

ENERGY AND ENVIRONMENT

The Intimate Link

A position paper of the EPS
Environmental Physics Division



European Physical Society
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In 2008 two EPS Environmental Physics Division workshops took place on the topic Energy and Environment, one in March together with the DPG Frühjahrstagung in Darmstadt, the other in June together with the EPS-SFP Energy conference in Les Houches. Contributions are synthesised in this report ^{i,ii}.

Adelbert P.H. Goede¹, Adrian Tuck², John P. Burrows³, Herbert Fischer⁴,
Thomas Leisner⁴, Matthias Beekmann⁵, Jean-Marie Flaud⁵, Herwig Paretzke⁶, Peter Suppan⁷,
Frank Baier⁸, Thomas Hamacher⁹, Ulrich Platt¹⁰, Prodromos Zanis¹¹.

¹ FOM Institute for Plasma Physics Rijnhuizen, Nieuwegein, the Netherlands,

² Formerly NOAA-ESRL/CSD6, Boulder Co, USA,

³ Institute of Environmental Physics and Remote Sensing (IUP/IFE), University of Bremen, Germany,

⁴ Institute for Meteorology and Climate Research (IMK-FZK), Karlsruhe Institute of Technology, Germany,

⁵ Laboratoire Interuniversit  des Syst mes Atmosph riques (LISA), CNRS/Univ. Paris Est, 7 Cr teil, France,

⁶ Helmholtz Centre Munich (formerly GSF), Institute of Radiation Protection, Neuherberg (near Munich), Germany,

⁷ Atmospheric Environmental Research (IMK-IFU), Garmisch-Partenkirchen, Karlsruhe Institute of Technology, Germany,

⁸ German Aerospace Centre DLR-DFD, Wessling, Germany,

⁹ Institute f r Plasma Physik, MPG Garching, Germany,

¹⁰ Institute of Environmental Physics (IUP), University of Heidelberg, Germany,

¹¹ Dept. Meteorology and Climatology, Aristotle University of Thessaloniki, Greece.

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BACKGROUND

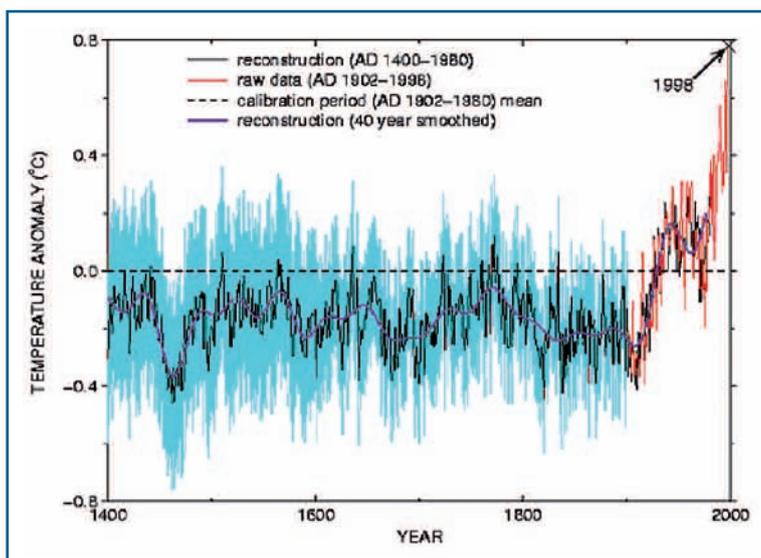
Energy and Environment are intimately linked. Concern about the environmental impact of energy production has taken many forms, not always leading to the most productive course of events. In the sixties, scientists showed that sulphur emissions from coal fired power plants in continental Europe and the UK caused acidification of Scandinavian lakes. For the first time, the global impact of local air pollution was recognised. Society responded, a decade later, by regulating these emissions through the UN Convention on Long-Range Trans-boundary Air Pollution.

In the seventies, the environmental debate shifted towards the limits on the energy supply side. “Limits to Growth” published by the Club of Rome coincided with the 1973 oil crisis. Public awareness was raised on the need for sustainable resources in the face of rapid rise in energy consumption. The discussion was defused by relatively low energy and commodity prices that followed in the eighties and nineties. The book echoed some of the concerns raised in 1798 by the reverend Malthus in his “Essay on the Principle of Population” arguing that the rate of population growth could not be sustained by the finite food supply. History has shown that the relation between population

growth and resources is not always linear, as was demonstrated by the scientific discovery of fertilizer applied in agricultural food production, raising productivity by orders of magnitude compared with the Malthusian assessment.

The eighties were dominated by the nuclear debate with public concern on the health effects of low dose radiation, reactor safety and the problem of long term storage of nuclear waste. The argument was sealed by the nuclear reactor accident in Chernobyl in April 1986 leading to a moratorium on nuclear power in many countries. Its heated discussion reverberates today, epitomised by the entrenched position of some political parties against the revival of nuclear power.

In the nineties the climate debate took public stage. The Intergovernmental Panel on Climate Change [1] (IPCC) proclaimed a consistent message of human induced climate change. Sceptics on the other hand, supported by the energy sector, constantly changed tack, thwarting the anthropogenic climate model. Eventually in 2006, public opinion swayed with the publication of the Stern Review “The Economics of Climate Change”, calculating the cost of climate change, in particular that of deferred action.



▲ FIG. 1: The tree ring global temperature record of the earth surface. Source: IPCC WG1 report 2007.

