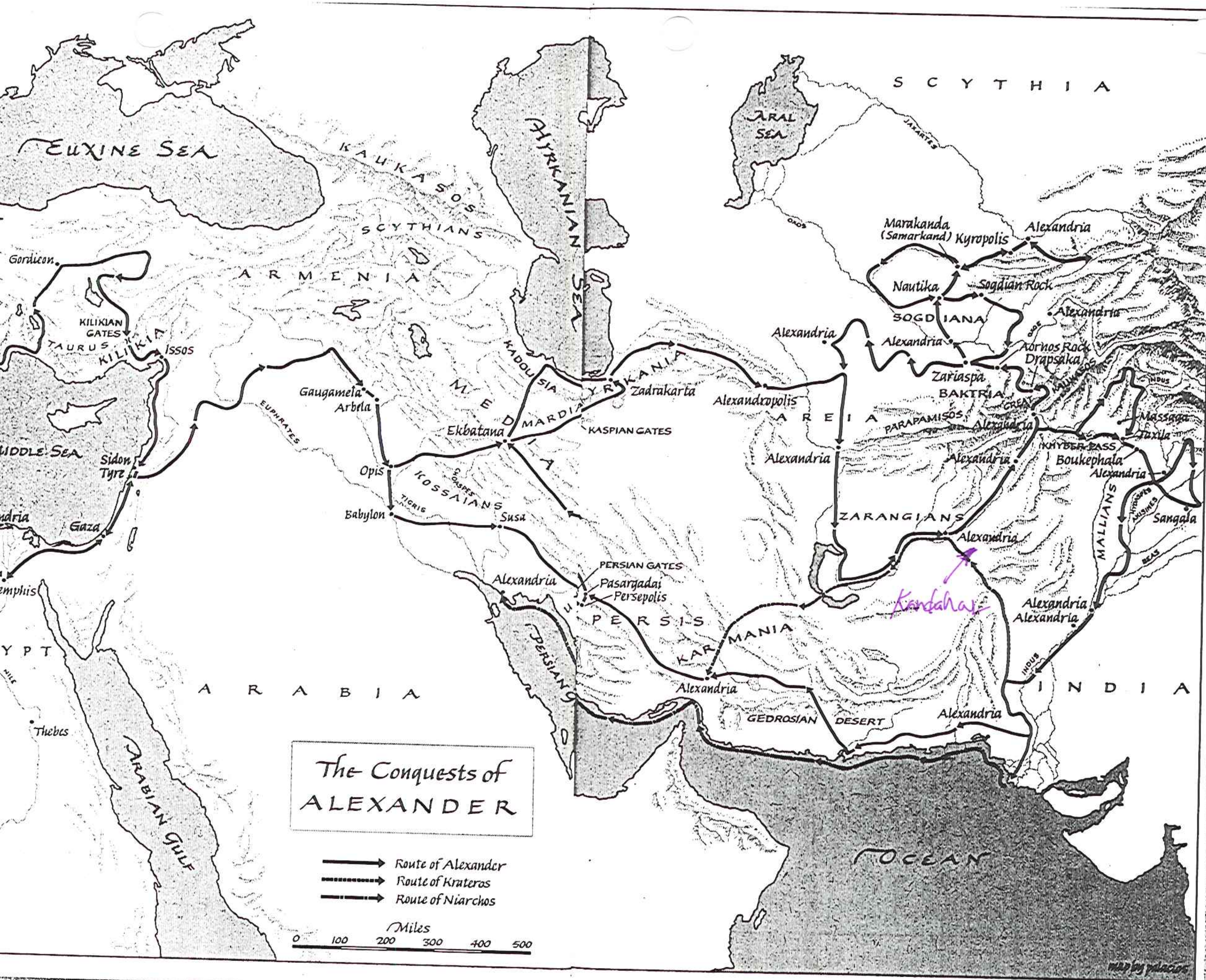
it's the time interval between major rainstorms

What is the residence time of an H_2O molecule in the oceans?

Conquest and Empire

The reign of
ALEXANDER THE GREAT

A. B. BOSWORTH


The Conquests of ALEXANDER
Route of Alexander
Route of Krateros
Route of Niarchos
Miles
0 100 200 300 400 500
SCYTHIA
ARAL SEA
EUXINE SEA
KAUKASOS
SCYTHIANS
ARMENIA
HYRKANIAN SEA
Gordieon
KILIKIAN GATES
TAURUS
KILIKIA
Issos
MIDDLE SEA
Sidon
Tyre
Gaza
Memphis
EGYPT
NILE
Thebes
ARABIAN GULF
ARABIA
EUPHRATES
Gaugamela
Arbela
Opis
Babylon
TIGRIS
KOSSAIANS
CHOASPES
Susa
MEDIA
Ekbatana
MARDIA
KADOUSIA
HYRKANIA
Zadrakarta
KASPIAN GATES
PERSIAN GATES
Pasargadai
Persepolis
PERSIS
Alexandria
PERSIAN
KARMANIA
GEDROSIAN DESERT
Alexandropolis
AREIA
ZARANGIANS
Kandahar
PARAPAMISOS
GREAT KAUKASOS
BAKTRIA
Zariaspa
Drapsaka
Aornos Rock
SOGDIANA
Nautika
Sogdian Rock
Marakanda (Samarkand)
Kyropolis
JAXARTES
OXOS
KHYBER PASS
Boukephala
Massaga
Taxila
Sangala
MALLIANS
INDUS
HYDASPES
AKESINES
BEAS
INDIA
OCEAN
map by palacios

different than 2001 exam problem because it ignored precipitation

$$\frac{1400 \cdot 10^{18}\ kg}{(\underbrace{0.398}_{rain} + \underbrace{0.036}_{runoff}) \cdot 10^{18}\ kg/yr} = \underline{3000\ years}$$

96% of surface hydrosphere

~~This~~ Since the oceans are the principal surface reservoir (96% of the total) we can regard this as the time for homogenization of the mobile reservoir.

Put a molecule of H_2O anywhere in the system. Then after ~3000 years, it has an equally likely chance of being anywhere.

Illustrate this with a (rather silly) calculation — remember to bring a bottle of water:

Consider a person who lived ~3000 years ago, say Alexander the Great (~300 BC). He travelled all over Asia Minor — every day he drank, allegedly nothing but wine (which is mostly H_2O) — he urinated daily, so lots of H_2O molecules passed through his body.

What are the chances that one of those is in a mouthful of water I drink today — an exercise in estimation.

$$1 \text{ mouthful} = 15 \text{ cc} = 15 \text{ gms}$$

$2 + 16 = 18$

Molecular weight of H_2O = 18 gms/mole

Avogadro's number $= 6 \cdot 10^{23} \dfrac{\text{molecules}}{\text{mole}}$

So, every mouthful contains

$$15 \text{ gm} \times \frac{1}{18} \frac{\text{moles}}{\text{gm}} \times 6 \cdot 10^{23} \frac{\text{molecules}}{\text{mole}}$$

$$= 5 \cdot 10^{23} \text{ molecules / mouthful}$$

i.e. two bottles of wine

How many of those passed through Alexander the Great? Say he drank and urinated 1.5 liters of wine per day for 26 years. This is

$$1500 \frac{\text{gm}}{\text{day}} \times 26 \text{ years} \times 365 \frac{\text{days}}{\text{year}}$$

$$\times \frac{1}{18} \frac{\text{moles}}{\text{gm}} \times 6 \cdot 10^{23} \frac{\text{molecules}}{\text{mole}} = 5 \cdot 10^{29} \text{ molecules}$$

i.e. about 10^6 mouthfuls

Alexander

These are homogeneously distributed through a total reservoir of

$$1400 \cdot 10^{21} \text{ gm} \times \frac{1}{18} \frac{\text{moles}}{\text{gm}} \times 6 \cdot 10^{23} \frac{\text{molecules}}{\text{mole}}$$

$$= 5 \cdot 10^{46} \text{ molecules in ocean}$$

(i.e.) in mobile reservoir)

The <u>dilution factor</u> is

$$\frac{5 \cdot 10^{29}}{5 \cdot 10^{46}} \approx 10^{-17}$$

So, one out of every 10^{17} H_2O molecules passed through Alexander the great. So, every mouthful contains

$$(5 \cdot 10^{23})(10^{-17}) = 5 \cdot 10^{6}$$

<u>5 million</u> of <u>Alex's H_2O molecules</u>!

