Making the Most of Earth Observation with Data Assimilation

Alan O'Neill
Data Assimilation Research Centre, Reading, United Kingdom

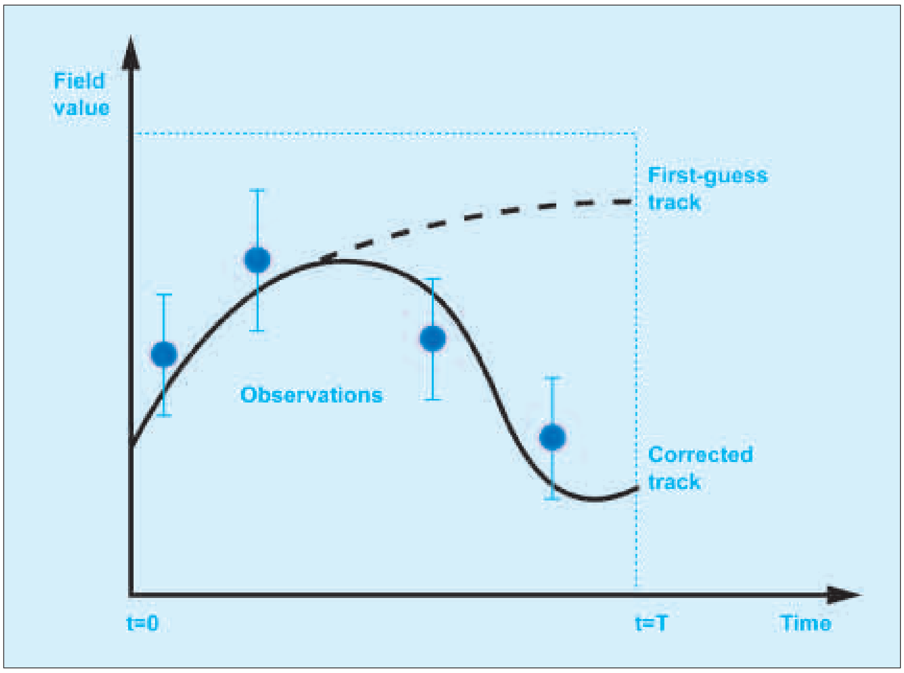
Pierre-Philippe Mathieu & Claus Zehner
Earth Observation Science and Applications Department,
ESA Directorate of Earth Observation Programmes,
ESRIN, Frascati, Italy

An international music company has invested in sophisticated recording equipment, and wishes to make a new recording of a Beethoven symphony. The Berlin Philharmonic Orchestra is hired, and sound engineers set up high-quality microphones among the players in a recording studio. The orchestra performs and each microphone produces a soundtrack. But only a part of the orchestra can be heard on each soundtrack, some soundtracks are noisy, and some are interrupted by periods of silence due to temporary faults in the equipment. Would the company market the recording as a boxed set of CDs, one CD for each soundtrack? Maybe 'yes' for the few music lovers with expert knowledge and sound equipment who could derive pleasure from such a set. But certainly 'no' for the vast majority who want a continuous, high quality, well-balanced blending of sound on a single CD.

Like the recording studio, planet Earth now has many very expensive, high-tech recording instruments deployed around it, in this case on satellites. By recording not sound, but electromagnetic signals covering a wide range of frequencies, this web of sensors is providing data of unprecedented quality and scope on the physical, chemical and biological processes occurring in the air, sea and land of the Earth System, a system of profound and far from understood complexity.

2020 Vision

It seems likely that, by the year 2020, every point on and above the Earth's surface will be viewed from space with a resolution better than 1 km in distance and 1 minute in time. Computing power, already impressive today, will be over 1000 times greater. To exploit this technological revolution, we must be able to synthesise



Schematic of a Data Assimilation System illustrating how a poor forecast (dotted line) can be corrected by assimilating noisy measurements (blue dots) into a mathematical model to provide the best estimate of the trajectory of the system (bold line), satisfying at the same time the dynamics and the observations within their error bounds (blue bar). This technique is used, for example, by automatic landing systems on aircraft in poor weather conditions. Noisy data on the aircraft's position must be combined with information on how the aircraft responds to movements of wing surfaces in order to achieve a smooth landing.

the huge amounts of data flowing from the foreseen dense halo of satellites. As in sound recording, deficiencies due to limited sampling by an individual instrument, as well as instrumental deficiencies, inconsistencies and failures, must be remedied. And as in the production of music CDs, a quality-controlled, uniformly sampled, digital version of the real world is needed.

