SATELLITE OBSERVATIONS FOR CLIMATE SCIENCE

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Abstract. The Intergovernmental Panel on Climate Change (IPCC) has finalised its Fourth Assessment Report in 2007. Our paper surveys the most important statements of the Report based mainly on the satellite-born observation. After the introduction, we briefly specify the potential and the constraints of remote sensing. The climate related applications are sorted into four groups. Firstly we deal with the so-called external forcing factors, emphasising the observations of atmospheric aerosols. The next group is the detection of the climate changes, namely those of temperature near the surface and in the atmosphere; the changes of snow and ice cover; and the sea-level rise. The third group of applications is the comparison of the present observed and the model-simulated climate. Finally, the fourth application is testing the simulations of feedback mechanisms, determining the radiation balance of the atmosphere. In this regard, we point out that the different sensitivity of models cause as wide uncertainty of the prediction, as the alternatives of future greenhouse-gas emission.

1. Introduction

The climate of our Planet has never been strictly constant, but the recent changes are by two orders of magnitude faster than the natural changes since the appearance of anthropogenic influence. The discernable global warming started in the 19th century and after speeding up in the 20th century, it has reached ca. 0.8°C. This fact and the realization of the likely reasons of the changes, plus quick development of computer technology have resulted in systematic investigations of climate science. The goal of the present paper is not the detailed review of climate change, but the systematisation of possible satellite application in connection with this issue.

The paper continues with a climate science oriented brief description of the specifics of satellite remote sensing (Section 2). Then, four different aspects of climate-oriented application are presented. The so-called external forces, causing climate modification are reviewed firstly (Section 3). We deal especially with atmospheric aerosol particles, having very high spatial variability, stressing the needs of satellite remote sensing.

Three climate variables will be emphasized (Section 4) among the changes of climate, representing all the three dimensions. The changes of air temperature are observed at different levels of atmosphere to establish the fact of changes in addition to the near-surface measurements. Further, we would neither be able to detect the changes of the snow and ice-cover in the unpopulated regions, nor to observe the sea-level far from the navigation routes. If the ocean level were be calculated only from harbours' measurements, we had to face the geodetic influences of tectonic motions, or the errors caused by motion of the world-ocean and the atmosphere.

In the third group of satellite climate applications (Section 5), a favourable example is presented in the satellite-based testing of climate models showing that the models can well reproduce the atmospheric water vapour content variations and trends of the recent past. Of course, the models are not so good in all respects.

The counter-examples i.e. less successful simulation are given in the fourth application, where the validation of the model simulated feedbacks is presented. Two examples illustrate if the intensity of these feedback mechanisms, determining the radiation balance, corresponds to their real values established from satellite observations (Section 6). These feedbacks are important, since they affect the future climate as strongly, as the expected changes in atmospheric composition.

The paper is closing with a conclusion focusing at the remote sensing aspects of climate science (Section 7).

2. Specifics of remote sensing in climate science

Satellite technology is based on electromagnetic radiation observations. The use of remote sensing technique from space is advantageous, since this is the only way to observe a wide range of geophysical parameters on a global scale to good accuracy in a consistent and repeatable manner (Silvestrin, 2010). The satellite images have fairly high spatial resolution (up to 3D) and high (though, costly) temporal resolution already achievable over vast areas. This technology allows to measure at locations of the Earth system impossible or difficult to access, mainly by the all-weather day-and-night capability for microwave sensing. This technology is able to measure several parameters at same time and it can be highly automatic, from acquisition to exploitation. One may even state that on a per-measurement basis, usually far less expensive than any other means of geophysical observations (Silvestrin, 2010.)

However, the technology has some caveats, too (Silvestrin, 2010). One must always consider that remote sensing data are results of indirect measurements where the observed signal is always affected by more factors than just the one, targeted by the observation. Therefore, further assumptions and models are needed to interpret the measurements, e.g. to calibrate sensor, to remove perturbing effects, etc. The area of the measurement target is often relatively large, rising the representativity issue, considering surface heterogeneities. Due to these problems, validation of remote sensing measurements is often not possible in optimal way and the estimation of the errors of the data products can be difficult

Satellite remote sensing is based on primary and combined electromagnetic quantities, e.g. absolute intensities in specific wavelength intervals, intensities relative to the intensity of a reference source at same wavelength, ratios of intensities at different wavelengths, etc. These quantities are observed in two characteristic groups according to the wavelengths. These are the microwave and the optical (infrared) parts of the parts of the electromagnetic spectrum.

Optical sensing of the surface takes place in visible and near-infrared (ca. 0.3-1.3 µm), middle-infrared (ca. 1.5-1.8, 2.0-2.6, 3.0-3.6, 4.2-5 µm) and thermal infrared (7.0-15 µm) parts of the spectrum, constrained to the atmospheric windows. The microwave sounding can use a rather large window between 10 MHz – ca. 100 GHz.

The wavelengths in the two regions differ by around 5 orders of magnitude: features observed are very different and usually highly complementary. The two groups exhibit very different spatial resolutions: only tens of km for the microwave, whereas 1 km is easily achieved for the optical sounding. On the other hand, microwave sensing is little affected by atmosphere and clouds (but rainfall may be a problem), and they can even penetrate vegetation, dry soil, snow. For the visible beams clouds are obstacles, and daylight is also a condition. In the optical part of the spectrum various atmospheric corrections are needed to clear the targeted signal from other effects. In this respect, wide and partly unknown radiation parameters of the aerosol components are the problem.

For the microwaves the surfaces appear smoother than in the optical region, hence larger occurrence of mirror-like reflections is available. This can be utilised in case of both passive and active ways of remote sensing. The active sensing offers larger control on incident energy, enabling new sensing capacities. However, legal and technological constraints also occur with the microwave spectrum allocation (interference with other sources), lidar safety issues, etc.

Let us further illustrate the possibilities and the limitations of remote sensing with respect the climate science by a recent effort, re-establishing the global radiation balance. The state of climate system largely depends on the radiation process, and the human activity can primarily modify the radiation processes, too. Hence it was inevitable to know the actual radiation balance of the Planet with undoubted accuracy. But, as we see below, this is not so easy.

Recently Trenberth et al (2009) re-considered (*Fig. 1*) their earlier radiation balance estimations (Kiehl and Trenberth, 1997). The earlier period was based on observations from 1985 - 1989, whereas the recent estimates are originated from March 2000 to May 2004 period. As it is seen in *Table 1*, very few terms of the radiation balance are unchanged during the 15 years. In some other cases the absolute difference between the two estimates is ca. 10 Wm^{-2}, sometimes over 20 % in relative terms. The majority of the changes are likely caused by the uncertainty of the estimation, not the climate variation of the Earth during this period.