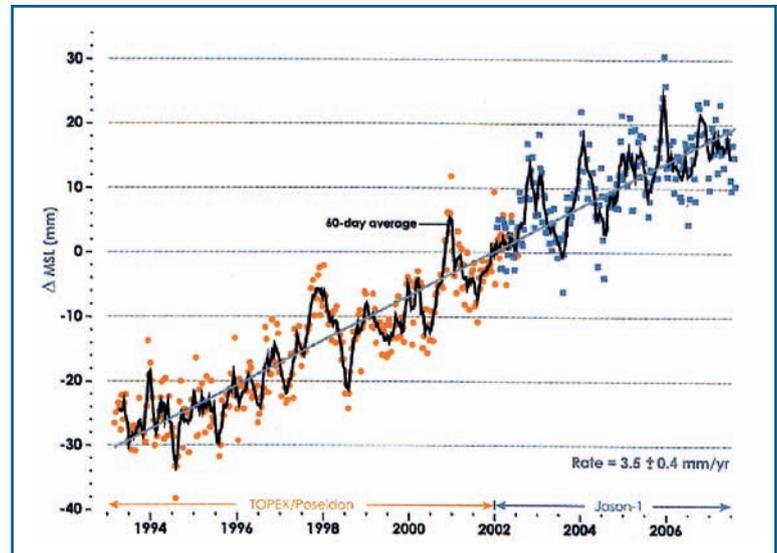
Obviously, these time periods are highly schematic. Indeed, the impact of fossil fuels on the environment has been recognised since the identification of smog in the 19th century. Already in 1896 Arrhenius [2] published his account “On the influence of Carbonic Acid in the Air upon the Temperature on the Ground” correctly identifying carbon dioxide and water vapour as important greenhouse gases that change climate. Fourier in 1827 and Tyndall [3] in 1861, based on early infrared absorption spectroscopy, and others had argued, “the atmosphere acts like the glass of a hot-house”. Arrhenius calculated, with the help of Langley [4] lunar plots of infrared absorption of the earth atmosphere, that doubling the atmospheric CO₂ content by burning fossil fuel would lead to an average global temperature rise of 5 to 6 °C, not far from the current

IPCC values ranging from 2 to 4.2 °C. Ironically, Arrhenius argued this temperature increase would be beneficial to humanity, averting the world plunging into the next ice age. As it transpired, by analysis of Milankovitch [5], this observation is apt as the earth finds itself geologically in an interglacial period, heading for a new ice age.

The climate debate stands out in complexity and consequence. Unlike the ozone layer attacked by CFC's, greenhouse gas emissions pervade the very fabric of affluent society. The Montreal Protocol of 1987 (and its subsequent amendments) could limit and eventually ban CFC emissions by targeting just one sector of the chemical industry. Limiting greenhouse gases, however, requires regulation of a vast range of industry, including the energy sector, the car industry, aircraft and shipbuilding, housing, agriculture, indeed all energy intensive industry are implicated. The problem is compounded by the current dramatic changes taking place in the global economy and the demography of the developing world which has lifted the world energy consumption into a different league. It is argued that the IPCC scenarios do not adequately cover this new situation. Unsurprisingly, the Kyoto Protocol will not meet its objective to reduce the global greenhouse gas emissions in the 2008-2012 period to below 10% of the 1990 level.

Beset by uncertainty, climate modellers seem rather confident in their predictions for this century. Glaciers are predicted to disappear around the year 2050, the Arctic ice cap around 2070 and the Gulf Stream will collapse around 2100. The Greenland ice sheet will probably disappear around 2300, causing a 7 m rise in the global sea level. Counteracting effects, however, of a stalling Gulf Stream and a rising greenhouse gas concentration do not seem to be reconciled in current climate models. Intricate phenomena such as the splitting of the ozone-hole in 2002, leading to much less ozone loss that year, are beyond the reach of meteorological let alone climate models.

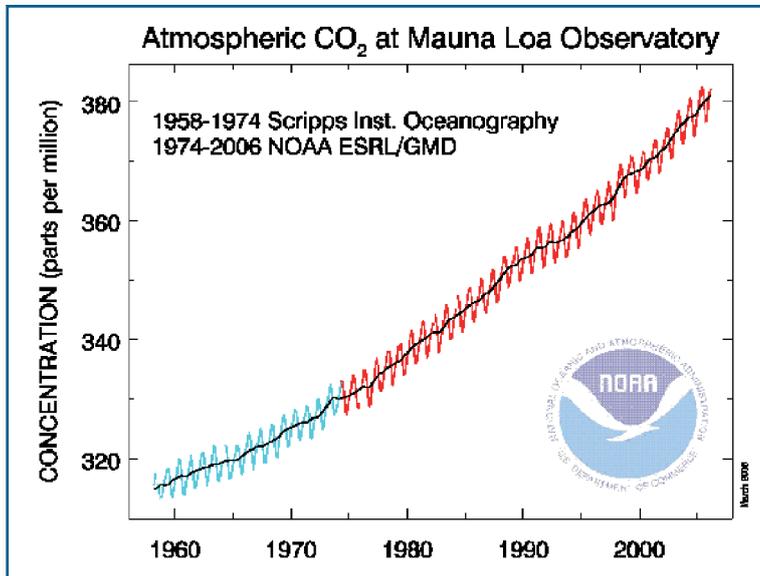
▼ FIG. 2: Global mean sea level derived from the French-American TOPEX/Poseidon and Jason-1 satellites show an average sea level rise of 3.5 cm per decade over the past 13 years. Source: Univ Colorado, LEGOS/CNES.



Thus, it would be useful to distinguish fact from fiction and to identify what we know, what we think might happen and what we do not know. Climate models are hardly validated over the period of interest and measurements contain large error bars. For example, the accuracy of global temperature measurement is not better than 1 °C, yet a change in global average temperature of 1 °C is significant. By comparison, during the last ice age the global average temperature was down by 2 to 3 °C.

Climate, often defined as average weather over 30 years, is described by a number of coupled hydrodynamic equations taking into account the interaction between atmosphere, ocean and land surface. The equations are non-linear, the interactions difficult to quantify. The energy balance of the earth relies on the radiation transfer calculations of incoming solar and emitted thermal radiation taking into account the absorption and emission properties of atmospheric constituents. Scattering and absorption by clouds and aerosol are known uncertainties. The chemistry of the atmosphere controls the concentration distribution of greenhouse gases and pollutants. Reaction channels and rates are not accurately known. Some sources and sinks carry large uncertainty.

▼ FIG. 3: The Keeling curve of carbon dioxide concentration increase since the Geophysical year. Note the break in data during 1964 when funding temporarily ceased. Source: IPCC WG1 report 2007.



