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Monitoring the Climate system from space: progress, pitfalls and possibilities

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Executive summary

PASSIVE SATELLITE SENSORS HAVE PROVIDED UNIQUE OBSERVATIONS OF THE Earth's climate system since the dawn of space-based weather observations in 1960. In the following years, such measurements have become ever more numerous, the instrumentation more complex and our use of the data more sophisticated. From combinations of different satellite measurements observing the Earth we can retrieve information about the Earth's surface, atmosphere and energy budget. In this way satellites can provide us with a global picture of the Earth that cannot be obtained by other means and their measurements can be used to provide detailed maps of, for example, surface and atmospheric temperature, humidity, greenhouse gas concentrations, circulation patterns, cloud amount and properties.

Satellite measurements have provided direct observational evidence that recent increases in greenhouse gas concentrations have produced the expected changes to the outgoing energy emitted by the Earth. They have also been key in confirming some aspects of the climate response to change, including the operation of a positive water vapour feedback acting on global temperatures. However, while they play a critical role in evaluating and improving the models used to make future climate projections required by policymakers they are not yet of sufficient accuracy to definitively establish the pace and scale of the climate response to changes caused by human activity.

Historically most satellite observations have been tailored to the needs of weather forecasting which demands highly detailed information on short timescales but places less stringent requirements on absolute accuracy, long term stability and comprehensive sampling. Climate monitoring is by contrast generally concerned with widespread but relatively small changes in statistical properties of fields which may occur over relatively long periods of time. This places somewhat different demands on the observations required. However, existing data has the advantage of spanning many years and because of its continuity, there is the possibility of overcoming some of the limitations of the measurement accuracy through the inter-comparison of different sensors.

Contents

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The process is not always straightforward, and artefacts in the measurements if not properly treated can compromise their use for the study of climate. It is also a high risk strategy from the point of view of climate monitoring, as any gaps in the record in the future, caused for example by the delay in the launch of a new sensor or the early failure of an existing one, destroy our ability to link the records from different sensors and thus effectively end the record. Hence, while existing observations have provided us with many insights into the state and the evolution of our climate, their limitations, coupled with the desire for rapid, 'policy relevant' results have also sometimes resulted in imperfect interpretation and flawed conclusions. This highlights the need both for better quality climate focused observations and careful, judicious exploitation.

However, the situation is changing. Innovative techniques are being employed to maximise the usefulness of existing observations for climate monitoring, and an increasing number of specifically climate focused satellite observations promise new advances. For the existing measurements, routine inter-calibration of instruments and tracking of their calibration stability over their operational lifetime is now performed. This tracking uses the results of dedicated programmes which have characterised both stable Earth sites and targets such as the Moon so that they can be used to provide known comparison points. In the near future planned missions will open up further possibilities such as directly monitoring CO_2 emissions from space. And, while there is a concern that even with these efforts the current observations are not sufficient for us to detect potentially important changes to our climate in time to mitigate their effects, or that we have sufficient information to test and improve our understanding of how the climate will change, sensors with the ability to do this are now possible.

Groups in the UK, led by the National Physical Laboratory, and in the US led by NASA have designed climate focused missions with high absolute accuracy and stability as cornerstones. Crucially the missions are optimised to distinguish small signals of climate change from natural variability and hence provide the information required to detect and attribute these signals to the correct underlying cause. If these missions can be brought to fruition they should offer a new perspective on the problem of observing climate from space, overcoming many of the current limitations and providing a robust monitoring system into the future. That such missions are now possibilities is a testament both to technological advances and to our improved understanding of the climate system, gained in no small measure from previous and current missions. Despite scientific approval of these plans, successful design phases of the projects and the magnitude of the risks associated with climate change, funding pressures on both sides of the Atlantic make the future of these ventures uncertain.

Introduction

The aim of this briefing paper is to provide an overview of the way measurements from space can provide a basis for the understanding and analysis of climate change, highlighting some of the insights that they have provided but also describing the difficulties that are inherent in constructing climate quality space-based records. We also introduce several proposed initiatives that may help to resolve some of these difficulties in the future and provide an indication of how these data may be used to address several important scientific and policy areas.

Since the launch of the first successful weather satellite, Television InfraRed Observation Satellite (TIROS-1) in 1960, space-based instrumentation has played an increasingly important role in monitoring our climate system. The state-of-the-art in space-based Earth Observation (EO) has evolved from what now appear relatively humble beginnings using simple cameras taking videos or photographs of the Earth and its atmosphere[1], to a billion-dollar industry[2,3] exploiting and developing a wide variety of instrumental techniques designed to target specific environmental variables.

The sheer breadth of the EO data currently collected makes it impossible to cover every use to which they could be put in this relatively short note. Given the focus on climate relevant time-scales, the scope of the paper is limited to discuss records derived from passive satellite sensors since these span the longest time period, being available on an operational basis from the late 1970s onward. Passive sensors collect radiation that emanates from the climate system, as compared with active systems, that send out a pulse and collect the reflected signal, and require significantly more power to operate. We look specifically at how such observations either have or could provide information about a number of key climate 'forcings' and 'feedbacks'.

For the purposes of this note we define a 'forcing' mechanism as a change applied externally to the climate system—an increase in atmospheric carbon dioxide concentrations as a result of human activities for example—to which the climate system must respond. A 'feedback' can then occur because of the response of the climate system itself to that forcing. For example, a reduction in the extent of the polar ice caps in response to surface warming caused by an increase in atmospheric carbon dioxide would reduce the reflectivity of these regions. This constitutes a positive feedback as it allows a larger fraction of incident solar radiation to be absorbed, resulting in additional warming. We frame the discussion in terms of measurements that can provide insight into the overall energy balance of the planet, and those which can identify and quantify specific quantities of direct interest to policymakers and the general public such as temperature and humidity.

Understanding the satellite measurements used to study climate change

Passive sensors and their applications

Passive satellite sensors measure the natural radiation (or energy) that is reflected or emitted by objects. Looking at the Earth from space there are two primary sources of energy that may be measured by such instruments: energy from the sun which has been reflected by the Earth (which may be referred to as solar, or shortwave radiation (i.e. light)), and the thermal emission from the Earth itself (the Outgoing Longwave Radiation or OLR) (Figure 1).

Looking at Figure 1, arguably the most fundamental climate variable that can be measured from space is the Earth's Radiation Budget (ERB), comprising the total incoming energy from the Sun, and the total outgoing energy, a combination of the reflected solar energy and the OLR. Why is the ERB so important? The incoming, shortwave energy from the Sun to the Earth is the basic power source driving our climate[5]. Solar energy absorbed by the Earth-atmosphere system is eventually re-emitted as thermal radiation, some of which escapes to space. The amount of thermal energy which escapes depends on the temperature and composition of the Earth-atmosphere system. To maintain a steady-state, i.e. to avoid warming or cooling, the amount of solar energy entering the Earth-atmosphere system must be balanced by the OLR leaving. Hence, if a change results in more energy leaving the system than is absorbed from the Sun, the net loss of energy will cause the average temperature to fall decreasing the outgoing energy until it balances the absorbed energy again[6]. Similarly, if a change causes less energy to escape than enter, the excess energy will cause heating and the average temperature will rise increasing the outgoing energy until balance is obtained. It is this basic principle that lies behind the theory that human-induced increases in greenhouse gases such as carbon dioxide, the associated increased absorption of thermal energy and hence the reduction in the amount of thermal energy which escapes to space—the anthropogenic greenhouse effect—will lead to increased surface temperatures and 'global warming'[7,8].

Satellite sensors designed to observe the ERB measure the total reflected shortwave and emitted longwave energy. However, this energy from the Sun and Earth is distributed over a range of wavelengths; in the shortwave these range from the ultraviolet (UV) through the visible spectrum to the near-infrared (IR) and a little beyond; in the longwave the majority of the energy is emitted at thermal and far infrared wavelengths but there is also a measurable amount at longer microwave wavelengths (Figure 2). Some sensors are designed to make measurements across specific wavelength intervals. As the properties of the Earth's surface and atmosphere vary with wavelength,

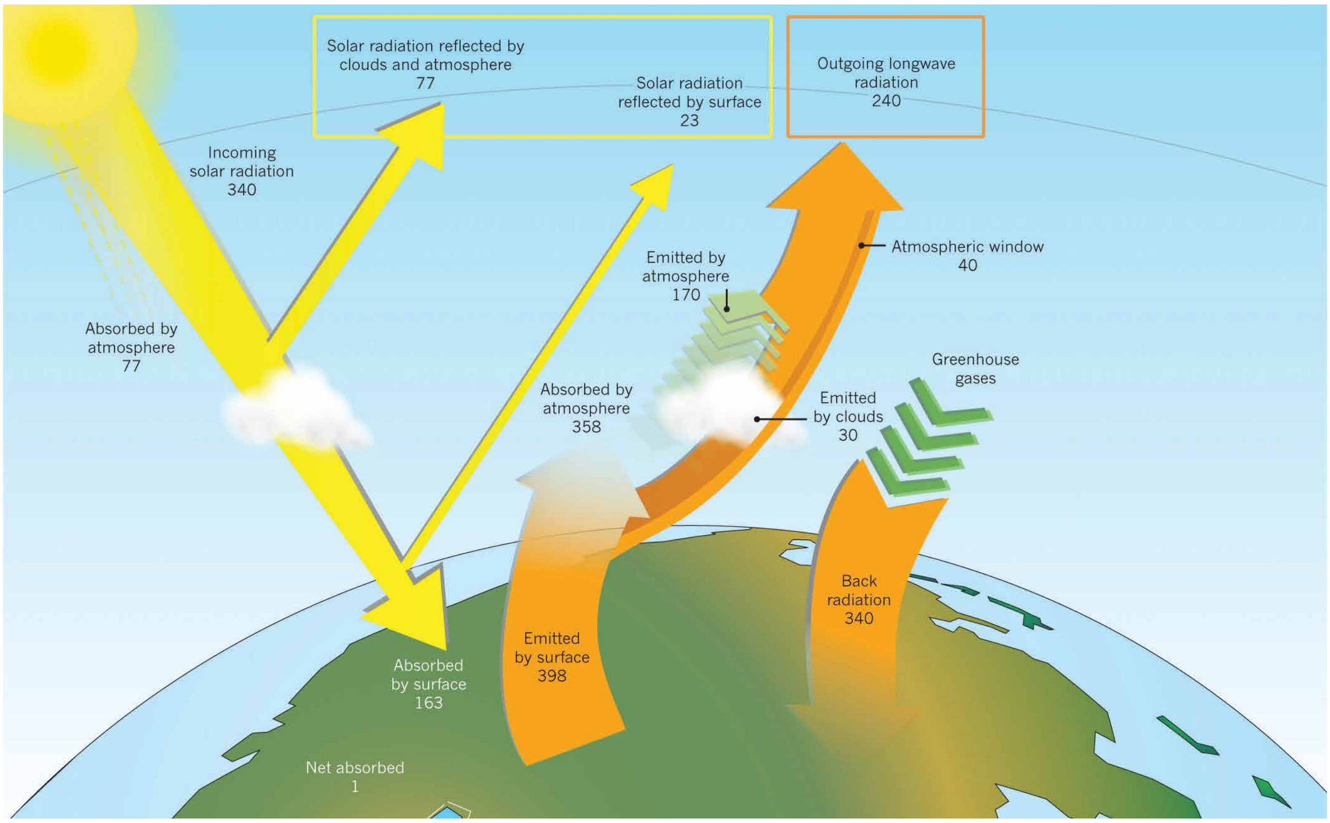

Figure 1: Components of the Earth's annual global mean energy budget (after Loeb et al., 2009)[4]. Each component is expressed as a flux of energy in $W\,m^{-2}$. Satellite based passive instruments viewing the Earth can measure the reflected solar radiation (yellow box) and the outgoing longwave radiation (orange box). Over the time and space scales considered here these outgoing fluxes approximately balance the incoming solar radiation.