But, could do the same thing for every one of his Macedonian troops, and troops from Asia Minor who joined his voyage of conquest.

This raises the question — is it possible that all of the water in our bottle is simply recycled urine? which the Frist Center sells so proudly for \$ 1.25 / bottle

To paraphrase Everett Dirksen "5 million here, 5 million there... pretty soon it all adds up"!

For a gross overestimate, add up the urine & water of all the people who have ever lived on $\oplus$ (even though most have lived too recently for their urinary H_2O to be well mixed in the reservoir)

100 billion $= 10^{11}$ people

$$\underset{\text{people}}{(10^{11})}\,\underset{\substack{H_2O \text{ molecules} \\ \text{per person}}}{(5 \cdot 10^{29})} = 5 \cdot 10^{41}$$

Total dilution factor $\dfrac{5 \cdot 10^{41}}{5 \cdot 10^{46}} \approx 10^{-5}$

So, the H_2O in 

is 99.999 % pure.

Another view of the precipitation & evaporation fluxes — zonal averages as a function of latitude

Precipitation exceeds evaporation in the tropics and ~ 60°N and 60°S

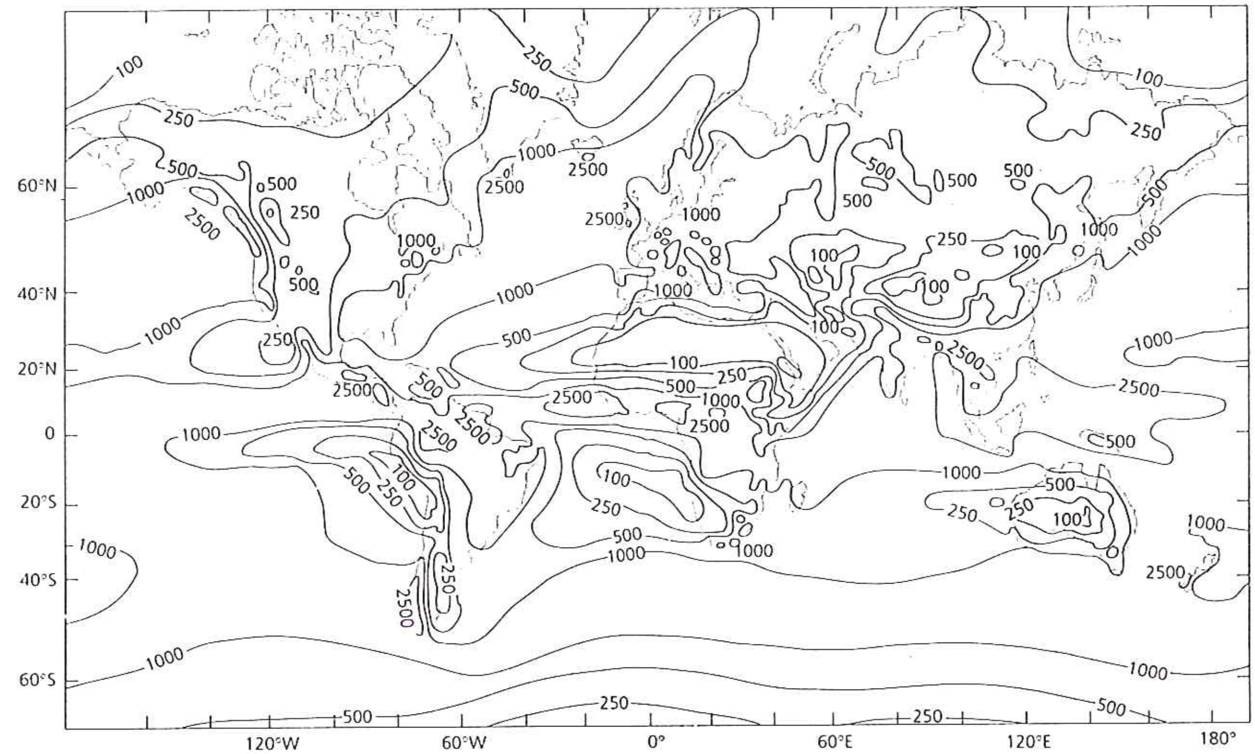


Fig. 1.17 The geographical variation of mean annual precipitation, in millimetres. After Lamb (1972) [19].

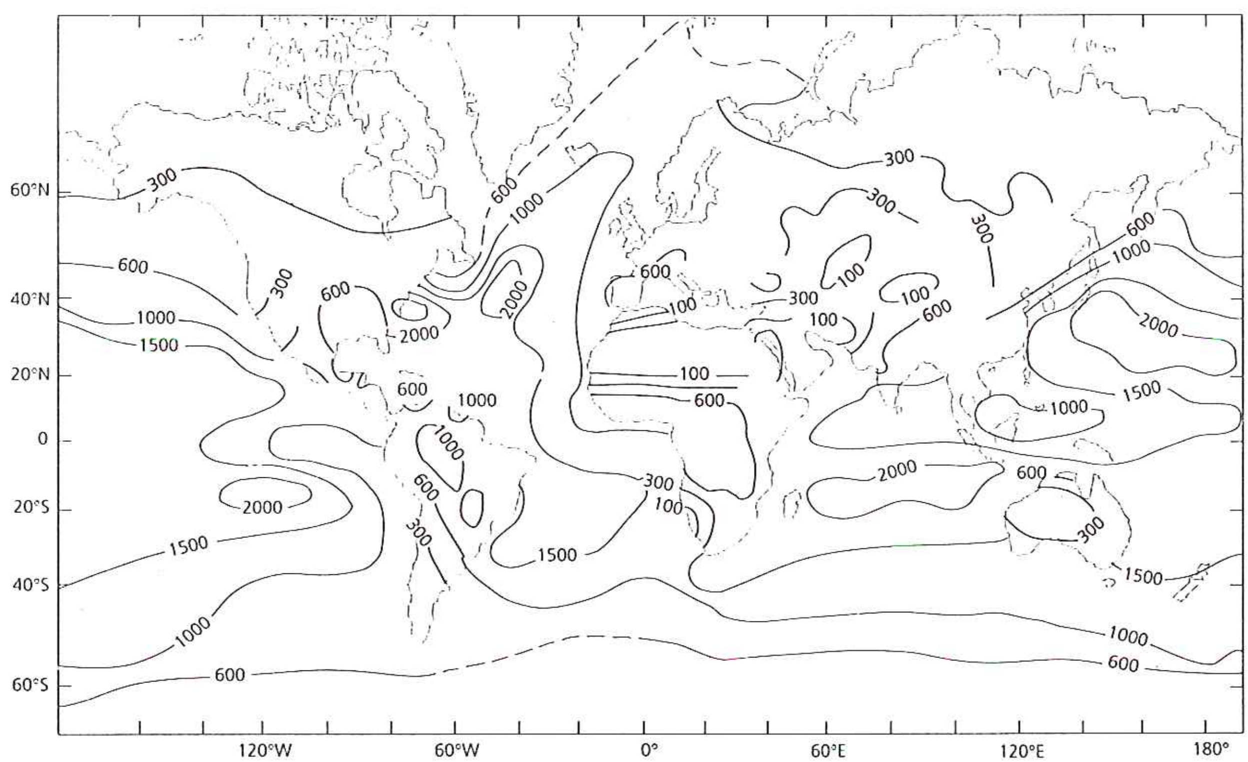


Fig. 1.18 Geographical variation of annual evaporation from ocean and evapotranspiration from land surface, in millimetres. After Barry (1970) [20].