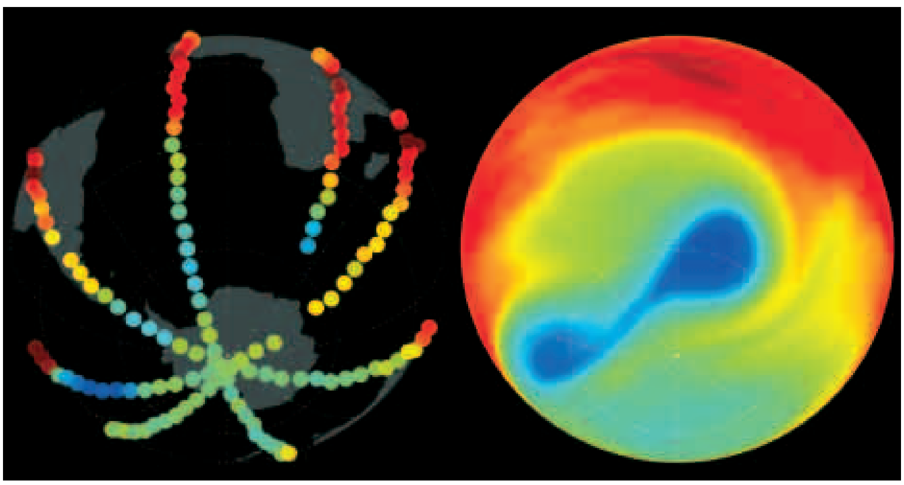
The Value of High-level Information

High-level, synthesised data products are vital in order to monitor and understand the physical, chemical and biological processes in the Earth System, and to analyse long-term trends. Serious environmental threats, of great concern for society and the sustainability of life itself, such as global change, require reliable predictions of what planet Earth will be like in the future. Skilful environmental prediction would provide guidance to policy-makers and help them in taking sound precautionary actions to protect society against the adverse impacts of climate fluctuations and weather extremes.

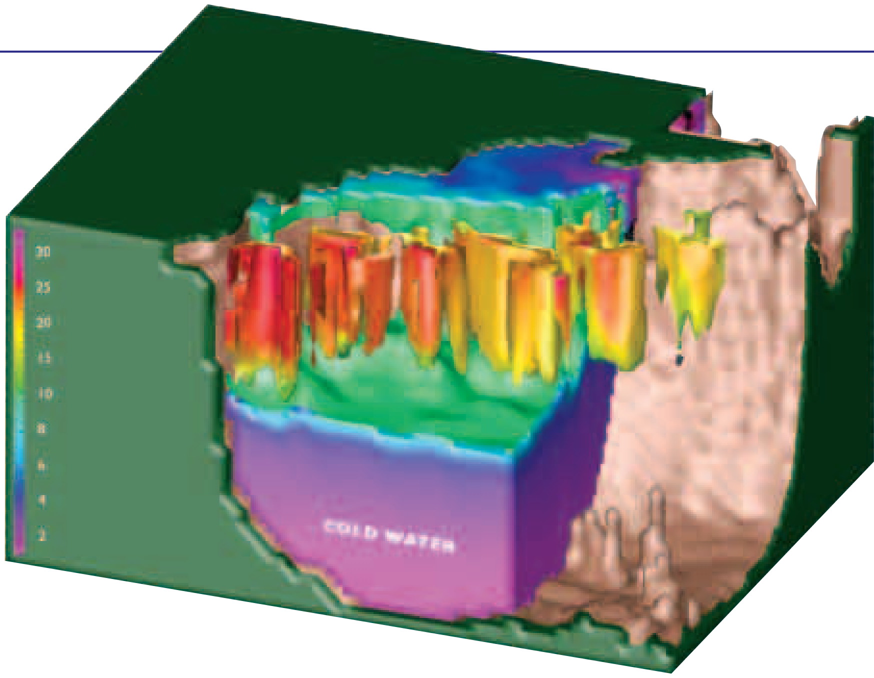
Scientifically based predictions such as weather forecasting utilise mathematical models that encapsulate our understanding of the evolution of the various components of the Earth System and of the interactions between them. The essential pre-requisite for prediction is a best estimate of the initial state of the system, encoded as numbers on a spatial grid, which may have little resemblance to the spatial pattern of available observations. For systems whose evolution exhibits sensitive dependence on initial conditions (or chaos), such as the atmosphere, the forecast can depend critically on how well the grid-based initial state is estimated from disparate observational data. In the case of satellite data, the problem is compounded by the fact that the quantity measured – spectral radiance at different frequencies – is related only indirectly to parameters represented in the model, such as winds, waves and temperatures.