Table 1: *Absolute and relative differences between the recent (Trenberth et al., 2009) and previous (Kiehl and Trenberth, 1997) estimations. (Calculations were made by the authors of the present paper and they are rounded in Wm^{-2}.) Components summarising other lines of the table are set in italics.*

No.	Component (Wm-2)	New	Old	Diff.	Rel. Diff.
S1	*Incoming Solar From the Sun*	*341*	*342*	*-1*	*0%*
S2a	Reflected by clouds and atmosphere	79	77	2	3%
S2b	Reflected by the surface	23	30	-7	-23%
S2	*Reflected Solar to the space*	*102*	*107*	*-5*	*-5%*
S3	Absorbed by.(short-wave balance of) the atmosphere	78	67	11	16%
S4	Absorbed by (short-wave balance of) the surface	161	168	-7	-4%
S5	*Shortwave balance at TOA (S1-S2)*	*239*	*235*	*4*	*2%*
L1	*Outgoing long-wave Radiation balance*	*239*	*235*	*4*	*2%*
L2a	Long-wave emitted by the atmosphere	169	165	4	2%
L2b	Emitted LW by the clouds	30	30	0	0%
L2	*Emitted LW from the atmosphere to Space*	*199*	*195*	*4*	*2%*
L3a	Emitted LW from the surface to the space	40	40	0	0%
L3b	Emitted LW from the surface to atmosphere	356	350	6	2%
L3	*Emitted LW from the surface: all*	*396*	*390*	*6*	*2%*
L4	Back LW radiation from the atmosphere	333	324	9	3%
L5	*LW balance of the atmosphere (L3b-L2-L4)*	*-176*	*-169*	*-7*	*4%*
L6	*LW balance at the surface (L4-L3)*	*-63*	*-66*	*3*	*-5%*
N1a	Thermal (sensible heat)	17	24	-7	-29%
N1b	Evapotranspiration (latent heat)	80	78	2	3%
N1	*Non-radiative energy balance of the atmosphere*	*97*	*102*	*-5*	*-5%*
O1	*Overall balance at TOA (S5-L1)*	0	0	0	
O2	*Overall balance of the atmosphere (S3+L5-N1)*	-1	0	-1	
O3	*Overall bal. at the surface (Net absorbed) (S4+L6-N1)*	1	0	1	

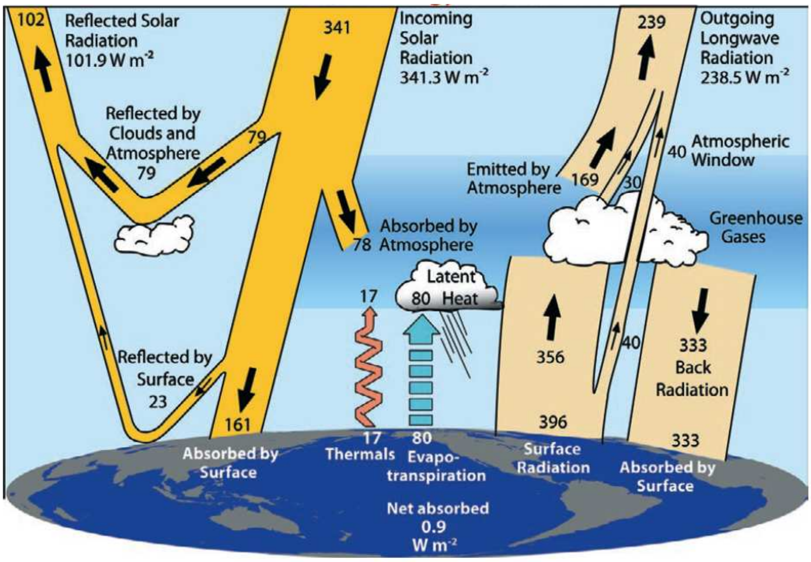

Figure 1: *The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (Wm^{-2}). The broad arrows indicate the schematic flow of energy in proportion to their importance. Source: Trenberth et al (2009) Remark: The Figure indicates global averages, independently from the type of the surface in the illustration.*

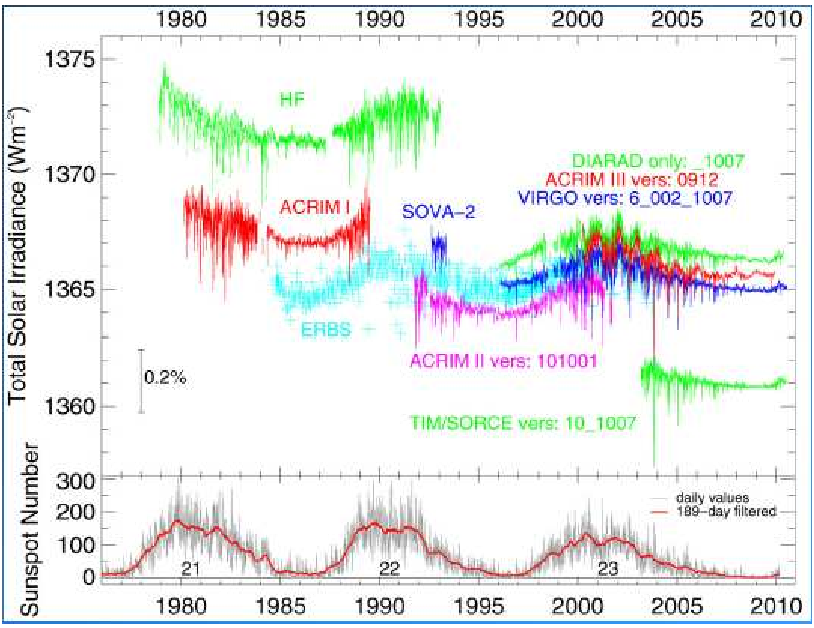

Figure 2: *<u>Top panel</u>: Compared are daily averaged values of the Sun's total irradiance from radiometers on different space platforms as published by the instrument teams since November 1978. <u>Bottom panel:</u> Sunspot number to illustrate the variability of solar activity for cycles 21, 22 and 23. (Source: Fröhlich, 2010)*

For example, *Fig 2* indicates that even the Solar constant varied by ca. 1 Wm^{-2}, which is comparable to the changes in the radiation balance due to most external forcing factors (Section 3). In the latter period, near the maximum of the 23rd solar cycle, the incoming radiation was higher by ca 0.5 Wm^{-2} than in the previous period of the estimations, near and after the minimum between the 21st and 22nd cycles. However the instruments of the previous period gave a much stronger overestimation, leading to a -1 Wm^{-2} decrease of the Solar constant in the latter estimation.

3. Detection of external forcing factors

The increasing of greenhouse effect modified the balance with 2.3 Wm^{-2} since the beginning of industrial revolution. The value is only 1% of the captured Sun originated energy but the 1/5 of the change has happened in the last decade. (The total energy balance remains zero at the top of the atmosphere, but it needs higher temperature near the surface, and above!)

