From weather to climate

The reanalysis of daily weather observations at ECMWF

The Earth's climate has traditionally been studied by statistical analysis of observations of particular weather elements such as temperature, wind and rainfall. Climatological information is often presented in terms of long-term averages, and sequences of observations are examined for evidence of warming, more-frequent severe storms, and so on.

A powerful new approach to climate analysis has emerged in recent years. It applies the tools and techniques of modern everyday weather forecasting in a process called reanalysis. The products, reanalyses, have applicability far beyond that of traditional climate information.

The role of Europe in the new approach to climate analysis

Europe has been the world leader in global weather forecasting since the late 1970s. Forecasts of increasing accuracy have resulted from refining the numerical model of the atmosphere used to make the forecast, and from refining the procedure used to determine the initial model state from which the forecast starts. Both refinements have been made possible by investment in powerful computer systems, complementing the even larger investment made in the meteorological observing system.

In daily forecasting the latest ground- and satellite-based observations are combined with a short forecast based on earlier observations to create the initial state for a new forecast. The initial state describes the elements of weather throughout the atmosphere and the geophysical properties of land and ocean surfaces. Weather charts with frontal structures can be drawn from this information to help display and diagnose current weather in the traditional way.

Weather analysis, a combination of observations and model

Targeted to provide products of the highest possible accuracy, daily forecasting is carried out with a much higher model resolution and accordingly with a much higher computational cost than the ERA-40 reanalyses.

By improving the model, the observations and/or the weather analysis algorithm the products are improved. Reanalysis is thus an iterative process. A new reanalysis extracts newer and more accurate information relating to the Earth's climate than the previous reanalysis.

	Period	Resolution	Levels	Top
ERA-15	1979–1993	125 km	31	32 km
ERA-40	1957–2002	125 km	60	65 km
Operations	2006 →	25 km	91	81 km

In a reanalysis, the weather observations collected in past decades are fed into a modern forecasting system that is much more refined than the systems available when most of the observations were made. Atmospheric and surface conditions are reconstructed for each day of the period over which suitable observations exist. Reanalysis differs from the traditional climatological approach in that it processes a wide variety of observations simultaneously, using the physical laws embodied in the forecast model and knowledge of the typical errors of forecasts and observations to interpret conflicting or indirect observations and fill gaps in observational coverage.

Europe is a key player in this activity. Its latest reanalysis, ERA-40, was carried out by the European Centre for Medium-Range Weather Forecasts (ECMWF), with support from Europe's National Weather Services and the European Commission's Fifth Framework Programme. It has provided products of unprecedented scope and quality.

The first reanalysis was carried out in the United States starting from 1948 and continues in near real time at NCEP (National Centers for Environmental Prediction). This was followed by two European reanalyses, both performed at ECMWF: ERA-15 (1979–1993) and ERA-40 (1957–2002). Japan also has recently joined the "reanalysis club" and reanalyzed the period 1979–2004. Interaction between groups helps ensure optimal collection of past observations and coordinated preparation for new reanalyses. Open access to the products of reanalysis enables users worldwide to benefit from a specialized and highly advanced central processing of observations made worldwide.

The historical observations

The quality of a reanalysis depends on both the observations and the weather analysis system. Whereas a reanalysis has a limited "useful" lifetime, the value of historical observations increases in time. More information than before can be exploited from a given set of observations in a new reanalysis using an improved weather analysis system.

The International Geophysical Year (IGY), July 1957 to December 1958, had as its goal: *"… to observe geophysical phenomena and to secure data from all parts of the world; to conduct this effort on a coordinated basis by fields, and in space and time, so that results could be collated in a meaningful manner."* As a consequence of the IGY, the observing system developed towards an integrated global system, including the polar areas, and reanalysis efforts became part of this objective.

The observing system has from then on evolved together with the development of operational forecasting requirements. Daily forecasts were produced by the National Meteorological Center, Washington, for the Northern Hemisphere from 1955 to 1974, and from then on for the whole globe. Consequently more observations and with higher frequency were needed over the model domain to produce the analysis.