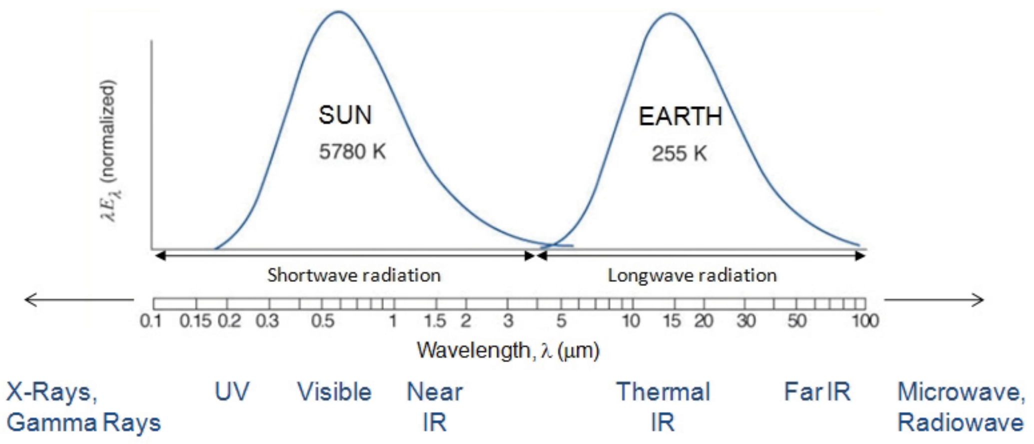

Figure 2: The distribution of energy across wavelength for perfect 'blackbody' emitters at temperatures typical of the emission from the Sun and Earth. Because the Sun is so much hotter than the Earth, incident and reflected solar energy at the top of the Earth's atmosphere is mainly confined to 'short' wavelengths whereas outgoing energy emitted by the Earth mainly falls within the 'long' wavelength regime. In reality the energy spectra from the Sun and Earth is more complicated due to variations in emission properties with wavelength (see Figure B1, Box 1), however the energy still falls within the envelopes of these basic blackbody curves (adapted from Goody and Yung[9]).

appropriate measurements at different wavelengths can provide a lot of information about the atmospheric or surface state. Combining observations from instruments measuring across the shortwave and longwave wavelength regimes is particularly beneficial, allowing us to exploit the sensitivities of each regime to investigate specific climate variables.

As an example, consider attempts to map sea ice extent, a climate variable believed to be highly sensitive to human-induced climate change[10]. Since sea-ice is much more reflective than the ocean at visible wavelengths, observations of reflected solar radiation in the visible can be used to monitor changes in its extent, usually at relatively high spatial resolution (~100m). However, such measurements can only provide such information during sunlit hours and when clouds do not obscure the surface. Fortunately, ocean and sea-ice also appear markedly different when viewed at microwave wavelengths because of differences in their emission at these wavelengths: a patch of sea-ice will emit more microwave radiation than a patch of ocean at the same temperature. Although microwave observations generally have a poorer spatial resolution (~ 10km) than those made at visible wavelengths, they have the advantage of being able to provide measurements at all times of day and microwave radiation can also penetrate through cloud.

Similar approaches, using carefully selected wavelength combinations, have been used to generate long-term records of many so-called 'Essential Climate Variables' from passive space-based sensors (Figure 3). For the Earth's surface these include: land and sea-surface temperatures; land use, with particular focus on vegetation mapping and productivity; ocean colour, a measure primarily of the chlorophyll and dissolved carbon content or the biological activity of the upper ocean; ocean currents; snow cover and surface albedo. This last quantity is the fraction of incident solar radiation that is reflected by the Earth's surface. It is dependent on the surface type—as we noted above, ice reflects a lot of solar radiation—and plays an important role in modulating the surface energy budget. Changing land use, for example, can alter the surface albedo, perturbing the surface energy budget and potentially further modifying surface conditions, thus acting as a climate feedback. Clearly then, many of the individual variables have complex inter-dependencies within the climate system.

What about the state of the atmosphere itself? Here again passive sensors can be used to obtain information concerning critical climate variables such as temperature, water vapour, carbon dioxide, cloud, atmospheric winds and aerosols. Box 1 shows how clear-sky infrared and microwave observations from operational satellite instruments are sensitive to different heights within the atmosphere, making it possible in theory to infer or 'retrieve' temperature and gas vertical profiles. Shortwave and longwave measurements can also be used either independently or together to first detect cloud and then build up a detailed picture of its properties. A similar approach can be employed to quantify and characterise aerosols within the atmosphere. These tiny solid particles or liquid droplets held in suspension in the air play a crucial role in modifying the energy budget of the Earth both directly, by reflecting and absorbing energy, and indirectly by modifying cloud properties and lifetimes[12].

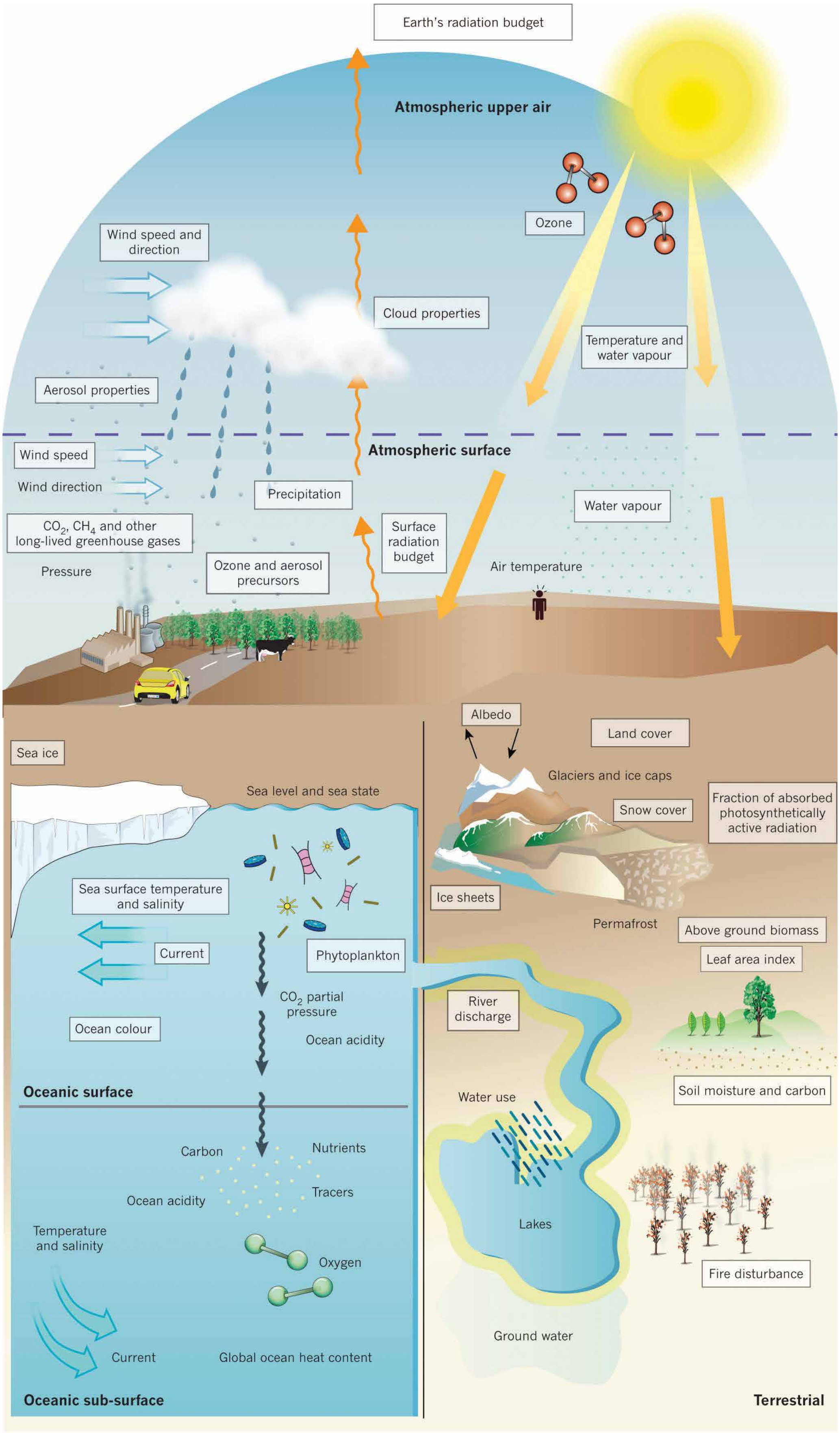

Figure 3: Essential Climate Variables (ECVs) as defined by the Global Climate Observing System (GCOS)[11]. Variables are defined as belonging to five general categories: terrestrial, oceanic surface and sub-surface, atmospheric surface or atmospheric upper air. Space-based passive EO sensors are currently used to infer those variables which are boxed.

Types of satellite orbit

For space-based Earth Observation there are two main categories of satellite orbit, 'low earth' and 'geostationary'. Satellites placed in low earth orbit generally fly at altitudes between 600–2,000 km above the Earth's surface. The weather satellites from which we have our longest global records are typically placed in special orbits—sun-synchronous near polar orbits—which pass above or nearly above both poles of the Earth. This allows them to gradually build up a picture of the whole globe as the Earth rotates beneath them. The sun-synchronous aspect means that the instruments on board the satellite will always observe a given location at the same local time or times (Figure 4). This may be useful if one does not wish the observations to be affected by, for example, the daily cycle in surface temperature.

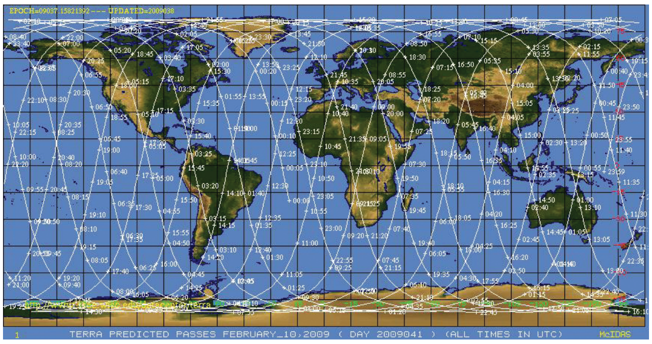

Figure 4: Orbital tracks and time of observation (in white) of the sun-synchronous Terra satellite for February 10th 2009. Over the course of a day the satellite samples a given location twice (Extracted from [13]).

Satellites in geostationary orbit on the other hand, are located some 36,000 km above the equator and orbit at the same speed as the Earth rotates and thus stay over the same point on the Earth throughout the day. As a result, they are limited in the area they can view but can monitor the behaviour of this area continuously in time. Hence measurements from instruments flying on these satellites are often exploited to track rapidly developing phenomena like hurricanes, wildfires, volcanic ash clouds and tropical storms (Figure 5). More generally, since the height of specific features (such as those due to cloud or water vapour) can be inferred, it is possible to use sequential imagery from these sensors to derive three dimensional atmospheric circulation patterns.