Climate change actually happening relies on a number of measurements relating to surface temperature, sea level and humidity. The surface temperature record is based on tree ring analysis of the past millennium, referred to as the hockey stick curve, because of its pronounced upward curvature coincident with the industrial revolution starting around 1860, see Figure 1. The isotopic ¹⁸O/¹⁶O ratio, serving as a proxy for temperature through the difference in evaporation rate of water, provides a temperature scale stretching back tens of millions of years. These data are useful for the study of higher CO₂ level climates experienced, for example 50 million years ago, when the CO₂ concentration was 5 times its present value.

Direct measurements of sea level stretch back to the seventeenth century when the water level in harbours was of crucial economic importance. The Amsterdam ordnance data show 1.5 cm rises per century around the year 1800 compared with 17 cm rise per century in 1920. Interestingly, these data illustrate the difficulty in interpretation of climate measurements. For example, Amsterdam being on the continental shelf loaded with ice during the past glacial period some 10 thousand

years ago rebounds over Scandinavia giving rise to a tilting of the tectonic plate that actually tips the Netherlands downwards. Sea level data taken in Amsterdam need to be corrected for this geological subsidence effect. Large variations in sea level are observed along the Dutch coast. Even larger variations exist globally. The appropriate measurement technique thus would be global and finely meshed. This is where satellite measurements come in. Figure 2 shows data from the French-American Topex-Poseidon and Jason satellites yielding a 3.5 cm sea level rise over the past decade. When considering the recently reported accelerated melting of the Greenland ice cap, this rate of sea level rise is likely to increase substantially during this century.

Much more difficult to measure temperature or sea level is humidity. Yet, the effect of humidity on climate is dramatic, as it governs the energy exchange between land surface and atmosphere through the evaporation precipitation cycle. A feed back loop is at work, dry soil enhances a temperature increase through lack of latent heat stored in soil moisture that would drive the temperature down. That was the mechanism at work during the 2003 heat wave in France causing around 10,000 deaths. Climate models are consistent in predicting increased dryness of soil. The arid North of China lost some 36,000 km² to desertification over the past ten years. Most affected are the transitions from wet to dry climates, experienced for example in Spain, that are very sensitive to a change in humidity. Exactly how sensitive depends on the model favoured.

The record of CO₂ and CH₄ greenhouse gas concentration data relies on ice cores containing trapped air bubbles that can be analysed for their constituents, thus providing a data record extending back up to 800 kyrs. The weak variation over the past 10,000 year changes abruptly into a steep rise, coinciding with the industrial revolution taking off. Measurements over the past 50 years are based on gas sample analysis taken at remote sites around the globe, notably Hawaii. The celebrated Keeling curve, painstakingly acquired since the start of the Geophysical Year in 1957, demonstrates

the strong upward trend of global CO₂ concentration. Figure 3 graphically displays the springtime uptake and autumn release of CO₂, the breathing of the earth. Detailed analysis reveals yet more information such as the influence of El Nino.

CLIMATE MODELLING

Modelling of the climate is important for understanding and predicting climate change and will help to develop mitigation and adaptation measures. As climate change is becoming a major driving force in national and international politics, reduction of uncertainties in climate modelling is paramount.

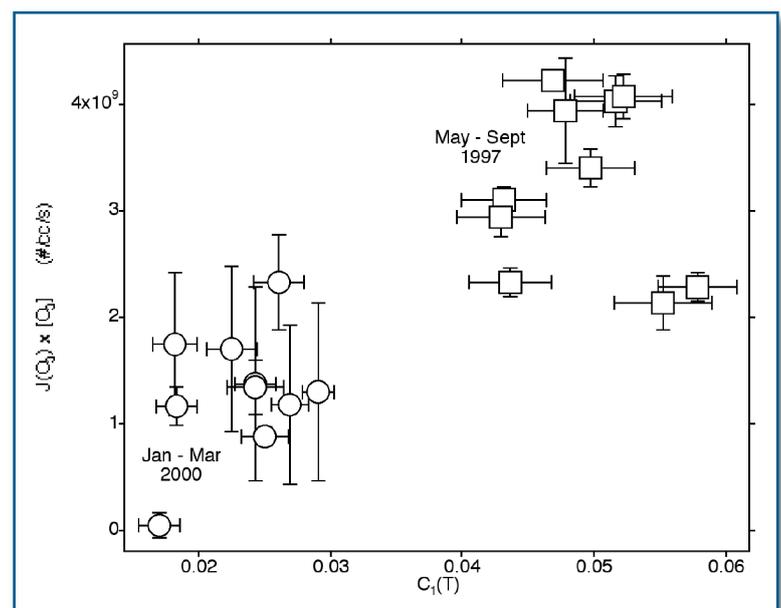
Climate prediction relies on models similar to weather forecast, albeit at lower spatial and temporal resolution and using a simplified parameterisation. Weather forecast is undoubtedly successful. This success, however, is largely due to the application of the data assimilation technique, a statistical method by which models are continuously fed by measured data such as to steer them in the direction of measured data. Depending on the type of weather, results tend to diverge from the truth after a couple of days up to a week. This approach is of limited value in climate modelling.

A new approach [6] considers the state of the atmosphere at the molecular dynamics scale taking due account of the non-Maxwellian nature of the particle velocity distribution. Vortices, winds and temperature are produced following the molecular absorption of solar photons. Via scaling exponents describing conservation, intermittency and fractality, evidence is considered that the atmosphere is never in equilibrium at any one time or at any spatial scale. Accordingly, a Maxwell-Boltzmann distribution of molecular velocities cannot occur. The consequences for the infrared spectral line shapes and the rates of chemical reactions need to be calculated.

The definition of temperature depends upon the existence of equilibrium microscopically, while macroscopically its definition is the derivative of energy with respect to entropy. The problem with the latter is that there is not a rigorous definition of

the entropy of a system not at equilibrium, which is the actual state of the atmosphere. The implication for climate is that the distribution of energy in the atmosphere must be calculated from first principles by summing over the occupied molecular energy states in a system not at equilibrium. Temperature remains operationally observable because the exchange of energy among molecules with velocities near the most probable velocity is rapid, but the velocity distribution is not characterized by a Maxwell-Boltzmann distribution.