Among the important anthropogenic forcing factors, the greenhouse effect influences the backward atmospheric long-wave radiation to the surface. (Its present value is 333 Wm^{-2}, see above in Fig. 1). The aerosol content modifies mainly the reflected short wave radiation (79 Wm^{-2}) and, in smaller extent, the atmospheric long wave emission (239 Wm^{-2}).

The land use determines mainly the surface-reflected short-wave radiation, and also, to a lesser degree, the sensible and latent heat exchange between the surface and the atmosphere. (Their present values are 17 and 80 Wm^{-2}.) Among the natural forcing factors, decadal oscillations of solar activity directly modulate the incoming short wave solar radiation (341 Wm^{-2}), while the few bigger volcanic eruption increases the reflected shortwave radiation 1-3 years. Changes of the mentioned factors will be briefly characterised in the followings.

The concentration of atmospheric carbon dioxide has grown from about 280 ppm before Industrial Revolution to 385 ppm in 2008 (Copenhagen Diagnosis, 2009). The methane concentration has grown from 0.715 to 1.774 ppm in 2005. Both values are much higher than any time in the last 650 thousand years! The atmospheric mass of similarly green house gas nitrous oxide has reached 0.319 ppm in 2005 from 0.270.

The components of atmospheric aerosols have modified the atmospheric radiation balance in the opposite direction, namely decreasing the warming. The direct effect of aerosols, mainly the backscattering of solar radiation is about -0.5 Wm^{-2}. Their indirect effect, through changes in cloud composition, is another -0.7 Wm^{-2} since the industrial revolution.

Further small effects, e.g. changes in land use, and increasing carbon content of snow leading to smaller reflectivity cause -0.1 − -0.2 Wm^{-2} in the radiation balance of the Planet. The Report also states that the influence of solar activity oscillations is +0.12 Wm^{-2} since 1750. This value is the half of the previous estimation (IPCC, 2001).

The concentration of greenhouse gases is equally distributed over the World, because of their long residence time (10-200 years). Furthermore, to our present knowledge the land use changes are less important forcing factors of the global radiation balance. Hence, we discuss the remote sensing activities to characterise the influence of aerosol particles.

Table 2: *The sensors used to determine the optical characters of aerosol particles. The activity period, the spectral interval and the derived aerosol parameters are indicated. (Source: IPCC, 2007; Table 2.2, abbreviated).* τ_{aer} *- optical thickness of aerosol at the given wavelength,* α *- albedo of aerosol layer,* ***DRE*** *– direct effect of anthropogenic and natural aerosols on the short wave energy balance of the Earth-atmosphere system.*

Satellite instrument	**Measurement interval**	**Spectral bands**	**Aerosol characteristics**
AVHRR (Advanced Very High Resolution Radiometer)	since 1975 up to the present	5 bands (0.63; 0.87; 3.7; 10.5 and 11.5 μm	τ_{aer}, α
TOMS (Total Ozone Mapping Spectrometer)	Nov. 1996- June 1997; April 2003 – Oct. 2003	0.33 and 0.36 μm	τ_{aer}, aerosol index
POLDER (Polarization and Directionality of Earth's reflectance)	Nov. 1996 – June 1997; Apr. 2003 – Oct. 2003; Jan. 2005 to the present	8 bands (0.44 – 0.91 μm)	τ_{aer}, α, ***DRE***
OCTS (Ocean Colour and Temperature Scanner)	Nov. 1996 – June 1997; Apr. 2003 – Oct. 2003; Jan. 2005 to the present	9 bands (0.41 –0.86 μm); 3.9 μm	τ_{aer}, α
MODIS (Moderate Resolution Imaging Spectrometer)	since 2000 up to the present	12 bands (0.41 – 2.1 μm)	τ_{aer}, α, ***DRE***
MISR (Multi-angle Imaging Spectro-Radiometer)	since 2000 up to the present	4 bands (0.47 – 0.86 μm)	τ_{aer}, α
CERES (Clouds and Earth's Radiant Energy System)	since 1998 up to the present	wide, integrated	***DRE***
GLAS (Geosciences Laser Altimeter System)	since 2003 up to the present	active lidar (0.53, 1.06 μm)	vertical aerosol profile
ATSR-2/AATSR (Track Scanning Radiometer/Advanced ATSR)	since 1996 up to the present	4 bands (0.56 – 1.65 μm)	τ_{aer}, α
SeaWiFS (Sea-Viewing Wide Field-of-View Sensor)	since 1997 up to the present	0.765 and 0.865 μm	τ_{aer}, α

Table 2 summarises the most important parameters of satellite instruments which could be applied in determination of optical characteristics. The direct effect of aerosols can be characterised by three different parameters: (i) The optical thickness of aerosol, τ_{aer}, indicates the ratio of the Sun radiation which does not reach the surface: Using this parameter as a negative exponent of the ***e*** **"**natural number", we get this ratio. (ii) The α albedo of a given aerosol layer shows the ratio of radiation reflected back towards the space in the given wavelength. (This term does not consider that part of the energy which is reflected from the surface.) Finally, (iii) the ***DRE***, the common effect of natural and anthropogenic aerosols, indicates the surplus of outgoing energy from the Earth-atmosphere system compared to the situation without aerosols, at all.

The satellite based estimation concerning the ***DRE*** influence is shown in *Table 3*. The different methods have given more or less the same value for the natural and anthropogenic direct radiation effect. The nine instruments using much more different approximation gave for this effect a -5.4 Wm^{-2} value. Comparing these values with the numbers of Fig. 1 we can express that their role is secondary beside the effect of cloudiness, atmospheric water content, or natural atmospheric greenhouse effect. On the other hand if we compare the latter effect (supposing that the natural and anthropogenic factors have got the same magnitude in DRE) with the magnitude of change the role of aerosol particles is not negligible either.

Table 3: *Direct radiation effect by aerosols on the radiation balance of the Planet, estimated by satellite remote sensing (IPCC 2007: Table 3. abbreviated)*

Satellite instrument	**Measurement period**	**DRE (Wm^{-2})**
MODIS, TOMS	2002	-6.8
CERES, MODIS	March 2000 –December 2003	-3.8 - -5.5
MODIS	November 2000 – August 2001	-5.7 ± 0.4
CERES, MODIS	August 2001 – December 2003	-5.3 ± 1.7
POLDER	November 1996 – June 1997	-5.2
CERES, VIRS	January 1998 – August 1998; March 2000	-4.6 ± 1.0
SeaWifs	1998	-5.4
POLDER	November 1996 – June 1997	-5 - -6
ERBE July 1987	July 1987 – June 1997	-6.7
Average (deviation)		**-5.4** ± **(0.9)**

4. Changes of climate

Detection of changes in the climate system is a rather difficult and long-term task of the satellite based remote sensing. The key problems are the limited *accuracy* of the observations, i.e. the non-random, systematic error, or bias, that defines the offset between the measured value and the true one. There is also a limited *precision* of each individual observation, i.e. its random errors. Suitable averaging of the random errors can improve the precision of the measurement, so this problem is not a strict obstacle of the long-term observations. But, the limited *stability*, i.e. the time varying accuracy, when no absolute standard is available can establish the systematic error as a function of time. Finally, the *representativity* might also be a constraint though a good sampling strategy can mitigate this problem (Doherty, 2010).