In essence then, polar-orbiting satellites can provide global coverage, with a repeat time (the time it takes to return to the original orbital track) of the order a few days to a month, while geostationary satellites provide high resolution temporal coverage for the part of the globe they can observe from their fixed location. In both cases, instruments on the satellites typically make observations continuously in time, generating a huge volume of data that needs to be transmitted back to Earth and subsequently exploited. For example, the Space and Atmospheric Physics Group at Imperial routinely receives and archives observations from the Spinning Enhanced Visible and Infrared Imager (SEVIRI), a passive narrowband imager in geostationary orbit. A day's worth of data from just this one instrument comprises of the order 40 gigabytes. Instrumentation planned for the next generation of geostationary satellites will have higher spatial, temporal and spectral resolution, substantially increasing the demand on data-reception and storage facilities.

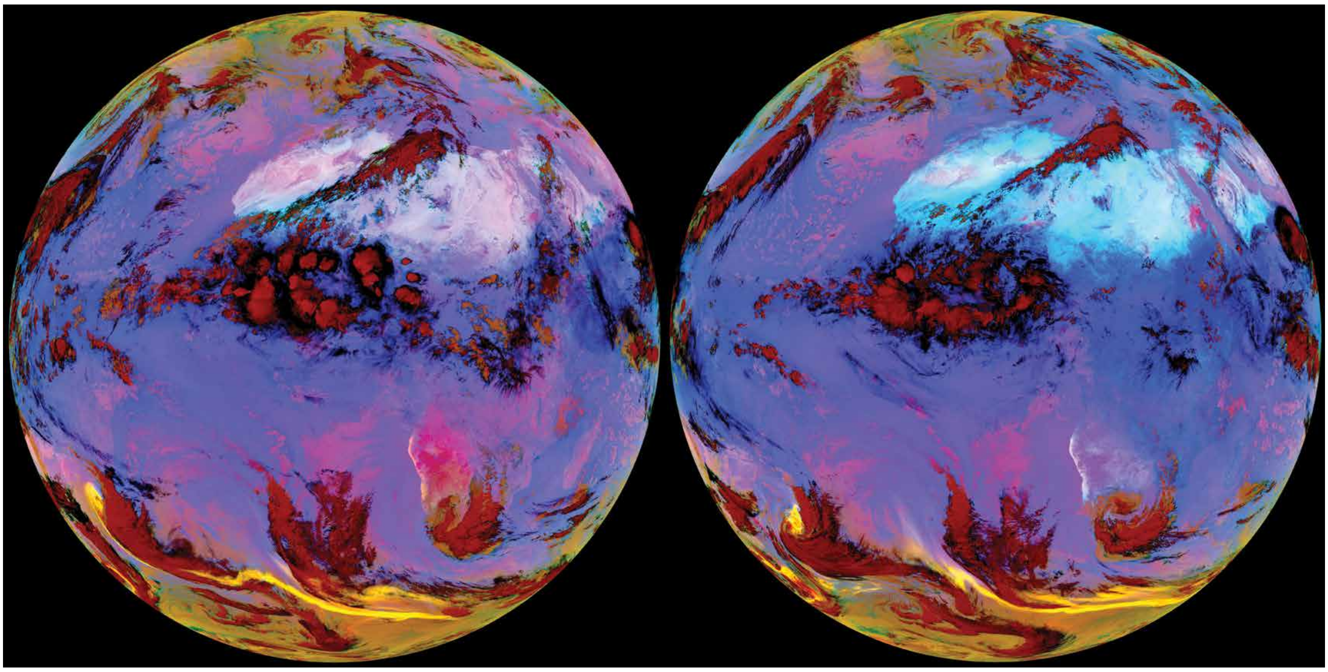

Figure 5: Imagery from SEVIRI on Meteosat-8 at midnight (left) and 12 pm (right) on 8th June 2011 viewing Europe, Africa, Arabia and the Atlantic. Deep red colours indicate cloud systems, the area of deep magenta over Sudan is a developing Saharan dust storm, while the yellow streaks are volcanic ash transported over the South Atlantic from the eruption of the Puyehue volcano in Chile (Source: Raw data from EUMETSAT, authors own imagery).

Instrument viewing geometry

Dependent on the particular application for which a passive instrument is intended it may be designed to look downwards through the Earth's atmosphere towards the surface, (a so-called 'nadir' view), or horizontally through the atmosphere without intersecting the Earth's surface (a 'limb' view). An individual instrument can be designed to operate in both modes but not simultaneously (Figure 6). Each observation from a limb viewing instrument is restricted to a limited altitude range in the atmosphere, but relates to a large geographical region. These instruments can step though the atmosphere in height, building up a highly detailed picture of the vertical distribution of a particular variable, but in general the observations suffer from poor horizontal spatial resolution because of the integrated nature of the signal they receive from along the long limb path. By contrast a nadir observation relates to a specific geographic location, but the effect of the surface and different levels in the atmosphere are combined in the measurement. However because the properties of the various components of the atmosphere vary with wavelength in a defined way, by combining nadir observations at many different wavelengths it is in principle possible to obtain a vertical profile (or 'sounding') of temperature or gas concentrations throughout the atmosphere. One can also infer the total amount of cloud or aerosol within the vertical column of atmosphere seen by the sensor. While it is a challenge for nadir viewing instruments to produce a large amount of vertical structure information for reasons we shall discuss below, when it is possible they can provide relatively detailed geographical maps of the variable of interest.

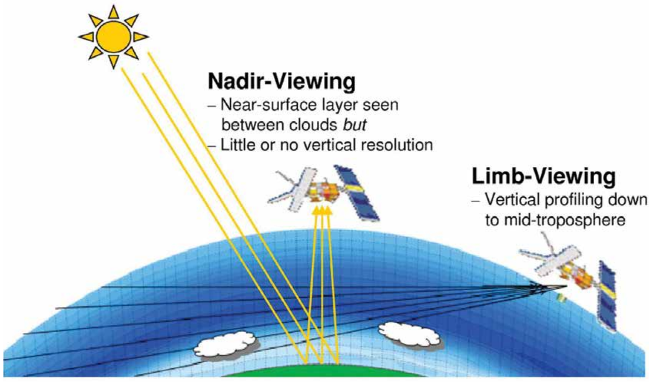

Figure 6: Schematic of a nadir and limb view through the Earth's atmosphere. In this case the instrument is measuring reflected solar radiation. Taken from [14].

Box 1: How do passive satellite sensors provide information about our atmosphere?

Consider a downward looking (nadir viewing) instrument measuring the outgoing energy from the earth at infrared wavelengths. The energy received by the sensor will comprise a component which has originated from the Earth's surface and is transmitted through the atmosphere, and a component which is emitted by the atmosphere itself. The balance between how much energy comes from the surface and how much comes from each height within the atmosphere varies with wavelength, and is a result of the surface properties and the temperature structure and composition of our atmosphere, since each gas has different characteristic wavelength bands over which it can absorb and emit energy. Clouds and some types of aerosol also affect the amount of energy received by the sensor in a way which varies with wavelength dependent on their properties, making it possible in theory to obtain information about them such as their height and amount.

Some of the key atmospheric gases that absorb at infrared wavelengths are shown in the left-hand panel of Figure B1. The panel shows an example of the effect these absorbers have on the clear-sky OLR wavelength spectrum of energy (in black). The dashed red lines show the amount of energy emitted at each wavelength by a blackbody' emitter at the temperatures (in Kelvin: Degrees Celsius are equal to Kelvin minus 273.15) marked on the curves (c.f. Figure 2). Where the black line is close to the top dashed curve (for example between 10-12.5 µm) there is relatively little absorption of energy by the gases in the atmosphere and most of the OLR lost to space at these wavelengths originates from or near to the surface (which has a temperature of 300 K). Marked differences between the black curve and the red 300 K line occur at wavelengths where there is significant atmospheric absorption (for example due to CO_2 between ~14-17 µm). As we move from a non-absorbing (12.5 µm) to more absorbing region (14.5 µm) the atmosphere is becoming more opaque and from space we are effectively seeing energy which has originated from higher in the atmosphere where it is colder (right-hand panel of B1). Hence, if we know how much of the absorbing gas is present and how its absorption changes with wavelength we can use measurements at different wavelengths to determine the temperature at different heights within the atmosphere[15] (usually referred to as the 'vertical temperature profile'). Since the concentration of CO_2 does not vary substantially with height within the lower atmosphere—the troposphere and stratosphere, passive measurements of OLR at wavelengths where CO_2 absorbs energy can be used to obtain the temperature profile of the lower atmosphere. Conversely, if we want to know how the concentration of a gas varies with height and location (for example water vapour), once the temperature profile is known, observations of OLR at wavelengths where this gas absorbs significant amounts of energy can be used to obtain a vertical profile of the gas amount[16].

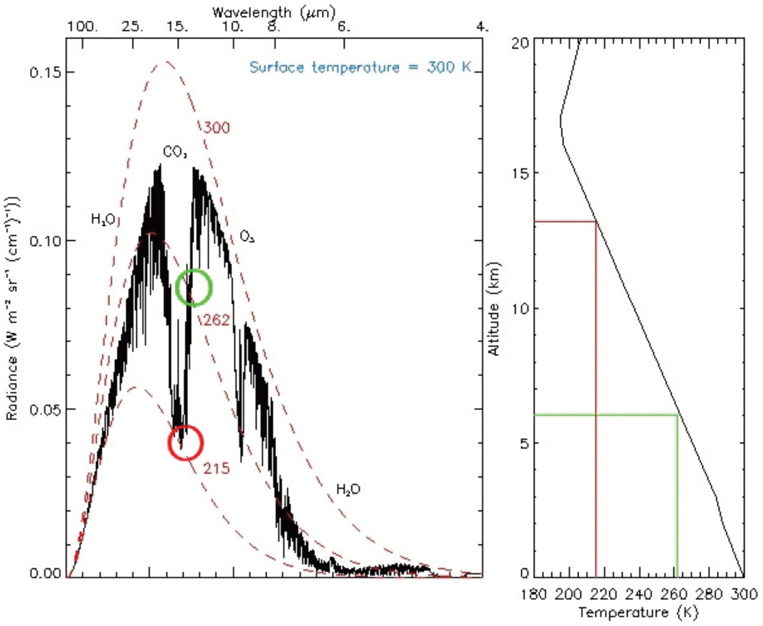

Figure B1: Left: Calculated clear-sky energy spectrum of OLR for a tropical atmosphere (black line). Red dashed lines show the energy that would be obtained from blackbody emitters at the temperatures marked on the curves. Right: The associated temperature profile. The point at which the blackbody temperature equals the actual environmental temperature provides an indication of where in the atmosphere the energy is originating from. Hence the red horizontal line shows approximately where the OLR circled in red on the left-hand side panel is originating from while the green horizontal line shows the same information for OLR within the green circle (Source: authors own calculations using GENLN2[17]).

In both cases, and apparent from Figure B1, for measurements over a certain wavelength range, increasing the wavelength resolution over this range or the number of individual absorption features that can be resolved, generally increases the amount of information about the vertical structure that can be obtained. Essentially, averaging over many adjacent wavelengths, as is generally done by so-called 'narrow band' instruments, smears out vertical information.