What is 'Data Assimilation' and How is it Done?

How do we produce, from a mixture of sometimes conflicting observational data, a best estimate of the state of the Earth System in a convenient form for diverse applications, especially prediction? How do we ensure that a time sequence of these



Ozone distribution in September 2002 derived from Envisat's MIPAS instrument (left panel) and from the assimilation of MIPAS data into a general global atmospheric circulation model (right panel), into which all the contemporaneous ground-based and satellite measurements used in operational weather forecasting are also assimilated. The coloured dots on the left panel show positions of MIPAS observations and inferred ozone concentrations (blue denotes low values, red high values) during a 24-hour period around the time when the stratospheric polar vortex, and the ozone hole within it, split rapidly into two. At this time, real-time measurements from MIPAS were fewer in number than usual because of some (temporary) data-processing difficulties.
(Courtesy of Data Assimilation Research Centre, UK)



Three-dimensional representation of Gulf Stream eddies, obtained by assimilation of satellite data into an ocean-circulation model. The plots shows warm eddies (associated with a 0.7 m/s speed) detaching from the main current and moving above the cold water (associated with the 10°C isotherm, in green). The consistent vertical structure of warm eddies associated with sea-level anomalies indicates how data assimilation has propagated the information content from surface observations down to greater depth.
(Courtesy of CNRS/LEGI Laboratoire des Ecoulements Géophysiques et Industriels, F)

estimated states is consistent with any known equations that govern the evolution of the system? The modern method for achieving these goals is known as 'data assimilation'.

As illustrated in the accompanying figure, the term 'assimilation' should not be taken to imply a vague process of absorbing data into some computer program, but a carefully constructed procedure that brings to bear all our knowledge of the measurement process, the known errors in the measurements, the governing equations of the system, and the expected errors in those equations as approximated on a computer.

Data assimilation in its various forms has a long heritage in many different areas of science and engineering, where the term 'state estimation' is commonly used. Estimating the orbits of planets from sparse astronomical data is a classical example. Others include (noisy) signal processing in electrical engineering, for which much of the basic theory was developed, and the wide branch of applied mathematics known as control theory. In fact, data assimilation is part of everyday life. You use a kind of assimilation scheme if you sneeze whilst driving along the motorway. As your eyes close involuntarily, you retain in your mind a picture of the road ahead and of the traffic nearby, as well as a mental 'model' of how the car will behave in the short time before you re-open your eyes and make a course correction.

More formally, data assimilation is the technique whereby observational data are combined with data from forecasts by a numerical model to produce an optimal estimate of the evolving state of the system. The model brings consistency to the observational data, and interpolates or extrapolates data into data-devoid regions in space and time. The observational data correct the trajectory of the imperfect model through state space, keeping it 'on the road' in a forecast – observe – correct feedback loop (see figure).

The word 'optimal' in the above definition indicates the statistical basis of most advanced implementations of the method. The state of the system is estimated essentially as a weighted combination of observations and numerical forecasts, the weights being determined from the (supposedly known) errors in the observations and in the numerical forecasts. The great mathematician J.C.F. Gauss showed how to do this as long ago as the 18th Century: weight the data by the reciprocal of a measure of their error (the error variance).

Although simple to state, proper implementation of this rule is very challenging, and is the focus of much intense research. To give a hint of the difficulties, note that the Earth System, comprising the ocean, atmosphere, land and ice subsystems, may need a billion numbers to represent its state usefully for predictions. Characterising the likely errors in all of these variables, their inter-relationships and evolution is extremely challenging and lies at the cutting-edge of scientific computing.