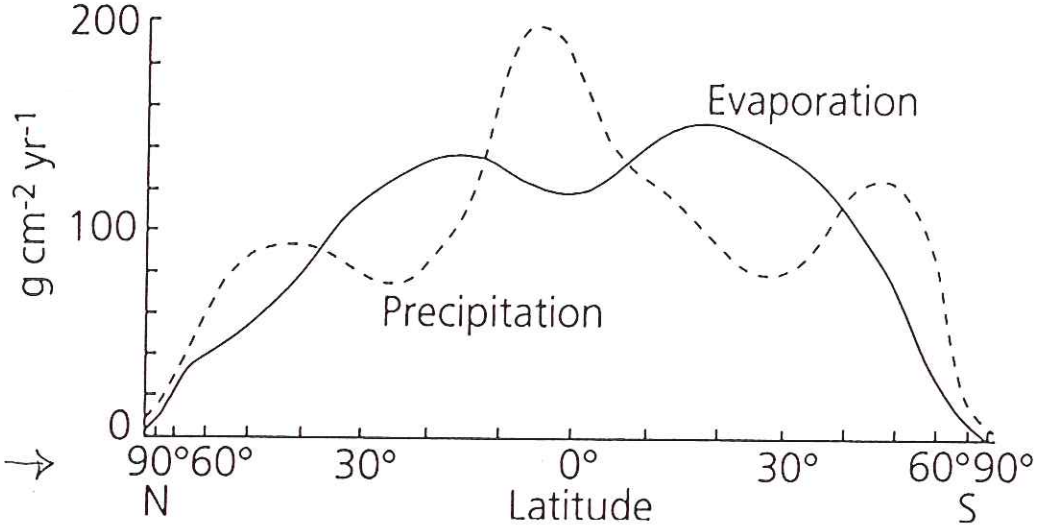


Fig. 1.19 Zonally averaged precipitation and evaporation as a function of latitude.

Note: the vergence of meridian lines near the poles (~ sin θ) has been accounted for in the distorted scale

However, this is irrelevant since its $\frac{gm}{cm^2\ yr}$

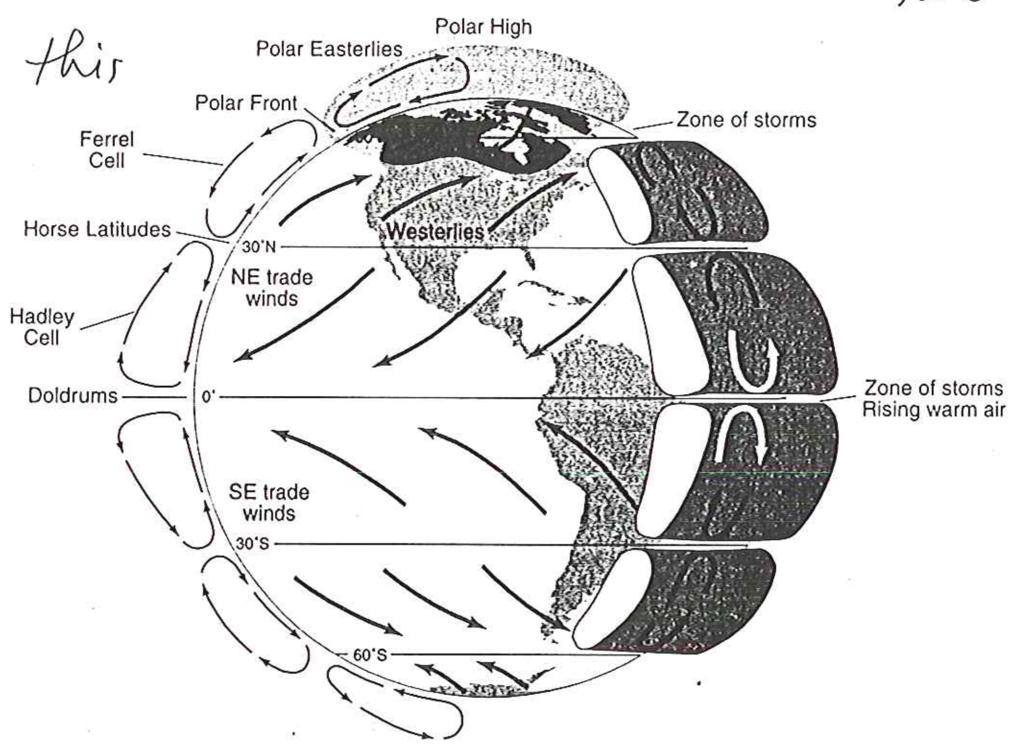


Figure 1.9 Schematic representation of the general circulation of the atmosphere. (Frederick K. Lutgens/Edward J. Tarbuck, *The Atmosphere,* 5th ed., Copyright © 1992, p. 170. Adapted by permission of Prentice Hall, Englewood Cliffs, New Jersey.)

Evaporation exceeds precipitation in the horse latitudes, 30°N and 30°S.

These variations simply reflect the large-scale circulation of the atmosphere

Hot air in the tropics rises — sinks at 30°N and 30°S. Another zone of rising air at 60°N and 60°S.

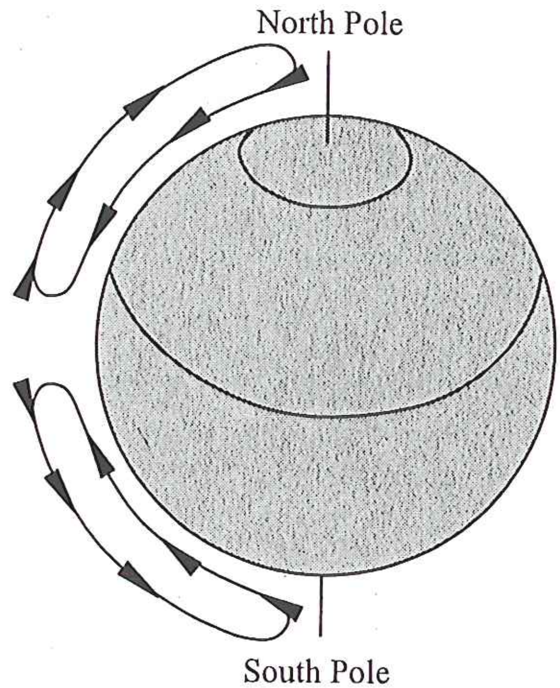
As the air rises it cools — cool air cannot hold as much H_2O (see breath on wintry day) — condenses out & rains

In the horse latitudes cold air is sinking — heats up — very little rain.

This is the region where all the world's deserts are — Sahara, Gobi, Sonora, Kalihari, Namibia, Patagonia, Australian outback.

The equatorial rain belt, on the other hand, is where the tropical rain forests are.

Note that both precipitation & evaporation are low near the poles.