In practice, satellite sensors will always have a finite wavelength or 'spectral' resolution. The newest atmospheric sounders, designed specifically to improve our weather forecasting abilities, have very high spectral resolution (1000s of individual 'channels' at different wavelengths across the OLR spectrum) and are classed as 'hyper-spectral'. However, the instruments from the past which are typically used to create multi-decadal climate records are of the narrow-band type. As we have seen, this means that the energy measured within each channel is the sum of the energy from a much wider vertical layer of the atmosphere. Or more technically, the 'weighting functions' for each channel, which describe how much each level in the atmosphere contributes to the total signal, are much broader.

Issues in creating long-term space-based EO records

The launch of TIROS-N in 1978 can really be considered to be the beginning of the global operational EO satellite era because of the way in which the observations were freely disseminated and could hence be routinely exploited for worldwide weather forecasting purposes. The TIROS programme essentially continues up until the present day, albeit with various name changes reflecting advances in the instrumentation carried by individual satellites and in the overall organisational structure of the programme. Space-based observations of the Earth from passive sensors are thus, in principle, available over several decades. While this is certainly not long in the context of the history of our climate as a whole, the observations can and have been exploited to provide multi-decadal information on a wide variety of topics including, but by no means limited to: trends in temperature, water vapour (or humidity) and cloud[18,19,20]; the impact of natural phenomena on atmospheric temperatures and the response of the climate system[21]; the variability of the ERB on decadal time-scales, and our ability to model and understand this variability[22]; the concept of 'missing energy' within the climate system and how this may relate to a recent slow-down in global mean surface temperature increases[23,24].

However, to reliably use satellite observations to make inferences about changes to our climate one must first be aware that most of the measurements, and in particular the programmes from which we have the longest records, were not designed for climate monitoring, but rather to improve our weather forecasting ability. There are subtle, yet important differences in the requirements for each purpose. In conventional weather forecasting the aim is to capture in as much detail as possible the behaviour of the

Earth-atmosphere system at the current time. Hence there is a need to reliably compare one measurement to the next over short time periods over the area of interest. This requires that errors in the measurement should not vary very much on these scales: that is, they need to have high 'precision' (Figure 7). However, large scale or long term fixed errors in the observations, known as systematic biases, can be corrected for, thus in general, weather forecasting does not demand, or at least prioritise, what is termed high absolute accuracy. Similarly, even changes to systematic biases over time, as long as they are slow, or occur suddenly at a known point such as due to a change in instrument, are not a huge concern. Thus for many weather forecasting applications there is no strong demand for high long term stability in the measurements.

In contrast, climate studies are often trying to do two different things. Firstly they want to test that we understand and can truthfully represent the climate system and the way it behaves. For example, do climate models faithfully represent the amount of energy absorbed by the atmosphere or reflected by clouds right? This requires measurements with high absolute accuracy, so we can have confidence in what we are measuring, and relatively high precision, so we can make repeatable measurements and achieve a detailed understanding. Secondly they are looking for relatively small but real changes to the climate which may be occurring gradually over relatively long periods of time, for example a change in global mean sea-surface temperature of 0.1 K per decade. The sooner we can confidently detect these small changes, the more warning we will have of what our future climate may hold. Hence it is crucial that we are as certain as possible that the change seen is a true change to the climate and not a result of errors in the observations or natural climatic variability. This requires comprehensive sampling (all parts of the globe at different times of day for example) spanning many years or decades; aspects almost totally unconsidered in the requirements for weather forecasting. Note that observations with high absolute accuracy and precision will implicitly have high stability.

The extent of the problem is greatest where the signals of change are small in comparison with natural variability and uncertainties in the stability or sampling of the measurements. Such behaviour is commonly seen in key climate variables, for example Figure 8 shows a number of records of global mean tropospheric temperature derived from in-situ observations and from a satellite instrument which is sensitive to the same vertical region. Over the period of the satellite observations there is, in general, a small positive trend, but the year to year variation is much greater. There are differences between all the records, even those derived from the same raw measurements, so for the period since 1980 the long-term temperature trend implied by each would vary slightly.

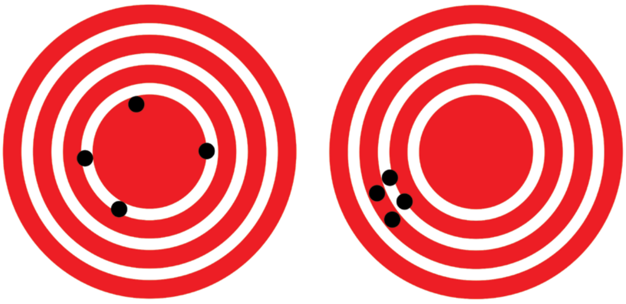

Figure 7: Concepts of precision and accuracy. Left: The observations have high accuracy (dots close to the bullseye) but are scattered with low precision. Right: The observations have high precision (clustered) but a systematic bias from the 'truth'[25].

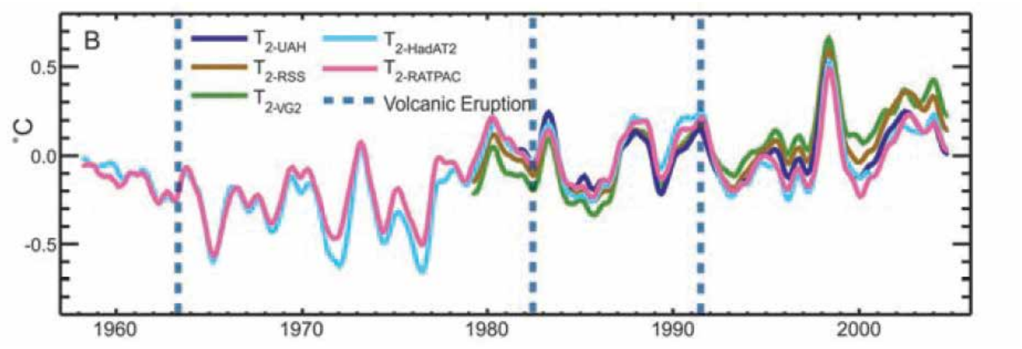

Figure 8: Global mean tropospheric temperature derived from in-situ radiosonde (T2-HadAT2, T2-RATPAC) and microwave satellite (Microwave Sounding Unit, MSU) observations (T2-UAH, T2-RSS, T2-VG2). Note that subtly different records can be derived from the same raw satellite observations because of differences in the approaches employed. This is due to factors explained below (adapted from Solomon et al[26]).

Although the situation is improving, our satellite observing system is far from optimised to the needs of climate monitoring. This does not invalidate the substantial efforts that have been made to exploit satellite observations for the purposes of long-term change detection, but it does mean that one must have a thorough understanding of the various factors that can influence the particular record being exploited. The first step in creating any reliable instrumental record involves relating the measurements a particular instrument makes to known, internationally recognised standards. In other words we need to 'calibrate' the instrument. Ideally, for satellite instrumentation, this should be done over the full range of conditions likely to be encountered in space. The harsh space environment also means that the lifetime of an individual instrument may be only around 3 to 5 years. Even if follow-on instrumentation is intended to be of an identical design, in practice there will always be small differences that one must be able to account for in order to create a consistent record. More often, over time there are less than subtle differences between instruments as technology improves and greater complexity is possible. Whilst these advances often allow a more detailed picture of the climatic state to be obtained, they do not necessarily help long term monitoring which is often better served by long consistent records. Accounting for any spurious differences that are introduced is generally achieved via a combination of theoretical modelling, assessing the expected impact of known changes to the instrument characteristics, and by ensuring that there is sufficient overlap between successive instruments to enable the instrument induced differences in the measurements to be observed over a range of conditions. The two sets of measurements can then be adjusted to a common scale, or 'inter-calibrated' using coincident observations. However, this approach does leave a record highly vulnerable to data gaps, a result perhaps of an instrument or launch failure, or simply budget constraints leading to the delay or cancellation of an ongoing program. In addition, while rising concern about the state of our climate has led to a number of national and international efforts to derive reliable, long-term satellite records[27,28], as we have noted, the original purpose of space-based EO predates this and was focused on improving short-term weather forecasts. Hence the necessary information concerning the calibration and design of, in particular, the earliest instrumentation may not be as detailed as required, or may even have been lost.

A further complication that must be addressed is the fact that satellite orbits tend to drift in time and altitude: the satellite does not retain the same sampling characteristics that it had at launch. This can introduce spurious changes to the records derived from space-based instruments[29]. The degree to which a record may be affected can depend on a number of factors such as the amount of drift, the particular wavelengths that the instrument is measuring, the scene type (land, ocean, clear or cloudy conditions) and the solar illumination[30]. For example, because of the large daily cycle in land surface temperature, a channel sensitive to thermal radiation emitted from near the Earth's surface, would show significant changes when observing a particular land location if there was a substantial drift in time of day the satellite observed that location (Figure 9).

Finally, one should also recognise that the raw space-based observations must undergo a substantial amount of interpretation in order to produce records of the climate variables that we actually measure on the ground or within the atmosphere like temperature or humidity. As outlined in Box 1 it is physically reasonable to 'retrieve' atmospheric and surface properties from the raw radiation measurements but to do this various assumptions must be made. Different research groups may make different assumptions and employ different retrieval methods. This means that the same initial set of raw observations can end up providing the basis for subtly different records of a particular climate variable (Figure 8). When climate change signals are themselves small and uncertain this has the potential to lead to great controversy, as we shall see in the following section.

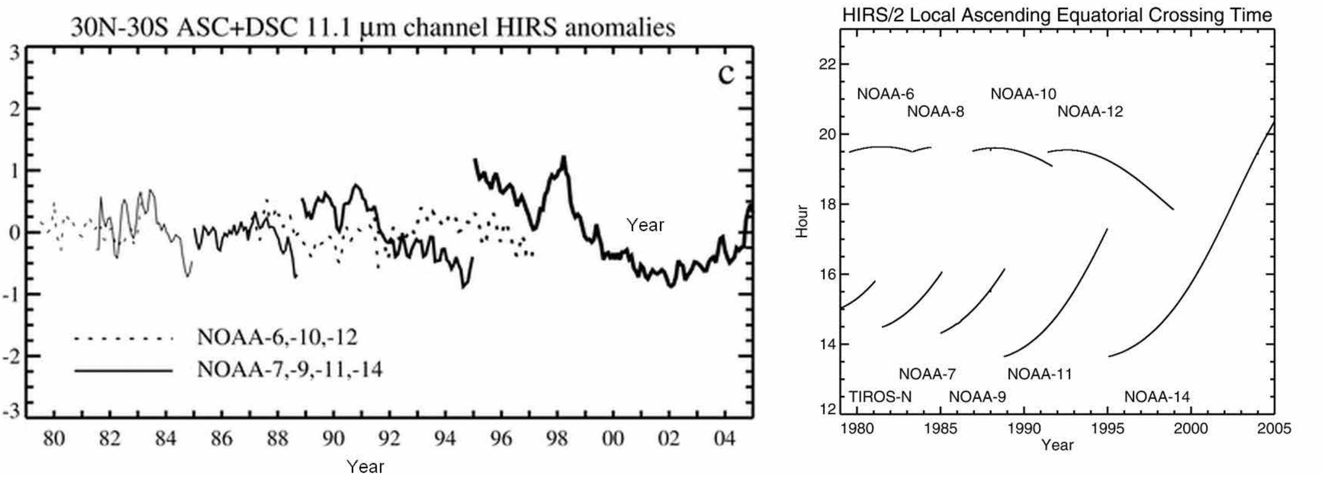

Figure 9: Left: Time-series of Brightness Temperature (a measure of radiated energy) anomalies derived from a surface sounding channel on the High resolution InfraRed Sounder from 1979-2005. The record comprises observations from seven different satellites carrying basically the same design of instrument: the curve thickness increases for successive satellites. The jumps in the record when moving from one satellite to the next are clearly apparent, the trends apparent within each satellite record correspond to drifts in an individual satellite's orbit overpass time through the day that occur over time—shown on the right (adapted from Jackson and Soden[30]).