The role of satellite observing systems has grown significantly over time. In 1972 the first operational meteorological satellite that sounded through the depth of the troposphere and stratosphere was launched. The increasing quality of the ERA-40 weather analysis resulted in better retrospective 10-day forecasts, in particular in the Southern Hemisphere. A dramatic further improvement in the ERA-40 analysis is seen from 1979 onwards. An observing system comprising two polar orbiting and five geostationary weather satellites, one of them European, was introduced. After proving successful, this system became a long-term component of the global observing system with further significant upgrades in 1987, 1991 and 1998.

The conventional observations for ERA-40 originate from many sources, reflecting the evolution of the global observing system and the archiving by various past users. Most of the data from the numerous pre-1979 sources were collected as a dedicated effort by NCAR (the National Center for Atmospheric Research, United States).

The coverage of the Northern Hemisphere by radiosondes is relatively good and to a large extent uniform throughout the period, and radiosonde quality gradually improves over time. Even though the number of radiosonde ascents decreased in the 1990s, the overall quality of the observing system has improved, due to increases in other data types such as radiances from polar-orbiting satellites, winds deduced from successive images recorded by geostationary satellites, and winds and temperatures from aircraft. The contribution of the fixed weather ships to the observing system over the North Atlantic and North Pacific was important before 1979. In the Southern Hemisphere and in the Tropics the amount of radiosonde data has increased gradually. Here however, over the large ocean areas, and over the Antarctic, Africa and South America, the conventional observing system alone is not sufficient to produce high quality analyses. Therefore 1979 brings a more dramatic improvement in the quality of analyses in the Southern Hemisphere than in the Northern Hemisphere.

Applications of reanalysis

The success of reanalysis can be measured by the number, variety and quality of applications of its products. There are few spheres of life that are not touched by weather and climate. Reanalyses have accordingly found application in sectors such as agriculture, water, air quality, health, ecosystems and biodiversity. Direct applications in the field of weather and climate include studies of predictability from days to seasons ahead, estimation of long-range transport of pollutants, investigation of recent climate change and assessment of the capability of climate-prediction models to simulate such change. As reanalysis systems are further refined, their products will increasingly form the backbone of the information essential for climate related policy- and decision-making in a changing global environment.

The potential of reanalysis is illustrated well by one of the most severe storms of the 20^{th} century over Europe, which occurred on 31 January/1 February 1953 causing the greatest surge on record for the North Sea as a whole. Its amplitude reached 2.74 m and 2.97 m at Southend and King's Lynn in England and 3.36 m in the Netherlands. Almost 100,000 hectares of eastern England were flooded and 307 people died. In the Netherlands, 50 dykes burst and 1,800 people drowned. Figure 1 shows the reanalyzed near-surface wind (maximum speed about $30ms^{-1}$) and ocean-wave height (metres) for 00 UTC, 1 February 1953. The strong winds from the north have a long fetch (the distance over which wind blows without changing direction) to develop more than 9 metres high waves over a large area. The high tide connected with the high waves had the devastating effect. In order to better understand the effects of the storm, the global reanalyzed fields have also been used as boundary conditions for high resolution limited area models to drive detailed storm surge models.

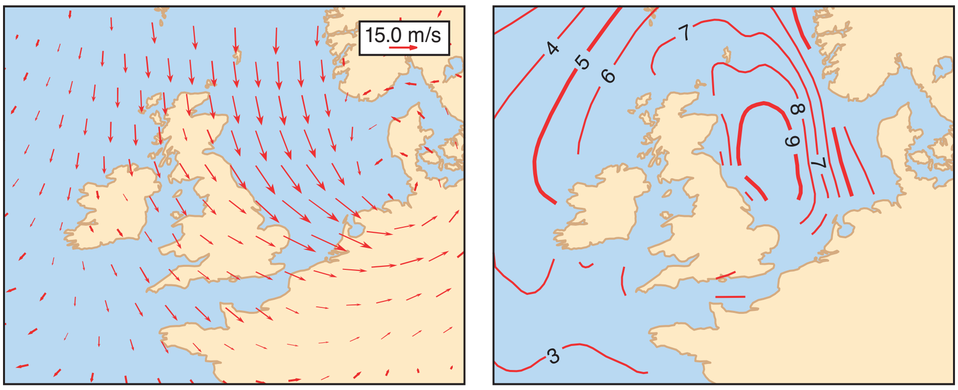

Figure 1 Near-surface wind (maximum speed about $30ms^{-1}$) and ocean-wave height (metres) from a reanalysis for 00 UTC, 1 February 1953, the night of a devastating North Sea storm.