There are high, nearly endless numbers of variables in the climate system. The most straightforward, and also realistic ones to observe by remote sensing, are listed in *Table 4*, according the present and future activity of the "ESA Climate Change Initiative" (Liebig, 2010).

It is not possible to overemphasise how important is to have multi-variable objective data on the recent climate changes. Any national or larger scale policy decision on the mitigation of the changes or on the adaptation to them should be based on the detection of the changes. (Attribution of them is another task, with substantial synergies with the detection, as well.)

Table 4: *Essential climate variables, as considered by the ESA Climate Change Initiative. Observation of the 11 bold-set variables is already in process (Liebig, 2010).*

Atmosphere	Surface	Air temperature, precipitation, air pressure, water vapour, surface radiation budget, wind speed & direction.
	Upper air	*Cloud properties,* wind speed & direction, Earth radiation budget, upper air temperature, water vapour
	Composition	*Carbon dioxide, methane & other GHGs, ozone, aerosol properties*
Ocean	Surface	*Sea-surface temperature. Sea-level, sea-ice, ocean colour,* sea state, sea-surface salinity, carbon dioxide partial pressure
	Sub-surface	Temperature, salinity, current, nutrients, carbon, ocean tracers, phytoplankton
Terrestrial	*Glaciers & ice caps, land cover, fire disturbance,* fraction of absorbed photo-synthetically active radiation, leaf-area index (LAI), albedo, biomass, lake levels, snow cover, soil moisture, water use, ground water, river discharge, permafrost and seasonally frozen ground	

Common sense, physical considerations and also the technical possibilities and constraint lead the decision on the priorities among these variables. The first two drivers are needed to have the maximum set of fairly independent physical state variables, as soon as possible. The first 11 variables of the ESA mission are bold set in the Table.

Among the variables in Table 4, the most frequently used one is the near surface air temperature, which increased as much as 0.8°C in the last 100 years (Copenhagen Diagnosis, 2009). The temperature of second part of 20th century in average was very probable above the in last 500 year's and no doubt in the last 1300 years of same period's average.

It was possible to detect same warming in the lower and middle during the layer of the troposphere together with the surface changes during the newer examination. It is import because according to the two pervious IPCC Reports (1996, 2001) this relation does not exist. Because of the warming in upper layers, we introduce two figures. *Fig. 3* shows the influence of the different level's temperature in the sensor of microwave sounding schematically. If we know these values, we can determine layer by layer the change of temperature in the last decades. Before going further, we summarise the substance of microwave air temperature sounding.

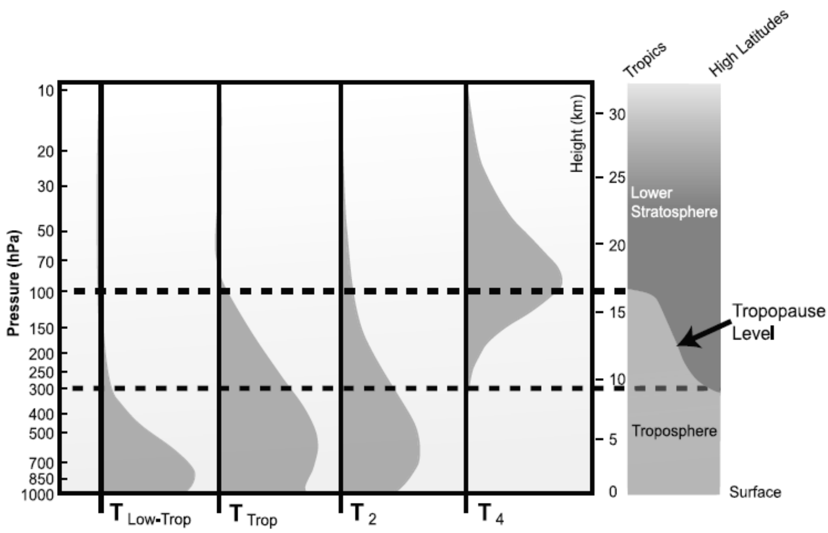

Figure 3: *The weighting function of microwave sounding. The right part of the Figure shows schematically that the height of tropopause (the top of the troposphere, where the temperature decreases with the altitude, in general) is double above the tropical than above polar areas. The second and third curve, right side, are the original weight functions of the T_4 (lower stratosphere) and T_2 channels. The next two profiles, combination of two mentioned channels, are the weight function of middle and upper troposphere's, using other channels too, lower troposphere's weight function. (Source: IPCC 2007, Fig. 3.16.) The reconstructions based on this weighing function are shown in Fig. 4.)*

The microwave sounding is able to estimate temperature of relatively thick layers. It measures the microwave emission (radiance) is emitted by oxygen molecules according to their complicated emission lines around 60 GHz, as a function of their thermal condition. The proper combination of the mentioned lines can characterize the different layer's temperature, and also their changes. The nine instruments of Microwave Sounding Unit (MSU) have carried out since 1978. The Advanced MSU has taken over their tasks. The great advantage of the microwaves is that the majority of clouds do not hinder the measurement at most the precipitation fall and the explicitly clouds high with water content.

The *Fig. 4* shows the change of air temperature in the different layers of atmosphere since 1950 up to the present. The years before 1978 are prepared of course not from MSU measurements, but they are the results of highly precise re-analysis. The essence of the re-analyse is that not the statistical relationships, but the agreement among the atmospheric variables according to the physical equations. The used abbreviations refer to the different analysis centres and authors. It is important, that the re-analysis shows good correlation with the microwave estimation.

From top to down in Fig. 4, it is conspicuous for the first sight that the stratospheric temperature is decreasing contrary to our expectation. But, considering that the increase of the greenhouse gases allows less energy to the stratosphere as before, we can already understand the temperature decrease. Furthermore, another reason contributes to this behaviour. It is the consequence of surface warming which leads to elevation of the tropopause and its lower temperature. This is the same process that leads to higher and cooler tropopause in summer than in winter.

The temperature of the upper and lower troposphere, and also of the near-surface level shows encouraging synchrony. It is important because we can (unfortunately) exclude the hypothesis that the near-surface warming is just a result of measurement errors, or of erroneous neglecting of urban influence caused by large number of urban stations, since this effect would be much more localized in its vertical extent, as well.