Reconciling space-based EO records with other evidence for change

Having discussed the issues involved in creating reliable space-based EO records, in this section we provide three examples illustrating why no dataset should be considered in isolation. Evaluating any observational record in conjunction with other available data can highlight inconsistencies which motivate work to understand and account for the discrepancies, potentially leading to improvements in the individual records as well as a greater understanding of their uncertainty. Only after this process can these records be used with confidence to test model simulations of our past climate to determine where the models are in agreement with the observations and where robust differences are present, helping to direct future research efforts.

Trends in global temperature and humidity

Conventional radiosondes are balloon-borne packages that are launched from the ground and transmit measurements of the atmospheric temperature, humidity and pressure as they ascend through the atmosphere. Such observations from a network of many locations over the globe have been used to create a dataset extending back to the middle of the 20th century[31]. However, geographically these measurements were, and still are, primarily distributed across the US, Europe and Asia (Figure 10). In contrast, the great advantage of satellite observations is the regular, global coverage that they can provide. Observations of the OLR at the appropriate wavelengths can, as we have seen, be used to obtain temperature and humidity information at different levels in the atmosphere. With careful instrument inter-calibration, long-term space-based records of both quantities, representative of various layers within the atmosphere, can be derived.

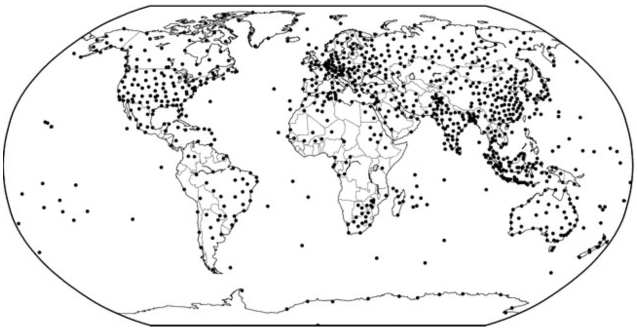

Figure 10: Locations of stations within the Integrated Global Radiosonde Archive active in 2003 (taken from Durre et al[32]).

What do these records tell us about the recent behaviour of our atmosphere? Climate modelling studies lead us to expect the Earth's surface and lower atmosphere (troposphere) to warm in unison as a result of the enhanced absorption of longwave energy caused by increases in carbon dioxide[33,34]. However, early observational evidence from MSU satellite data[35] did not show the warming of the troposphere that was expected and had previously been seen in numerous radiosonde analyses. The absence of a tropospheric temperature trend was also inconsistent with observed positive surface temperature trends measured over the same period[36].

The results sparked a huge international effort to understand the reason for the discrepancy between the observed trends. These detailed analyses unearthed flaws in both the radiosonde and satellite records. From the satellite perspective, these flaws were related to many of the points raised in the previous section. One key extra issue related to the sensitivity of the satellite measurements used to create the records to temperatures in the stratosphere. In contrast to the surface and troposphere, increasing carbon dioxide concentrations would be expected to cool the stratosphere because of enhanced stratospheric emission from the centre of strong carbon dioxide bands resulting in more energy being lost from the stratosphere (Figure B1). Over time any such cooling would be further exacerbated by stratospheric ozone loss since ozone strongly absorbs solar radiation. Hence, if an instrument has some sensitivity to the stratosphere as well as the troposphere, the effects of changes in stratospheric temperatures must be properly accounted for when deriving a tropospheric temperature record. Without such an effort the inferred tropospheric temperatures would include the effect of the decreasing stratospheric temperature, which in this case partially masked the tropospheric temperature increase.

Problems were also present in the radiosonde records due in part to the limited geographic coverage of these data, but also arising from changes in the time of day the measurements were made, and variations in the sensor type used, as a result for example, of changes in technology or sensor manufacturer[37]. Subsequent analysis taking these issues into account derived improved results from both the space-based and the radiosonde observations. Figure 11 shows how estimates of the global mean trend in surface and mid-tropospheric temperature trends derived from different analyses of radiosonde and MSU satellite data have changed over time, as a result of both the increasing length of the time-series available, but also more critically because of changes and improvements made to the analyses. The most recent results show greater consistency between the surface, radiosonde and satellite derived products, a result which, with consideration of the uncertainties in each record, led to the 2007 Inter-governmental Panel on Climate Change (IPCC) report concluding that there was no evidence for a discrepancy between observed and modelled surface and tropospheric warming trends on the global scale[26].

However, the same IPCC report noted that there were still marked deviations in the tropics between modelled and observed surface and tropospheric temperature trends. This is an important difference as enhanced tropical upper tropospheric warming relative to the surface has remained a robust signal in climate model simulations for some time. The physics behind this relates to the process of 'moist convection' in the tropics. In the tropics the surface is subject to intense solar heating, which leads moist tropical air to rise. As the moist air rises into a cooler part of the atmosphere it cools, and the cooling results in some of the moisture condensing to form liquid water droplets (i.e. clouds). The change from a gas to a liquid, releases energy or 'latent heat' to the surroundings, and warms them. So the whole process effectively moves some heat from low down in the atmosphere to higher up, so reducing the temperature difference between the heights. Technically it decreases the lapse rate, the rate at which temperature changes with height (see Figure B1 for a typical tropical temperature profile) within the tropical troposphere. This lapse rate is itself dependent on temperature and humidity since warmer air can 'hold' more water vapour and thus more water vapour is available to condense and release latent heat as the air rises. Hence, as a result of this process an increase in surface temperature due to increases in CO_2 would result in an even larger increase in the temperature of the upper troposphere in tropical convective regions. Although there is still vigorous debate as to whether observations and model simulations can be reconciled in this region, there is now a much greater awareness of the uncertainties in models and observations associated with the natural variability of our climate, and of the difficulties inherent in creating climate quality datasets from observations which were not originally designed for this purpose[38].

A further, related robust prediction from models is that as the climate warms the amount of water vapour within the atmosphere will increase[39]. Although this is now generally accepted, it has been questioned by some authors[40]. It is important because, as evident from Box 1, water vapour absorbs energy across much of the OLR spectrum. So, if CO_2 induced warming caused the amount of water vapour in the atmosphere to increase this would result in even more outgoing energy being trapped, enhancing the initial warming. This amplification of the original temperature change due to CO_2 alone would constitute a significant positive climate feedback. Although the total amount of water vapour in the upper troposphere (UT) is small, increases in water vapour in this part of the atmosphere are most effective at reducing the amount of outgoing energy[41].

There are two reasons for this: firstly, there is strong absorption by UT water vapour in the far infrared part of the longwave spectrum wavelengths where the Earth's surface emits a great deal of its energy; secondly, the low temperatures typical of the UT mean that increased absorption within and re-emission by water vapour from this region can substantially reduce the amount of longwave energy which escapes to space (Figures 1 and B1). Instruments like radiosondes find it very difficult to

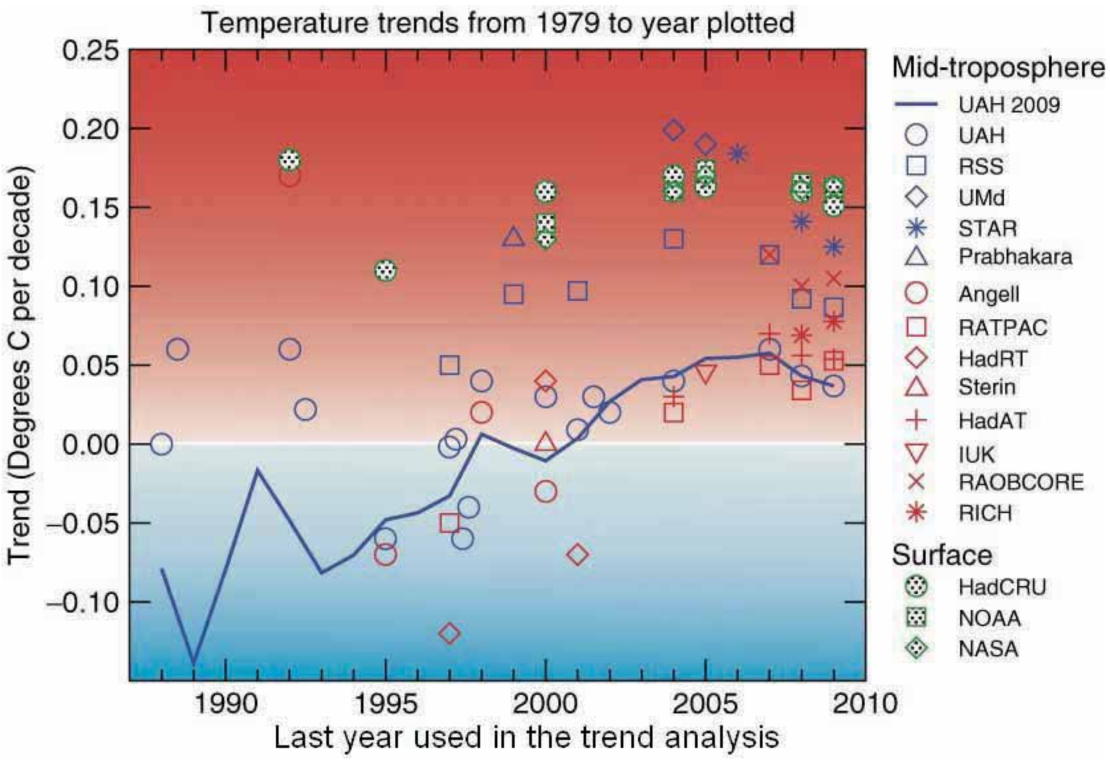

Figure 11: How estimates of the observed trend in the global mean mid-tropospheric (MT) temperatures from satellite (blue) and radiosonde (red) and in the surface temperature from ground based (green) measurements has changed with time, as more data became available and analysis evolved. The linear trend, shown on the y axis in degrees C per decade, is calculated from changes observed between 1979 and the year shown on the x-axis, which is when the estimate was made. Differences in the trend occur both because of different analysis techniques and because of increasing amounts of data being used. The blue line shows the trend for a single analysis technique (described by University of Alabama (UAH) group in 2009) for an increasing amount of MSU MT observations, with estimates being based initially on less than 10 years of data in 1988 and finally determined from a 30 year record in 2009. (Adapted from Thorne et al.[38]).