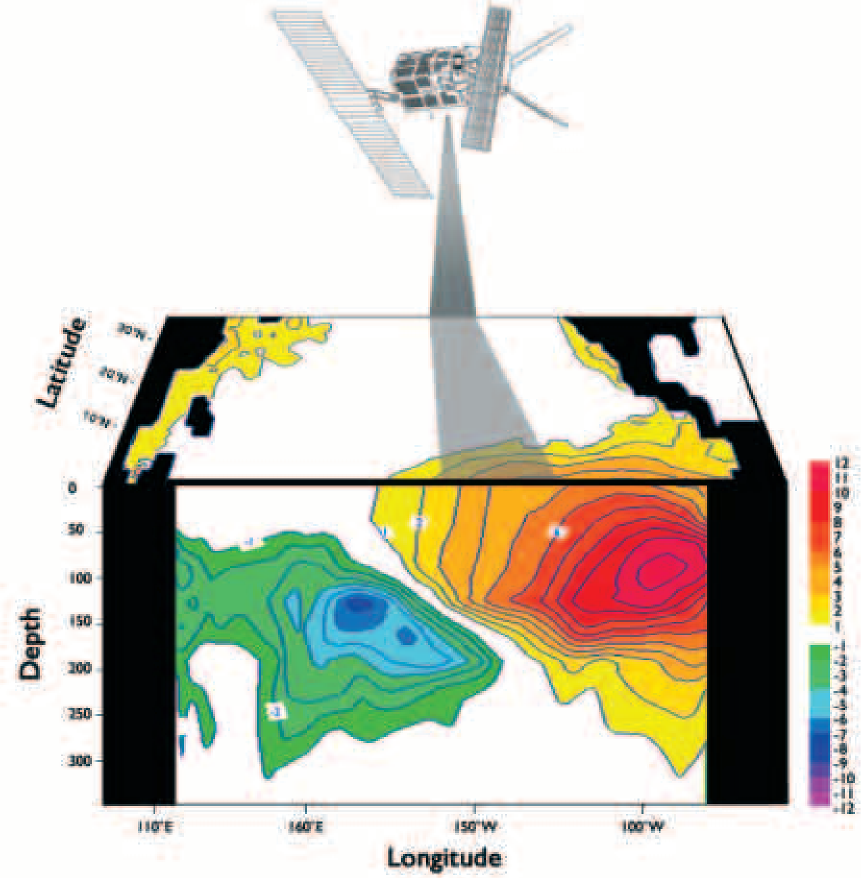
New techniques have allowed the direct assimilation of satellite observations in their 'pure' (calibrated) form as radiances, avoiding some of the pitfalls inherent in the assimilation of off-line estimates (retrievals) of geophysical parameters, such as temperature. This is an important example of how data assimilation has been a catalyst technology, enabling the full exploitation of data from remote sensing. The full benefit of satellite data in operational weather forecasting took over 25 years to materialise, because early satellite soundings were treated not as radiances, but as though they were soundings from radiosondes. The impact of the satellite measurements on forecasts was thereby diminished.

Today, direct assimilation of satellite radiances has been shown to lead to dramatic improvements in forecasting accuracy, particularly in the Southern Hemisphere where the lack of conventional data coverage makes prediction difficult. Five-day weather forecasts are now twice as accurate as in the late 1970s, and as skilful as three-day forecasts were ten years ago. This example illustrates how Earth Observation data, acquired at great expense, were under-exploited for decades because data-assimilation techniques had not been developed to make best use of the data.

What are the Benefits of Data Assimilation?

Before giving a brief description of several applications of data assimilation in Earth System sciences, we can summarise its benefits, some already alluded to, for maximising the scientific and economic value of Earth Observation data:

- *Forecasting and error tracking*. By regularly confronting numerical fore-



Anomalous Pacific temperature signal (deg C) in December 1997 simulated by the European Centre for Medium-Range Weather Forecasts ocean model assimilating in-situ and satellite data.
(Courtesy of ECMWF, UK)

casts with observations, extremely valuable error statistics can be built up, which can be used to improve the quality of the observations (e.g. by revealing biases in instrument calibration) as well as the quality of the models. This routine confrontation has led to enormous improvements in weather-forecasting models during recent decades. Data assimilation is now used to validate numerical simulations of climate.

