

ΕΙΣΑΓΩΓΗ ΣΤΗ ΦΥΣΙΚΗ ΤΗΣ ΑΤΜΟΣΦΑΙΡΑΣ

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Γ' εξάμηνο

Τμήμα Φυσικής

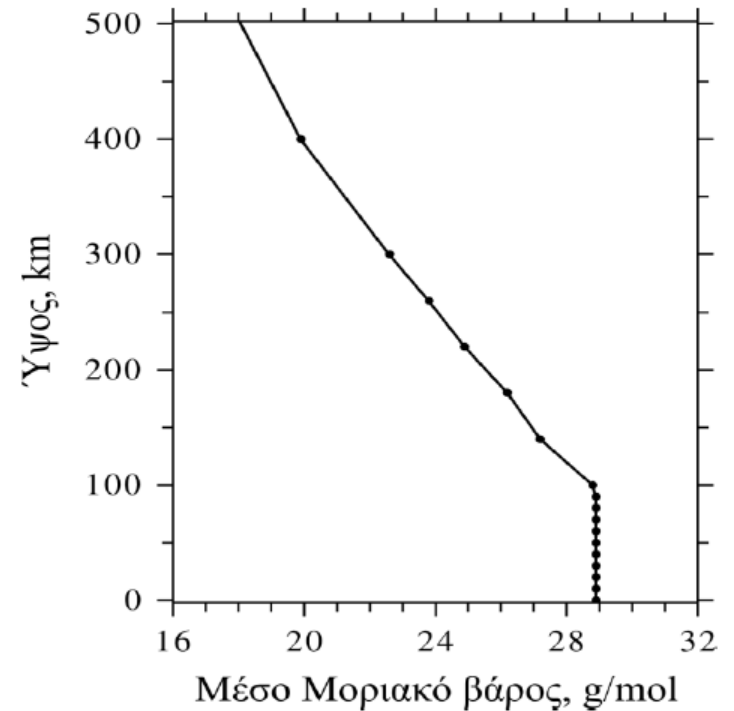
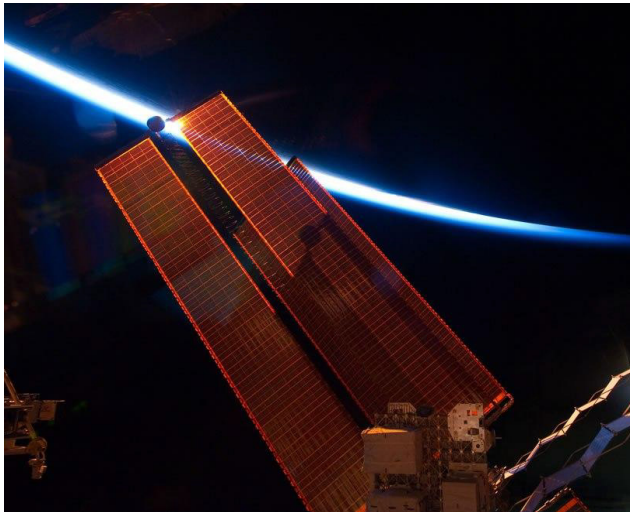
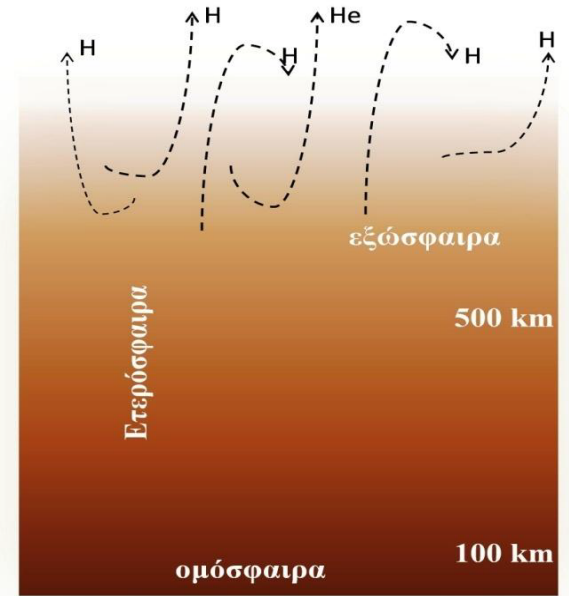
Εθνικό και Καποδιστριακό Πανεπιστήμιο Αθηνών

Εισαγωγή στη φυσική της ατμόσφαιρας

- *Η ατμόσφαιρα της γης*
- *Το πεδίο βαρύτητας της γης*
- *Ατμοσφαιρική χημική σύσταση*
- *Προέλευση της ατμόσφαιρας*
- *Μεταβολή της θερμοκρασίας με το ύψος - Ατμοσφαιρικές περιοχές*
- *Μεταβολή της μάζας με το ύψος*
- *Ομοιόσφαιρα και Ετερόσφαιρα*
- *Εξώσφαιρα*
- *Ιονόσφαιρα*
- *Μαγνητόσφαιρα*

Η ατμόσφαιρα της γης

- Ατμόσφαιρα (εισαγωγικά στοιχεία)
- Ομοιόσφαιρα
- Ετερόσφαιρα
- Εξώσφαιρα
- Οροφή της ατμόσφαιρας



Χ. Χαλδούπης, Εισαγωγή στην Ατμοσφαιρική Φυσική

Το πεδίο βαρύτητας της γης

$$\mathbf{F} = -\frac{GM_E m}{r^2} \hat{\mathbf{r}}$$

$$\mathbf{g} \equiv -G \frac{M_E}{r^2} \hat{\mathbf{r}}$$

$$g = \frac{GM_E}{R_E^2 (1 + z/R_E)^2} = \frac{g_0}{(1 + z/R_E)^2}$$

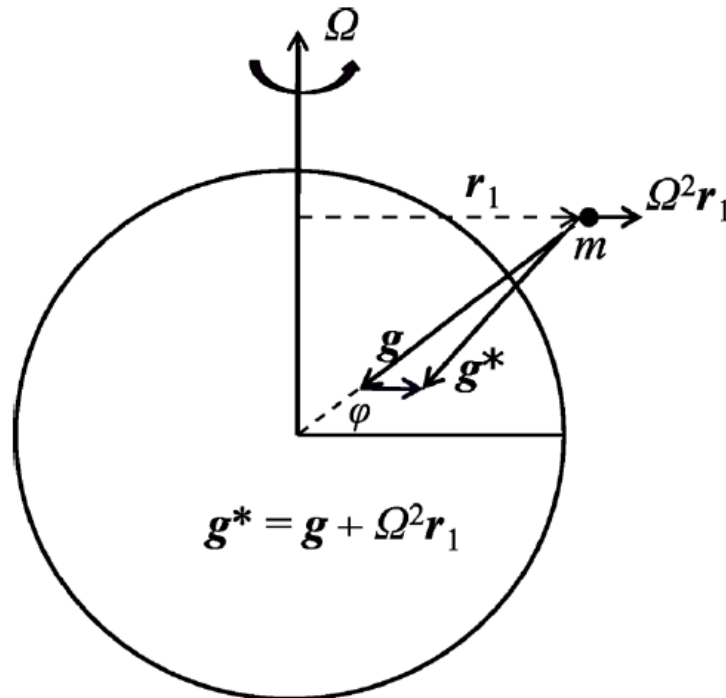
$$g_0 = GM_E/R_E^2$$

$$g = g_0(1 - 2z/R_E)$$

➤ *Ενεργός επιτάχυνση της βαρύτητας*

$$\mathbf{g}^* = \mathbf{g} + \Omega^2 \mathbf{r}_1$$

$$g^* = \frac{GM_E}{R_E^2 (1 + z/R_E)^2} - \Omega^2 (R_E + z) \cos^2 \varphi$$



➤ Γεωδυναμικό

$$\Phi(z) = \int_0^z g dz$$

➤ Γεωδυναμικό ύψος

$$Z = \frac{\Phi(z)}{g_0} = \frac{1}{g_0} \int_0^z g dz$$

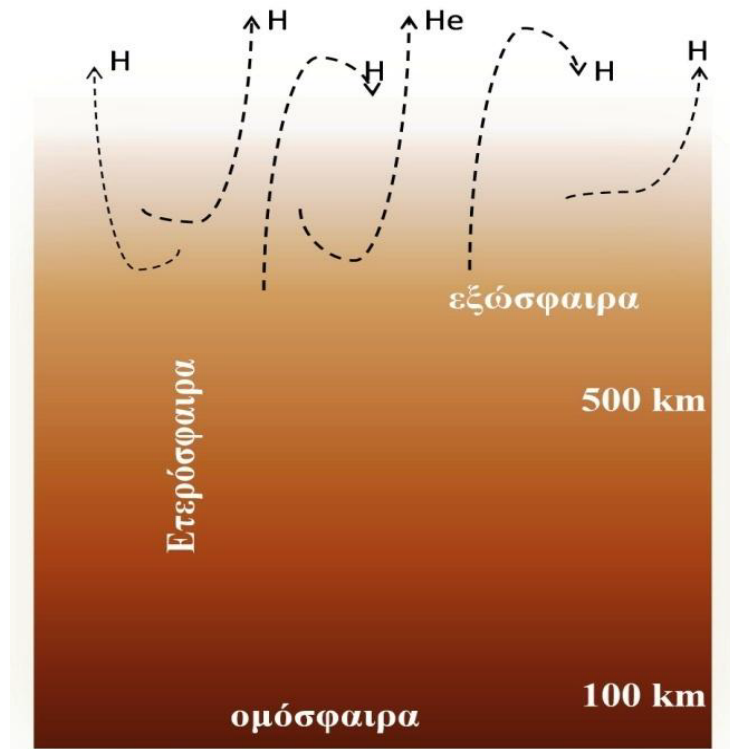
$$\Phi(z) = \frac{GM_E z}{R_E(R_E + z)} - \Omega^2 \cos^2 \varphi \left(R_E + \frac{z}{2} \right) z$$

z (km)	Z (km)	g (m/s ²)
0	0	9.81
1	1.00	9.80
10	9.99	9.77
100	98.47	9.50
500	463.6	8.43

➤ Ταχύτητα διαφυγής

$$v_{\delta} = \sqrt{2g_0 R_E} = \sqrt{\frac{2GM_E}{R_E}}$$

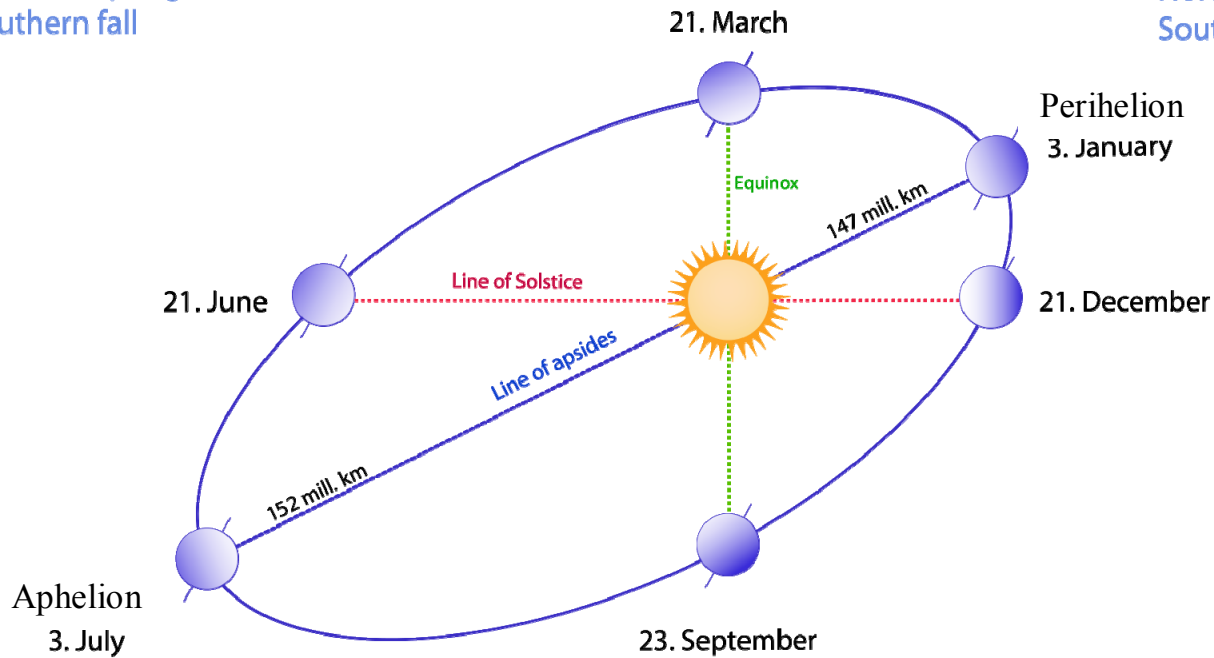
$$v_{\delta} = \sqrt{\frac{2GM_E}{r}} \quad (r=R_E+z)$$



Κινήσεις της γης

Northern spring/
Southern fall

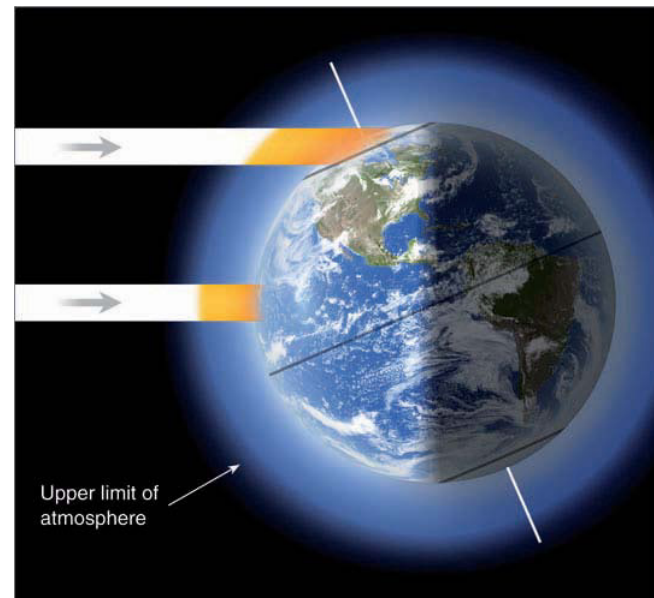
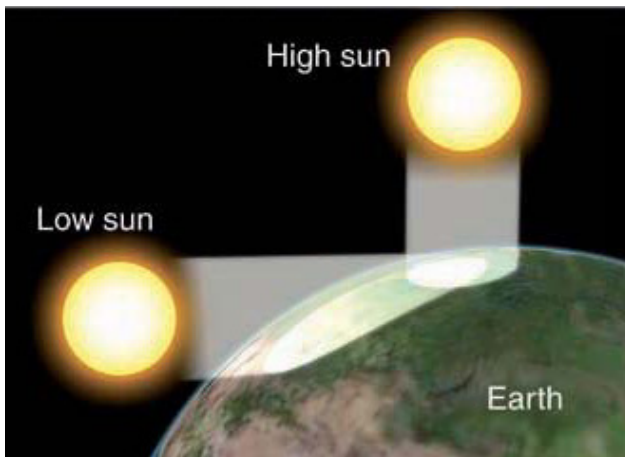
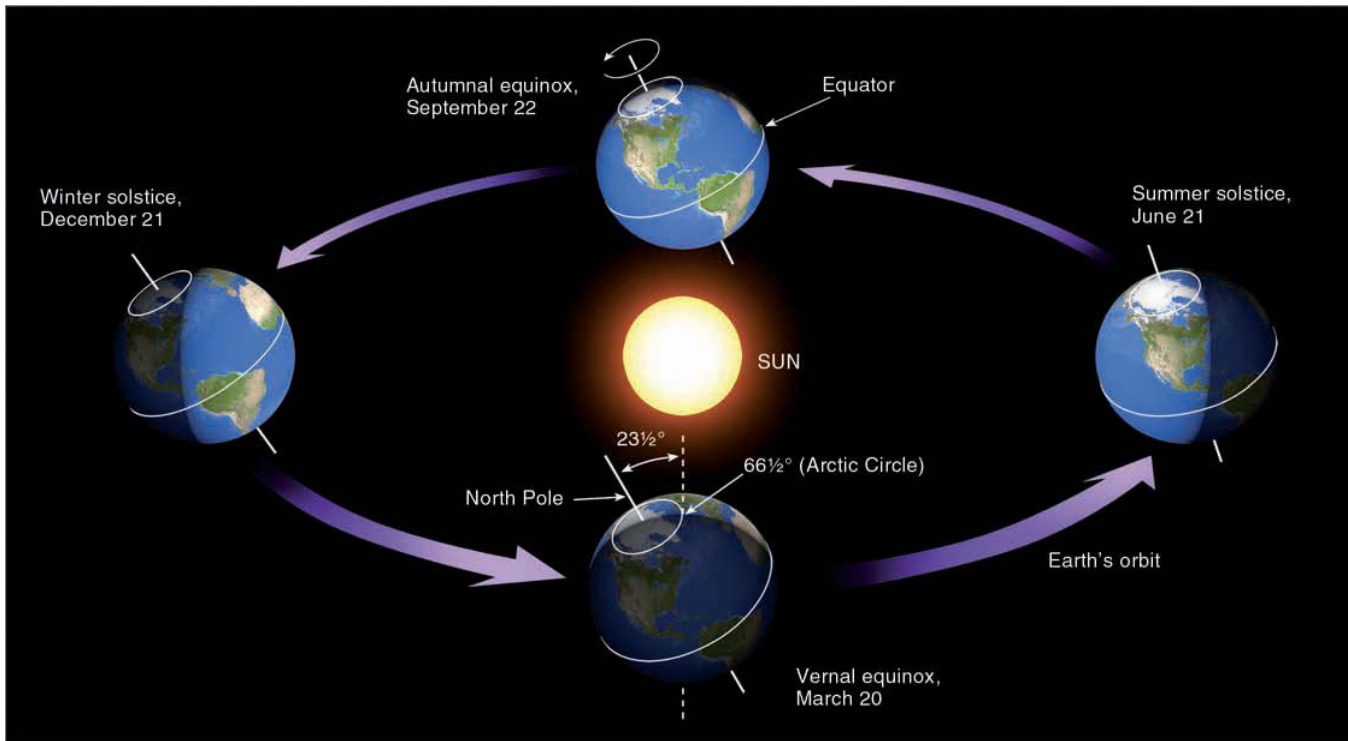
Northern winter/
Southern summer



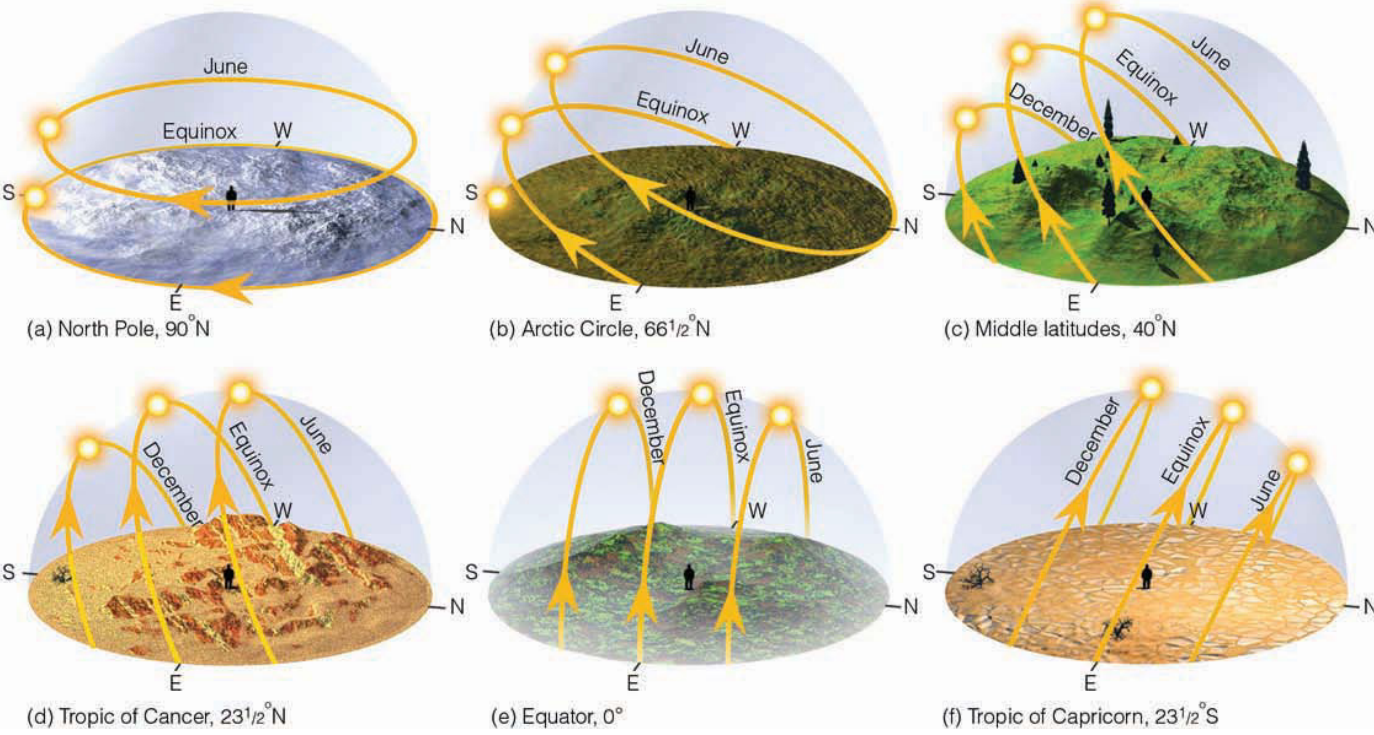
Northern summer/
Southern winter

Northern fall/
Southern spring

<https://commons.wikimedia.org/wiki/File:Seasons1.svg>



Ahrens, 2009



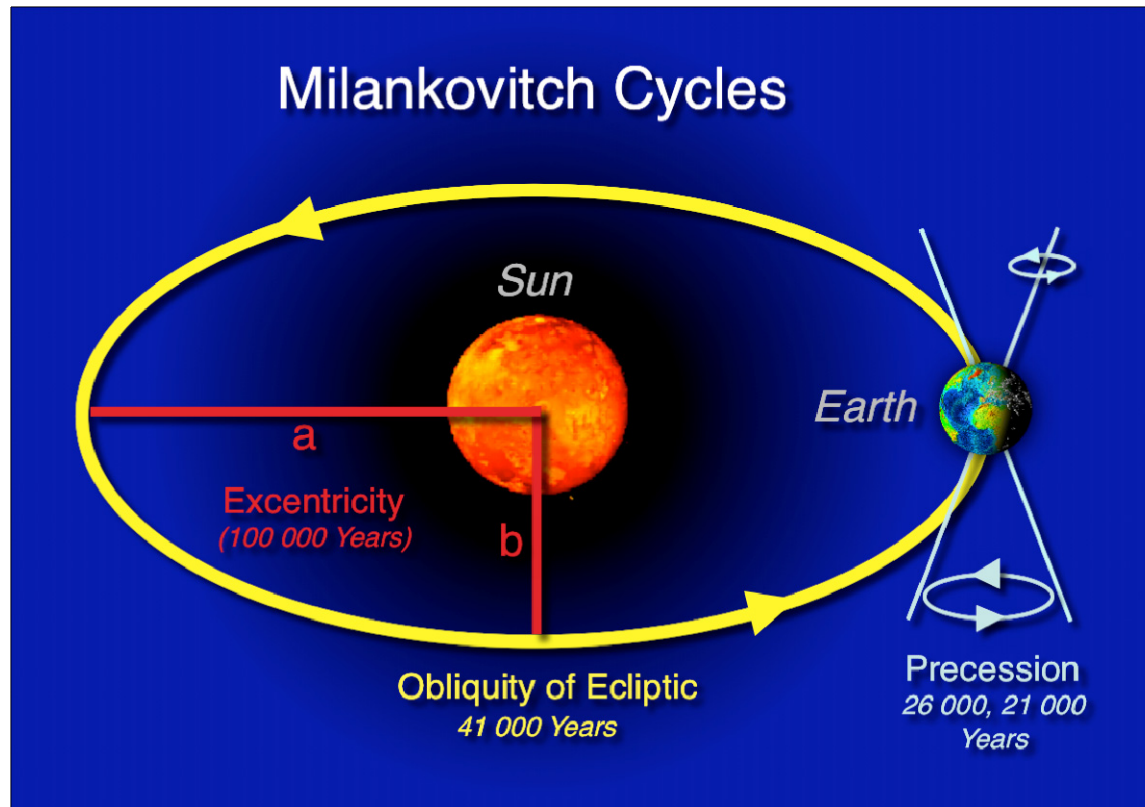
The apparent path of the sun across the sky as observed at different latitudes on the June solstice, the December solstice and the equinox. (Ahrens, 2009)

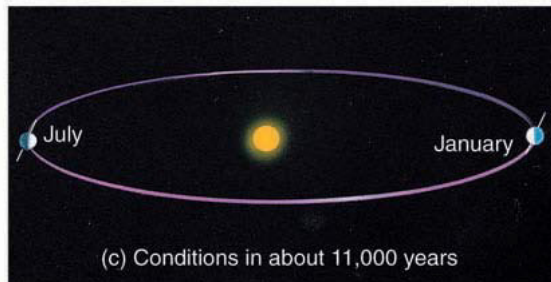
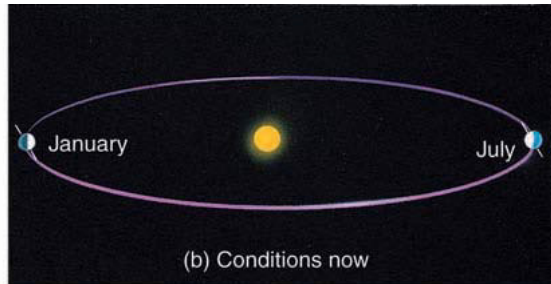
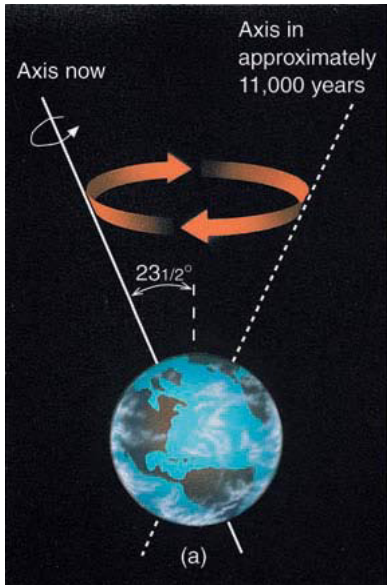
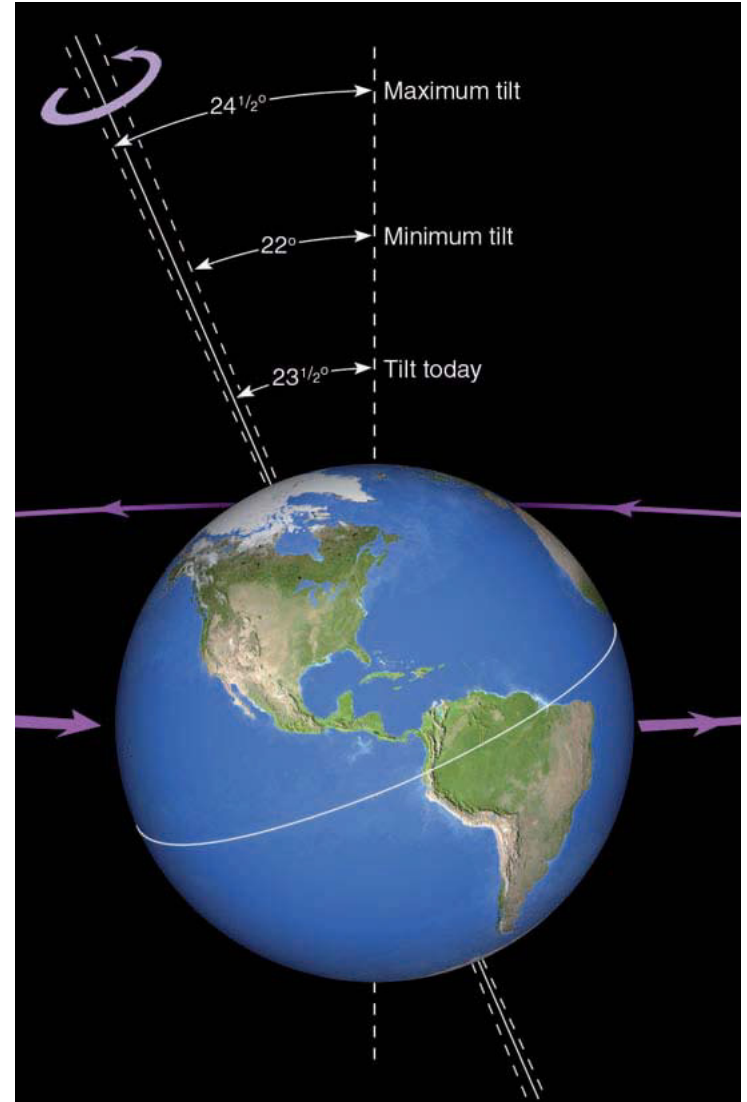
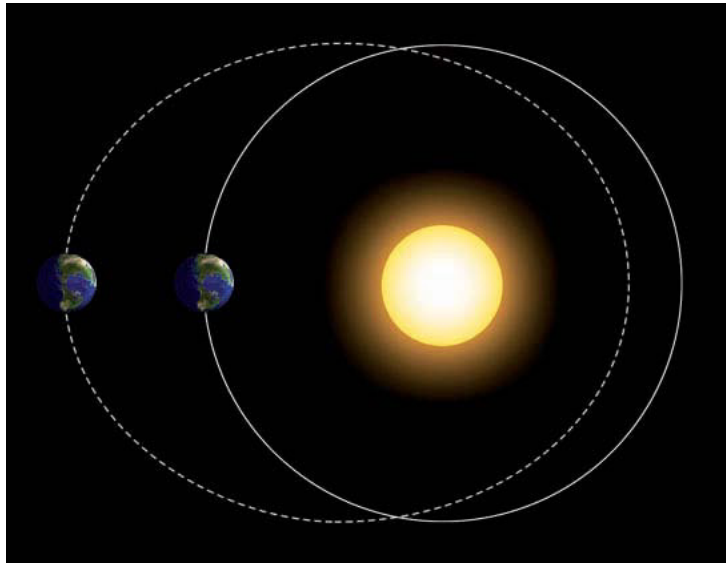
Length of time from sunrise to sunset for various latitudes on different dates in the Northern Hemisphere. (Ahrens, 2009)

LATITUDE	MARCH 20	JUNE 21	SEPT. 22	DEC. 21
0°	12 hr	12.0 hr	12 hr	12.0 hr
10°	12 hr	12.6 hr	12 hr	11.4 hr
20°	12 hr	13.2 hr	12 hr	10.8 hr
30°	12 hr	13.9 hr	12 hr	10.1 hr
40°	12 hr	14.9 hr	12 hr	9.1 hr
50°	12 hr	16.3 hr	12 hr	7.7 hr
60°	12 hr	18.4 hr	12 hr	5.6 hr
70°	12 hr	2 months	12 hr	0 hr
80°	12 hr	4 months	12 hr	0 hr
90°	12 hr	6 months	12 hr	0 hr

Οι κύκλοι του Milankovitch

- Κύκλος της εκκεντρότητας
- Κύκλος της λόξωσης
- Κύκλος της μετάπτωσης





Ahrens, 2009

Ατμόσφαιρα της γης

$$dp = -g\rho dz \quad p(z) = \int_z^{\infty} g\rho dz$$

$$\rho = p \frac{\mu}{R^*T} = \frac{p}{RT}$$

$$dp = -p \frac{\mu g}{R^*T} dz = -\frac{p g}{RT} dz$$

$$p(z) = p_0 \exp\left(-\int_0^z \frac{\mu g}{R^*T} dz\right) = p_0 \exp\left(-\int_0^z \frac{g}{RT} dz\right)$$

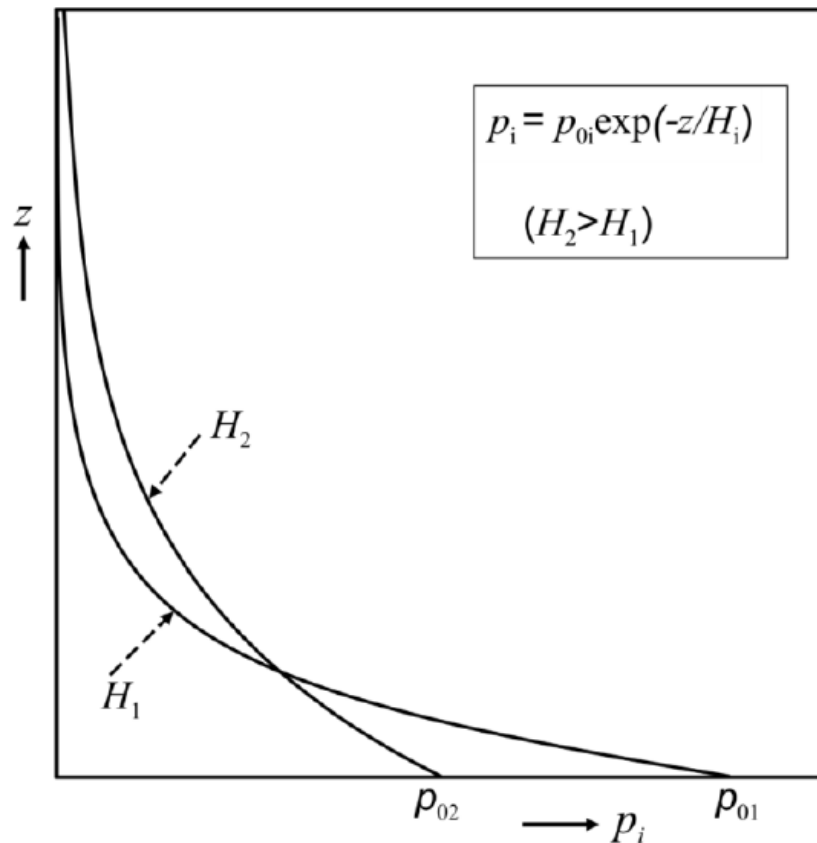
$$\rho(z) = \rho_0 \frac{T_0}{T(z)} \exp\left(-\int_0^z \frac{\mu g}{R^*T} dz\right)$$

$$H = R^*T / \mu g \rightarrow \text{κλίμακα ύψους}$$

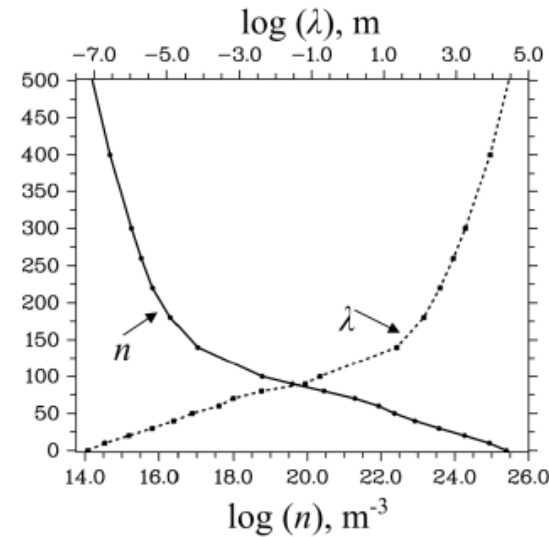
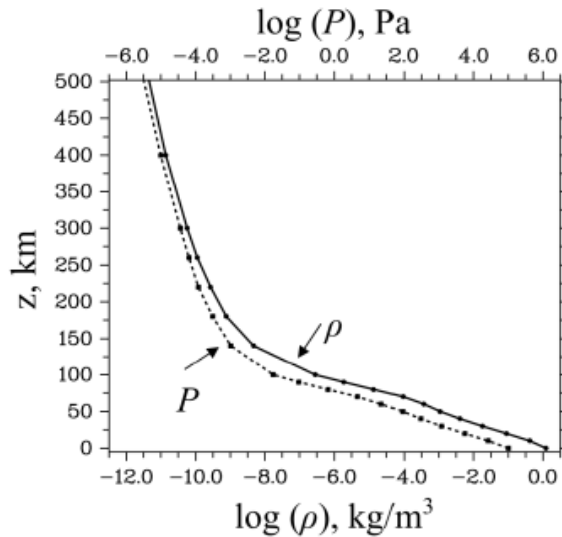
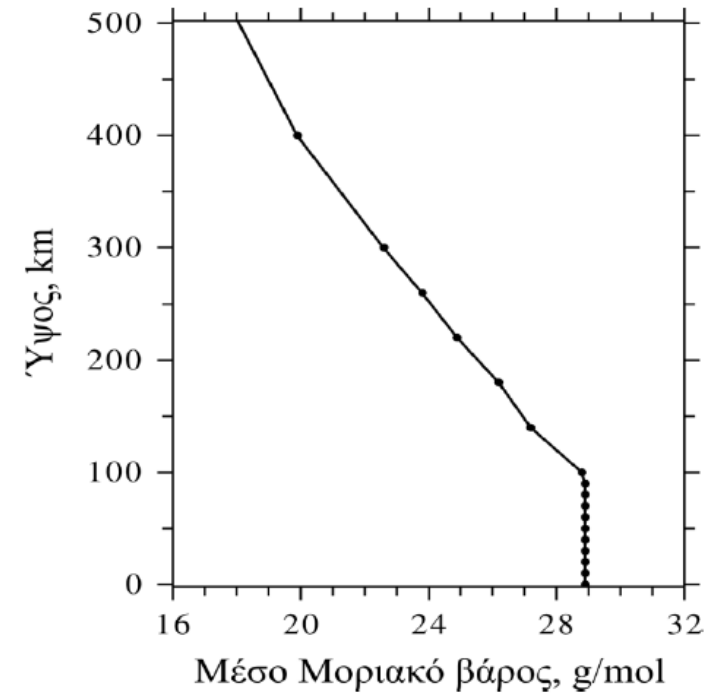
$$\text{Σταθερή θερμοκρασία} \rightarrow p(z) = p_0 e^{-z/H} \quad \rho(z) = \rho_0 e^{-z/H}$$

$$p_i(z) = p_{0i} \exp\left(-\int_0^z \frac{g\mu_i dz}{R^* T(z)}\right) = p_{0i} \exp\left(-\int_0^z \frac{dz}{H_i}\right)$$

$$H_i = R^* T / g\mu_i$$



z (km)	T (K)	ρ (kg/m ³)	p (Pa)	n (m ⁻³)	μ (g/mol)	λ , (m)
0	288	$1,23 \times 10^0$	$1,01 \times 10^5$	$2,60 \times 10^{25}$	28,9	$6,6 \times 10^{-8}$
2	275	$1,01 \times 10^0$	$7,95 \times 10^4$	$1,87 \times 10^{25}$	28,9	$8,1 \times 10^{-8}$
4	262	$8,19 \times 10^{-1}$	$6,15 \times 10^4$	$1,41 \times 10^{25}$	28,9	$9,9 \times 10^{-8}$
6	250	$6,60 \times 10^{-1}$	$4,70 \times 10^4$	$1,08 \times 10^{25}$	28,9	$1,2 \times 10^{-7}$
8	236	$5,26 \times 10^{-1}$	$3,57 \times 10^4$	$7,89 \times 10^{24}$	28,9	$1,6 \times 10^{-7}$
10	223	$4,14 \times 10^{-1}$	$2,65 \times 10^4$	$8,60 \times 10^{24}$	28,9	$1,9 \times 10^{-7}$
20	217	$8,89 \times 10^{-2}$	$5,53 \times 10^3$	$1,85 \times 10^{24}$	28,9	$9,1 \times 10^{-7}$
30	231	$1,79 \times 10^{-2}$	$1,19 \times 10^3$	$3,70 \times 10^{23}$	28,9	$4,0 \times 10^{-6}$
40	260	$4,01 \times 10^{-3}$	$3,00 \times 10^2$	$8,30 \times 10^{22}$	28,9	$1,6 \times 10^{-5}$
50	283	$1,08 \times 10^{-3}$	$9,00 \times 10^1$	$2,30 \times 10^{22}$	28,9	$4,9 \times 10^{-5}$
60	245	$3,70 \times 10^{-4}$	$2,25 \times 10^1$	$7,53 \times 10^{21}$	28,9	$2,7 \times 10^{-4}$
70	173	$9,40 \times 10^{-5}$	$4,70 \times 10^0$	$1,96 \times 10^{21}$	28,9	$6,7 \times 10^{-4}$
80	168	$1,36 \times 10^{-5}$	$6,60 \times 10^{-1}$	$2,84 \times 10^{20}$	28,9	$4,1 \times 10^{-3}$
90	176	$1,88 \times 10^{-6}$	$9,50 \times 10^{-2}$	$3,90 \times 10^{19}$	28,9	$6,5 \times 10^{-1}$
100	210	$2,80 \times 10^{-7}$	$1,74 \times 10^{-2}$	$6,00 \times 10^{18}$	28,8	$1,6 \times 10^{-1}$
140	175	$4,70 \times 10^{-9}$	$1,04 \times 10^{-3}$	$1,07 \times 10^{17}$	27,2	$2,2 \times 10$
180	1150	$7,70 \times 10^{-10}$	$3,10 \times 10^{-4}$	$2,00 \times 10^{16}$	26,2	$1,2 \times 10^2$
220	1295	$2,70 \times 10^{-10}$	$1,20 \times 10^{-4}$	$6,60 \times 10^{15}$	24,9	$3,5 \times 10^2$
260	1375	$1,12 \times 10^{-10}$	$6,40 \times 10^{-5}$	$3,30 \times 10^{15}$	23,8	$8,3 \times 10^2$
300	1430	$5,70 \times 10^{-11}$	$3,60 \times 10^{-5}$	$1,80 \times 10^{15}$	22,6	$1,8 \times 10^3$
400	1485	$1,38 \times 10^{-11}$	$9,80 \times 10^{-6}$	$4,70 \times 10^{14}$	19,9	$8,6 \times 10^3$
500	1495	$4,10 \times 10^{-12}$	$2,90 \times 10^{-6}$	$1,40 \times 10^{14}$	17,9	$3,2 \times 10^4$