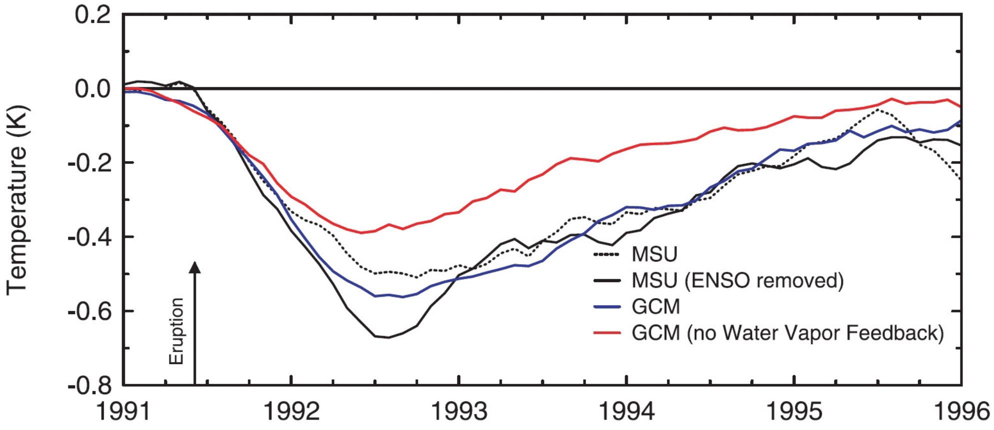

Figure 12: Comparison of satellite-observed (black) and model-predicted change in global-mean lower tropospheric temperature with (blue) and without (red) water vapour feedback included after the eruption of Mount Pinatubo in 1991 (adapted from Soden et al[21]).

measure the very small amounts of water vapour in the UT accurately. Satellite based measurements that observe the large effect this small amount of water has on the outgoing energy and are thus very sensitive to UT humidity can therefore play an important role in assessing the patterns and trends in some of the most critical parts of the global humidity field over the recent past. For example, on the global scale, vertical profiles of specific humidity derived from thermal infrared hyper-spectral measurements show an increase in the amount of tropospheric water vapour with increasing surface temperature[42].

Even more compellingly perhaps, the volcanic eruption of Mount Pinatubo in 1991 has been used as a test to see how well we understand the response of the climate system to a perturbation to the ERB. The eruption injected a large amount of reflective material into the upper atmosphere, reducing the amount of solar radiation reaching the surface and decreasing global tropospheric and surface temperatures over the following couple of years. A positive water vapour feedback would cause a subsequent reduction in UT absolute humidity and a further cooling of the troposphere, and this was indeed observed from space. Moreover, without including this positive feedback in climate model simulations of the period, the observed result could not be simulated (Figure 12)[21].

Variability in the Earth's Radiation Budget

Starting with the Earth Radiation Budget instrument on the Nimbus-7 satellite in 1978, accurate measurements of the total, broadband energy reflected and emitted by the Earth have been made by a variety of satellite instruments up to the present day. Given the fundamental link between the radiation budget at the top of the atmosphere and the evolution of our climate, these data offer an invaluable way to test our overall understanding of the workings of our climate system. By carefully combining such measurements with observations from other instruments which are sensitive to specific components of the climate system like water vapour, clouds or aerosols it is also possible to see how sensitive the radiation budget is to changes in these variables. Key studies exploiting ERB measurements have provided observational evidence for the greenhouse effect[43]; insights into how aerosol pollution may act to cool the surface but heat the atmosphere, potentially changing circulation patterns[44]; the suggestion that the tropical atmospheric circulation has intensified, leading to moistening of already moist regions and drying of dry regions[45]; and estimates of the way in which the response of clouds to a warming climate can further accentuate this warming[46].

Again however, constructing long-term climate quality records from the observations is far from straightforward. One such attempt showed large decadal variability in the ERB observed over the tropics. Comparisons with model simulations over the same period showed that they were unable to capture this behaviour. It was initially thought that the problem lay with the way the models simulated clouds[22] but subsequent analysis revealed three issues with the observations. First, the way in which averages had been calculated from the observations meant that the change in incident solar energy through the day had introduced spurious variations in the calculated values. Second, the altitude of the satellite carrying the ERB instrumentation decreased over time, leading to an artificial increase in the energy fluxes measured. Third, a small drift in calibration of the instrument measuring the solar component of the ERB was found. Applying suitable corrections to account for these issues much improved the agreement between the model simulations and observations[47] (Figure 13).

More recently, ERB measurements used in conjunction with observations of ocean heat content have suggested that we do not yet fully understand the energy flows within our climate[23]. In particular, it has been argued that the net energy leaving the Earth, responding, in the main, to increases in greenhouse gas concentrations such as CO_2, has, since about 2004, reduced at a faster rate than the ocean heat content has increased. Since

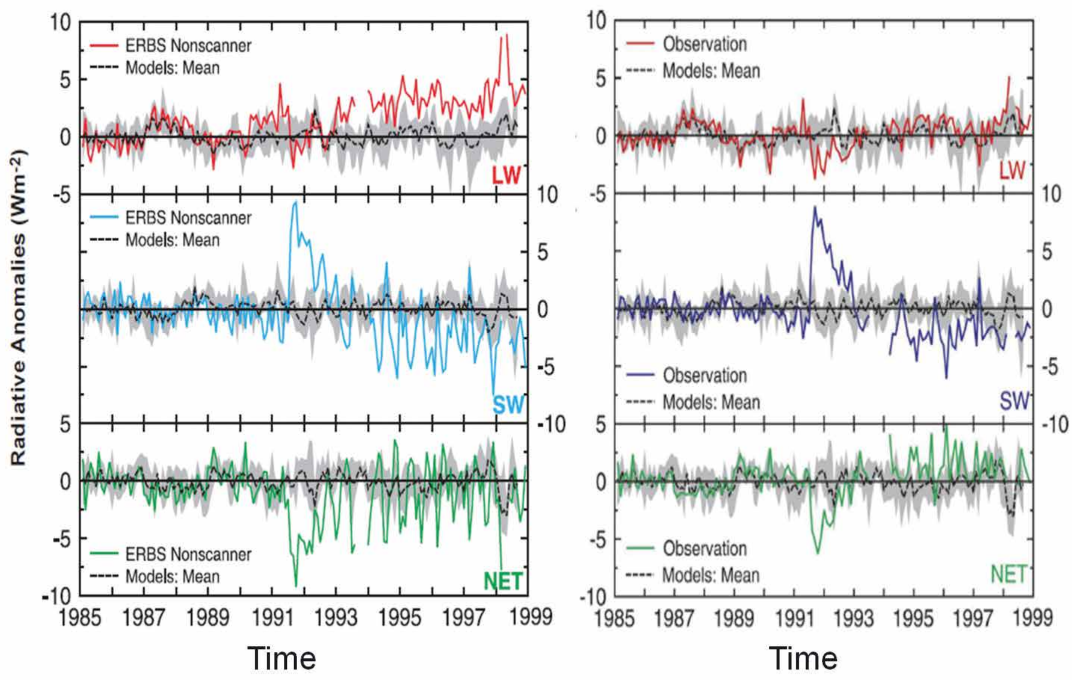

Figure 13: Observed (coloured lines) Longwave (LW); Reflected shortwave (SW) and Net outgoing tropical (20°S -20°N) radiation anomalies relative to the 1985-1989 average calculated from the Earth Radiation Budget Wide Field of View Instrument. Left: As originally reported by [22], Right: After corrections for spurious solar diurnal signal and satellite orbit decay[47]. In both cases the observations are compared to the simulations from the same set of five climate models. The black dotted line shows the multi-model mean, while the shading shows the total model range. The distinct feature from mid-1991 to early-1993 is due to the eruption of Mount Pinatubo which injected a large amount of highly reflective material into the Earth's atmosphere[21]. The models did not attempt to simulate this eruption so the discrepancy over this period is to be expected (adapted from figures presented by Wielicki et al[22] and Wong et al[47]).

over 90% of the extra energy trapped in the climate-system is stored in the ocean these two records should track each other. A reduction in the amount of excess energy going into the ocean would be expected to lead to an increase in the rate at which the surface temperature was rising, so the discrepancy, which led to the coining of the term 'missing energy' is inconsistent with the recent slow-down in the rise of global mean surface temperature. A subsequent analysis, taking full account of the uncertainties both in the ERB and ocean heat content observations has shown that the updated records can be reconciled[24]. Nonetheless, both sets of scientists agree that upgrades to the measurement network are needed in order to improve our ability to track the behaviour of these crucial climate variables.

Direct use of spectrally resolved information

Up to now we have either discussed how climate variables can be retrieved from passive space-based measurements of the outgoing energy, or considered the ERB. While ERB observations provide the overall energy budget at the top-of-the-atmosphere, alone, they are not the ideal tool to identify specific climate processes. Since the measurement sums the energy across all the wavelengths in the shortwave or longwave, the combined effect of changes in energy due to changes in specific climate variables like cloud or water vapour may, and do, compensate. Hence although climate change signals over specific wavelength ranges may be large, the net impact on the ERB, comprising the effects of a myriad of different processes, may be very small[48]. In contrast, if measurements of the solar energy and OLR can be made separately at each wavelength or spectrally resolved, we may be able to avoid the compensating effect inherent in the broadband approach and identify and monitor the effects of changes in many different components. Essentially the same information that is used to perform retrievals of different climate variables would be used, but without introducing the uncertainties associated with the retrieval process itself.

Could this work in practice? Although the situation is improving, continuous records of space-based spectrally resolved radiation are only available from the early 2000s onwards, and even these are not over the full shortwave and longwave ranges. Isolated missions have provided measurements for short periods from the 70s and 90s which have been used to show the power of such data in terms of highlighting the effects of changes in greenhouse gas concentrations on the Earth's OLR spectrum[49] (Figure 14).

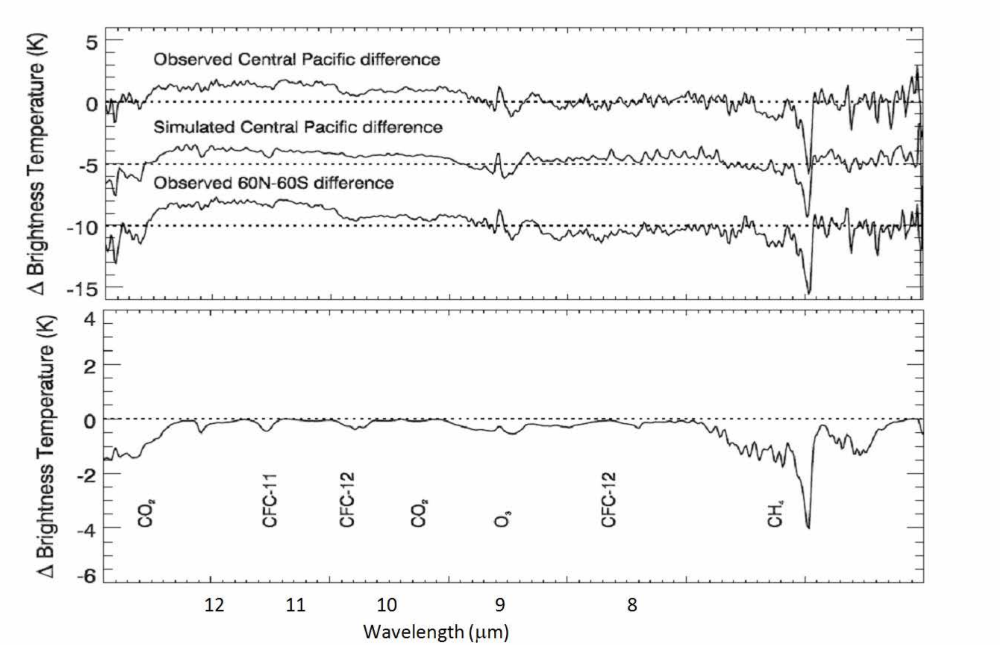

Figure 14: Top: Observed and simulated 1997–1970 difference in spectrally resolved outgoing longwave energy at the top of the atmosphere, expressed as brightness temperatures. The simulated Central Pacific and observed 60N-60S curves have been offset by 5 K and 10 K respectively for clarity. Using best estimates of the atmospheric conditions during the observation periods it is possible to simulate these observed differences (middle curve, top section) and identify the effects of long-term increases in specific greenhouse gases as shown in the lower section of the figure (adapted from Harries et al[49]).