The nonlinear response of a thermalised population of molecules to an anisotropic flux, which is always present on all scales in the atmosphere because of gravity, planetary rotation and the solar beam, results in fluid flow on scales of picoseconds and nanometres. Thus, while the historical record of calibrated temperature observations remains, its interpretation is complicated. For example, the substantial increases in the amount of tropospheric ozone since the 19th century and the decreases in stratospheric ozone in the latter half of the 20th century, changes the rate of production of translational hot photo fragments in the atmosphere, which changes the velocity distribution of ■■■



▲ FIG. 4: Correlation between temperature intermittency C_i and ozone photo dissociation rate J in the Arctic lower stratosphere showing the correlation between microscopic change and macroscopic quantities. Source A Tuck.

- the molecules away from the Maxwell-Boltzmann distribution and ultimately will change the nature of turbulent fluid flow in the atmosphere from the small scales upwards.

This concept is observationally supported by high resolution aircraft observations and drop sondes, which show correlations of the Hurst exponent for wind and temperature with measures of jet stream strength in both the horizontal direction, in the lower stratosphere and upper troposphere, and in the vertical direction through the depth of the troposphere. Correlation between temperature intermittency and ozone photo-dissociation rate presents evidence of the nonlinear interaction between high velocity molecules and large-scale order, see Figure 4. The jet stream speed reaches a substantial fraction of the average molecular speed. While this will probably have little effect on weather prediction on synoptic scales, because the models are continually fed with observations, there will be implications for climate models, where the models are run for time scales that lose any memory of the initial conditions. Their small scale parameterisations should be formulated from the bottom up, with an operationally cor-

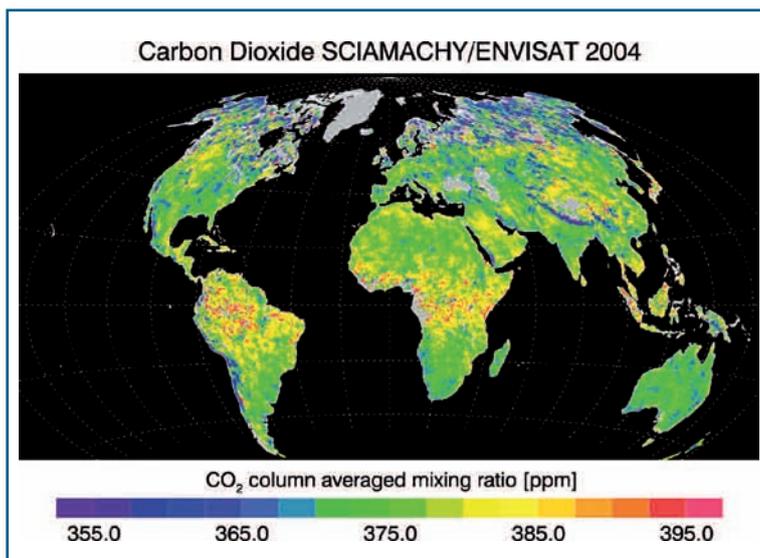
rect statistical mechanics reflecting the molecular realities outlined above. This is not the case in current climate models.

GLOBAL OBSERVATION OF GREENHOUSE GASES

In order to improve our understanding of the climate system it is necessary to take global measurements of the greenhouse constituents at adequate spatial (50-100 km) and temporal (days) scale. From their vantage point in space, satellites offer the global picture, the Holy Grail being the measurement of tropospheric constituents. The difficulty lies in separating the troposphere layer from the stratosphere and mesosphere whilst obtaining sufficient sensitivity in the boundary layer where the emissions take place. A measurement precision better than 1%, capable of improving our knowledge of the greenhouse gas sources and sinks, is a challenge.

SCIAMACHY flying aboard the European ENVISAT is the first Earth Observation instrument to attempt this feat [7,8]. Figure 5 shows yearly averaged column amounts of CO₂ retrieved at 30x60 km² scale. The retrieval of atmospheric constituents from spectral data measured requires a sophisticated forward calculation of radiation transport through the atmosphere involving multiple scattering and polarisation. Inversion by statistical methods, such as maximum likelihood, yields the concentration distribution of trace gases and aerosol. Reproduction of the Keeling curve from space, shown in Figure 6, demonstrates the validity of the new technology. Interesting differences between these measurements and theoretical models suggest the breathing of the Earth is actually heavier than predicted.

Nadir viewing space instruments like SCIAMACHY produce two dimensional maps of total columns of atmospheric constituents. The third dimension, altitude, is important in order to understand the characteristic layered structure of the atmosphere, in particular to distinguish the troposphere from the stratosphere and the exchanges between them. MIPAS on ENVISAT pointing towards the Earth



▲ FIG. 5: First direct observation of CO₂ column height from space by SCIAMACHY on the European earth observing satellite ENVISAT. Source: M Buchwitz, IUP Uni-Bremen, Germany.

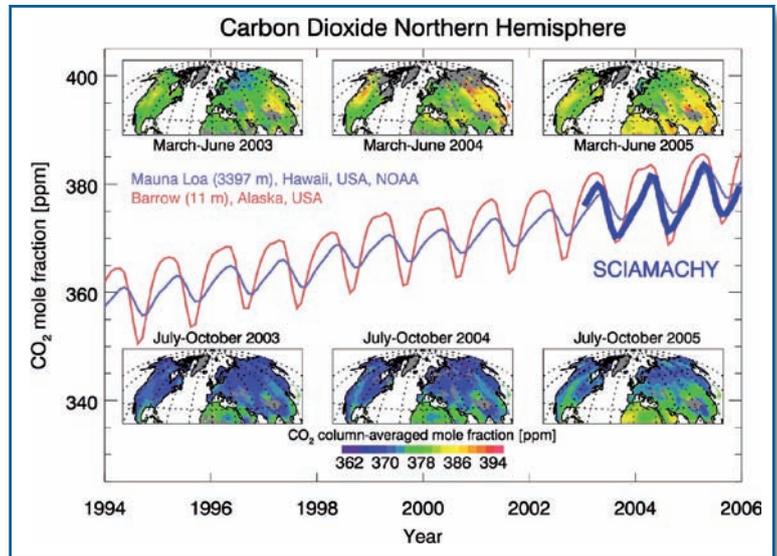
horizon (limb) targets a considerable number of trace species in the upper troposphere and lower stratosphere, including the greenhouse gases H₂O, O₃, CFCs and related pollutants such as CO.