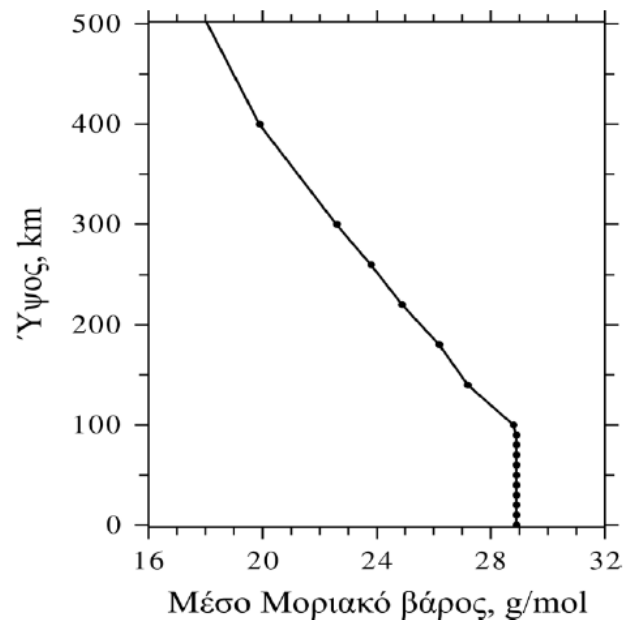


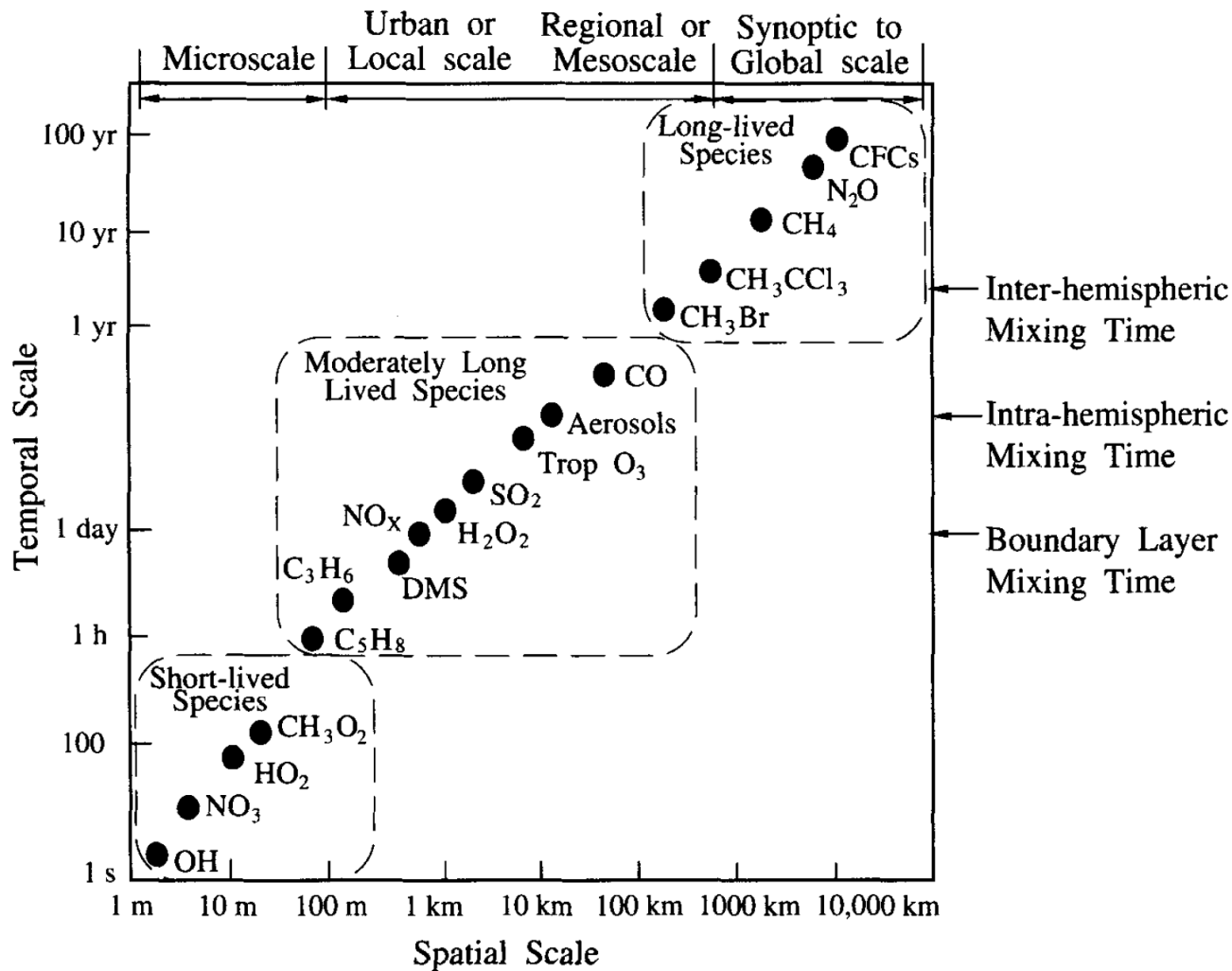
Ατμοσφαιρική χημική σύσταση

➤ Ομοιόσφαιρα

➤ Ετερόσφαιρα

	Συστατικό	Μορ. Βάρος	Αναλογία
1	Άζωτο (N ₂)	28,02	78,08 %
2	Οξυγόνο (O ₂)	32,00	20,95 %
3	Αργό (Ar)	39,94	0,93 %
4	Υδρατμοί (H ₂ O)	18,02	0,01–5 %
5	Διοξ. Άνθρακα (CO ₂)	44,01	400 ppm
6	Νέο (Ne)	20,18	18 ppm
7	Ήλιο (He)	4,00	5 ppm
8	Κρυπτό (Kr)	83,70	1 ppm
9	Υδρογόνο (H ₂)	2,02	0,5 ppm
10	Όζον (O ₃)	48,00	1–12 ppm





Spatial and temporal scales of variability for atmospheric constituents. (Seinfeld and Pandis, 2006)

➤ **Συστατικά που περιέχουν θείο**

- H_2S (υδρόθειο)
- DMS (διμεθυλοσουλφίδιο, CH_3SCH_3)
- CS_2 (διθειάνθρακας)
- OCS (καρβονυλικό σουλφίδιο)
- SO_2 (διοξείδιο του θείου)
- H_2SO_4 (θειϊκό οξύ), κ.λπ.

➤ **Συστατικά που περιέχουν άζωτο**

- N_2O (υποξείδιο του αζώτου)
- NO (μονοξείδιο του αζώτου)
- NO_2 (διοξείδιο του αζώτου)
- HNO_3 (νιτρικό οξύ)
- NH_3 (αμμωνία), κ.λπ.

➤ **Συστατικά που περιέχουν άνθρακα**

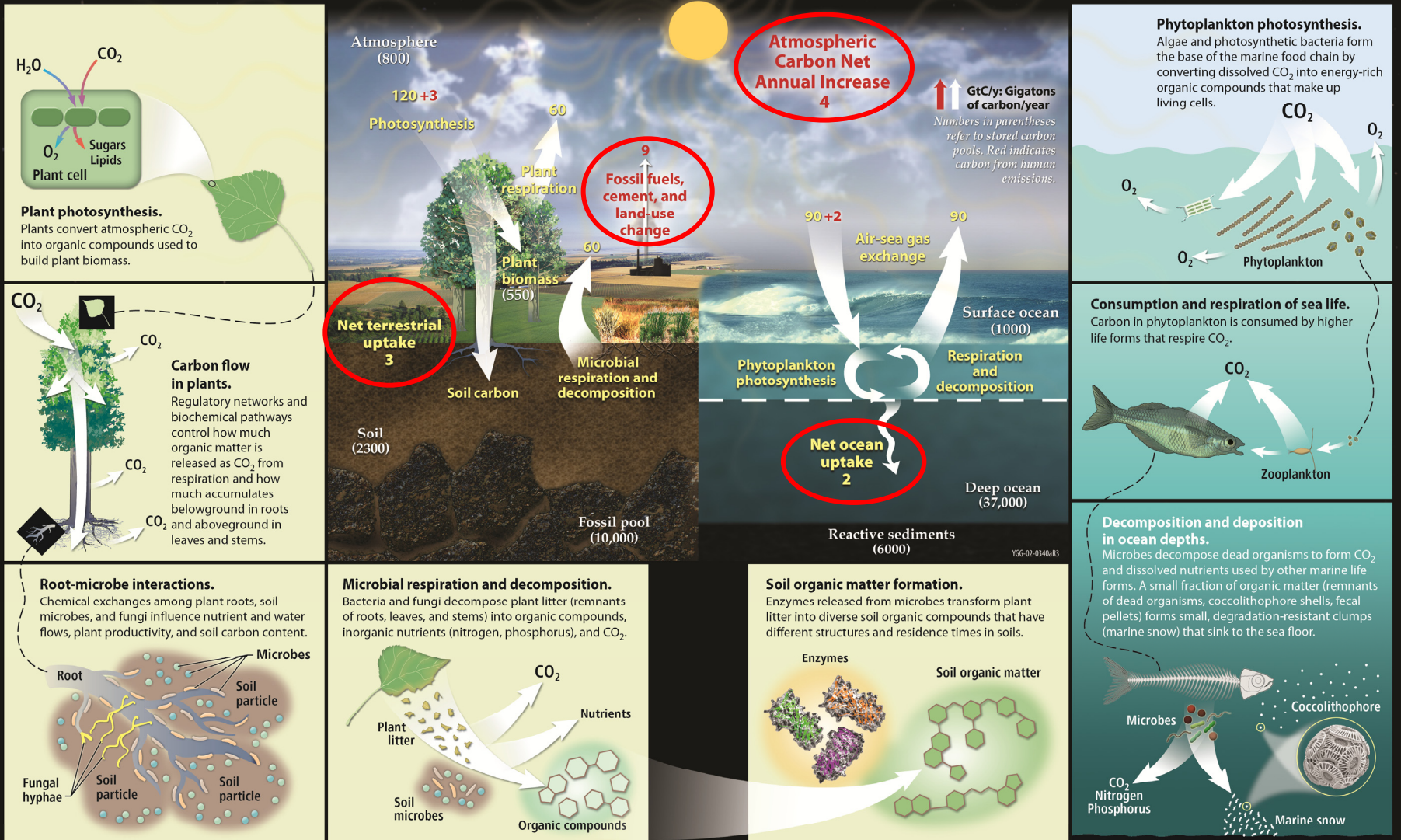
- $NMHCs$ (μη μεθανικοί υδρογονάνθρακες)
- CH_4 (μεθάνιο)
- $VOCs$ (πτητικές οργανικές ενώσεις)
- Βιογενείς υδρογονάνθρακες (π.χ. ισοπρένιο, C_5H_8)
- CO (μονοξείδιο του άνθρακα)
- CO_2 (διοξείδιο του άνθρακα), κ.λπ.

➤ **Συστατικά που περιέχουν αλογόνα**

- O_3 (όζον), OH (υδροξύλιο), κ.λπ.

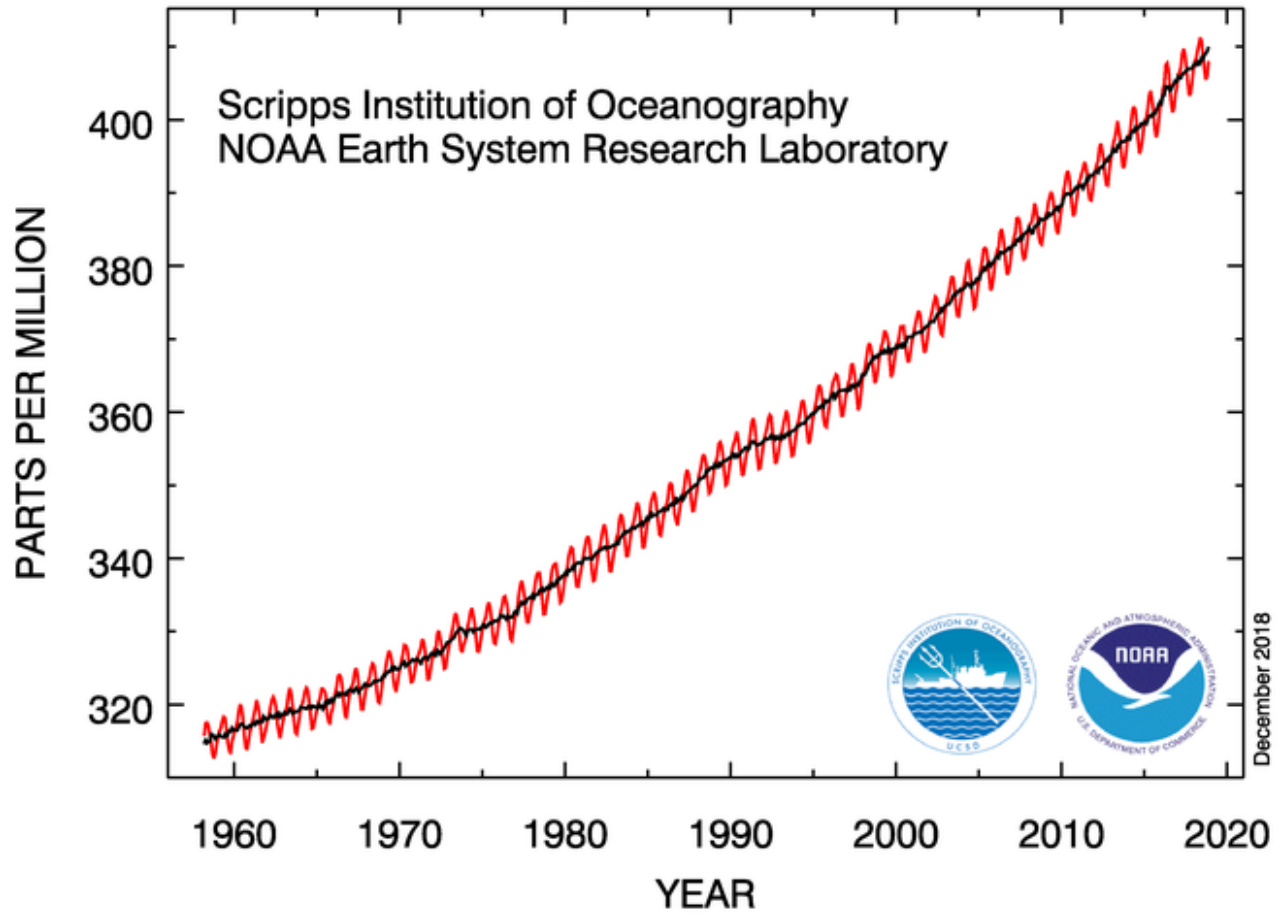
Διοξείδιο του άνθρακα

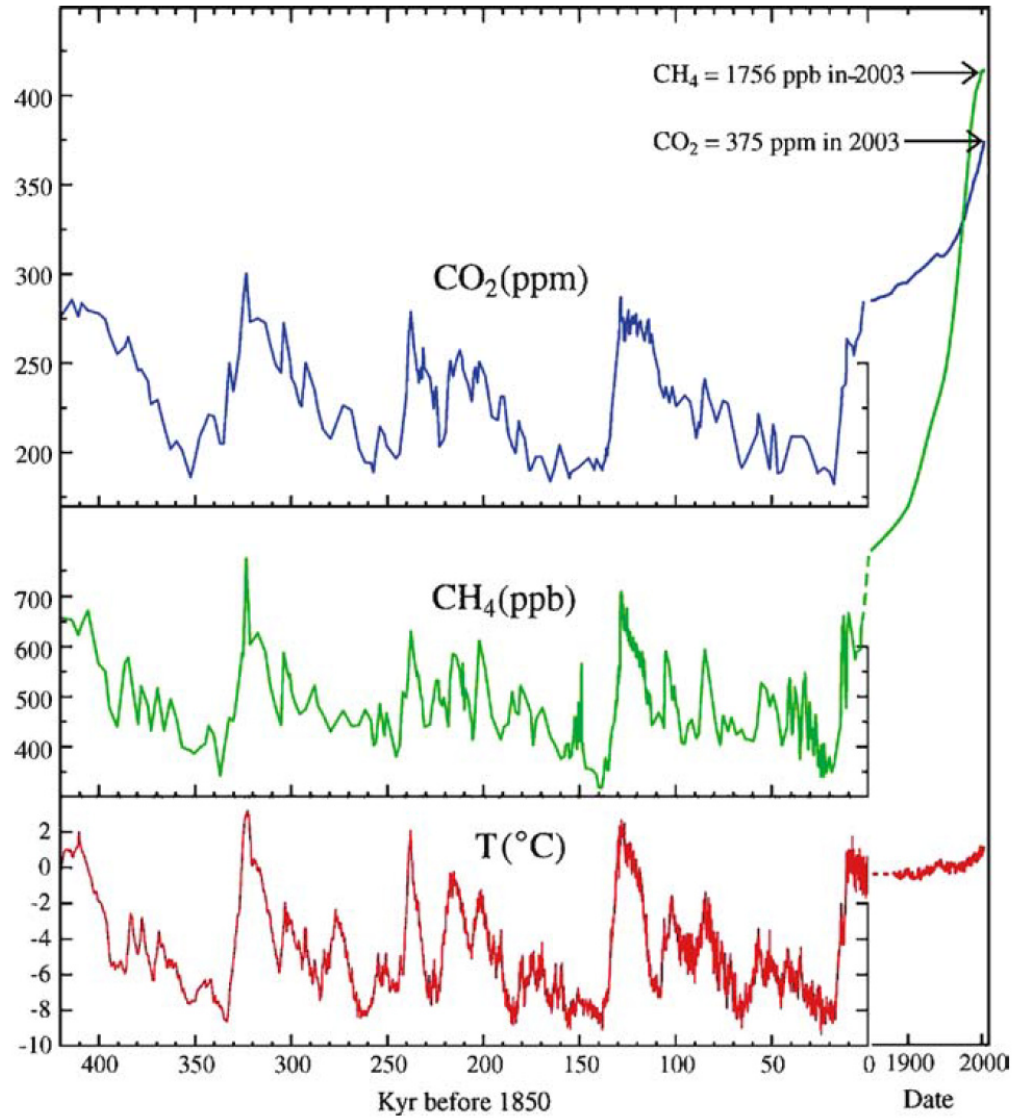
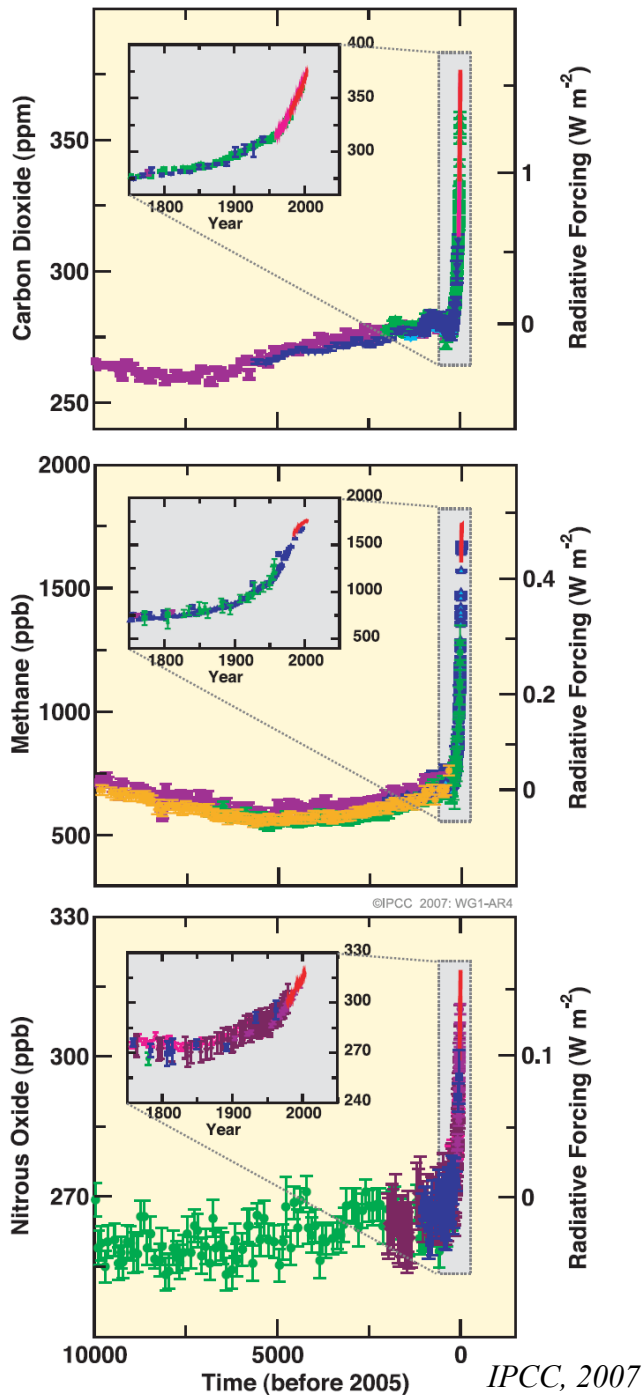
Components of the Global Carbon Cycle



Movement of carbon between land, atmosphere and oceans. Yellow numbers are natural fluxes, red are human contributions and white numbers indicate stored carbon. (U.S. Department of Energy Genomic Science program, <https://genomicscience.energy.gov/>)

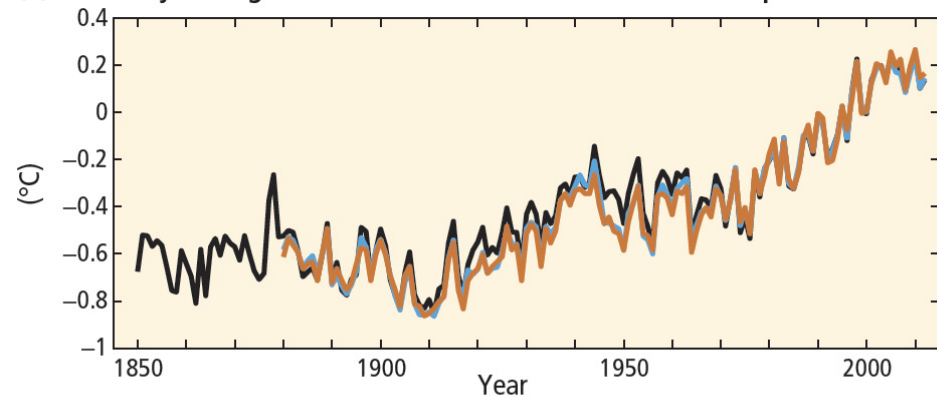
Atmospheric CO₂ at Mauna Loa Observatory



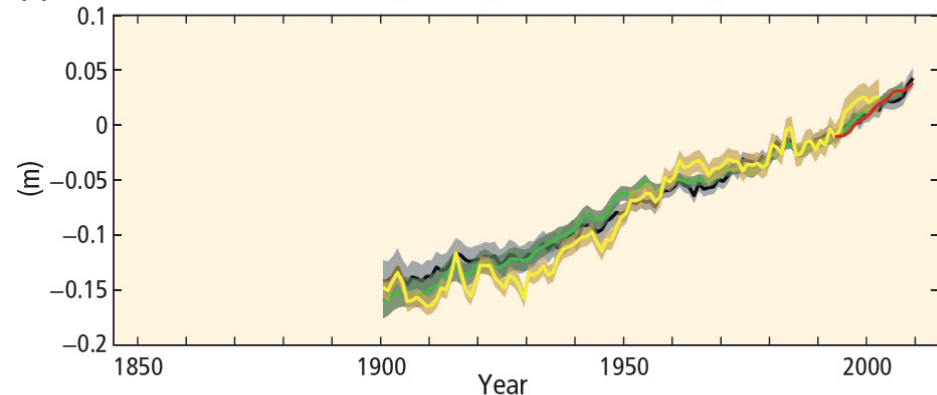


*The temperature zero-point is the mean for 1880–1899.
(Hansen, 2005)*

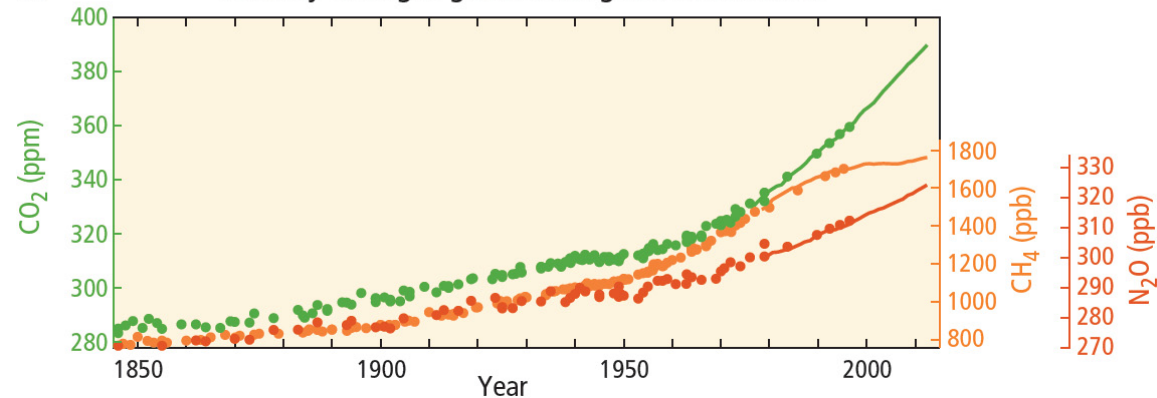
(a) Globally averaged combined land and ocean surface temperature anomaly



(b) Globally averaged sea level change



(c) Globally averaged greenhouse gas concentrations



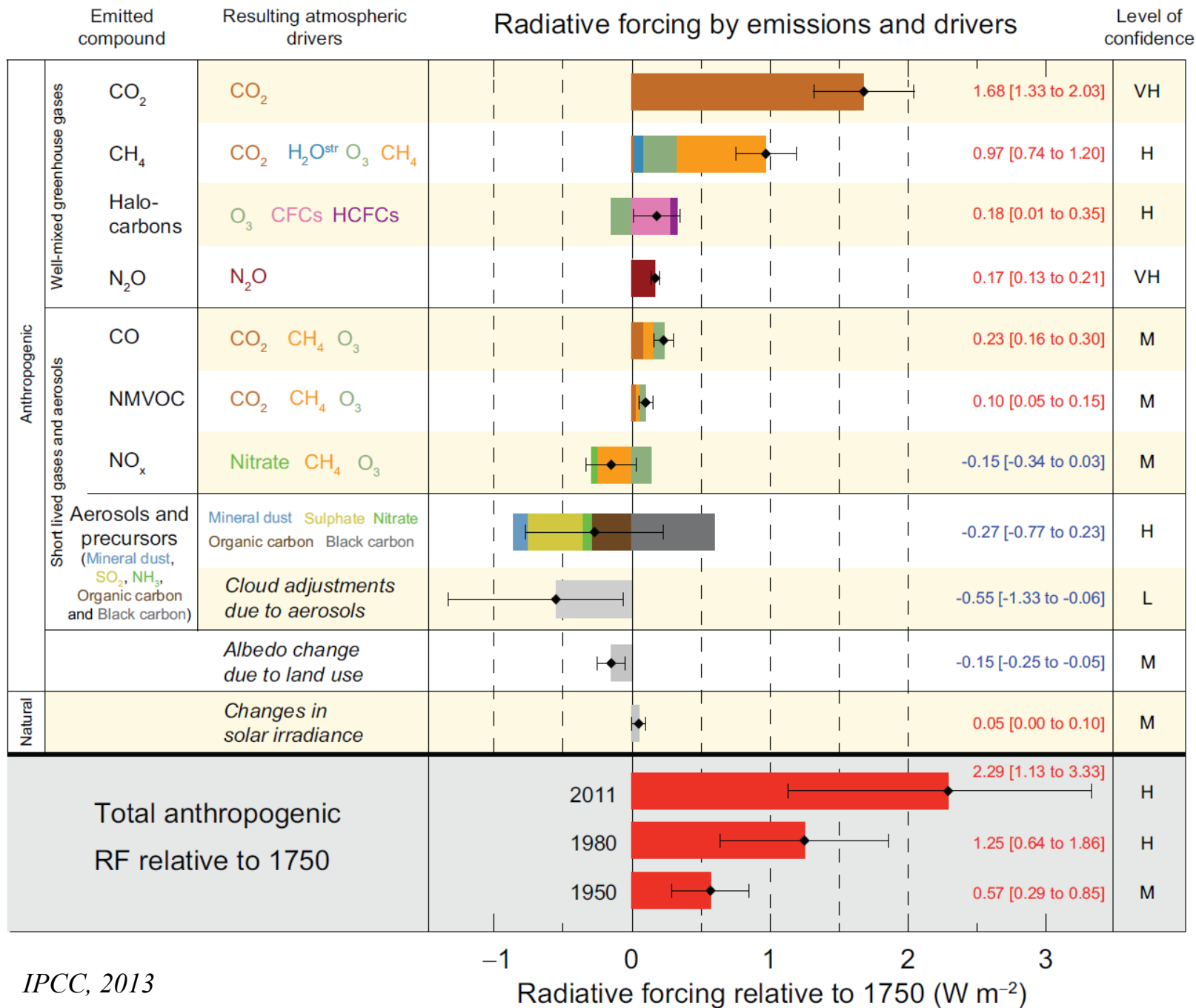
(a) Annually and globally averaged combined land and ocean surface T anomalies relative to the average over the period 1986 to 2005.

Colours indicate different data sets.

(b) Annually and globally averaged sea level change relative to the average over the period 1986 to 2005 in the longest-running dataset.

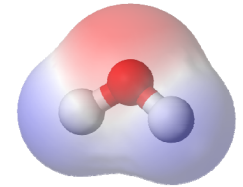
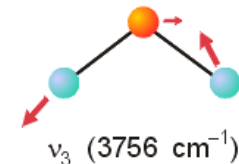
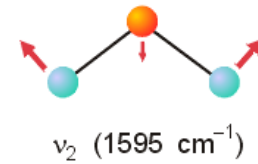
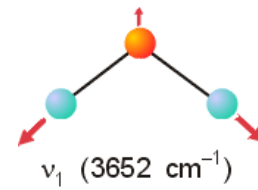
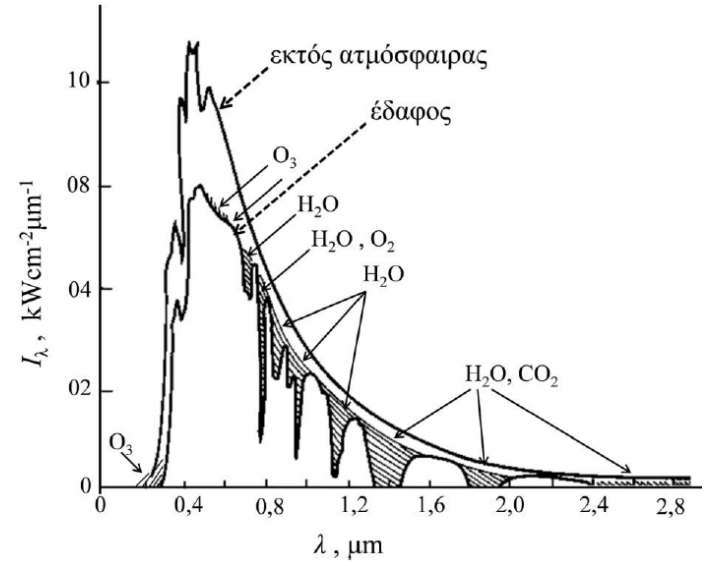
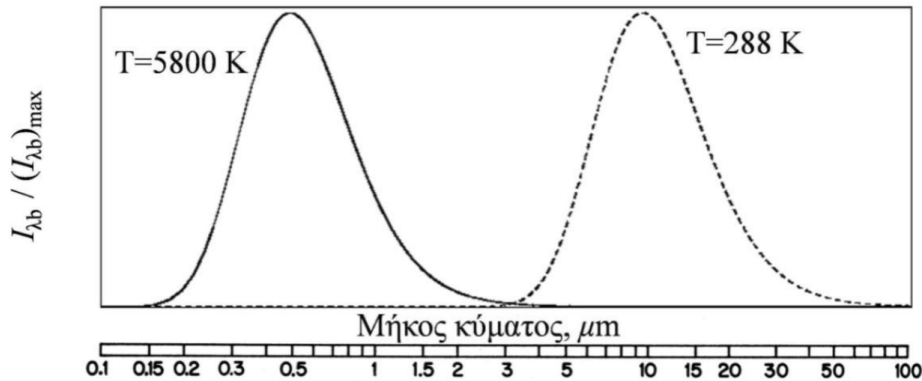
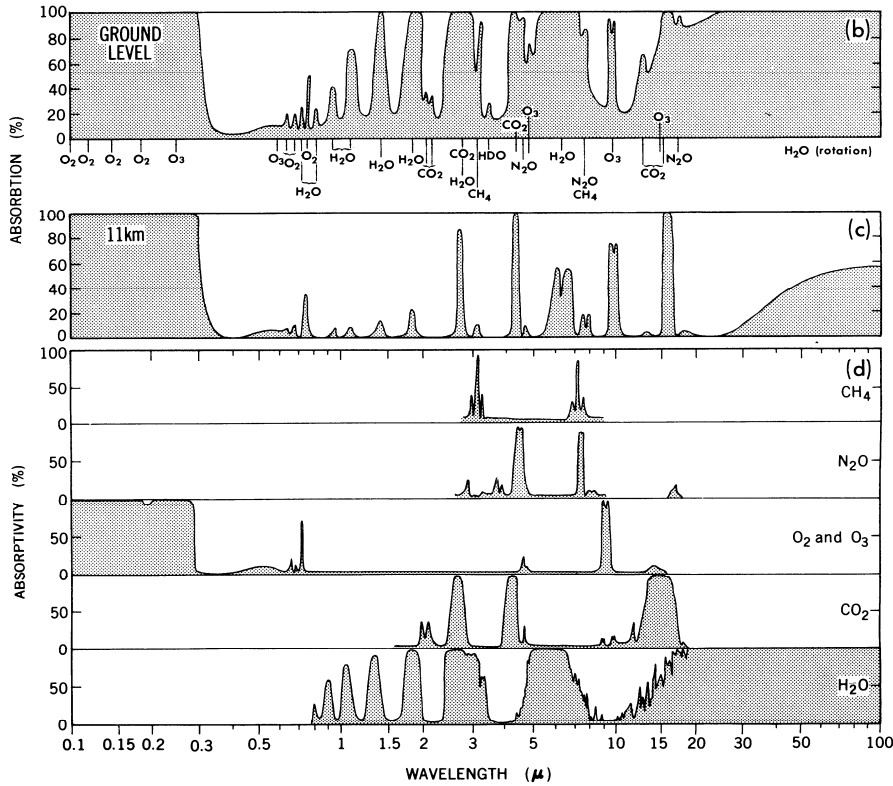
Colours indicate different data sets. All datasets are aligned to have the same value in 1993, the first year of satellite altimetry data (red). Where assessed, uncertainties are indicated by coloured shading.

(c) Atmospheric concentrations of (CO_2 , green), (CH_4 , orange) and (N_2O , red) determined from ice core data (dots) and from direct atmospheric measurements (lines). (IPCC, 2014)

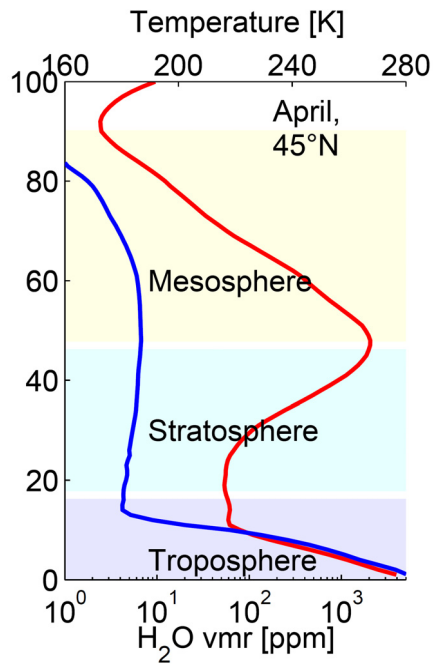


Υδρατμοί

Peixoto and Ort, 1993

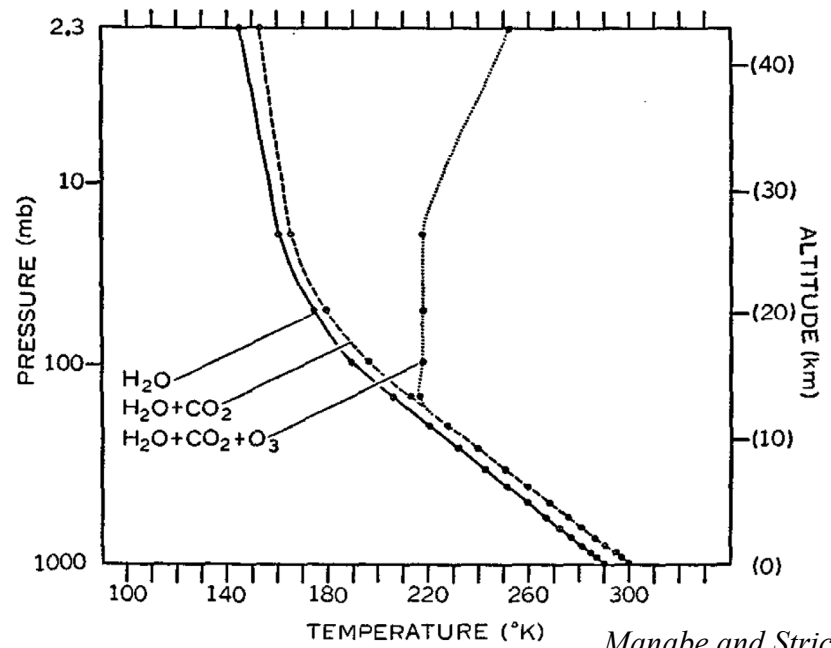


H₂O
(6.3 μm)

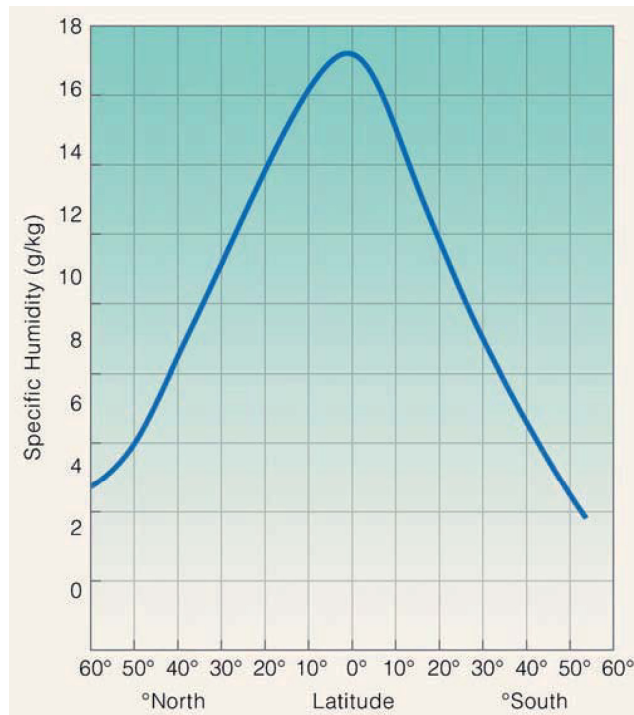


— Temperature
— Water vapor

Straub, 2010



Manabe and Strickler, 1964



Ahrens, 2009

Radiative forcing of surface climate per 1 km thick layers at 35°N for observed stratospheric H₂O decrease

Water Vapor & Radiative Processes

Shading indicates June average H₂O mixing ratio: Minimum values are shown in light blue

Contours show June average temperatures: coldest temperatures are just above the tropical tropopause