However, as might be anticipated from Figures 8 and 13, there is a large amount of short-term natural variability in the infrared spectra of outgoing energy. Hence, while the effect of increases in several well-mixed greenhouse gases can be observed from clear sky observations as shown in Figure 14, distinguishing and identifying climate change signals from natural variations in cloudy data or due to other causes, such as increasing surface temperature, changing atmospheric temperatures or humidity is much more difficult (Figure 15)[50].

Nevertheless, more recent work has combined spectrally resolved and broadband (summed over wavelength) OLR observations from one year to highlight how climate model deficiencies in the representation of specific climate components such as upper tropospheric humidity and low-level cloud over ocean are more clearly seen in the spectrally resolved data[51,52]. At the same time, observations of the spectrally resolved reflected solar radiation have been used to characterise the variability in this field. The results show that changes in particular atmospheric and surface variables result in unique identifiable features in the observed spectra[53]. The measurements have also been used to assess the performance of dedicated climate simulations which enable us to determine how changes in the climate will alter the observed reflected solar spectrum and estimate when and at which wavelengths such changes will be greater than the effect of natural variability[54]. Such studies are being used to drive the design of future missions to detect and understand climate change, as we will discuss in the following section.

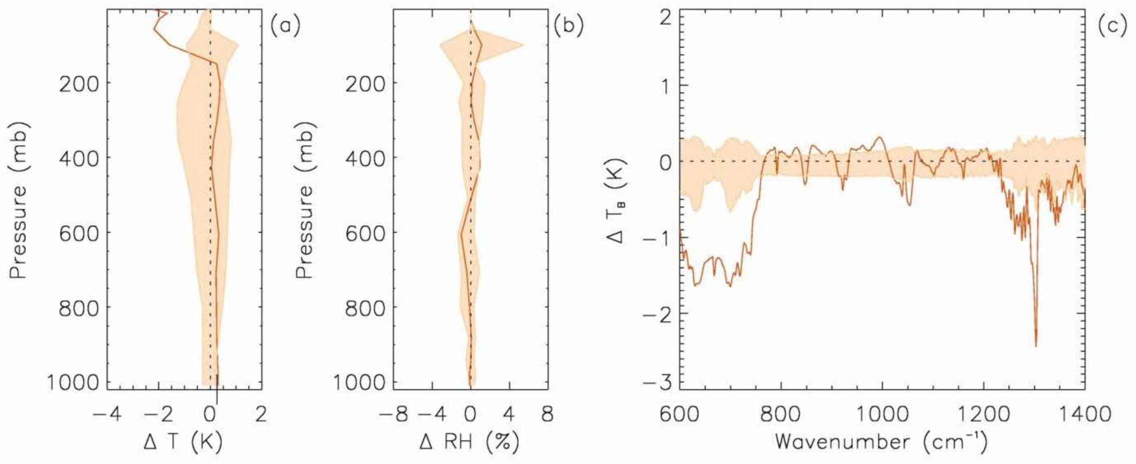

Figure 15: An example of the size of year to year variability compared to a 'snapshot' long-term change signals over the tropical oceans (30°N-30°S) in (a) temperature, (b) relative humidity (RH) derived from the Hadley Centre Atmospheric Model, and (c) the associated variability and snapshot change expected in the top of the atmosphere clear-sky brightness temperature spectra. In each case the orange curve shows the difference between 1997-1970 conditions and the shading indicates the range of year-year differences. This shading is a measure of the difference you might see due purely to short-term natural variability within the climate system. Hence in (c) we see that only limited parts of the spectrum show differences greater than those that might have occurred due to natural variability. These are in wavelength regions which are sensitive to the stratosphere where the long-term temperature change emerges from year-to-year variability (a) or in the centre of strong greenhouse gas absorption (see Figure 14). This indicates the need for individual instruments to observe for enough time to fully capture the short-term variability (adapted from Brindley and Allan[50]).

Future capabilities and implications for climate policy

While this briefing paper has highlighted some of the issues associated with obtaining reliable climate records from space, there is no question that space-based observations have vastly improved our ability to monitor the behaviour of our planet, and greatly increased our understanding. In some cases observations have confirmed our expectations; in others challenged them and motivated work to better understand key climate processes. Indeed, in remote areas and for certain key variables, such observations provide the only source of information available to us. Looking forward it is vital to reconcile the understandable desire to exploit innovative new technology to provide enhanced capability, with the need to ensure the greatest consistency possible over time. An understanding of where space-based measurements might provide the largest benefit is also desirable, not just in terms of driving scientific advance but also from the viewpoint of informing climate mitigation and adaptation strategies.

For example, from a policy perspective, it will be fascinating to see whether existing and planned sensors designed specifically to monitor CO_2 are capable of achieving the accuracy and sampling in space and time required to meet their goals, which include better estimates of the carbon exchanges between the biosphere, ocean and atmosphere, and tracking anthropogenic fossil fuel emissions. Although we have seen that CO_2 has a large effect at thermal infrared wavelengths, obtaining information about surface exchanges passively from space using these wavelengths is difficult because CO_2 is well mixed through the lower atmosphere such that the signal mainly originates from the mid-upper troposphere[56]. Instead, use can be made of CO_2 absorption of solar energy which occurs in bands in the near-infrared (at wavelengths of ~ 1.6 μm) which is more sensitive to near surface concentrations. The total amount of CO_2 in a column of atmosphere can be determined from such measurements[57,58], which, if sufficiently accurate, can be used to constrain our estimates of surface carbon fluxes. Several studies have sought to evaluate the precision in column abundance that would be required to improve on existing information available from the surface based CO_2 observing network alone, taking into account different instrument characteristics. The general consensus is that to improve annual global flux estimates on a sub-continental scale requires a precision in the column abundance which is of the order 1% for weekly, large scale (1000s km^2) averages[59]. Such a target is extremely challenging because it requires not only high measurement precision, but also a thorough evaluation of potential sources of uncertainty in the retrieval process (for example, aerosol particles in the atmosphere also have a sizeable effect in the near-infrared region of the spectrum, thus their presence and properties would need to determined). Nonetheless, better quantifying the global carbon cycle will not only advance scientific understanding into the relative strength of different sources and sinks and how these may evolve over time[60], but also has the potential to provide effective policing with regard to targets agreed under international emission treaties (Figure 16). Initiatives such as the Japanese led Greenhouse Gas Observing Satellite[61], the US Observing Carbon Observatory-2 and ESA's Earth Explorer 8 candidate CarbonSat mission illustrate the global recognition of the importance of obtaining such information from space. Clearly, as evident from Figure 3, space-based EO can inform on many other inter-linked, policy relevant variables, hazards and risks (e.g. components of the hydrological cycle; aerosol, pollution and air quality; climate extremes) and the range and number of current and future planned missions, with more than 250 EO orientated missions expected to be launched before 2030[62] are, to a high degree, a reflection of this.

A further relevant question might be how best we can merge existing and new EO space-based observations to create a consistent picture of our evolving climate. While the focus here has been on the creation of long-term records, EO space-based data has played a vital role in improving our short-term weather-forecasting skill because of its ubiquitous coverage. In the forecast procedure, model predictions are merged with available ground based, in-situ and satellite observations via a process called data assimilation to create the best possible analysis of the current state of our atmosphere and to predict its evolution. Over the years that satellite observations have been assimilated by forecast models, the models themselves have undergone many improvements and upgrades some of which have been as a direct result of space-based observations indicating that a particular aspect of the model physics is flawed[63]. So a model used today would probably give a slightly different result if used on the observations from 10 years ago than the model at that time did. However, it is possible to go back and use the current forecast model to reanalyse all the past data. Such a multi-decadal 'reanalysis', incorporating all reliable, relevant observations, is one way to derive a picture of the climate state over a long period that is consistent with all the observations. Reanalyses have been performed by a number of different international groups[64,65,66] and have proved an invaluable tool in climate research. To avoid introducing retrieval uncertainties, for passive sensors the assimilation process can use raw satellite radiation observations. However, while the reanalysis approach does provide a consistent approach to interpreting the data, it can still be affected by jumps in the measurement record, especially in data-sparse regions. It is also worth mentioning that the final re-analysis products will still implicitly contain the imprint of the specific model used in the assimilation procedure. It is hence worth retaining independent sets of observations which can be used to evaluate these outputs. Both of these points re-emphasize the need to fully understand and characterise the uncertainties associated with observations used for long-term climate monitoring.

Recognition of this need is certainly not new. The Global Climate Observing System (GCOS) was established twenty years ago to provide a conduit for the supply of climate related observations, including those from space (see Figure 3) and to provide support to the United Nations Framework Convention on Climate Change (UNFCCC), the World Climate Programme and the Intergovernmental Panel on Climate Change. A broad set of principles for climate monitoring was established and adopted in 2003 by the World Meteorological Organisation, the Committee on Earth Observation Satellites (CEOS) and the UNFCCC. This included acknowledging the importance of radiometric calibration, calibration monitoring, and cross-calibration

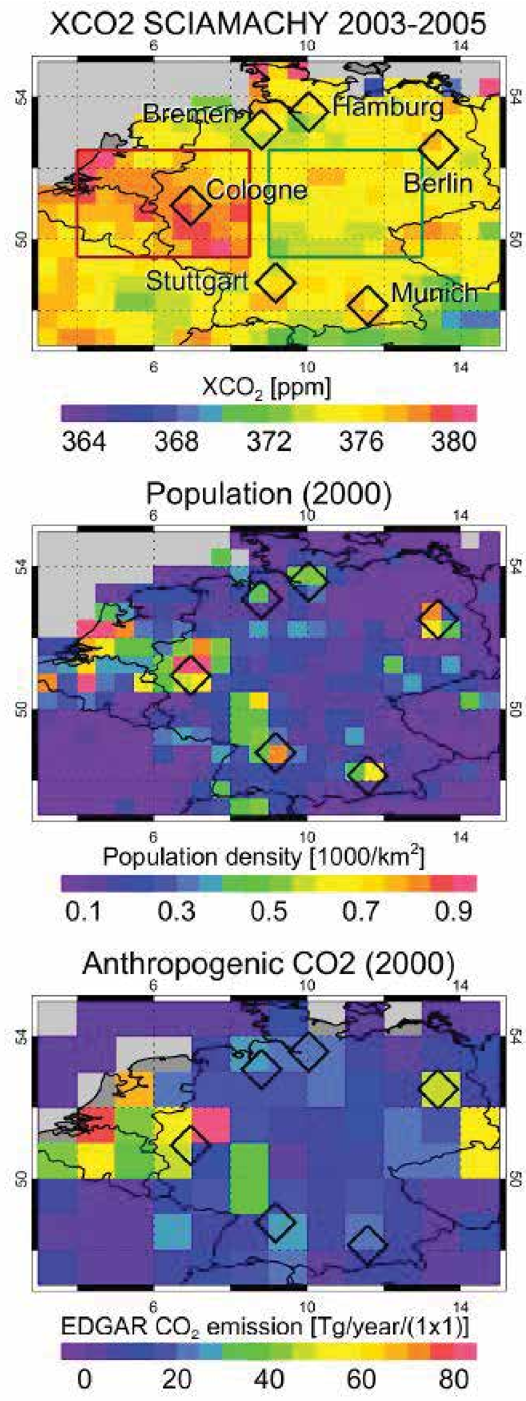

Figure 16: Top: Mean Dry air column abundance of CO_2 (XCO_2) in parts per million by volume (ppm) over Germany retrieved from the *Scanning imaging absorption spectrometer for atmospheric chartography* (SCIAMACHY) instrument over 2003-2005. Middle: Population density taken from the Center for International Earth Science Information Network in 2000. Bottom: Estimated anthropogenic CO_2 emissions for 2000 from the Emission Database for Global Atmospheric Research. Comparison shows that the larger retrieved abundances match reasonably well with the region of enhanced emissions. The difference between the area of enhanced abundances (red rectangle) and background levels (green rectangle) is around 2.7 ppm (adapted from Schneising et al[55]).