Figure 7 shows MIPAS data [9] of polar stratospheric clouds playing a crucial role in the destruction of stratospheric ozone. Stratospheric ozone and climate interact in a complex way. Changes in stratospheric temperature distribution and transport affect the ozone concentration distribution, whilst changes in stratospheric ozone influence troposphere temperature and chemistry rates. The strength of the Brewer Dobson circulation and the excitation and dissipation of planetary waves are known uncertainties in the control of ozone and climate. Evidence of the interaction between stratospheric ozone depletion and climate change suggest a delayed recovery of the stratospheric ozone layer well into to the second part of this century [10,11]. Continuous monitoring is paramount. Figure 8 shows the evolution of the Antarctic ozone hole over the past 14 years recorded by the European satellite instruments GOME and SCIAMACHY. Note the unexpected shallow ozone hole of 2002.

AIR POLLUTION

Similarly related to energy is air pollution, but unlike climate change it acts now. Worldwide approximately 1.3 billion people suffer from air pollution through pulmonary and heart disease, according to the World Health Organization. The steep rise in allergies (asthma, eczema) over the past decades is generally attributed to air pollution. Air pollution is concentrated in urban areas and because, as of 2007, more people live in urban rather than in rural areas, a disproportionate amount of the population is at risk. The trend in urbanisation is set to continue; by 2030 around 5 billion people are expected to live in urban areas. Urbanisation exacerbates the air pollution problem. This is illustrated by Table 1 where the per capita carbon monoxide emission in megacities is compared with OECD countries with similar population [12], showing a factor two higher level of air pollution in megacities.

▼ FIG. 6: Reproduction of the Keeling curve from space by SCIAMACHY compared with ground based measurements. Source M Buchwitz, IUP Uni-Bremen, Germany.

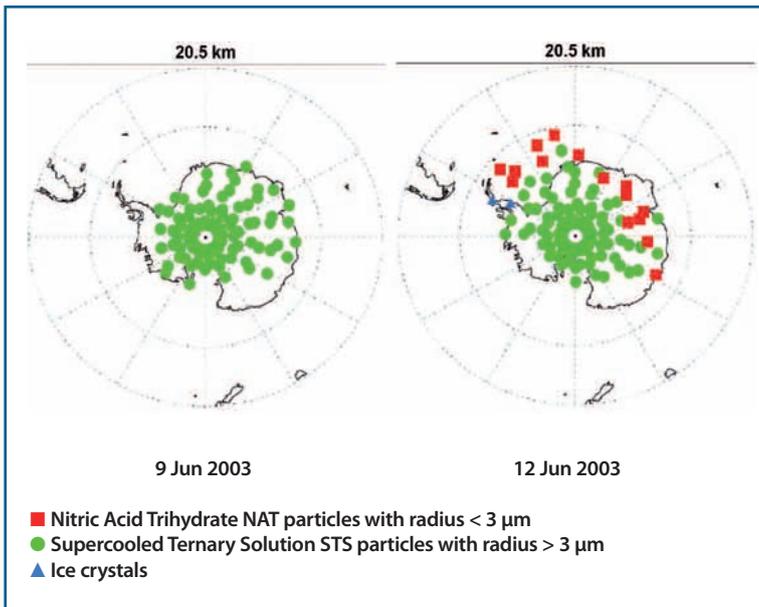


Air pollution is determined by primary emissions of nitrogen oxides (traffic), volatile organic compounds VOC (traffic, solvents, industrial processes, biogenic emissions), sulphur dioxide (coal-fired power plants), carbon monoxide (bio-mass burning) and airborne particles (traffic, heating, biogenic). Activated by sunlight, and in the presence of nitrogen oxide, VOC oxidation leads to the formation of tropospheric ozone. Multiphase processes, including nucleation and condensation of gaseous precursors, determine the chemical

		CO Emissions per citizen (kg/person)	Citizen (Mill.)
Megacities	Beijing	253	10.0
	Shanghai	167	13.2
	Los Angeles	166	11.8
	Moscow	131	10.1
	Mexico City	101	18.1
OECD countries	Portugal	110	10.0
	Belgium	101	10.3
	Hungary	073	10.0
	Czech R.	063	10.3
	Netherlands	043	15.9

▲ TABLE 1: Comparison of per capita carbon monoxide (CO) emissions in megacities and OECD countries with equal number of inhabitants. Source: Gurjar and Lelieveld, 2005.

▼ FIG. 7: Distribution of various PSC types at 21 km altitude over the Antarctic, derived from MIPAS observation showing the evolution of PSC type during the austral winter 2003. Microphysical and chemical PSC compositions are derived from the infrared spectral signature of these particles. PSC are key to the destruction of stratospheric ozone and hence the depth of the ozone hole developing during the austral spring of September 2003. Source: H Fischer IMK-FZK Germany.



composition and size of the airborne particles (aerosol). Long-range transport of pollutants and regional background complete the overall air quality picture.

Traditionally air pollution measurements are taken from the ground. Spatial sampling and global coverage form the usual limitations. Measurements from space can bridge the gap between the local and the global scale and capture long range transport. Figure 9 shows the global distribution of tropospheric NO₂ columns measured by the Dutch-Finnish satellite instrument OMI [13]. Retrieving tropospheric ozone from underneath the ten times thicker stratospheric layer requires technique that is more sophisticated. By employing an altitude dependent regularisation method on the infrared data from the French IASI instrument on Europe’s MetOp-A satellite, the first day-by-day tropospheric ozone columns (0 to 6 km altitude) over Europe could be retrieved during the July 2007 heat wave. As shown in Figure 10, the ozone concentrations from IASI match well the predictions of the regional chemistry transport model CHIMERE [14,15].