W/m²
0

Reflected and Scattered Solar Radiation

Incoming Solar Radiation

Brewer Dobson (Diabatic) Circulation

Slow Ascent

Cirrus

Tropopause

Longwave radiation

Equator

40°N

~30 km

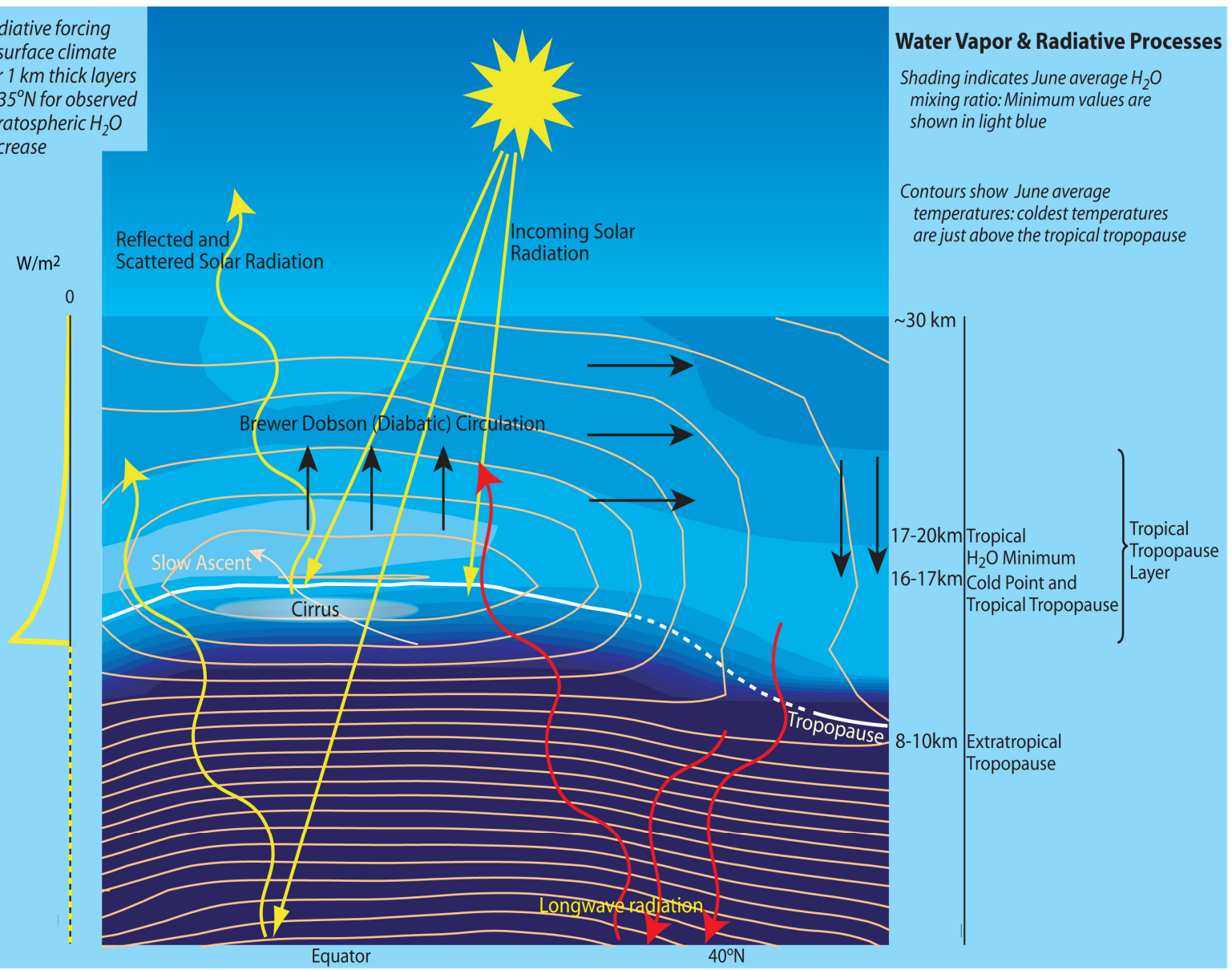
17-20km

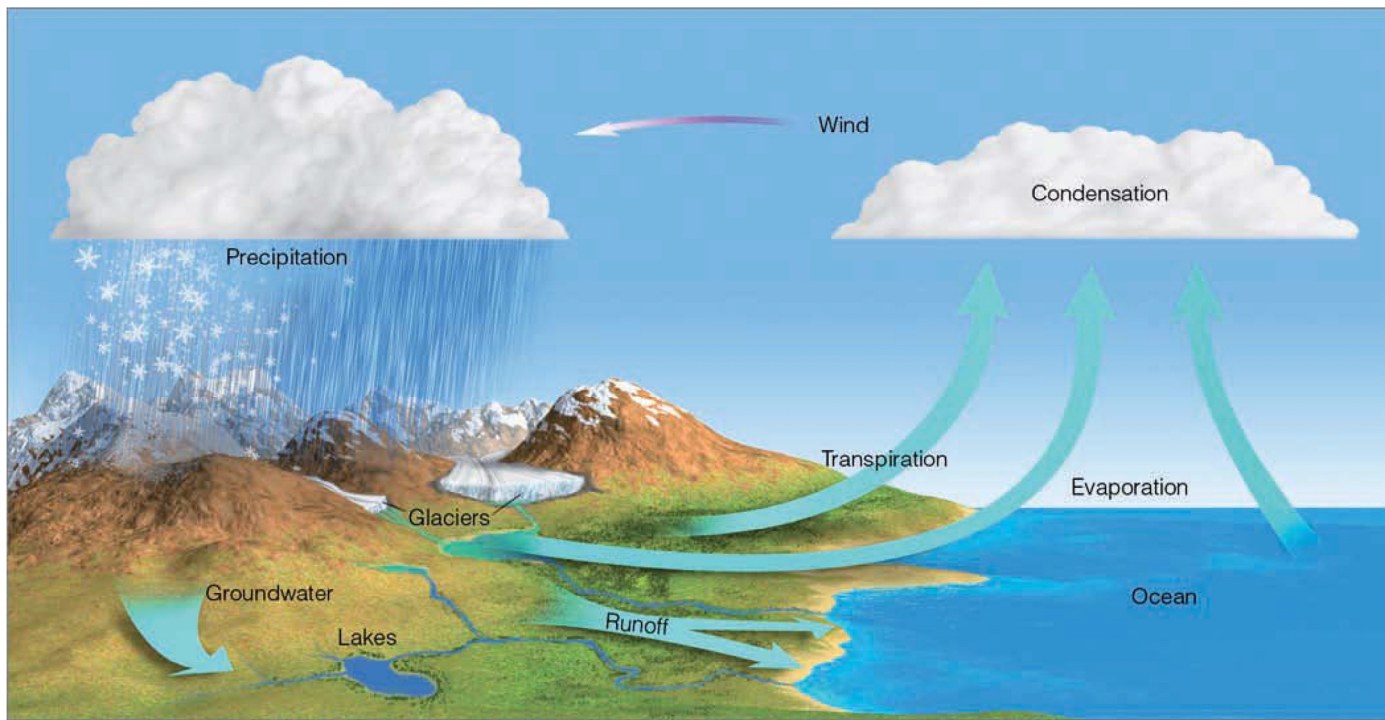
16-17km

8-10km

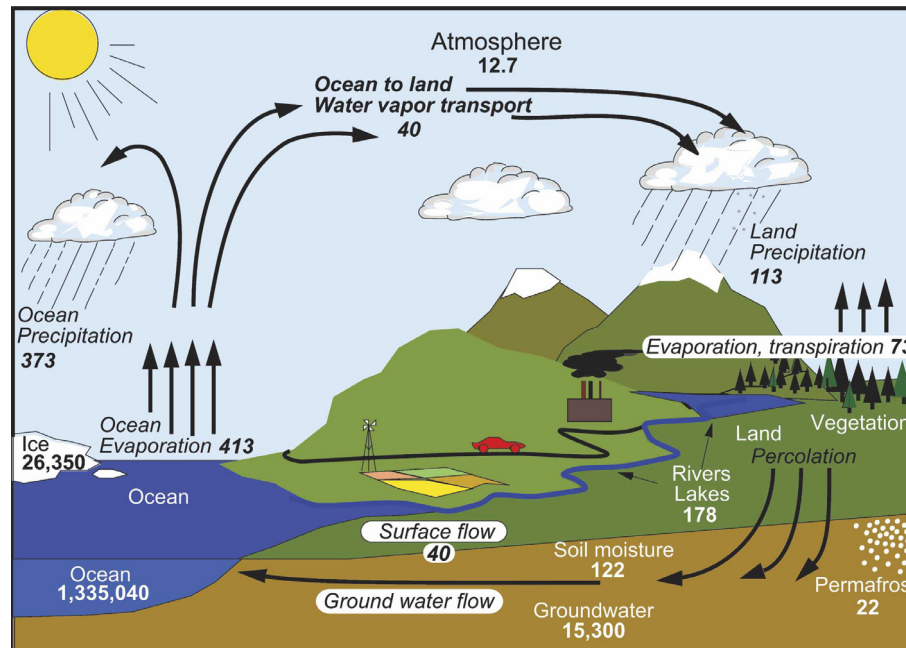
Tropical H₂O Minimum Cold Point and Tropical Tropopause Layer

Extratropical Tropopause





Ahrens, 2009



Units: Thousand cubic km for storage, and thousand cubic km/yr for exchanges

The hydrological cycle.
(Trenberth et al., 2007)

Water in major global reservoirs. (Seinfeld and Pandis, 2006)

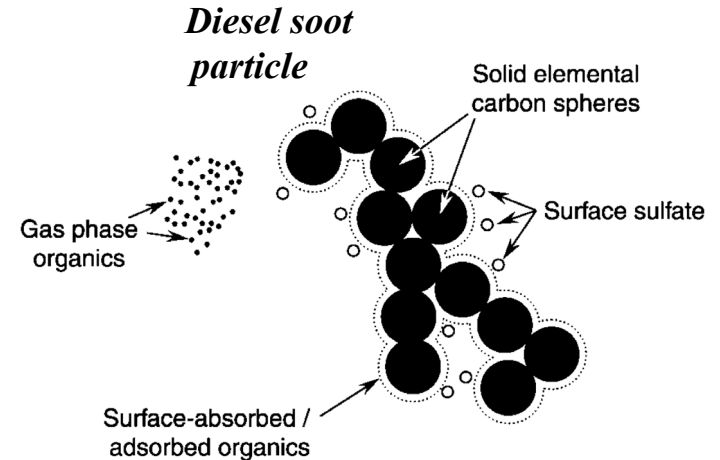
Reservoir	Volume of water, km ³	Percentage of total
Oceans	1,370,000,000	97.25
Glaciers and ice sheets	29,000,000	2.05
Underground aquifers	9,565,000	0.69
Lakes	125,000	0.01
Rivers	1,700	0.0001
Atmosphere	13,000	0.001
Biosphere	600	0.00001
Total	1,408,705,300	100

Water fluxes between reservoirs. (Seinfeld and Pandis, 2006)

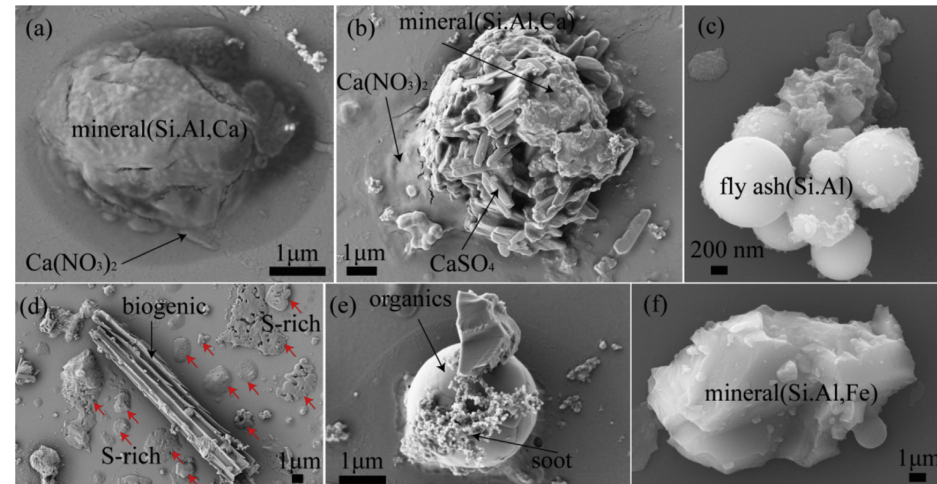
Reservoirs	Process	Flux, km ³ yr ⁻¹
Ocean–atmosphere	Evaporation	400,000
	Precipitation	370,000
Land masses–atmosphere	Evaporation	60,000
	Precipitation	90,000
Land masses–ocean	Runoff	30,000

Ατμοσφαιρικά σωματίδια

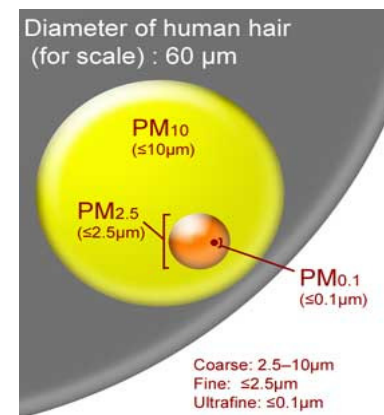
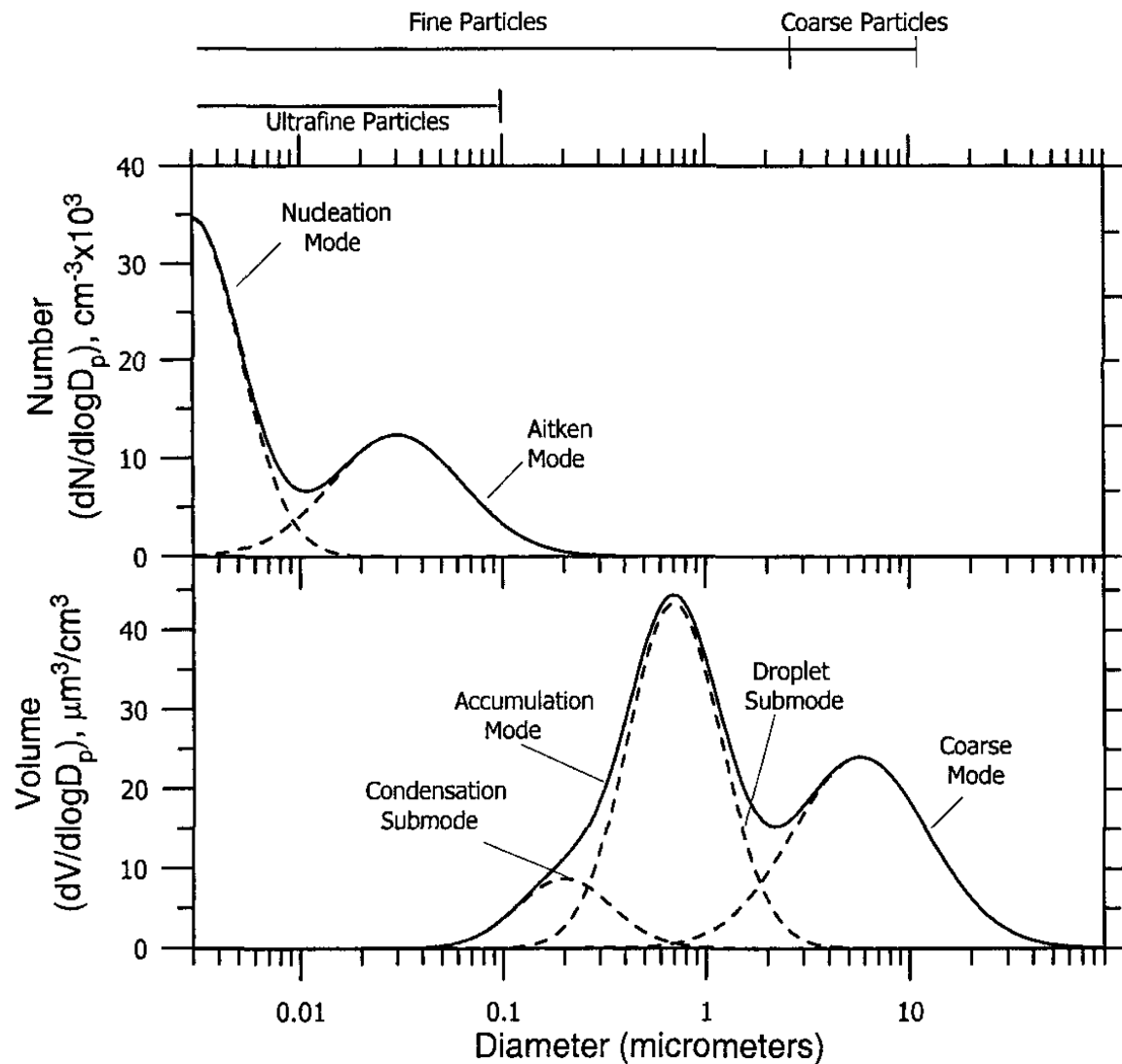
- *Aerosols*
- *Particulate matter (PM)*
- *Μέγεθος αιωρούμενων σωματιδίων*
- *Μορφές αιωρούμενων σωματιδίων*
- *Πηγές*
- *Δημιουργία των σωματιδίων*
- *Απομάκρυνση (Ξηρή -Υγρή εναπόθεση)*
- *Χημική σύσταση*
- *Ιδιότητες*
- *Επιδράσεις*



Finlayson-Pitts and Pitts, 2000



Li et al., 2016



Typical number and volume distributions of atmospheric particles with the different modes. (Seinfeld and Pandis, 2006)

Terminology relating to atmospheric particles. (Seinfeld and Pandis, 2006)

Aerosols, aerocolloids, aerodisperse systems	Tiny particles dispersed in gases
Dusts	Suspensions of solid particles produced by mechanical disintegration of material such as crushing, grinding, and blasting; $D_p > 1 \mu\text{m}$
Fog	A term loosely applied to visible aerosols in which the dispersed phase is liquid; usually, a dispersion of water or ice, close to the ground
Fume	The solid particles generated by condensation from the vapor state, generally after volatilization from melted substances, and often accompanied by a chemical reaction such as oxidation; often the material involved is noxious; $D_p < 1 \mu\text{m}$
Hazes	An aerosol that impedes vision and may consist of a combination of water droplets, pollutants, and dust; $D_p < 1 \mu\text{m}$
Mists	Liquid, usually water in the form of particles suspended in the atmosphere at or near the surface of the Earth; small water droplets floating or falling, approaching the form of rain, and sometimes distinguished from fog as being more transparent or as having particles perceptibly moving downward; $D_p > 1 \mu\text{m}$
Particle	An aerosol particle may consist of a single continuous unit of solid or liquid containing many molecules held together by intermolecular forces and primarily larger than molecular dimensions ($>0.001 \mu\text{m}$); a particle may also consist of two or more such unit structures held together by interparticle adhesive forces such that it behaves as a single unit in suspension or on deposit
Smog	A term derived from smoke and fog, applied to extensive contamination by aerosols; now sometimes used loosely for any contamination of the air
Smoke	Small gasborne particles resulting from incomplete combustion, consisting predominantly of carbon and other combustible materials, and present in sufficient quantity to be observable independently of the presence of other solids. $D_p \geq 0.01 \mu\text{m}$
Soot	Agglomerations of particles of carbon impregnated with "tar," formed in the incomplete combustion of carbonaceous material

Global emission estimates for major aerosol classes.

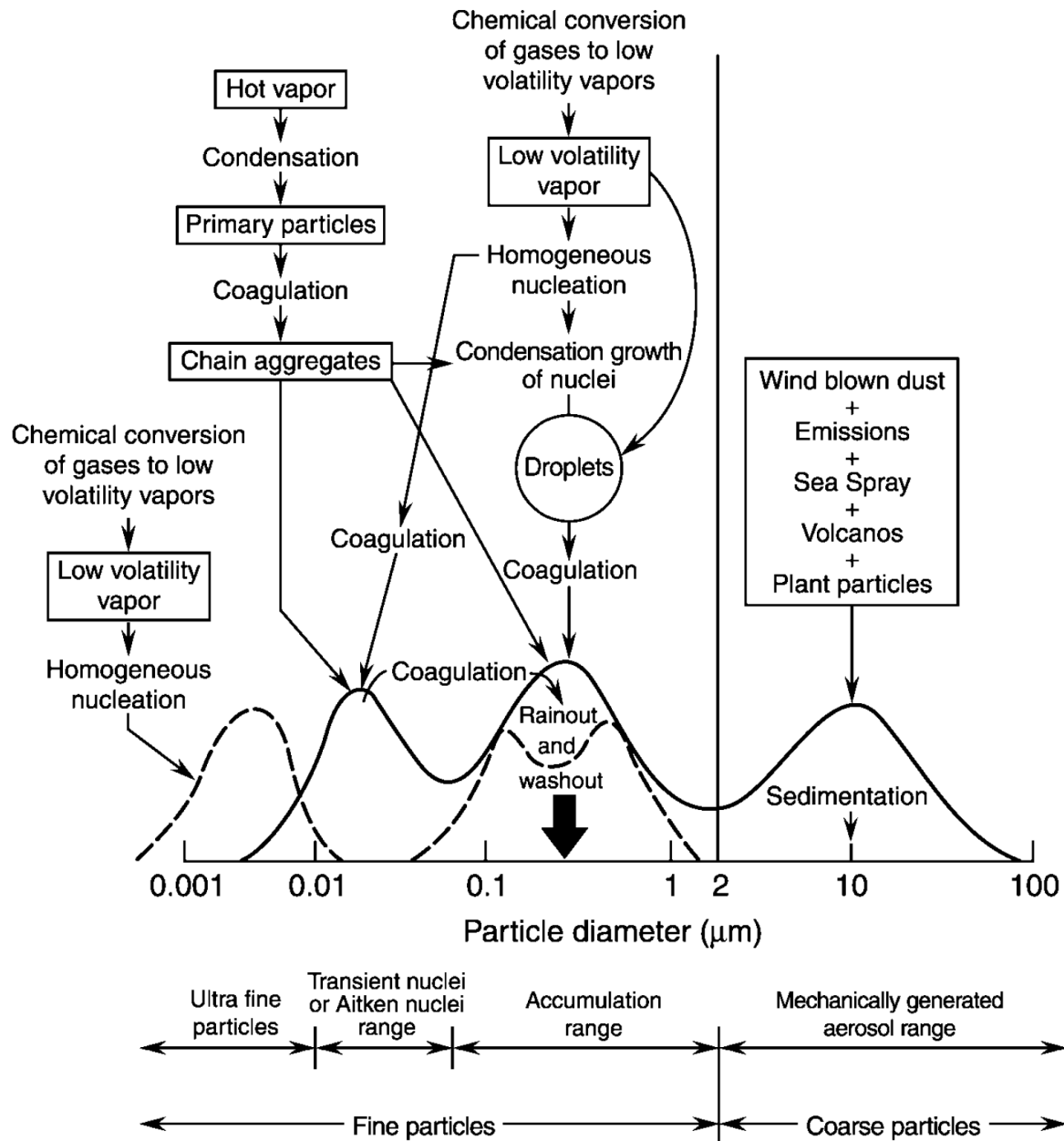
Source	Estimated Flux, Tg yr ⁻¹
Natural	
Primary	
Mineral dust	
0.1–1.0 μm	48
1.0–2.5 μm	260
2.5–5.0 μm	609
5.0–10.0 μm	573
0.1–10.0 μm	1490
Seasalt	10,100
Volcanic dust	30
Biological debris	50
Secondary	
Sulfates from DMS	12.4
Sulfates from volcanic SO ₂	20
Organic aerosol from biogenic VOC	11.2
Anthropogenic	
Primary	
Industrial dust (except black carbon)	100
Black carbon	12 ^a
Organic aerosol	81 ^a
Secondary	
Sulfates from SO ₂	48.6 ^b
Nitrates from NO _x	21.3 ^c

^aTg C.

^bTg S.

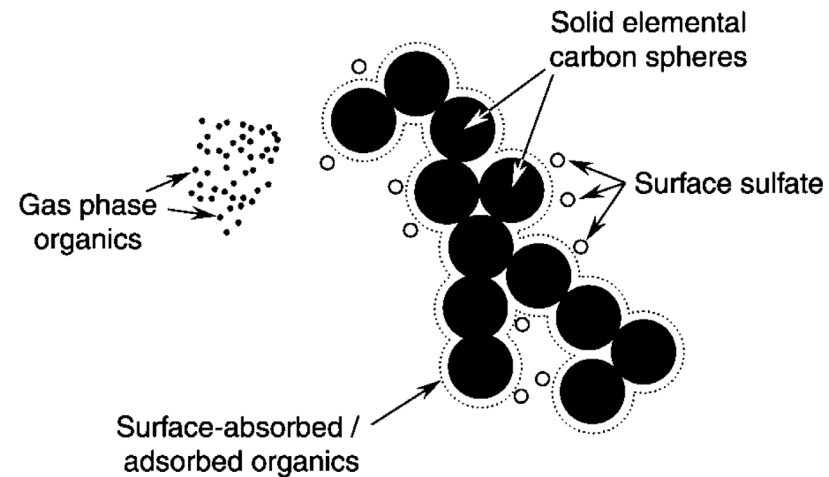
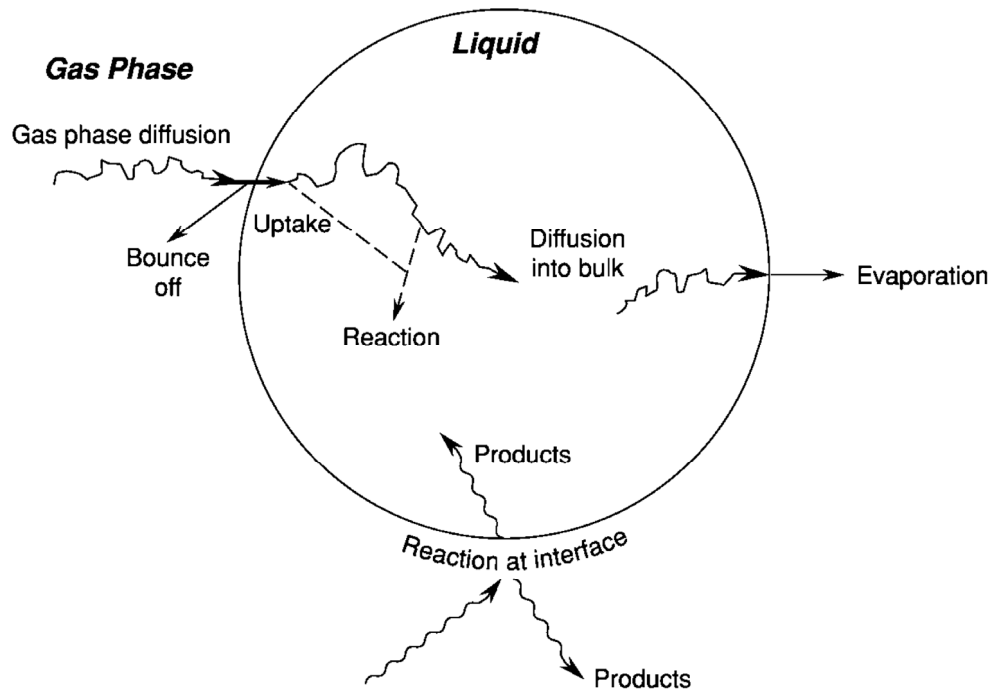
^cTg NO₃⁻.

Seinfeld and Pandis, 2006

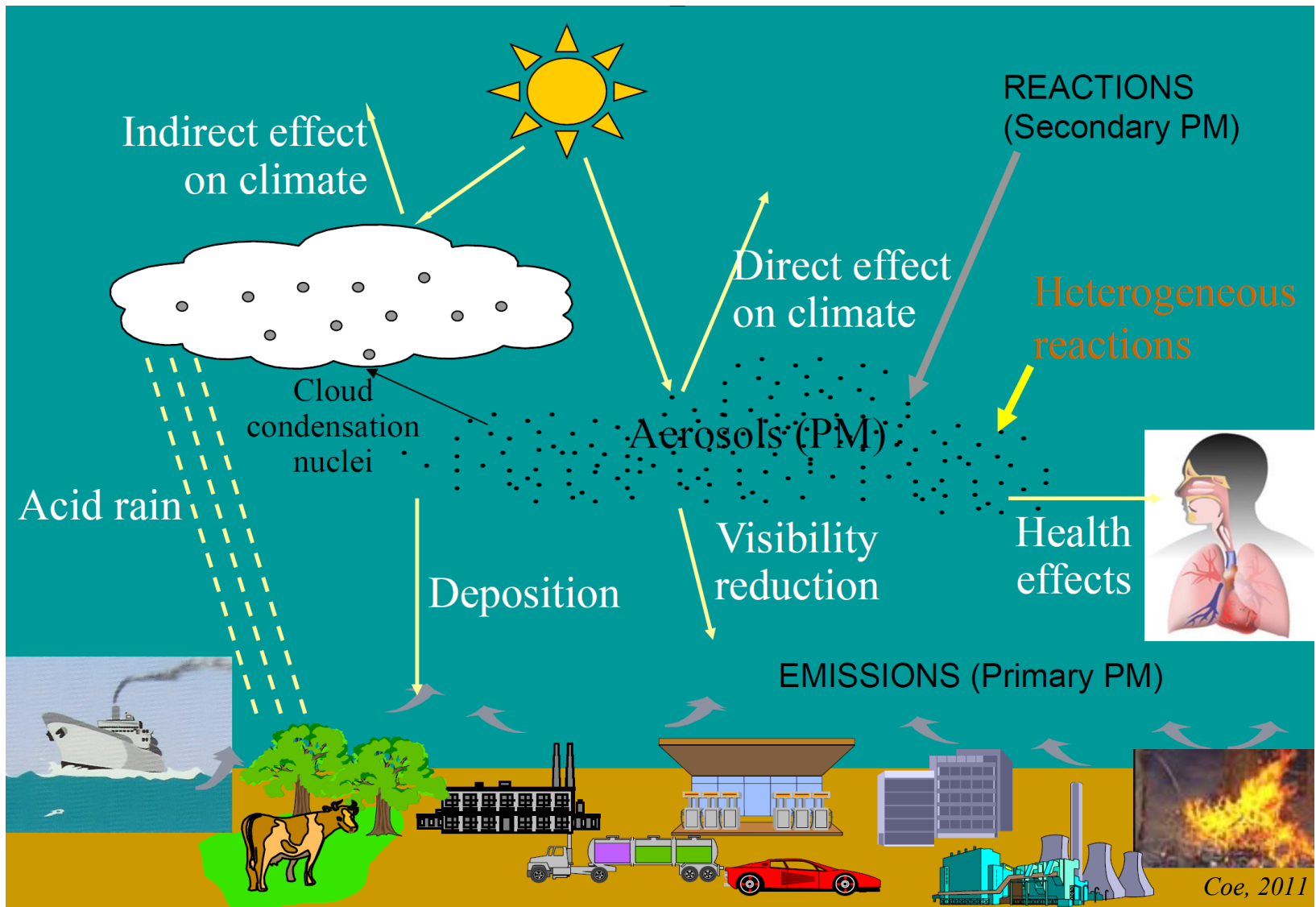


*Mass concentrations and composition of tropospheric aerosols.
(Seinfeld and Pandis, 2006)*

Region	Mass ($\mu\text{g m}^{-3}$)	Percentage Composition				
		C (elem)	C (org)	NH_4^+	NO_3^-	SO_4^{2-}
Remote (11 areas) ^a	4.8	0.3	11	7	3	22
Nonurban continental (14 areas) ^a	15	5	24	11	4	37
Urban (19 areas) ^a	32	9	31	8	6	28
Rubidoux, California ^b (1986 annual average)	87.4	3	18	6	20	6

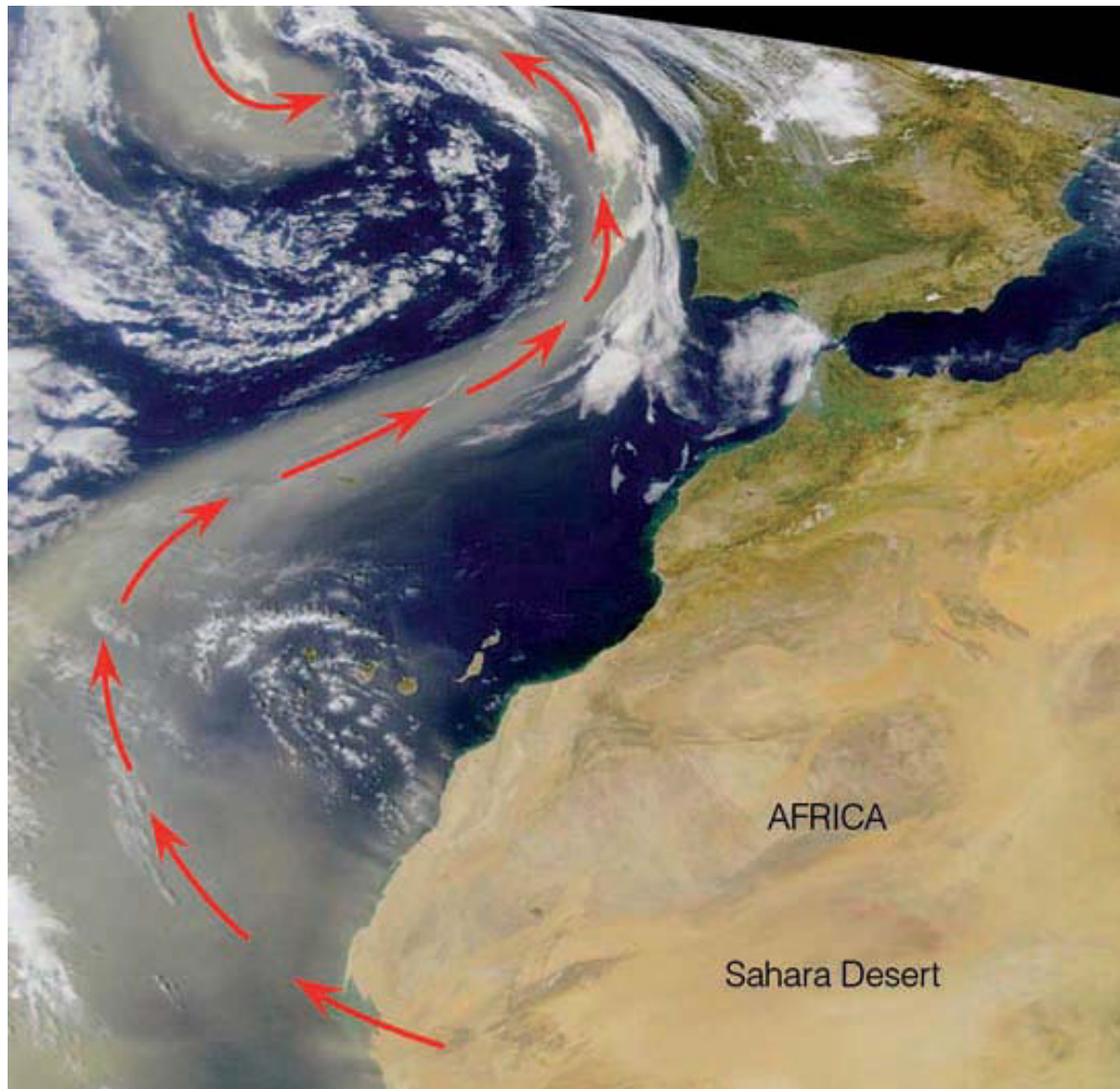


Diesel soot particle. (Finlayson-Pitts and Pitts, 2000)



Effects of atmospheric aerosols

Coe, 2011

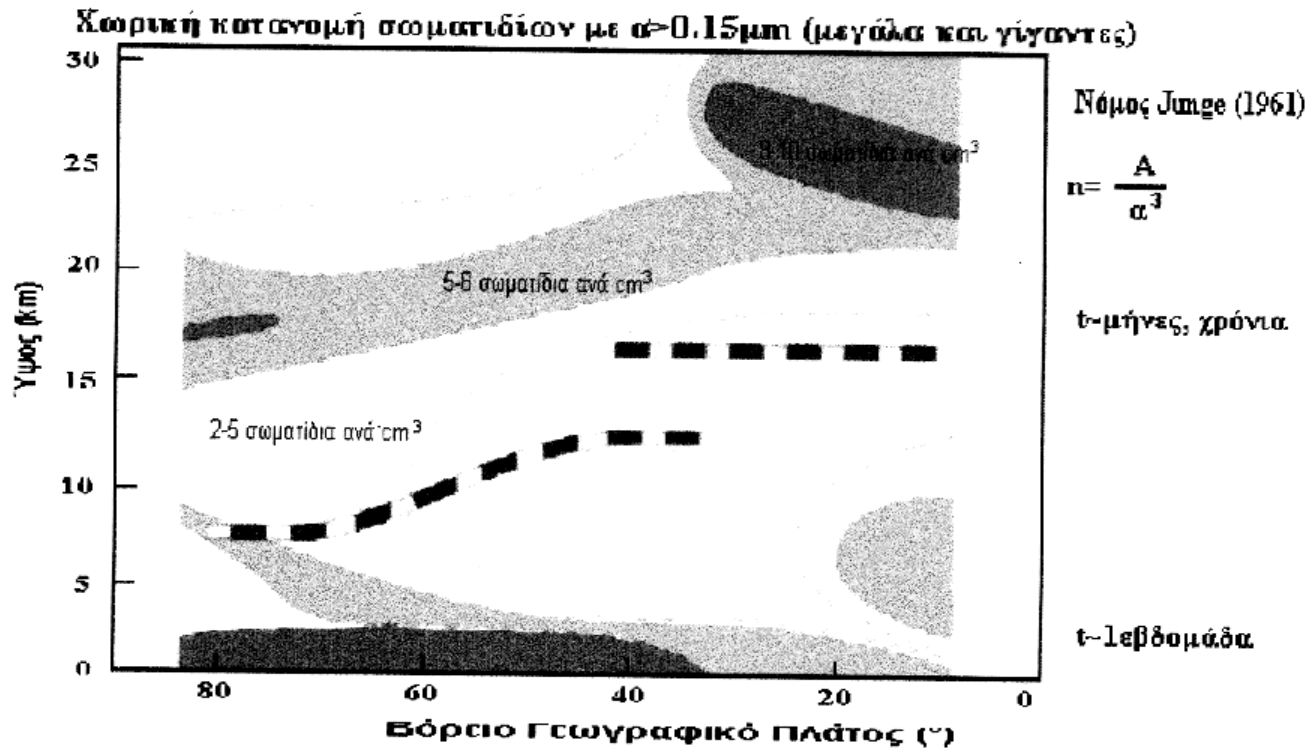


AFRICA

Sahara Desert

Ahrens, 2009

Στρατοσφαιρικά αιωρούμενα σωματίδια (στρώμα Junge)

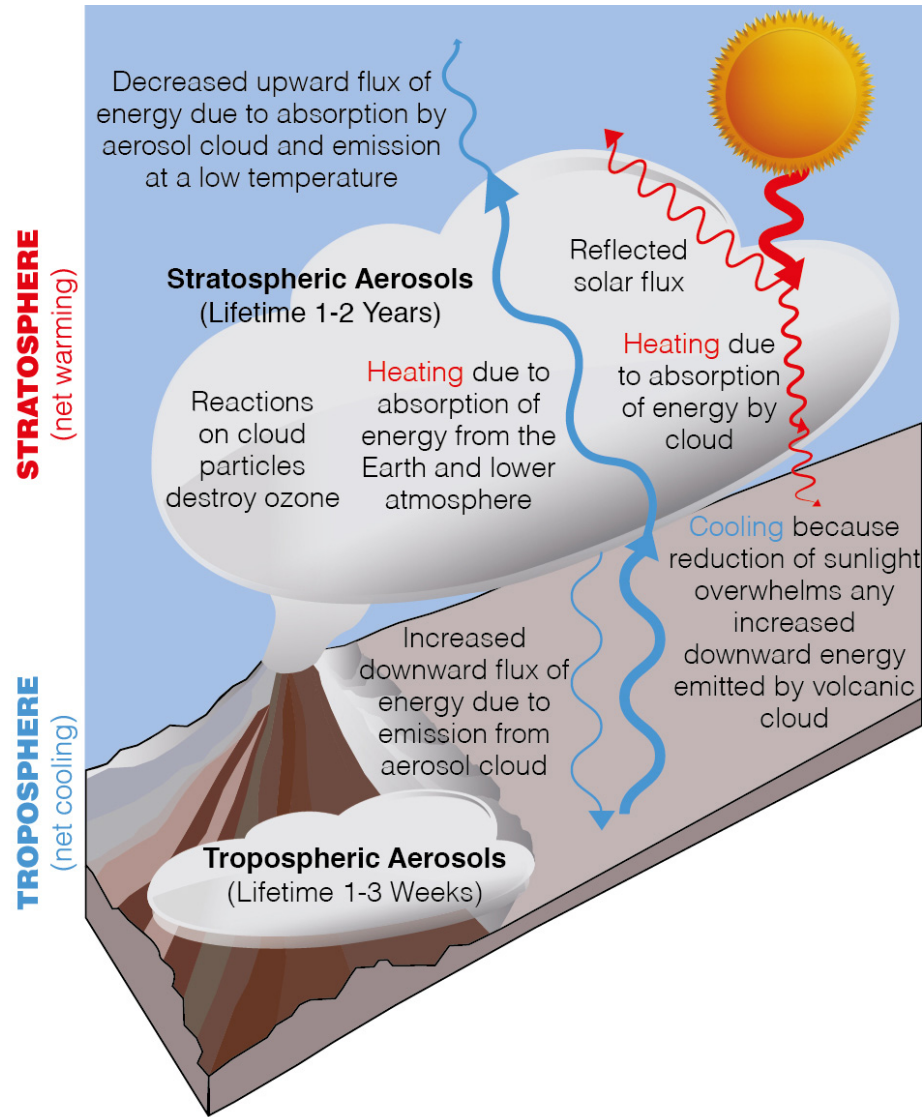


Έδαφος: Ωκεανός: 10^3 σωμα/cm³

Ηπειρωτική περιοχή: 10^4 σωμα/cm³

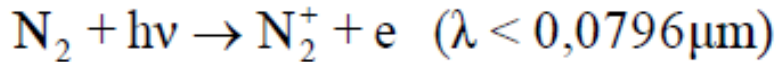
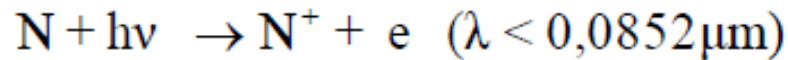
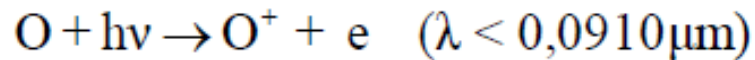
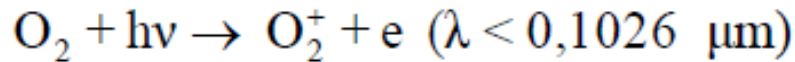
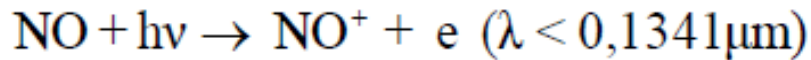
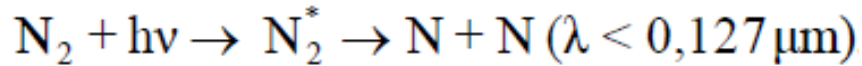
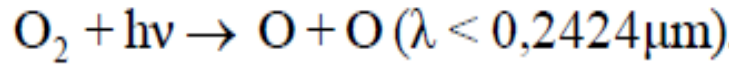
Πόλις: 10^5 σωμα/cm³