Reanalysis used for climate studies

Climate, defined as the long-term statistics of the atmosphere, is demonstrated here with a few examples. A common climate quantity is the annual mean surface 2-metre temperature. Figure 2 shows this from ERA-40, averaged over the period 1979–2001, during which the global observations are more numerous and uniform and therefore the reanalyses more accurate. The spatial structure over the oceans follows the warm and cold ocean currents near the continents. The warming effect of the Gulf Stream is seen throughout Europe and extreme cold temperatures are found over the high Antarctic plateau.

Figure 3 compares a time-series of monthly means of the ERA-40 reanalyses and the climatological temperature analyses by the Climate Research Unit (CRU) of the University of East Anglia, for the Northern Hemisphere. The ERA-40 temperature trend agrees very well with the CRU data from the late 1970s onwards, indicating that the quality of the reanalysis temperatures is good. Earlier, however, the ERA-40 temperatures indicate systematically too warm temperatures, the main reason being that not all observations used in the CRU analysis were available for ERA-40.

Figure 4 shows the mean surface wind patterns (mean vector wind and speed). The small but persistent winds over the tropical oceans and high latitudes are well represented. The mean winds and their fluctuations are the driving forces of the ocean circulation, and have been successfully used in ocean simulation studies.

Annual daily mean precipitation is shown in Figure 5. This is a product from the dynamical and physical processes of the model used in the reanalysis. Its quality is related both to the quality of the model and to the quality of the initial state. It can be seen that most of the global precipitation is produced in the equatorial convergence zones. The patterns of precipitation are in good agreement with independent precipitation analyses, but values are too high over the tropical oceans.

When the amount of precipitation is subtracted from the amount of evaporation, Figure 6, areas of net evaporation and net precipitation can be seen. Energy exchanged between the atmosphere and the surface is an important component needed to understand how the Earth's climate system works and, in time, how the climate is changing and for what reason.