Activity	Mode of release	
	Routine	Accidental
MILITARY PURPOSES		
Weapons production	Hanford, USA (1944-51) Chelyabinsk, USSR (1948-56)	Techa River, USSR (1949-51) Kystim, USSR (1957) Windscale, UK (1957) Rocky Flats, USA (1969) Tomsk-7, USSR (1993)
Atmospheric tests	Nevada, USA (1951-62) Semipalatinsk, USSR (1949-62) Novaya Zemlya, USSR (1955-62)	Altay, USSR (1949) Marshall Islands, USA (1954)
Nuclear fleet	Kola Peninsula, USSR	Chazhma, USSR (1985)
Weapons transport		Palomares, Spain (1966) Thule, Greenland (1968)
POWER PRODUCTION		
Reactor operation	Worldwide	Three Mile Island, USA (1979) Chernobyl, USSR (1986)
Fuel processing	Sellafield, UK La Hague, France	
RADIOISOTOPE USE		
Loss of sources		Cuidad Juarez, Mexico (1982) Goiania, Brazil (1987)
Satellite reentry		SNAP-9A, global (1964) Cosmos-954, Canada (1978)

▲ TABLE 2: Major accidental and routine releases of radioactivity into the environment

Current research activities include the building of an operational air quality prediction system [16,17]. Figure 11 shows an air quality forecast by the European GMES atmosphere service [18] providing information on ozone, UV, air pollution and climate based on the integration of ground, airplane and satellite measurements in atmospheric chemistry models by employing data assimilation. Results are promising, but improvement is needed for specific pollutants and pollution episodes. For example, uncertainty in emission inventories is still a major source of error. Key processes of multiphase chemical transformation of pollutants, in particular formation of organic aerosol from gaseous VOC precursors, are not yet well quantified. Therefore, aerosol chamber experiments, field observations and improved process modelling are needed.

Apart from health and environmental effects, air pollution induces climate change through radiatively active species such as tropospheric ozone and aerosol. Vice versa, climate change will alter

transport and dispersion patterns and thus affect air quality. The interaction between aerosol and climate remains one of the largest uncertainties in climate prediction [1]. Aerosol particles influence climate by modifying both the global energy balance through absorption and scattering of radiation (direct effects), and the reflectance and persistence of clouds and the development and occurrence of precipitation (indirect effects). Global climate-chemistry models try to capture these air pollution effects [19,20]. Few models emphasise the regional scale focussing on the volatile temporal and spatial variability of tropospheric ozone and aerosol [21,22].

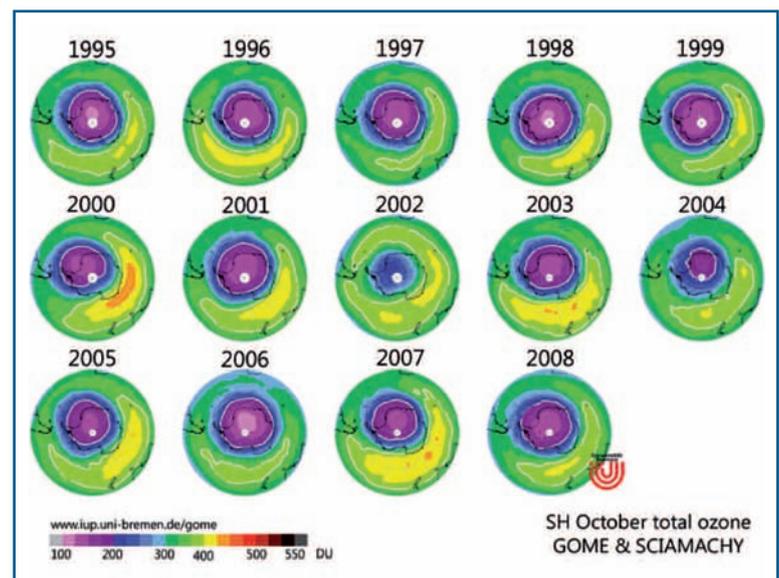
NUCLEAR ENERGY

Nuclear energy, be it based on fission or fusion processes, offers a highly centralised form of energy production that is free from greenhouse gas emission and saves fossil fuel resources. Thus, the recent revival of interest in nuclear fission as a source for electrical power comes as no surprise. Similarly, the recent approval of the ITER project will advance the nuclear fusion concept towards a commercial reactor in the long run. With roughly 400 nuclear fission plants in operation worldwide, nuclear power covers 17 % of the global electricity production and 6 % of the global primary energy production.

The environmental impact of nuclear fission reactors revolves around the dispersal of radioactive material be it through leaks during operation and storage, proliferation or accident. Empirical evidence acquired over 60 years includes the atmospheric atomic bomb tests in the sixties, accidents in the nuclear weapons industry, for example the Kystim accident in 1957, and accidents in the nuclear power industry, notably the Chernobyl accident in 1986. Events are summarized in Table 2. Scientific studies have shown that chronic exposures below 1 mGy per day are not likely to lead to any observable adverse effect on plants, animals and on the population at large. This level of exposure is more than two orders of magnitude higher than can be expected from the present generation of nuclear power stations.

The radiological hazards of fusion reactors are much smaller compared with those of nuclear fission but are nevertheless finite. A limited inventory of radioactive material, either in the form of tritium embedded in the walls of the reactor or induced by fast neutrons in the structural elements of the machine, constitutes the main radiological hazard. A leak of tritiated cooling water would be most damaging to the environment. Waste mainly concerns the structural materials of the reactor activated by energetic neutrons produced by the D-T fusion reaction and can be mitigated by judicious choice of material. Deuterium fuel is abundantly available; a lithium blanket breeds the tritium with sufficient abundance for the coming centuries. Proliferation does not seem to be an issue.

Fusion, if successfully demonstrated in the first part of this century will have a significant impact on the energy production not until the end of this century, as simple arithmetic on the timescales involved to build a thermo-nuclear reactor will show. Similarly, building up capacity in nuclear fission reactors, notably the 4th generation reactors that address present shortcomings, will take many decades. Be it as it may, nuclear fission is most likely to serve a transitional period where issues of safety, waste and



▲ FIG. 8: Evolution of the Antarctic ozone hole over the past 14 years, observed by the European GOME and SCIAMACHY satellite instruments. Source: M Weber, IUP Uni-Bremen, Germany.