The warming (caused by anything) could be proven beside the air temperature with the change of other geophysical characters. Such variables are the area of snow cover and sea ice which could be detected well only in the era of satellites. *Fig. 5* (in the over-next page, after Fig. 4) shows the changes of these components of the cryosphere in the last decades. As it is shown in Fig. 5 both the snow cover and the sea ice area have decreased in the last decade parallel to the global warming over the Northern Hemisphere. Both changes are apparent and statistically significant.

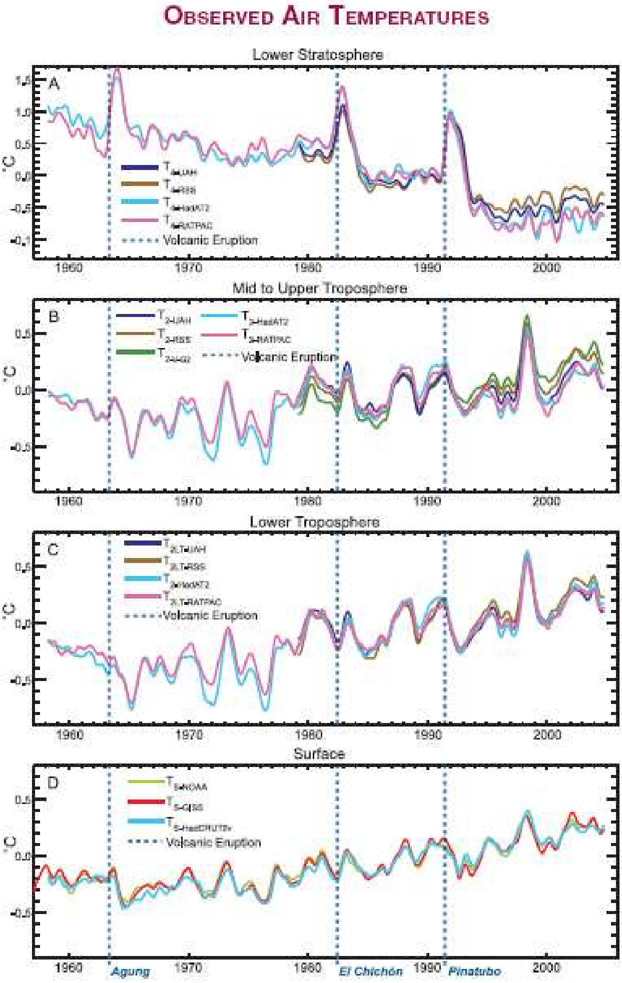

Figure 4: *Variations of air temperature at different levels from 1950 until 2005. A) The temperature decreases in lower stratosphere, because the increasing greenhouse effect blocks the long-wave radiation emitted by surface and the clouds. This part of energy is not able to reach this layer. Years of the three large volcanic eruptions are indicated with their names at the lower axis. The other graphs show increasing tendency with synchronous year-by-year oscillation in the middle, and upper troposphere (B), in the lower troposphere (C), and near the surface (D). All values are differences from the mean of 1979-1997, filtered by seven-month moving average (IPCC, 2007: Fig. 3.17).*

On other hand, around the Antarctica the sea ice has been increasing, despite the near-surface warming over the majority of the continent (Steig et al., 2009). This pattern has been attributed to intensification of the circumpolar westerlies, in response to changes in stratospheric ozone, letting less warm air masses into the centre of the island. This, in turn, leads to colder centre of Antarctica and southward shift of the Polar front.

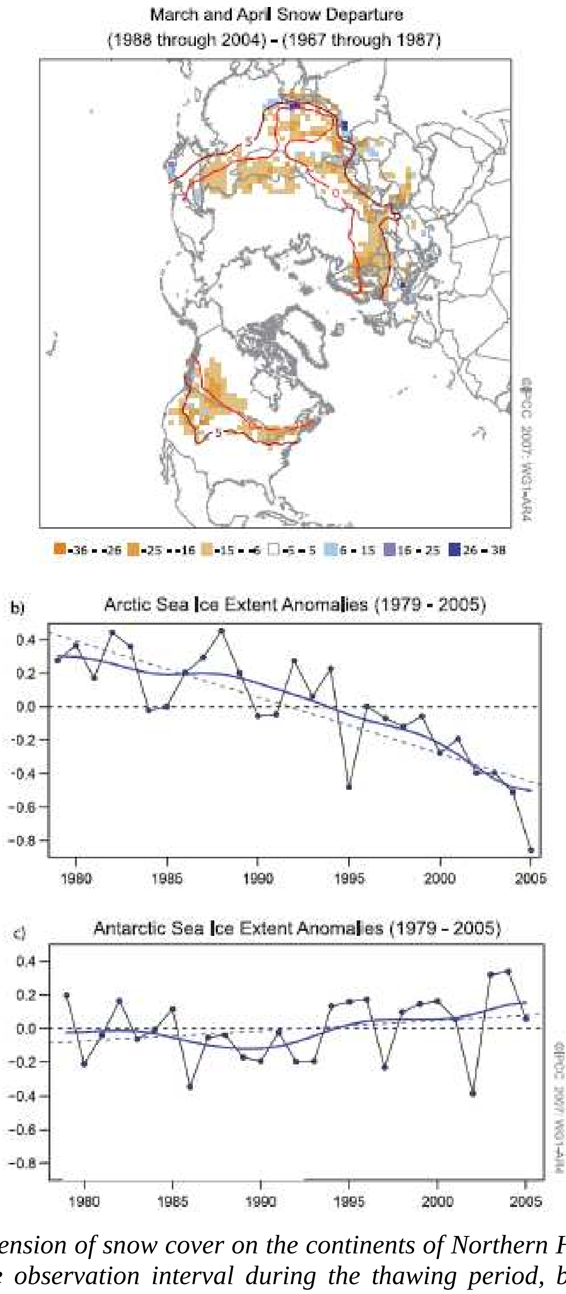

Figure 5: *The extension of snow cover on the continents of Northern Hemisphere in two following satellite observation interval during the thawing period, between 1967 and 1987, and 1988 and 2004 respectively (a). The modification of snow cover represented by colour squares showing almost on every place 5-15 or 15-25% shortening in time. The continuous lines are 0 and 5°C mean isotherms of air temperature for total 1967-2004 periods in March-April. The biggest area decreasing is nearly parallel with the isotherms. The next two figures show the extension of oceanic ice cover on the Northern (b) and Southern Hemispheres (c) between 1979 and 2005. The dots show the yearly mean ice extension, with decadal smoothing. (IPCC 2007: Fig. 4.3, 4.8 and 4.9).*

In Fig. 5, the linear trend of ice cover decreasing is 33±7 thousand km^2 per decade. Its magnitude is -2.7 %, and it is significant. Simultaneously, the ice-cover expansion, as much as 6±9 thousand km^2 per decade, is not significant in the Southern Hemisphere.