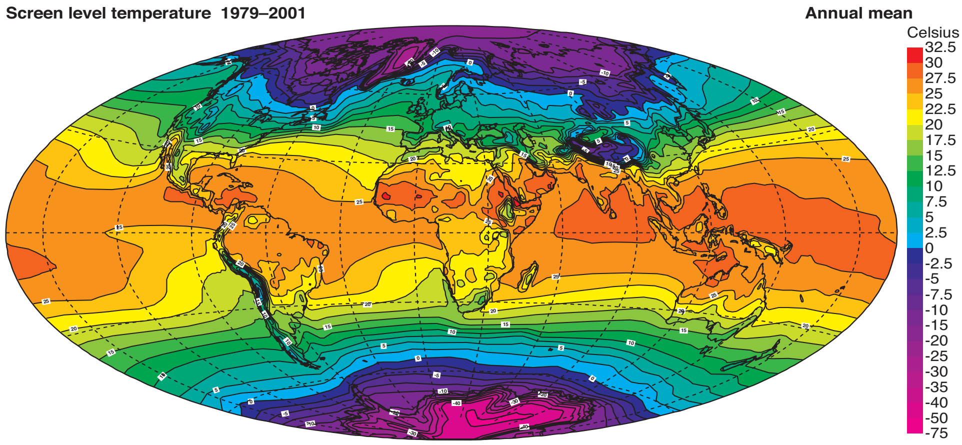

Figure 2 Global mean 2-metre temperature 1979–2001

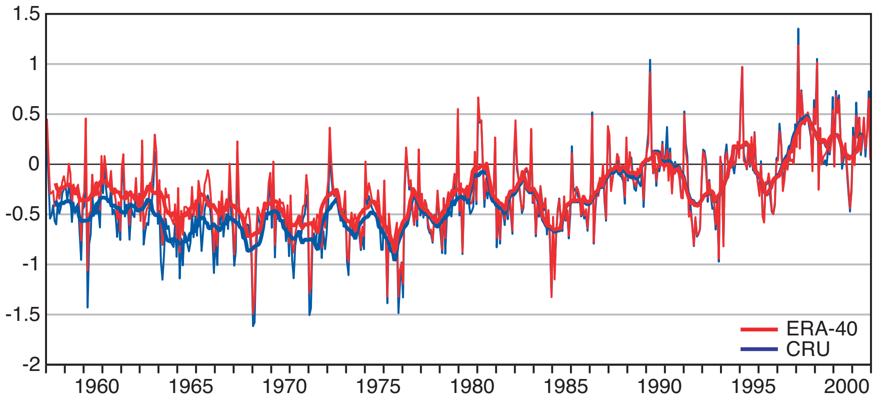

Figure 3 The temperature trends represented by temperature anomalies (°C) from the 1987–2001 mean for the ERA-40 reanalysis and for the CRU analysisin the Northern Hemisphere. Monthly means and 12-months running means are shown.

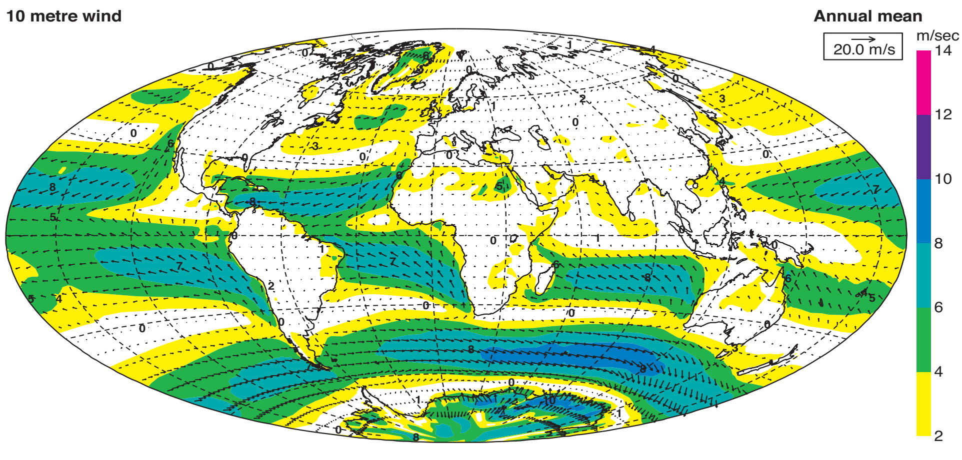

Figure 4 Mean annual near surface wind speed (m/s) and direction 1979–2001.

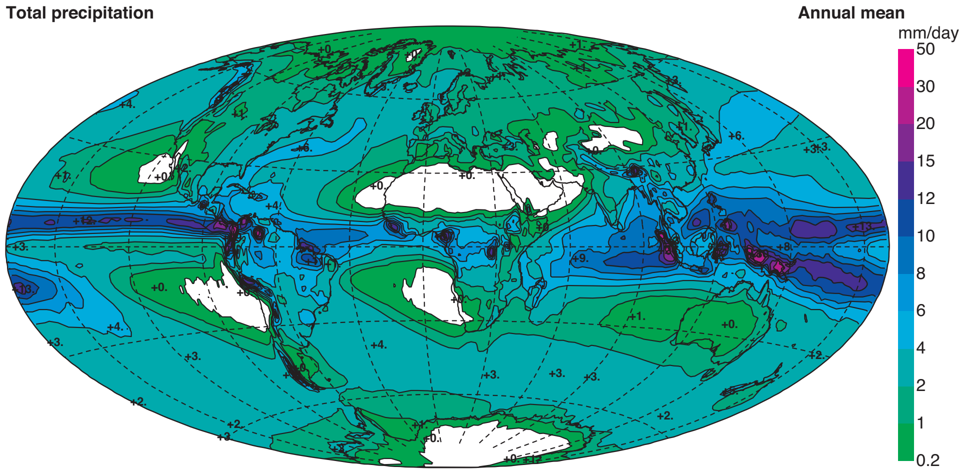

Figure 5 Annual daily mean precipitation (mm/day) 1979–2002.