Σχηματικό διάγραμμα του στρώματος των αερολυμάτων (στρώμα Junge) σε συνάρτηση με το ατμοσφαιρικό ύψος και το γεωγραφικό πλάτος. (Βαρώτσος, 2001)

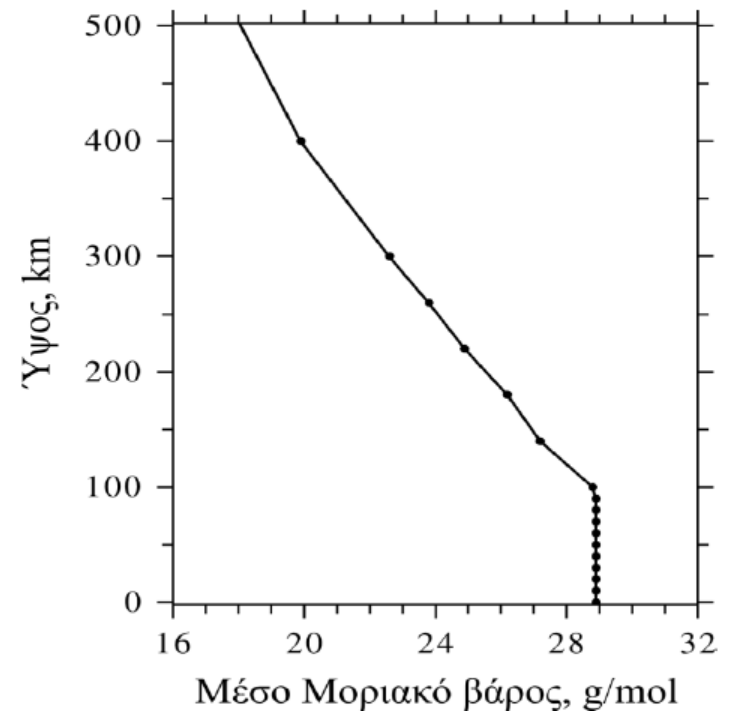
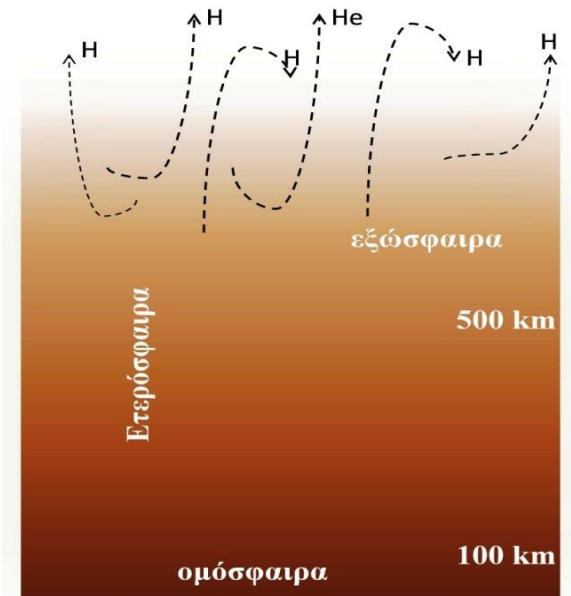


Schematic of how large tropical or sub-tropical volcanoes impact upper atmospheric (stratospheric) and lower atmospheric (tropospheric) temperatures. (IPCC, 2013)

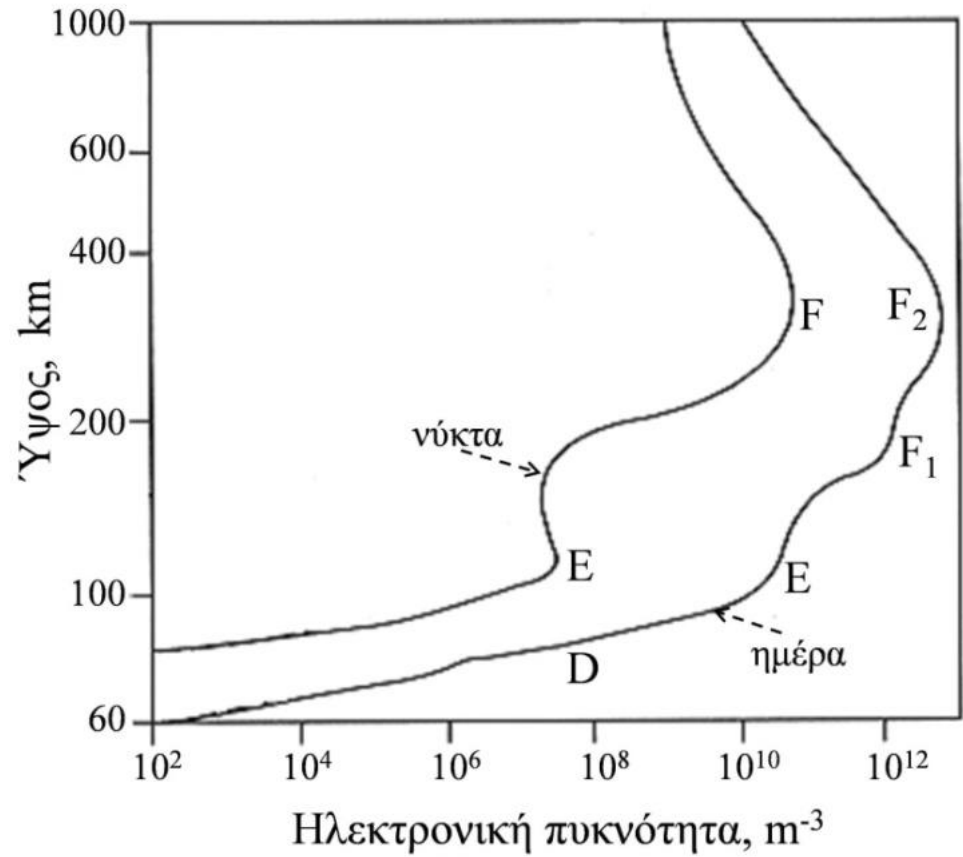
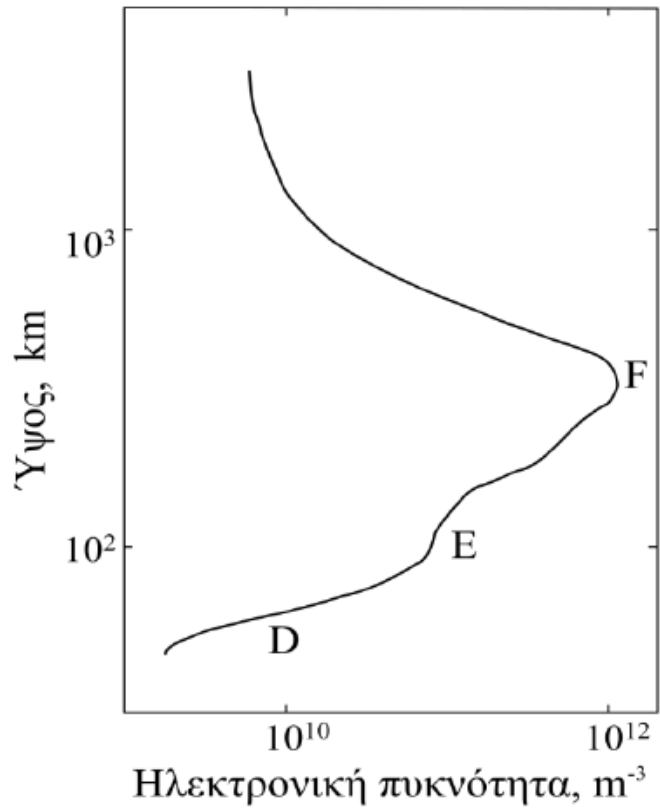
Ετερόσφαιρα



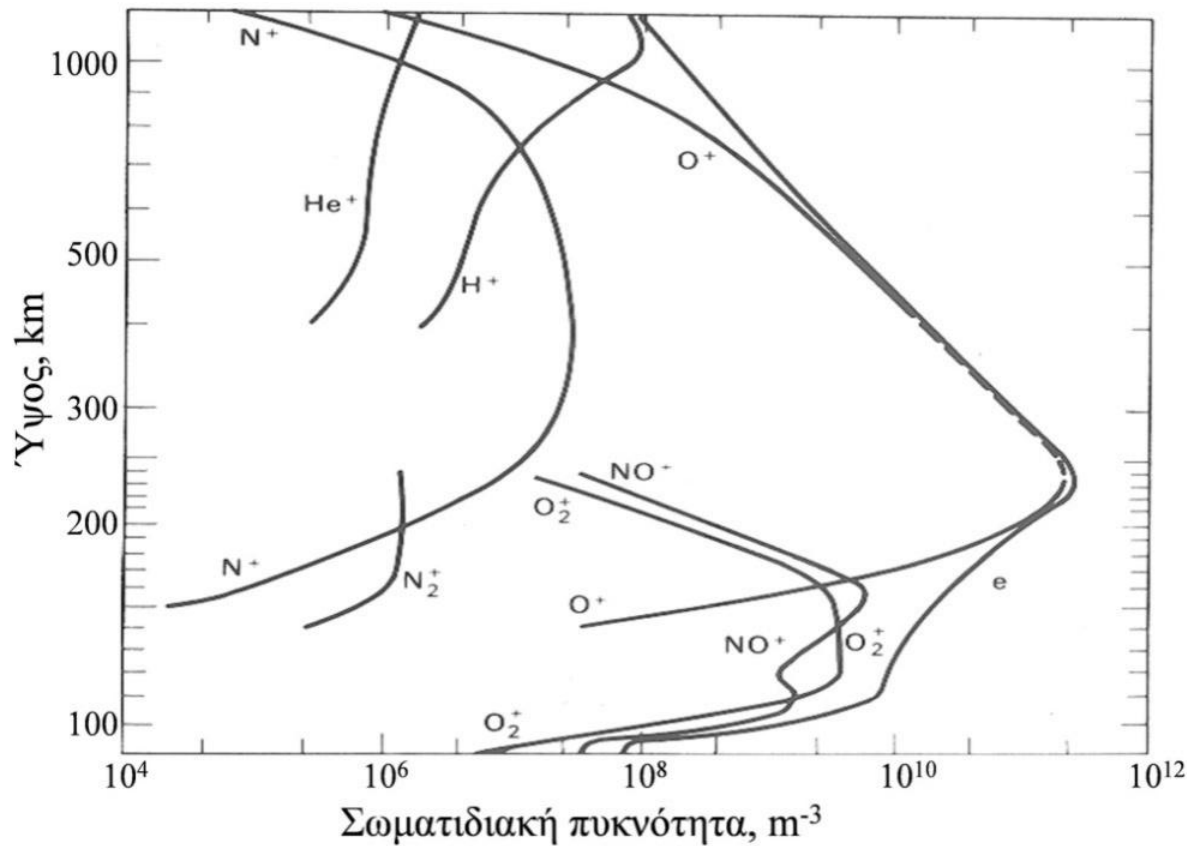
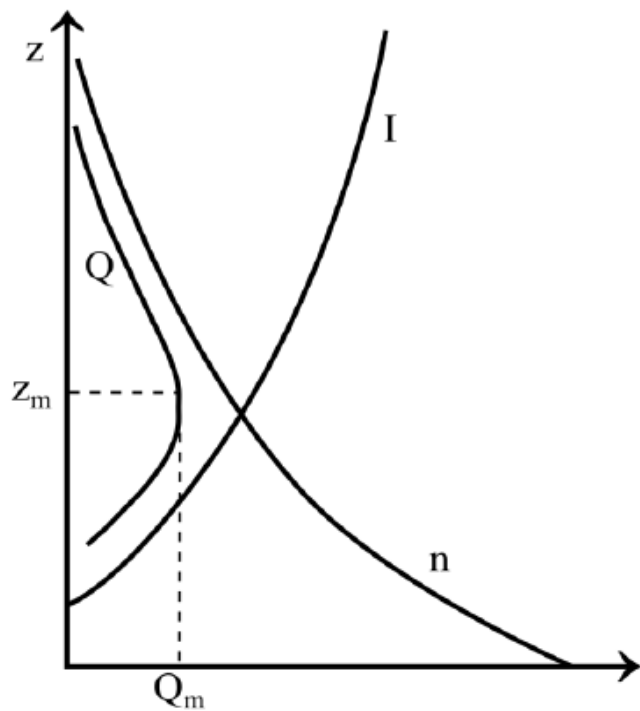
Περιοχή φάσματος	Φασματική ζώνη μήκους κύματος λ , μm	Κλάσμα ηλιακής εκπομπής, %
Ακτίνες X	$\lambda < 0,01$	0,00005
Ακραίο υπεριώδες	$0,01 < \lambda < 0,10$	0,0003
Μακρινό υπεριώδες	$0,10 < \lambda < 0,20$	0,01
Υπεριώδες UV-C	$0,20 < \lambda < 0,28$	0,5
Υπεριώδες UV-B	$0,28 < \lambda < 0,32$	1,3
Υπεριώδες UV-A	$0,32 < \lambda < 0,39$	6,2
Ορατό	$0,39 < \lambda < 0,76$	39,0
Κοντινό υπέρυθρο	$0,76 < \lambda < 4,0$	52,0
Θερμικό υπέρυθρο	$4,0 < \lambda < 100,0$	0,9
Μακρινό υπέρυθρο	$100,0 < \lambda < 1000,0$	0,09



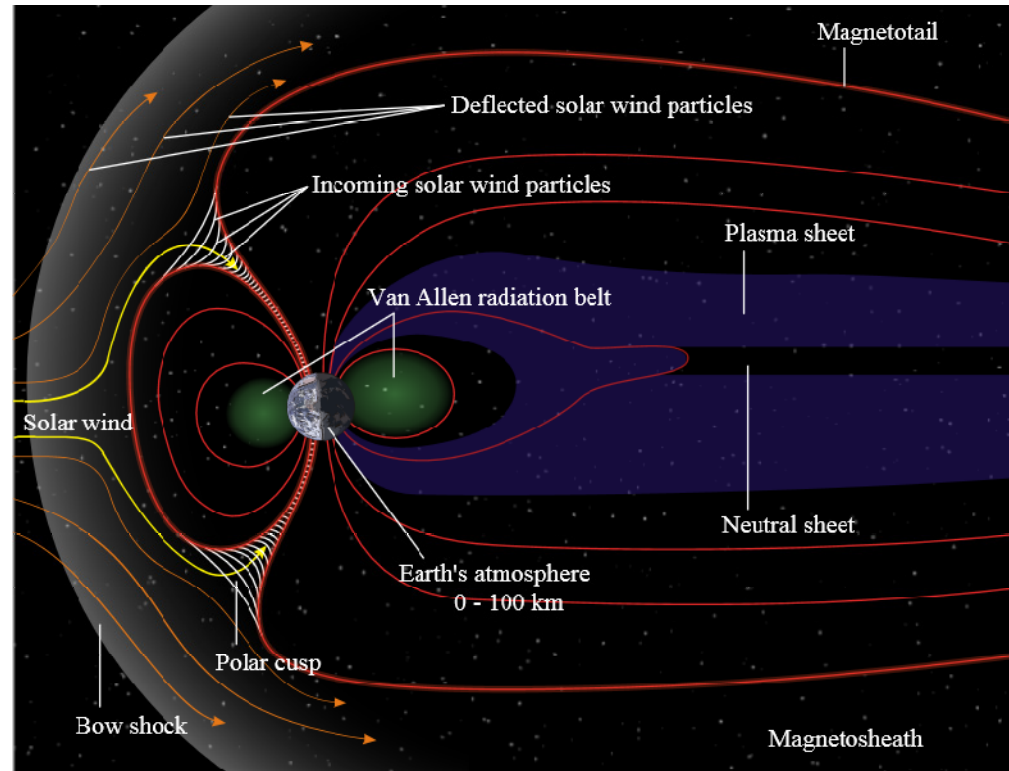
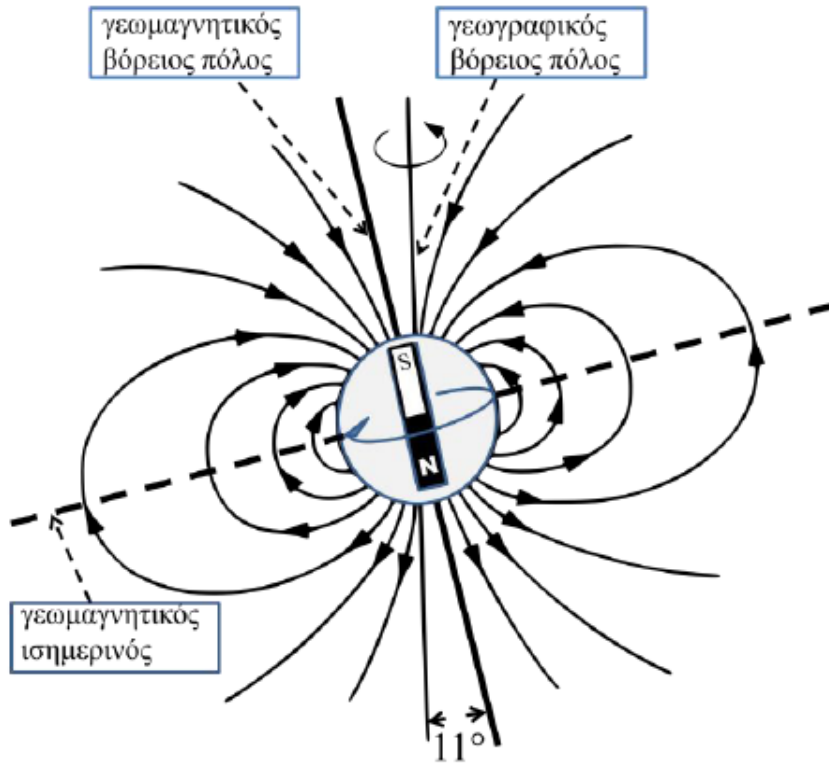
Ιονόσφαιρα



Ιονόσφαιρα



Μαγνητόσφαιρα



William Crohot, http://science.nasa.gov/newhome/headlines/guntersville98/images/mag_sketch_633.jpg

Προέλευση της ατμόσφαιρας

➤ Δημιουργία ατμόσφαιρας με σημερινή σύσταση

➤ Άζωτο (N_2)

➤ Οξυγόνο (O_2)

➤ Υδρογόνο (H_2)

➤ Ευγενή αέρια

➤ Υπόλοιπα αέρια

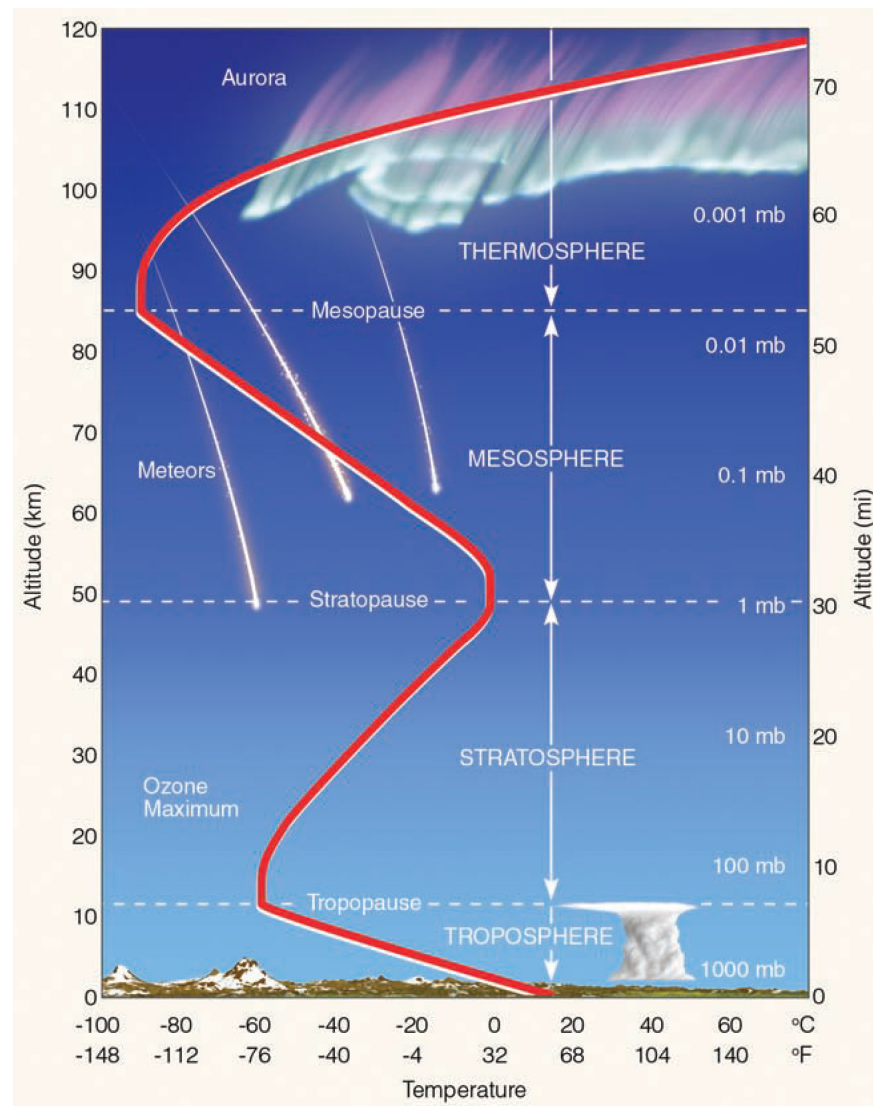
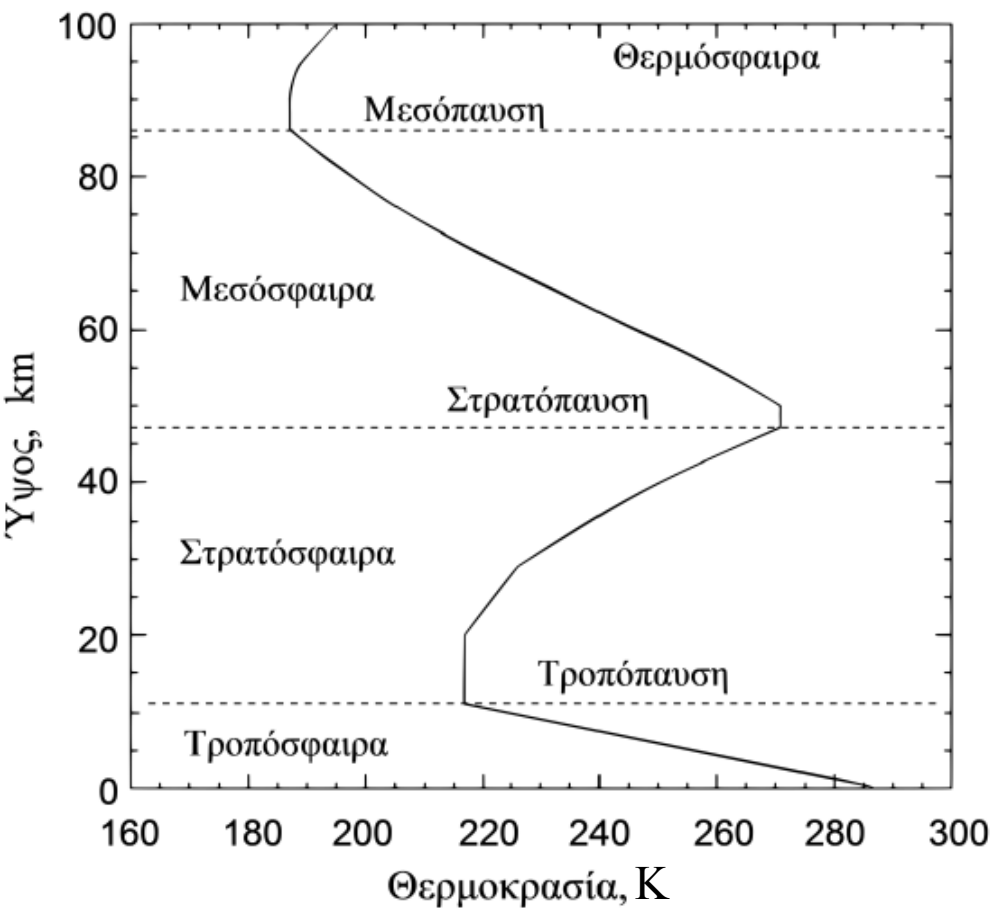
	Συστατικό	Μορ. Βάρος	Αναλογία
1	Άζωτο (N_2)	28,02	78,08 %
2	Οξυγόνο (O_2)	32,00	20,95 %
3	Αργό (Ar)	39,94	0,93 %
4	Υδρατμοί (H_2O)	18,02	0,01–5 %
5	Διοξ. Άνθρακα (CO_2)	44,01	400 ppm
6	Νέο (Ne)	20,18	18 ppm
7	Ήλιο (He)	4,00	5 ppm
8	Κρυπτό (Kr)	83,70	1 ppm
9	Υδρογόνο (H_2)	2,02	0,5 ppm
10	Όζον (O_3)	48,00	1–12 ppm

Μεταβολή της θερμοκρασίας με το ύψος - Ατμοσφαιρικές περιοχές

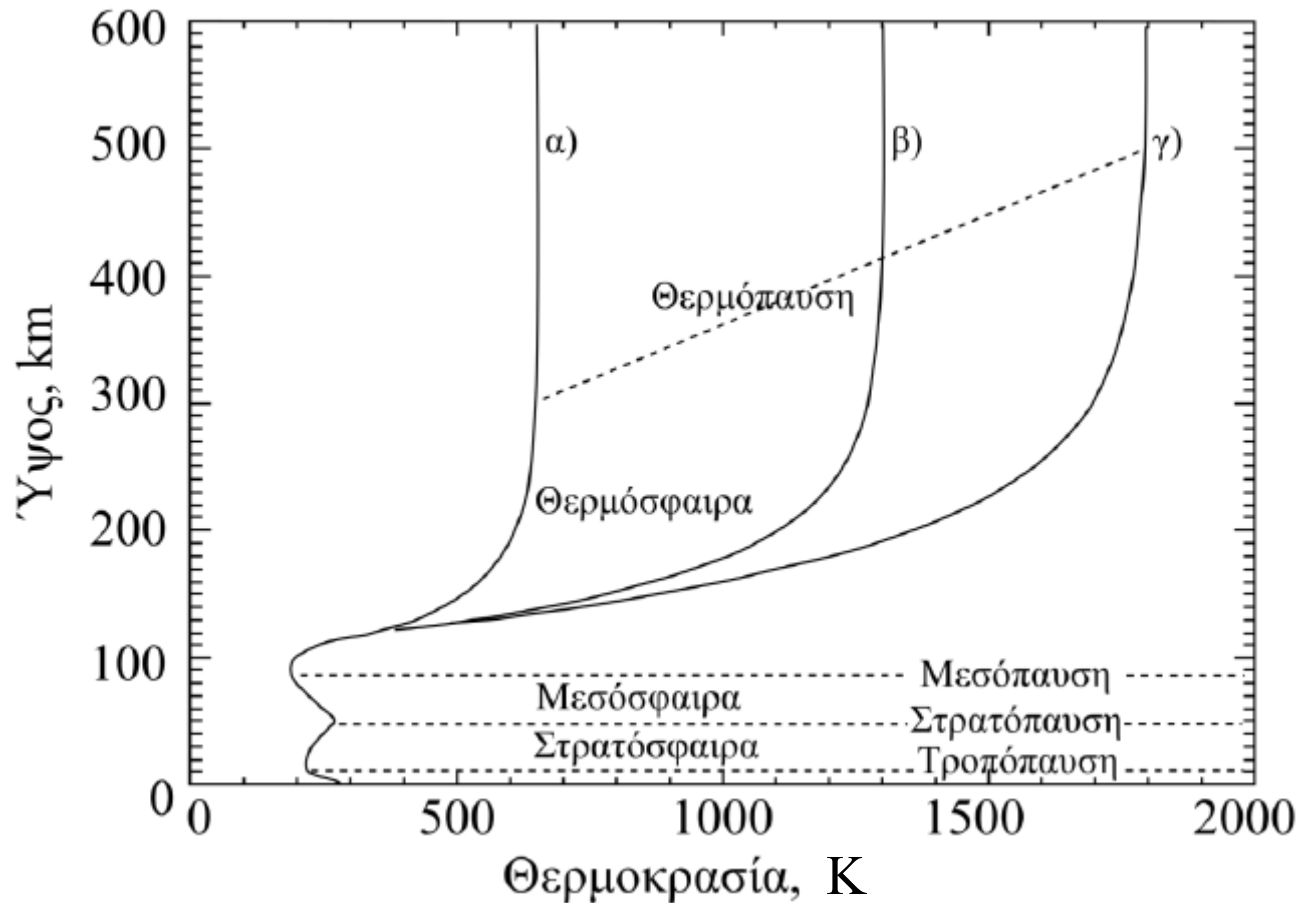
➤ Τροπόσφαιρα

➤ Στρατόσφαιρα

➤ Μεσόσφαιρα



Θερμόσφαιρα



Κατακόρυφη μεταβολή της θερμοκρασίας της ατμόσφαιρας μέχρι τα 600 km, για: (α) μικρή, (β) μέση, και (γ) ισχυρή ηλιακή δραστηριότητα

Θερμοδυναμική της ατμόσφαιρας

- *Εφαρμογή των νόμων ιδανικών αερίων στον αέρα*
- *Παράμετροι υγρασίας*
 - *Απόλυτη υγρασία*
 - *Ειδική υγρασία*
 - *Αναλογία μίγματος*
 - *Σχετική υγρασία*
- *Αντίστοιχη θερμοκρασία*
- *Υψομετρική εξίσωση*
- *Θερμοδυναμικά αξιώματα και εφαρμογή στην ατμόσφαιρα*
- *Εξίσωση Clausius–Clapeyron*
- *Θερμοδυναμικές μεταβολές αερίων μαζών*
 - *Σχηματισμός δρόσου, πάχνης και ομίχλης*
 - *Αδιαβατικές μεταβολές*
 - *Κορεσμένες αδιαβατικές και ψευδοαδιαβατικές μεταβολές*

Εφαρμογή των νόμων ιδανικών αερίων στον αέρα

$$K_t = \frac{3}{2} NkT$$

$$pV = NkT$$

$$pV = MRT = nR^*T$$

$$p = p_1 + p_2 + p_3 + \dots + p_i$$

$$p_{o\xi} = \Sigma p_i = \rho_{o\xi} R_\xi T$$

$$\rho = \frac{M_\xi + M_v}{V} = \rho_\xi + \rho_v$$

$$p_\xi = \rho_\xi R_\xi T \qquad e = \rho_v R_v T$$

$$\varepsilon \equiv \frac{R_\xi}{R_v} = \frac{\mu_v}{\mu_\xi} = 0,622$$

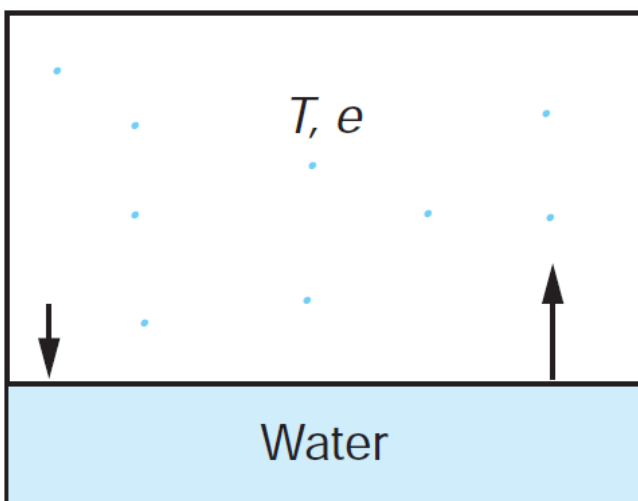
Παράμετροι υγρασίας

➤ Υγρασία

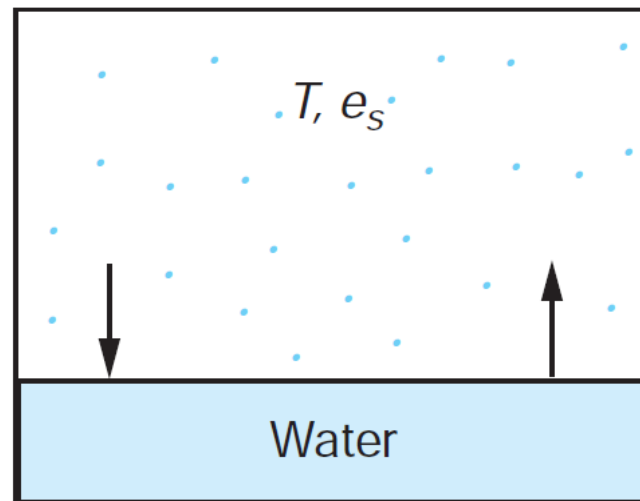
➤ Κατάσταση κόρου

➤ Τάση κόρου (e_s) (ή τάση κορεσμένων υδρατμών)

Εξίσωση Clausius-Clapeyron
$$\frac{de_s}{dT} = \frac{L_v e_s}{R_v T^2}$$



Ακόρεστος αέρας



Κορεσμένος αέρας

Απόλυτη υγρασία

$$\rho_v = M_v / V$$

$$\rho_v = (e / R_v T)$$

$$\rho_{vs} = (e_s / R_v T)$$

$$C-C \rightarrow e_{sv} = A_v \exp\left(-\frac{B_v}{T}\right)$$

T (°C)	Απόλυτη Υγρασία (g/m ³)	T (°C)	Απόλυτη Υγρασία (g/m ³)
-40	0,12	0	4,84
-35	0,20	5	6,79
-30	0,34	10	9,40
-25	0,55	15	12,8
-20	0,89	20	17,3
-15	1,40	25	23,0
-10	2,15	30	30,3
-05	3,26	35	39,5
0	4,84	40	51,1

Ειδική υγρασία

$$\alpha = \frac{M_v}{M} = \frac{M_v}{M_\xi + M_v} = \frac{(M_v/V)}{(M_\xi/V) + (M_v/V)} = \frac{\rho_v}{\rho_\xi + \rho_v}$$

$$\begin{aligned} a &= \frac{\rho_v}{\rho_\xi + \rho_v} = \frac{\left(\frac{e}{R_v T}\right)}{\left(\frac{p_\xi}{R_\xi T} + \frac{e}{R_v T}\right)} = \frac{\left(\frac{\mu_v e}{R^* T}\right)}{\left(\frac{\mu_\xi p_\xi}{R^* T} + \frac{\mu_v e}{R^* T}\right)} = \frac{\mu_v}{\mu_\xi} \frac{e}{p_\xi + (\mu_v/\mu_\xi)e} = \\ &= \varepsilon \frac{e}{p - (1 - \mu_v/\mu_\xi)e} = 0,622 \frac{e}{p - 0,378 e}. \end{aligned}$$

$$\alpha = 0,622 \frac{e}{p}$$

Ειδική υγρασία

$$\alpha_s = 0,622 \frac{e_s}{p - 0,378e_s}$$

<i>p</i> (mb)	1000	900	800	700	600	500
<i>T</i> (°C)						
-40	0,11	0,13	0,14	0,16	0,19	0,23
-35	0,19	0,21	0,24	0,29	0,32	0,39
-30	0,31	0,35	0,39	0,45	0,52	0,63
-25	0,50	0,55	0,62	0,71	0,83	1,00
-20	0,78	0,87	0,98	1,12	1,30	1,56
-15	1,20	1,33	1,49	1,71	1,99	2,39
-10	1,79	1,99	2,23	2,55	2,98	3,58
-5	2,63	2,92	3,29	3,76	4,39	5,27
0	3,80	4,23	4,76	5,44	6,35	7,62
5	5,44	6,05	6,81	7,79	9,09	10,9
10	7,67	8,53	9,60	11,0	12,8	15,4
15	10,7	11,9	13,4	15,3	17,9	
20	14,7	16,3	18,4	21,1		
25	20,0	22,2	25,0			
30	26,9	29,9	33,7			
35	35,8	39,8				
40	47,3					

Αναλογία μίγματος

$$w = \frac{\rho_v}{\rho_\xi}$$

$$w = \frac{\mu_v}{\mu_\xi} \frac{e}{p - e} = 0,622 \frac{e}{p - e} \quad (\cong 0,622 \frac{e}{p})$$

$$w_s = 0,622 \frac{e_s}{p - e_s} \quad (w_s \cong 0,622 \frac{e_s}{p})$$

$$\alpha = \frac{\rho_v}{\rho_\xi + \rho_v} = \frac{(\rho_v / \rho_\xi)}{1 + (\rho_v / \rho_\xi)} = \frac{w}{1 + w} \approx w$$

Σχετική υγρασία

$$h = 100 \frac{w}{w_s} \%$$

$$h = 100 \frac{\rho_v}{\rho_{vs}} = 100 \frac{e}{e_s} \%$$

➤ *Σημείο δρόσου (T_δ)* → δείκτης ανθρώπινης δυσφορίας

Αντίστοιχη θερμοκρασία

$$T_v = \frac{T}{1 - (e/p)(1 - \varepsilon)}$$

Καταστατική εξίσωση υγρού αέρα $\rightarrow p = \rho R_\xi T_v$

$$T_v \approx T(1 + 0.61w)$$

$$R_m \approx R_\xi (1 + 0.61w)$$

Υψομετρική εξίσωση

$$Z_2 - Z_1 = \frac{R_\xi \bar{T}_v}{g_0} \ln\left(\frac{p_1}{p_2}\right) = \bar{H}_v \ln\left(\frac{p_1}{p_2}\right)$$

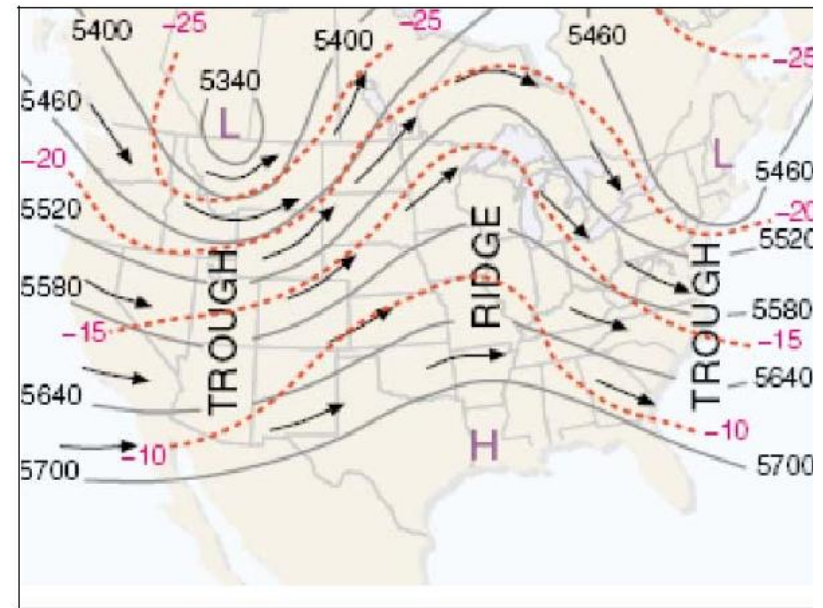
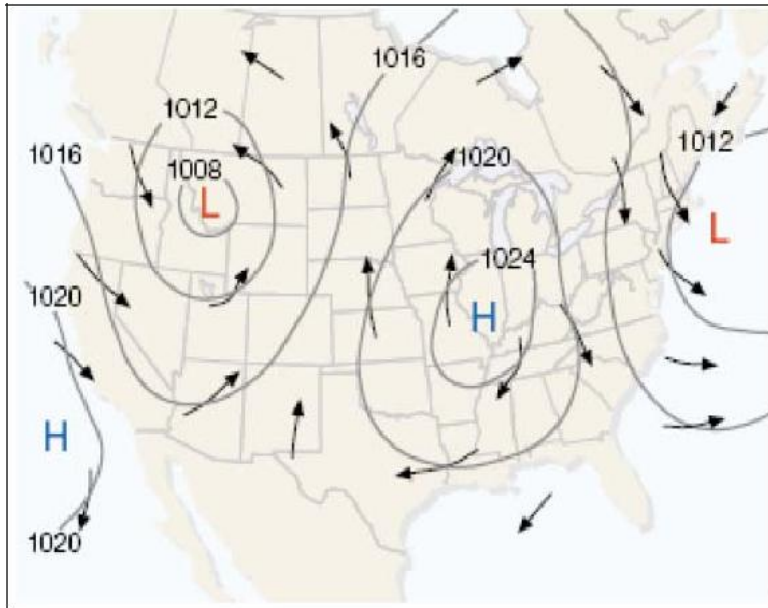
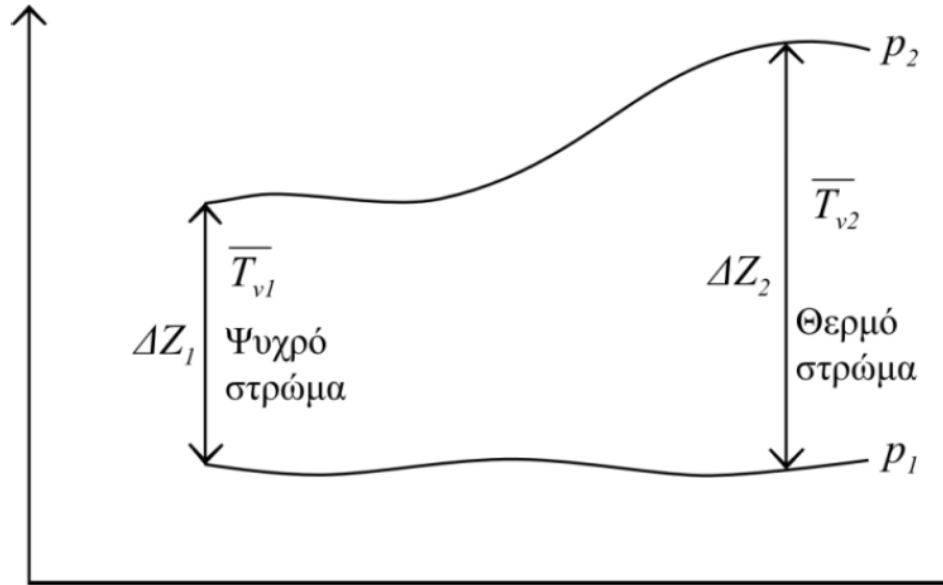
$$H_v = R_\xi T_v / g_0 = 29.3 T_v \rightarrow \text{κλίμακα ύψους}$$

➤ *Αναγωγή της πίεσης στην επιφάνεια της θάλασσας*

$$z_s = \bar{H}_v \ln(p_0 / p_s) \rightarrow$$

$$p_0 = p_s \exp(z_s / \bar{H}_v) = p_s \exp\left(\frac{g_0 z_s}{R_\xi \bar{T}_v}\right)$$

➤ *Εύρος ισοβαρούς στρώματος*



Θερμοδυναμική της ατμόσφαιρας - Θερμοδυναμικά αξιώματα

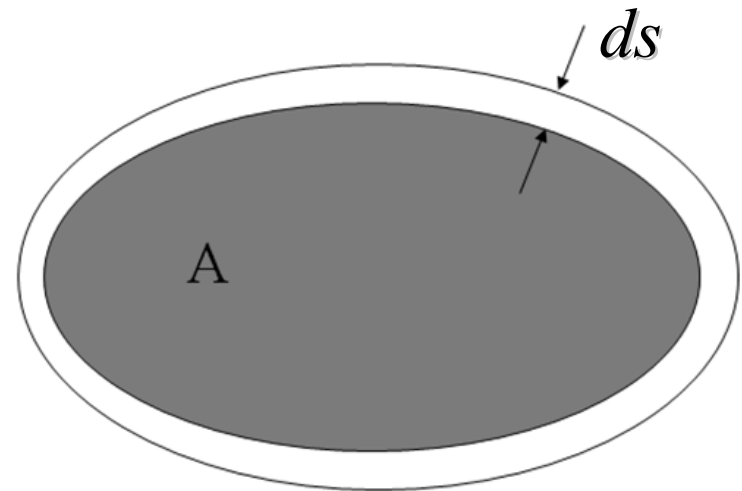
$$dQ = dU + dW$$

$$dq = du + dw$$

$$dW = Fds = pdV.$$

$$\text{Ειδικό έργο} \rightarrow dw = pdu$$

$$\text{Ειδικός όγκος} \rightarrow v = V/M = 1/\rho$$



$$dq = cdT$$

$$dq = du = c_v dT \quad \left(\frac{dq}{dT} \right)_v \equiv c_v$$

$$dq = c_v dT + p dv$$

$$dq = c_p dT - v dp \quad (c_p = c_v + R)$$

➤ *Ισοβαρής μεταβολή* ($dp=0$) $\rightarrow dq = c_p dT = (c_p / c_v) c_v dT = (c_p / c_v) du$

➤ *Ισόθερμη μεταβολή* ($dT=0$) $\rightarrow dq = p dv = -v dp = dw$.