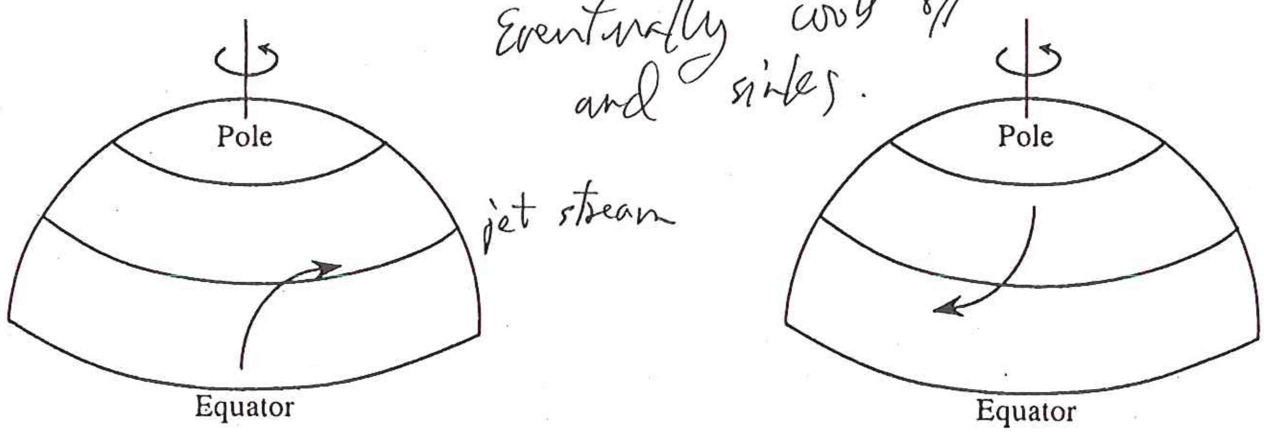


Atmospheric circulation on Venus

Rotation period ~240 days

Figure 6.3 On a nonrotating planet, air that rises in low latitudes flows poleward aloft, sinks in high latitudes, and returns equatorward near the surface.

why the air sinks at 30°N and 30°S
Because by then it has been deflected due eastward.
Eventually cools off and sinks.



jet stream

Figure 6.4 *Left,* Parcels of air in low latitudes are initially far from Earth's axis of rotation and therefore are moving rapidly eastward. When they move poleward and retain their angular momentum, they move eastward relative to Earth's surface beneath them. *Right,* Equatorward-moving parcels, on the other hand, move westward relative to the surface beneath them.

Hadley circulation

Westerly winds in US

If it rained in Ohio yesterday it'll rain in Princeton today

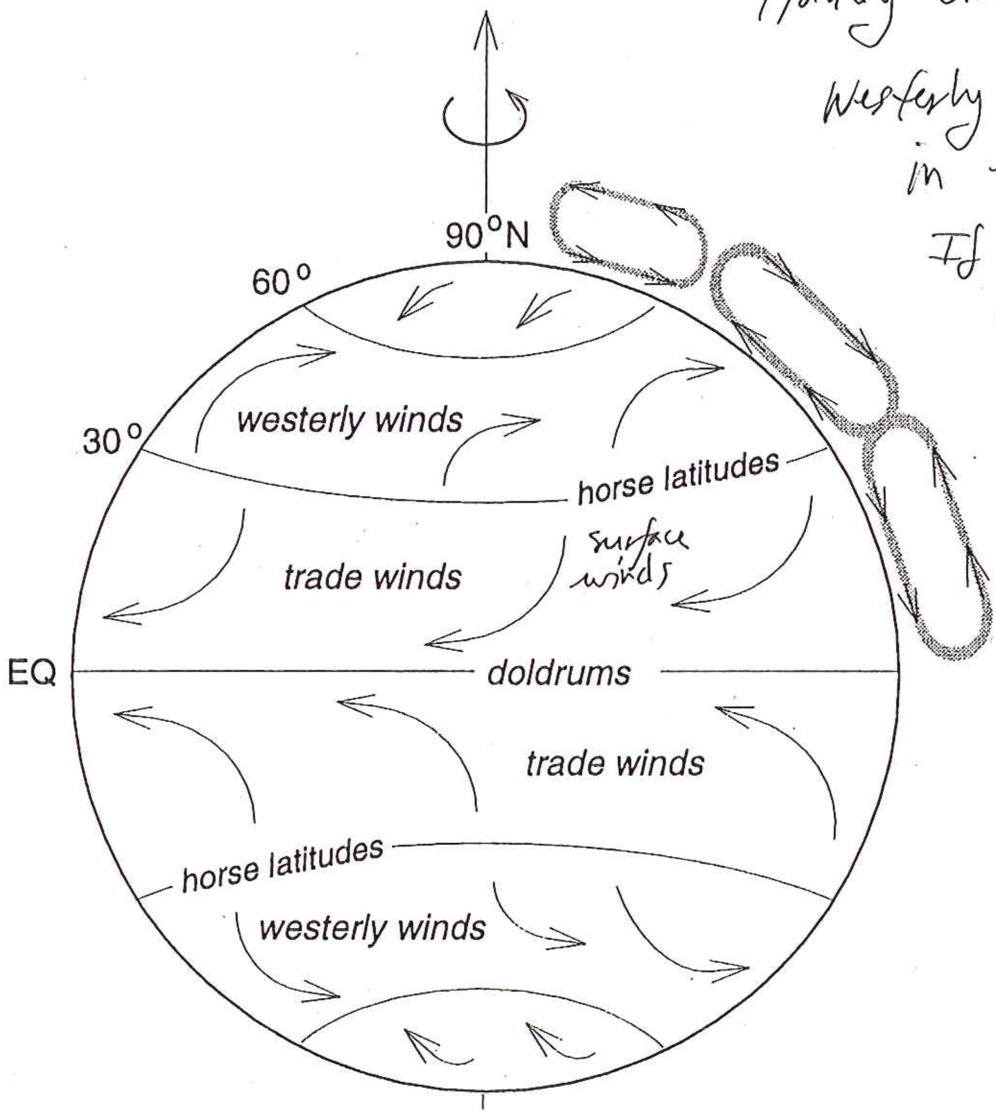


Figure 6.6 The southeast and northeast trade winds in the tropics converge onto the doldrums, rainy regions where moist air rises. In the subtropics, the easterly and westerly winds diverge from the horse latitudes, sunny, dry regions over which dry air subsides. The easterly winds in polar regions, and the westerlies in subpolar regions, converge onto rainy regions near 60°N and 60°S, respectively.