Another indicator of the thermal processes is the sea level, driven mainly by the thermal expansion and the water balance with the continental ice. Sea ice melting does not influence the sea level, in correspondence with the Archimedes' principle on the floating objects.

Fig. 6 is an evidence of warming showing the sea level rise combining the tide gauges and microwave satellite observations. The latter observations are based on the TOPEX/Poseidon and Jason satellite altimeter measurements programmes. They measure the sea level heights between 66°N and 66°S in ten-day averages since 1993. The precision of the individual ten-day average sea-level anomalies, based on satellite microwave measurement, is ±5 mm. According to the processing of the measurements, the rise of sea level is 3.1±0.7 mm per year which mainly happens in the Southern Hemisphere.

Hence, the temperature increase has already been detected in the upper 3 km layer of the oceans. The reason is that 80% of the radiation balance surplus is absorbed by the oceans. (This is the 0.9 Wm^{-2} deviation of the total balance in Fig. 1) This warming together with the thawing of land ice has already caused 17 cm elevation of sea level (IPCC, 2007).

According to the Copenhagen Diagnosis (2009), this increase of the sea level, its causes and the projected future can be summarised, as follows: The contribution of glaciers and ice-caps to global sea-level has increased from 0.8 mm/year year in the 1990s to be 1.2 mm/year today. The adjustment of glaciers and ice caps to present climate alone is expected to raise sea level by ~18 cm, (i.e. by 1 cm more after three years from 2005, than the IPCC AR4 estimation).

The area of the Greenland ice sheet, experiencing summer melt, has already been increasing by 30% since 1979, parallel to the increasing air temperatures. The net ice loss from Greenland accelerated since the mid-1990s and is now contributing as much as 0.7 mm/year to sea level rise due to both increased melting and accelerated ice flow.

Antarctica is also losing ice mass at an increasing rate, mostly from the West Antarctic ice sheet due to increased ice flow. Antarctica is currently contributing to sea level rise at a rate nearly equal to Greenland. Ice-shelves connect continental ice-sheets to the ocean. Signs of ice shelf weakening have been observed elsewhere than in the Antarctic Peninsula, indicating a more widespread influence of atmospheric and oceanic warming than previously thought.

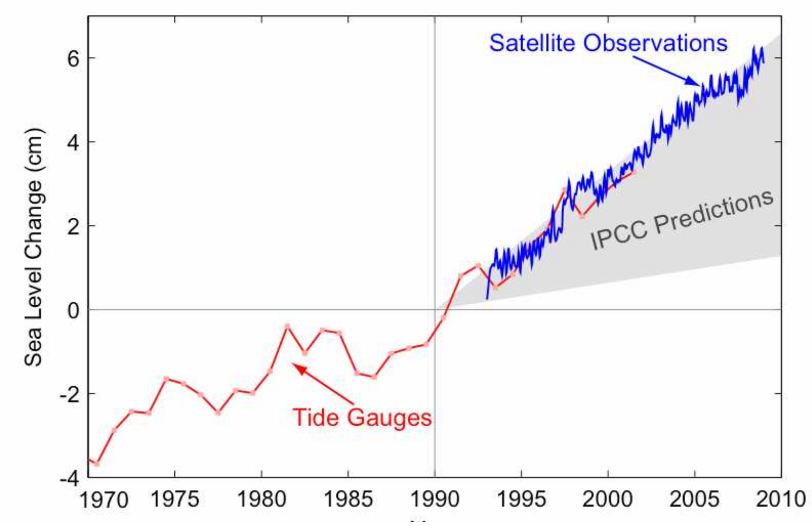

Figure 6: *Sea level change during 1970-2010. The tide gauge data are indicated in red (Church and White 2006) and satellite data in blue (Cazenave et al. 2009). The grey band shows the projections of the IPCC Fourth Assessment report for comparison. The graphs show the difference from the 1993 - June 2001 period's average in mm unit. The satellite data till 2002 are based on TOPEX/Poseidon, later on Jason satellites. (Copenhagen Diagnosis, 2009: Fig. 16)*

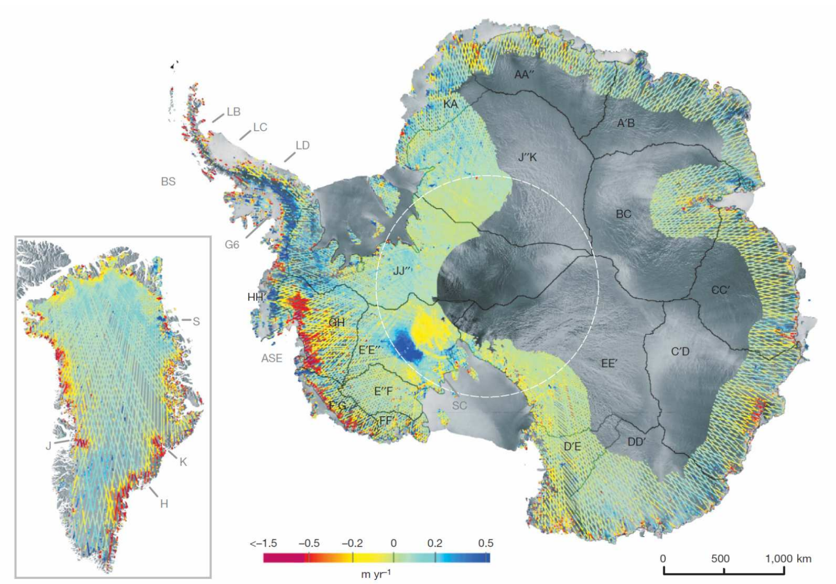

Figure 7: *Rate of surface elevation for Antarctica and Greenland. The measured changes are median-filtered, spatially averaged and gridded over the period 2003-2007 (with missing data, but always more than 365 days of data existence). East Antarctic data are cropped to 2,500 m altitude. White dashed line (at 81.5^o S) shows southern limit of radar altimetry measurements. (Pritchard et al., 2009)*

There is a strong influence of ocean warming on the mass balance via the melting of ice-shelves. The observed summer melting of Arctic sea-ice has far exceeded the worst-case projections from climate models of IPCC AR4. The warming associated with the atmospheric greenhouse gas levels makes it very likely that in the later decades the summer Arctic Ocean will become ice-free, though the timing of this remains uncertain.

An evidence of the fact that much fast-moving glaciers are changing the ice sheets is seen in *Fig. 7*. (Pritchard, et al., 2009) In the framework of the British Antarctic Survey, the authors developed a new method to map out elevation change using data from NASA's Ice, Cloud and land Elevation Satellite. These images illustrate changes to the edges of the ice sheets in 2003-2007 as observed by ICESat. Places where glaciers thinned from lost ice over time are red, while areas where glaciers or the ice sheet gained ice are blue. The greatest areas of ice loss are along the northwest and southeast coasts of Greenland and the west coast of Antarctica with some glaciers thinned more than 9 m/year. The average rate of thinning for fast-flowing glaciers in Greenland was 0.84 m/year.