➤ *Ισόχωρη μεταβολή* ($dv=0$) $\rightarrow dq = c_v dT = du$

➤ *Αδιαβατική μεταβολή* ($dq=0$) $\rightarrow c_v dT = -p dv$
 $c_p dT = v dp$

➤ *Αδιαβατική μεταβολή*

Εξίσωση Poisson → $T = T_0 (p / p_0)^\kappa$

$$\kappa = \frac{R}{c_p} = \frac{c_p - c_v}{c_p} = 1 - \frac{c_v}{c_p} \quad (\kappa_\xi = 0.286)$$

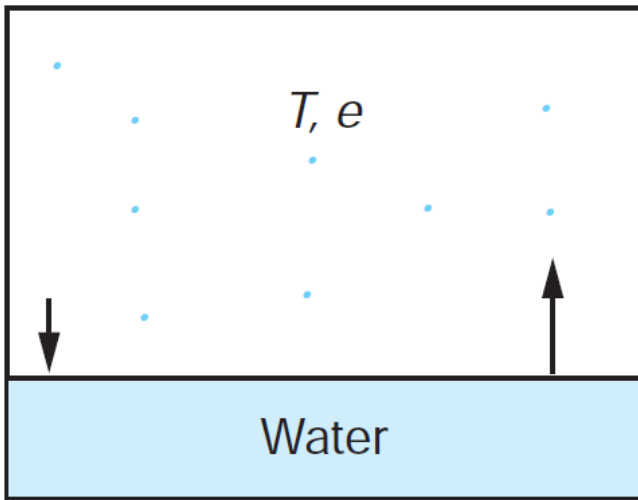
Δυναμική θερμοκρασία → $\Theta = T \left(\frac{p_0}{p} \right)^\kappa = T \left(\frac{1000}{p} \right)^\kappa$

Εντροπία → $ds = \frac{dq}{T}$

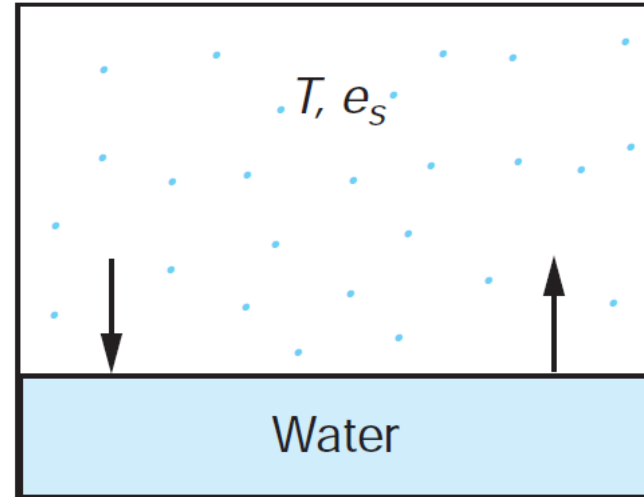
$$s = c_p \ln \Theta + const$$

Εξίσωση Clausius–Clapeyron

- Εξάτμιση και συμπύκνωση
- Ακόρεστος αέρας
- Κορεσμένος αέρας
- Τάση κόρου (e_s) (ή τάση κορεσμένων υδρατμών)



Ακόρεστος αέρας



Κορεσμένος αέρας

Εξίσωση Clausius–Clapeyron

➤ *Λανθάνουσα θερμότητα εξάτμισης, L_v*

$$\frac{de_s}{dT} = \frac{S_2 - S_1}{v_2 - v_1} = \frac{L_v}{T(v_2 - v_1)} \approx \frac{L_v}{Tv_2} = \frac{L_v}{T(R_v T / e_s)} = \frac{L_v e_s}{R_v T^2}$$

$$\frac{de_s}{dT} = \frac{L_v e_s}{R_v T^2}$$

➤ $L_v \rightarrow$ σταθερή (με T) $e_{sv} = e_{s0} \exp\left(\frac{L_v}{R_v T_0}\right) \exp\left(-\frac{L_v}{R_v T}\right) = A_v \exp\left(-\frac{B_v}{T}\right)$

➤ $L_v \rightarrow$ δεν παραμένει σταθερή (με T) $L_v(T) = L_0 - (c_{1v} - c_{2p})(T - T_0)$

Εξίσωση Clausius–Clapeyron

➤ Λανθάνουσα θερμότητα εξάχνωσης, L_π

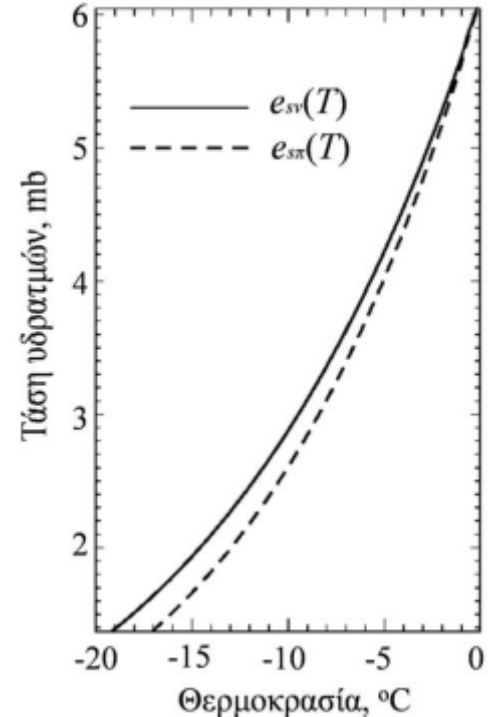
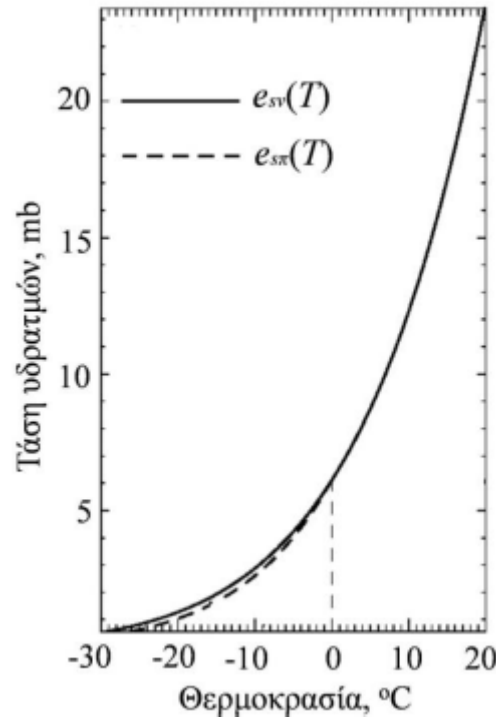
$$\frac{de_{s\pi}}{dT} = \frac{L_\pi e_{s\pi}}{R_v T^2}$$

➤ $L_\pi \rightarrow$ σταθερή (με T) $e_{s\pi} = e_{s0} \exp\left(\frac{L_\pi}{R_v T_0}\right) \exp\left(-\frac{L_\pi}{R_v T}\right) = A_\pi \exp\left(-\frac{B_\pi}{T}\right)$

➤ Λανθάνουσα θερμότητα τήξης,

$$L_\tau = L_\pi - L_v$$

$$\frac{e_{sv}(T)}{e_{s\pi}(T)} = \exp\left\{\frac{L_\tau}{R_v T_0} \left(\frac{T_0}{T} - 1\right)\right\}$$



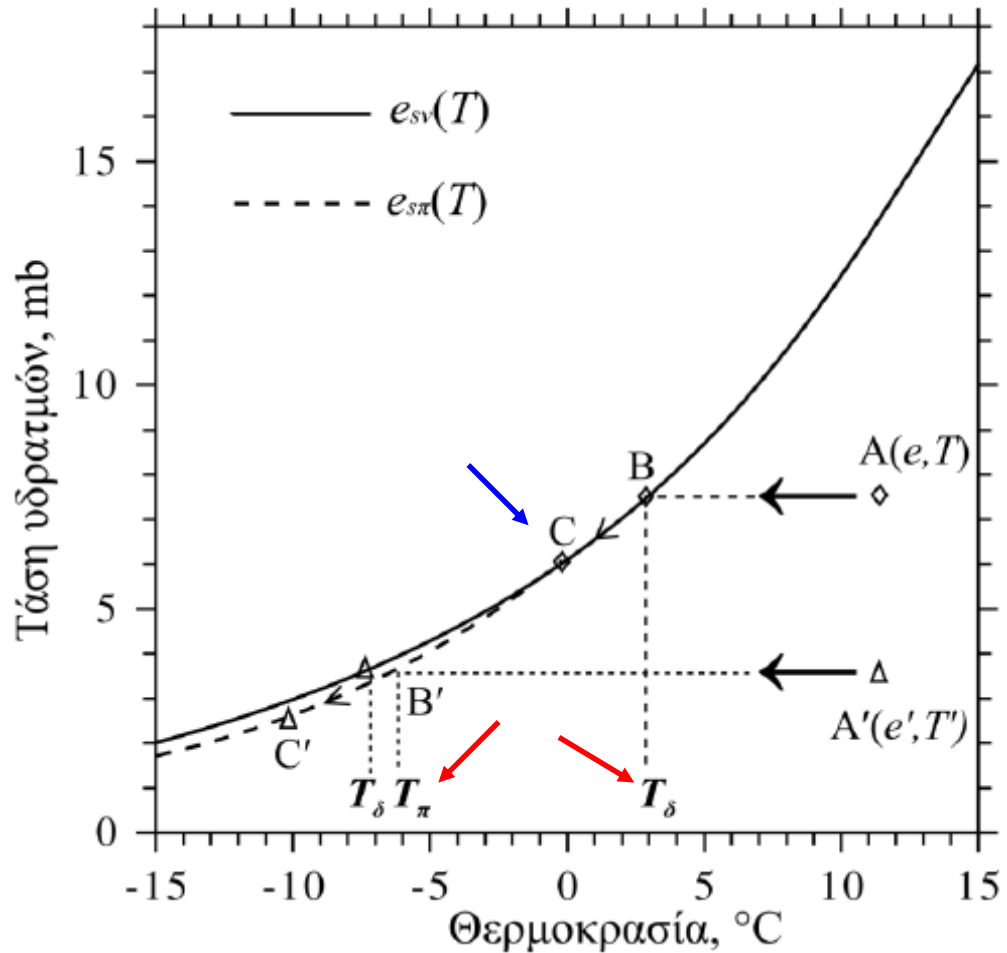
Θερμοδυναμικές μεταβολές αερίων μαζών

➤ Ισοβαρής ψύξη

➤ Δρόσος, δροσόπαγος

➤ Πάχνη

➤ Ομίχλη



Αδιαβατικές μεταβολές

➤ Ξηρή αδιαβατική θερμοβαθμίδα

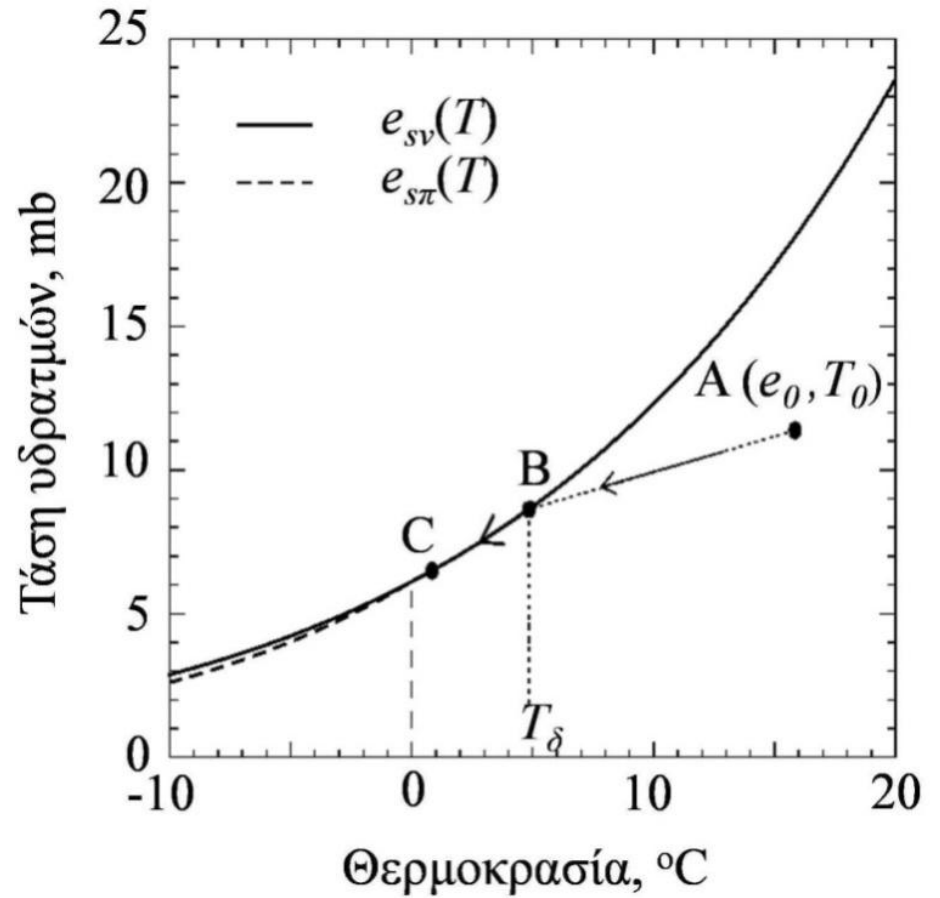
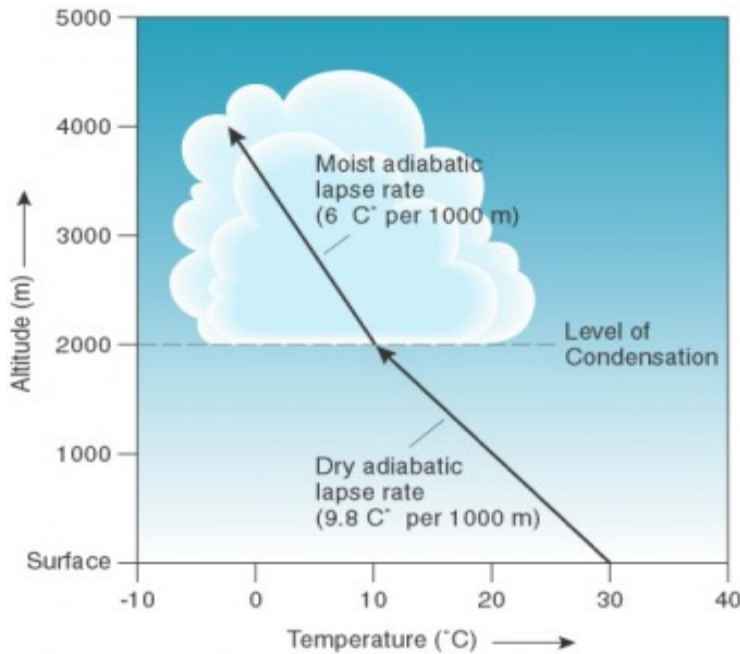
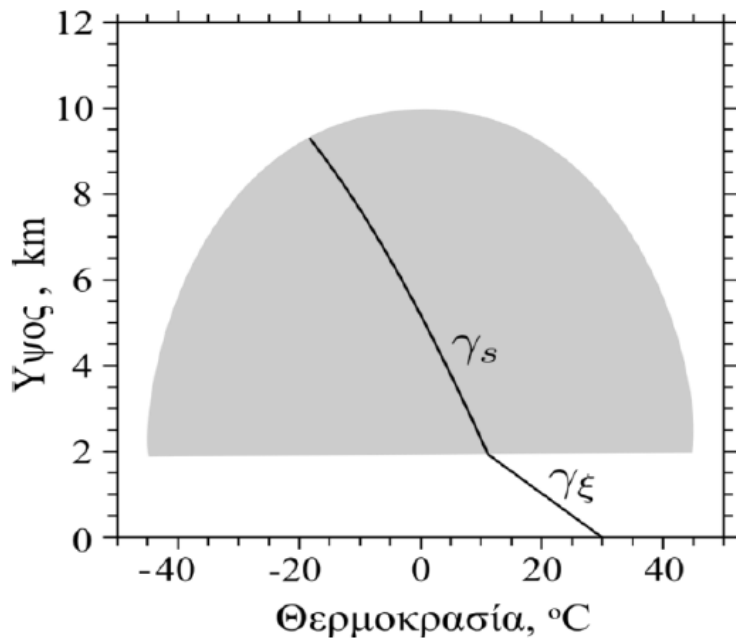
$$-\frac{dT}{dz} = \frac{g}{c_p} \quad \gamma_{\xi} \equiv \frac{g}{c_p} = 9,8 \text{ K / km}$$

➤ Κορεσμένη αδιαβατική και ψευδοαδιαβατική μεταβολή

➤ Κορεσμένη (ή υγρή) αδιαβατική θερμοβαθμίδα

$$-\frac{dT}{dz} = \gamma_s = \gamma_{\xi} / \left(1 + \frac{L_v}{c_p} \frac{dn_{vs}}{dT}\right)$$

$$\gamma_s < \gamma_{\xi}$$

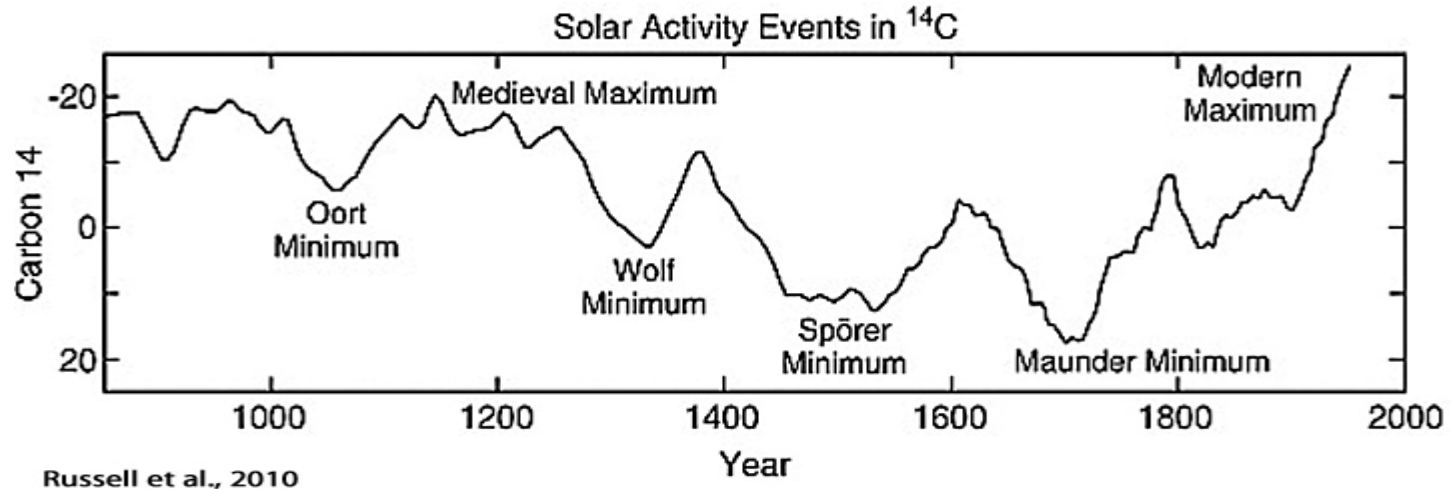
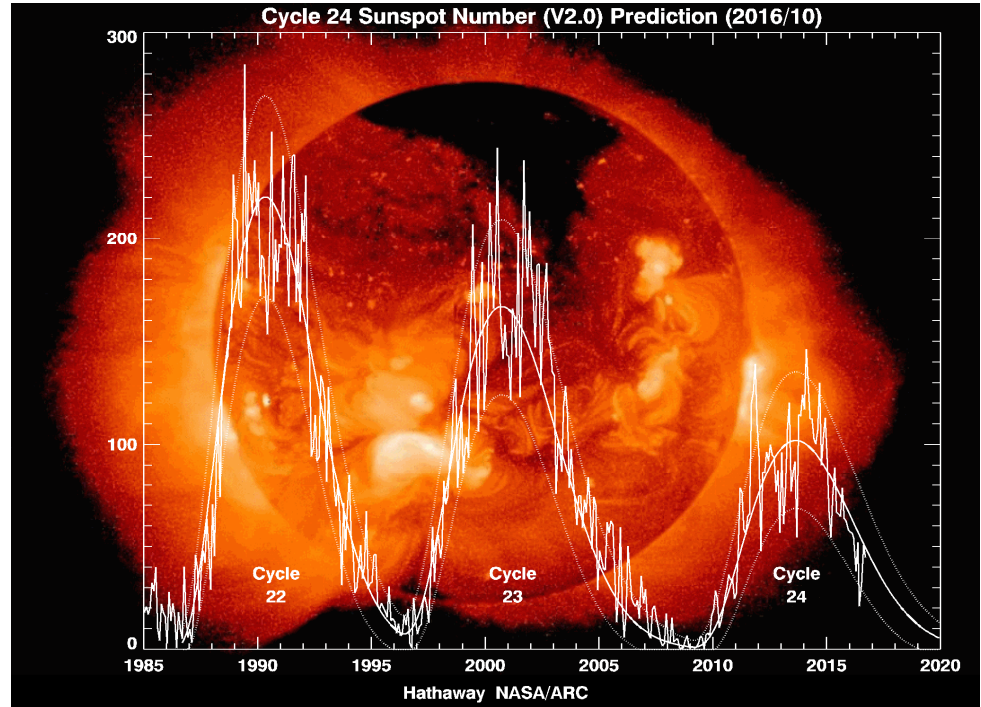
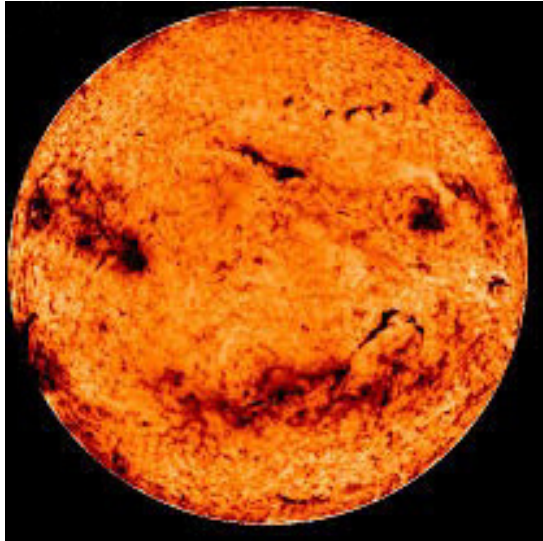


Ψύξη και συμπύκνωση υγρής αέρας μάζας λόγω αδιαβατικής ανόδου

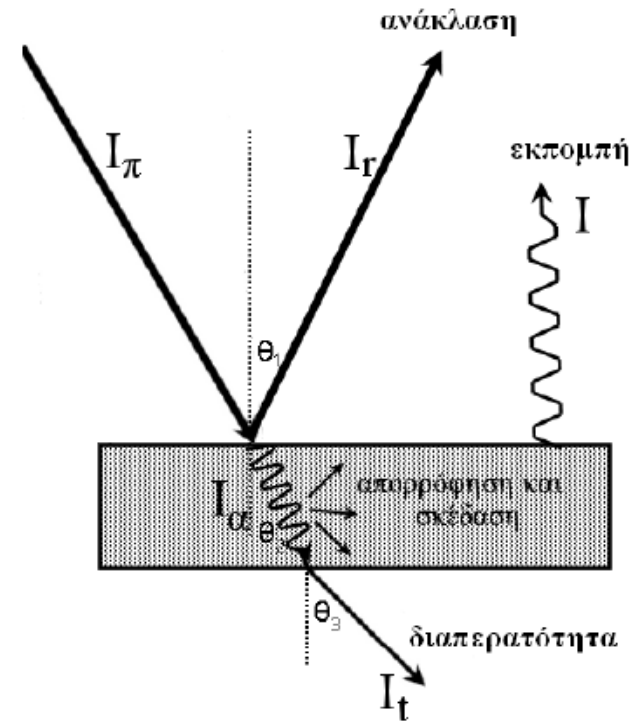
Ακτινοβολία στην ατμόσφαιρα

- *Νόμοι ακτινοβολίας μέλανος σώματος*
- *Ηλιακή ακτινοβολία*
- *Ηλιακή ακτινοβολία στην ατμόσφαιρα*
- *Γήινη ακτινοβολία*

Ήλιος



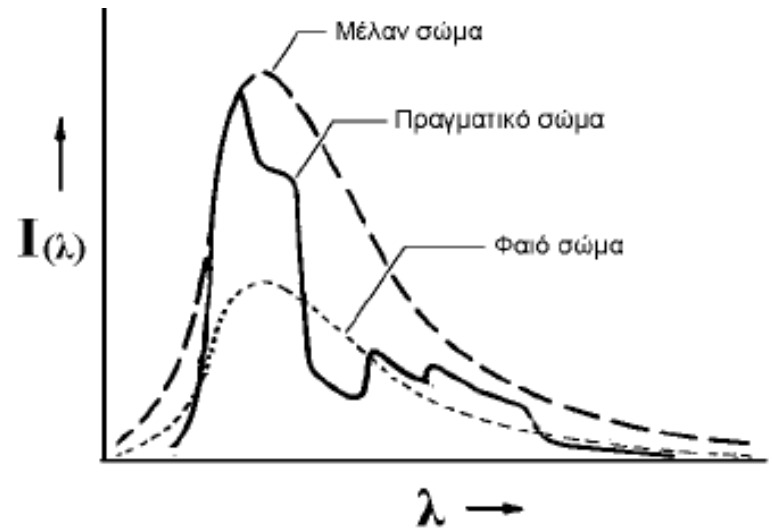
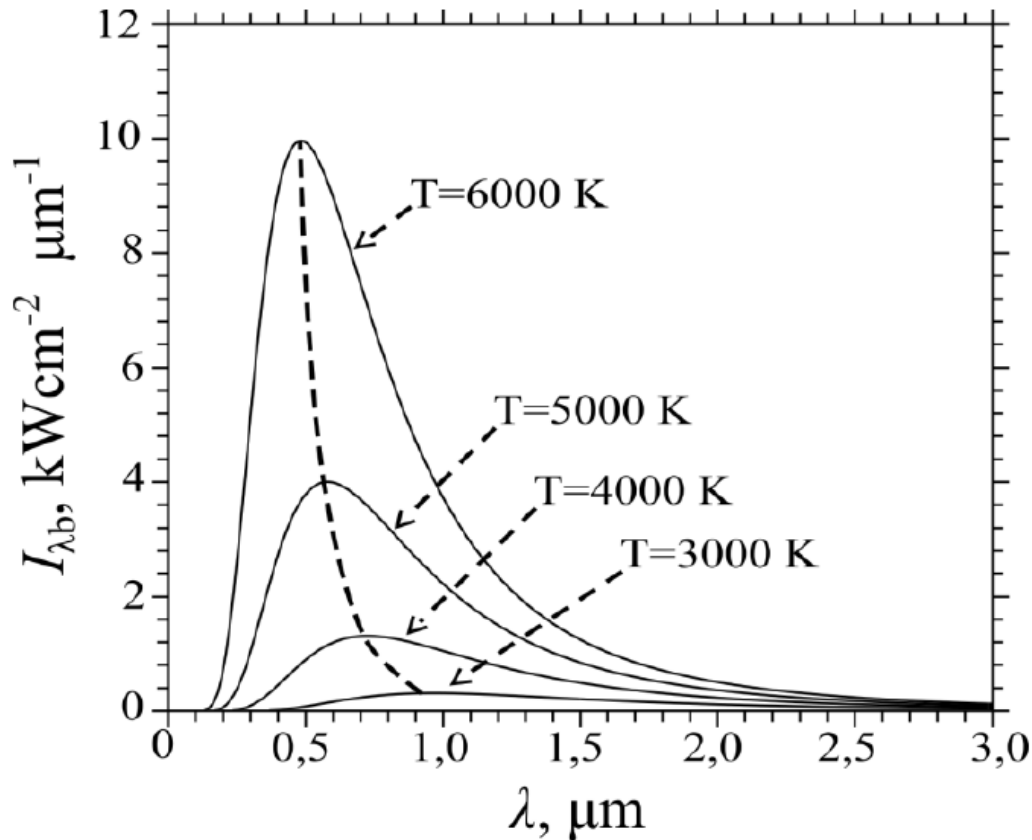
- Τρόποι διάδοσης θερμότητας
- Στοιχεία Η/Μ ακτινοβολίας - Διάδοση ακτινοβολίας
- Ένταση ακτινοβολίας
- Ροή ακτινοβολίας
- Αλληλεπίδραση της ακτινοβολίας με την ύλη
- Εκπομπή ακτινοβολίας
- Απορρόφηση ακτινοβολίας
- Διαπερατότητα



Νόμοι ακτινοβολίας

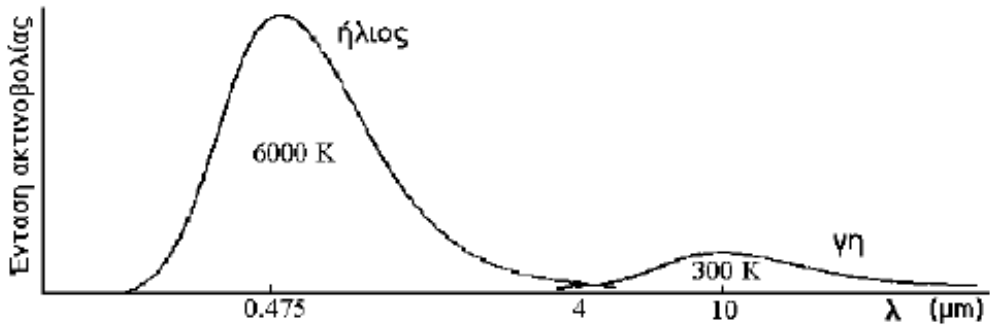
➤ Νόμος του Planck

$$I_{(\lambda)M} = \frac{c_1}{\lambda^5 \left(e^{\frac{c_2}{\lambda T}} - 1 \right)}$$



➤ **Νόμος μετατόπισης του Wien**

$$\lambda_{max} = \frac{C_1}{T}$$

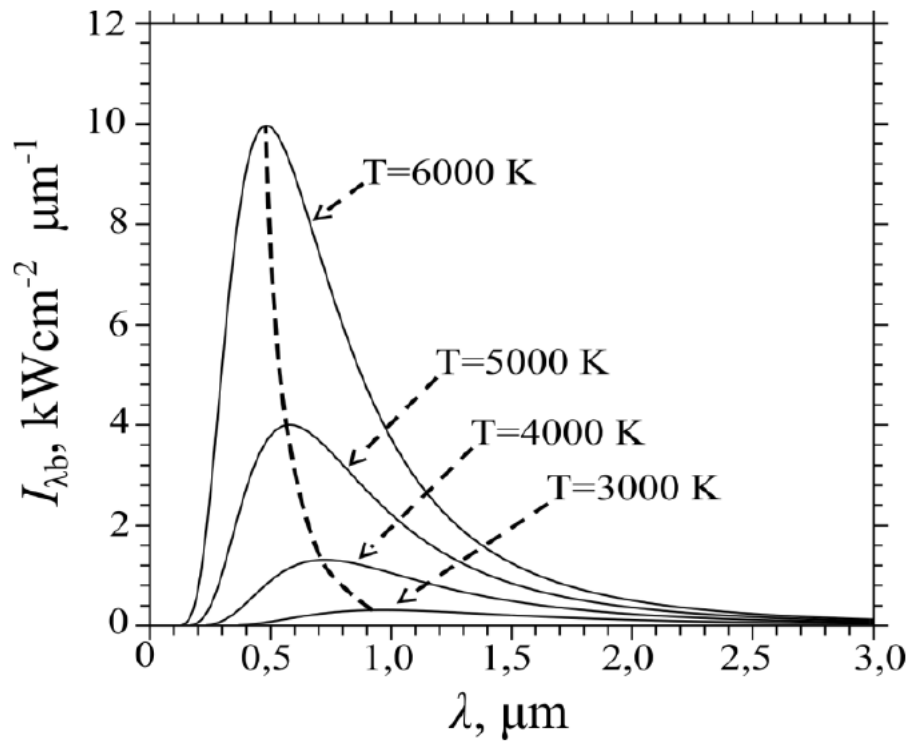


➤ **Νόμος των Stefan – Boltzmann**

$$F_M = \sigma T^4$$

➤ **Νόμος του Kirchhoff**

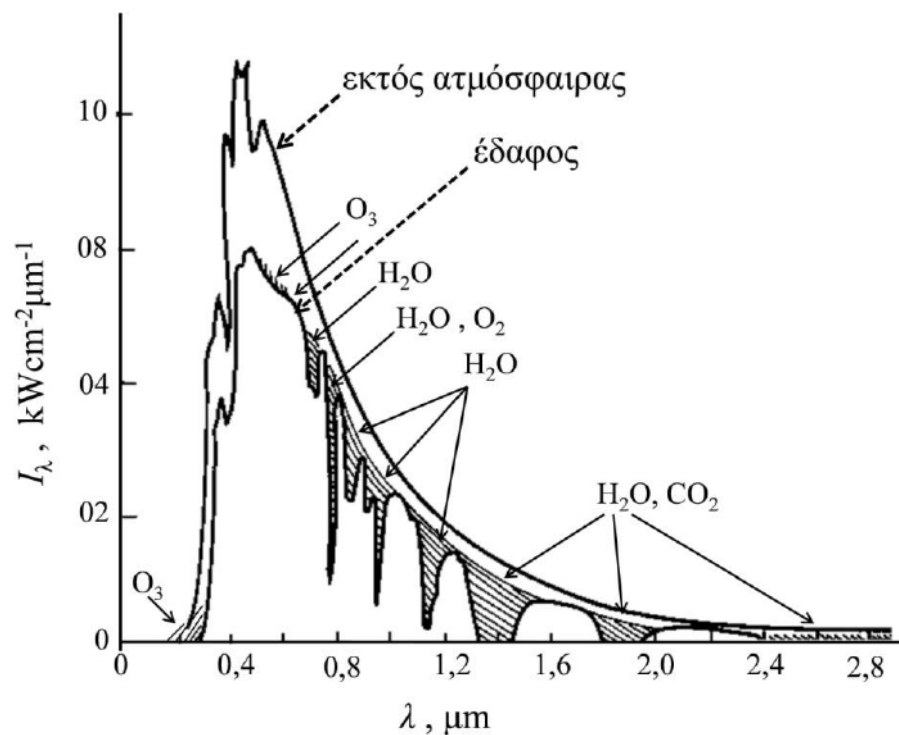
$$\epsilon_\lambda = \alpha_\lambda$$



Ηλιακή ακτινοβολία

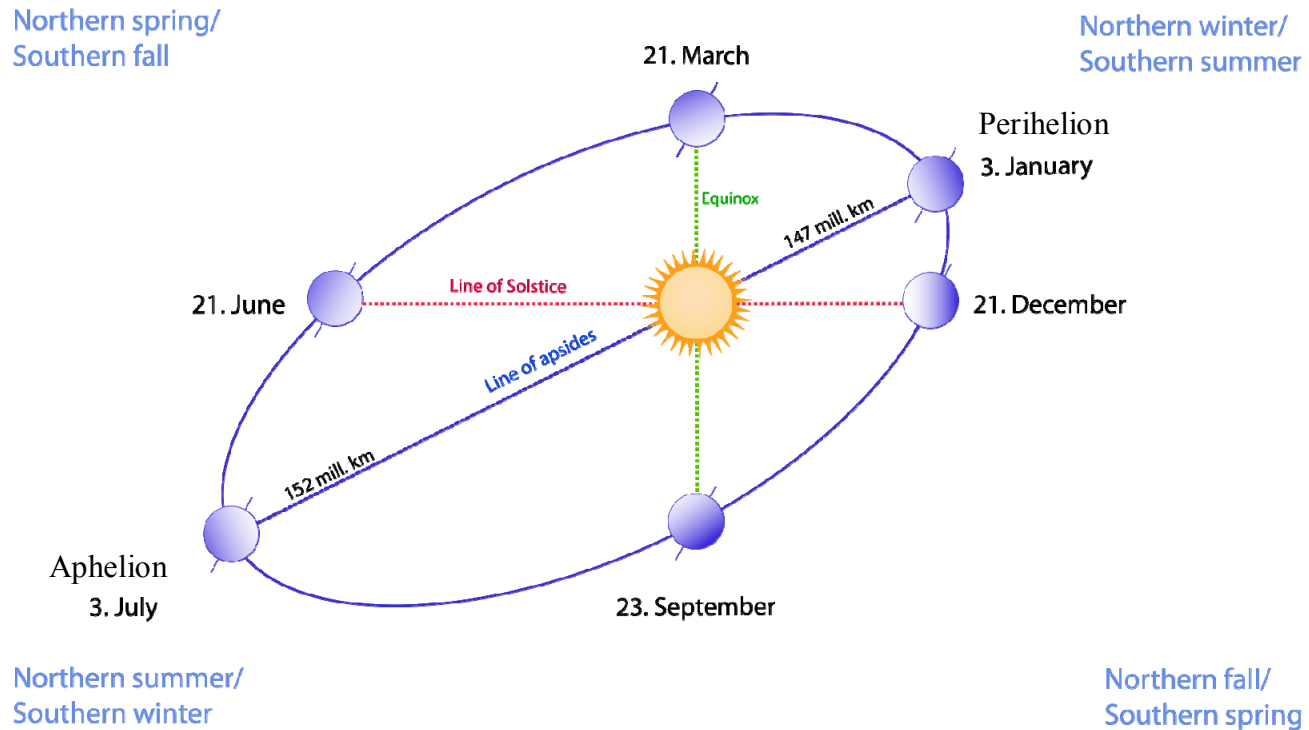
Περιοχή φάσματος	Φασματική ζώνη μήκους κύματος λ , μm	Κλάσμα ηλιακής εκπομπής, %
Ακτίνες Χ	$\lambda < 0,01$	0,00005
Ακραίο υπεριώδες	$0,01 < \lambda < 0,10$	0,0003
Μακρινό υπεριώδες	$0,10 < \lambda < 0,20$	0,01
Υπεριώδες UV-C	$0,20 < \lambda < 0,28$	0,5
Υπεριώδες UV-B	$0,28 < \lambda < 0,32$	1,3
Υπεριώδες UV-A	$0,32 < \lambda < 0,39$	6,2
Ορατό	$0,39 < \lambda < 0,76$	39,0
Κοντινό υπέρυθρο	$0,76 < \lambda < 4,0$	52,0
Θερμικό υπέρυθρο	$4,0 < \lambda < 100,0$	0,9
Μακρινό υπέρυθρο	$100,0 < \lambda < 1000,0$	0,09