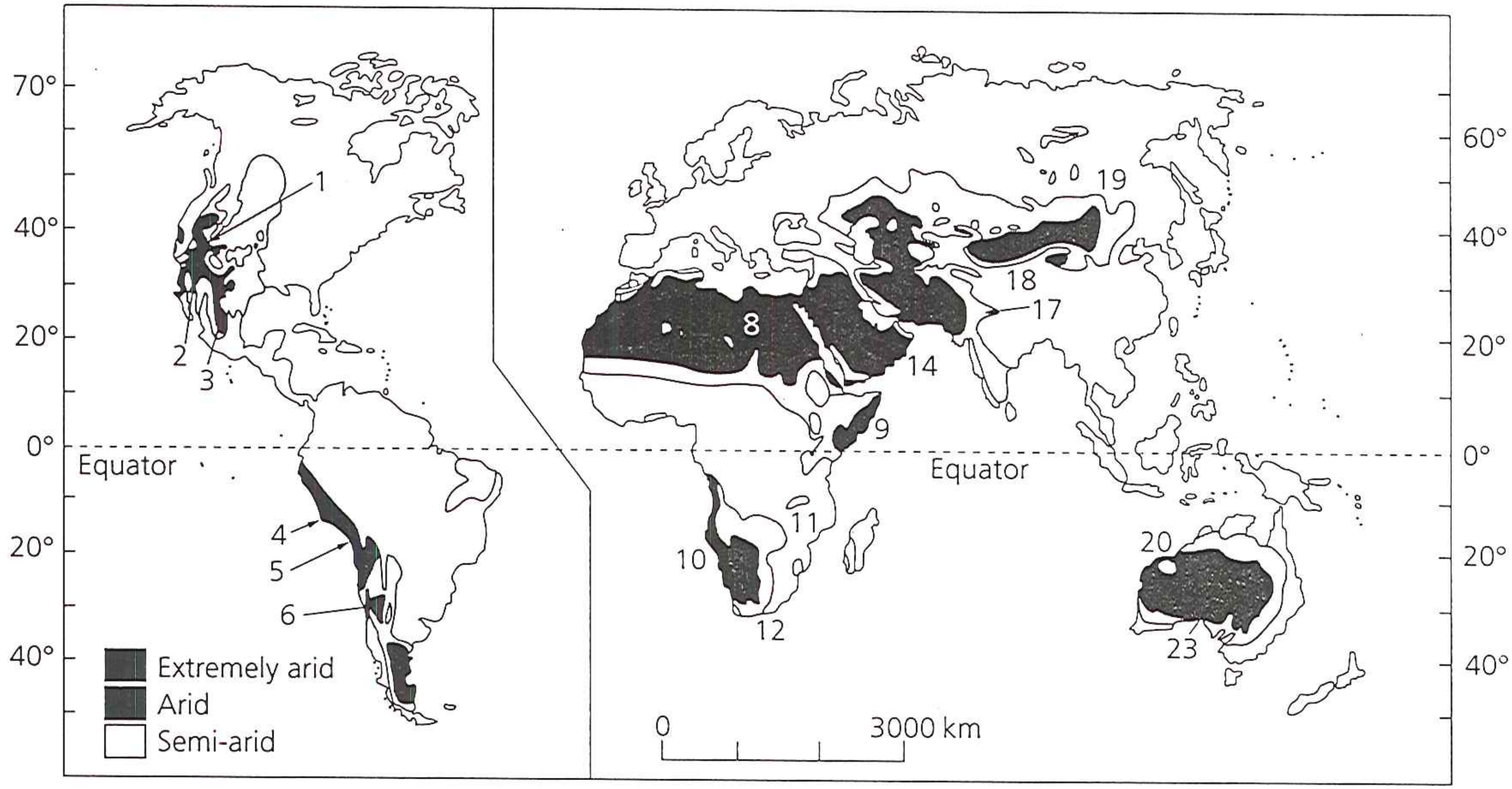
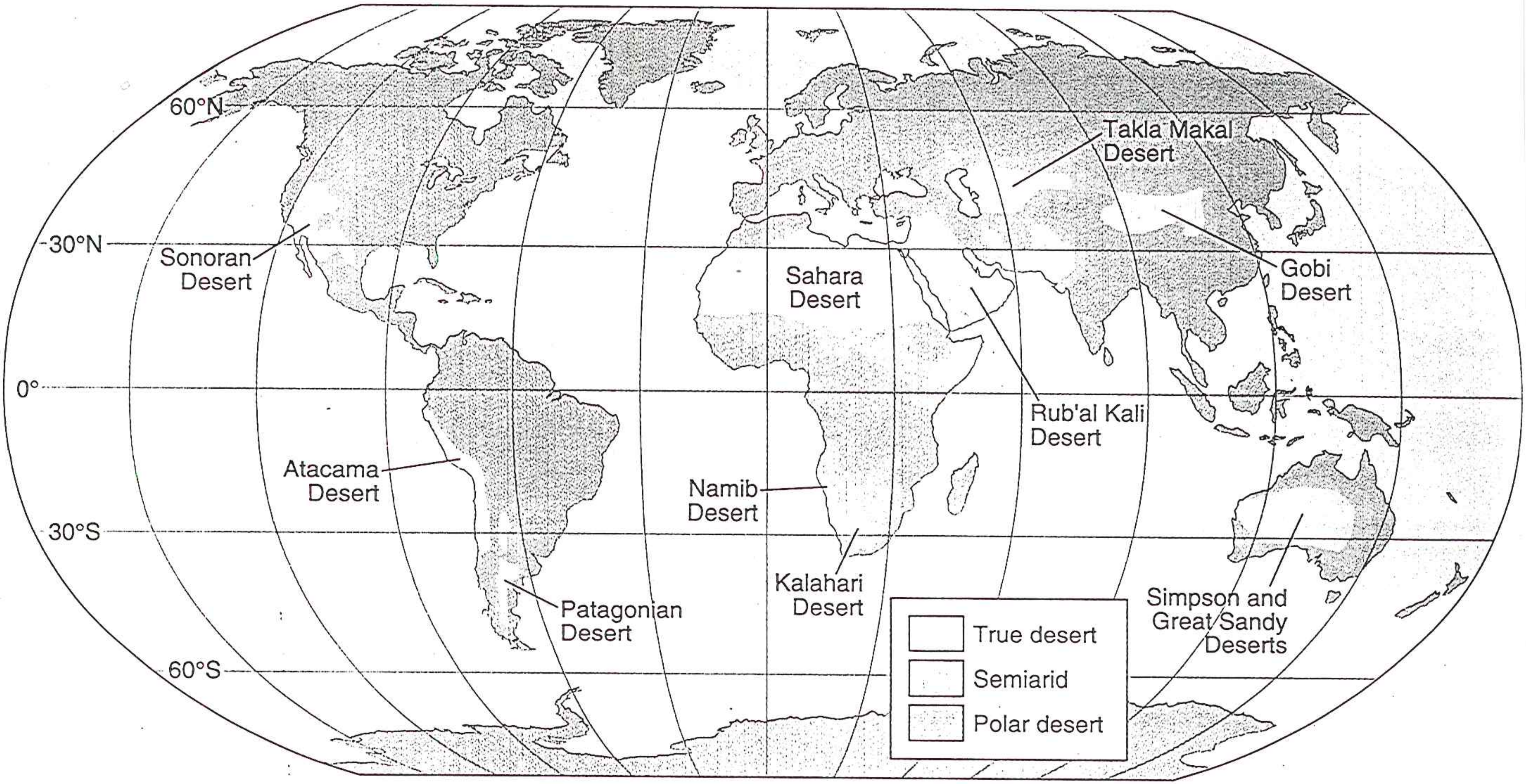


Fig. 10.24 Distribution of the world's drylands. The main deserts are: (1) Great Basin; (2) Sonoran; (3) Chihuahuan; (4) Peruvian; (5) Atacama; (6) Monte; (7) Patagonian; (8) Sahara; (9) Somali-Chabli; (10) Namib; (11) Kalahari; (12) Karroo; (13) Arabian; (14) Rub al Khali; (15) Turkistan; (16) Iranian; (17) Thar; (18) Taklimakan; (19) Gobi; (20) Great Sandy; (21) Simpson; (22) Gibson; (23) Great Victoria; (24) Sturt. After Cooke & Warren (1973) [32] and Greeley & Iversen (1985) [9].

FIGURE 18.1 Distribution of desert and semiarid regions of the world. *(David Turnley, Black Star)*