- *Combination of data*. Different observing systems have different virtues and deficiencies. These differences can be exploited or catered for to optimise the value of the resulting data set – the single CD to play on standard home equipment, referring back to the music analogy.
- *Filling in data-poor regions*. The model provides a way to propagate information in a consistent manner from data-rich regions in space and time to data-poor regions. This capability is vital to exploit satellite observations, which due to their limited and sequential sampling provide only a fragmented picture of the Earth – like a jigsaw puzzle with missing pieces.
- *Estimating unobserved parameters*. Through relationships expressed in the governing equations of the model, parameters that are measured provide information on those that are measured inadequately or not at all. For example, temperature (or radiance) observations can be used to deduce winds, concentrations of hard-to-measure chemical species can be inferred from the observed evolution of other species, and emission rates of gases from the Earth's surfaces can be inferred from their observed concentrations in the atmosphere.
- *Designing observing systems*. When deciding whether to deploy a new satellite-borne instrument, a critical question to be asked is: What is the incremental value of the new instrument? For instance, given that the wind field in the atmosphere is closely related (outside the tropics) to the comparatively well-known temperature field, what is the value of a newly proposed wind measurement? Provided they are designed carefully, data assimilation experiments provide an objective, quantitative way to answer such questions. In addition, data assimilation can optimise the sampling pattern from an observing system, and can target observations to capture features of concern, such as a rapidly developing storm.

Data Assimilation in Practice

The parallel developments of both data assimilation and Earth Observation have received tremendous impetus from the demands of operational weather forecasting. The benefits are huge, and are felt every day as almost every aspect of our society is sensitive to weather fluctuations. Typical examples of the wider application of data assimilation to Earth sciences include forecasting the 'chemical weather', operational oceanography, seasonal climate prediction, greenhouse-gas monitoring and land modelling. Each is an example of innovative use of European satellite data by European scientists.

The first example illustrates the central role that data assimilation now plays in forecasting the chemical state of the atmosphere – the so-called 'chemical weather' – and in monitoring the impacts of man-made pollution. In September 2002, there was a completely unexpected splitting of the ozone hole over Antarctica. Ozone-poor air migrated over populated regions, giving greater exposure to damaging solar ultraviolet radiation. This unprecedented event was recorded by atmospheric instruments onboard Envisat. The left panel of the accompanying figure shows the ozone amounts inferred from measurements along the viewing tracks of Envisat's MIPAS instrument near the time of the split.

Although the spatial resolution of the measurements along the tracks is good, there are large gaps between the tracks, and only tantalising glimpses of the split are provided by the basic measurements on each day. The panel on the right shows the corresponding distribution of ozone produced by assimilating the MIPAS data into an atmospheric global-circulation model, along with all other meteorological data available for operational weather forecasting (this is a good example of the benefits of combining research-satellite data with routine measurements made by operational observing systems). Data assimilation has filled in the gaps in space and time in a manner consistent with the movement of ozone by air currents and with the changes in concentrations due to chemical reactions. Data assimilation provides a consistent sequence of global, 3D fields, which can be used to quantify the damage to the ozone layer from man-made pollutants.

Data assimilation is also at the heart of operational oceanography. The accompanying illustration is a three-dimensional rendition of the Gulf Stream eddies in the ocean off the North American coast. The Gulf Stream has a significant moderating effect on Europe's climate by carrying large amounts of heat from the warm tropics to the colder polar latitudes. The structure depicted in the figure was produced by assimilating satellite data on surface temperature and sea-level anomalies (from Topex/Poseidon and ERS-1 altimeters) into an ocean model. The model has propagated the surface information downward to reveal the 3D structure of eddies in the Gulf Stream, as though an obscuring veil were pulled away from the ocean surface. These eddies are the ocean's equivalent of storms in the atmosphere, and predicting them is useful not only for climate research, but also for ship navigation as well as exploitation and conservation of the marine environment.

Seasonal climate forecasting is a revolutionary technology in meteorology and oceanography aimed at predicting long-range fluctuations in climate (as opposed to day-to-day weather events) several months in advance. This endeavour draws heavily on a wide range of satellite observations, which are synthesised via coupled atmosphere–ocean models. The scientific basis for long-term climate prediction lies in the ocean, which acts as a 'pacemaker' by slowly nudging the atmosphere into a potentially predictable mean state. A striking example of the societal benefits of seasonal forecasting was the prediction, more than six months ahead, of the severe 1997 El Niño event. In July 1997, various satellites, including ERS-2, detected an anomalous warming of a few degrees of the ocean surface in the equatorial Eastern Pacific. A data-assimilation system fed this anomaly downwards into the ocean component of a coupled model, as shown in the adjacent figure. The coupled model in turn successfully predicted the onset of the event, and thereby allowed people to cope better with the worldwide impacts of El Niño by taking appropriate precautionary measures.