Χρώμα	λ , μm	Τυπικό λ , μm
Ιώδες	0,390 - 0,455	0,430
Βαθύ μπλε	0,455 - 0,485	0,470
Ανοιχτό μπλε	0,485 - 0,505	0,495
Πράσινο	0,505 - 0,550	0,530
κιτρινοπράσινο	0,550 - 0,575	0,560
Κίτρινο	0,575 - 0,585	0,580
πορτοκαλί	0,585 - 0,620	0,600
Κόκκινο	0,620 - 0,720	0,670

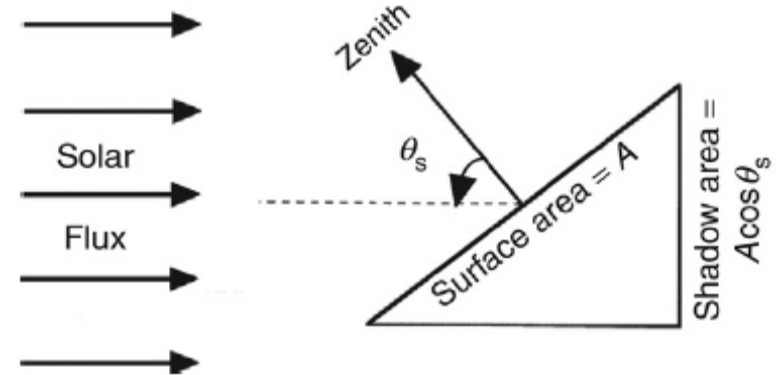
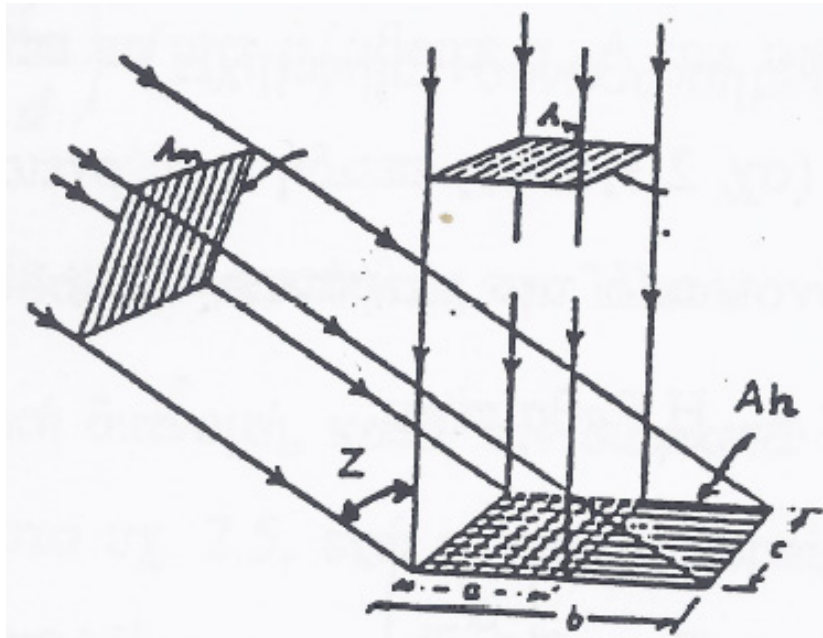


$$F = \frac{\Phi_{\text{H}}}{4\pi d_r^2}$$

Ηλιακή σταθερά → $S \approx 1360.8 \pm 0.5 \text{ Wm}^{-2}$

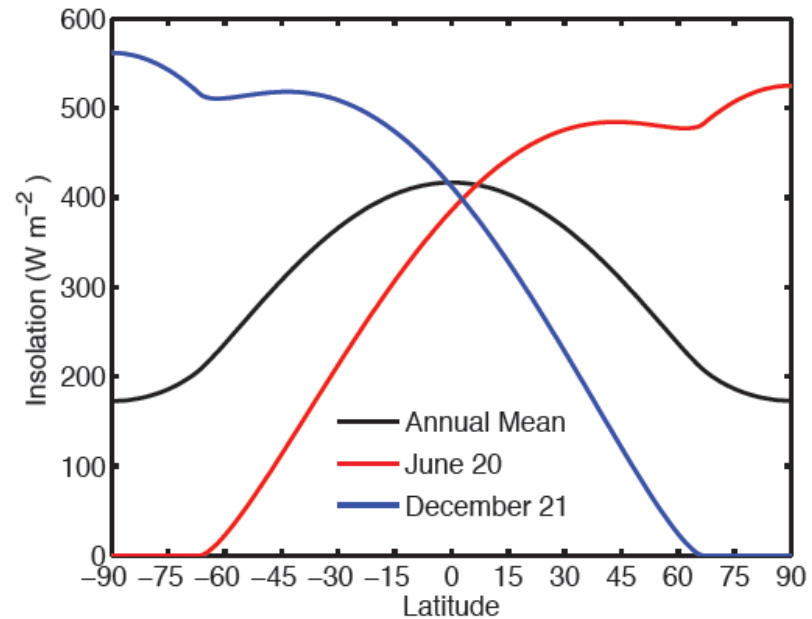
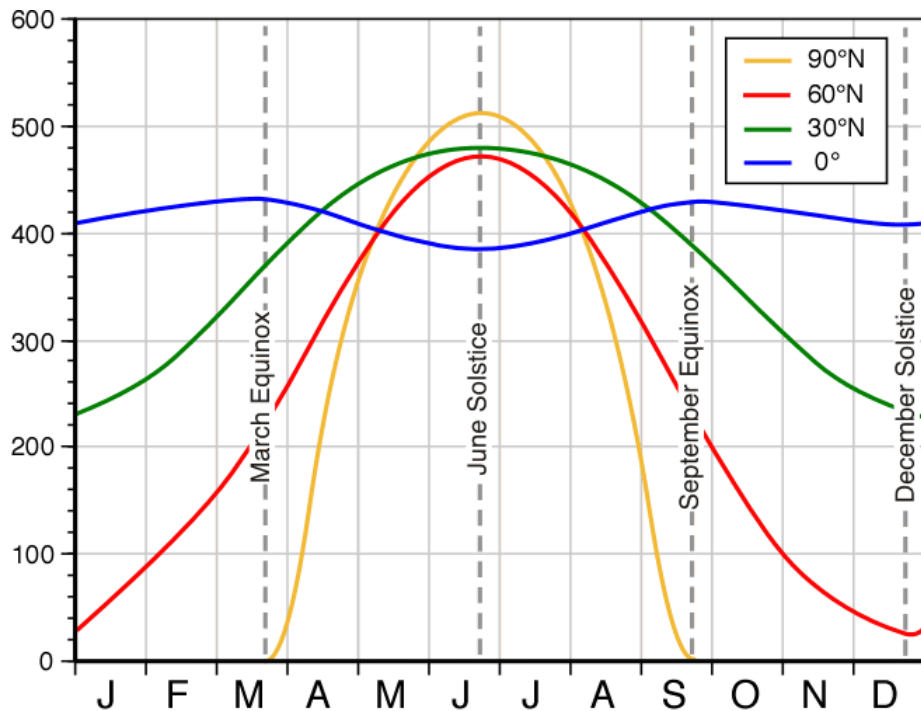


➤ Εισηγία

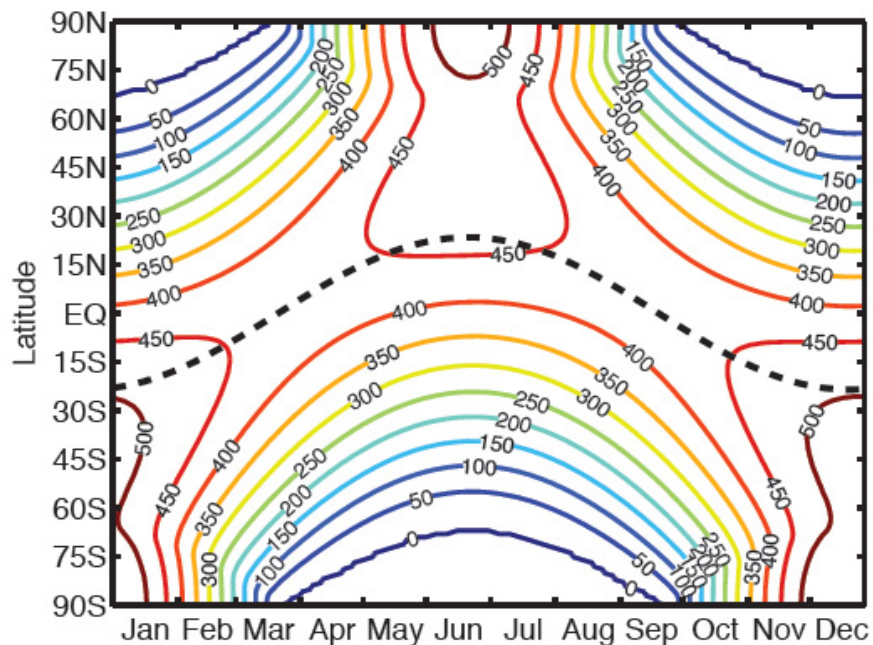


$$F_0 = S \left(\frac{d_m}{d} \right)^2 \sigma \omega z$$

$$Q_0 = S \left(\frac{d_m}{d} \right)^2 \int_A^{\Delta} \sigma \omega z dt$$



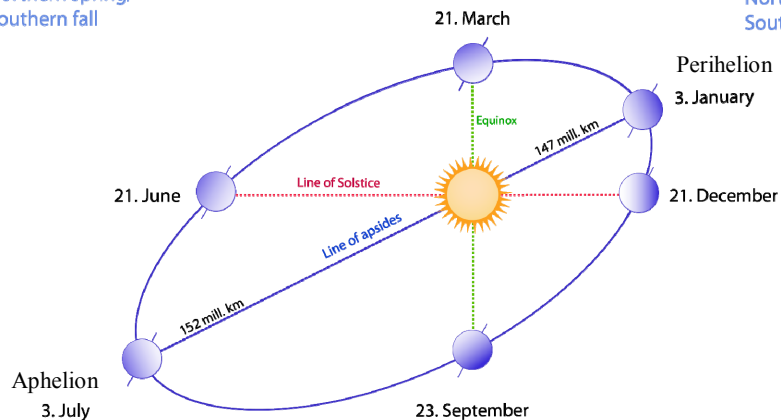
Pidwirny, 2006



➤ Περιοδικές μεταβολές της ηλιακής ακτινοβολίας

Northern spring/
Southern fall

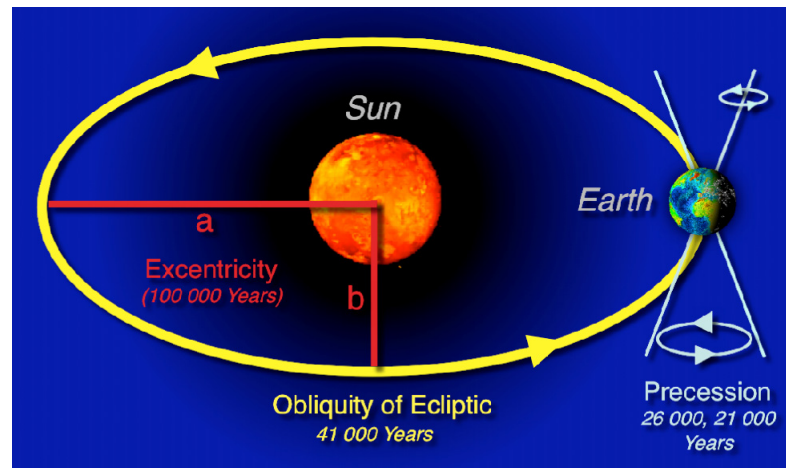
Northern winter/
Southern summer



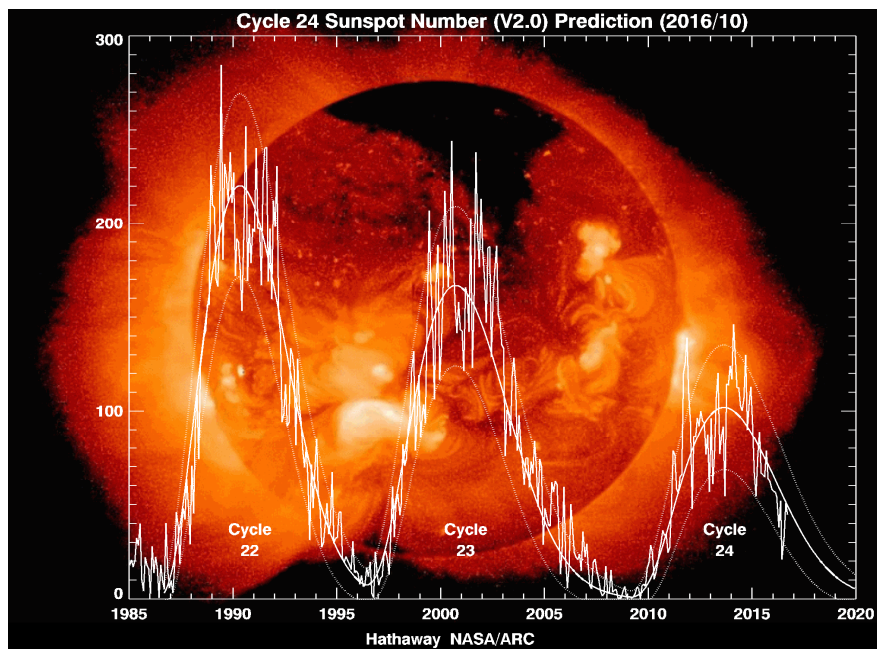
Northern summer/
Southern winter

Northern fall/
Southern spring

<https://commons.wikimedia.org/wiki/File:Seasons1.svg>



Grobe H., https://commons.wikimedia.org/wiki/File:Milankovitch-cycles_hg.png

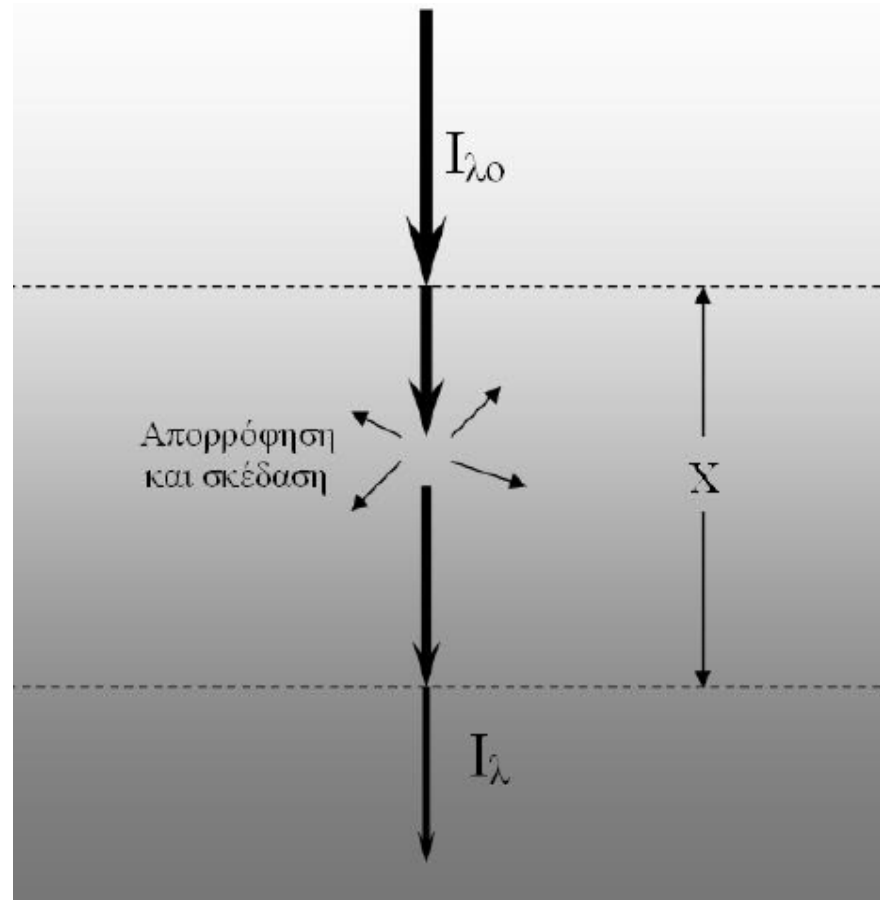


Επίδραση της ατμόσφαιρας στην ηλιακή ακτινοβολία

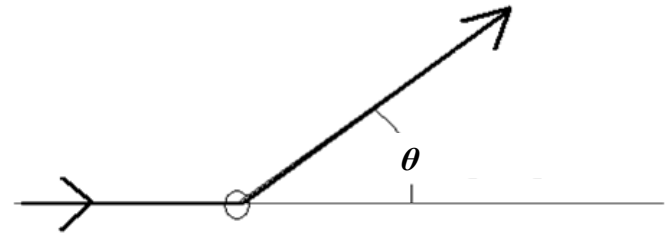
➤ Νόμος Beer-Lambert

$$I_{\lambda} = I_{\lambda 0} e^{-k_{\lambda} \rho x}$$

$$I_{\lambda} = I_{\lambda 0} e^{-u}$$



Σκέδαση

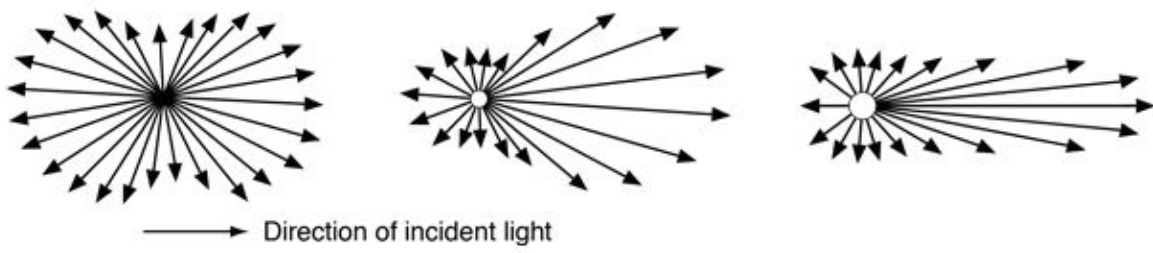
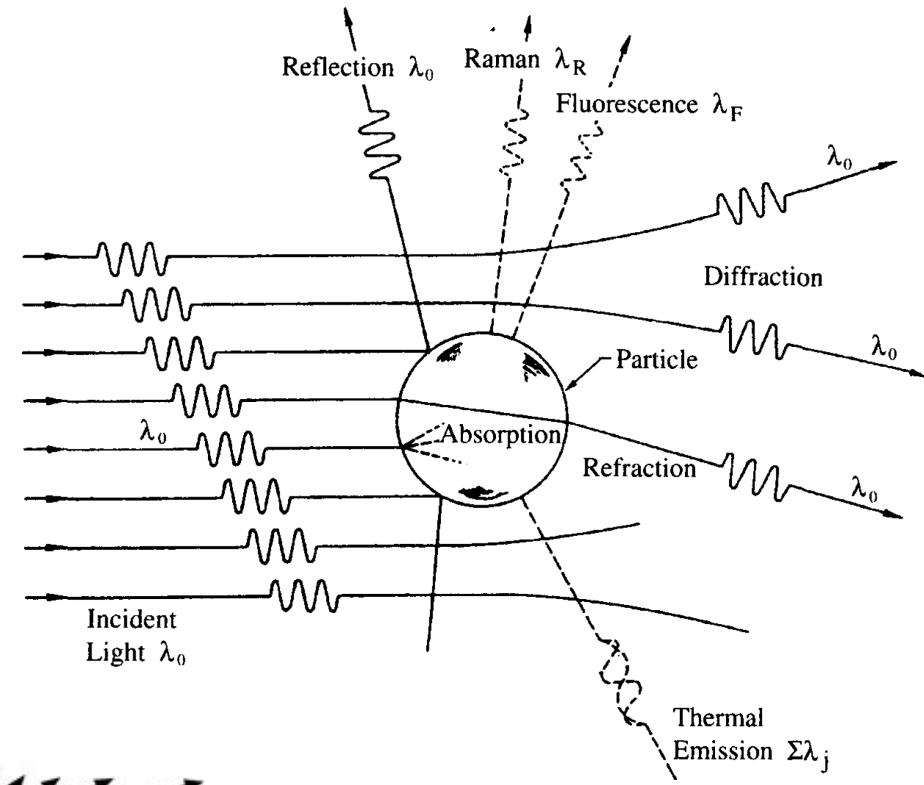


- Ελαστική σκέδαση
- Ημιαστική σκέδαση
- Ανελαστική (μη-ελαστική) σκέδαση

➤ Σκέδαση Rayleigh $I_{\lambda_{sc}} \propto I_{\lambda} \frac{1 + \cos^2 \theta}{\lambda^4}$

- Σκέδαση Mie
- Γεωμετρική σκέδαση

$$a = 2\pi R / \lambda$$



Ηλιακή ακτινοβολία

➤ *Άμεση*

➤ *Διάχυτη*

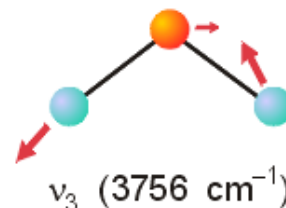
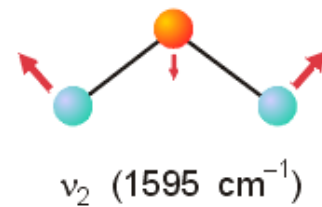
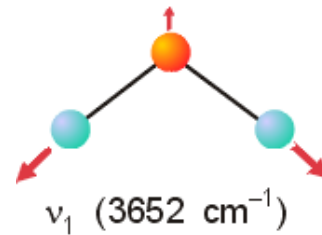
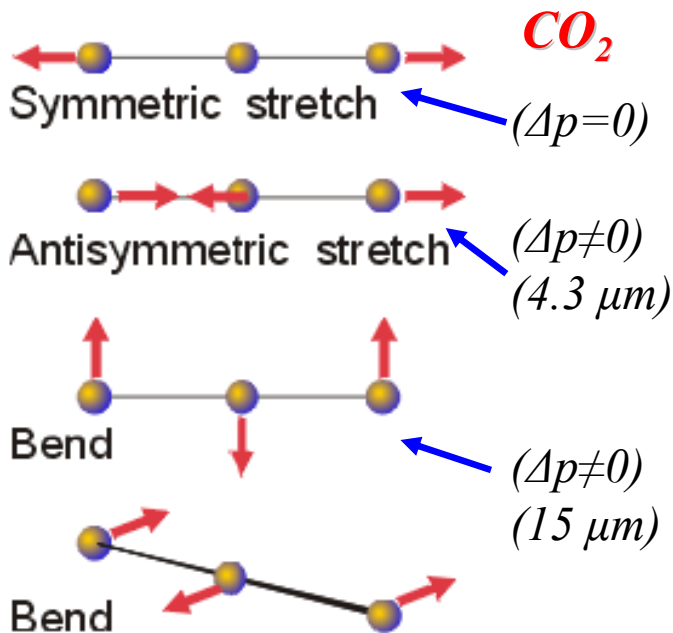
➤ *Ολική*

➤ *Ανακλώμενη*

➤ *Λευκαύγεια*

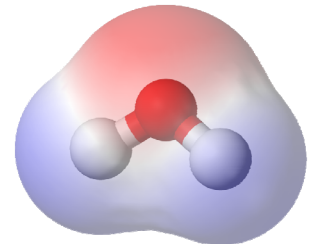
Αλληλεπίδραση ακτινοβολίας και αερίων της ατμόσφαιρας

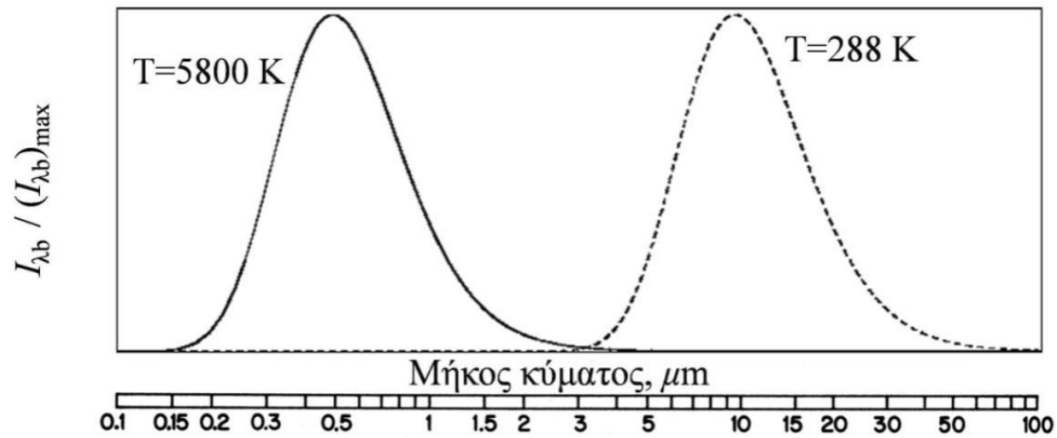
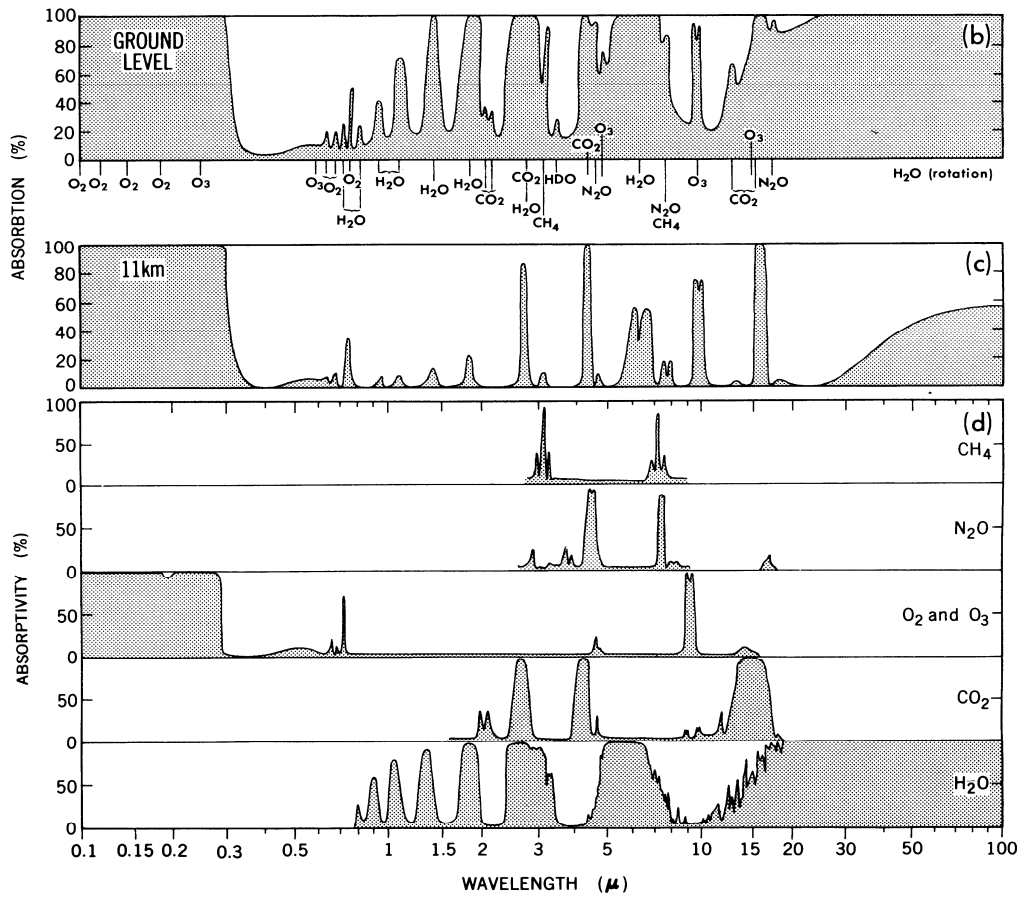
- $E_{\text{translational}}$
- Ηλεκτρονική ενέργεια ($E_{\text{electronic}}$)
- Περιστροφική ενέργεια ($E_{\text{rotational}}$)
- Ταλαντωτική ενέργεια ($E_{\text{vibrational}}$)



H₂O

(6.3 μm)

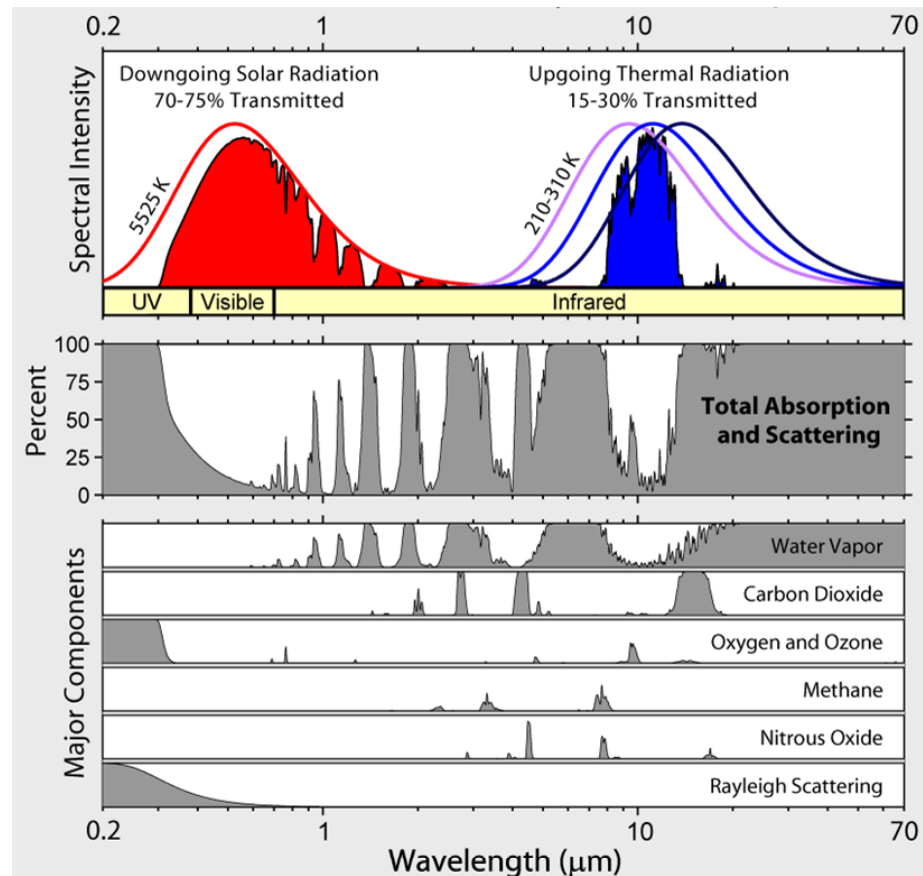




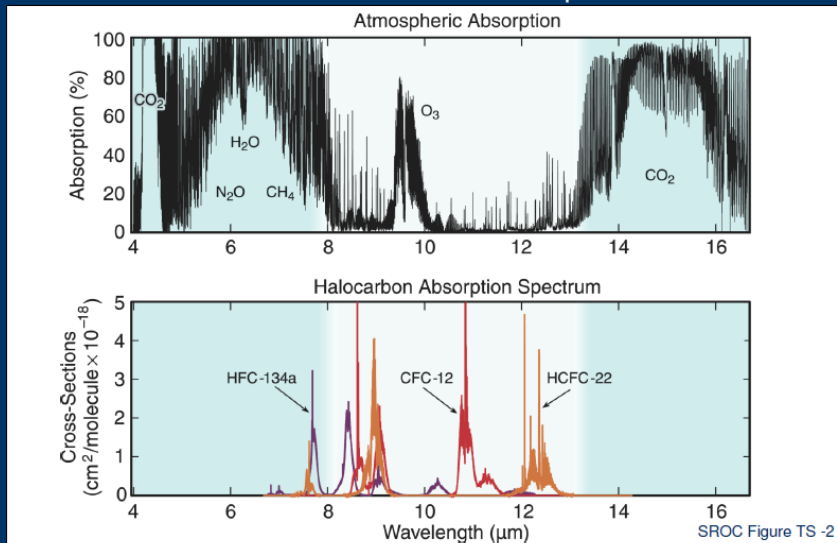
➤ *Γραμμές / ζώνες απορρόφησης (absorption lines or bands)*

➤ *Διεύρυνση λόγω κρούσεων ή πίεσης (pressure or collision broadening)*

➤ *Διαπλάτνση Doppler (Doppler broadening)*



Infrared atmospheric absorption and absorption cross-sections for halocarbons in the infrared atmospheric window



➤ *Ατμοσφαιρικό παράθυρο*

Επίδραση των αιωρούμενων σωματιδίων

$$\tilde{F}_{scat} = C_{scat} \cdot F_0$$

$$\tilde{F}_{abs} = C_{abs} \cdot F_0$$

➤ C_{scat} (m^2), ενεργός διατομή σκέδασης (single-particle scattering cross section)

➤ C_{abs} (m^2), ενεργός διατομή απορρόφησης (single-particle absorption cross section)

➤ C_{ext} , ενεργός διατομή εξασθένισης (extinction cross section) $C_{ext} = C_{scat} + C_{abs}$

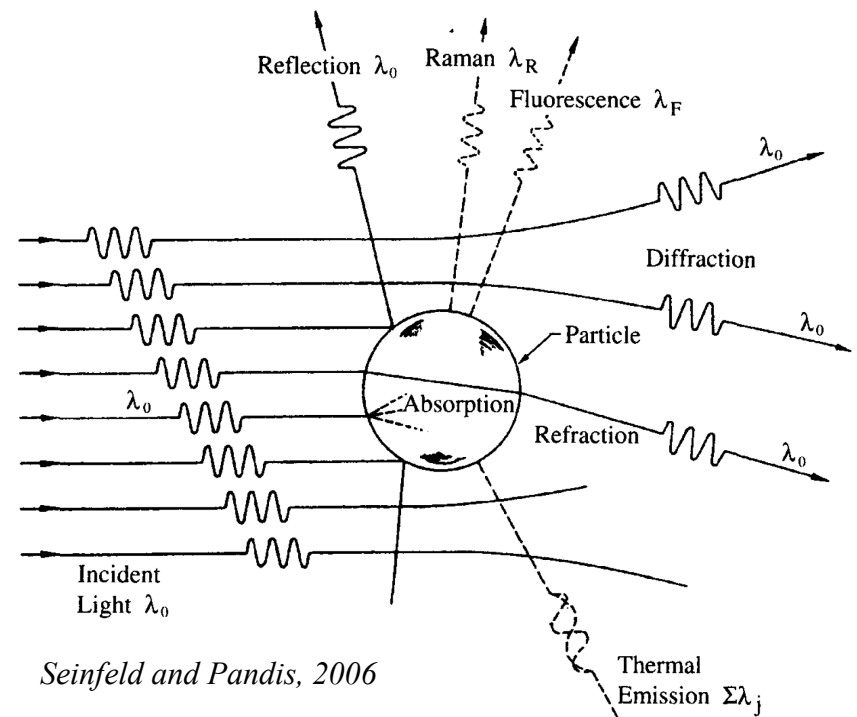
➤ Ικανότητα σκέδασης (scattering efficiency) $Q_{scat} = C_{scat} / A$

➤ Ικανότητα εξασθένισης (extinction efficiency)

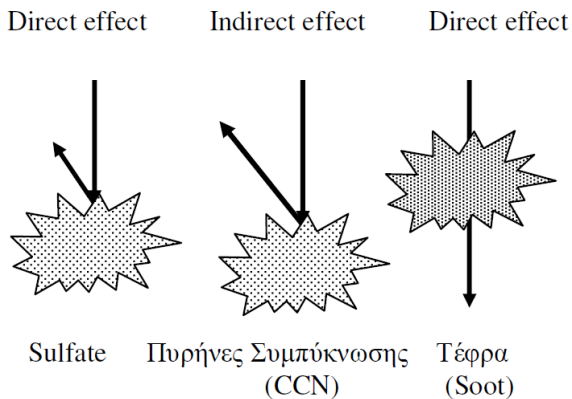
$$Q_{ext} = Q_{scat} + Q_{abs}$$











➤ Ανακλαστικότητα μεμονωμένης σκέδασης (single-scattering albedo)

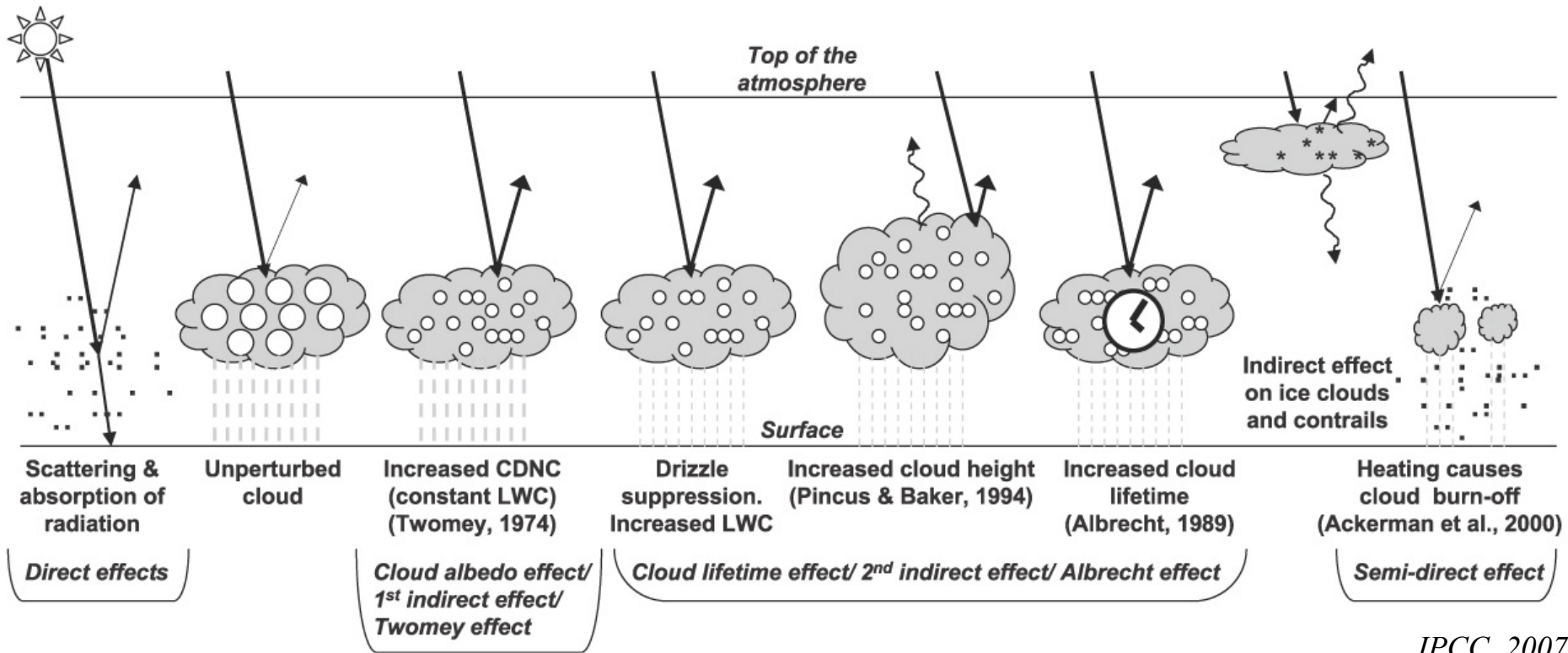
$$\omega = \frac{Q_{scat}}{Q_{ext}} = \frac{C_{scat}}{C_{ext}}$$



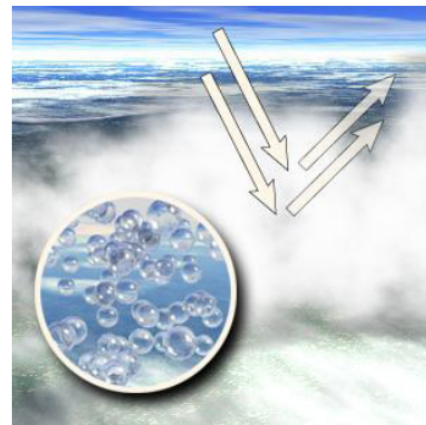
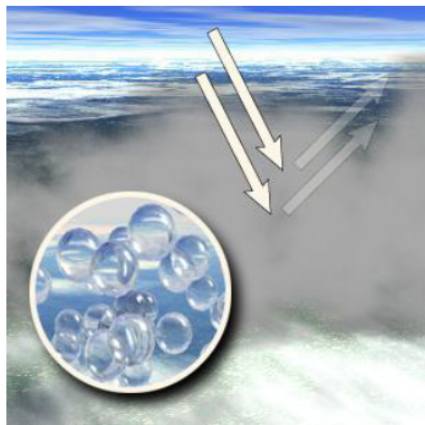
Seinfeld and Pandis, 2006