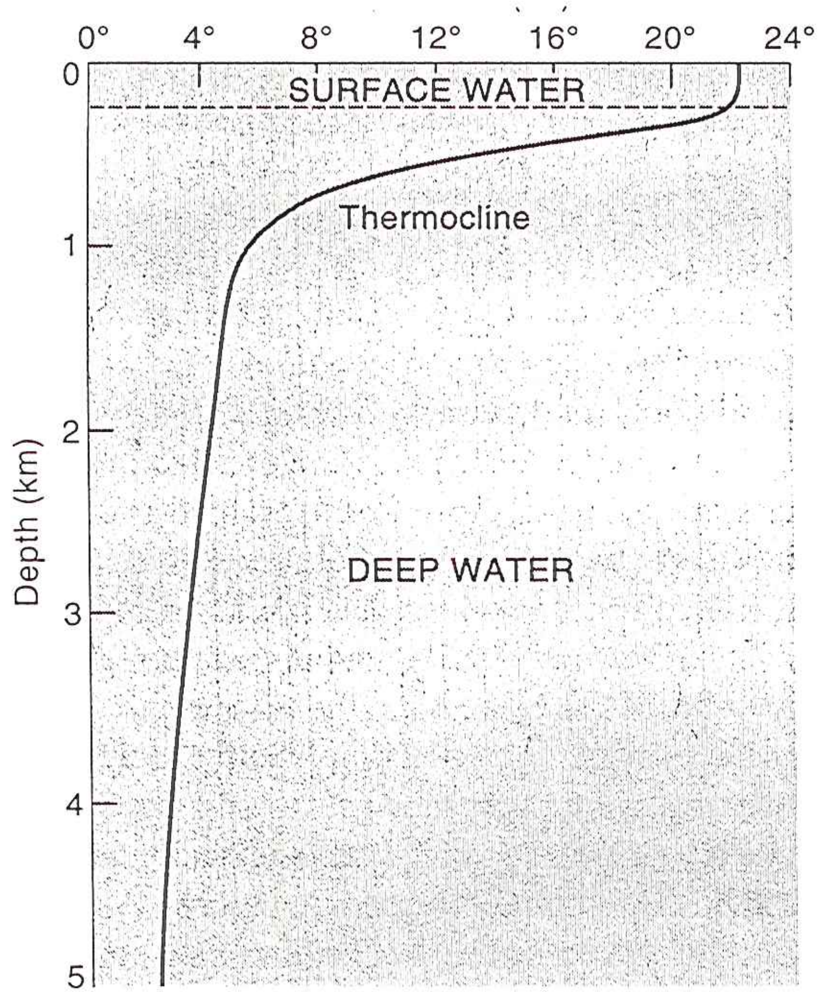


Figure 1.10 Generalized temperature-versus-depth profile for the oceans (at low to middle latitudes), showing vertical stratification into surface and deep water masses.

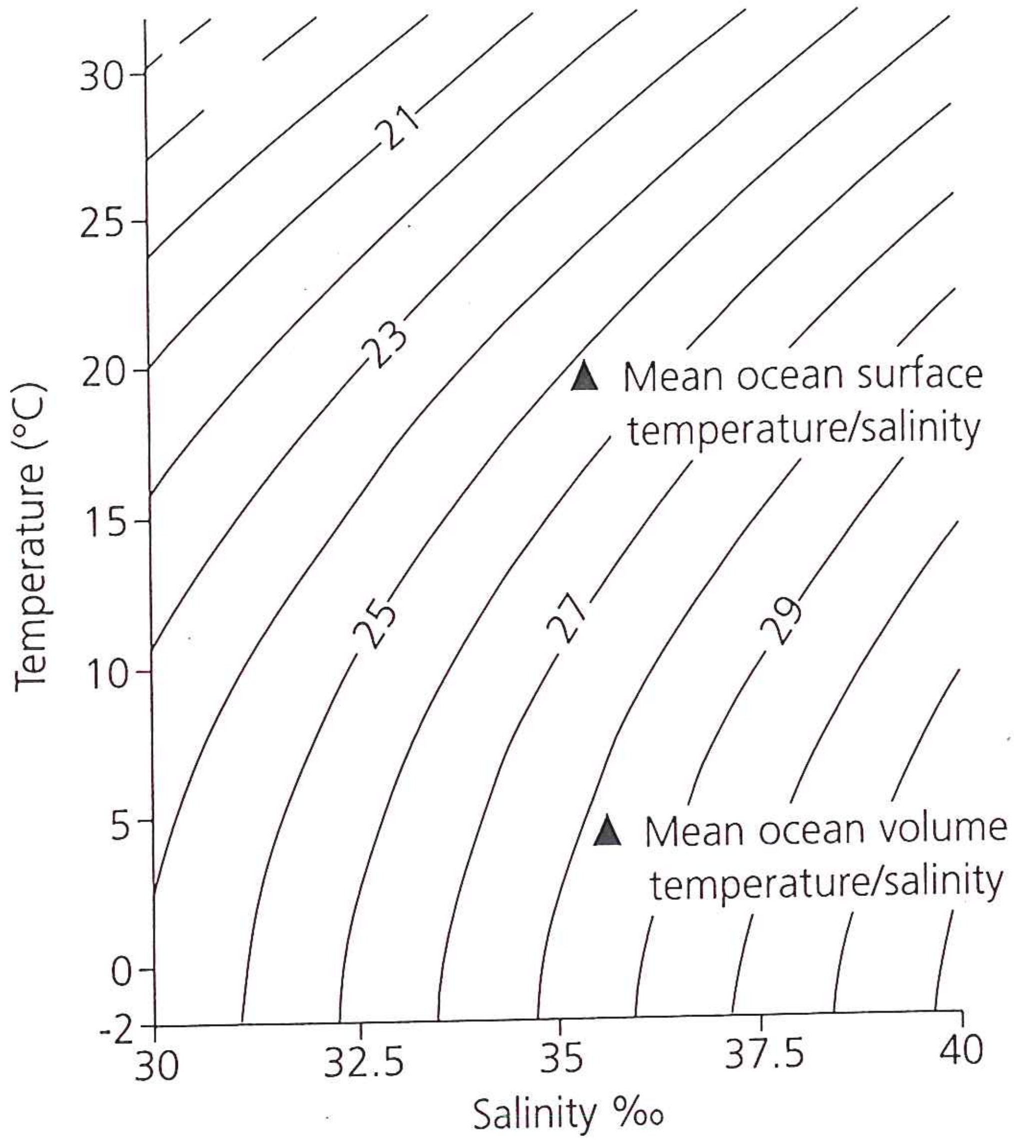


Fig. 1.8 The sensitivity of the density of seawater to changes in temperature and salinity. Density shown in kilograms per cubic metre in excess of 1000. Water masses in tropical and high-latitude regions have markedly different sensitivity to a given change in temperature or salinity. See Practical Exercise 1.1.