Another example for changes of the sea-level and its components is given in *Table 5*, where these empirically determined terms were derived for different short periods with different methodologies. All terms except the land waters estimation apply satellite-born observations.

Table 5: *Two recent trend-estimations of the global sea level and its components.*

Sea-level rise estimations	Ice-sheets mm/yr	Glaciers mm/yr	Land-ice mm/yr	*Thermal expansion mm/yr*	Land waters mm/yr	**Total climatic mm/yr**	**Observed increase mm/yr**
*IPCC AR4, 2007 (*1993-2003):	0.4	0.8	1.2	*1.6*	?	**2.8**	**3.1**
*Cazenave and Llovel, 2010 (*2003-2009):	1.1	1.1	2.2	*0.6*	-0.2*	**2.6**	**2.8**

**Llovel et al., 2010*

5. Testing of climate reproduced by models

The climate system, the atmosphere, the lands, the oceans, the biosphere and solid water, i.e. the cryosphere is one of the most complicated non-linear systems. The spatial scales of the system start from the millimetre magnitude of cloud-physical processes until the length of the Equator.

The temporal scales of the system changes between the few minutes' long micro turbulence and the many hundred year long ocean circulation. Not any model is able to take everything into consideration. Besides the insufficient computer capacity, we have to consider the lack of knowledge derived form the limitations of the observation network.

For this reason, testing the climate models is very important. The simpler part of testing is to check whether the fields in the models, simulated with present external circumstances, fit to the reality. A positive example of this validation is shown in *Fig. 8*. It demonstrates that the water content of atmosphere and its changes relatively well was given back by the model was fitted to the reality via sea surface temperature as lower boundary condition. We can state that the dynamical processes of the atmosphere can well handle the atmospheric water content.

It is also worth mentioning, that the increasing trend of water content during this two decades, with global warming behind, points at the positive inter-relatedness of temperature and water content at global scales: Warming climate initiates increased water vapour content, leading to further warming, as it is also mentioned in the next Section.

6. Testing of climate model sensitivity

The final aim of climate modelling is to project the future climate in response to reasonable changes in the external forcing factors. These external factors and their uncertainty are influenced by many circumstances. Among others, they are the world population, the structure of energy industry, development difference between the regions, etc.

The other uncertainty factor is how correctly we simulate the sensitivity of climate system, namely the expected temperature in response to given changes of the external factors. We are not really able to estimate the first uncertainty source, due to its complexity, but we can validate the climate sensitivity simulations through testing certain particular processes. These particular processes are the climate feedback mechanisms, including variables and processes, that change due to climate changes, but which re-direct the measure of climate change, as well.

The expected changes in the global average could be determined by the *Fig. 9*. The expected changes are shown using the three stressed scenarios of Report (IPCC 2007) supposing constant atmospheric composition as it was in 2000. See left side of the mentioned Figure. The right side of the Fig. 9 shows the absolute uncertainty of three basic scenarios furthermore of three more popular alternatives given in Report 2001.

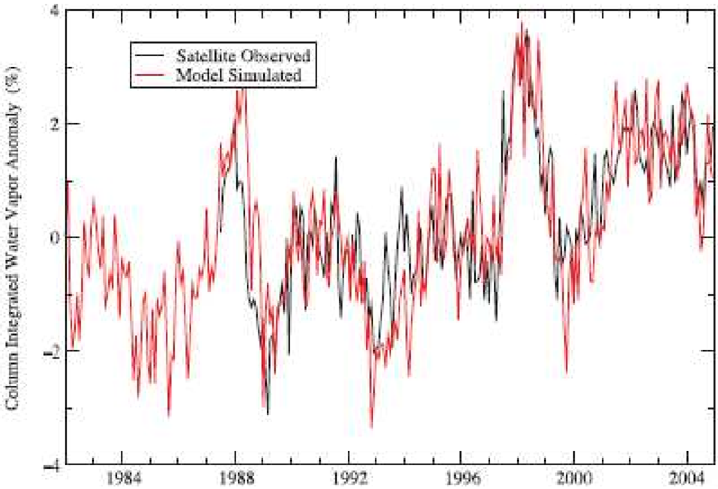

Figure 8: *The anomaly of vertically integrated water vapour content above the ocean, expressed in percent of 1987-2000 period average. The values are simulated by the general circulation model of Geophysical Fluid Laboratory, Princeton and observed by the SSM/I satellite. The model was driven by observed sea-surface temperature, as lower boundary condition, otherwise by external climate forcing. The model well reproduces the slow increase of water vapour content in connection with warming, and the inter-annual fluctuation in relation to the El Nino/La Nina oscillation (IPCC 2007: Fig. 9.17).*

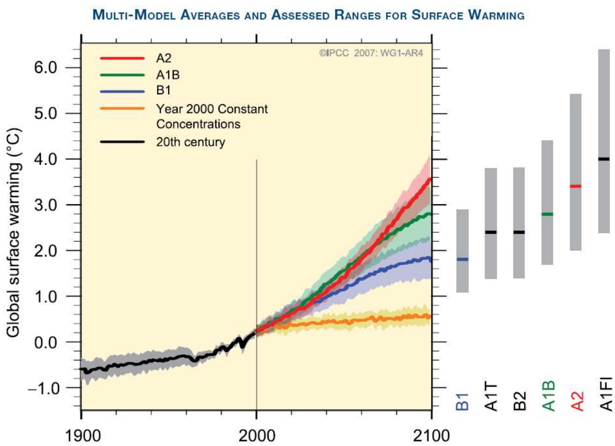

Figure 9: *Global mean temperature scenarios. The solid lines of the figure show the changes of global mean temperature. The lines before 2000 show the observed values and their ±1 standard deviation. Later they are the results of all available model simulations as deviation from the 1980-1999 average. The future is shown in the inner figure according to the A2, A1B, and B1 scenarios. The orange line is for the experiment where concentrations are held constant after 2000. The right hand columns show the model uncertainty. They could be characterised by +60% higher and -40% lower values. (IPCC 2007: Fig. 10.29). So, horizontally the uncertainty of emission scenarios, vertically the uncertainties of climate sensitivity are shown in the right side of the Figure.*

If we compare the uncertainty originated from different emission scenarios, on one hand, and from sensitivity differences of the models, on the second hand, we have to assess both uncertainty sources to be similar. Hence, decreasing the difference of climate models, reflecting better knowledge of the real sensitivity, would be equally useful from the point of view of the prediction as reduction of the uncertainty of future emissions. It makes quite a difference if we reach the 1.1°C or the 6.4°C end of the overall uncertainty interval. Or, if speaking about a medium rapid emission scenario, with uncertainty just from the model physics, than 1.6°C, or 4.4°C, as in the popular case of A1B scenario. The assumptions projected numbers and primary sources of the so called SRES scenarios can be seen in several pages of the IPCC AR4 Report (2007).