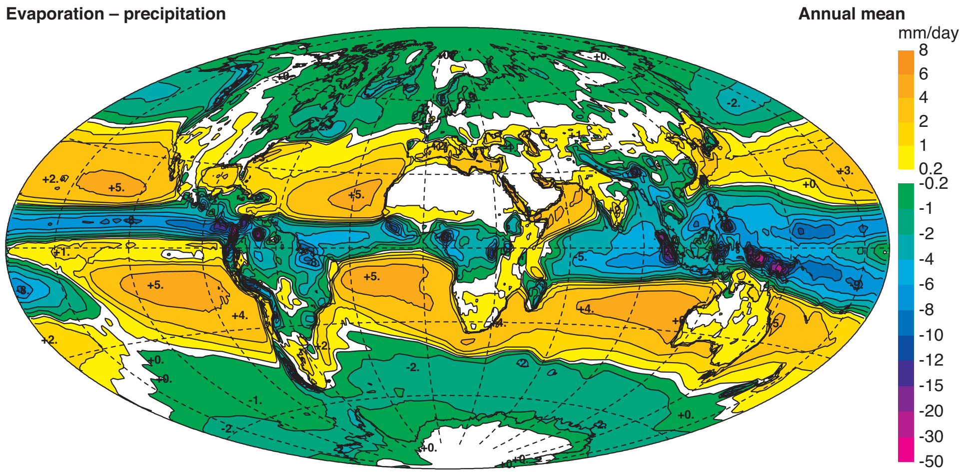

Figure 6 Annual mean evaporation-minus-precipitation (mm/day) 1979–2002.

Outlook

An ECMWF "interim reanalysis" with higher horizontal and vertical resolution than ERA-40, covering the period from 1989 onwards, will use an upgraded data assimilation and forecasting system, thus addressing several problems occurring in the ERA-40 analysis. The "interim reanalysis" will be produced during 2006 and 2007, and subsequently updated on a near-real time basis.

ECMWF will cooperate with the climate science community to prepare the next re-analysis project. There is a considerable potential in this activity to deliver the most reliable estimates of regional temperature and humidity trends over the period from the 1930s to the present. The scope of the re-analysis activity will be progressively extended to atmospheric chemistry, to the oceans and to the continental surfaces through cooperation with relevant institutes in the Member States. This will provide access to, inter alia, the detailed history of the ozone hole, or an accurate account of some of the most severe droughts of the last century in various parts of the world. There will also be return-on-investment in the quality of medium-range weather forecasts, through studies of the inter-annual variability of the forecast skill and through the possibility of testing new model formulations on past severe weather cases.

ECMWF's experience with global reanalysis makes ECMWF well placed to serve the development of a proposed European regional reanalysis (EURRA), a project of around ten years duration that would culminate in a mesoscale reanalysis using a 2 km-resolution data assimilation system, focussing on surface parameters, such as sea surface temperature and ice distribution, lake temperatures and ice state, land surface and soil characteristics, precipitation and snow analysis.

Public access to the ERA-40 reanalysis data

In the ERA-40 archive, in total 33 Terabytes, the analyzed weather elements and model products are available at six-hour intervals. Public access to a subset archive is via the web: http://data.ecmwf.int/data

National Meteorological Services of Member States have direct access to the full archive. Some countries have also set up specialized data archives to provide their research institutes and universities with fast access to the data.

ERA-40 products are extensively used by the worldwide scientific community. Results are being documented in thousands of publications / presentations, among them the ERA-40 Reports Series. The latter includes the ERA-40 Atlas, which describes the climate for the period 1979–2001.

For further information on the ERA-40 reanalysis see http://www.ecmwf.int/research/era/
and newsletter articles and technical reports available from http://www.ecmwf.int/publications.