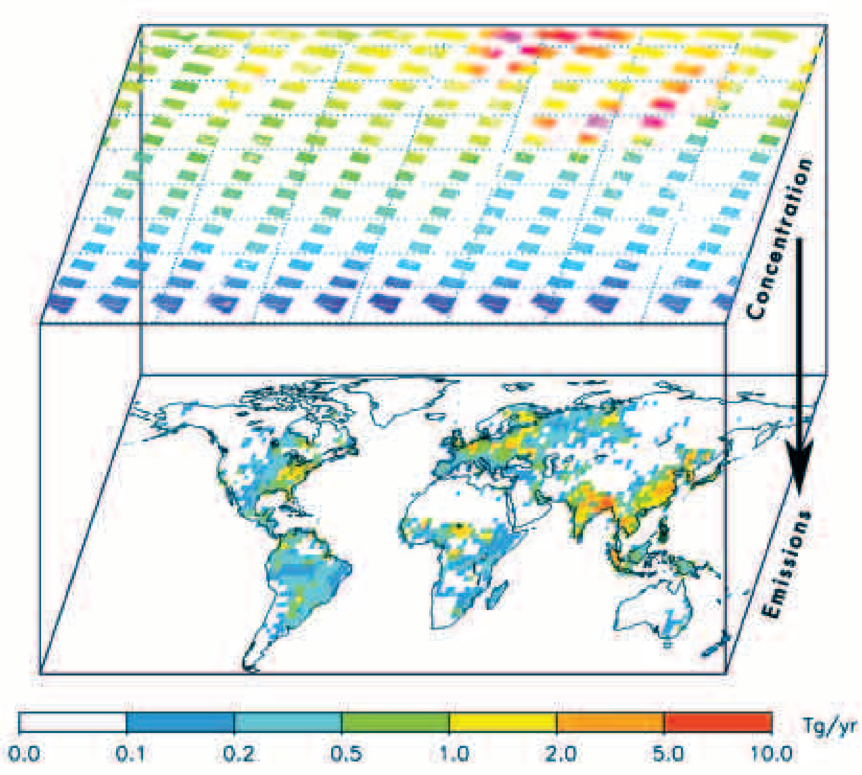
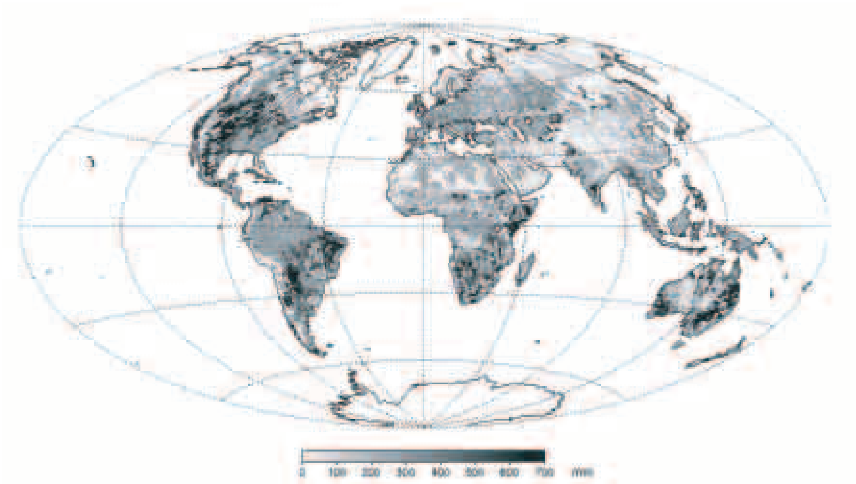


Illustration of the use of data assimilation for the retrieval of methane emissions. Assimilation of synthetic measurements of total column methane from Envisat's SCIAMACHY instrument (upper panel) into a chemistry transport model can help improve our currently poor understanding of the distribution of methane sources and sinks (lower panel in Teragram/grid cell).
(Courtesy of KNMI (NL), Evergreen Project)

Another interesting example of the use of data assimilation is to infer quantities that are not well measured (such applications are often called 'inverse modelling'). The accompanying figure shows how satellite measurements of methane in the Earth's atmosphere can help us quantify the sources and sinks of this important greenhouse gas at the surface, especially in regions where ground-based measurements are sparse (e.g. in the Southern Hemisphere or in developing countries). In this case, synthetic measurements of total column amounts of methane, made by the SCIAMACHY instrument on Envisat, are assimilated into a chemistry-transport model to reveal, for example, a strong methane source in the Amazon region of South America. Such information is crucial to understanding the cycles of greenhouse gases, and also to support the implementation of international regulations such as the Kyoto Protocol, which requires national inventories of emissions.