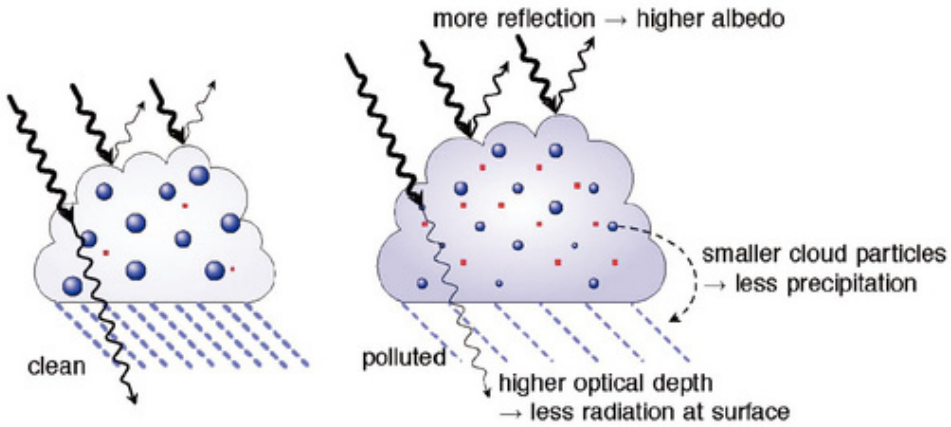
Particle	Type	Radiative Properties
	Black carbon ^a	Absorbing (all solar wavelengths)
	Brown (or yellow) carbon ^b	Absorbing (UV and some visible)
	Non-absorbing carbon ^b	Scattering
	Nitrate ^c	Scattering
	Sulfate ^c	Scattering
	Black carbon coated with brown or non-absorbing carbon ^d	Absorbing (enhanced by partial internal reflection of solar radiation); fractionally scattering
	Black carbon associated with sulfate or nitrate ^e	Absorbing plus some scattering
	Cloud and fog droplets ^f	Scattering
	Complex of several particles ^e	Absorbing and scattering
	Mixed particle (cloud processed) ^g	Absorbing (enhanced by partial internal reflection of solar radiation); fractionally scattering



IPCC, 2007

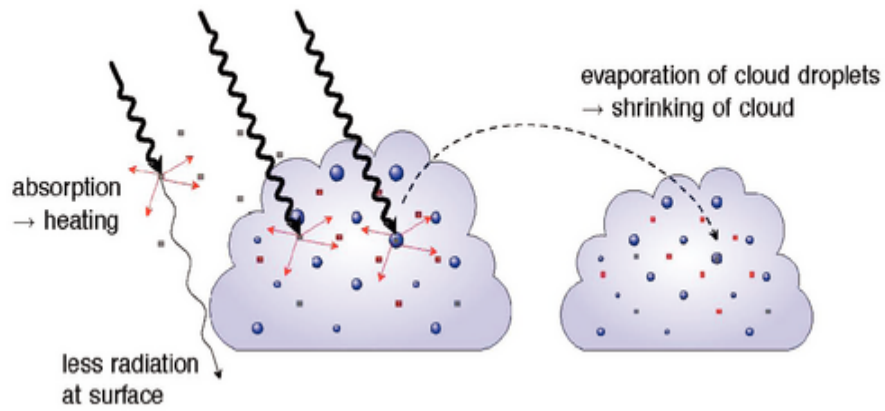


Cloud albedo and lifetime effect (negative radiative effect for warm clouds at TOA; less precipitation and less solar radiation at the surface)

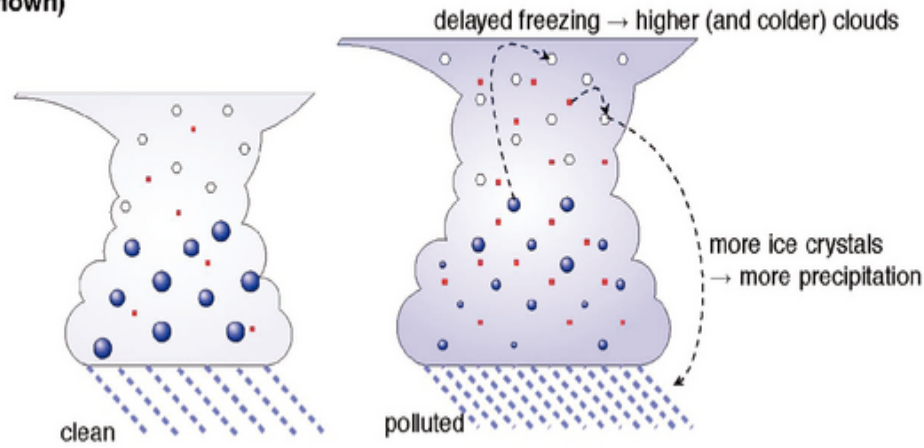


Effect	Cloud Types Affected	Process	Net Effect
Cloud albedo effect (first indirect effect)	All clouds	Smaller cloud particles reflect more solar radiation	Cooling
Cloud lifetime effect (second indirect effect)	All clouds	Smaller cloud particles decrease precipitation so increase lifetime	Cooling
Semi-direct effect	All clouds	Absorption of solar radiation by absorbing aerosols changes atmospheric stability and cloud formation	Cooling or warming
Glaciation indirect effect	Mixed-phase clouds	An increase in ice nuclei due to some aerosols increases precipitation	Warming
Thermodynamic effect	Mixed-phase clouds	Smaller cloud droplets delay freezing causing super-cooled clouds to extend to colder temperatures	Cooling or warming

Semi-direct effect (positive radiative effect at TOA for soot inside clouds, negative for soot above clouds)



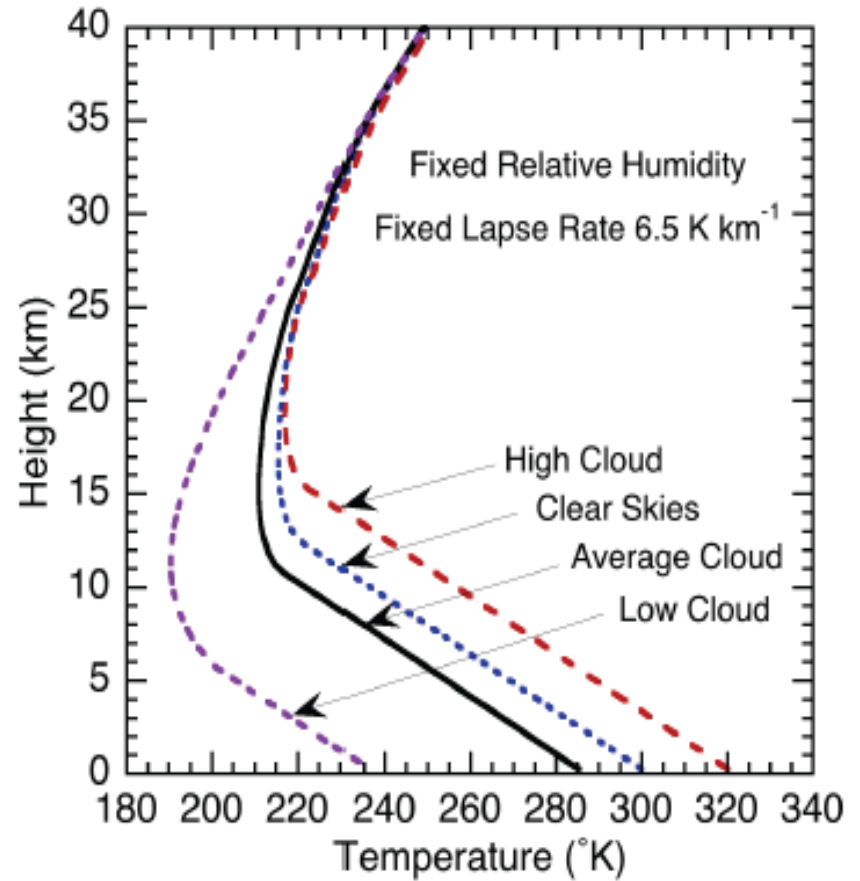
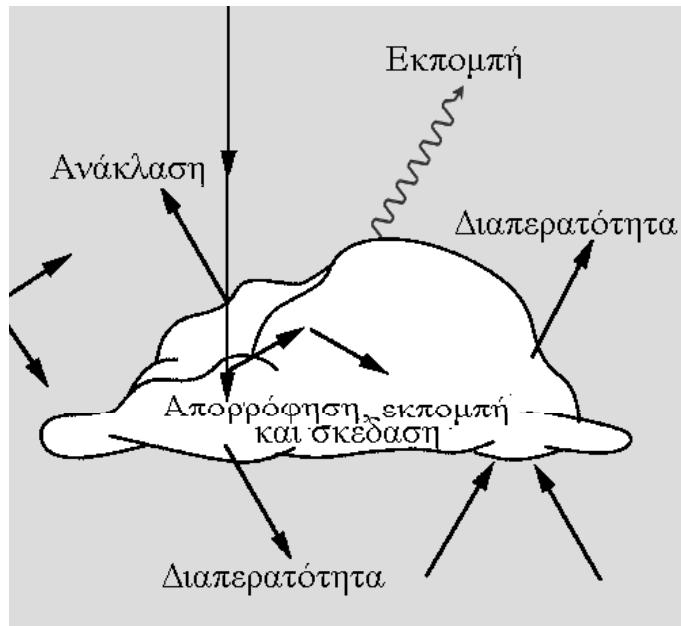
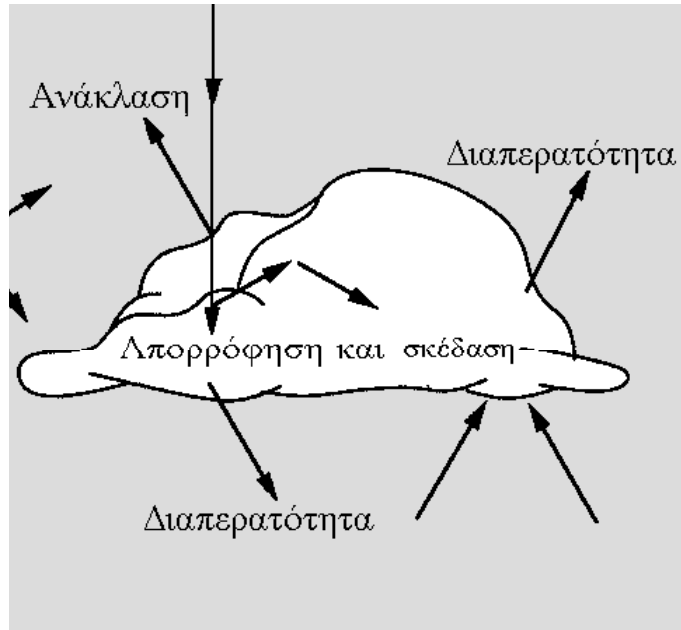
Glaciation effect (positive radiative effect at TOA and more precipitation), thermodynamic effect (sign of radiative effect and change in precipitation not yet known)

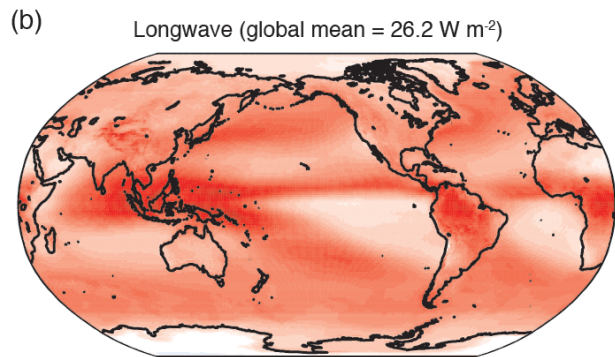
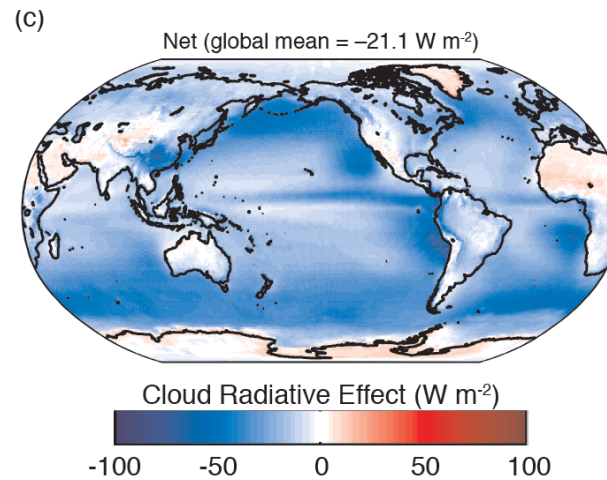
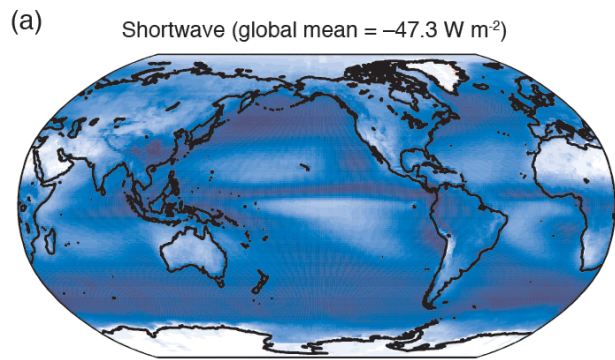


U.S. EPA, 2012

IPCC, 2007

Επίδραση των νεφών

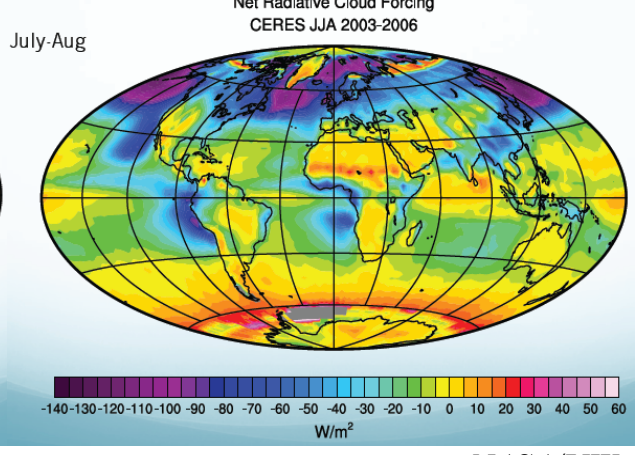
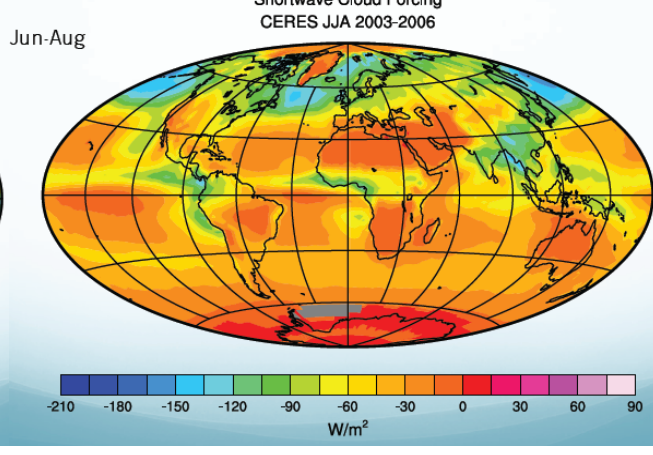
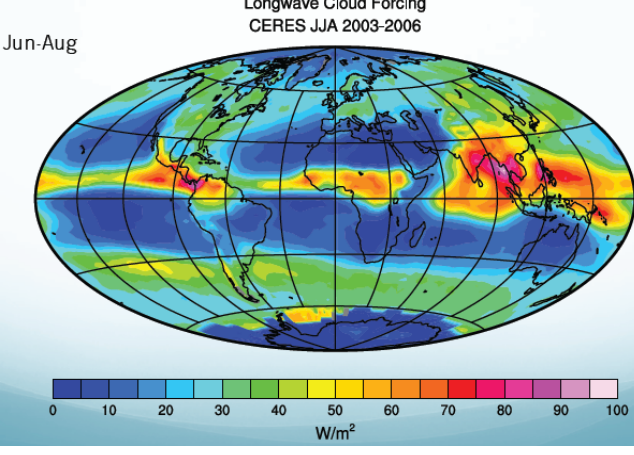
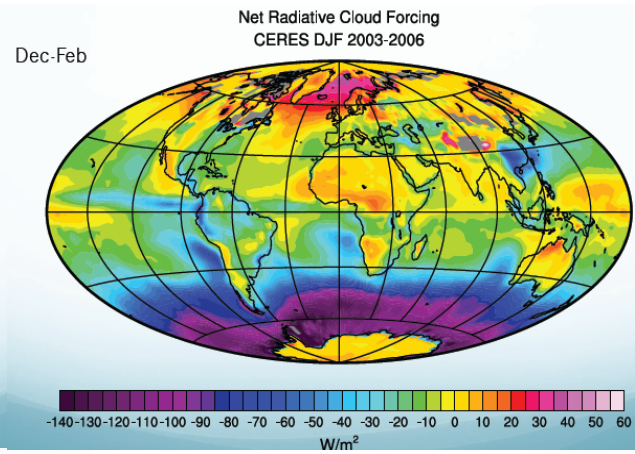
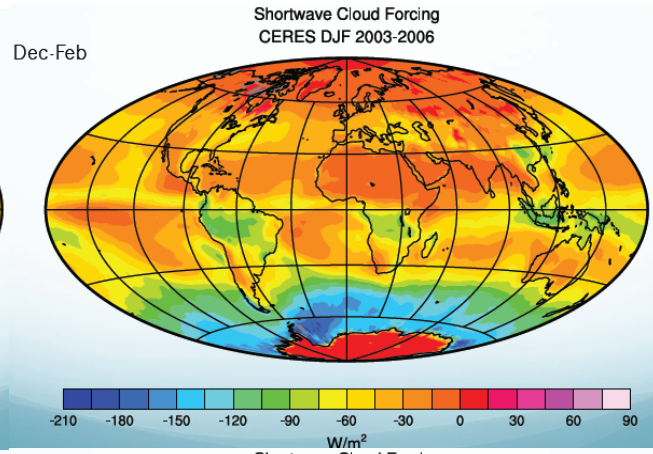
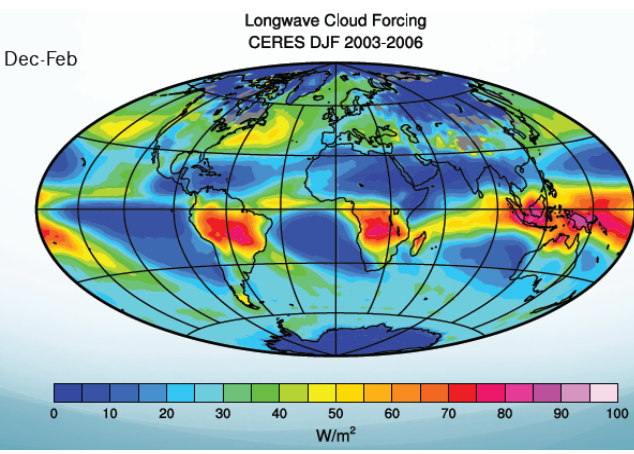
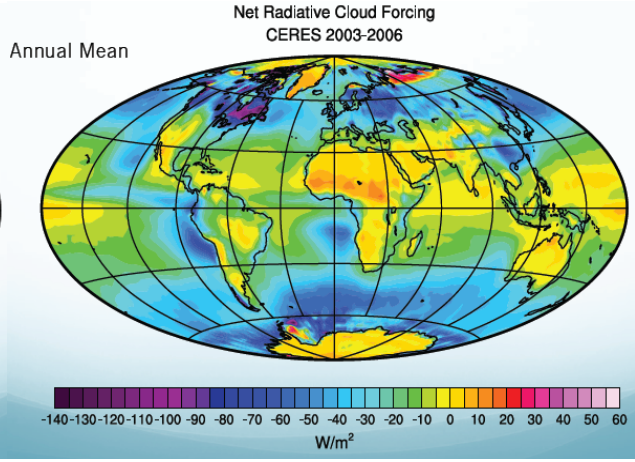
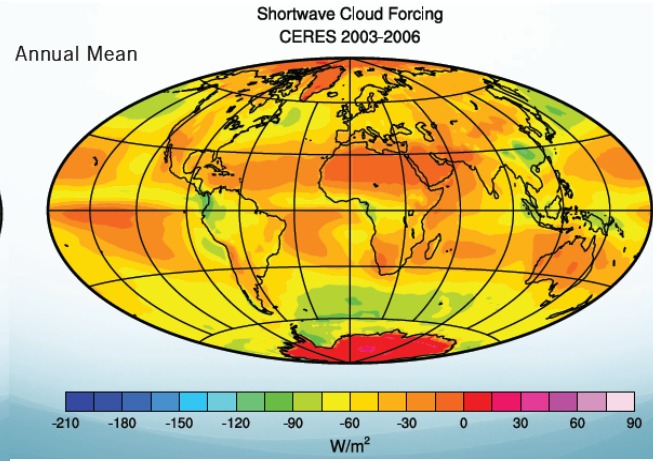
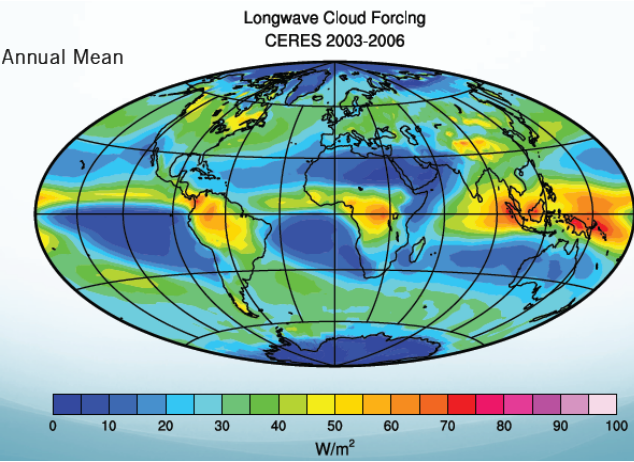


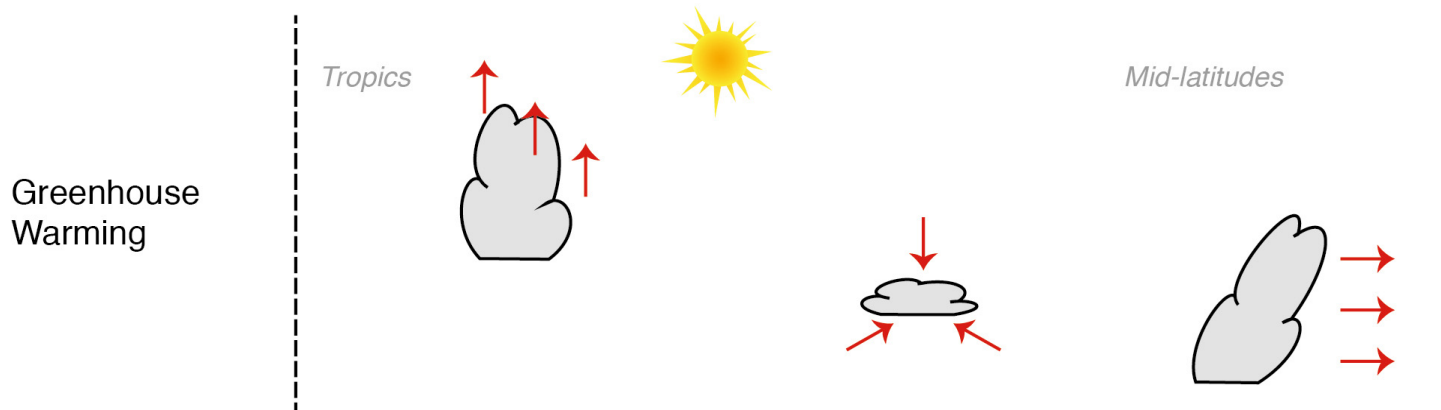
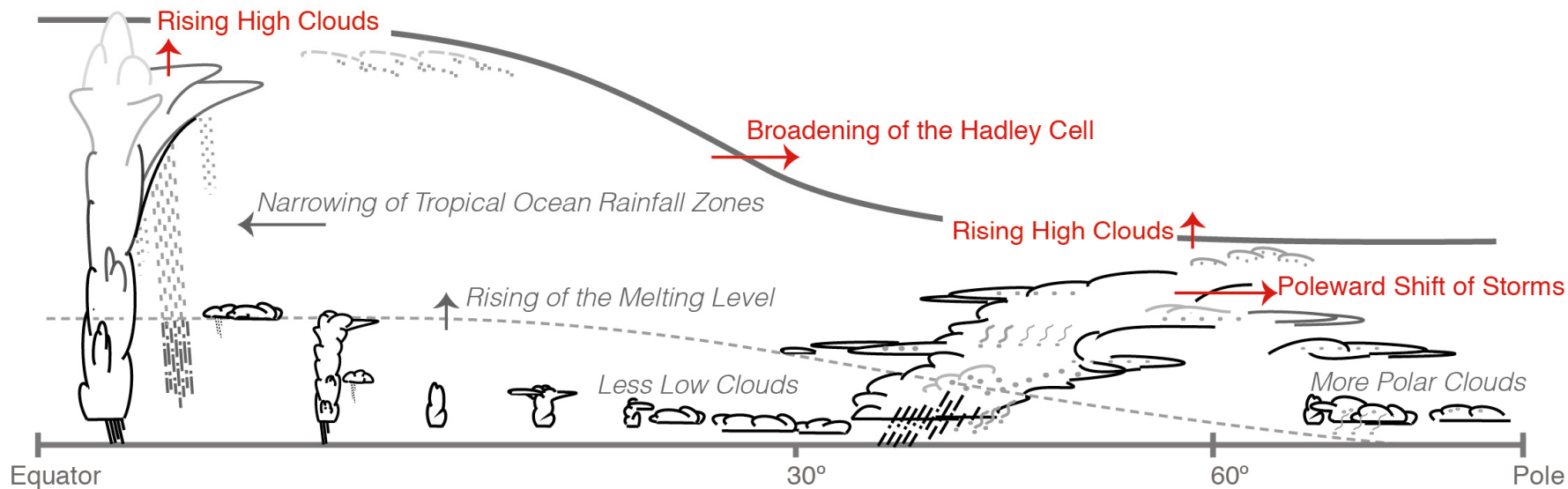


Distribution of annual-mean top of the atmosphere (a) shortwave, (b) longwave, (c) net cloud radiative effects averaged over the period 2001–2011 from the CERES Energy Balanced and Filled (EBAF) Ed2.6r data set (Loeb et al., 2009). (IPCC, 2013)

	Average	Cloud free	Cloud effect
OLR (Wm^{-2})	240	266	+26
Absorbed solar radiation (Wm^{-2})	240	288	-47
Net radiation (Wm^{-2})	+0.56	+22	-21
Albedo (%)	29%	15%	+14%

From CERES data (Loeb et al., 2009)

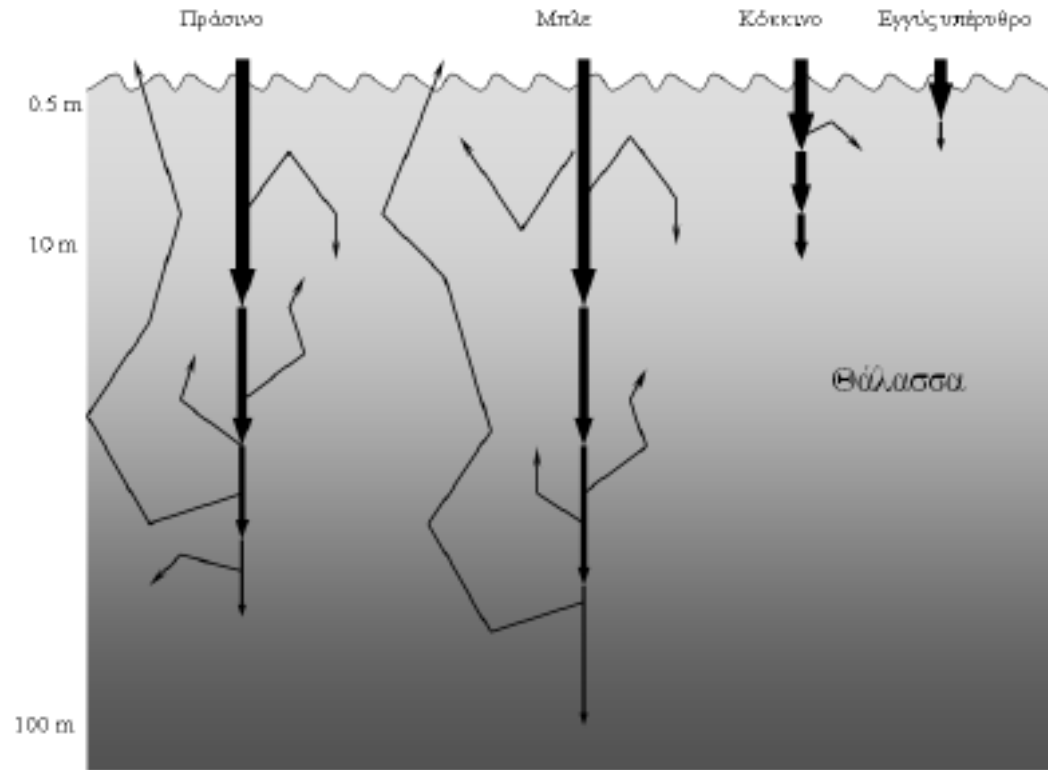
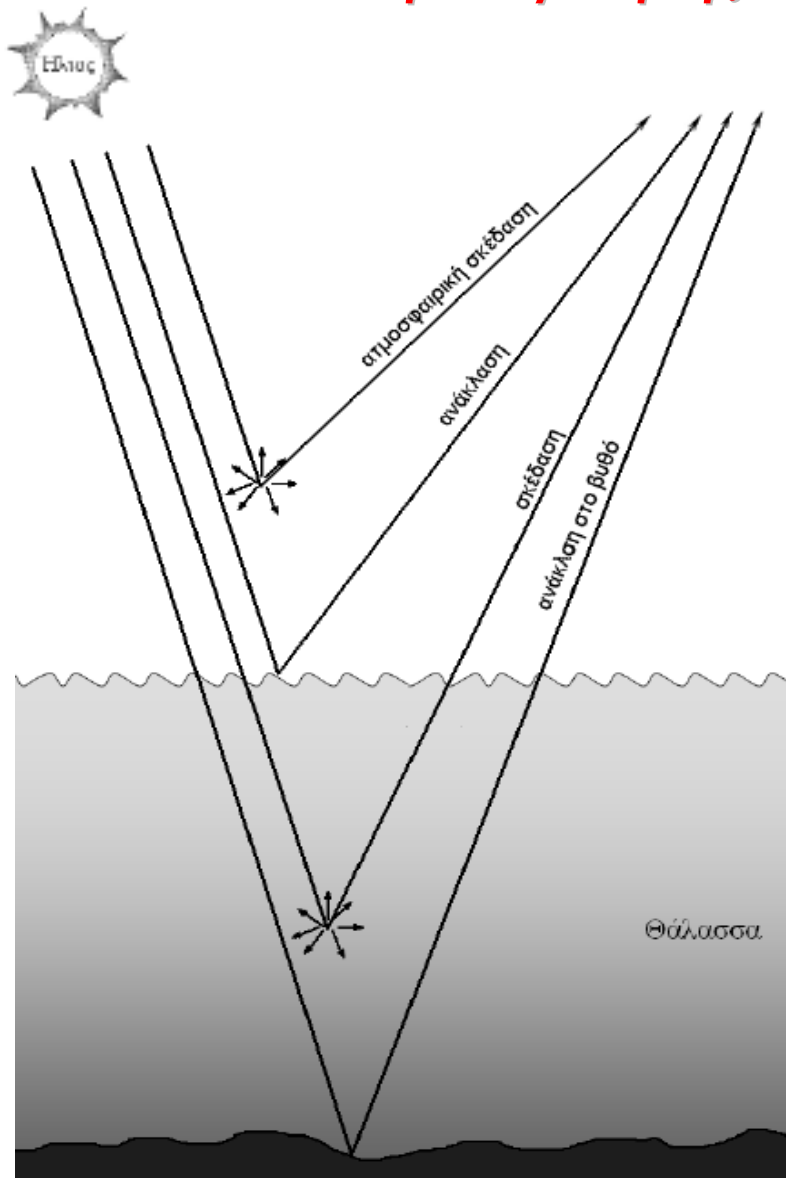




<p>Cloud Response</p>	<p>High clouds rise as troposphere deepens, increasing difference between cloud top and surface temperature.</p>	<p>Reduction in mid- and low-level cloudiness (left). Shift of cloudy storm tracks poleward into regions with less sunlight (right).</p>
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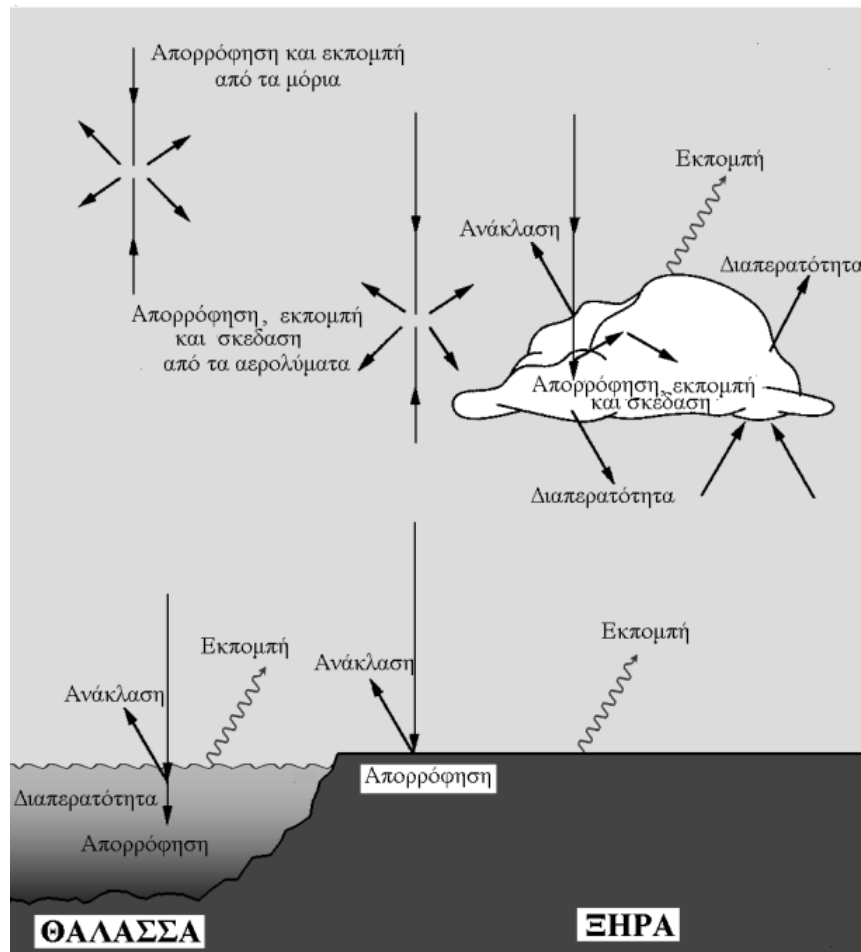
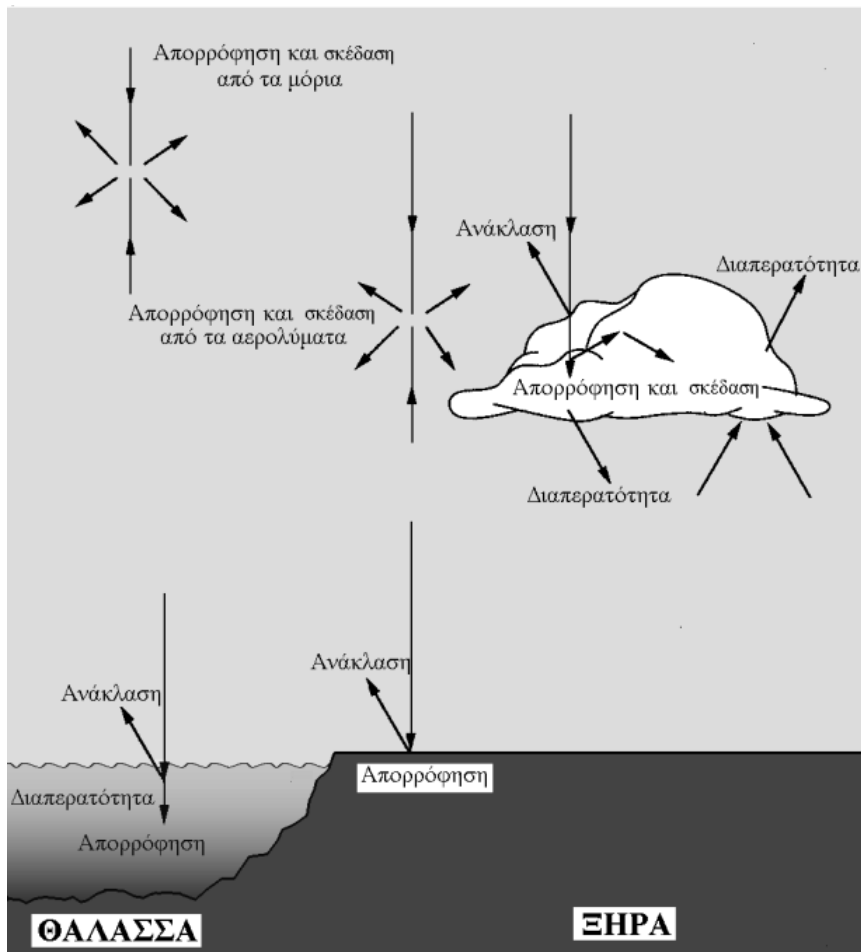
<p>Feedback Mechanism</p>	<p>High clouds more effectively trap infrared radiation, increasing surface warming.</p>	<p>Less sunlight reflected by clouds back to space, increasing surface warming.</p>
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Αλληλεπίδραση της ακτινοβολίας με υδάτινες επιφάνειες

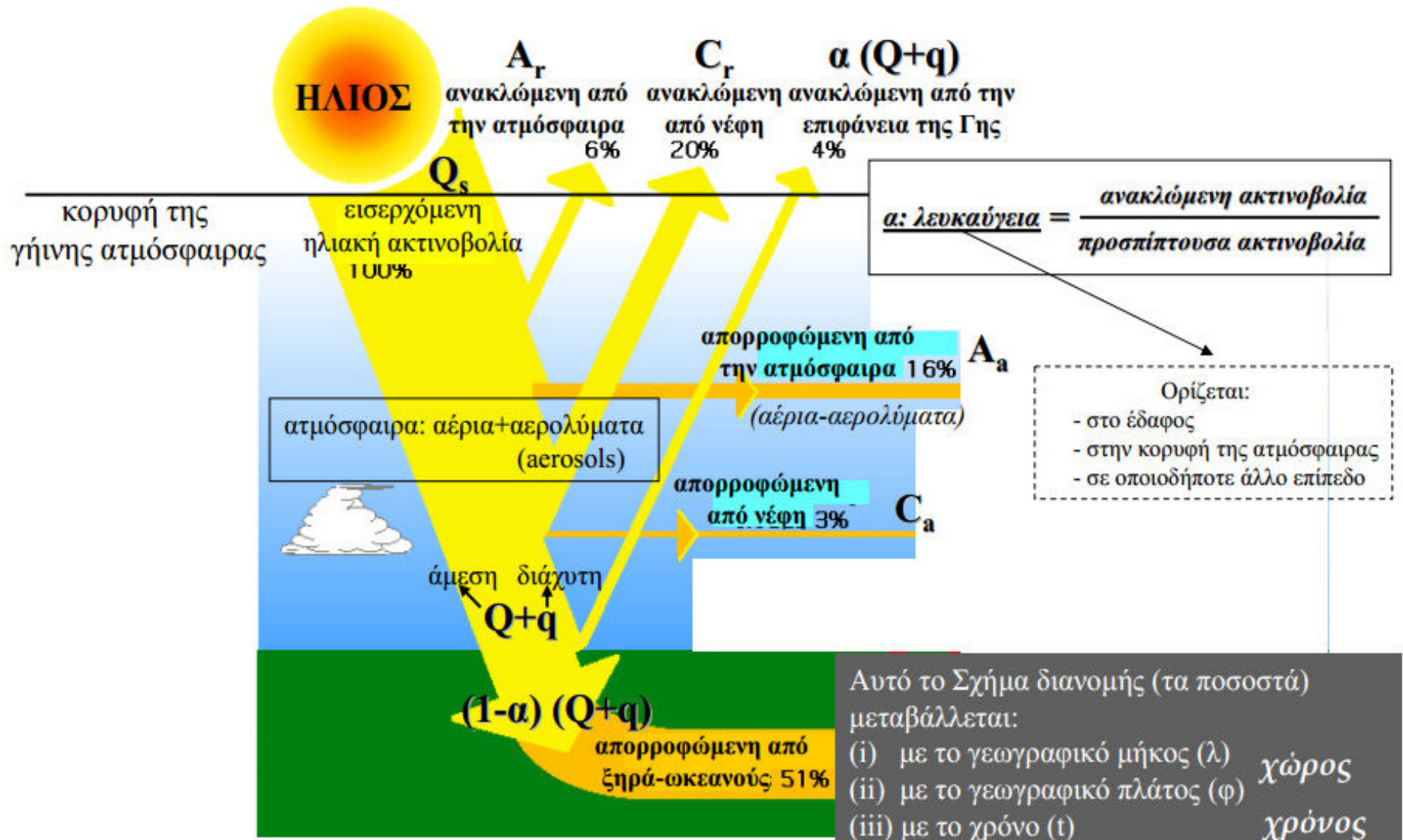


- *Ανάκλαση*
- *Απορρόφηση*
- *Σκέδαση*

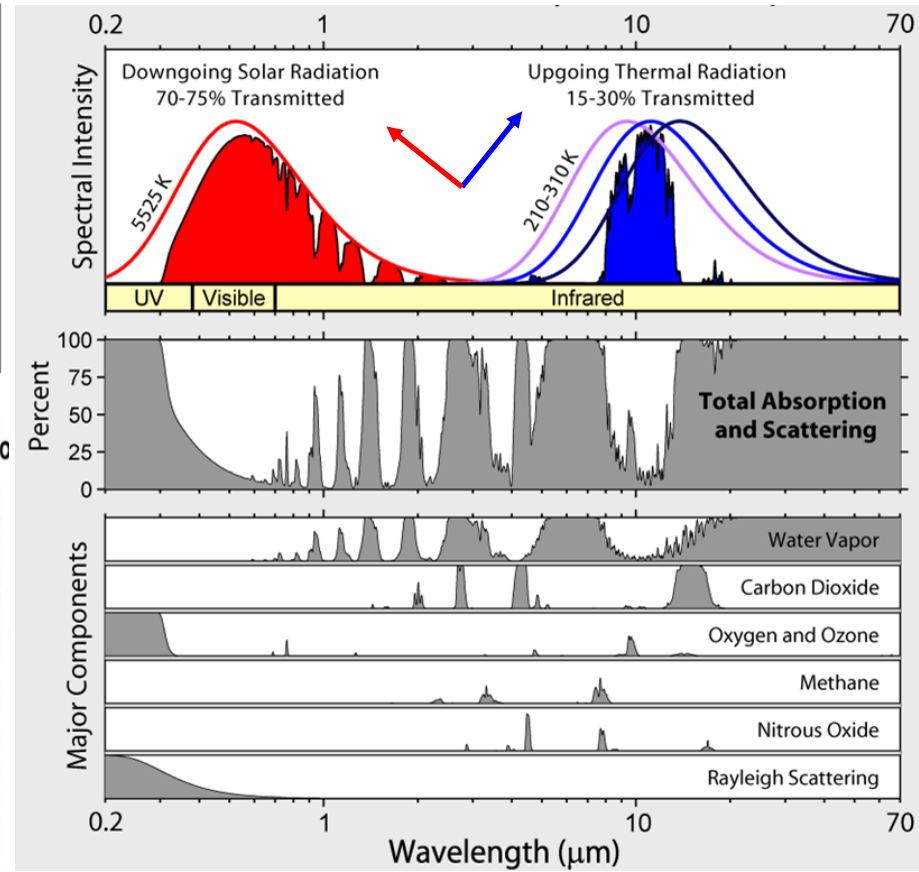
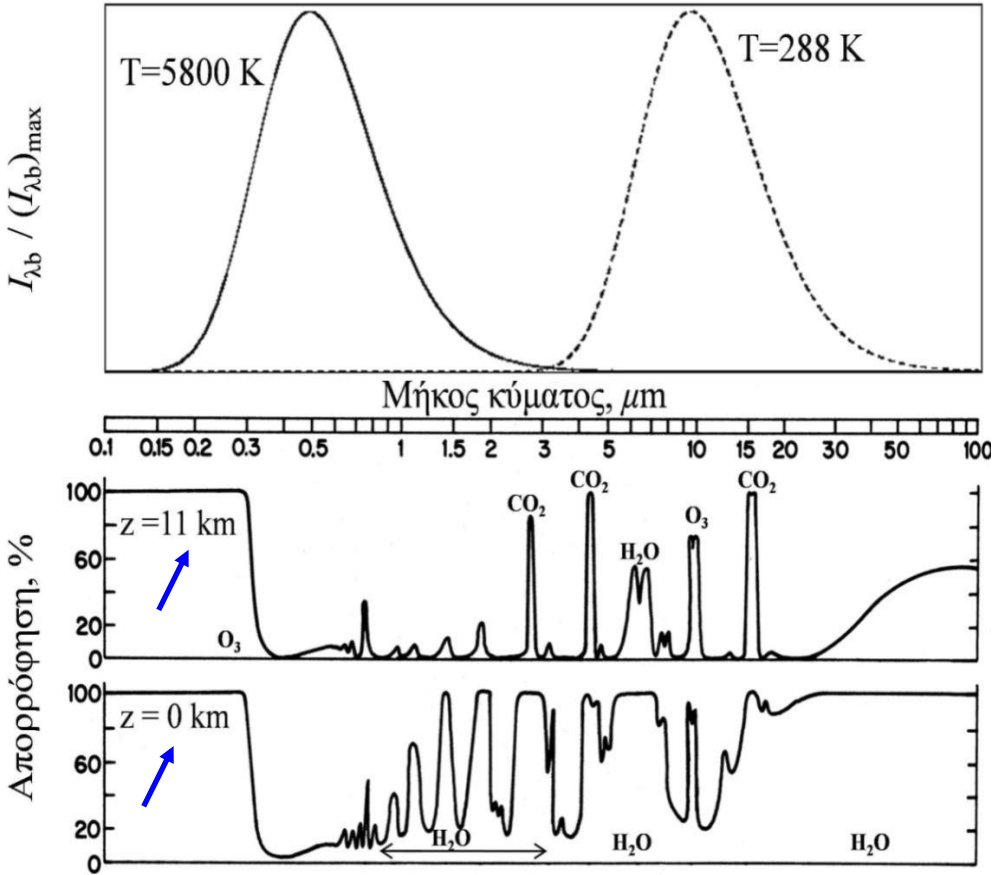
Αλληλεπίδραση ακτινοβολίας με το γήινο σύστημα