- proliferation are not likely to deviate substantially from present conditions. It is not a perfect answer, but when it comes to the oxymoron energy and environment there are no perfect answers.

RENEWABLE ENERGY

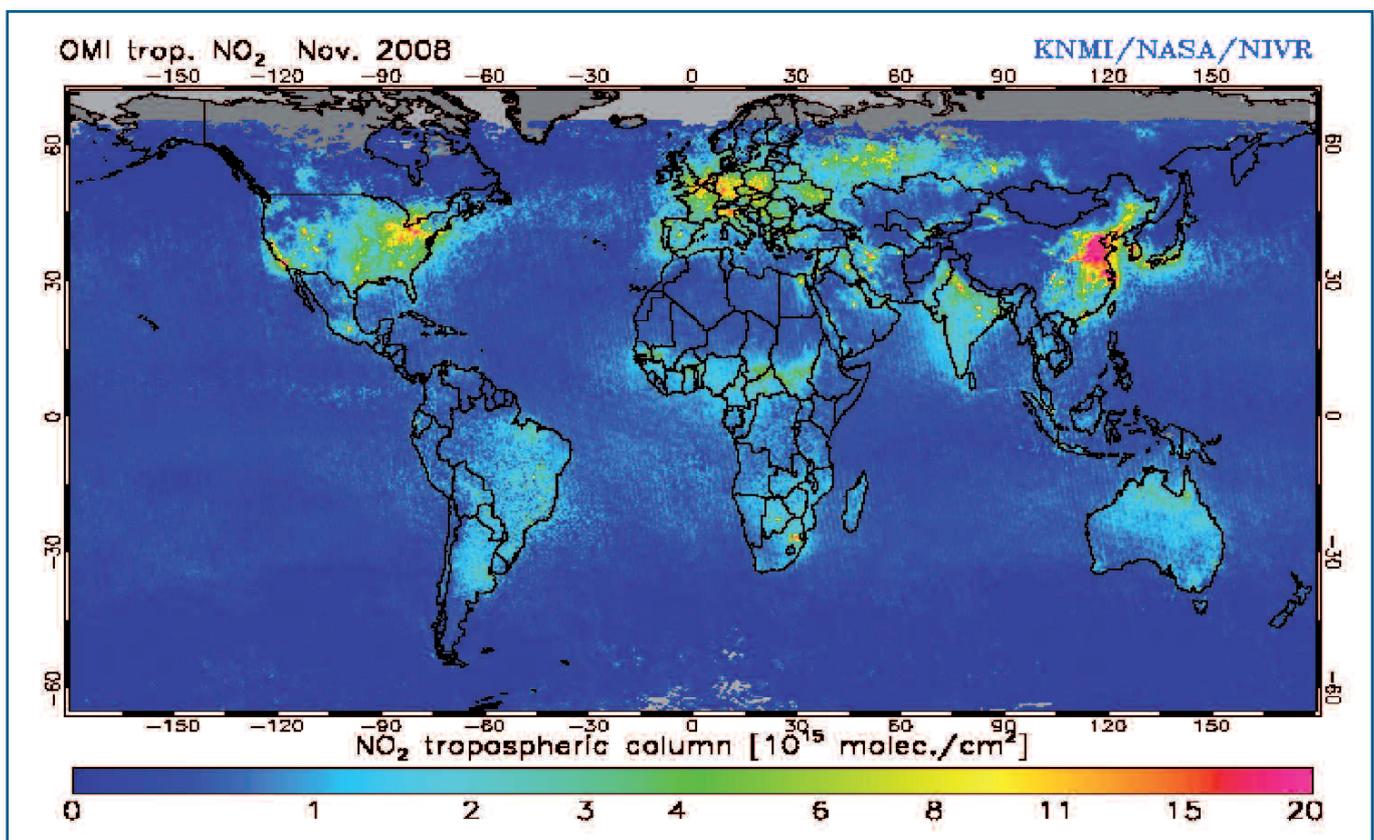
Renewable energy derives from the sun in the form of direct solar, wind, biomass and hydropower. Environmental impact arises from the diluted and intermittent nature of these energy sources requiring vast surface area, storage and transport to urban centers. Thus, the environmental impact can only be assessed by a full system analysis. For example, the carbon footprint of an electrical battery is rather large. Material sustainability is another aspect to consider in photo-electric generation, battery storage and superconductive transport.

Bio-fuels can be greenhouse gas neutral at best, releasing as much CO₂ by burning as taking up during growth. However, the use of nitrogen based

fertilizer needed to grow the bio-fuels at reasonable efficiency yields it a net greenhouse gas emitter [23]. Depending on the crop, nitrous oxide (N₂O) is released as a known and strong long-lived (110 yr) greenhouse gas with global warming potential (GWP) of 296 averaged over 100 years, *i.e.* causing a global warming contribution of 296 times an equal mass of CO₂. In terms of GWP, the production of bio-fuels such as biodiesel from rapeseed or bio-ethanol from corn (maize), offsets or even exceeds the savings derived from avoided fossil fuel CO₂ emissions.

CLIMATE ENGINEERING

Popular in current debate is the concept of climate engineering, the deliberate modification of the earth climate to suit human needs. Examples are mirrors in space or injecting sulphate particles in the stratosphere to reflect incoming sun light, cloud seeding to increase the earth albedo or feeding the ocean with iron to increase algae growth



▲ FIG. 9: Tropospheric NO₂ columns averaged over November 2008 showing the global hot spots of air pollution as measured by the Dutch-Finnish satellite instrument OMI. Source: KNMI-TEMIS, the Netherlands.