Above it was shown that the sensitivity of climate model highly differs form each other. It is important scientific task the further testing of simulated feedbacks in the models, and absolute (comparison with some kind independent reference value) and relative (comparison of different models) study in which the satellite observation will have important role. The most frequently referred Figure of IPCC (2007) Report shows how the mean Earth's temperature can change according to the possible scenarios and climate sensitivity values.

In *Fig. 10* two tests of such a feedback are shown. The long wave radiation emitted from the surface is influenced only by water vapour content of atmosphere under clear sky. The more water vapour is in the atmosphere, the bigger part of the surface originated long wave radiation can be absorbed. It means that smaller part of the energy could leave into the space. (In scientific meaning, the water vapour is greenhouse gas itself causing more than the a half of the natural greenhouse effect. But, since water vapour content of the atmosphere is changing mainly due to internal processes of the climate system, from environmental point of view we do not consider it as a greenhouse gas.)

The upper part of Fig. 10 demonstrates that the mentioned model overestimates the influence of water vapour on the irradiance. It means that the model simulates the most important stabilising negative feedback of the climate system to be weaker than in the reality. Contrary to this, the positive feedback has got the biggest influence on short wave balance connected with the changes of snow and ice cover. The stronger the warming is, the larger area of the elements of cryosphere will thaw, and the albedo of a large area will be darker instead of snow and ice with high reflectivity. Since the snow-free surface is able to absorb more energy and use it for warming of the atmosphere, it will amplify the warming as well.

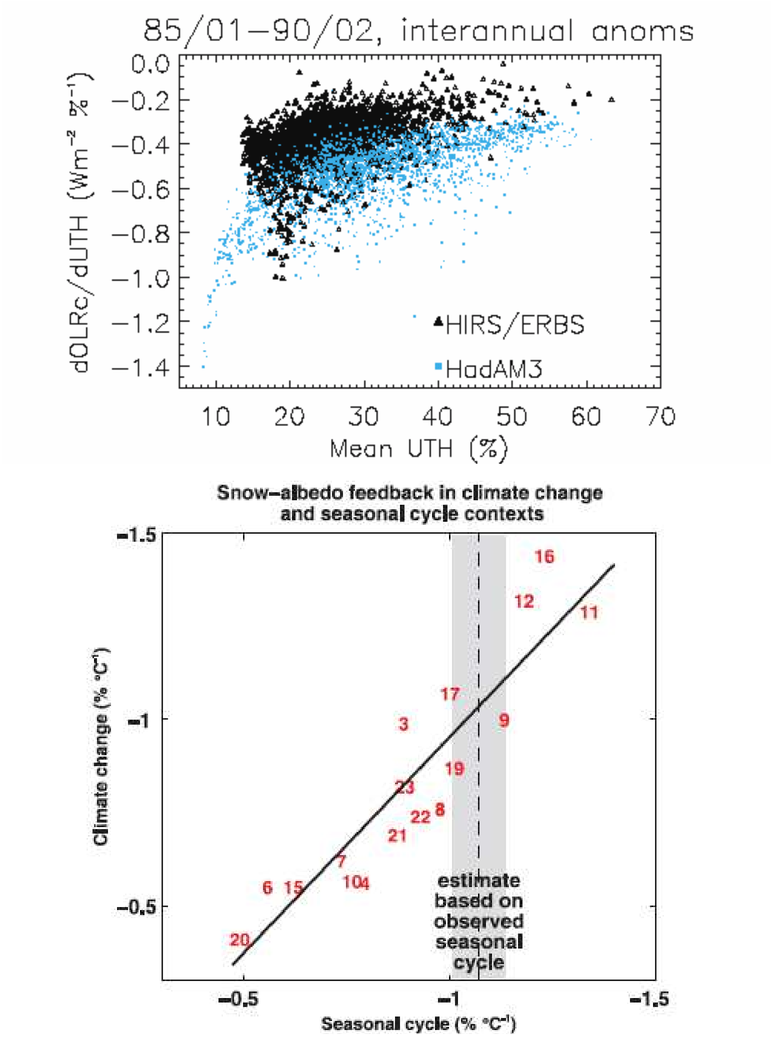

Figure 10: *Model estimation of most important elements of (cloudless) long wave (a) (Allan et al., 2004: Fig. 2) and shortwave balance (b) (IPCC, 2007: Fig. 8.16). In first figure the HadAM3 climate model of British Hadley Centre, calculated for tropical area, under clear sky, shows that the long-wave component decreases too fast with increasing water vapour content of upper stratosphere. It means that the model simulates a bigger value for the irradiance than it was measured by ERBS and HIRS satellites. This error means too strong negative feedback in the model. We can also see how the short-wave balance depends on surface albedo in case of 17 different models in the lower part of the figure. The vertical axis shows the albedo decrease depending on unit global warming as one difference between 20th and 22nd Century simulated climates. The horizontal axis shows the ratio of satellite observed April-May albedo and temperature values for the Northern Hemisphere. The seasonal albedo sensitivity is estimated using data fields of ISCCP cloud climatology and ERA-40 atmosphere analysis projects. The models produce large deviations from this value, and in majority they exhibit weaker feedback than the empirical estimation. Both errors lead to smaller climate sensitivity than in reality.*

7. Conclusion

The use of Remote Sensing from space is advantageous, since it allows us to observe a wide range of climate parameters on a global scale in a consistent and repeatable manner. There are several parameters that can practically be observed only this way. Though there are some constrains in accuracy and in precision, as well, the moderate space and time resolution, which is enough for climate science applications, makes them not especially limiting.

Besides the traditional passive optical sounding, passive and active microwave sensors are also of great and increasing importance. The paper does not contain too much detail in technical aspects but we tried to go through the useful aspects of the application.

Monitoring of the external climate forcing, with special emphasis on the new developments of the global radiation balance estimations atmospheric aerosols made clear for us, that this aspect still needs the ongoing further development to reduce the uncertainties. Detection of climate change is important since ground-based detection has many local influences and other practical constraints, especially concerning the cryosphere and the strongly related sea-level.

The third group, the validation of the present climate model simulations could have been more detailed, but the results of the comparison are rather model-dependent also with some uncertainties in the indirect observations. More attention was paid to the validation of the feedback mechanisms, determining the radiation balance of the atmosphere and largely influencing the sensitivity of our climate to the external forcing factors. Undoubtedly, this aspect is the most related one to the climate policy, obtaining primary reflection of climate science, in optimum case.

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