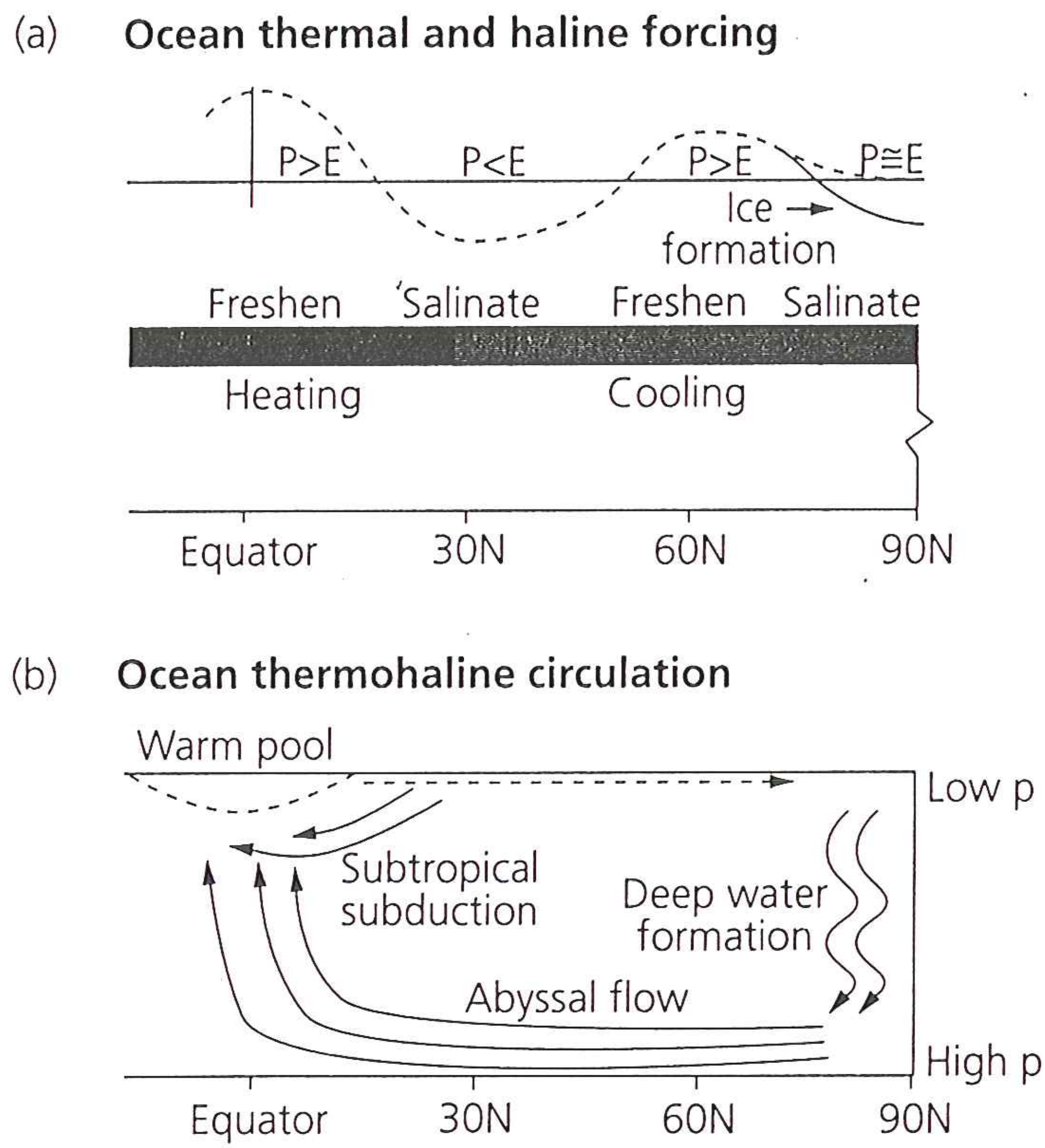


Fig. 1.7 Forcing mechanisms and circulation in the ocean. (a) Thermal and haline forcing. (b) Resulting thermohaline oceanic circulation (P = pressure). After Webster (1994) [7].

The latitudinal variation in precipitation and evaporation, in turn, drive the thermohaline circulation of the ocean.

Surface H_2O at equator is warm & relatively non-saline. More saline water in horse latitudes is slightly denser.

Density varies from 1020 to 1030 kg/m^3 as a result of temperature and salinity changes.

Cold fresh H_2O sinks near the poles — salt is removed by freezing to form sea ice.

In detail, there are two principal regions of deep water formation — Weddell Sea in Antarctica and North Atlantic near Greenland.

Drives the conveyor belt circulation seen in Fig. 1.10 — black deep H_2O, white shallow return flow

We can find the residence time of an H_2O molecule in the deep ocean

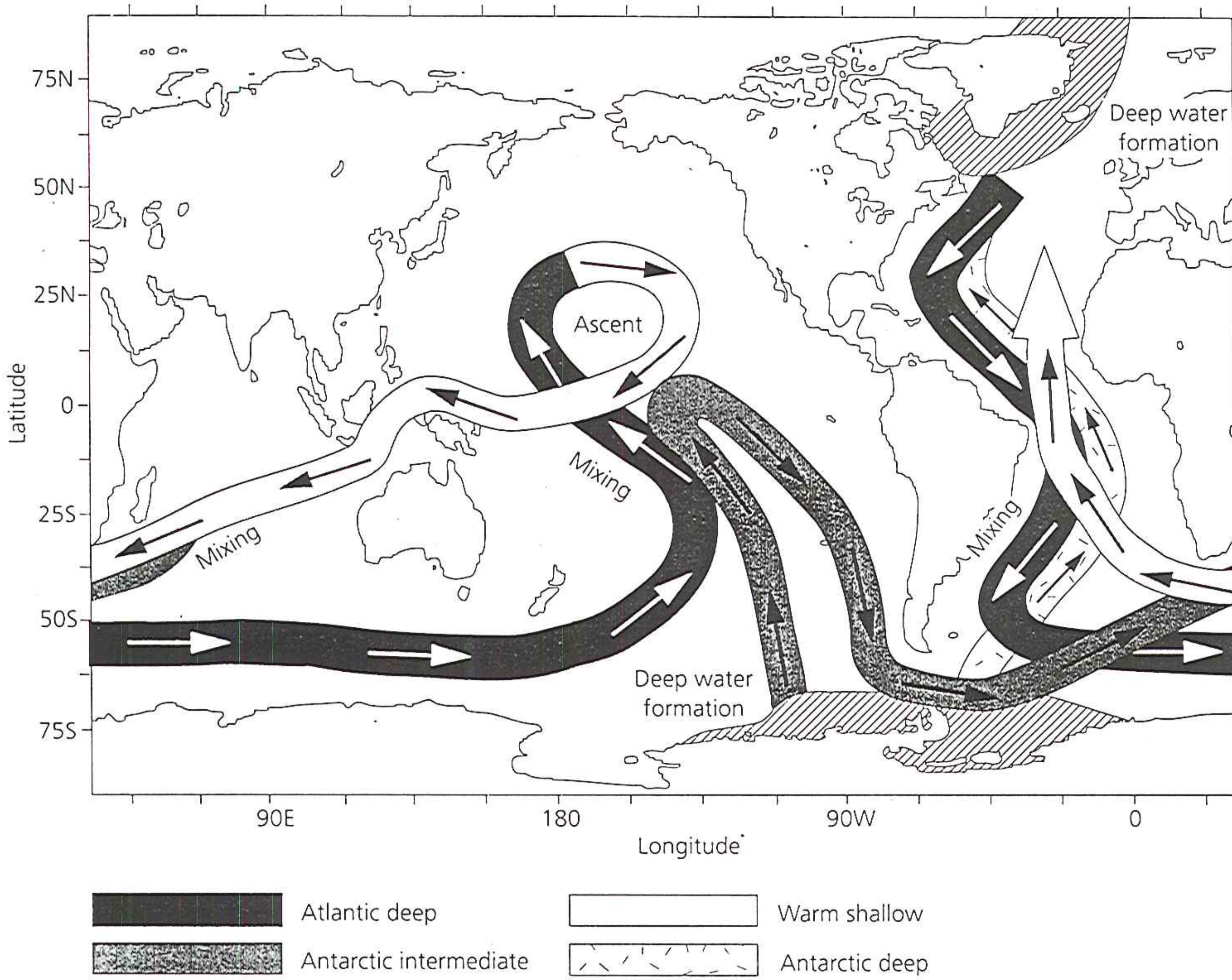
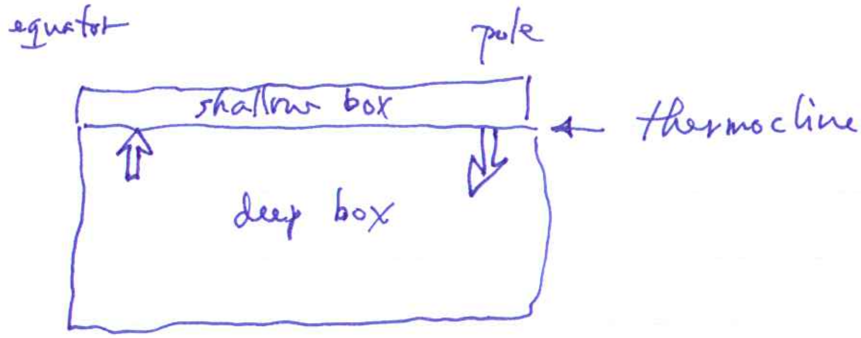


Fig. 1.10 The deep thermohaline circulation of the oceans, modified from Stommel (1958) [12]. The major sources of deep water at the present day in the north Atlantic and Weddell Sea are shown by hatching. The lack of deep water formation in the north Pacific may be due to the greater stability of the Pacific caused by the higher fresh water flux. The text describes the circulation patterns observed.