Applications of data assimilation now extend beyond the atmospheric and oceanographic sciences, where they are long-standing and quite mature. The method is increasingly being employed to understand the properties and evolution of the land surface using both ground-based and satellite data. For instance, knowledge of the soil moisture near the surface is obviously important for hydrological and agricultural applications, but it is also important for climate prediction, as part of the hydrological cycle in the atmosphere.



Maximum plant-available soil moisture (mm) obtained from a land-surface vegetation model after assimilation of satellite-based optical measurements of vegetation productivity.
(Courtesy of Max Planck Institute for Meteorology, D)

The accompanying figure shows an estimate of the global distribution of soil moisture derived after assimilating satellite-based estimates of vegetation productivity into a model of the land surface. As a component of a coupled system, such models are beginning to be used to make forecasts of agricultural production.

Training a New Generation of Scientists

Better understanding, monitoring and forecasting of the state of the Earth System present enormous intellectual and technological challenges. To meet them, a new generation of scientists with multi-disciplinary skills must be trained to have an end-to-end knowledge of remote sensing, modelling and data assimilation. Many of the traditional, discipline-based courses at universities do not offer such an integrated view and need to be supplemented with cross-disciplinary training.

To this end, ESA has set up a long-term Summer School training programme promoting the exploitation of Earth Observation across disciplines, and in particular through integration of measurements into forecasting models via data-assimilation techniques. The first Envisat Data Assimilation Summer School was organised from 18 to 29 August 2003 at ESA/ESRIN in Frascati and it concentrated on the assimilation of data from the three atmospheric instruments on Envisat: MIPAS, SCIAMACHY and GOMOS. The School was designed to attract first-class young scientists beginning their careers in Earth Observation, as well as those who had a desire to enter the field. Almost 60 students from 17 countries attended keynote lectures by leading scientists, and they rated the course a great success. A key feature of the training was that the material presented during lectures was reinforced by computer-based exercises (e.g. one practical involved using the latest satellite data to analyse the state of the ozone hole). All lectures, practicals and presentations are available on-line at: http://envisat.esa.int/envschool/.

The next Envisat Data Assimilation Summer School will be held at ESRIN from 16 to 26 August 2004. It will broaden the scope of the first Summer School by providing training in the synergistic use of observations of all the components of the Earth System, for which a multi-instrumented platform like Envisat is ideally suited. The second School has already attracted 200 applications from students from 47 countries, 55% being from ESA Member States. These Schools are part of an ongoing series of ESA activities designed to help maximise the benefits of Earth Observation from space.

Conclusions

When numerical prediction models can enhance the value of measurements, data assimilation should be an essential component of the ground segment of all Earth Observation satellite missions. Data assimilation fuses disparate data streams into a coherent picture of the evolving world. By routinely confronting models with observations, it facilitates rapid advances in our ability to simulate the profoundly complex, highly non-linear, multi-component Earth System, a capability yet to be fully exploited in climate modelling. It provides the essential scientific basis for using models to forecast the evolution of the system. It also allows the incremental value of new observing systems to be judged, enabling objective decisions to be made when faced with competing opportunities.

Data assimilation is a catalyst technology to effect the transition from today's innovative, research-oriented satellite missions to the design and deployment of tomorrow's operational satellites. It is a field at the forefront of scientific computing, requiring a new generation of scientists with inter-disciplinary skills. At a time when long-term measurements of our planet's 'vital signs' are indicating rapid changes, it constitutes one of the key building blocks of a numerical laboratory of the Earth System, providing globally consistent data sets that go well beyond simple imagery (the 2D snapshots of basic satellite measurements). By meeting the geo-information needs of a wide and diverse user community, data assimilation is helping to fulfil the vision of the Global Monitoring for Environment and Security (GMES) initiative and ESA's Oxygen (O2) project.

Like the market-wise music company of our opening analogy, ESA can exploit data-assimilation techniques to deliver high-quality products in a form that can readily be used to listen to the Earth System symphony. Good listening! esa