between satellite instruments, as well as encouraging sampling strategies which would be able to resolve climate signals over a range of different timescales[67]. Explicit in these guidelines is the requirement of sufficient overlap between successive instruments to allow the construction of long-term records. As we have seen, without such overlap we can lose the ability to distinguish differences between measurements due to climate change from differences due to changes in instrument and sampling characteristics over time. This requirement, so necessary in the absence of high absolute accuracy and optimised sampling, clearly makes the observing network highly vulnerable to satellite or instrument failures and may also inhibit technological advance since consistency in observing technique is a key aspect of this form of climate monitoring.

Can we mitigate this vulnerability? Recently, CEOS established a new Quality Assurance Framework for Earth Observation (QA4EO[68]), which has at its core the key requirement to assign and document a traceable uncertainty to the climate variables derived from the satellite measurements. Significant advances have been made over the last 10 or 15 years using well characterised targets on the Earth[69,70] and even the Moon[71,72] to inter-calibrate instruments and maintain their stability. However, at present these targets can only provide a good relative calibration, as the absolute accuracy available from these sources is still too poor to be useful for climate applications[73]. So although these advances go some way to addressing the problem, they fall short on providing the absolute accuracy that is required if we are quantitatively assess the changes in our climate and evaluate our ability to model them.

Fundamentally, achieving and maintaining high absolute accuracy ensures instruments are on the same scale without the need for cross calibration, and by definition provides stable measurements and quantitative data that can be used directly to measure the current state of the climate and evaluate models. In principle, if climate observations could be made with appropriate sampling and for a sufficient time period to characterise the short-term variability in the measurement and if high enough absolute accuracy was ensured, measurements from two such instruments separated in time could be guaranteed to be on the same scale even without overlap. Using this approach, measurements repeated at regular intervals would be sufficient to provide 'benchmark' data of the climate state that could act as anchor points in time, enabling us to accurately characterise the evolution of our climate. In addition, if appropriately chosen, such measurements could also enhance the observing system as a whole by acting as a calibration reference for other instruments. In order for the benchmark to be as useful as possible it would need to be able to capture significant changes in the climate state. As we have seen in the previous section, spectrally resolved radiances are an attractive candidate to fulfil such a role as they implicitly contain a high degree of climate relevant information, and, if observed with high enough temporal, spatial and spectral resolution and over a large enough spectral range, could be used to inter-calibrate a large number of other sensors. Two such missions, which plan to directly measure spectrally resolved radiances, have been proposed and are currently in various stages of development.

In the US, studies in support of the NASA led Climate Absolute Radiance and Refractivity Observatory (CLARREO[74]) mission have shown that it is possible to substantially reduce the time required to detect specific signals of climate change compared to the capabilities of current sensors (Figure 17). This requires measurements with high absolute accuracy and precision, which can only be achieved through a combination of novel in-orbit calibration techniques, directly traceable to international measurement standards, and a carefully selected orbital pattern

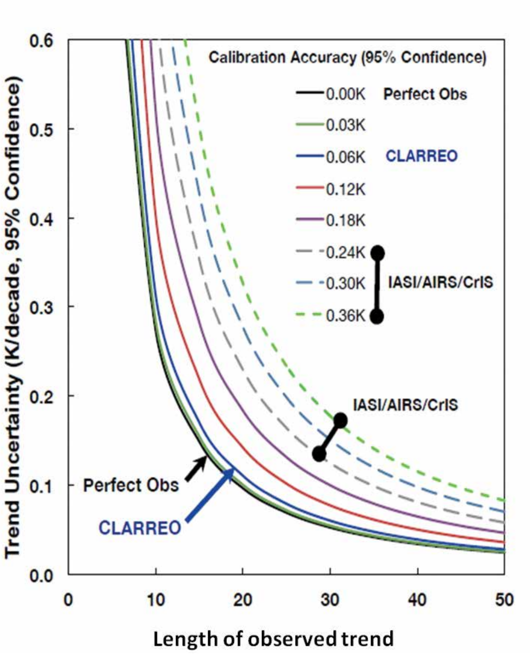

Figure 17: Relationship between absolute calibration accuracy and the accuracy of observed decadal temperature trends. Curves are shown for different levels of assumed accuracy in the infrared spectral measurements. Each curve provides a measure of the minimum trend that can be detected (vertical axis) as a function of the time needed to detect a trend of that size (horizontal axis) given the assumed measurement accuracy. Dashed lines show the results for a selection of current infrared instruments. The limit imposed by natural variability is given by the solid black line labelled 'perfect observations', CLARREO's design specification is also shown. The target CLARREO accuracy is a factor of 5 to 10 better than the absolute accuracy of the current instruments. So, for example, a trend of 0.2 K/decade could be detected within ~ 13 years with CLARREO, but would take a further twelve years to be detected with confidence using the most accurate of current instruments. Accuracy improvements beyond CLARREO have little difference in terms of the time required to meet a specific trend uncertainty level or compared to having a perfect observing system—the blue solid line is very close to the black line in both cases (adapted from Wielicki et al[74]).

and sampling strategy enabling the characterisation of short-term natural climate variability. In particular, this work has shown that observations of this type of the OLR and reflected shortwave spectra will provide insights into the magnitude of important climate feedbacks due to, amongst others, water vapour and cloud[75,54]. A complementary initiative, TRUTHS (Traceable Radiometry Underpinning Terrestrial and Helio- Studies[76]), focusing on spectral shortwave observations is being led by the National Physical Laboratory in the UK.

If these missions can achieve their accuracy and sampling goals, besides their own intrinsic value, their measurements would provide an absolute benchmark for many important space-based observations, benefiting the global observing system as a whole. However, despite passing its Mission Concept Review, a key step for any space-based mission, US budgetary reductions in 2011 have effectively put an indefinite delay on the CLARREO mission at the time of writing this note. Similarly, finding a suitable funding path for the UK TRUTHS mission has proved difficult thus far. In terms of driving future policy, the earlier these or similar initiatives are adopted, the sooner we can have greater confidence that any subtle changes seen in space-based climate records are both real and a signal of long-term change rather than merely a manifestation of shorter-term natural variability or instrument calibration drift over time. Without such initiatives it will certainly take longer to detect real climate changes, and there is the risk that we may miss important signals and that our ability to monitor climate will be irrevocably compromised by gaps in the data record.

Conclusions

Space-based Earth Observation is an invaluable resource. Over 50 years of observations have stimulated progressive improvements to our ability to predict short-term behaviour for the purposes of weather forecasting, and also increasingly to our efforts to monitor the global climate system. The range of applications to which EO orientated passive satellite sensors—the focus of this note—can be put is impressively large, as evidenced by the number of 'essential climate variables', spanning the land, atmosphere and ocean, that can be retrieved from measurements of this type. Due to the sampling characteristics of different EO satellites, and the measurement techniques used by different sensors on board these satellites, it is possible to build up detailed maps of a particular variable of interest over a range of spatial and temporal scales, something that is not possible from land, oceanic or atmospheric instrument networks. Space-based EO data can thus be used to track both the behaviour of these individual variables and the relationships between them in order to test our understanding of specific climate processes. In addition, we can, and do, use this data to evaluate the performance of climate models over those scales which potentially have the greatest relevance for the detection of longer term climate change.

Nevertheless, historically, space-based EO programmes have been orientated towards improving our weather forecasting capability rather than being focused on providing the basis for understanding and analysis of longer term climate change. The measurement priorities which would best serve the requirement for consistent long-term climate records are somewhat different to those needed for shorter-term weather forecasting and this mismatch has limited the usefulness of the data. The situation is improving: there is now a much better understanding and acceptance of the requirements of a climate dataset, and knowledge of how the current data can be best used to study climate. For example, the latest innovations mean that in the near future measurements will provide new insights into the sources and sinks of atmospheric CO_2 and even offer the possibility of directly monitoring anthropogenic CO_2 emissions from space.

However, the space-based observing system is still far from optimised for the study of climate, and the limitations of the current observations mean there is a risk that significant changes to the climate system will not be detected in time to inform mitigation strategies appropriately, a risk that our modelling of future climate will not be adequately tested, and a risk that gaps in the data will end our ability to monitor climate in the future.

Innovative approaches to overcome these limitations are being developed, and significant improvements have been made, including the use of stable Earth sites and the development of a reflectance model of the Moon, both of which can provide independent comparison points with long term stability. Such strategies can address some of the issues with monitoring climate from space, but to benchmark the state of the climate with sufficient accuracy to test our ability to predict its evolution a different approach is required.

Thus missions employing comprehensive sampling of natural variability, carrying instruments with high absolute accuracy and in-orbit calibration traceable to internationally recognised standards, have been proposed. These plan to make detailed measurements of the outgoing longwave and reflected shortwave energy spectra, and offer the potential to detect climate change on much shorter timescales that is currently possible. This strategy will remove the problems associated with a gap in the record, by providing the absolute accuracy necessary to relate measurements even if they do not overlap, ensuring stability of the records and providing a quantitative assessment of our climate. Furthermore the unique information contained in these spectra can be used to understand which climate components are the cause of the changes observed and thus provide a stringent test of the climate models used to predict how our climate will evolve. The remaining challenge is neither technological nor scientific, but rather financial, as the current missions of this type planned in the US and UK are both stalled by lack of funding. The delay is unfortunate but the quicker it can be overcome the sooner we can make the measurements necessary for the optimum detection of climate change from space.

Acronyms

CEOS—Committee on Earth Observation Satellites

CLARREO—Climate Absolute Radiance and Refractivity Observatory

ECVs—Essential Climate Variables

EO—Earth Observation

ERB—Earth's Radiation Budget

GCOS—Global Climate Observing System

IPCC—Inter-governmental Panel on Climate Change

IR—Infrared

MSU—Microwave Sounding Unit

MT—Mid Troposphere

OLR—Outgoing Longwave Radiation

SEVIRI—Spinning Enhanced Visible and Infrared Imager

TIROS—Television InfraRed Observation Satellite

TRUTHS—Traceable Radiometry Underpinning Terrestrial and Helio-Studies

UNFCCC—United Nations Framework Convention on Climate Change

UT—Upper Troposphere

UV—Ultraviolet

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