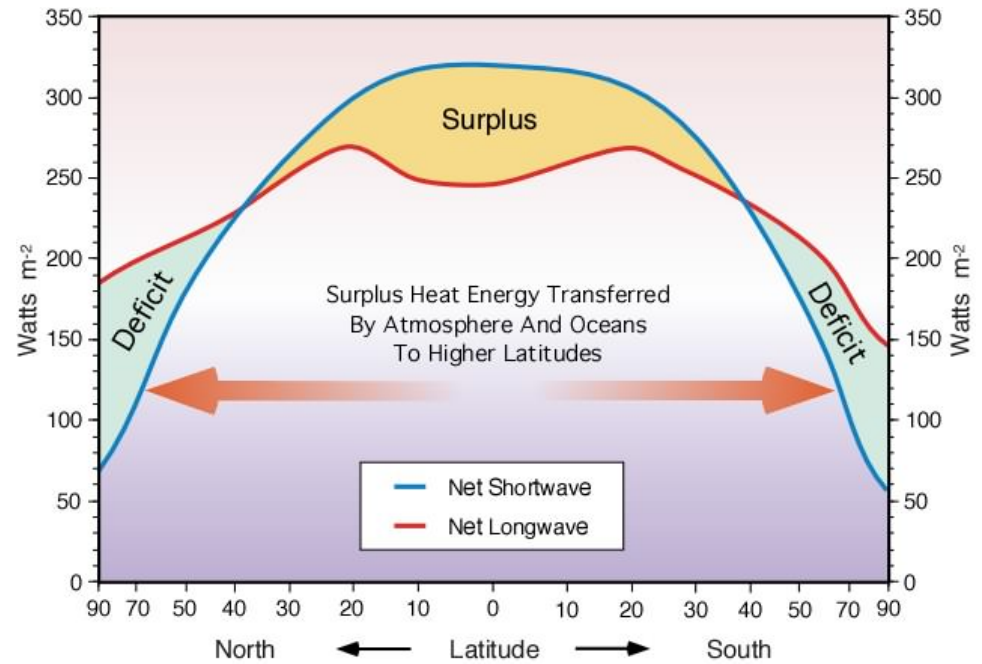
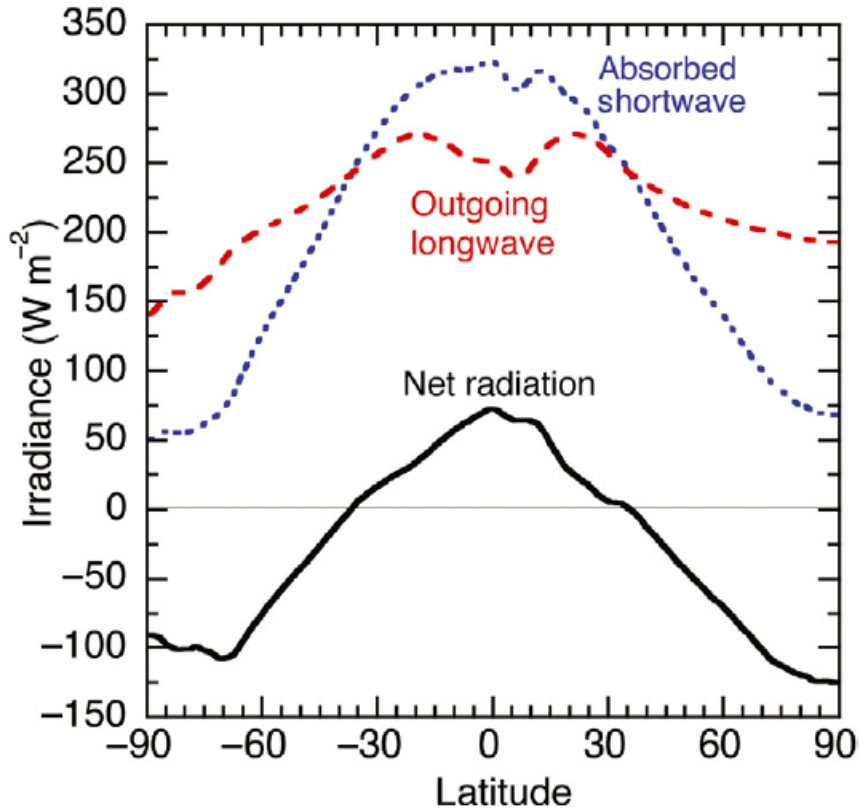
Διανομή της ηλιακής ακτινοβολίας στο σύστημα Γη-Ατμόσφαιρα



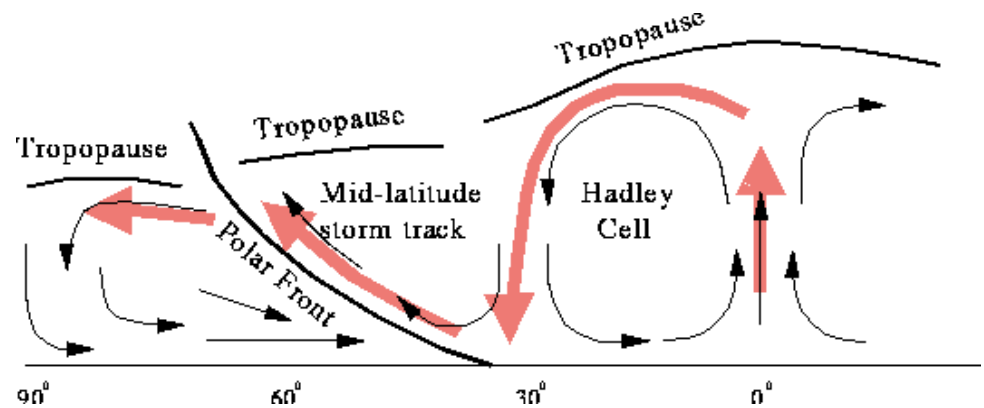
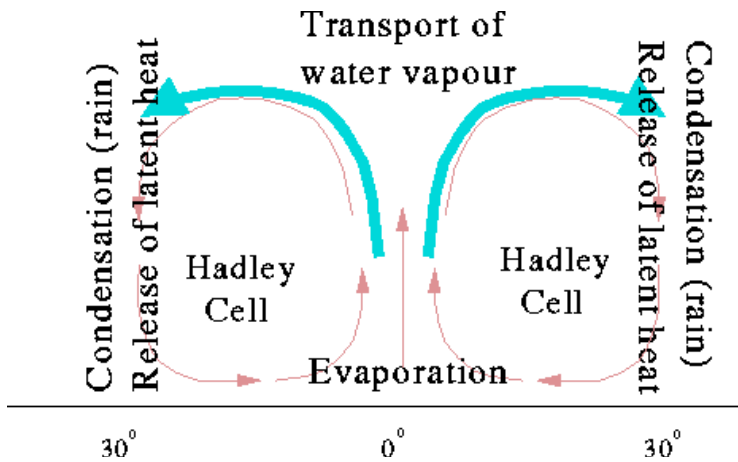
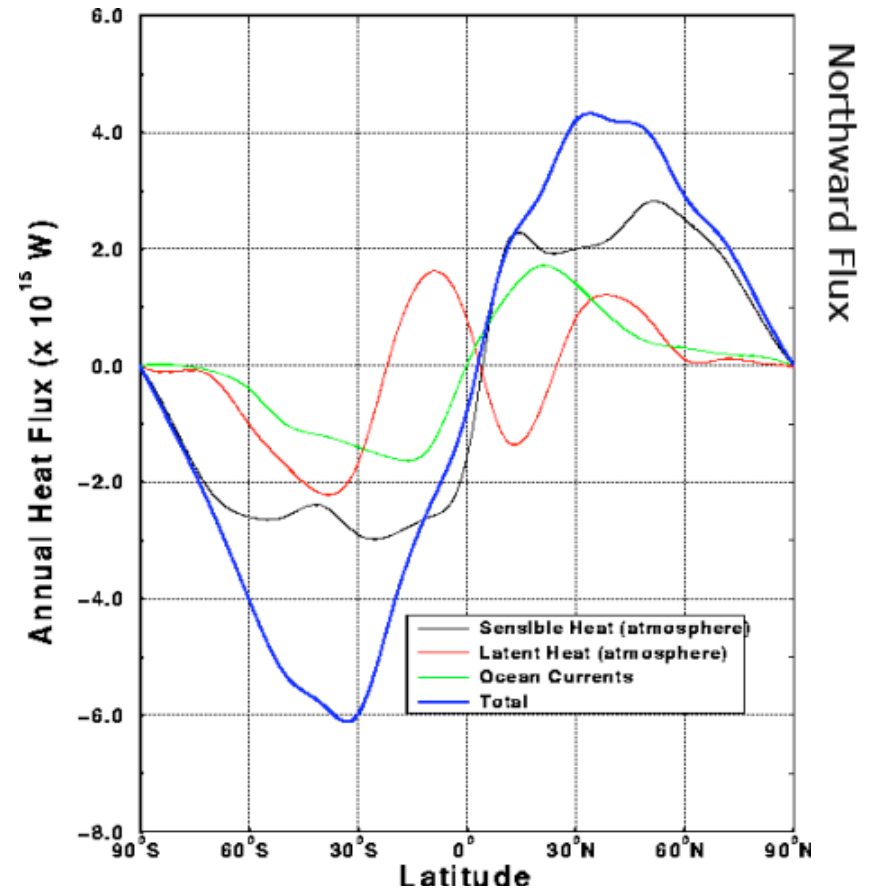
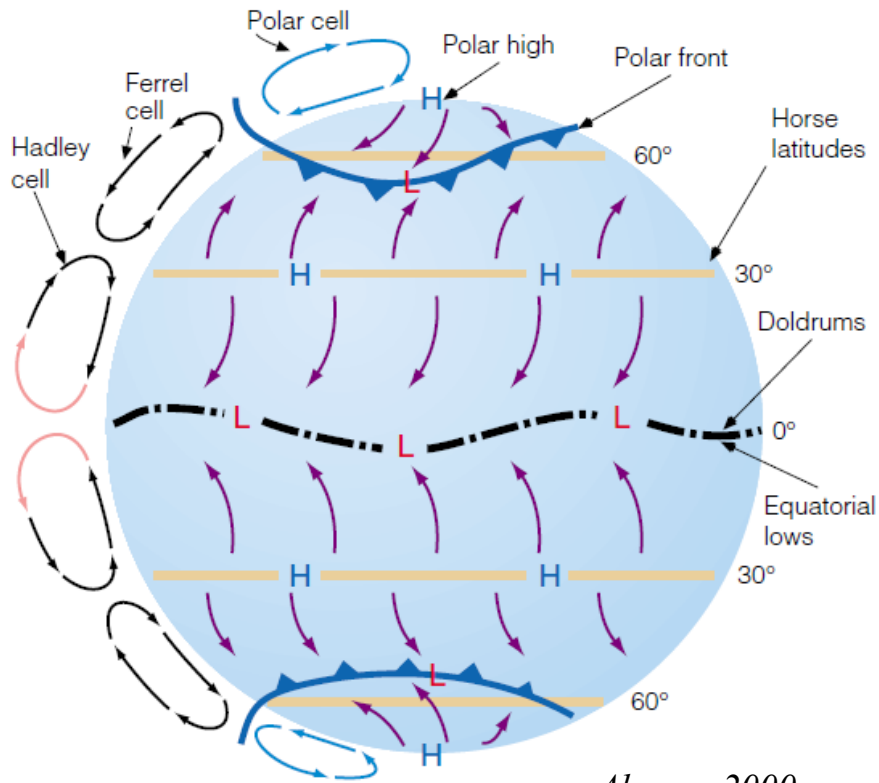
Γήινη ακτινοβολία και ατμόσφαιρα

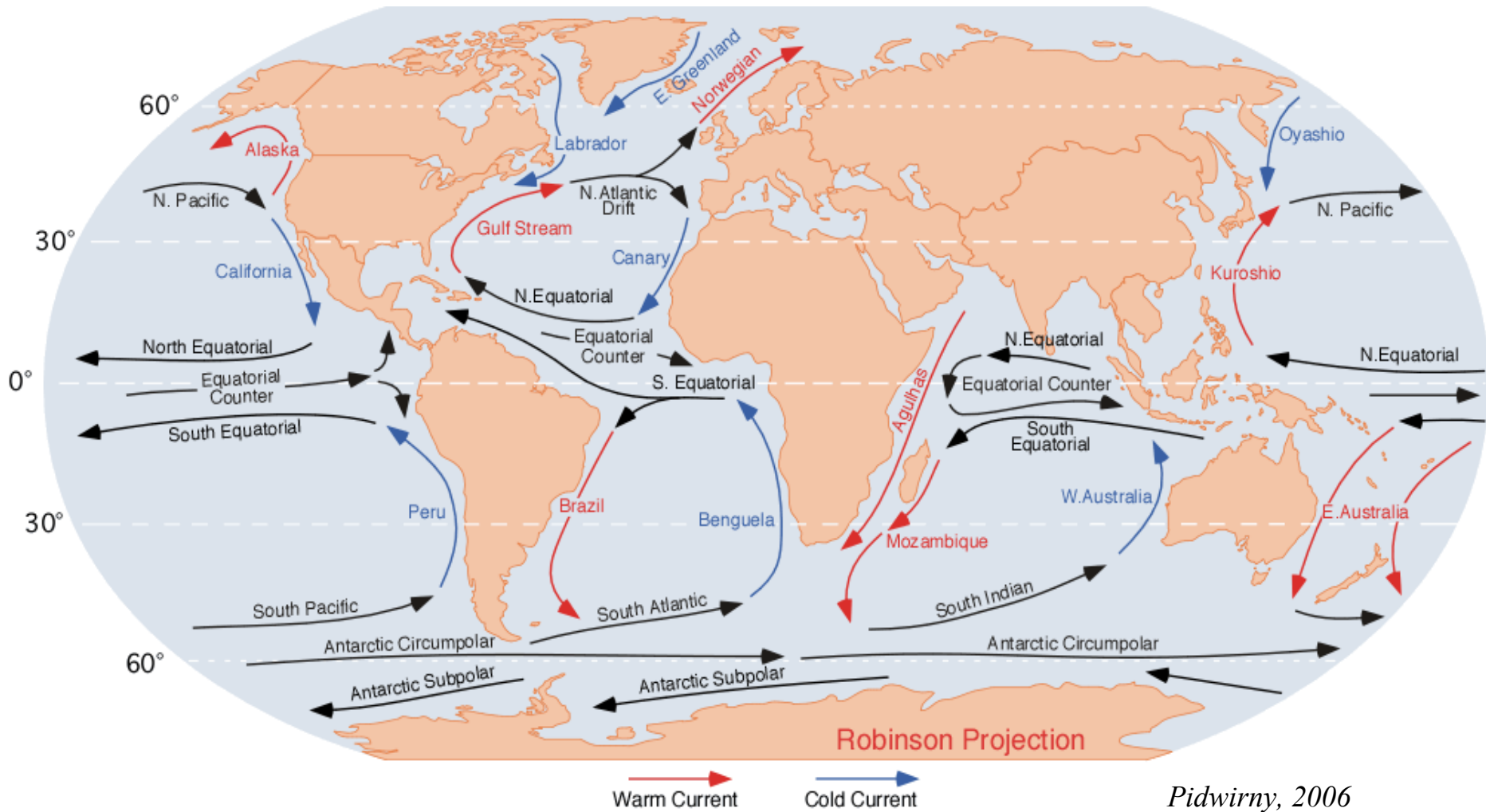


Ηλιακή και γήινη ακτινοβολία (ως συνάρτηση του γεωγραφικού πλάτους)

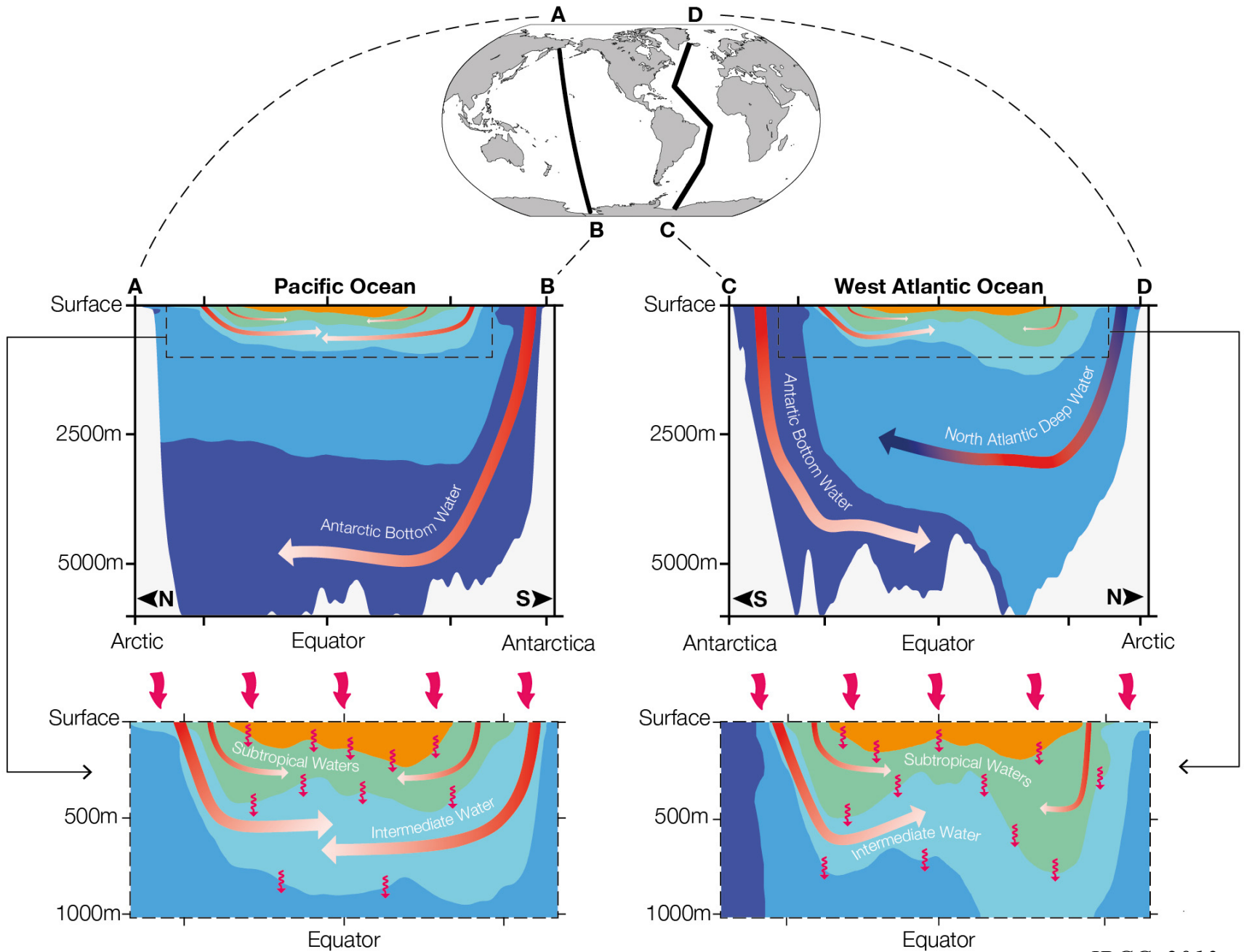


Pidwirny, 2006

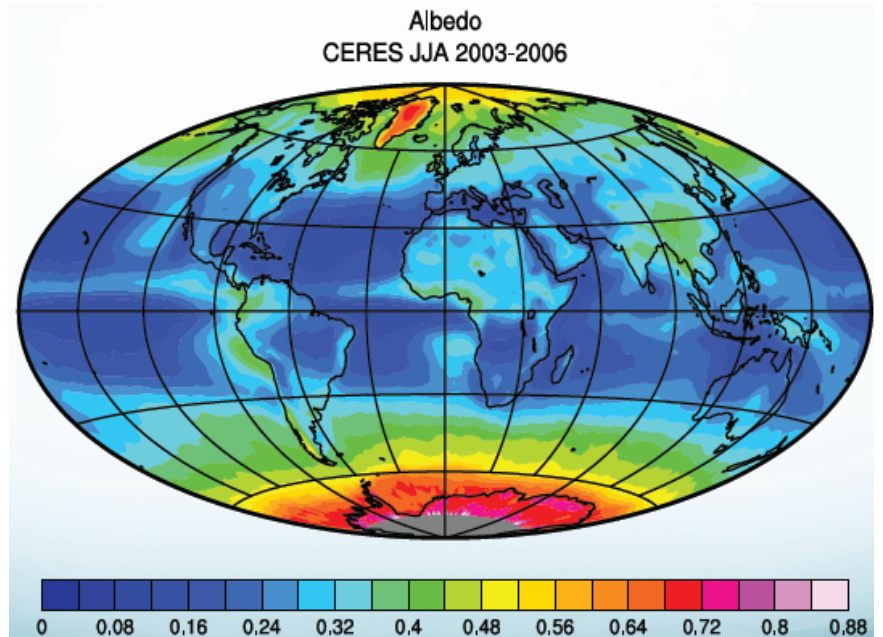
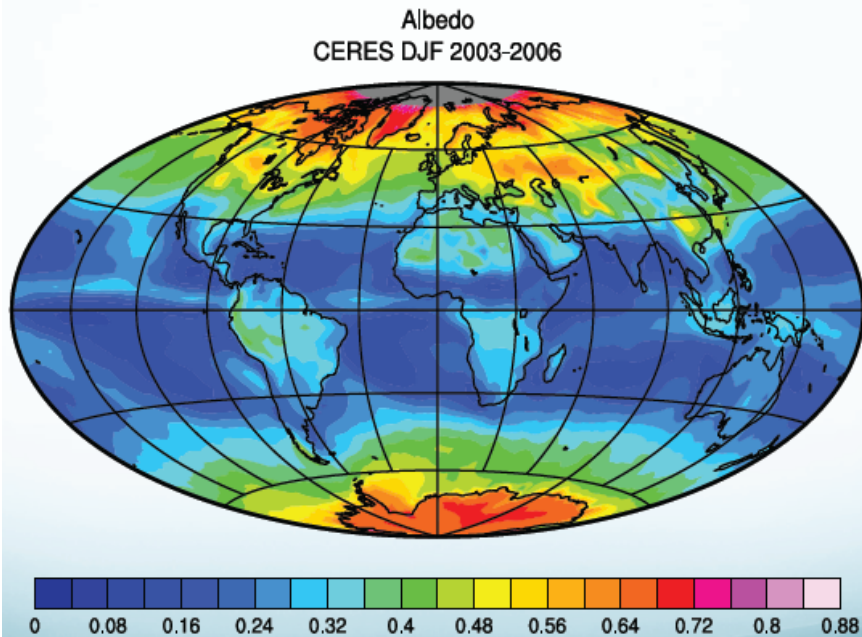
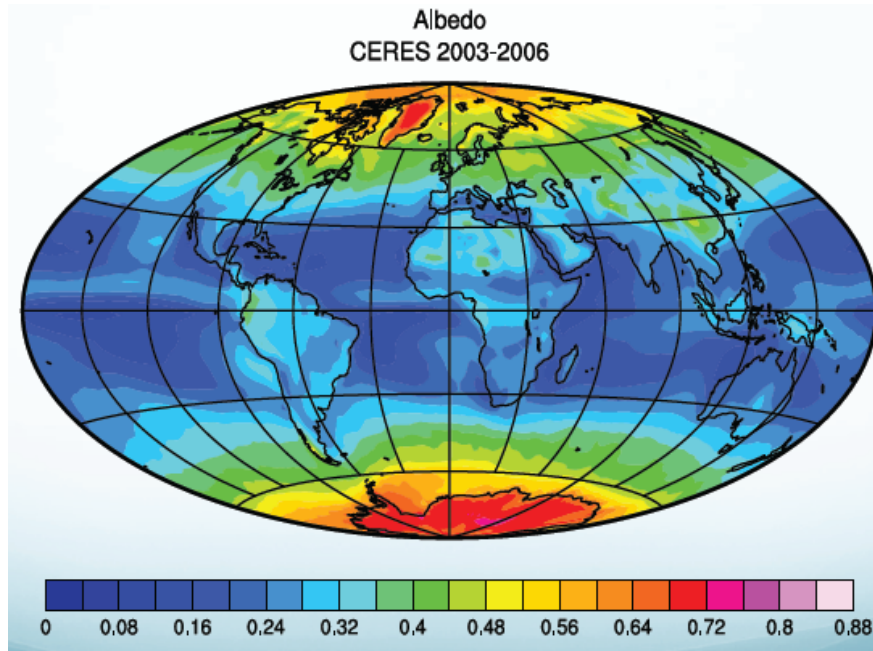




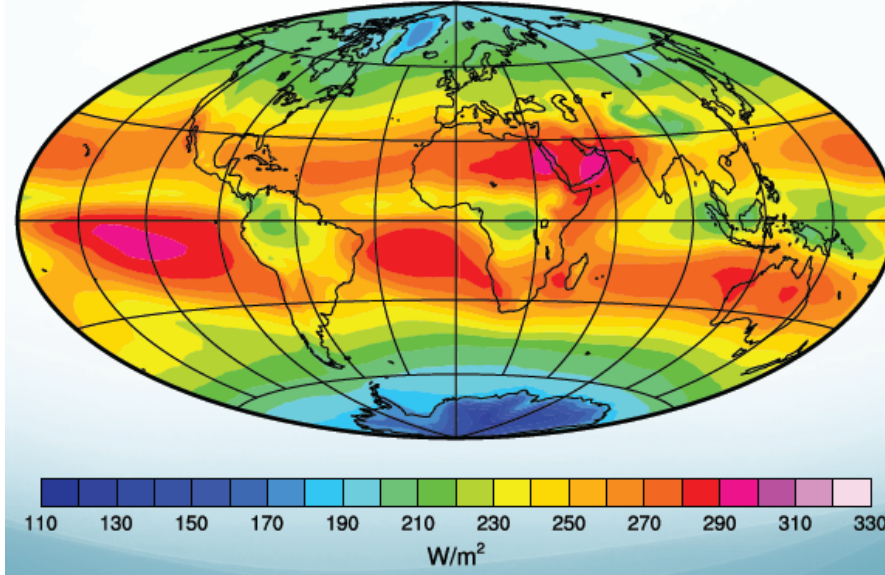
Pidwirny, 2006



Ισοζύγιο ακτινοβολίας - Ενεργειακό ισοζύγιο

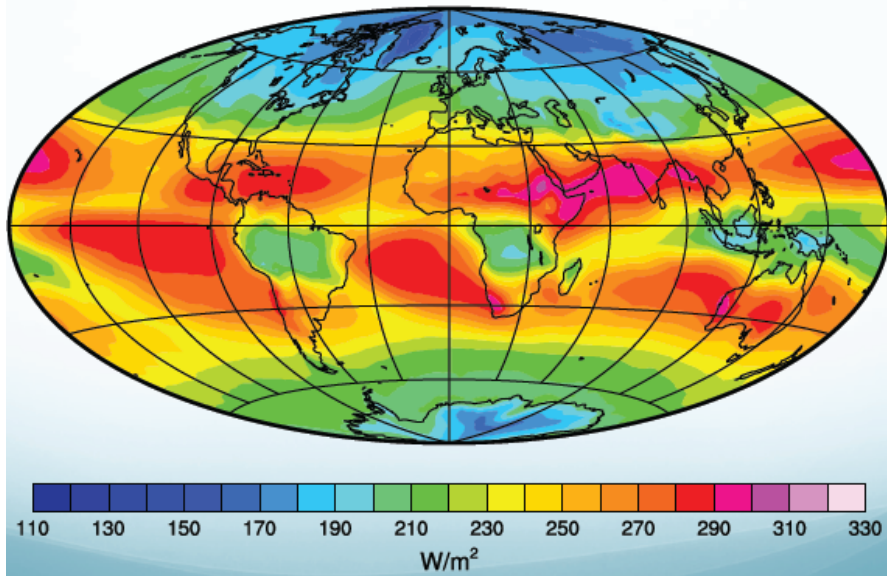


Outgoing Longwave Radiation
CERES 2003-2006

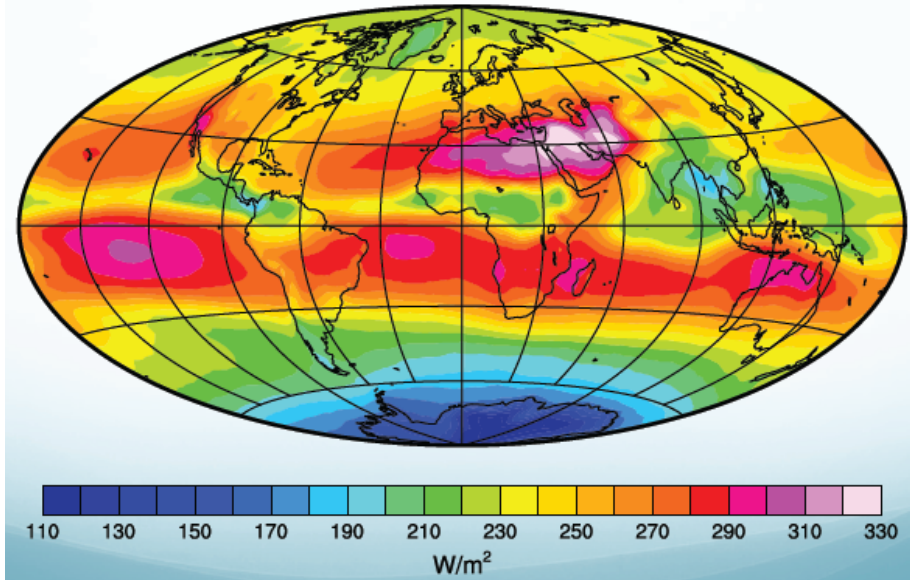


NASA/UW

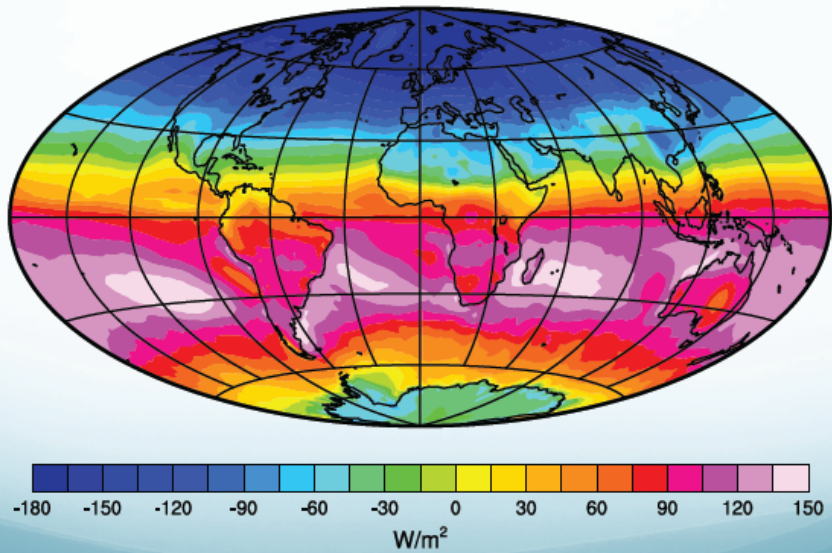
Outgoing Longwave Radiation
CERES DJF 2003-2006



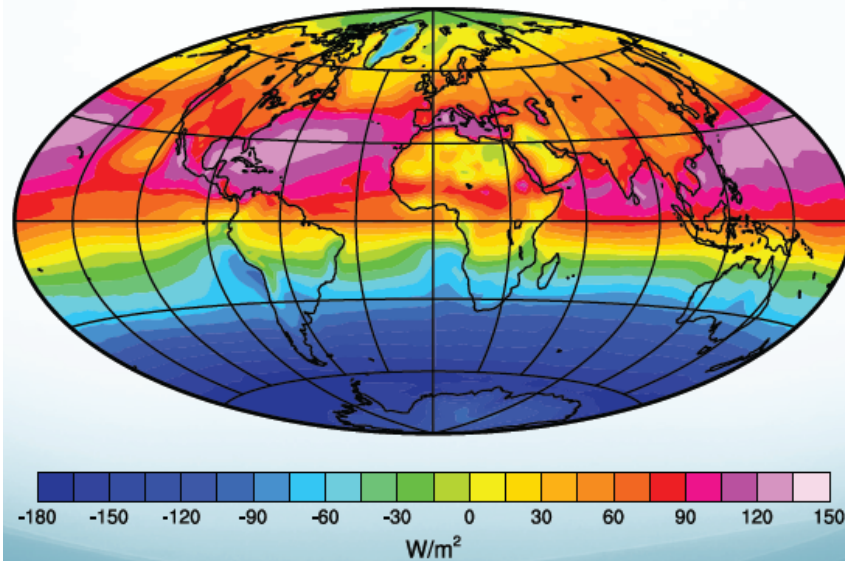
Outgoing Longwave Radiation
CERES JJA 2003-2006



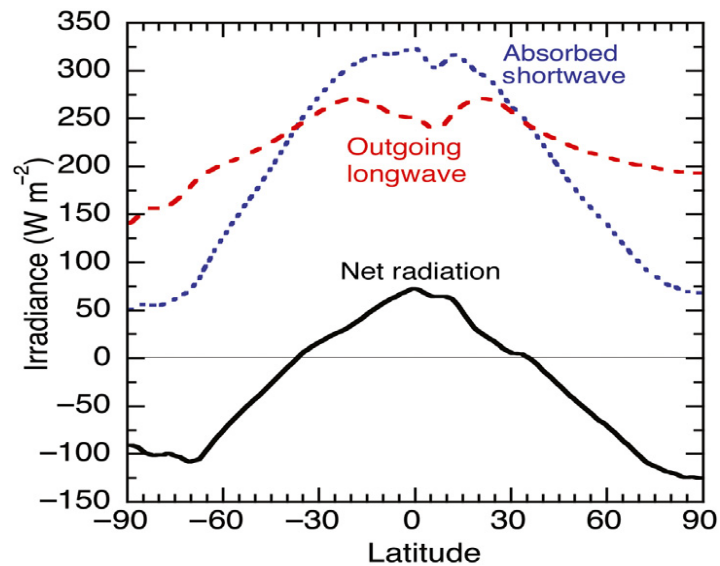
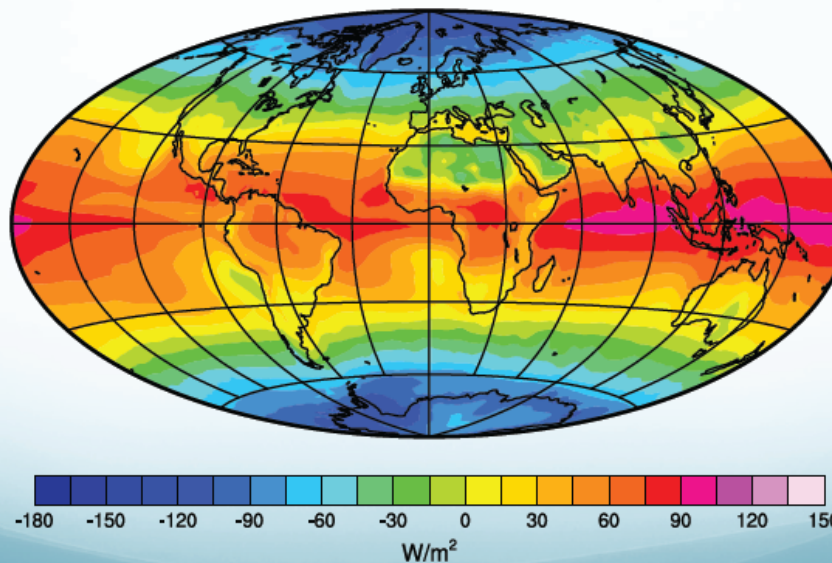
Net Radiation
CERES DJF 2003-2006

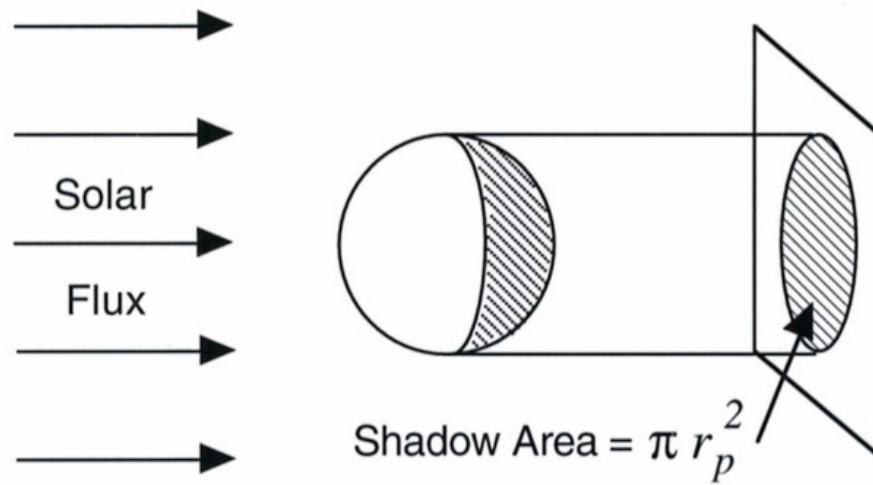


Net Radiation
CERES JJA 2003-2006



Net Radiation
CERES 2003-2006





$$(1 - \alpha) S \pi r_p^2 = \sigma T_e^4 4\pi r_p^2$$

$$T_e = \sqrt[4]{\frac{(1 - \alpha) S}{4\sigma}} \approx 255 \text{ K} = -18^\circ \text{ C}$$