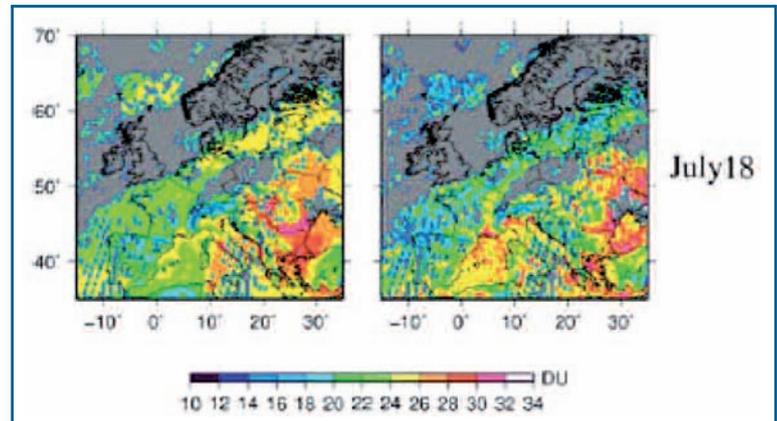
absorbing CO₂. The atmospheric science community has reacted aloof, exceedingly weary of disastrous tampering with nature by humankind. However, in a few decades from now when climate change strikes in anger, public pressure for counter measures will mount and generate the necessary financial incentive for entrepreneurs to venture into climate engineering. Better, therefore, to be prepared by carrying out interdisciplinary research and assess the effectiveness, side effects and risks involved in climate engineering.

Amidst the wreckage of industrial revolution a decidedly non-Malthusian future may unfold. Electric cars humming from A to B remotely controlled by GPS, their batteries charged at night by electricity generated by wind and nuclear power. High voltage superconducting DC cables, connecting an off-shore belt of wind turbines stretching from Hammerfest to Cadiz, supplying electricity to the grid immune to the vagaries of wind. Large band gap metal-oxides nano-layered with photo-active molecules, nano-engineered battery electrodes and a new class of high temperature iron based superconductors, improving the generation, storage and transport of electricity. Well insulated homes heated by solar thermal converters and cooled by underground heat sinks. Harnessing power from nuclear fusion remains the challenge of the century. In the mean time, energy from the natural fusion reactor in the sky will be collected by mirrors in geostationary orbit, not hindered by diurnal variation, high latitude or clouds, beamed to earth by microwaves at pin point accuracy.

BACK TO THE FUTURE

A sustained measurement series of key climate variables covering many decades with reliable and accurate data is the prime requirement. Long term monitoring going hand in hand with model development is one of the most effective ways to understand the Earth climate. Without the long term stratospheric ozone record dating back to 1924 and the Keeling CO₂ curve, the current climate debate would be at a loss. The problem here is that long-term monitoring is often regarded as

▼ FIG. 10: (left) Lower tropospheric O₃ columns over Europe predicted by the model CHIMERE (0–6 km), compared with (right) lower tropospheric O₃ columns (0–6 km) measured by the IASI satellite instrument during the morning overpass on 18 July 2007. The observations have been interpolated on the 0.5° x 0.5° model grid. Cloudy pixels are shown in grey. Source LISA-CNRS, France



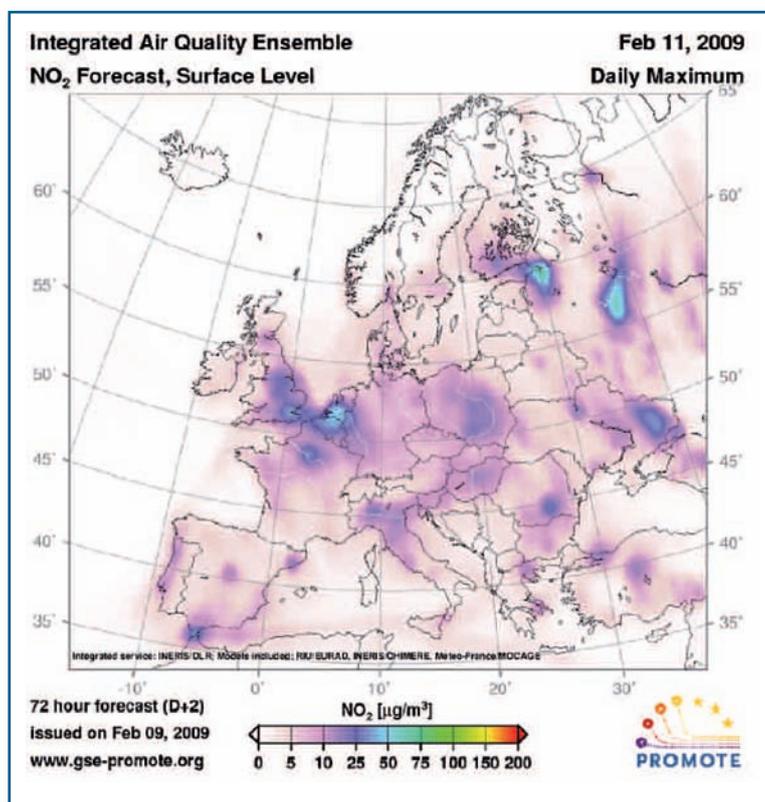
a menial task, not scoring high on the citation index and less appealing to funding agencies.

Increased demand on accuracy, spatial and temporal resolution of greenhouse gases and air pollutants and stratospheric ozone needs to be accommodated by advanced observational techniques. For example, diurnal resolution of global air quality data can be achieved by spectrally resolved observations from geostationary orbit. New approaches in climate modelling need to be explored built up from the molecular scale. Air quality modelling and observation require a system that connects the local to the global scale. These efforts need to be supported by underlying research, including improvement of the spectroscopic molecular database, the physical and chemical characteristics of aerosol, and calibration, validation and algorithm development for data retrieval.

This science is of fundamental importance for understanding global climate change. System earth is complex and in the past has changed in unforeseen and dramatic ways in response to anthropogenic activity. It has to be recalled that no model predicted the ozone hole or the speed with which it developed as a consequence of the release of chlorofluorocarbons. Sustained monitoring is needed to understand changing climate parameters and to verify and validate climate models.

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▲ FIG. 11: Daily air quality forecast by the European GMES atmosphere service element PROMOTE. Source: www.gse-promote.org.



European Physical Society

6, rue des Frères Lumière • 68200 Mulhouse • France

tel: +33 389 32 94 42 • fax: +33 389 32 94 49

website: www.eps.org