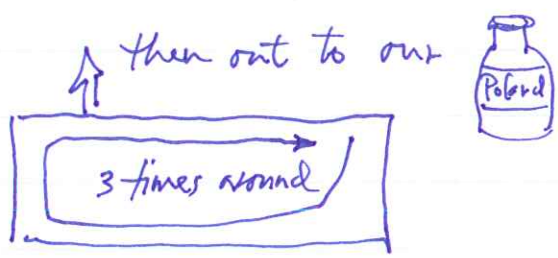
Need to measure rate of deep H_2O formation. Use oceanic tracers, e.g., bomb ^{14}C and tritium, together with GCM's.

$\boxed{\text{Answer:} \quad t \approx 1000 \text{ years}}$

Time to mix ocean

Recall the oceans mix with the atmosphere, lakes and rivers in ~3000 years.

So... an average H_2O molecule: first urinated by Alexander the Great in the Euphrates



insert page 14.1 here

There is one even longer cycle involving H_2O on ⊕ — the bound water in the oceanic crust — about 5% of the ⊕'s total hydro

Recall the hydrothermal circulation at the mid-ocean ridges

Hot H_2O expelled from black smokers accounts for $\frac{1}{3}$ of total oceanic heat flow

The rate at which seawater is cycled through the basaltic crust is
6000 m^3/sec = $\frac{1}{3}$ flow of Mississippi

$\boxed{\text{i.e. } 200\ km^3/yr}$

$\approx$ 18,000 m^3/sec
= 600 km^3/yr

The time to cycle the entire ocean through the crust in this manner is

or could just note that this is $1400 \cdot 10^6\ km^3$

depth ; convert km to m

$$\frac{\text{volume of ocean}}{6000\ m^3/s} = \frac{4 \cdot 10^3 \cdot (0.7)\,(4\pi\ 6371^2) \cdot 10^6}{6000}$$

$$\boxed{\frac{1400 \cdot 10^6\ km^3}{200\ km^3/yr} = 7 \cdot 10^6\ yrs} = 2.4 \cdot 10^{14}\ \text{secs}$$

= 7 million years

Rapid on age-of-$\oplus$ timescale. Has an important effect on ocean chemistry.

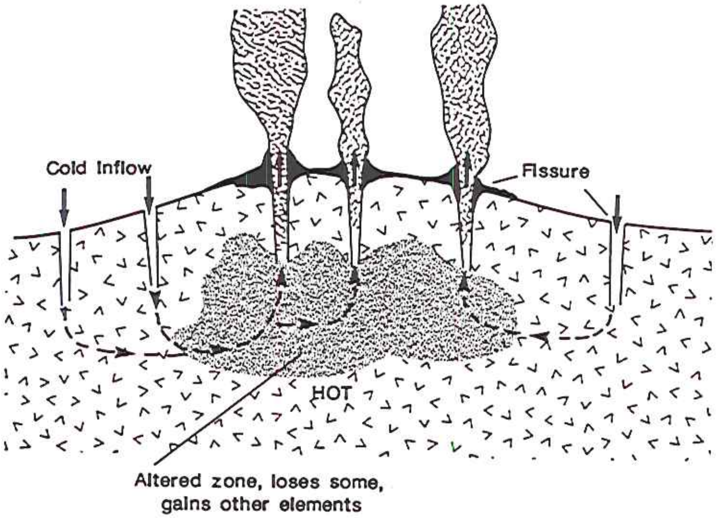


Figure 14.3. The hot crust of the mid-ocean ridges is cooled partly by conduction of heat to the seafloor. Almost as much heat is carried away by cold ocean water that enters fissures and circulates through the hot crust. Once heated, the water returns to the ocean as hotsprings, with exit temperatures that range from a few degrees to 350 °C. While passing through the hot crust the seawater leaves some constituents behind and extracts others, thereby altering the rocks substantially. At the vents, manganese and iron oxides and hydroxides (black) are deposited that may contain valuable amounts of such metals as silver and copper.

not boiling because of high pressure

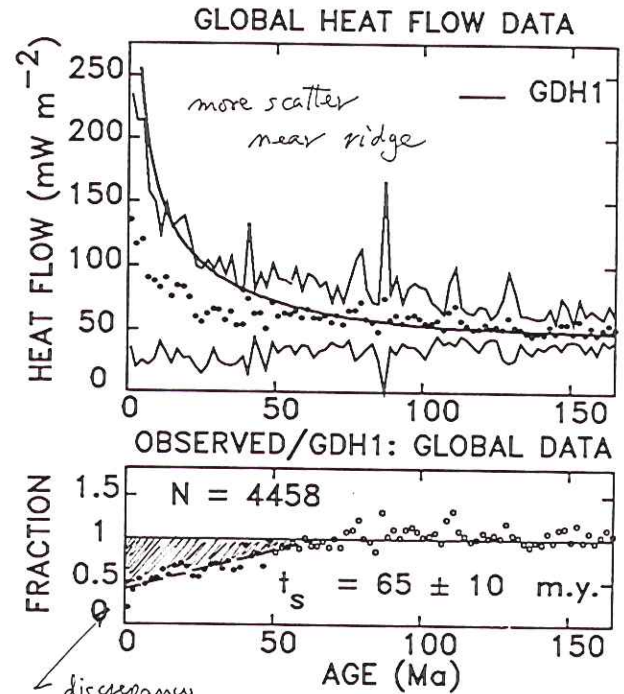
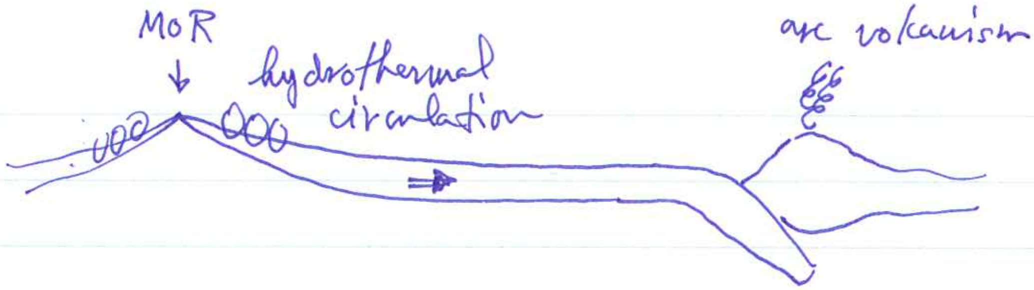


Fig. 2. Observed heat flow versus age for the global data set from the major ocean basins and predictions of the GDH1 model, shown in raw form (*top*) and fraction (*bottom*). Data are averaged in 2-m.y. bins. The discrepancy for ages < 50-70 Ma presumably indicates the fraction of the heat transported by hydrothermal flow. The fractions for ages < 50 Ma (closed circles), which were not used in deriving GDH1, are fit by a least squares line. The sealing age, where the line reaches one, is 65 ± 10 Ma [107].



20 km^3/yr of basalt produced at MOR

0.3% by volume H_2O

0.06 km^3/yr H_2O bound into oceanic crustal minerals (serpentine, etc.) per year

Total reservoir size is

$$(0.003)(6 \text{ km thick})(0.7)(4\pi \cdot 6371^2)$$

this is 0.5% of the ocean reservoir

$$= 7 \cdot 10^6 \text{ km}^3$$

<u>Residence time</u> of bound H_2O in ocean crust

$$\frac{7 \cdot 10^6}{0.06} = \underline{120 \text{ million years}}$$

Not surprisingly, simply the (mean) age of the ocean basins. Some of the incorporated H_2O at the MOR is derived from the mantle, some by hydration of basalt due to the hydrothermal circulation. On other end, some released into atmosphere in arc volcanism, some incorporated into mantle.